Detection of Equipment Faults Before Beam Loss

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USPAS

Long Beach CA,

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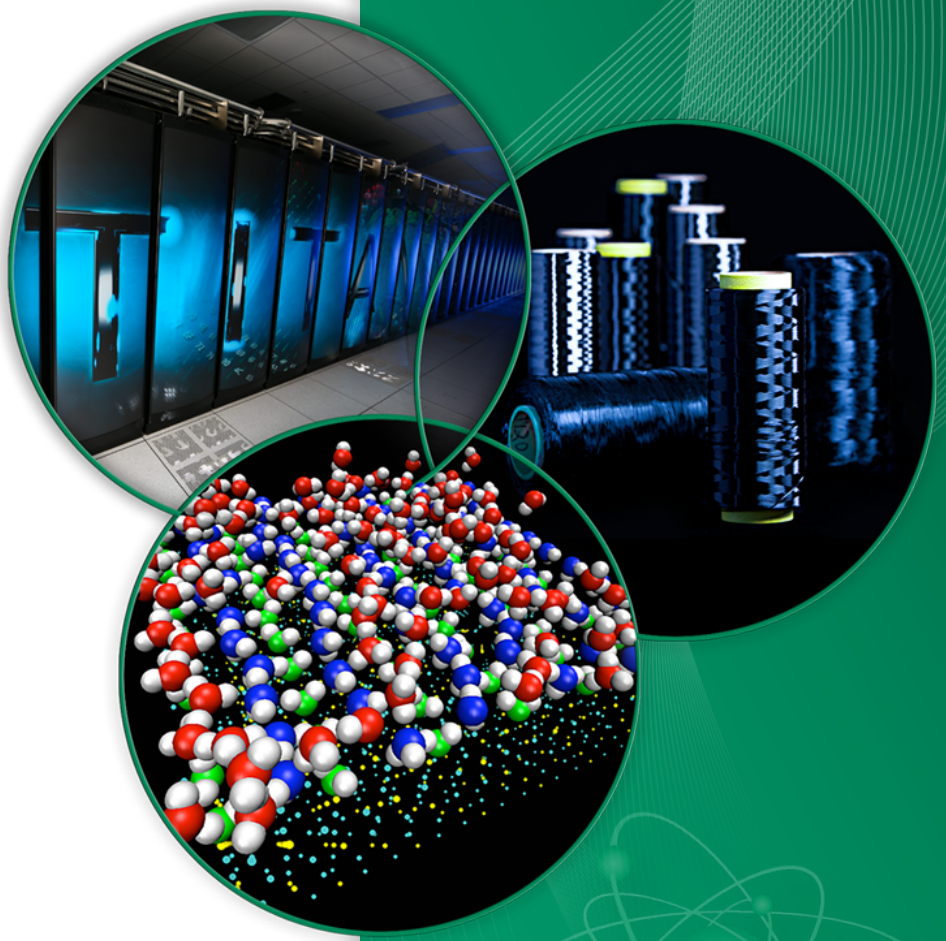

Outline

- Devices types that affect the beam :
  - Magnets
  - RF
  - Vacuum
  - Sources
  - Rotating equipment
- Measurement types
  - Current, voltage, temperature, beam loss
- Using the beam as an equipment issue precursor indicator

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Beam Loss: How To Define

- Different classes of beam loss / equipment protection
  - "Melting metal":
    - Gross beam loss
    - Short period of time
    - Fast hardware protection
  - Activating the machine
    - Constant level of higher than normal loss
    - Accrued over long periods
    - Slower response protection is possible (software)
  - "Noise level" fluctuations in operational beam loss
    - Loss monitor trip limits are set to allow stable operation (factor of 1.5 – 2 above nominal loss monitor response)
    - There is opportunity to look for trends in this range

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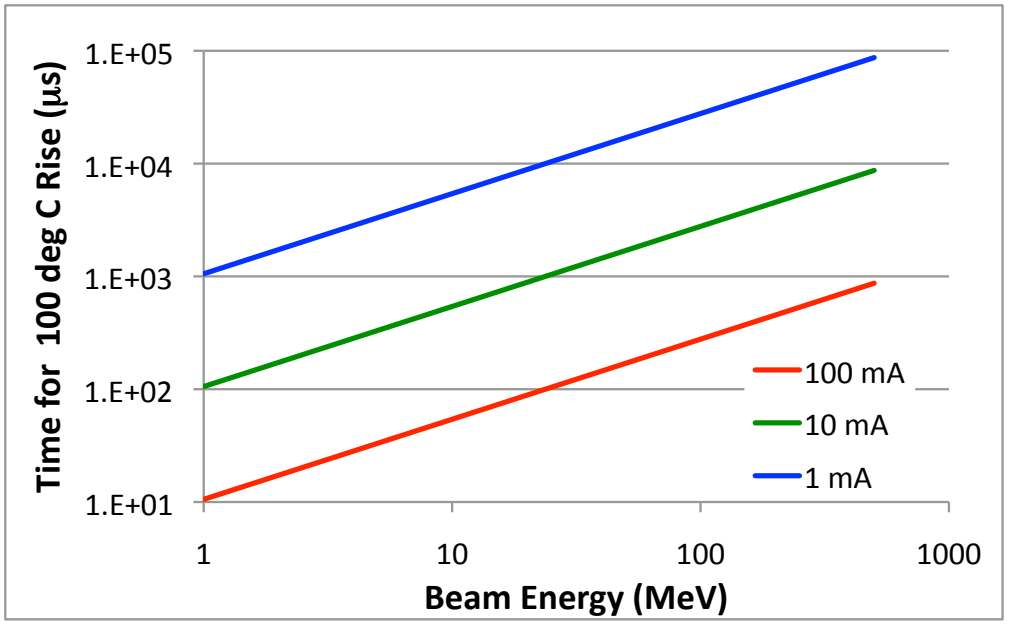
Beam Loss: Protecting against Gross Beam Loss



Ideal case:
Proton on Cu

- Machine Protection Systems (MPS) provides a hardware system for fast shut-off (typically < 1 ms)
- Most problematic at low beam energies, due to the smaller stopping distance
- Equipment precursor issues typically show up before gross beam loss is a problem

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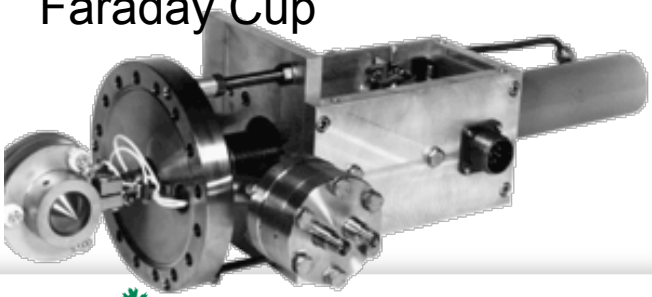
Is The Machine Ready for Beam?

- Make sure nothing is in the way of the beam
  - No closed valves, in-appropriate interceptive beam diagnostics, etc., where beam is being directed

limit switch

- Machine Protection Systems typically protect against this with appropriate beam inhibits
  - "Slow protection" since these systems typically do not move fast
  - Easy to prevent this problem
  - In principle, things can be over-ridden – be careful

Faraday Cup



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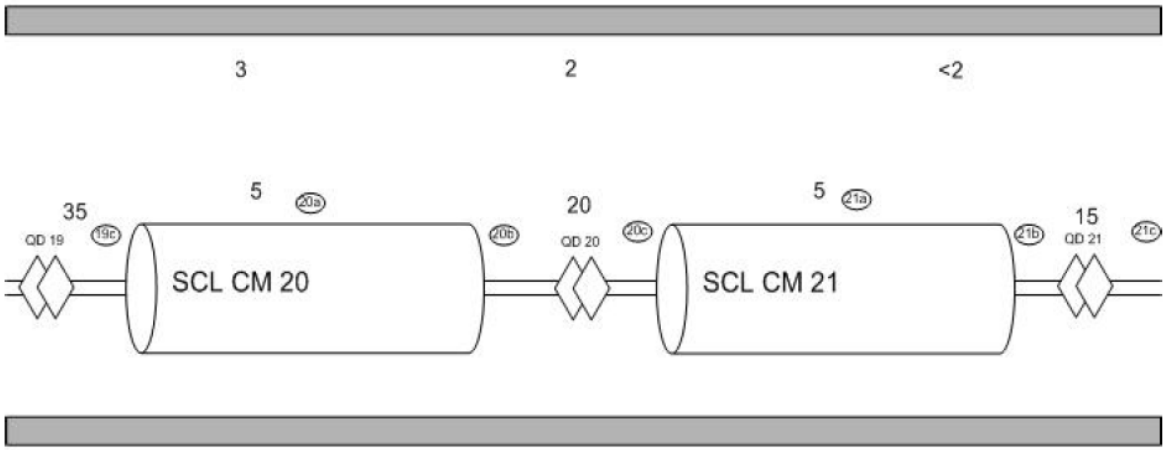
Beam Loss: Preventing Activation

- Machine activation
  - "1 W/m" loss rule applies for proton beams > ~ 100 MeV for hands on maintenance
  - "Slow" software systems can average over 1-10 seconds
  - Need to provide some margin in the trip limit for reliable operations (say factor of 2)



Sample activation map

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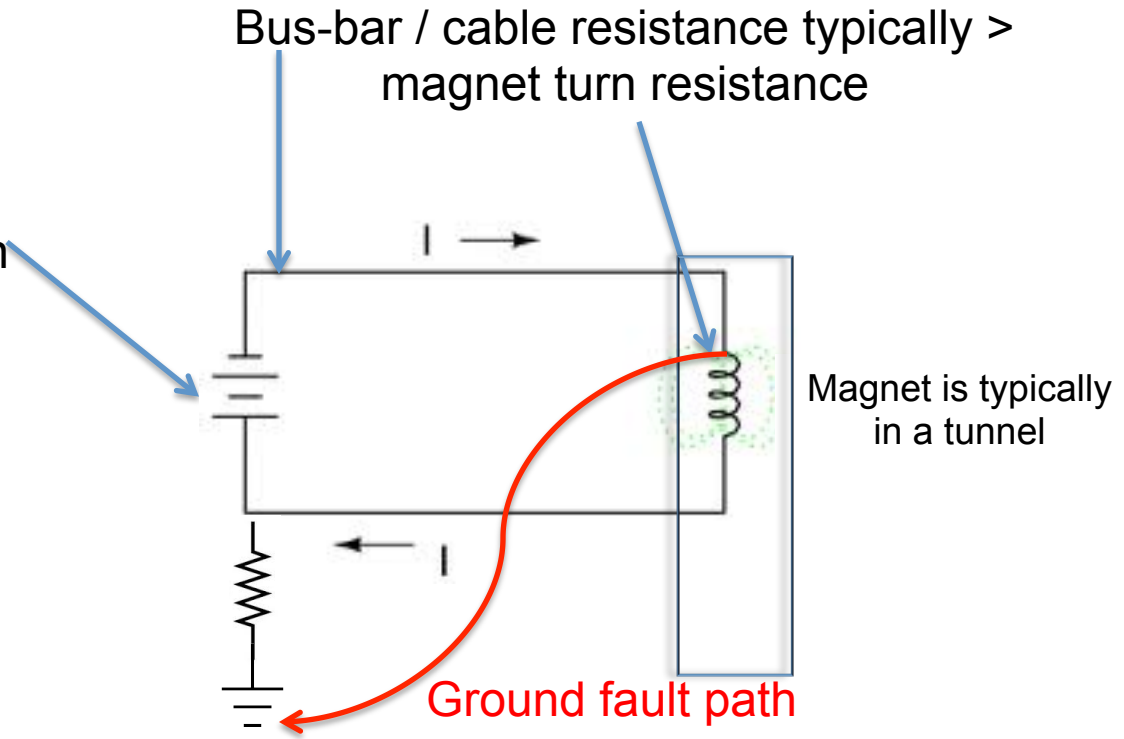
Magnets: High Level View

- Power supply with regulation control
  - Typically in a remote service building
  - Interface is through a controller supplied by vendor



- Purpose: provide a prescribed field (current) to control beam
- Ground Faults
  - Can shunt current away from the magnet
  - Detect through metering resistor to measure ground fault current (standard)

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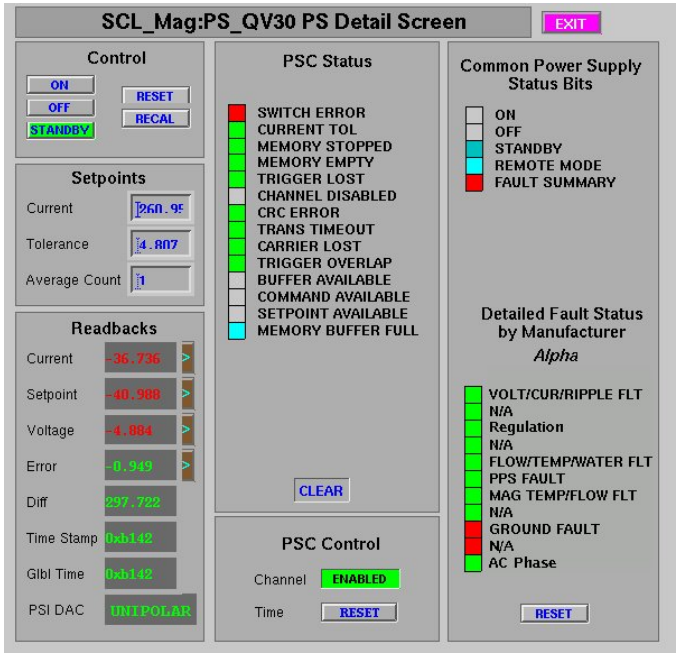
Ground Fault Examples

Hard to understand engineering screen



Obvious cause

- Can bypass a ground fault and run
  - Dangerous

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Magnets

- Turn-to-turn faults
  - Difficult to detect with equipment signals (unless magnet is only a few turns)
  - Masked by temperature fluctuations.
    - Copper resistance varies by ~0.5% per degree C
    - Water/magnet temperature can vary by as much as 10 degrees C
    - Only be seen in magnet with fewer than 10 turns if the turn to turn fault is “hard” – large contact area
    - Typically a small contact area with small current diversion.
  - Can be seen by beam steering effects (covered later)
- Cooling issues
  - Detected by temperature sensors
  - Water loss of cooling systems (level sensors)
  - Water running on a floor….

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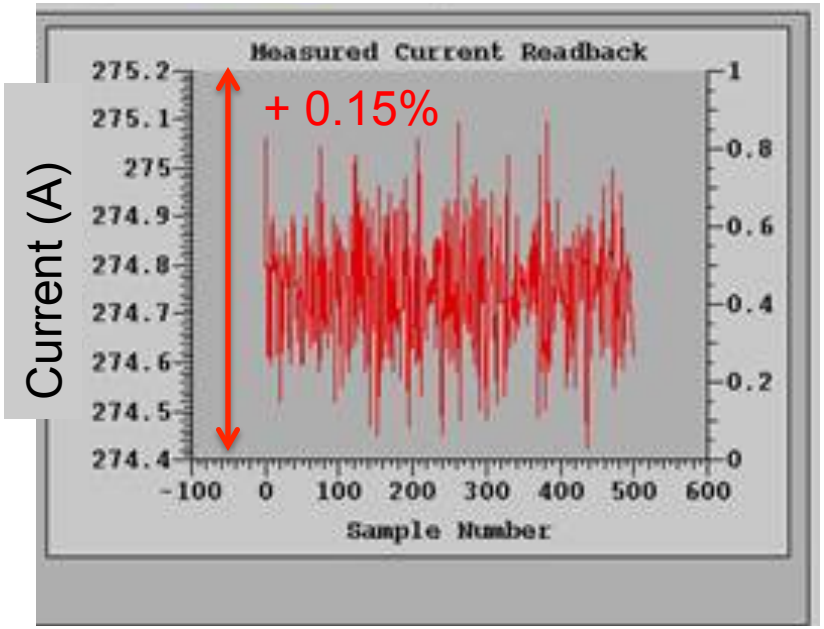
DC Magnet Power Supplies: Current Monitoring

Current Control: Good



- Magnets are required to have tightly controlled current
  - Power supply controllers typically have a tight current control and read-back specification
  - 10^{-3} for single pass beam (linac, transport line), $\leq 10^{-4}$ for rings
- Loss of current regulation can cause beam loss
  - Usually easy to spot
  - Current is not at it's set point, usually a power supply issue

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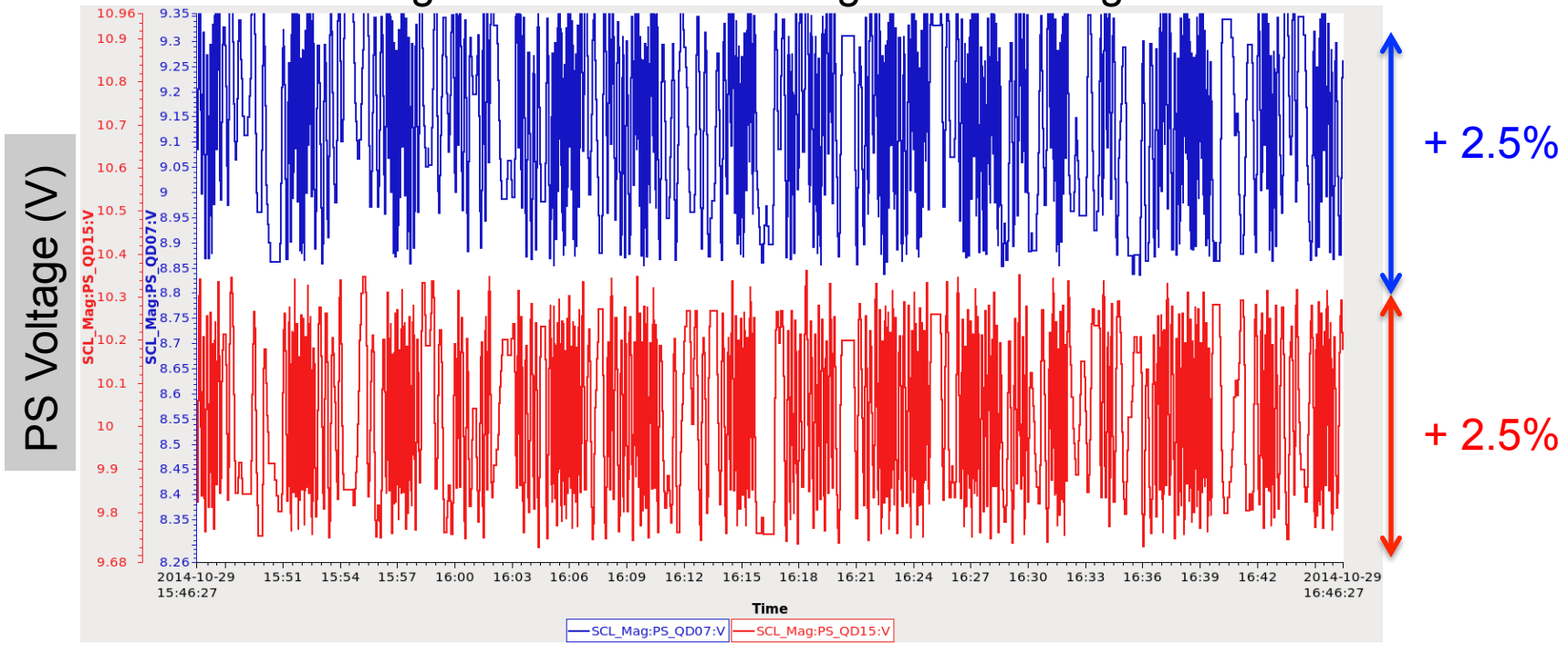
DC Magnet Power Supplies: Voltage Monitoring

Voltage read-back on 2 magnets: not so good



- Often power supply voltage read-backs specifications are not given when buying
  - End up with lousy read-back
- Because the voltage signal fluctuates (system noise), it is difficult to spot magnet hardware faults
  - E.g.: turn-to-turn short – these are rare – can detect with beam
  - Poor terminal contact – can cause hot spot – harder to detect with beam

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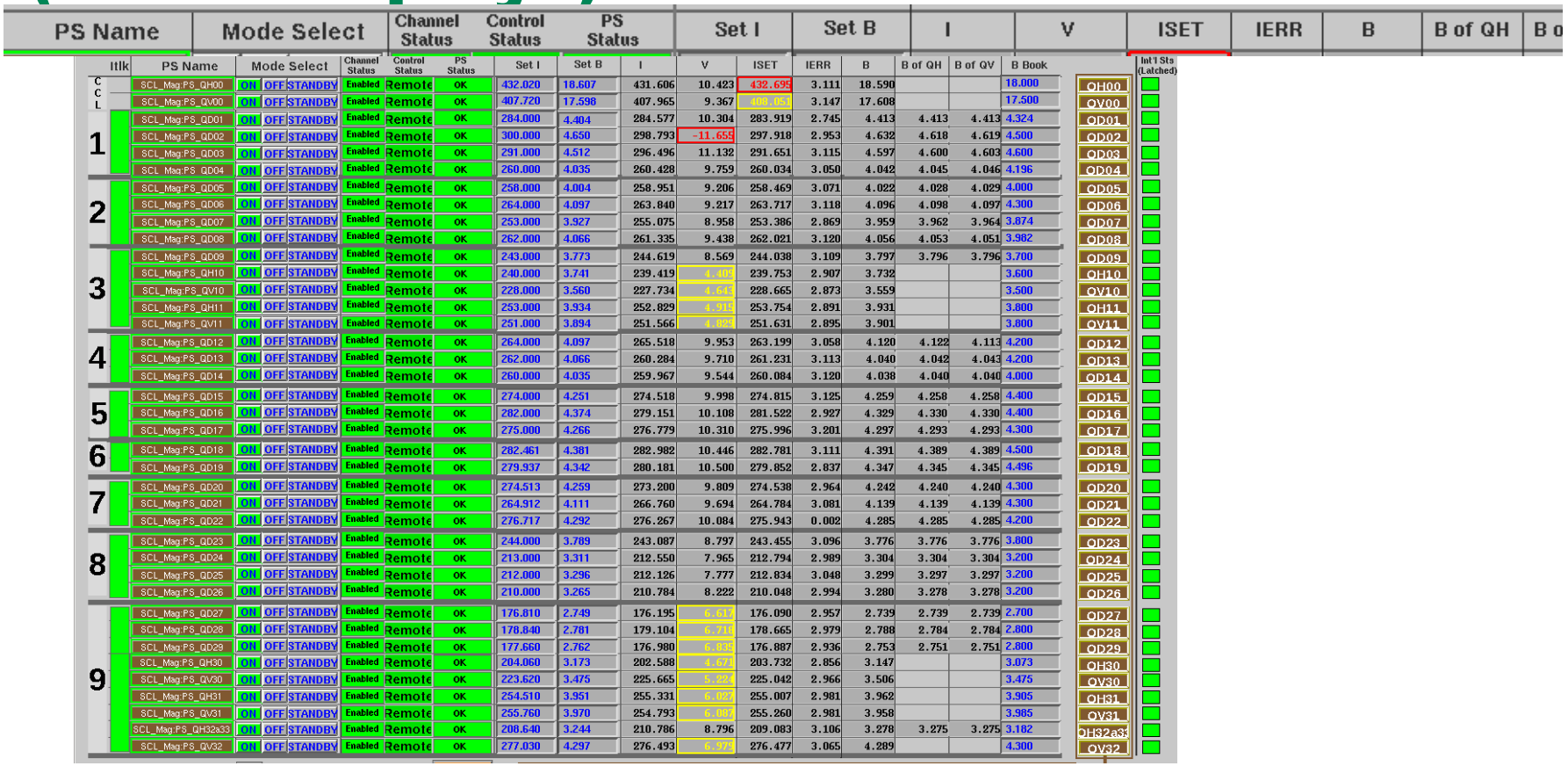
Monitoring Magnet Power Supplies (Fixed Displays)



- Engineering screens
  - Fixed displays, with warning (yellow) and error (red) status displays
  - Lots of information
  - Difficult to maintain

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Monitoring Magnet Power Supplies (dynamic displays)

Setpoint PV	Saved Setpoint	Live Setpoint	Readback PV	Saved Readback	Live Readback	Setpoint Error(%)	Readback Error(%)
HEBT_Mag:PS_DCV31:I_Set	0.19924	0.19924	HEBT_Mag:PS_DCV31:I	0.18512	0.19927	0.001	7.37
HEBT_Mag:PS_QH10:I_Set	241.28000	245.28000	HEBT_Mag:PS_QH10:I	241.27289	245.27934	1.644	1.64
HEBT_Mag:PS_DCH06:I_Set	-0.03969	-0.03969	HEBT_Mag:PS_DCH06:I	-0.03949	-0.03999	0.000	1.25
HEBT_Mag:PS_DCV23:I_Set	0.48689	0.48689	HEBT_Mag:PS_DCV23:I	0.48093	0.48124	0.000	1.16
HEBT_Mag:PS_DCV05:I_Set	-0.24315	-0.24315	HEBT_Mag:PS_DCV05:I	-0.24118	-0.24110	0.000	0.84
HEBT_Mag:PS_DCV15:I_Set	-1.59817	-1.59817	HEBT_Mag:PS_DCV15:I	-1.58625	-1.58634	0.000	0.74
HEBT_Mag:PS_QV09:I_Set	249.72700	249.72700	HEBT_Mag:PS_QV09:I	248.52235	248.27945	0.000	0.58
HEBT_Mag:PS_DCV29:I_Set	-2.16824	-2.16824	HEBT_Mag:PS_DCV29:I	-2.15838	-2.17082	0.000	0.57
HEBT_Mag:PS_DCH28:I_Set	3.53712	3.53712	HEBT_Mag:PS_DCH28:I	3.52062	3.53568	0.000	0.42
HEBT_Mag:PS_QV07:I_Set	328.45000	328.45000	HEBT_Mag:PS_QV07:I	330.05597	329.70675	0.000	0.38
HEBT_Mag:PS_DCH14:I_Set	0.58088	0.58088	HEBT_Mag:PS_DCH14:I	0.58041	0.58245	0.000	0.35
HEBT_Mag:PS_DCH30:I_Set	-1.49716	-1.49716	HEBT_Mag:PS_DCH30:I	-1.50142	-1.50023	0.000	0.20
HEBT_Mag:PS_DH11:I_Set	525.76100	525.76100	HEBT_Mag:PS_DH11:I	526.65859	525.71314	0.000	0.18
HEBT_Mag:PS_DCH22:I_Set	1.99466	1.99466	HEBT_Mag:PS_DCH22:I	1.99235	1.99195	0.000	0.13
HEBT_Mag:PS_QH30:I_Set	353.67700	353.67700	HEBT_Mag:PS_QH30:I	354.30819	353.87591	0.000	0.12
HEBT_Mag:PS_DCV07:I_Set	0.32206	0.32206	HEBT_Mag:PS_DCV07:I	0.32176	0.32170	0.000	0.11
HEBT_Mag:PS_DH25:I_Set	532.90700	532.90700	HEBT_Mag:PS_DH25:I	533.37903	532.83455	0.000	0.10
HEBT_Mag:PS_DCH08:I_Set	1.19927	1.19927	HEBT_Mag:PS_DCH08:I	1.19798	1.19821	0.000	0.08
HEBT_Mag:PS_QV11:I_Set	211.14300	211.14300	HEBT_Mag:PS_QV11:I	210.93965	211.10213	0.000	0.07
HEBT_Mag:PS_QV25t31o:I_Set	221.77200	221.77200	HEBT_Mag:PS_QV25t31o:I	221.51534	221.68365	0.000	0.07
HEBT_Mag:PS_QH08:I_Set	241.61600	241.61600	HEBT_Mag:PS_QH08:I	241.63946	241.45666	0.000	0.07

- Filter capabilities (area of accelerator, device type, ….)
- Sorting (largest deviation in set-point, read-back, ….)
- Applicable for any equipment
- Easy to create / search for saved configurations

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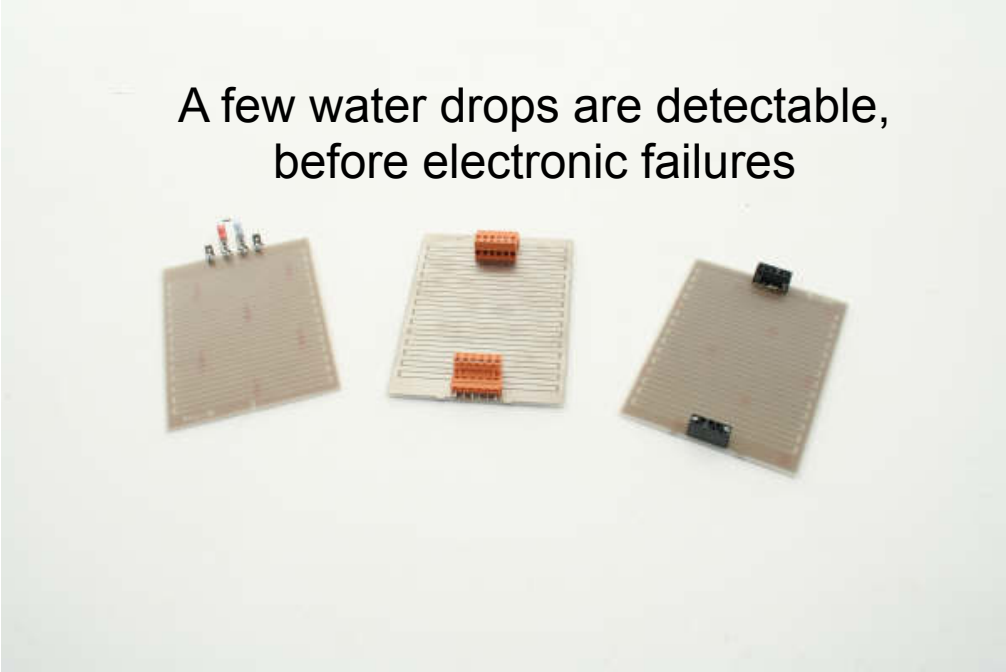
Magnet Power Supplies

- Water Faults (most large power supplies require active cooling)
  - Over-temperature sensors on components
  - Water mats are an early drip detection technique



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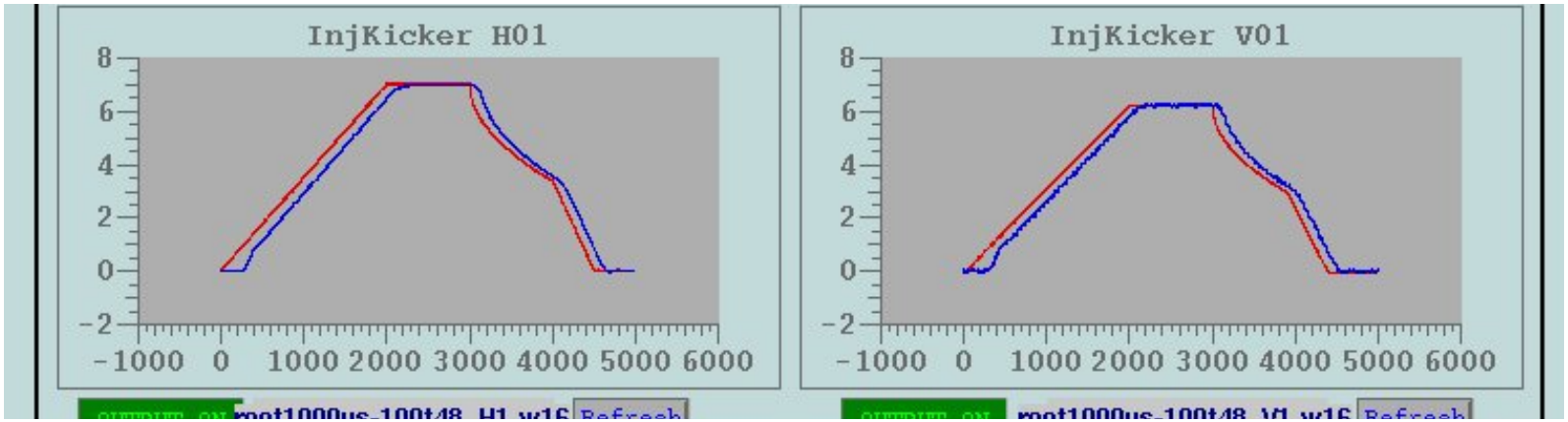
Pulsed Magnets (Slow: 1-10 ms)



Red = target waveform, Blue = actual

- Used in injection painting bumps
- Rapid Cycling Synchrotron acceleration ramps
- Waveform monitoring
  - Compare the actual waveform with a “target pattern”, point by point
  - Trip beam if the deviation becomes too large
- Problem causes:
  - Random component failure
  - Drift with temperature

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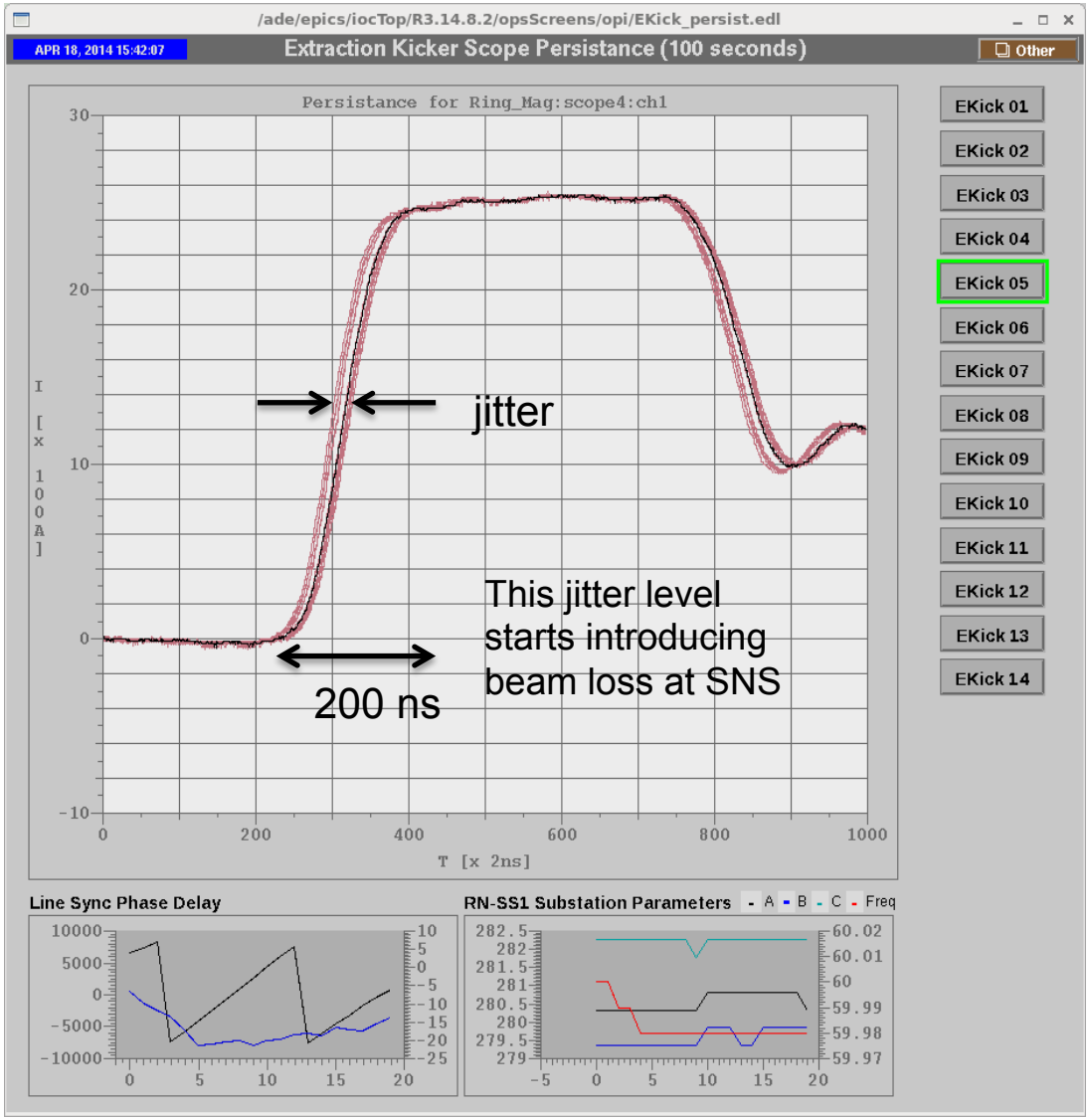
Pulsed Magnets (Fast: < 1 μs)

- Used for fast extraction in rings
- If waveform starts drifting in time, it causes extraction beam loss
- Need strict monitoring for drift
  - Use a “persistence display” to display the drift
  - Can identify the onset of thyratron end of life



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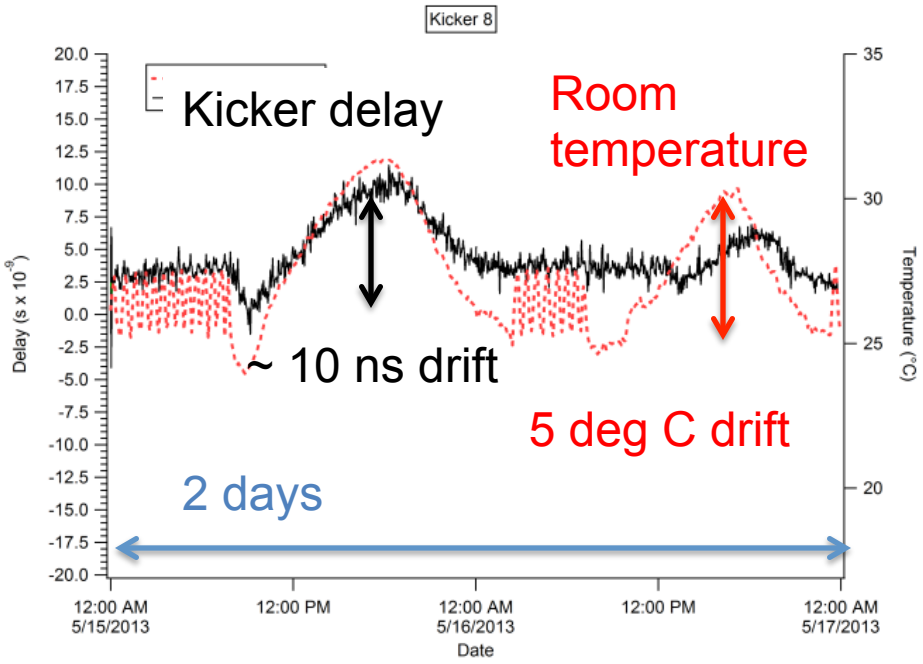
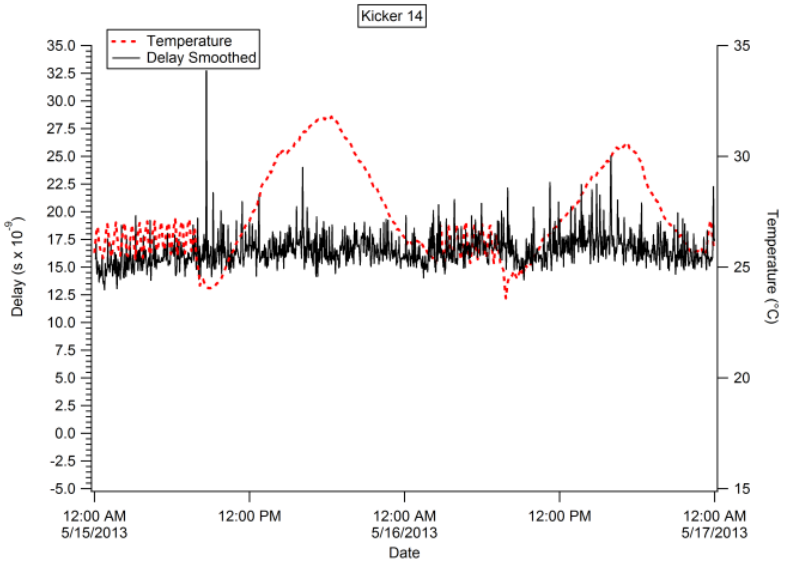
Pulsed Magnets

- What can cause “fast trigger” drift?
- Temperature change
  - Low voltage transformer !
- Issue was identified during production run

Before



After thermal isolation of trigger electronics



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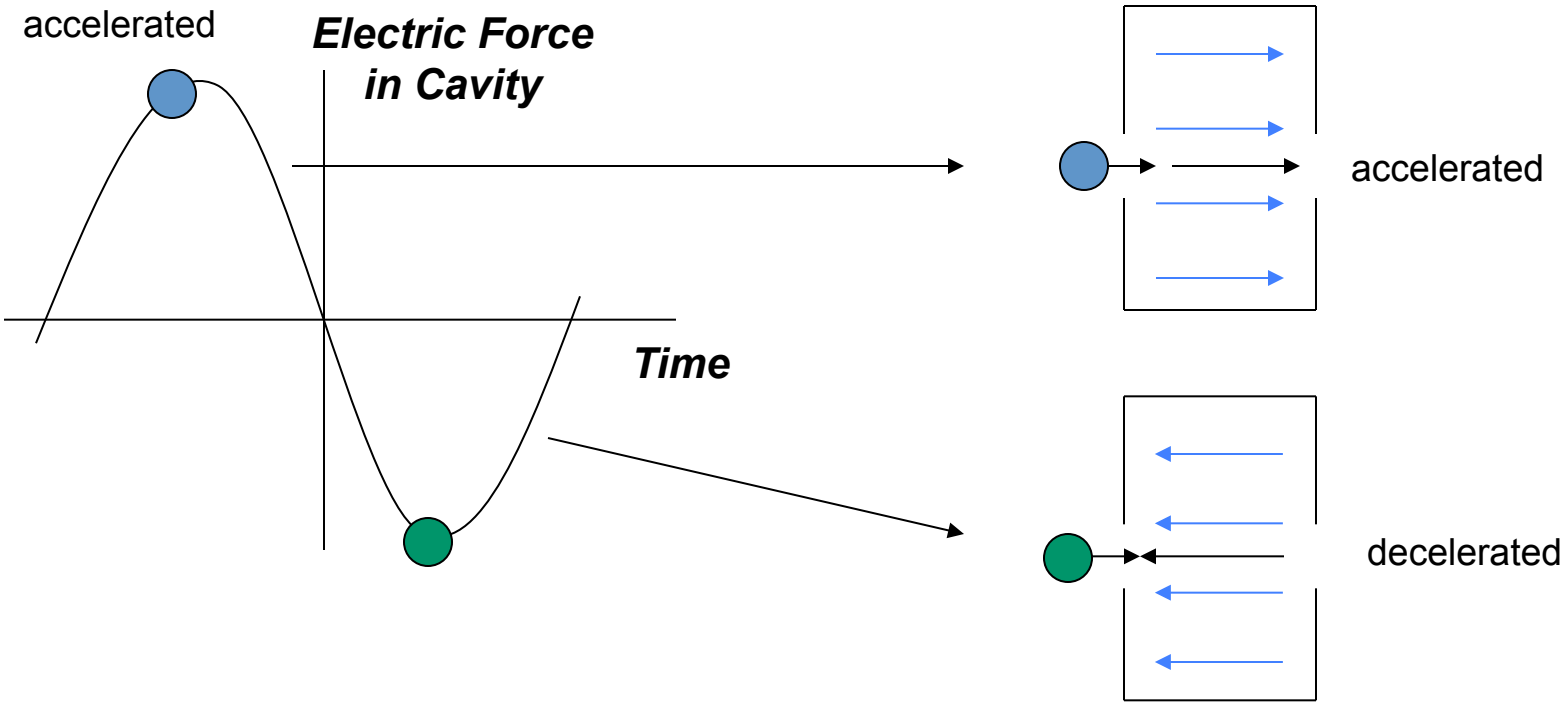
Sinusoidal Nature of RF Fields

The beam must be timed right to pass through the field only during acceleration, and be shielded from the field during deceleration.



- Linac RF runs at a frequency of 100-1000 MHz (1 billion sign changes of the field per second).
- Setting the RF timing relative to the beam within a “degree” at 1 GHz corresponds to < 3×10^{-15} s

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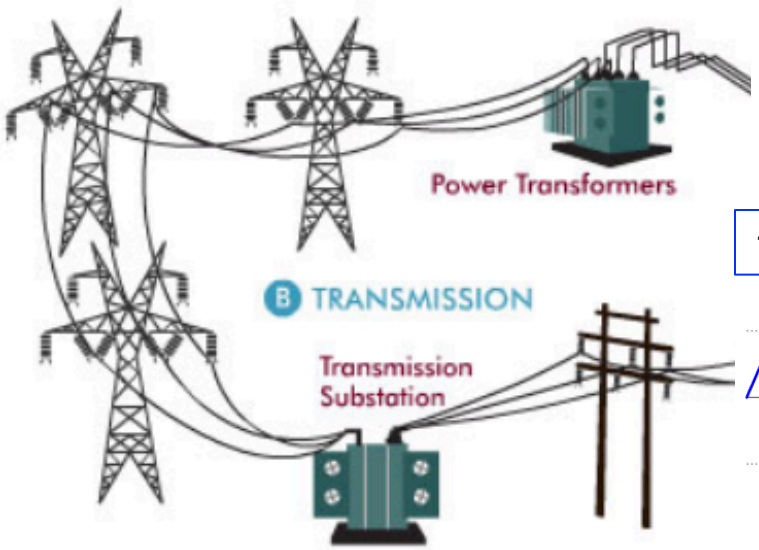
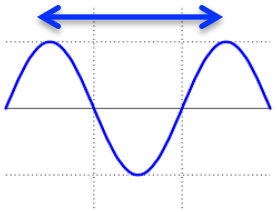
RF Power Systems Overview (SNS Example)

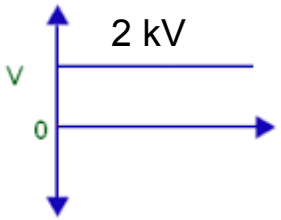


13.8 kV AC

16.7 ms, 60 Hz



SCR: Convert to DC

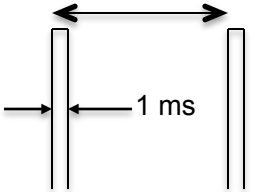


Pulsed Forming Network (PFN), Modulator, HVCM:

- uses fast switching IGBT (20 kHz)
- Creates 1 ms DC pulses x 60 Hz

100 kV, 100 A

16.7 ms, 60 Hz



RF Source, (Klystron): 805 MHz RF 1 ms x 60 Hz

RF Structure

- Lots of equipment, lots of opportunity for things to fail

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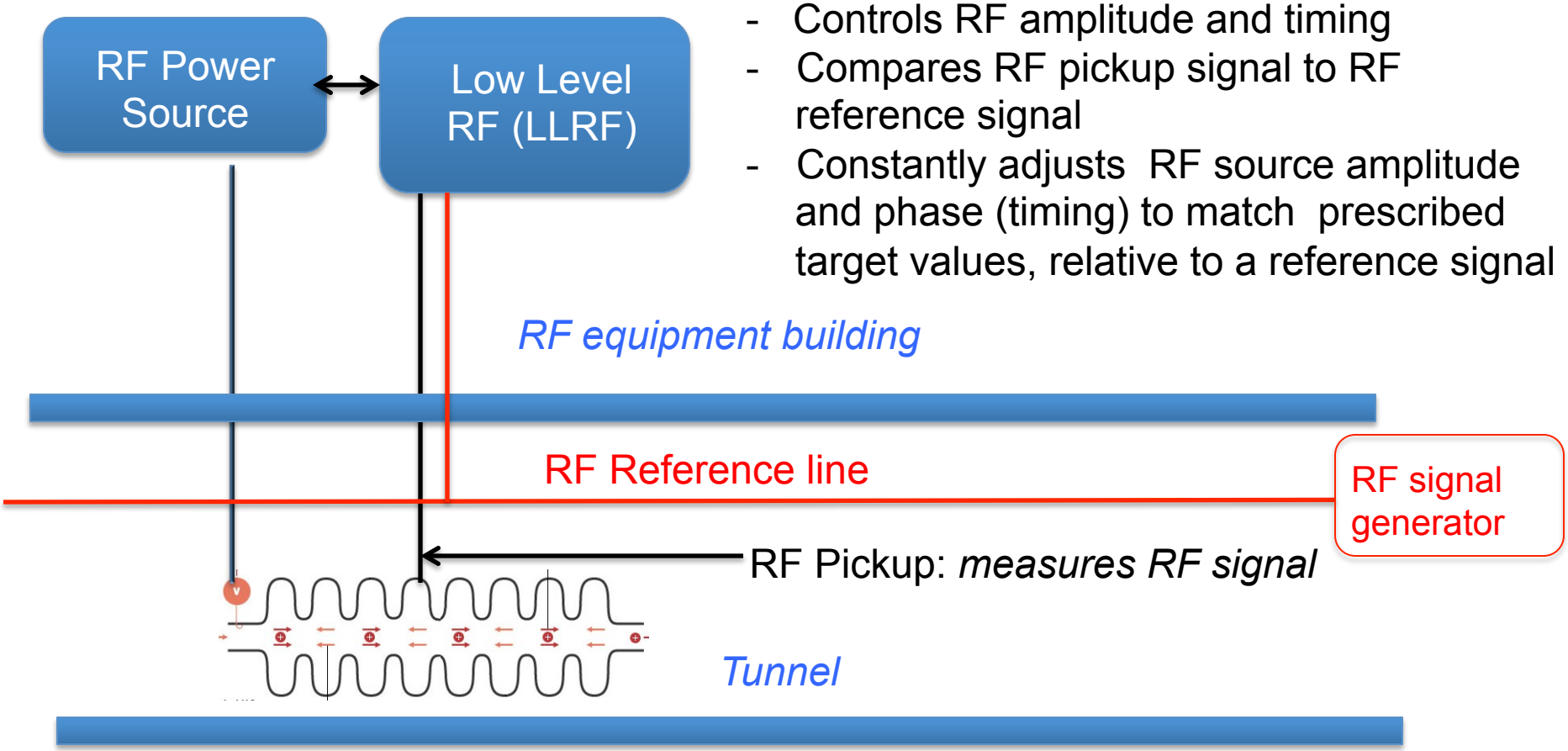
RF Control Overview



LLRF

- Controls RF amplitude and timing
- Compares RF pickup signal to RF reference signal
- Constantly adjusts RF source amplitude and phase (timing) to match prescribed target values, relative to a reference signal

- What could go wrong?
  - Stable RF reference line is critical
  - Time for RF signal to propagate through the tunnel is temperature dependent

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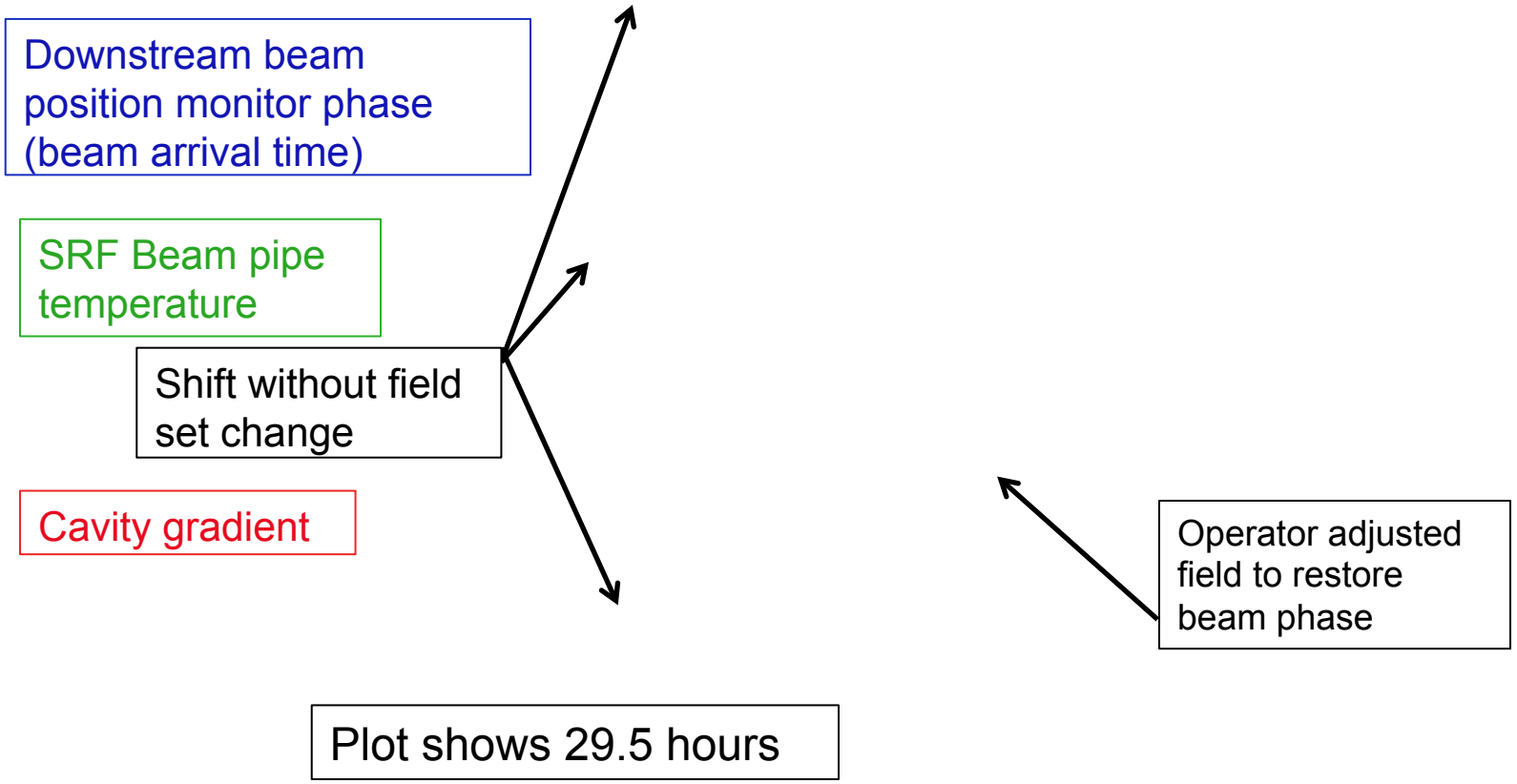
Detecting RF Equipment Issues (I)
(Event Time History)



- Use downstream superconducting linac cavity temperature and beam arrival time, to detect cavity amplitude control problem
  - LLRF field control module problem

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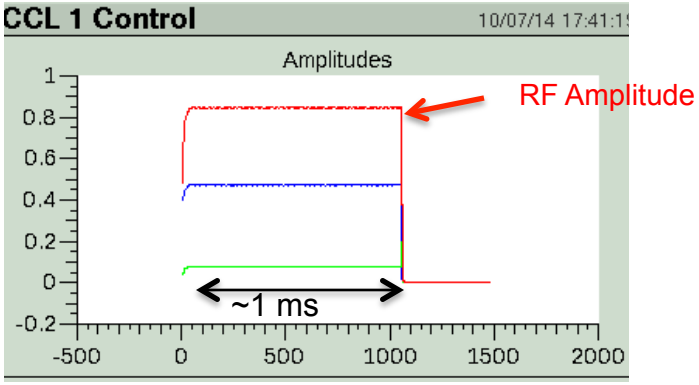
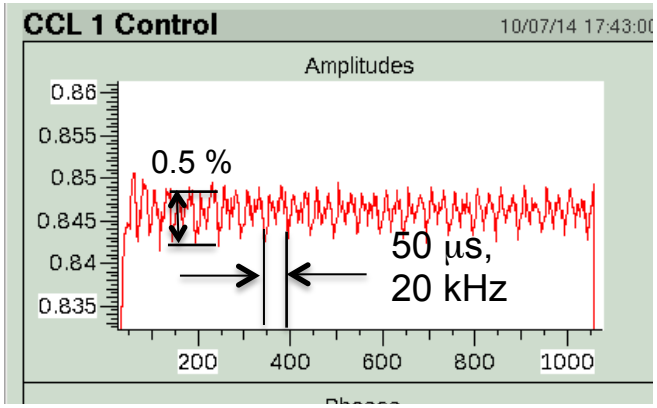
20 kHz from the HVCM Can Bleed into the RF



- RF amplitude waveform looks good from a distance…



- But zoom in reveals a 20 kHz ripple
  - Ripple in this case is < allowed 1% variation
  - But should be monitored, could be a precursor to HVCM capacitor failure

- RF amplitude waveforms from a field probe indicate a 20 kHz ripple
- Ripple is from the high voltage convertor modulator that provides voltage/power to the klystrons which power the cavity

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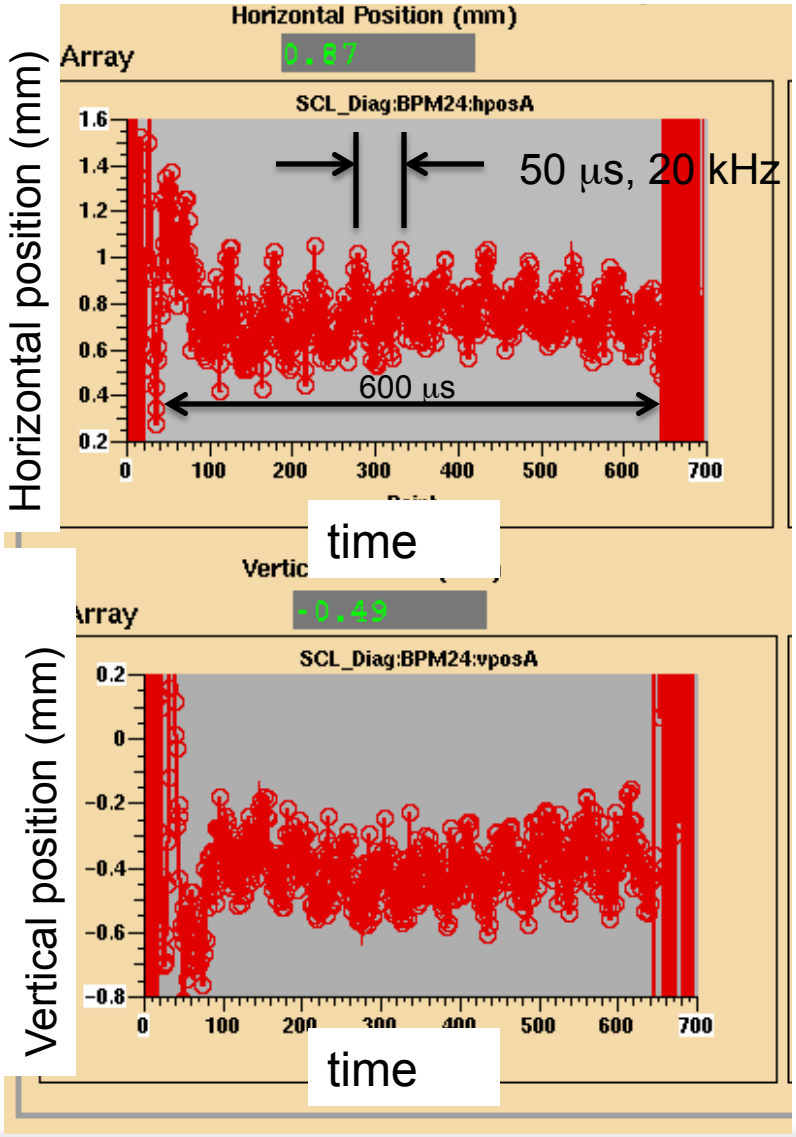
Measuring HVCM 20 kHz Ripple with Beam
Equipment degradation indicator !



- HVCM = High Voltage Convertor Modulator
  - Power source for RF
- 20 kHz ripple from RF power source is evident on beam position monitor measurements
  - … if you "zoom in"
    - Not enough to produce beam loss, … yet
    - But HVCM capacitors may need replacing soon
- Extra credit: How does RF affect beam position ???

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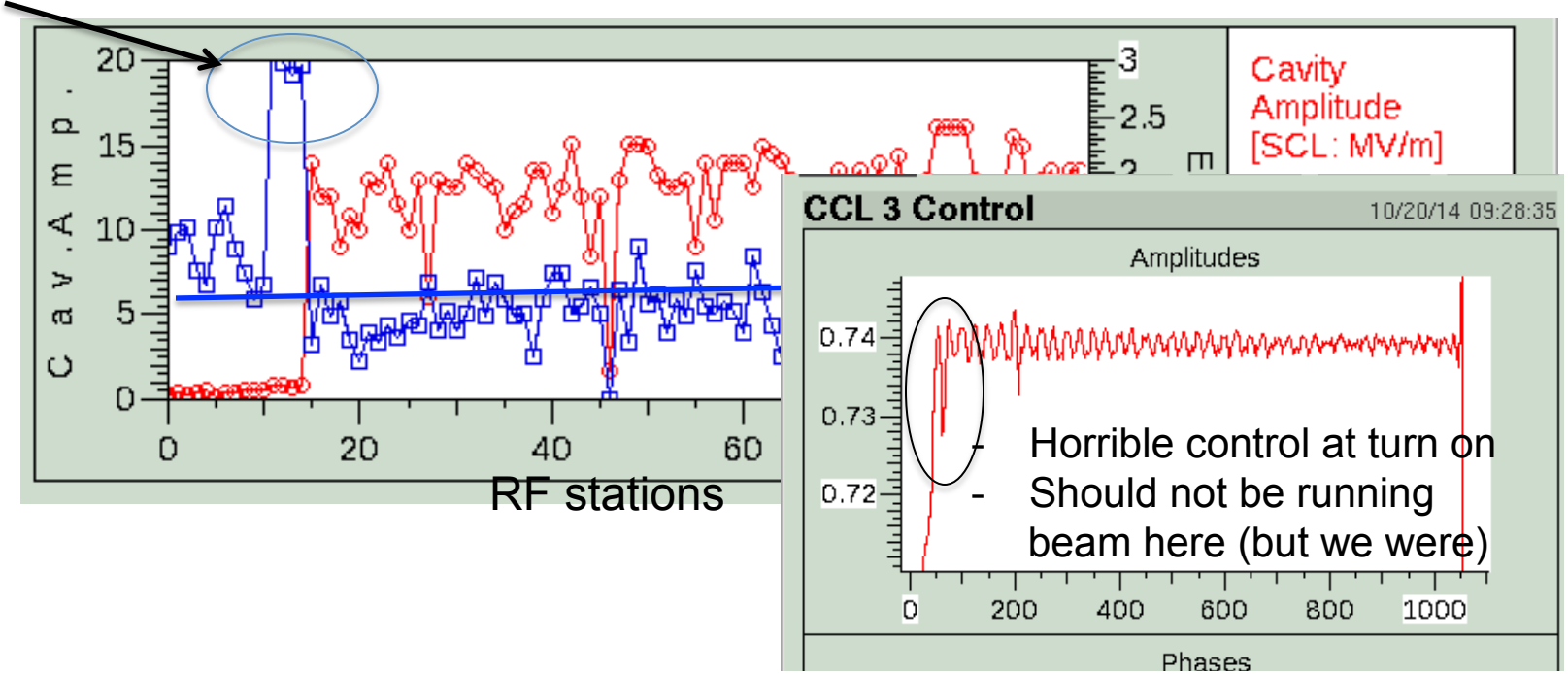
Monitoring RF Field Stability

Blue = peak error in RF amplitude over a 1 ms pulse

What's up here????



- Compare the waveform deviation from prescribed set-point and display the maximum error
- Convenient common display

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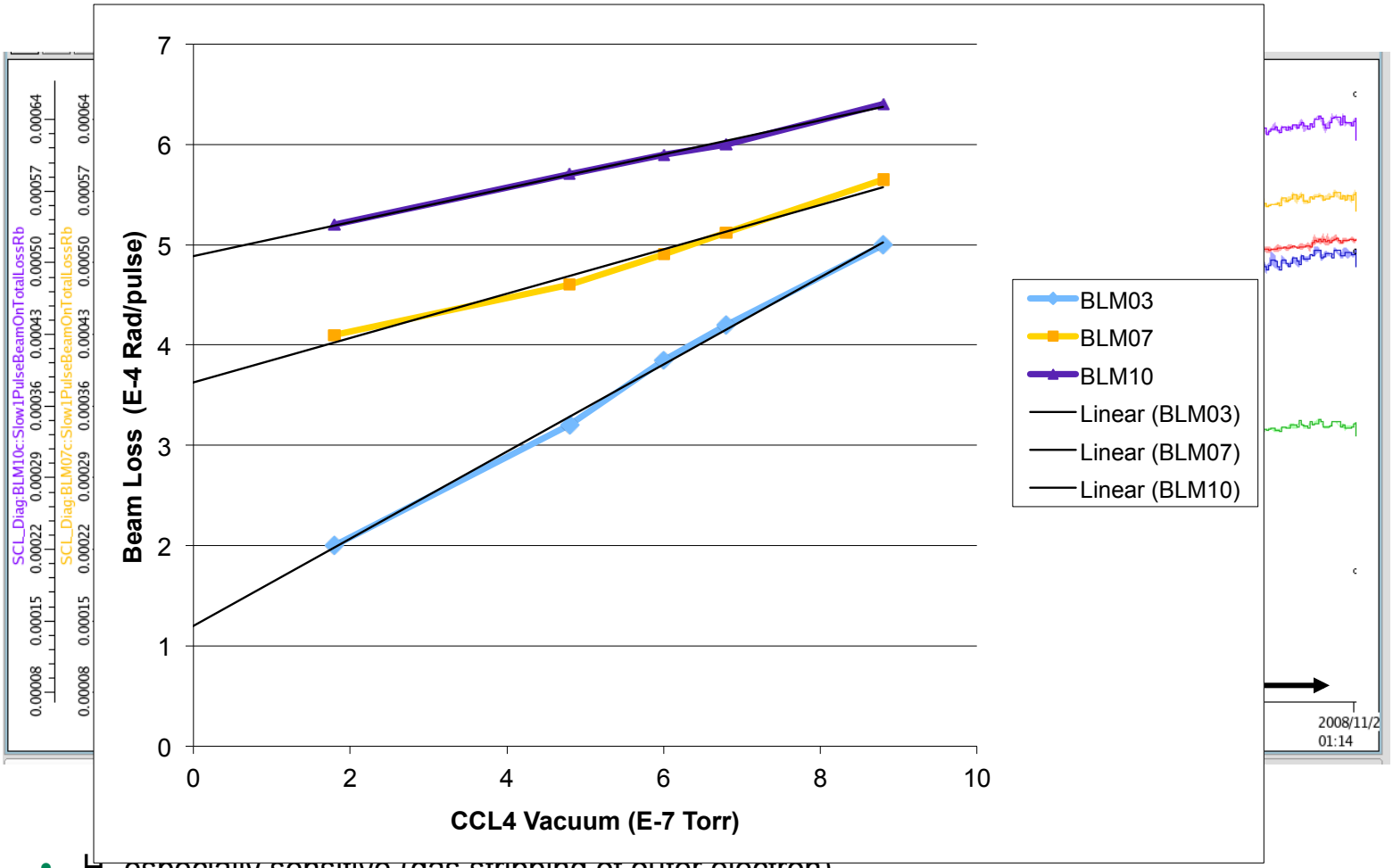
Poor Vacuum can Cause Beam Loss



- H- especially sensitive (gas stripping of outer electron)
- Protons also affected (scattering)

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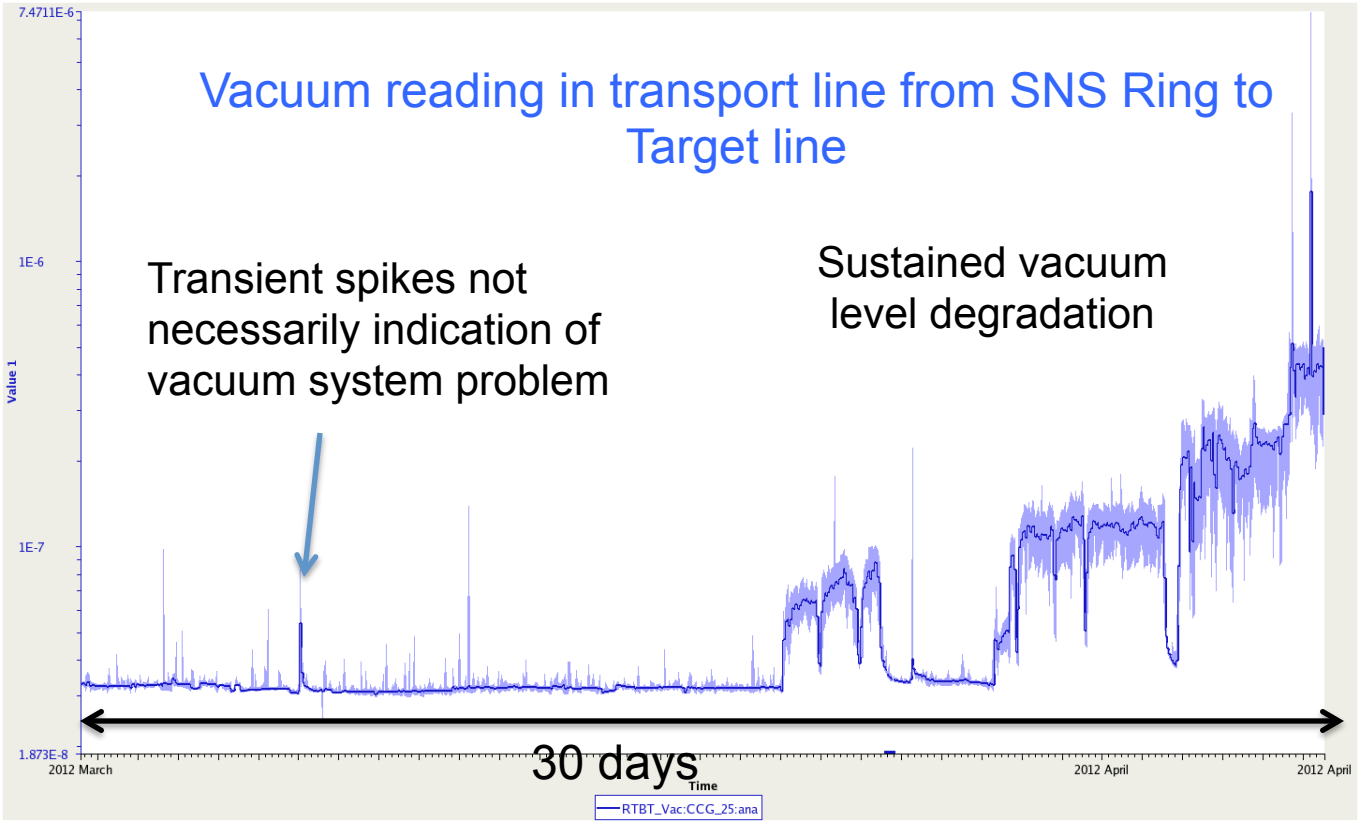
Vacuum Levels: Monitor



- Long term vacuum level degradation: replace/ refurbish pumps
- Transient “blips” can be caused by beam loss (bad extraction from ring)

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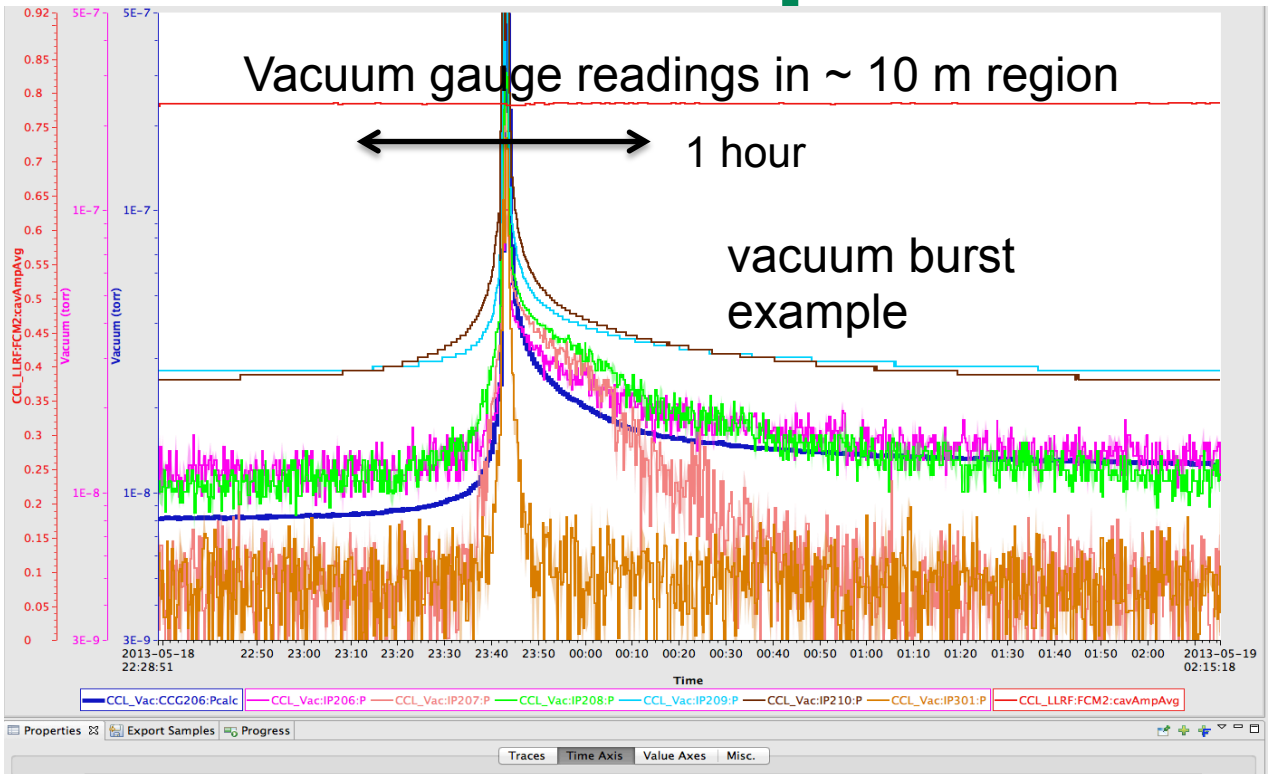
Vacuum Burst Example



- Easy to detect perturbation to high vacuum
- Not always easy to know cause
  - Leak?
  - RF discharge?
  - Pump?

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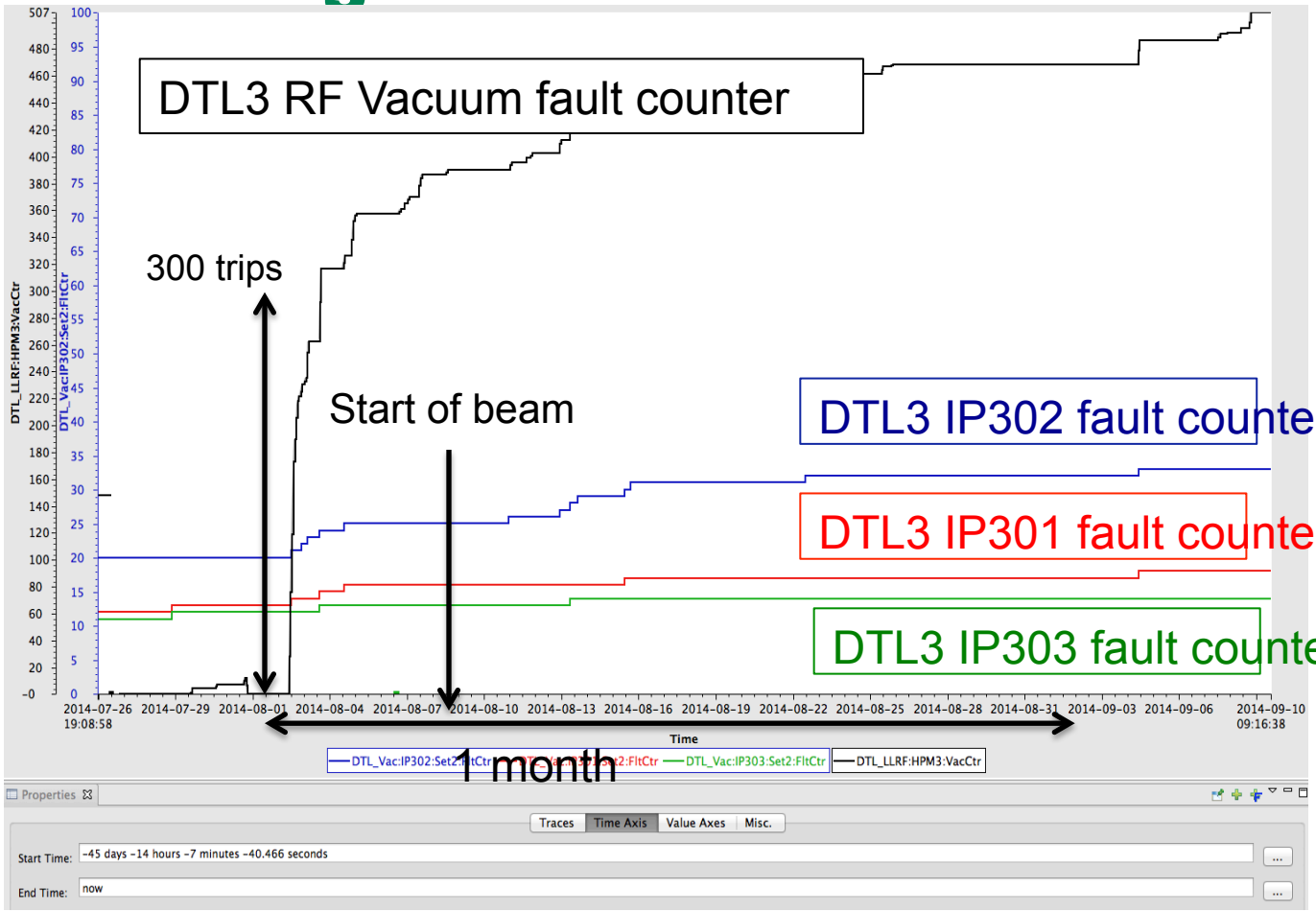
RF Structure Induced Vacuum Excursions: Conditioning



- RF structures can condition over time
  - Monitor trip frequency to asses whether things are improving / getting worse
  - If structures are exposed to atmosphere – must condition

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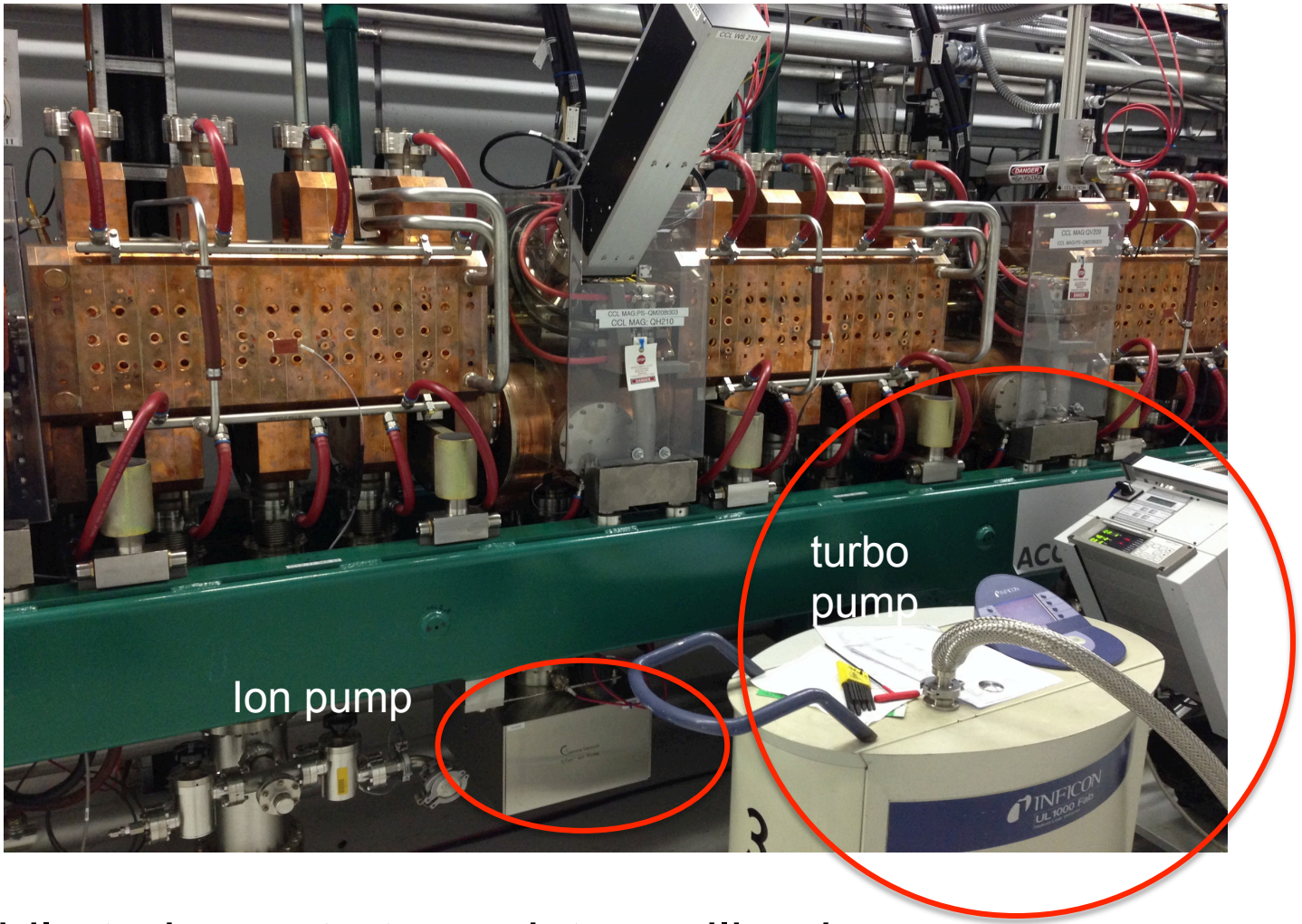
Vacuum “Limp-Along” Set-up



- Put a mobile turbo cart , to assist an ailing ion-pump

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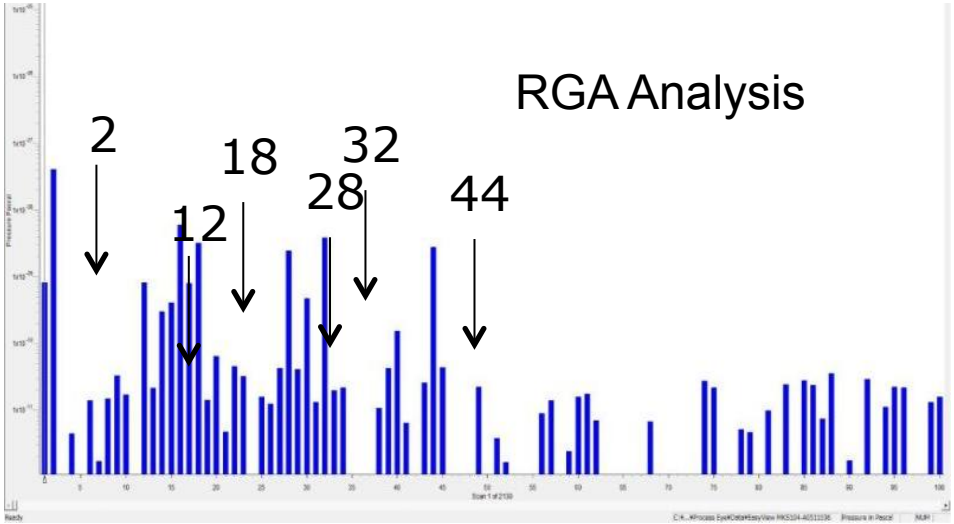
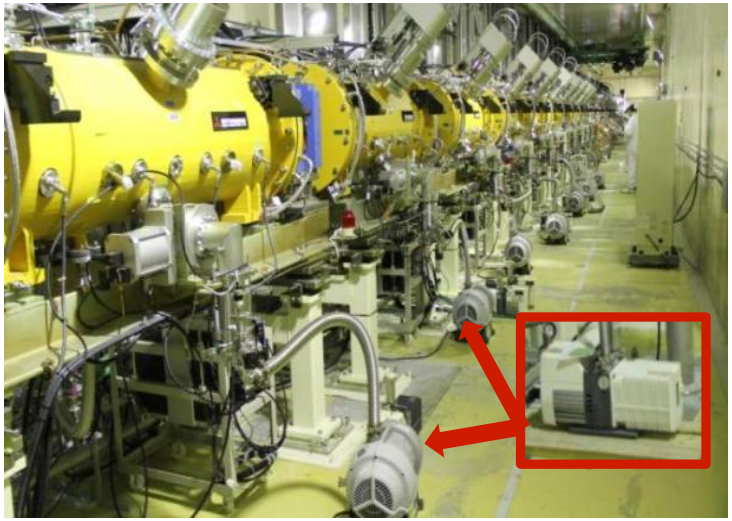
J-PARC: Measures of the SDTL Discharge

- There were many peaks in the Q-mass data: some hydro-carbon origin components.
- We suspected that the cause is multipacting by hydrocarbons.
- We used oil rotary pumps. Routine operation with ion pump had seldom problems, but at restoration, by several vacuum purge processes, oil vapor may back streamed.
  → We replaced oil rotary pumps with oil free ones.
- Lessons Learned: We should consider quality of vacuum.



Q_{mass} results in the SDTL5B vacuum



Oil rotary pumps are replaced with scroll pumps

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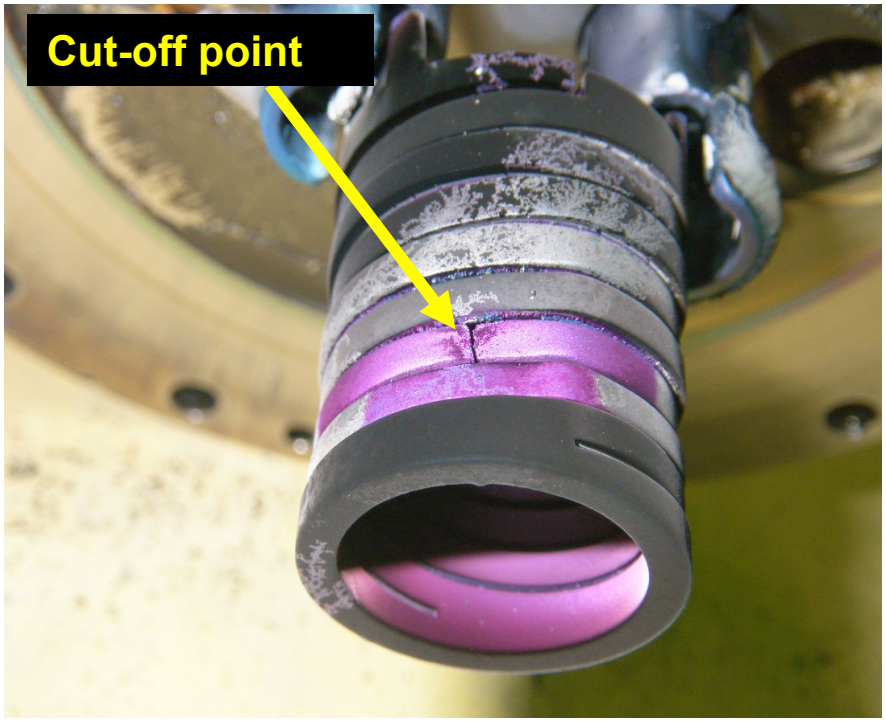
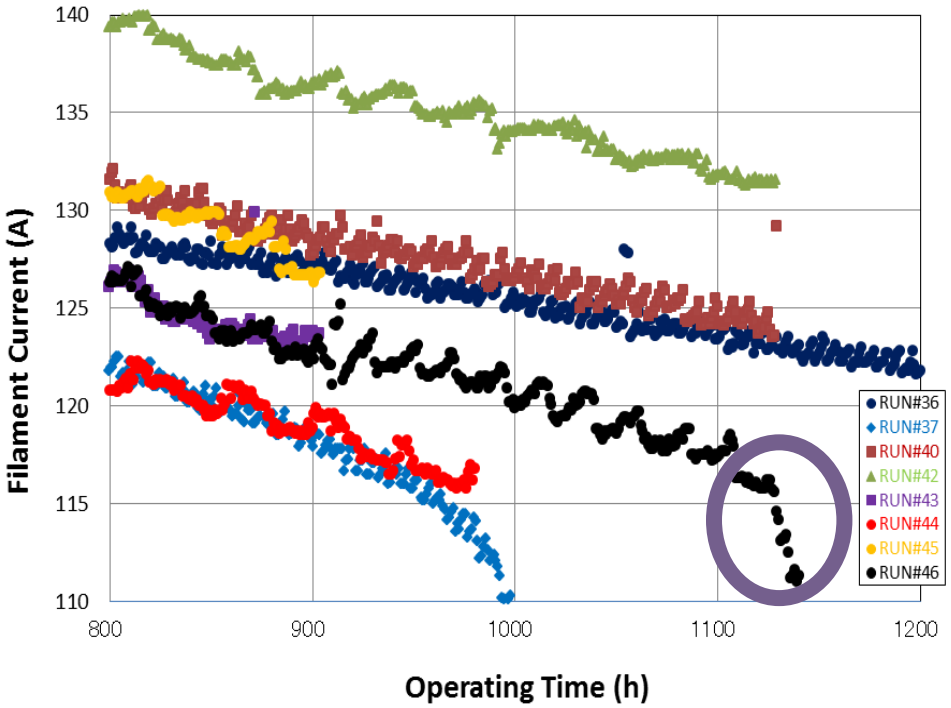
J-PARC Ion Source: Filament Failure



Photograph of the broken filament



Variation of the filament current with time

- J-PARC used an ion source with filament. The filament failure due to the breaking occurred after about 1100 hours in the run#46.
- Thickness of the coil decreased gradually, it leads to the cut-off finally. The cut-off was induced by the evaporation due to the local heating.
- The decrease rate of the filament current suddenly increased about 10 hours before the failure. This was a symptom of the lifetime.

Temperature: Air Temperature Easy To Monitor – Often Useful

- Why does it matter?
  - Electronics can be temperature sensitive
  - Sensitive timing can be affected
  - System lifetimes can be affected by temperature
- Hint: make sure the building HVAC controls are linked to the accelerator control system

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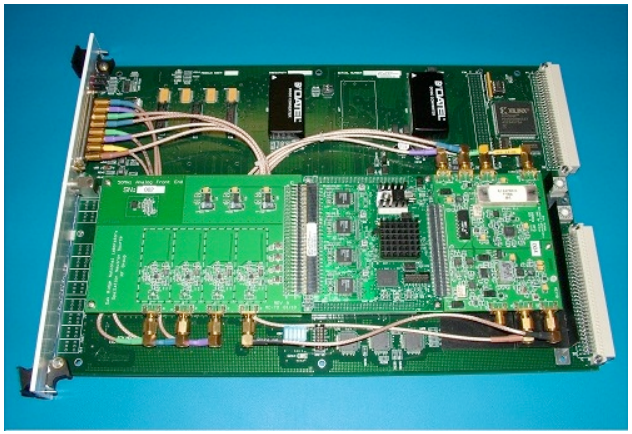
Why Does Temperature Matter ?

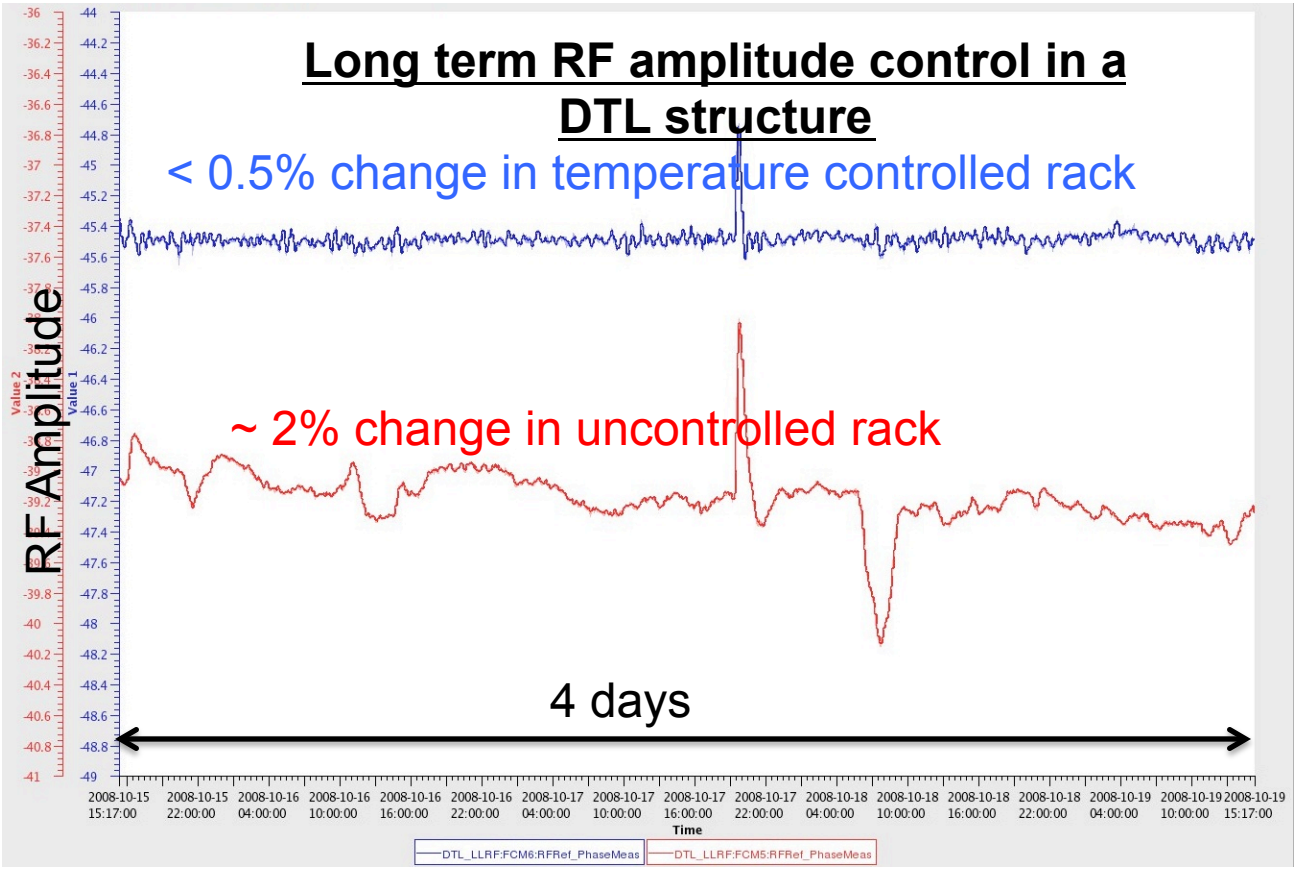
- Lengths can change
- Electronic component performance can change
- Put test setups in an “oven” and measure performance

Average Amplitude Drift dB/deg C			
Channel	**Commercial**	**SNS**	**50 MHz**
A	0.2848	0.0451	0.0031
B	0.3452	0.0269	0.0031
C	0.0157	0.0038	0.0029
D	0.0112	0.0077	0.0023



M. Croffrod et al.,” SNS LLRF Temperature Dependence and Solution” XXV Linear Accelerator Conference) Tsukuba, Japan on September 12-17

Controlling Rack Temperatures



- Measure and monitor rack temperatures to see if there is a problem
- Possible to stabilize electronic rack temperatures
  - PID controlled 250 W heater, with 5° C avg. temperature elevation
  - Not ideal – better to keep racks cool
  - Use in critical applications (RF reference line)

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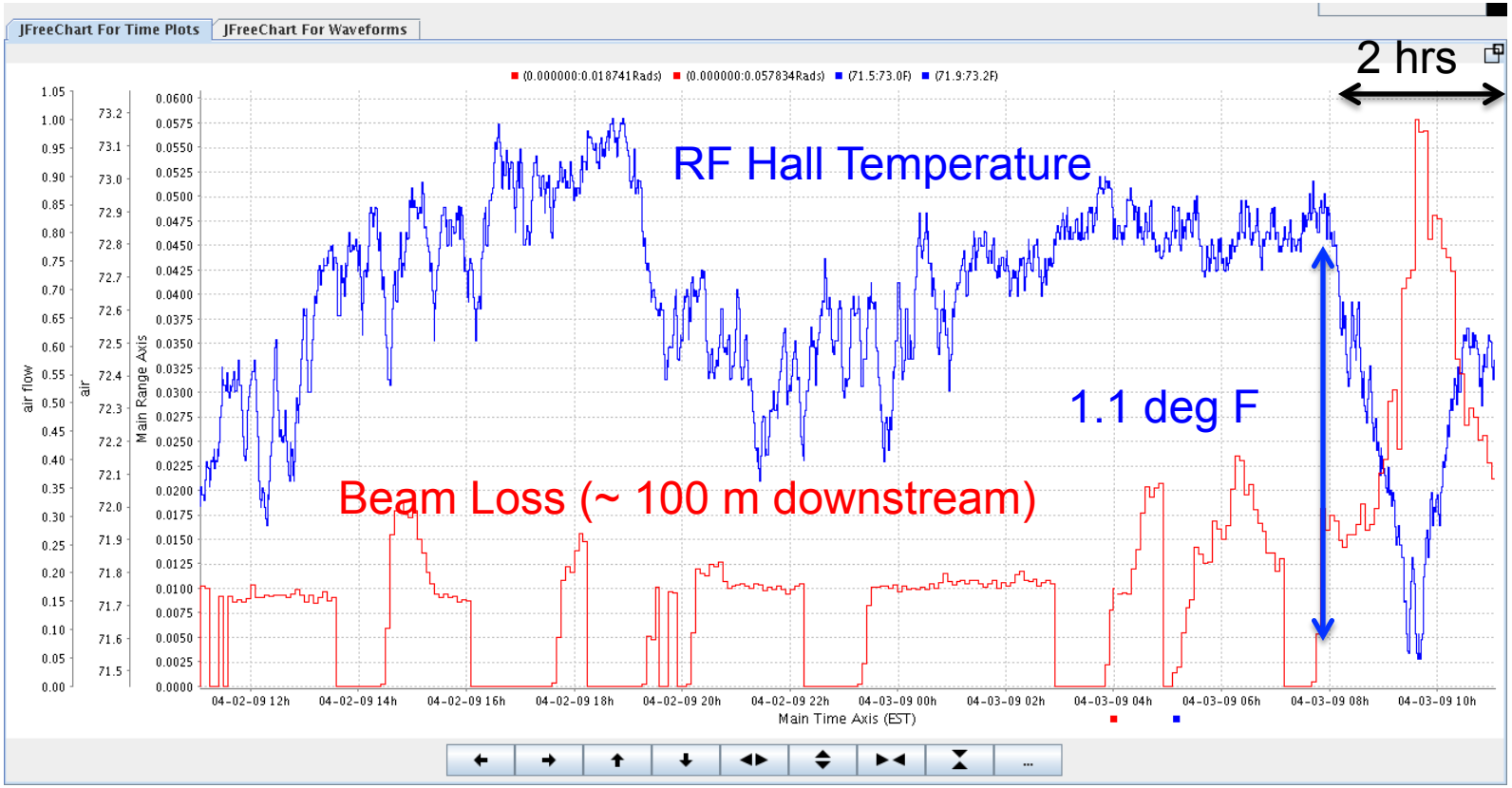
Example: HVAC Affecting Beam Loss



- Sometimes the temperature drift only affects beam in certain temperature ranges

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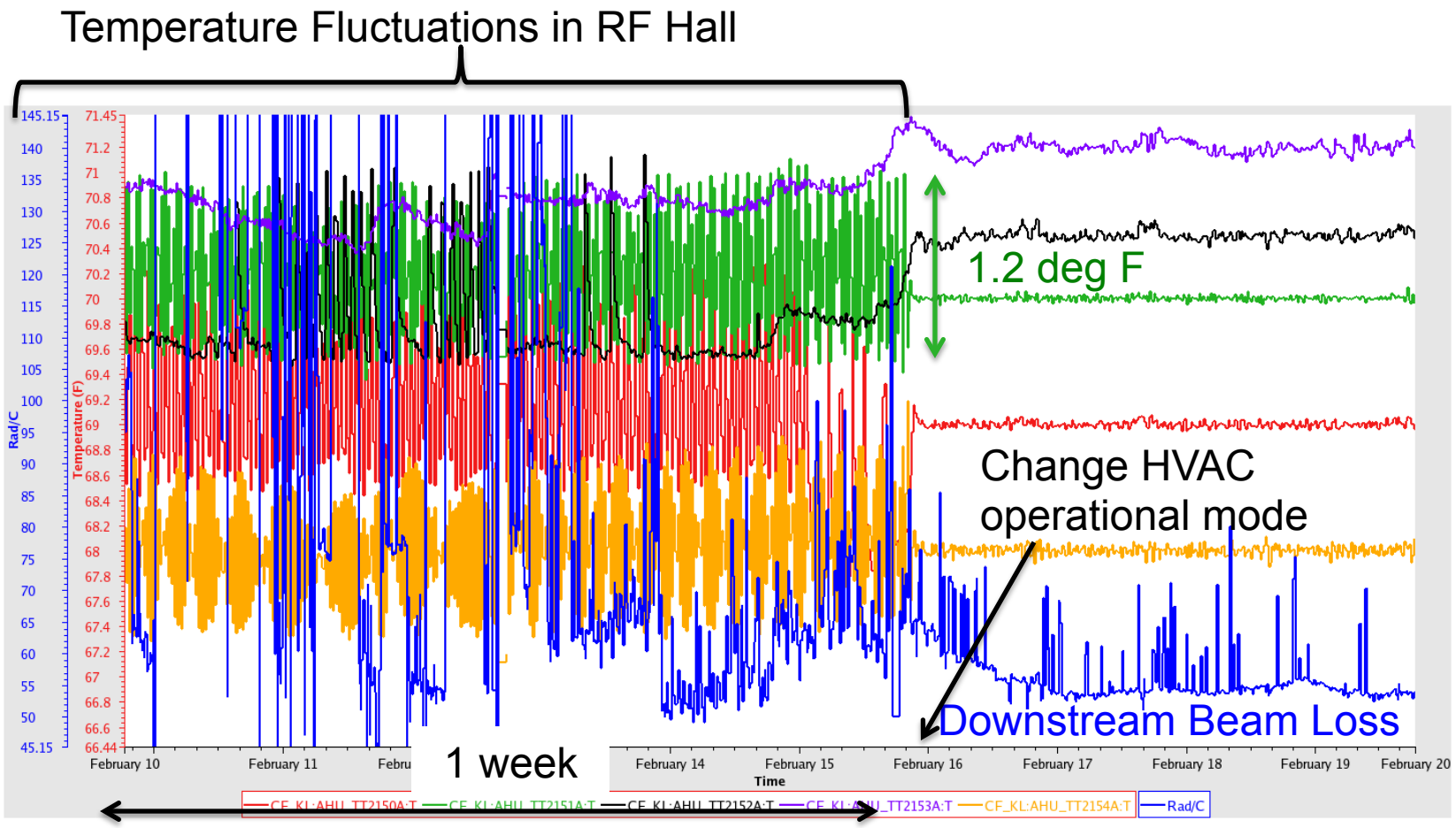
Example of HVAC Operational Setup Affecting Beam Loss



- A new "improved" HVAC control scheme implementation impacted beam loss
  - Unstable temperature led to erratic beam loss changes

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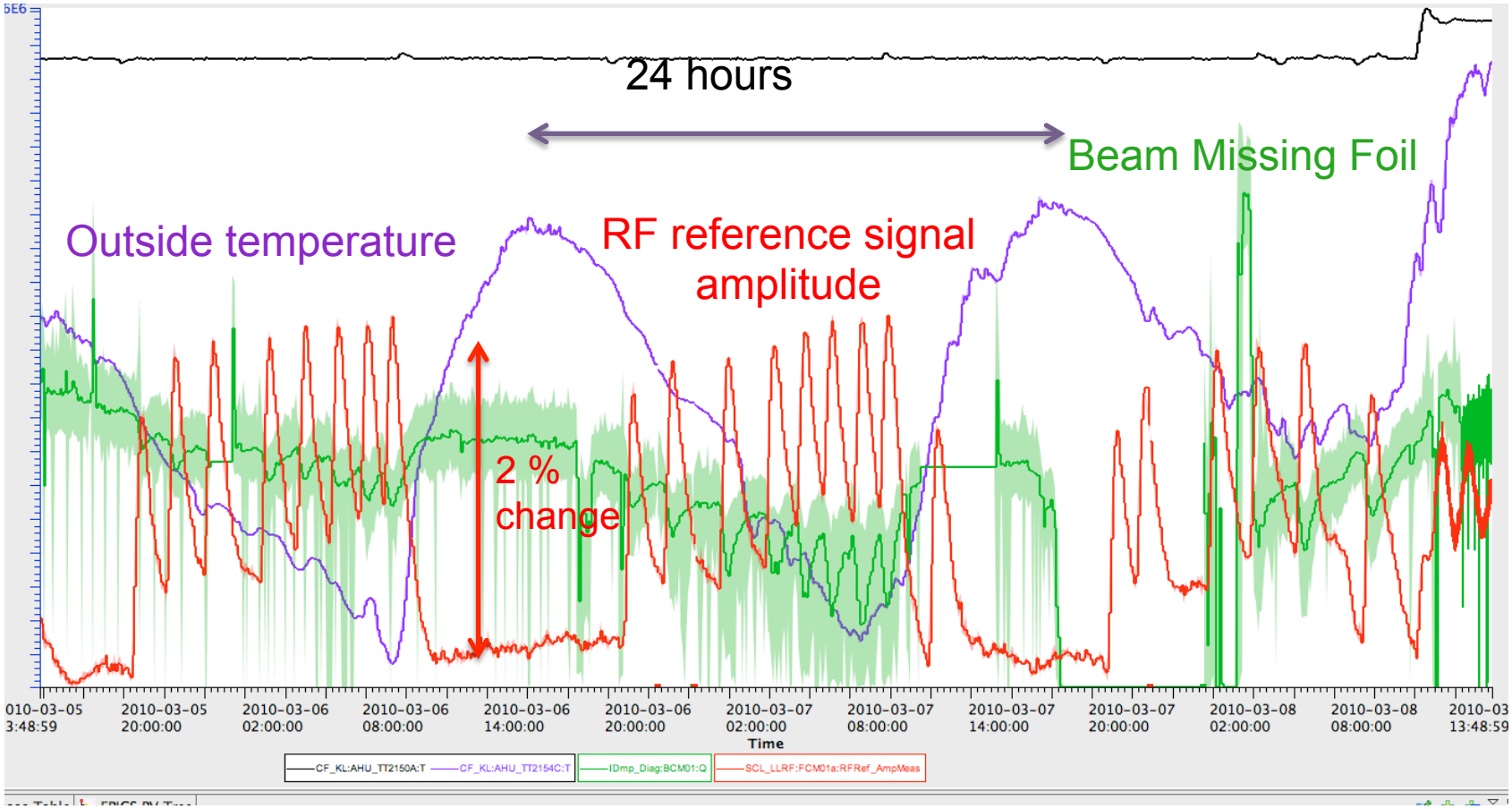
Diurnal Cycles: Temperature control?



- Example of the RF reference line starting to deteriorate, indications at night
  - Impacted the beam properties at the injection foil

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Temperature Lessons Take-Away

- Make sure building and utility parameters are available to the accelerator control system
- Make sure the conventional facility cooling requirements are well understood
- Do not ask the conventional facility systems to do silly things
  - Cool an entire building beyond the HVAC design spec. because a rack is running too hot

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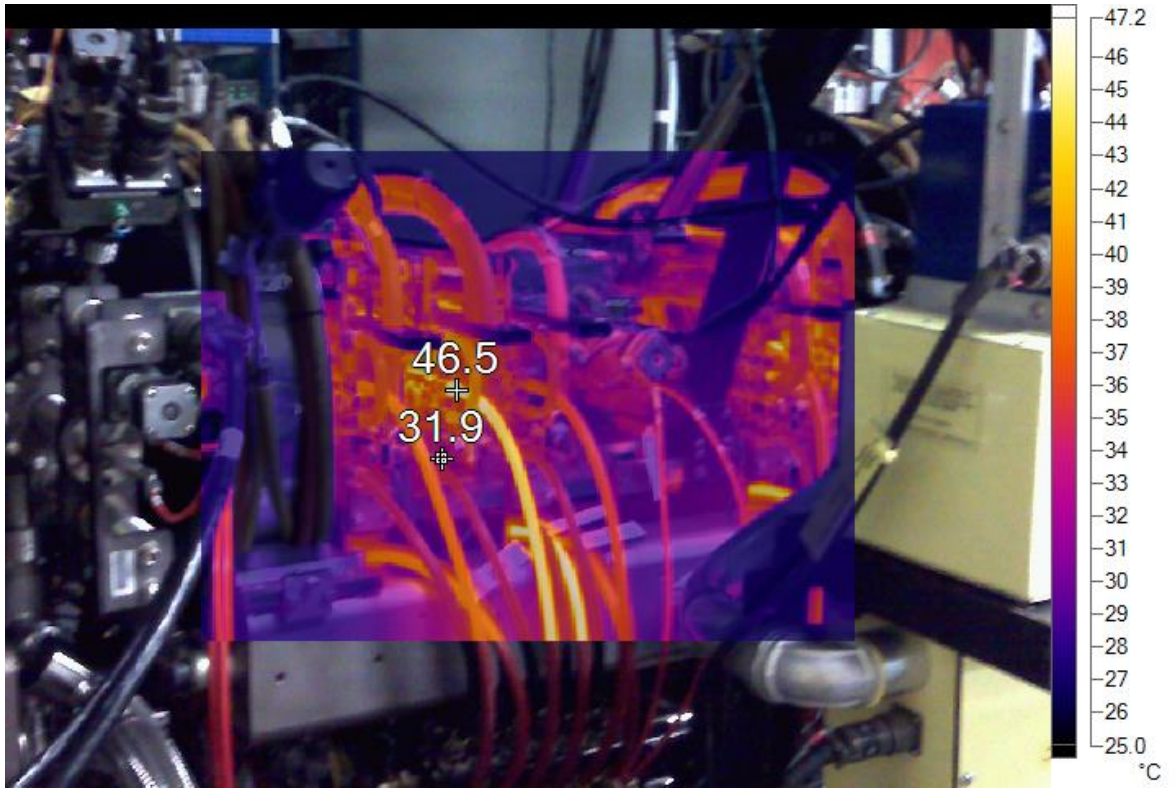
Thermal Imaging to See “Hot Spots”

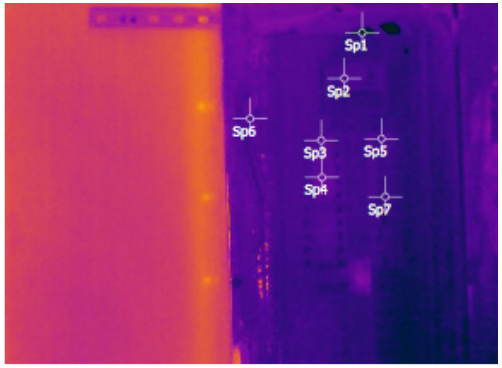


Magnets in a low energy beam section

- Infrared images are powerful tools for isolating “hot-spots” that may be precursors to equipment failure
- Magnets:
  - Cooling problems
  - Magnet lead connections

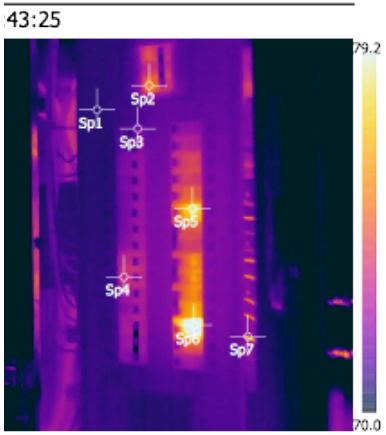
IR Temperature Measurements (II)

OK panel



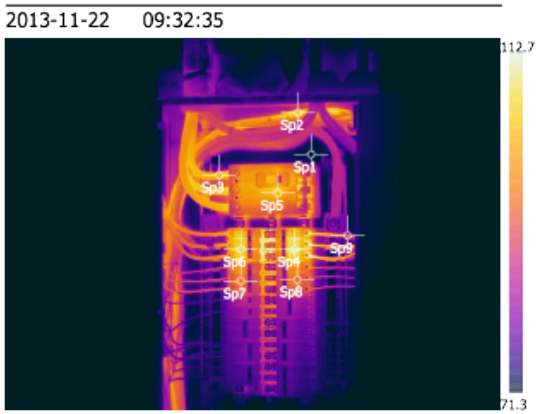
IR_0568.jpg
2014-01-15 09:59:15

Not so OK panel



43:26

Peak Inside Too



IR_0445.jpg
2013-11-22 09:32:36

DC_0446.jpg

- Useful for identifying issues in racks, power supplies, electrical panels, ….

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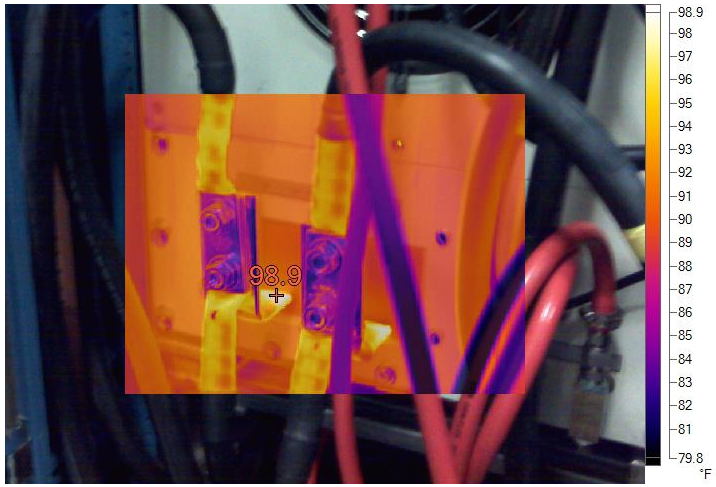
Power Supply Imaging

Normal heating in a small magnet power supply



BNL power supply, after a failed capacitor

- Thermal imaging of active electrical components is disruptive
- Often requires special electrical worker training

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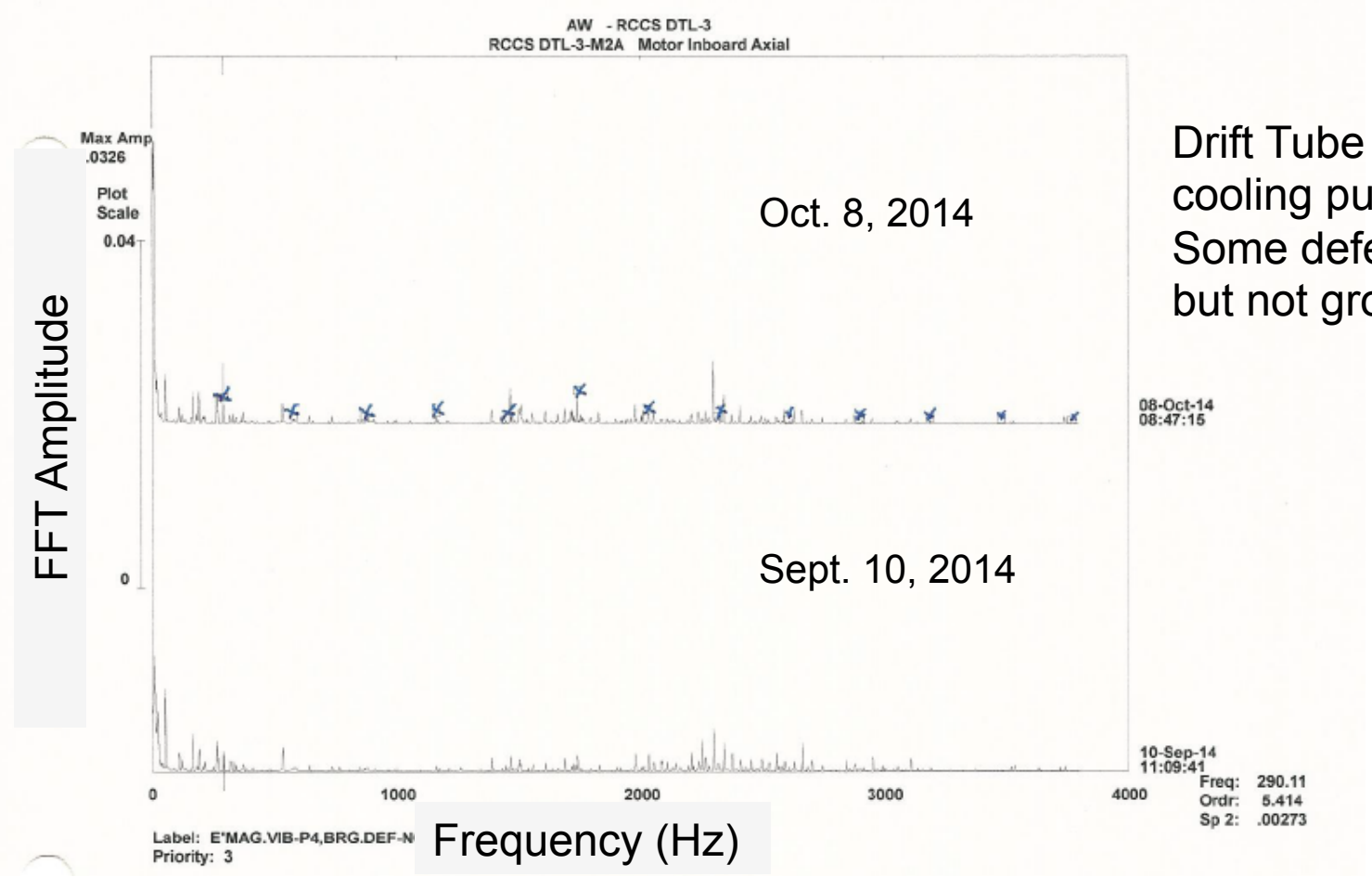
Rotating Equipment (I)



Drift Tube Linac tank 3 cooling pump:
Some defect indication, but not growing too fast.

- Water pumps
  - Beam loss can occur during transition to backup pumps
  - FFT analysis of pump vibration can identify failure precursors
    - passive measurement

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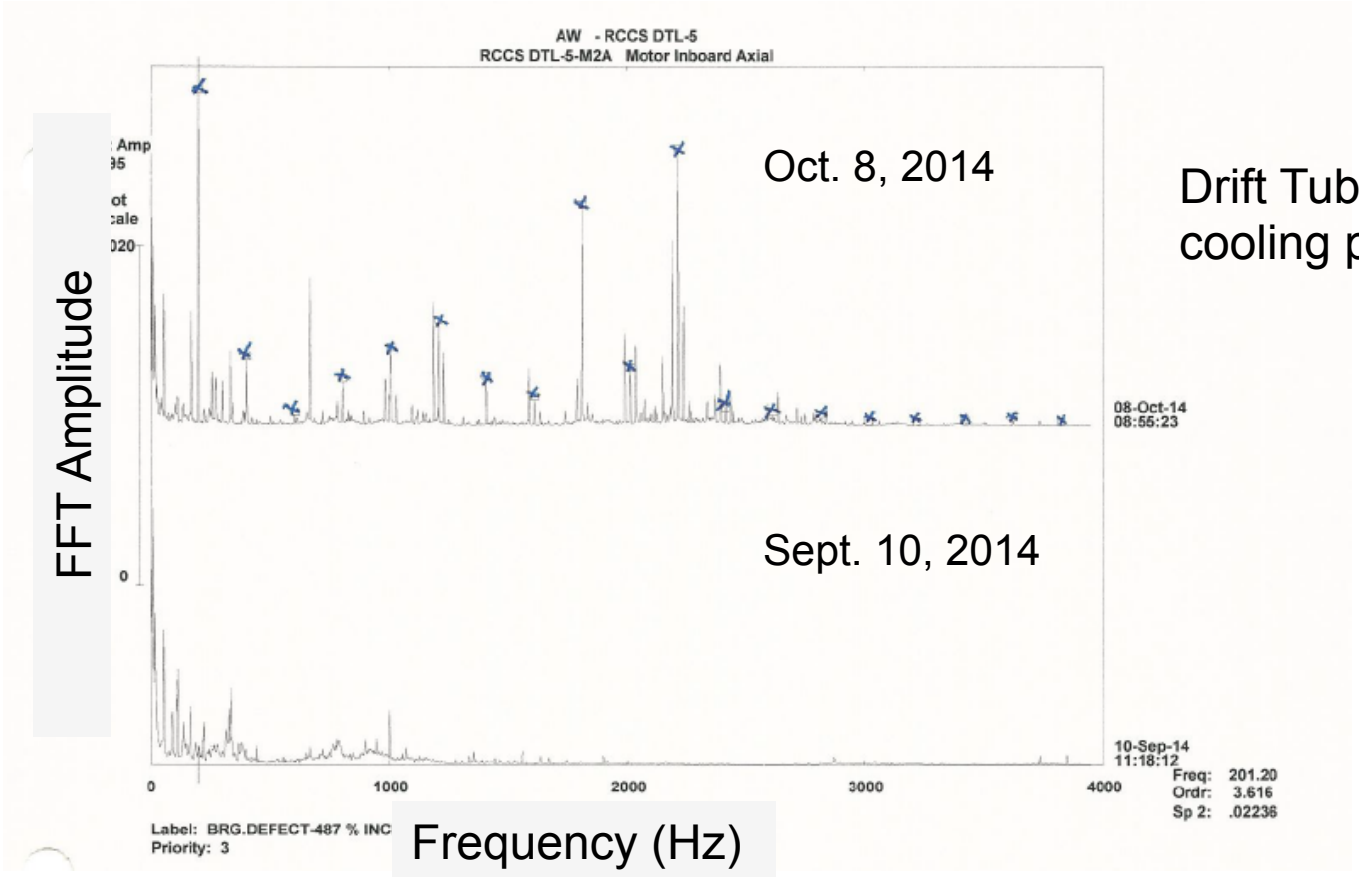
Rotating Equipment (II)



Drift Tube Linac tank 5 cooling pump

- Water pumps
  - This one is degrading (bearing defect)
  - Repair/replace on the next maintenance day

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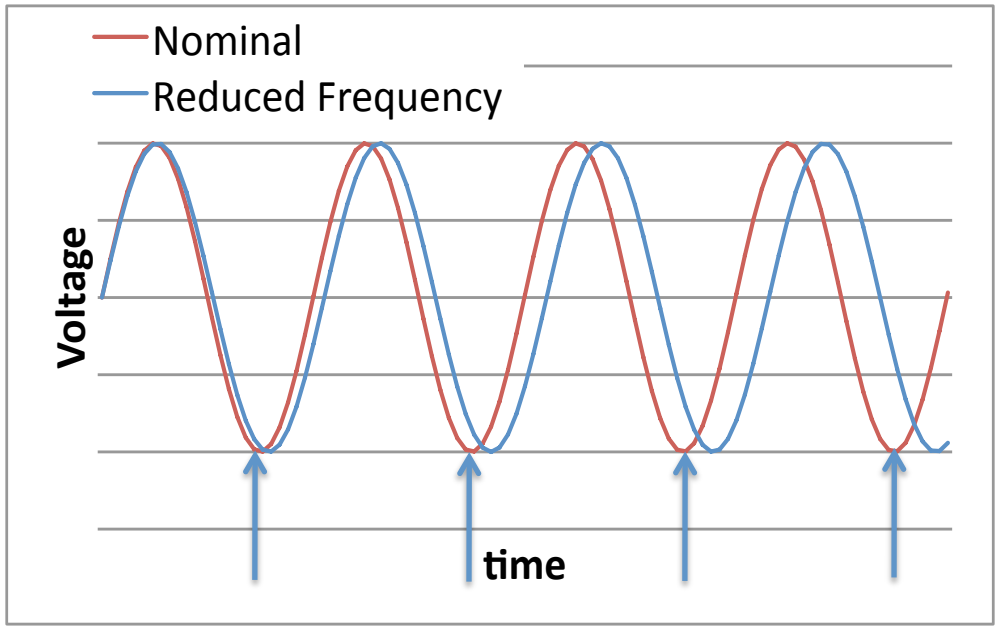
Power Grid Line-Synchronization Issues

- The line frequency (electrical grid) has some variation



- **Constant frequency operation will "walk-away" from the grid pulse**
  - **E.g. if the grid operates at 59.95 Hz (50 mHz off-normal) …**
    - **… it takes 20 sec to swing through a complete AC cycle**

- **Not hard to land on the same part of the 60 Hz "sine wave" (target phase) if you want to**
  - **Older accelerators did follow the grid frequency**
  - **But modern high power facilities tend to operate at fixed frequency (J-PARC, SNS, ESS)**

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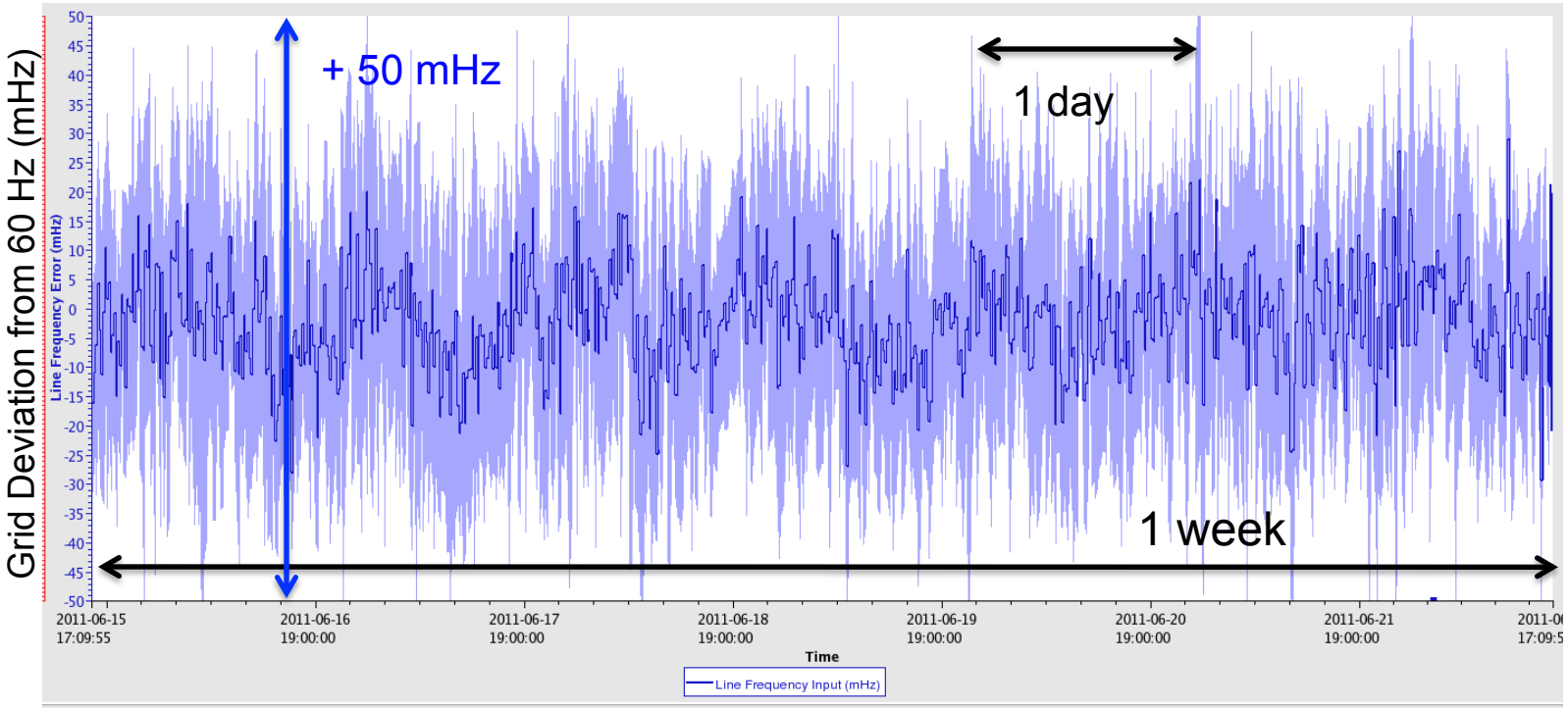
Line Frequency Variation (1 Week)



- Important for pulsed machine operation
- In fixed frequency operation, you end up sampling the" 60 Hz grid", at all phases constantly slews through the
- This can lead to beam loss if you are not careful

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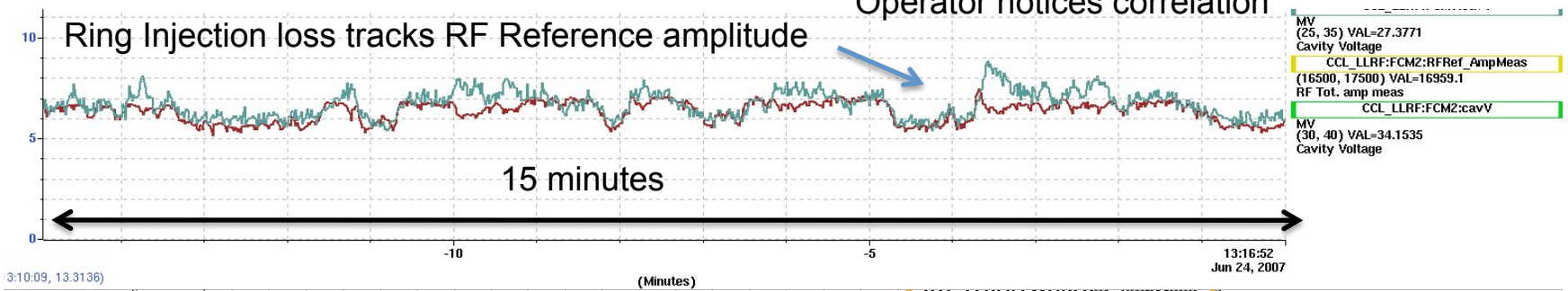
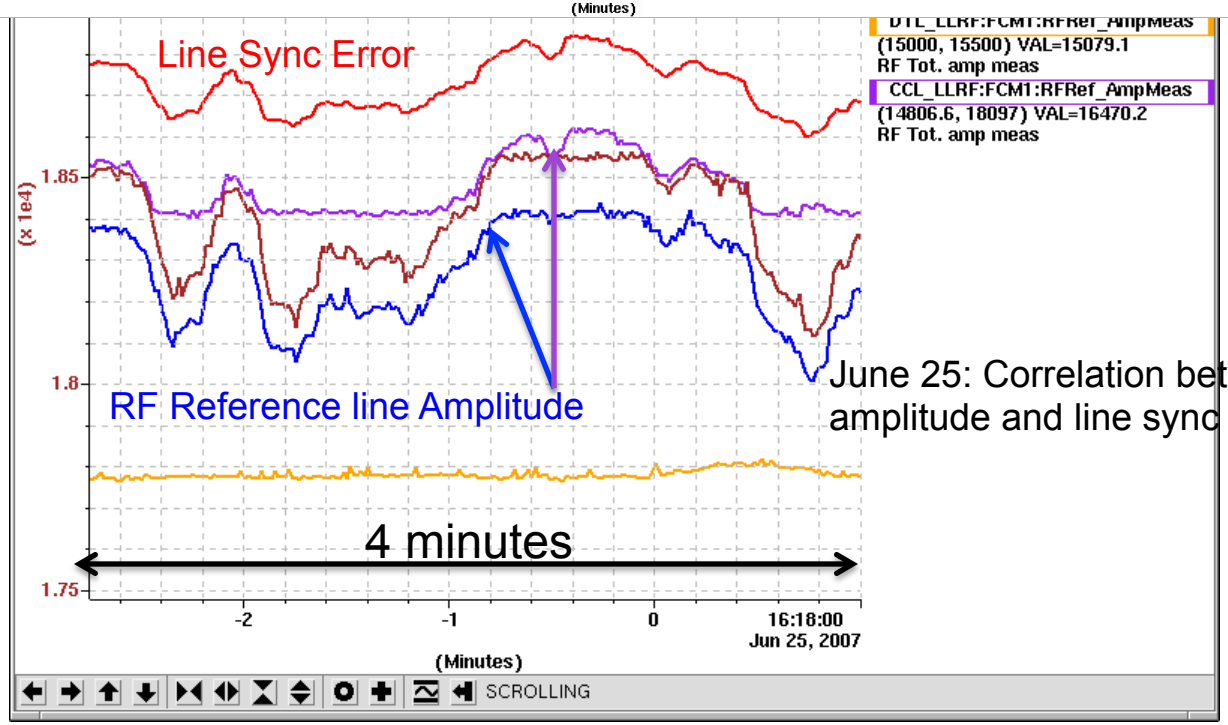
Beam Loss Correlated with Line-Sync Variation

June 24, 2007:
Operator notices correlation





June 25: Correlation between the RF Reference amplitude and line sync error noticed

- Problem was a degrading power supply on the RF reference line generator board

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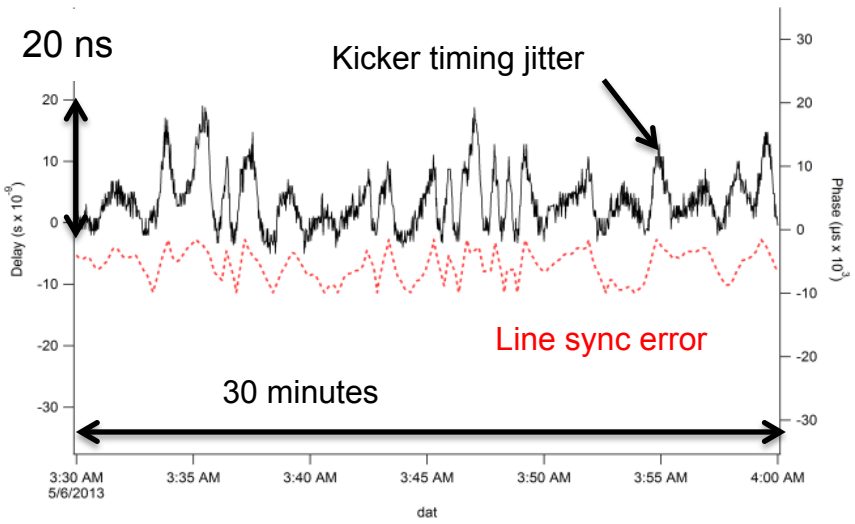
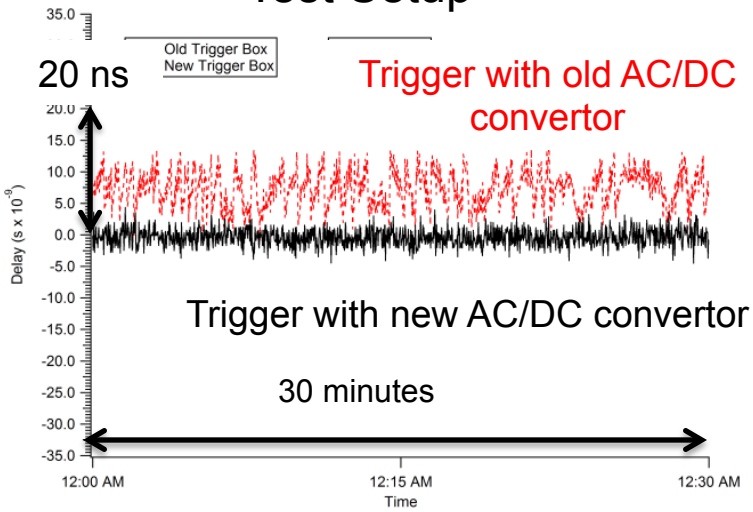
Line Sync Impact on Ring Extraction Kicker Timing



Test Setup



- Look for beam loss and equipment performance correlations with the grid line sync
  - AC-DC convertors, and AC heated filaments are culprits

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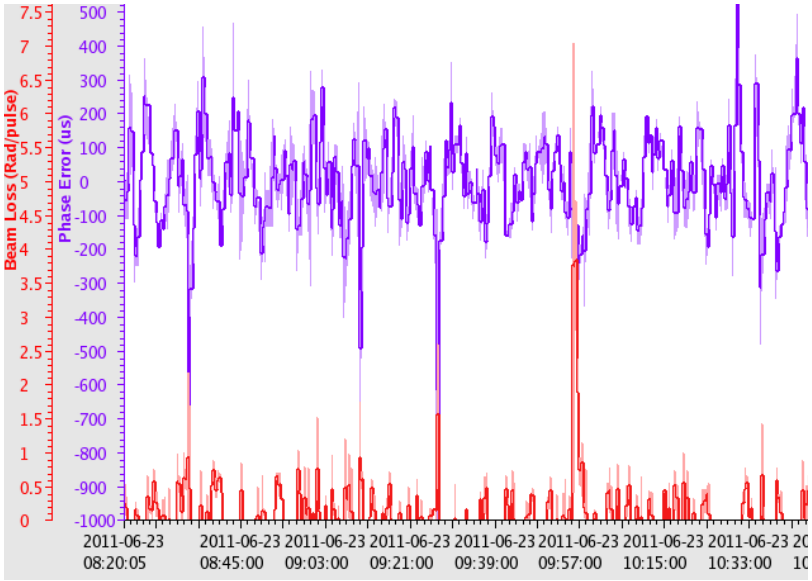
Beam Loss: Real or Equipment Induced False Indicator?

3. Thu, Jun 23, 2011 14:33 *John Galambos* Re: Beam Loss not correlated with line syncronization {Operations} () 1

some RTBT BLM13 loss jumps (extraction loss) are correlated with line sync excursions, but not all of them.



Line sync error

RTBT Beam Loss

- Beam loss background is sampled every 10 sec.
  - For background subtraction
- Line sync error was leaking into the background signal (bad power supply on electronics board)
- Only when line sync changed fast relative to 10 s, did we see “a loss problem”
- Question everything you see !

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Beam Difference Techniques to Pinpoint Equipment Issues

- "Memorize" the beam positions and arrival times along a section of accelerator after setup (production state, golden state,…)
  - Actual beam positions along the accelerator may not be ideal (e.g. 0)
- Watch differences in the beam trajectory and arrival times along the accelerator section
- In a focusing channel, small changes in focusing elements result in a "wave" displacement, originating at the offending piece of equipment
  - Magnet changes result in position displacement waves
  - RF changes give arrival time displacement waves
- Passive techniques!

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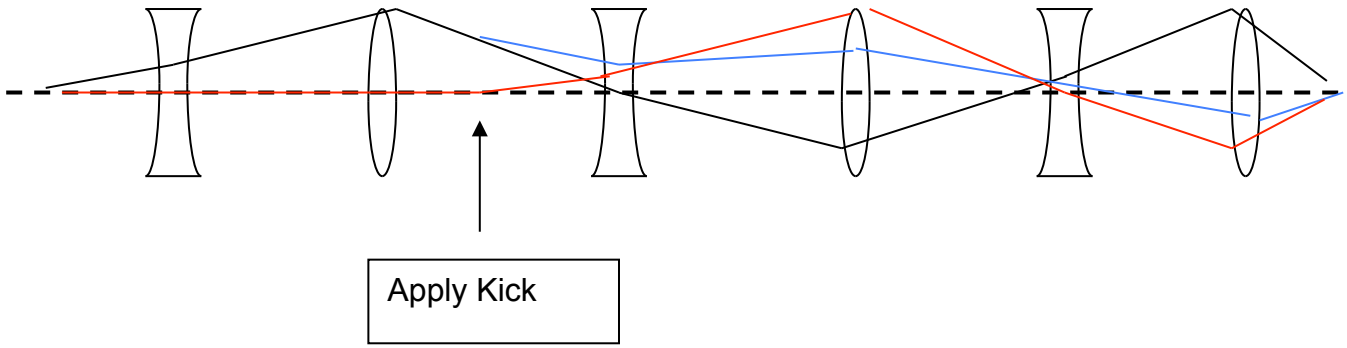
Orbit Difference (Transverse)



- Black = original beam trajectory
- Blue = trajectory after a kick is applied
- Red = difference orbit (black – red)

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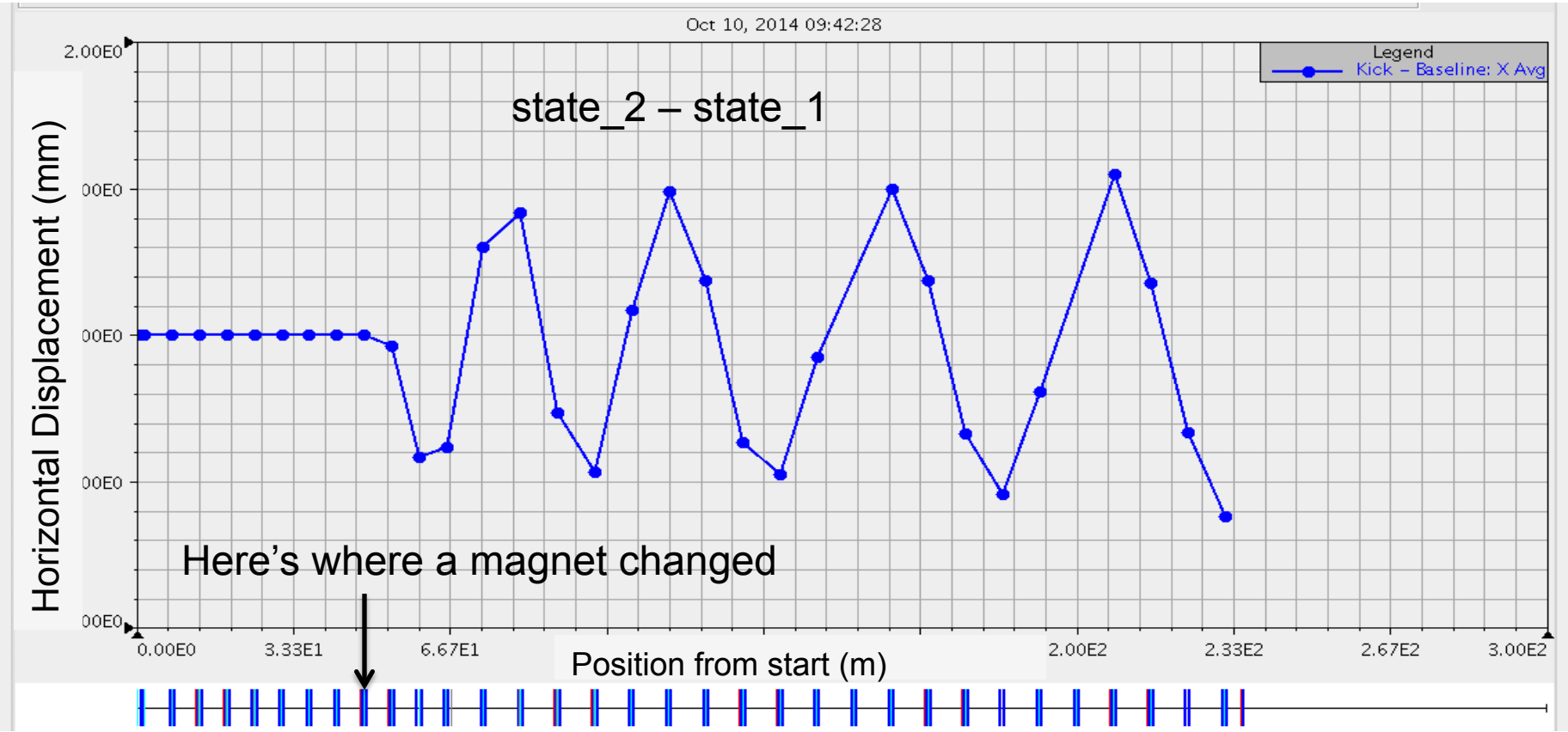
Transverse Orbit Difference (Beam position monitors)



- Difference techniques are powerful method to highlight change origins
  - Use averaging methods to see subtle changes

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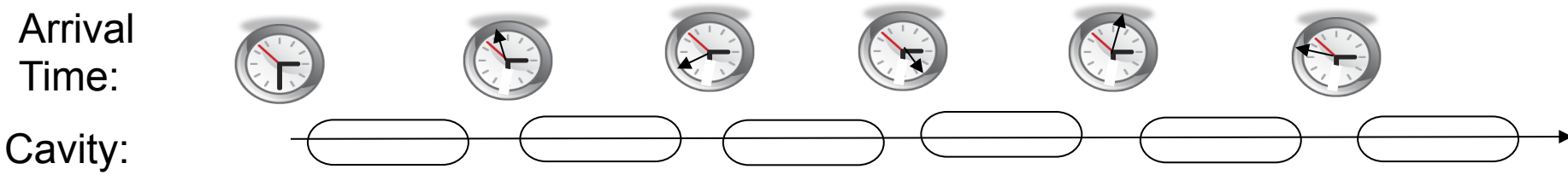
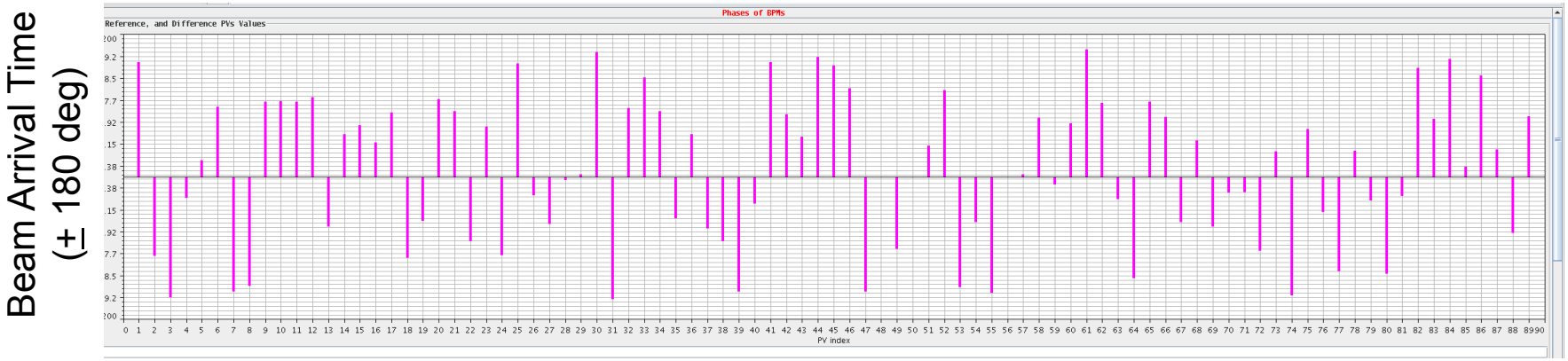
Beam Arrival Times Along a Proton Linac



- Beam arrival time at a cavity is often measured in degrees of RF phase
  - Arrival time at measurement points (RF pickups, phase monitors) is basically random
  - But it is easy to memorize the arrival times, and display changes



Example of beam arrival time measurements along the SNS linac
- good setup

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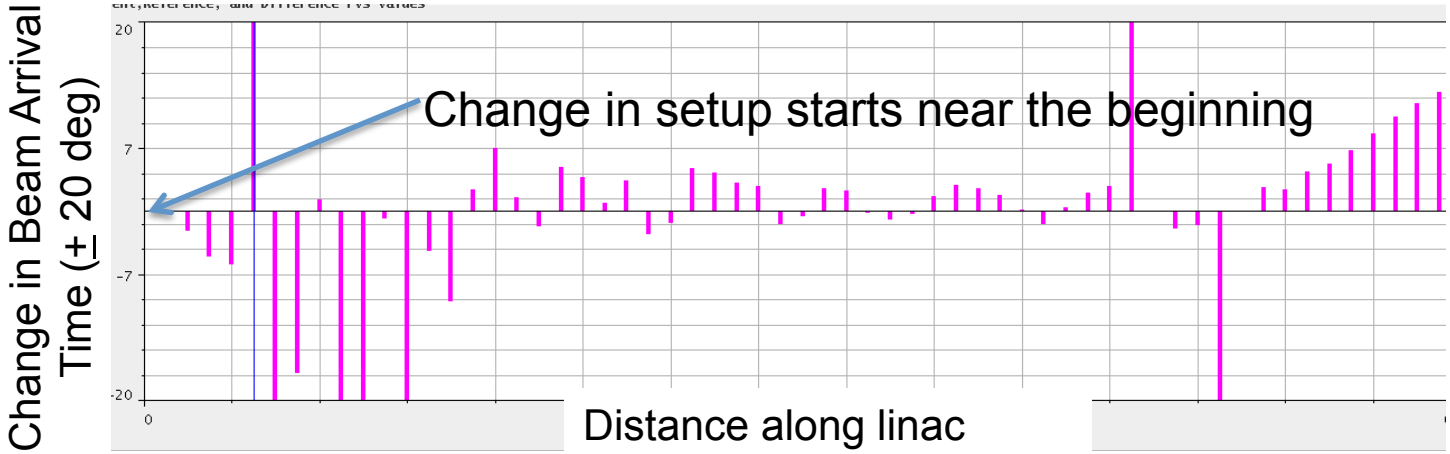
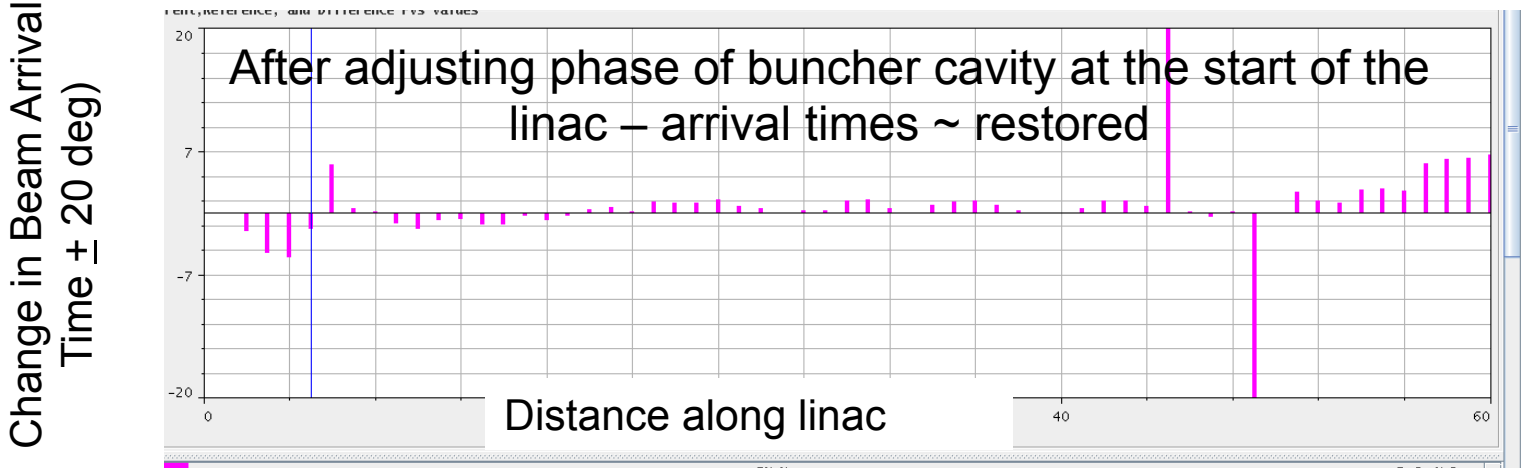
Beam Arrival Time Difference: Pinpoint RF Equipment Problem (Linac)





- LLRF cable contact was found to be intermittent

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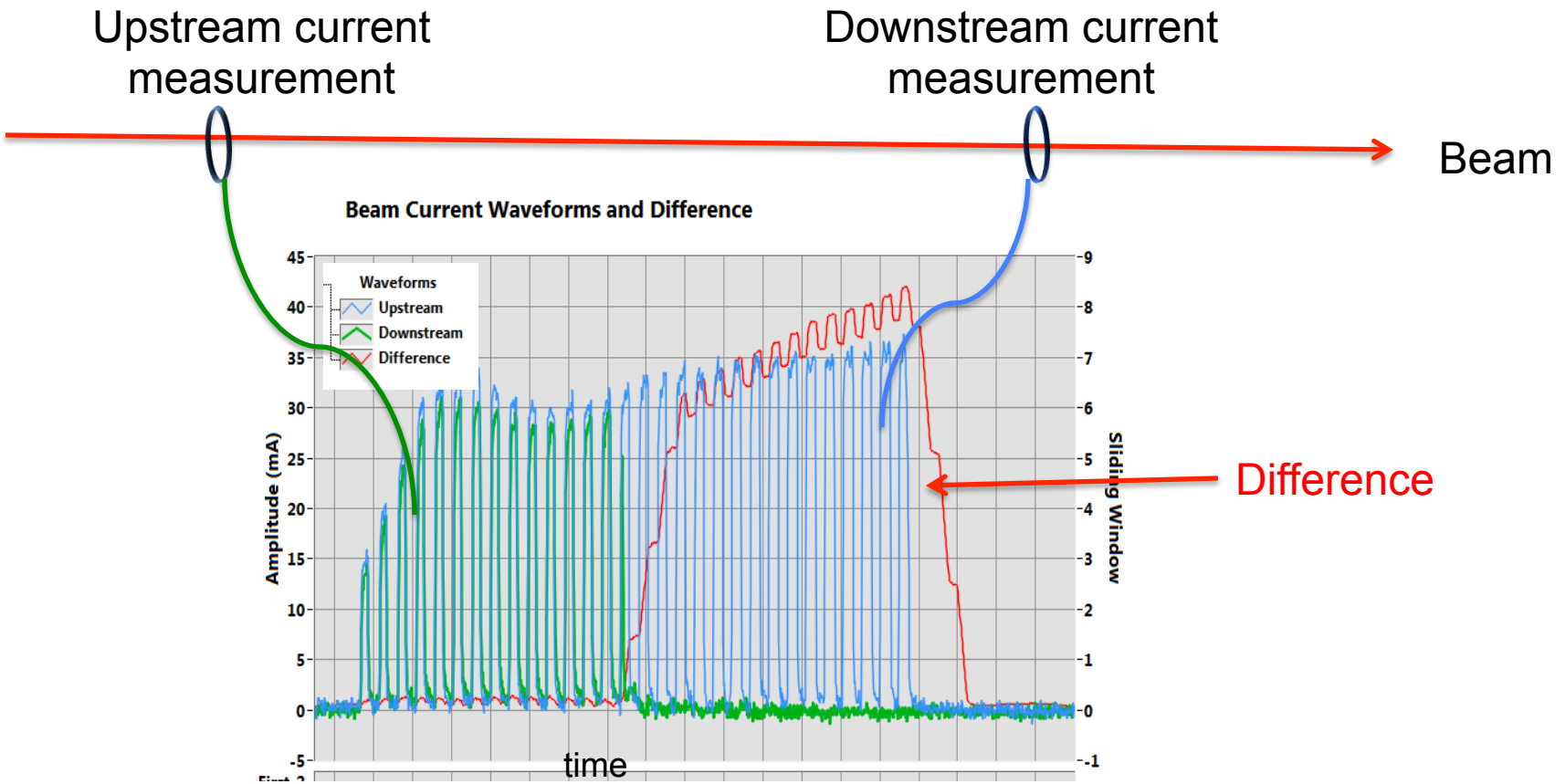
“Errant Beam” Analysis: Current Waveform Differences



- Difference between upstream and downstream pulses indicates equipment problem likely in-between
  - Monitoring done within a pulse (can react in a few μs)
- With multiple current measurement points, can isolate the region of equipment issue
  - Signature of the current decay can also help identify problem equipment

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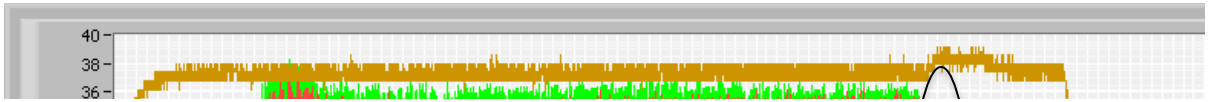
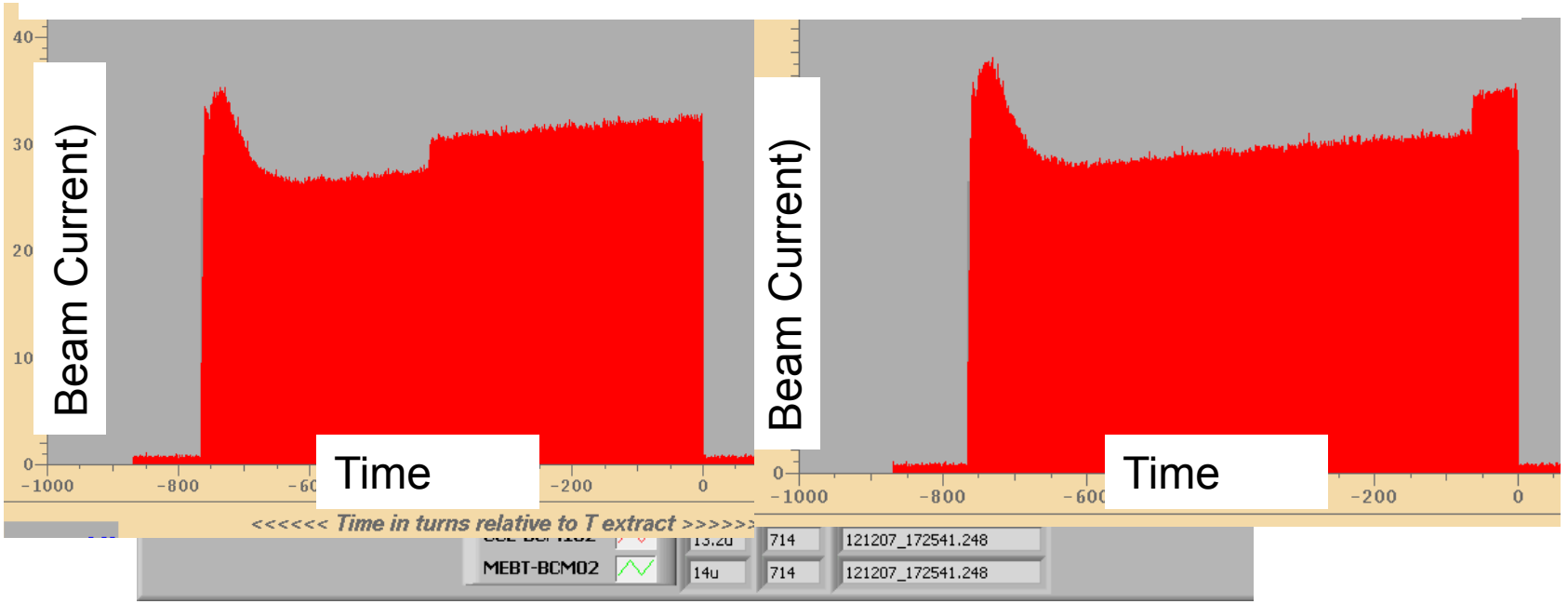
Pulse to Pulse Source Jitter Can Cause Beam Loss



Source pulse “fluctuations, pulse to pulse



- Upstream and downstream current waveforms both drop suddenly
  - Ion source problem
  - Difficult for RF feed-forward to handle
- Compare wave-forms with previous pulse for fast shut-off

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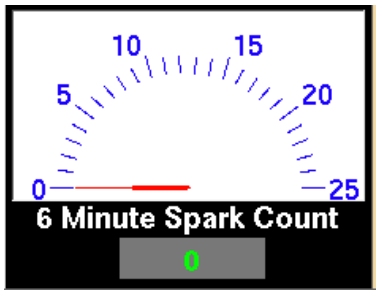
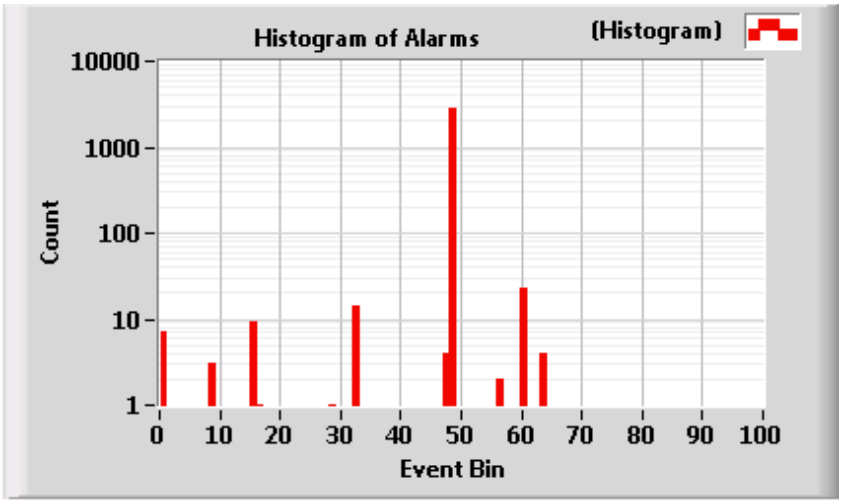
Errant Beam Statistics Identify Equipment Health Issues



- *If too many source sparks/interval, shutdown beam and choppers*
- *Allows chopper hardware "cool-down". This is a form of pre-mortem protection against catastrophic failure.*



Example of alarm histogram

"Errant Beam" data analysis:

- Based on "signature" assign equipment vault
- Statistics determine actions taken, e.g.
  - Increase in event rate for category can indicate:
    - equipment is starting to fail → equipment must be serviced or replaced.
    - accelerator operation must be adjusted

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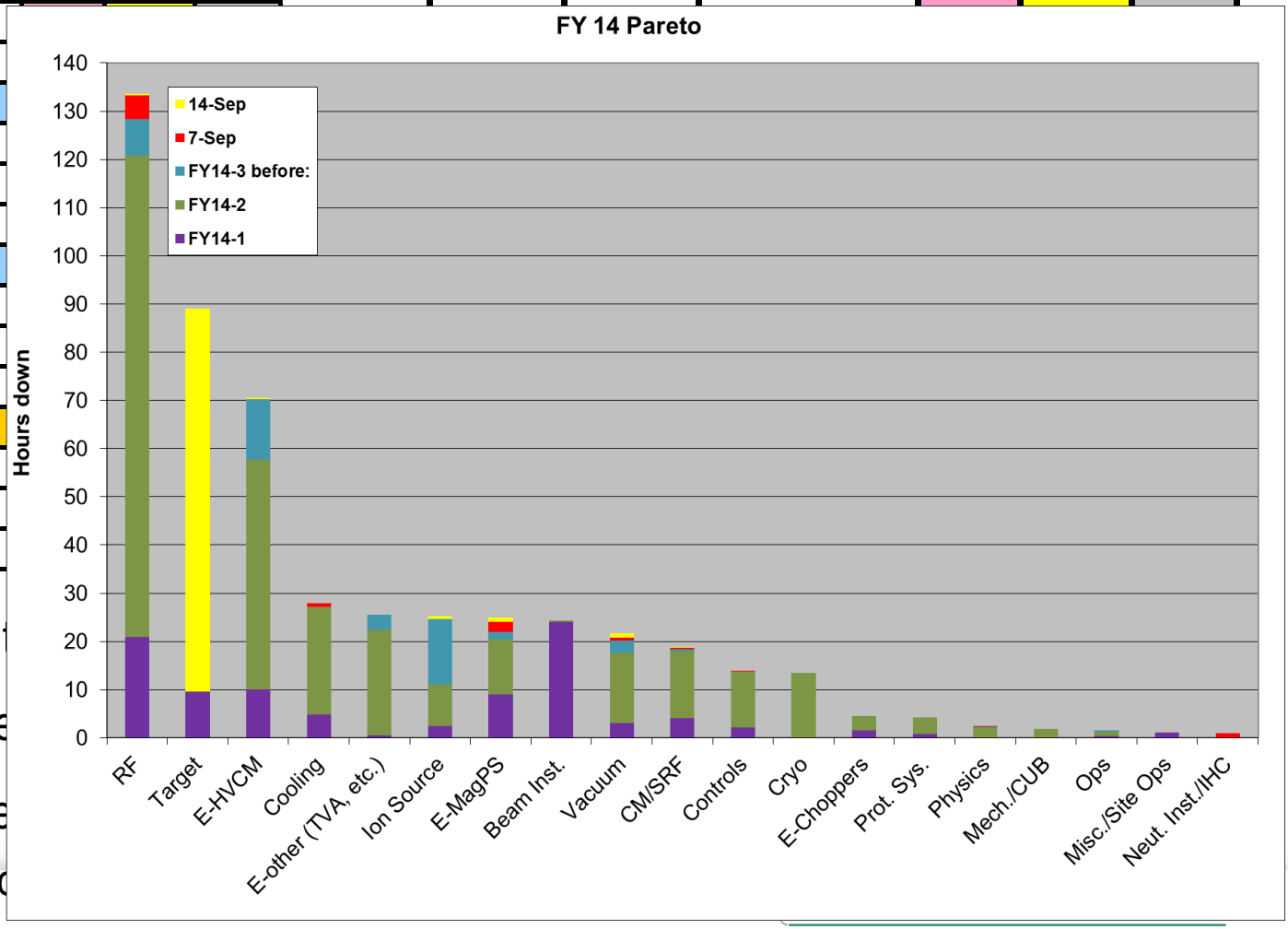
Follow Equipment Health Trends

Top trip Statistics: 8/15 – Sept. 06

FPAR 3 wk. trends			First Hits		
System	Subsys.	Device	Last week	2 wks. ago	3 wks. ago
LLRF	HPM	RFQ	2197	1497	1818
LLRF	HPM	SCL_22c			
LLRF	HPM	SCL_06b			
Diag	BLM	SCL_06c			
Diag	BLM	Ring_B06			
Diag	BLM	RTBT_13			
Mag	PS	Ekick_WF04			
Mag	PS	Ekick_WF02			
Mag	PS	Ekick_WF01			
FPL 3 wk. trends					
Mag	PS	SCL_QD09			
Mag	PS	HEBT_QV23			
Mag	PS	HEBT_QH20			

Top trip Statistics: 8/22 – Sept. 13

FPAR 3 wk. trends			First Hits		
System	Subsys.	Device	Last week	2 wks. ago	3 wks. ago
LLRF	HPM	RFQ	845	2197	1497



- Constantly monitor
- Can identify emerge
- Important to be able
  - Need good time

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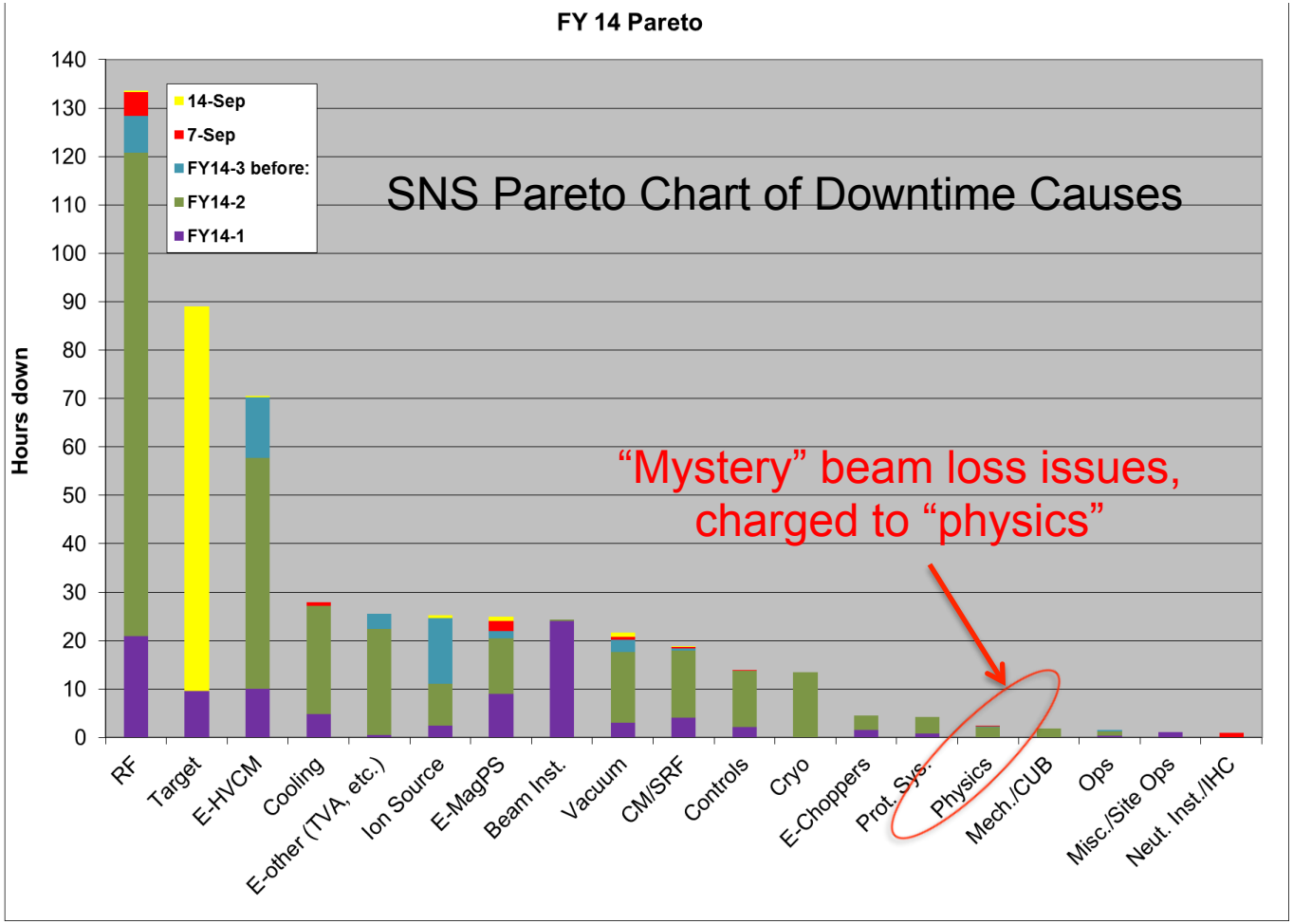
Not All Beam Loss Causes are Understood / Solvable



- Sometimes beam loss cause is not obvious

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Summary: Detecting Equipment Issues before Beam Loss Arises

- Monitor the equipment directly
  - Lots of equipment, so use intelligent displays, applications
  - Use multiple measurements when possible (doubt everything)
- Beam measurements are useful to diagnose equipment
  - Passive techniques are possible even at high power
- Be inquisitive
  - Look for correlations (need good control system / instrumentation)
- Beam loss issues are caused by equipment issues
  - Need to understand equipment / instrumentation to diagnose beam related issues

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