Commissioning of the LCLS-II Machine Protection System for MHz CW Beams

TU3I01

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Stanford University | U.S. DEPARTMENT OF ENERGY

What is a Machine Protection System at SLAC

- The Machine Protection System (MPS) protects components in the accelerator from damage caused by the electron beam
- Types of damage:
  - Accumulation of radiation damage over time due to partial beam loss
  - Material melting and/or ablation by direct electron or x-ray beam impact
- MPS works to disable the electron beam.
  - Rate reduction (power reduction)
  - Complete shutoff of photocurrent
- The MPS is *NOT* a credited safety system. It is designed to protect the investment

At SLAC, the Beam Containment System is designed to protect people from the accelerator, and the MPS is designed to protect the accelerator from people

Each *accelerator* has its own MPS

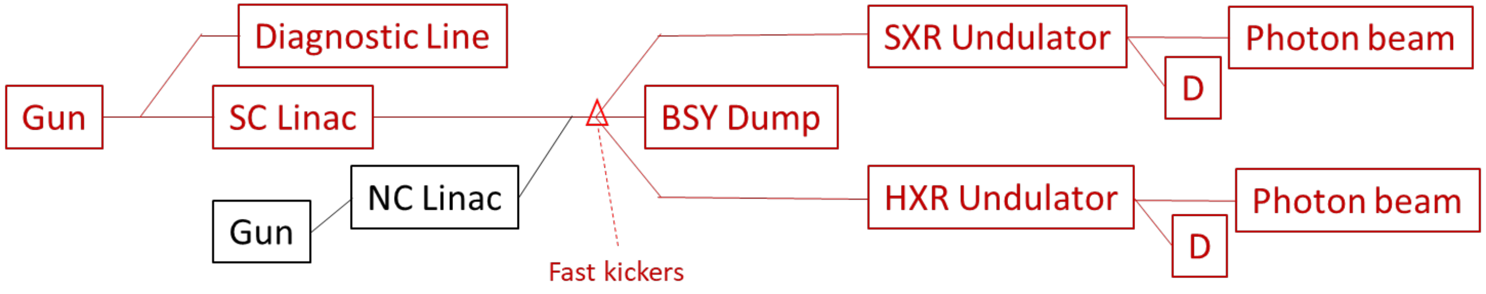
SLAC Linear Accelerator Facility

SLAC Linear Accelerator Facility consists of the LCLS complex and the FACET-II accelerator

LCLS Complex consists of LCLS and LCLS-II Accelerators, 2 undulator beamlines to produce FEL, multiple experimental end stations, and a switching scheme in the middle to facilitate delivery of either accelerator to either undulator beamline

The LCLS Complex and FACET-II each have their own Machine Protection Systems

MPS in the LCLS Complex



LCLS-II MPS needs to respond to avoid damage to critical accelerator components such as superconducting cavities, beamlines, undulator permanent magnets, photon optics, etc.

- LCLS-I: MPS responded to a fault by the next bunch (~8 ms)
- LCLS-II: MPS required to respond within 100 us to avoid catastrophic damage

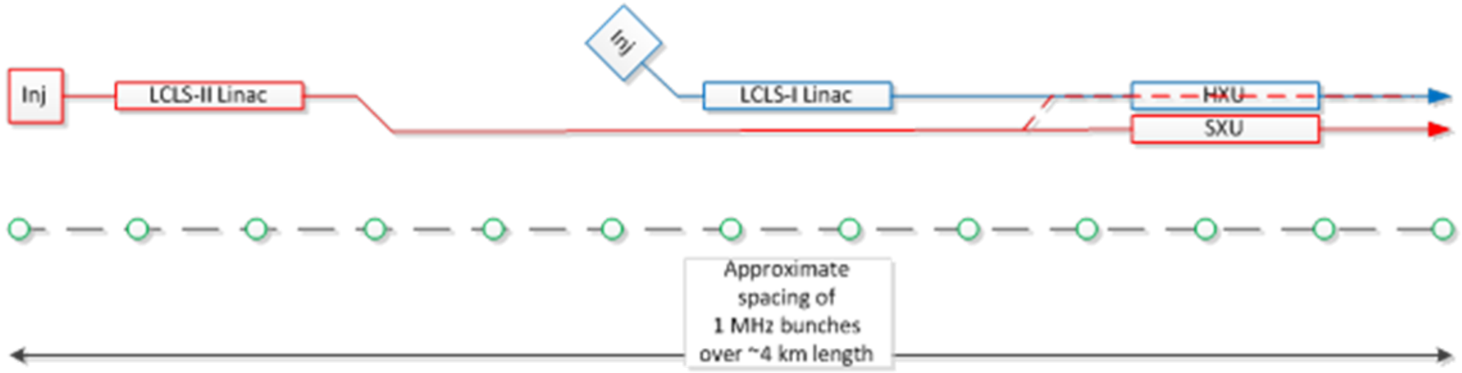
LCLS-II Upgrade

- Original LCLS was 1 source to 1 user, pulsed RF, 120 Hz duty cycle, fixed gap undulator system for FEL
- LCLS-II project installed:
  1. New accelerator with superconducting RF cavities capable of CW RF and 1 MHz duty cycle
  2. 2 variable gap undulator beamlines (soft x-rays and hard x-rays) to support 2 FEL simultaneously
- SC accelerator produces 4 GeV electrons at maximum rate of 1 MHz for maximum power of 120 kW

LCLS SC MPS Requirements

System requirements

- Must be compatible with different beam rates, from low-rate startup to full 1 MHz CW operation
  - Includes complex burst patterns
  - MPS must be aware of beam power levels
- MPS must lower the beam rate or shut off the beam completely according to fault severity or device insertion
- Rate should recover automatically when fault conditions clear (if the fault opts-in to automatic recovery)
- Must support different destinations for each pulse to allow interleaved delivery to multiple users.
- Must operate in parallel with LCLS-I
- Time between fault occurrence and beam shutdown must be less than 100 µs for "fast" faults.
  - Must also remain as low as reasonably achievable (ALARA)
  - Standard faults will follow LCLS-I's requirements: shutdown within 2.3 ms.



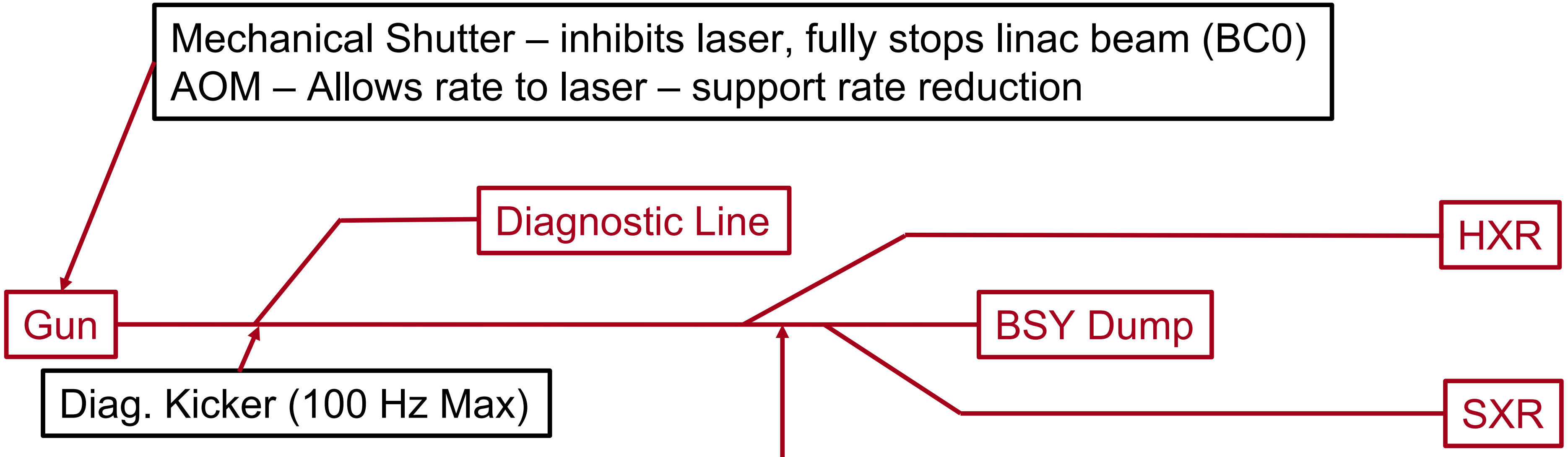
Mitigation Strategy

MPS uses two mitigation paths to inhibit the beam

1. Rate reduction
   - The MPS imposes a Beam Class. A Beam class is defined as a maximum integrated charge in a defined time interval with some fixed beam spacing (rate)
   - The timing master has a series of pre-programmed "Allow Tables" that correspond to each beam class. The allow table is combined with the user request table to define the actual beam rate. See TH1I01 from Carolina Bianchini Mattison on Thursday for more about the LCLS-II timing system
   - Mitigation Devices listen to these triggers to fire, and MPS verifies they have fired when expected. If a mismatch, go to beam off condition
2. Beam Shut Off
   - Beam Class 0 is defined as no beam allowed
   - MPS has permit signals to each mitigation device that are revoked when in beam class 0

MPS permits are *per destination*, so each destination has a mitigation device to allow beam into that zone

MPS Mitigation Devices



UND mitigations means spreader kicker does not allow beam to beamline → beam goes to BSY dump

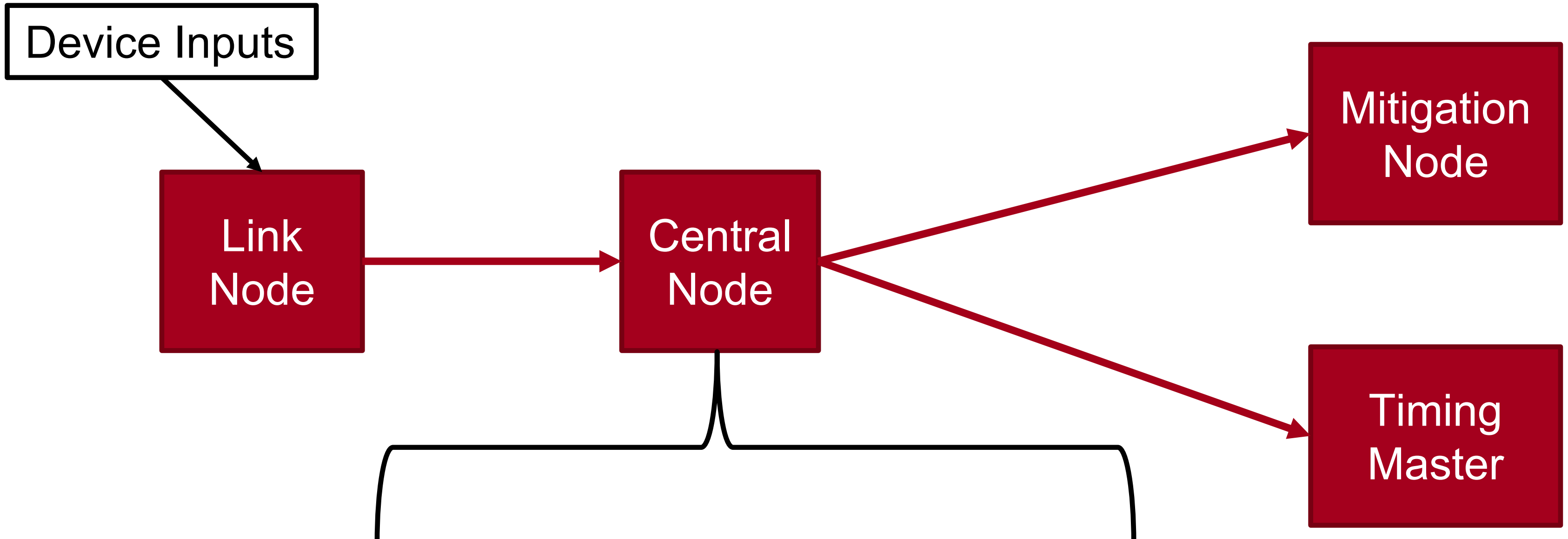
Linac mitigations means laser does not produce beam

<u>HXR and SXR spreader kicker magnets:</u>

- BC0 – permit revoked and magnet enters OFF state
- Rate reduction – Magnet listens to Timing Master and only allows beam into beamline when permitted

Each link node required to respond to central node or timeout faults all destinations to BC0

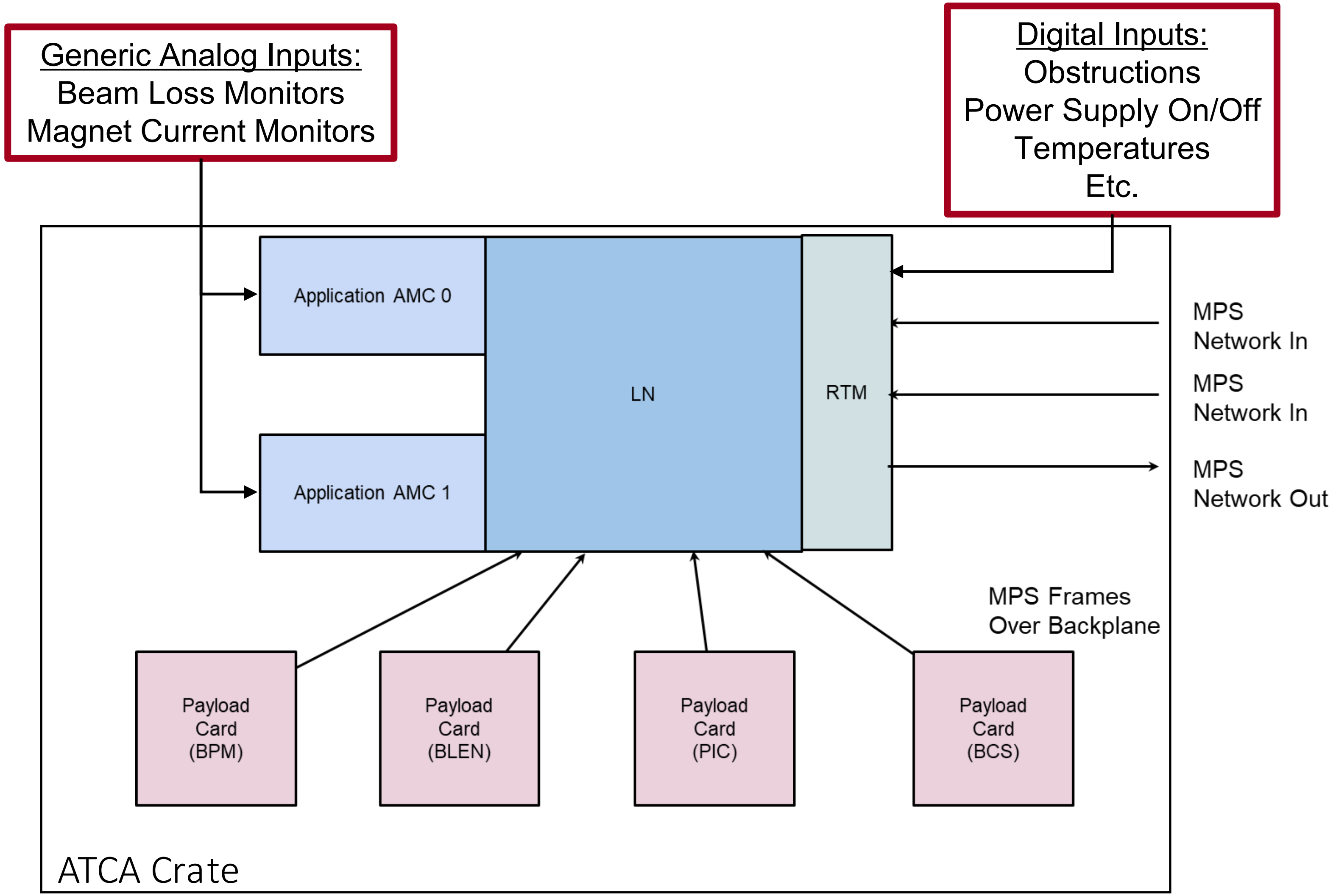
LCLS SC MPS High Level Architecture



- Device states sent through ***pre-programmed*** static logic tables to calculate high level machine state
- High level machine state sets mitigation for each destination

- Timing master contains ***pre-programmed*** rate allow tables for each beam class
- Applies appropriate allow table for each destination

LCLS SC MPS Link Node



Link Node is a data collector

- Built upon SLAC common platform ATCA architecture
  - Every ATCA crate has 1 link node and multiple other application payloads
- Signals enter application
  - Thresholds applied if applicable (analog signals)
  - Message constructed and sent to link node
- Link node collects messages, aggregates them, and resends them to next node in the chain
- Final link node sends complete aggregate to central node

LCLS SC MPS Inputs

Type	Number
Beam Position Monitor	302
Beam Loss Monitor	276
Bunch Charge Monitor	7
Magnet Current	84
Photon MPS	62
Obstruction	636
Total	**1367**

Pre-emptive: limit beam power if beam trajectory deviates from nominal

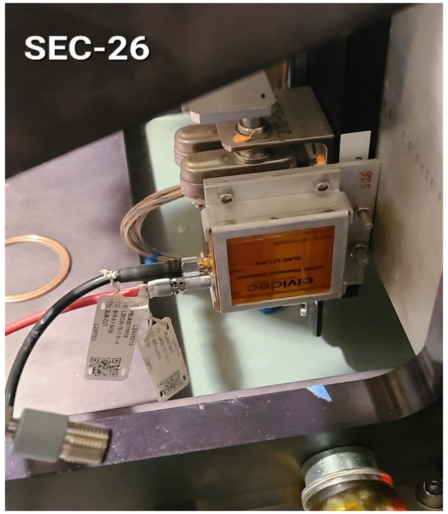
React to loss of beam

Primary verification of power levels and destination

Ensure bend magnets are set properly for beam transport

Photon systems manage end station MPS for agility

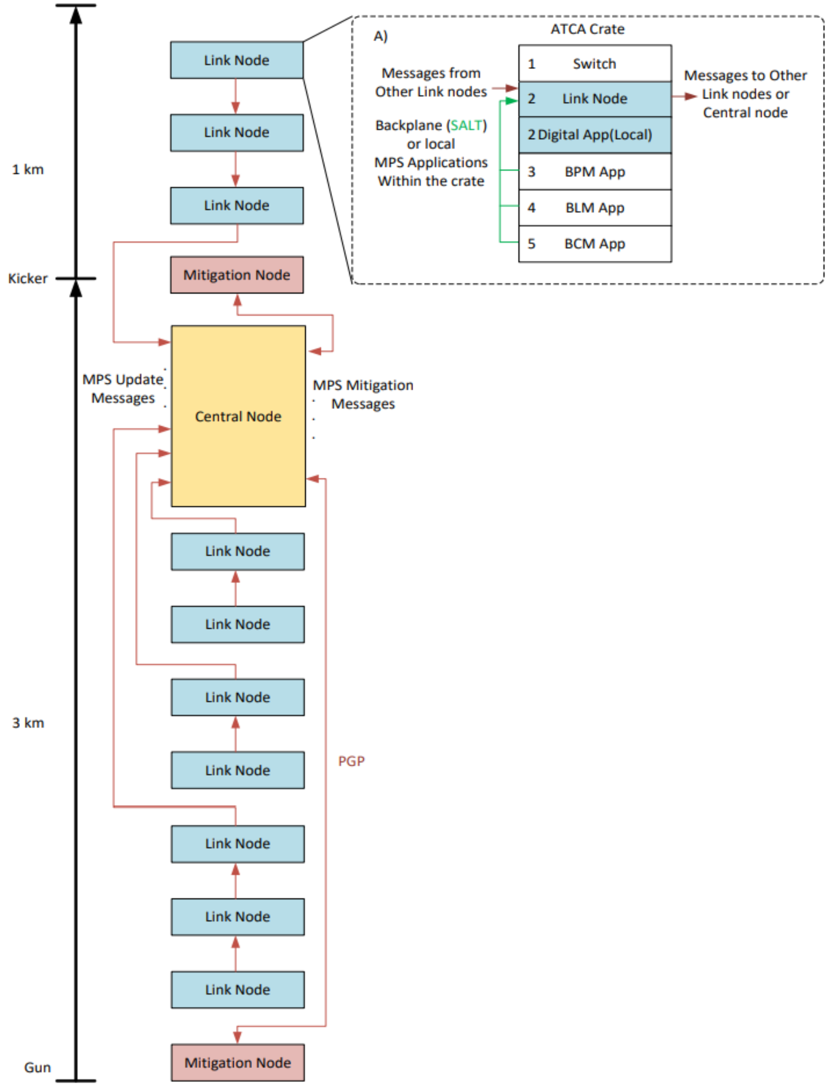
Reactive to beamline obstructions



Point beam loss monitor at a linac collimator

See Alan Fisher and TUP005 this evening for a description of the LCLS-II Beam Loss Monitor System

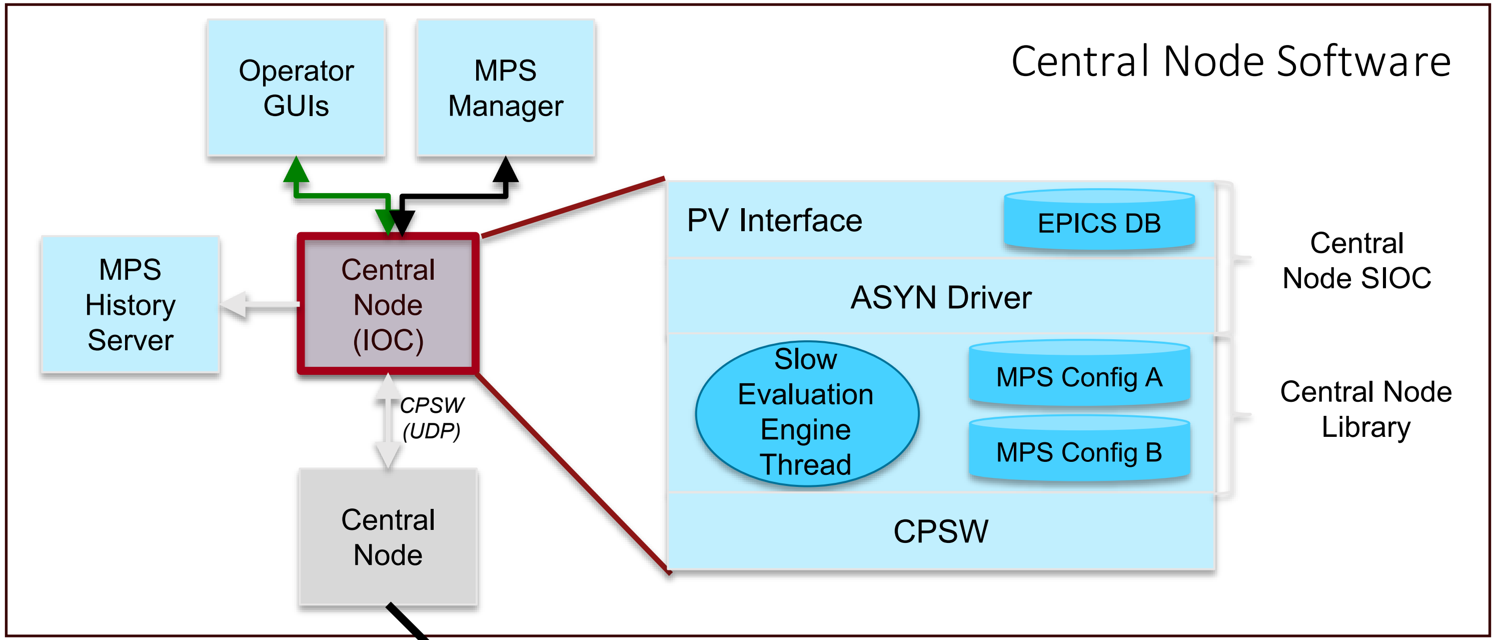
LCLS SC Low Latency Network

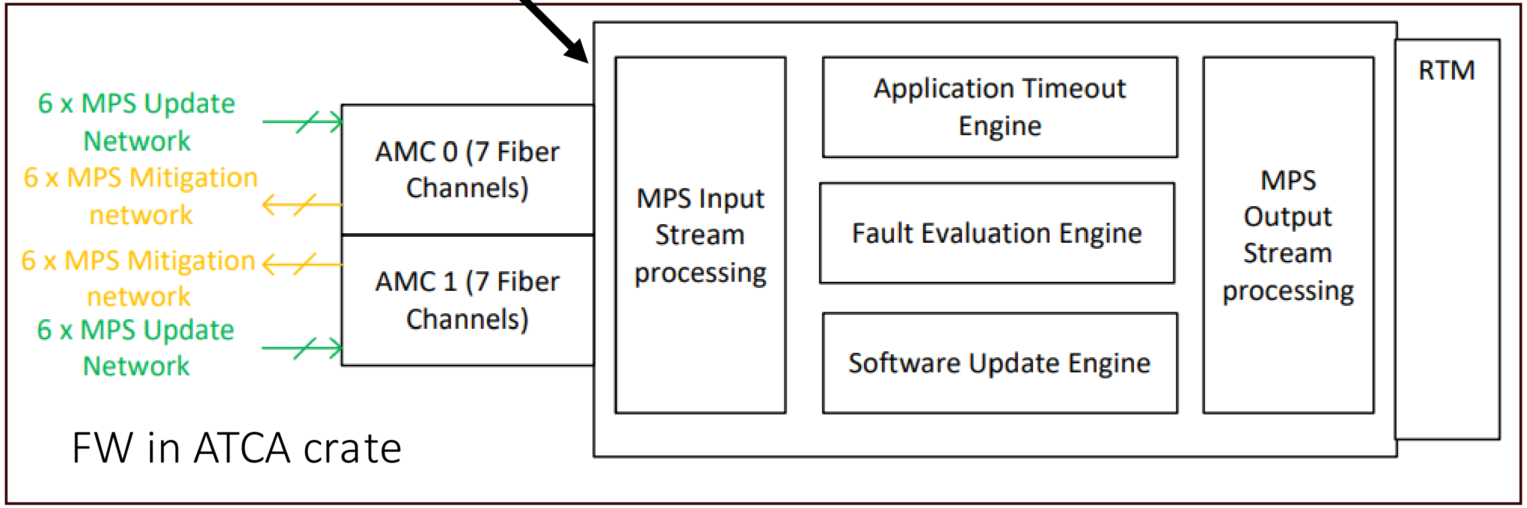


- Link nodes are arranged into groups, chained from one to the next
- Communication is one direction and event driven – each accelerator clock cycle (1 us) link nodes send out a message
- Bandwidth of each group is 5 Gbps
  - 25 link node groups organized so group bandwidth < 2.5 Gpbs → room for future infill if needed
- Central node collects data from up to 12 link node groups

MPS central nodes

LCLS SC MPS Central Node



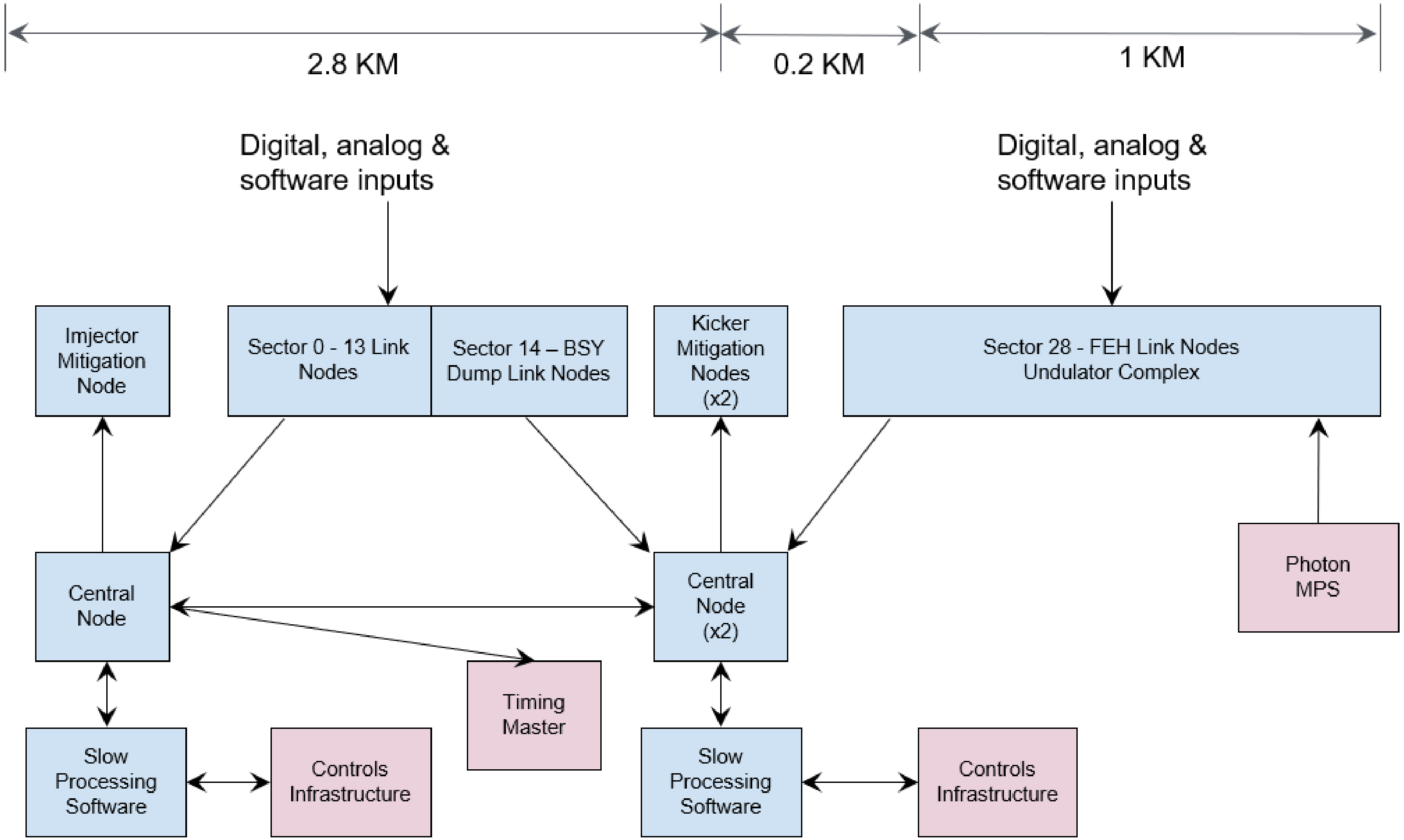


Central Node monitors:

1. Fast rules evaluation
   - Single bit decisions are made in FW rules table in 1 us
2. Application timeout
   - Each discreet application must send a new message
3. Slow rules evaluation
   - Information streamed to computer at 360 Hz for evaluation of complex rules
4. Timing pattern
   - Timing system information is monitored for compliance

Final permit is the result of the combination of *all* the above

System Implementation



To further manage latency and bandwidth, three central nodes are installed

Each central node operates independently

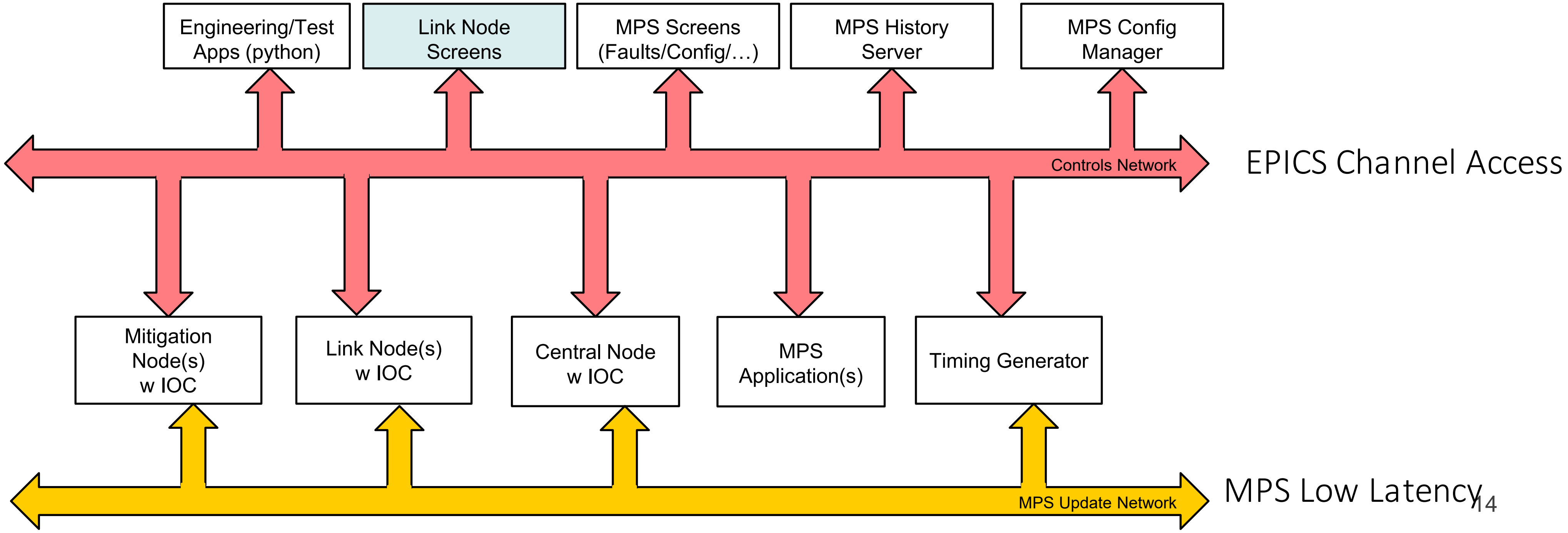
The three central nodes exchange permit data after each cycle (1 us)

The final permit each reports is the lowest of any of the three

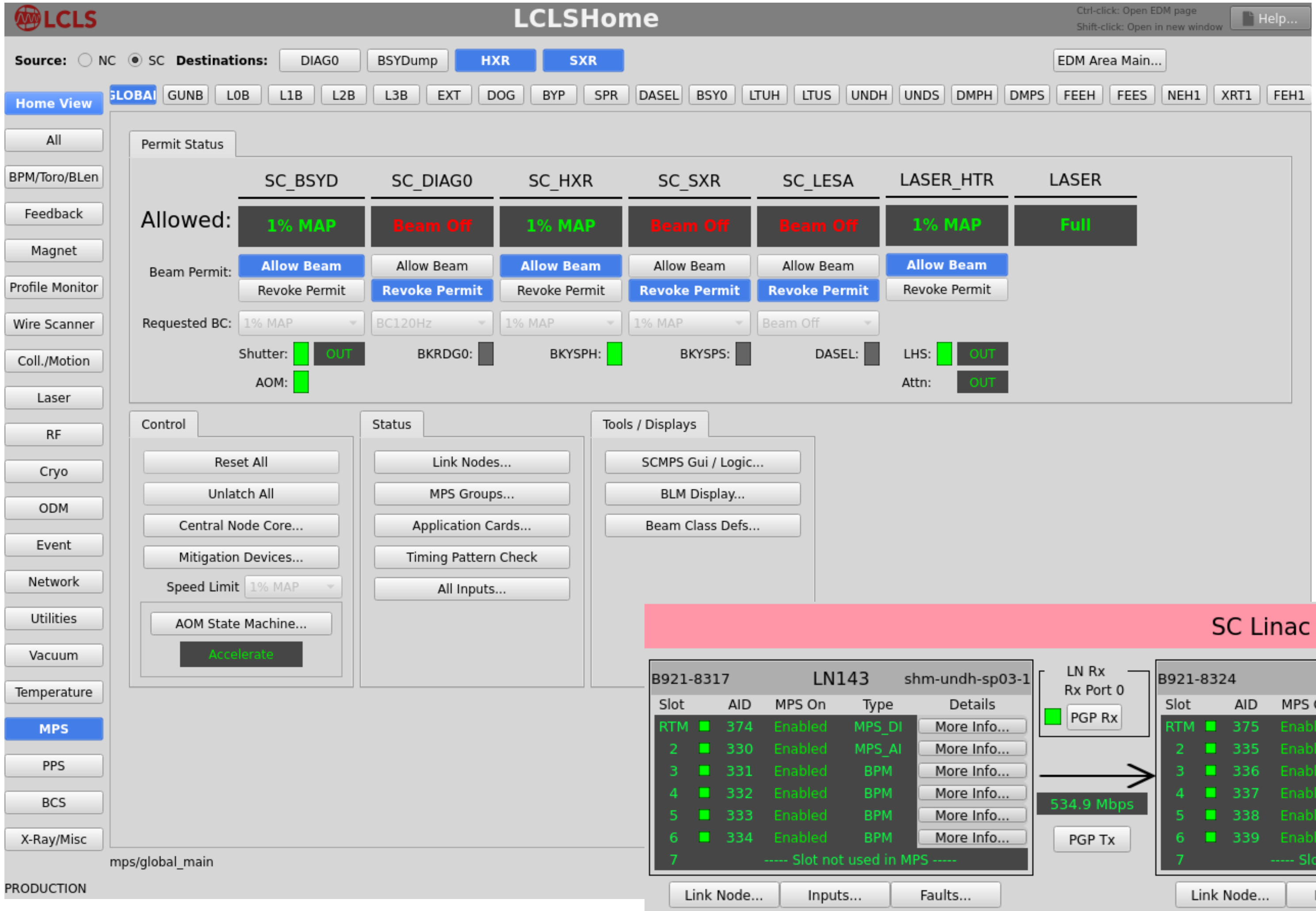
Software Support

MPS Software built against the EPICS toolkit

- SLAC common platform has an industrial CPU attached to each ATCA crate
- Kernel driver support provides a mechanism to attach one EPICS IOC to each payload in the crate
- EPICS IOC for link node and central node provides asynchronous and some beam synchronous data for consumption
- EPICS channel access is used to send and receive information from operations into the hardware

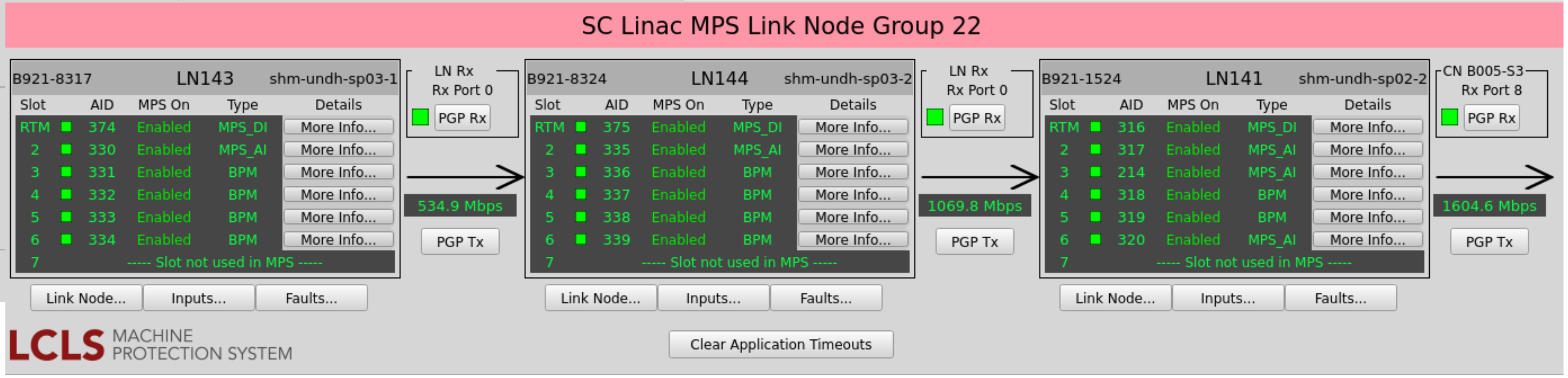


Software Tools



High level permit and status

Example low-latency group



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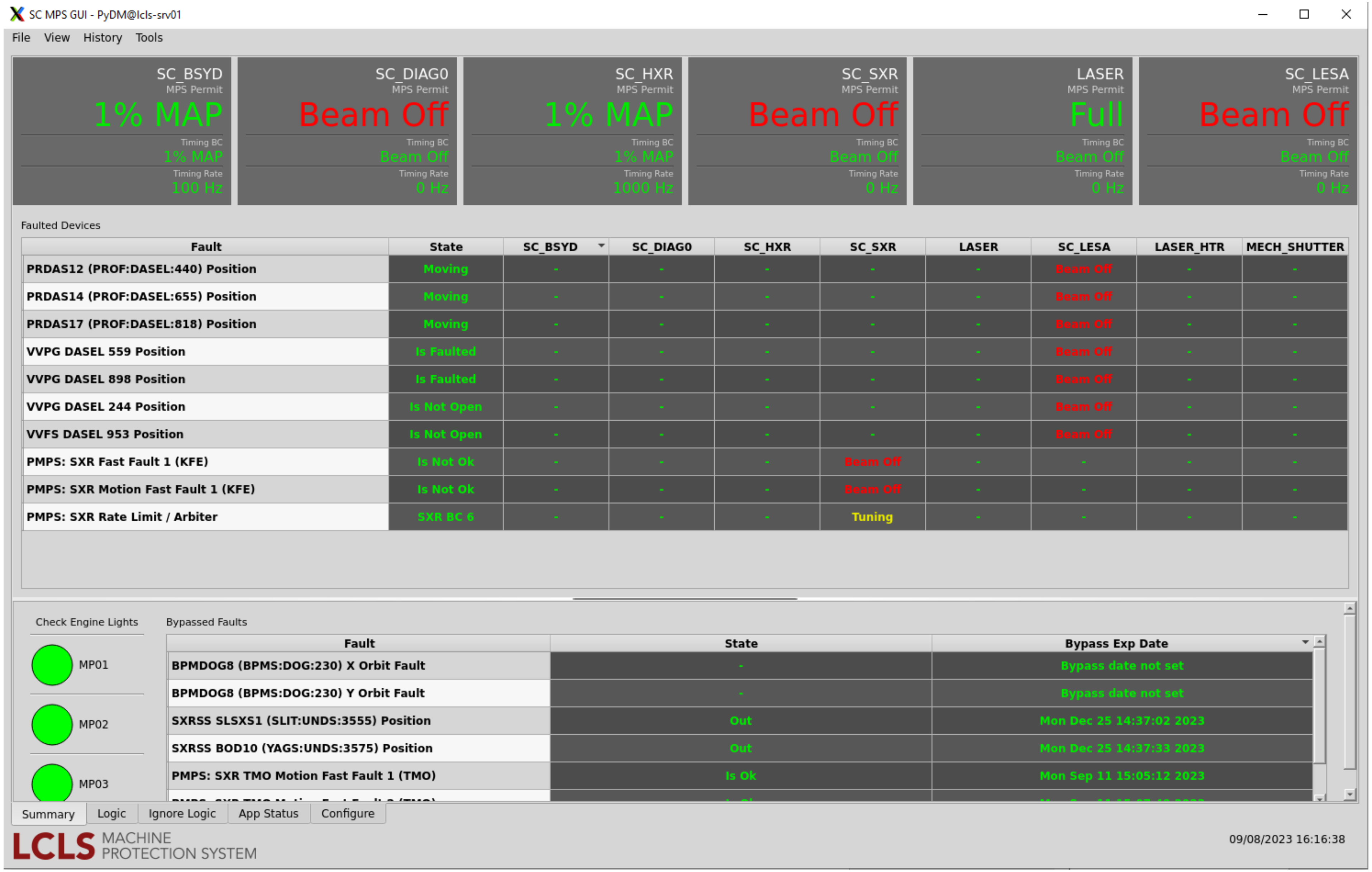
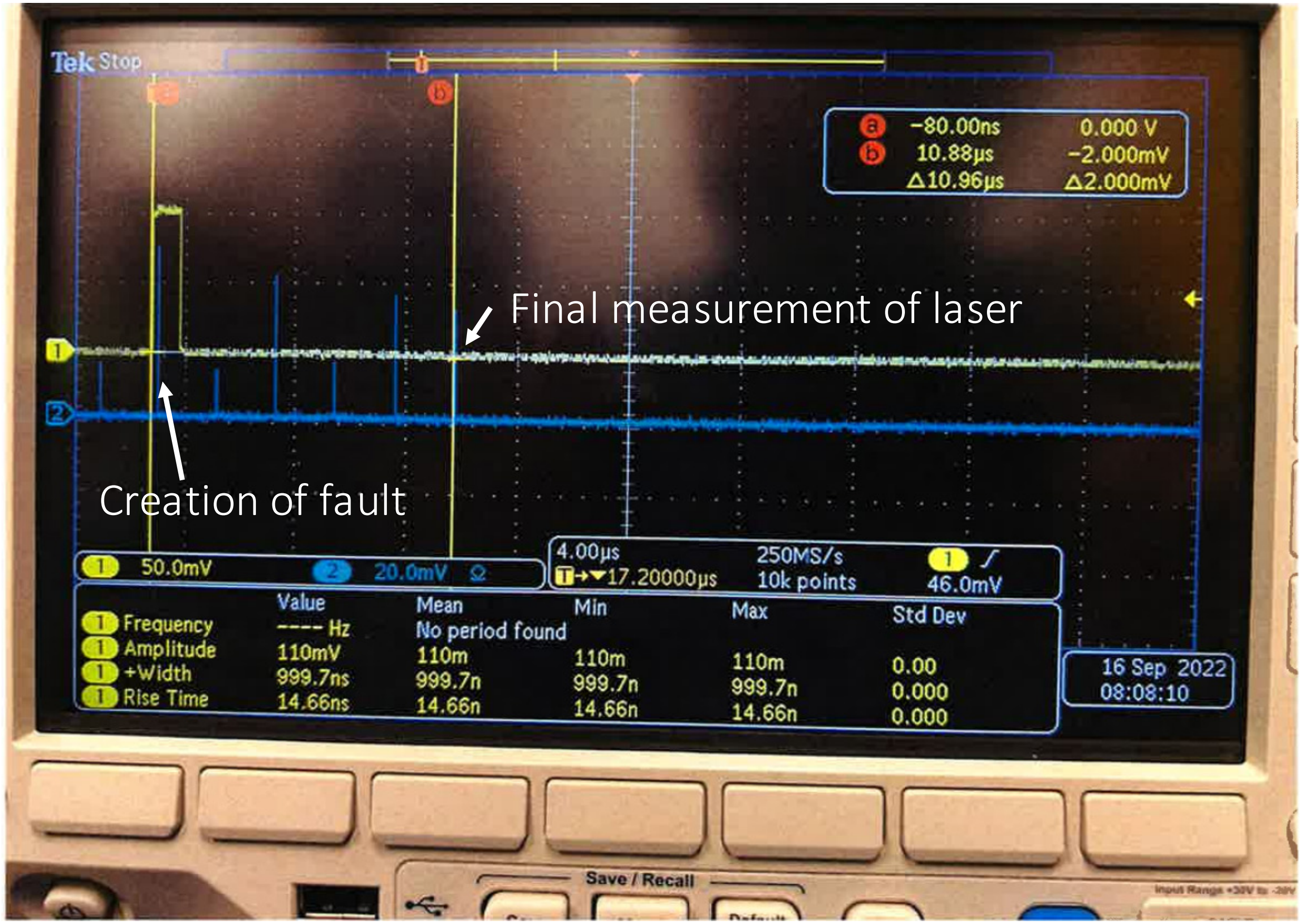


Measurement of shutoff times



Use a signal generator to drive an analog fault in a link node (yellow trace)

Measure the laser pulses at 500 kHz (blue)

Time between start of fault and last blue spike is the shutoff time

Repeat for the kicker magnets

Destination	Maximum Commissioning Rate	Minimum Commissioning shutoff time	Measured shutoff time
Linac high power dump	93 kHz	100 us	12 us
HXR Undulator Beamline	1 kHz	1 ms	70 us
SXR Undulator Beamline	1 kHz	1 ms	110 us

Kicker magnet shutoff times are acceptable for commissioning but not higher power modes. More work needs to be done to understand where the slowdown comes from

Commissioning Experience

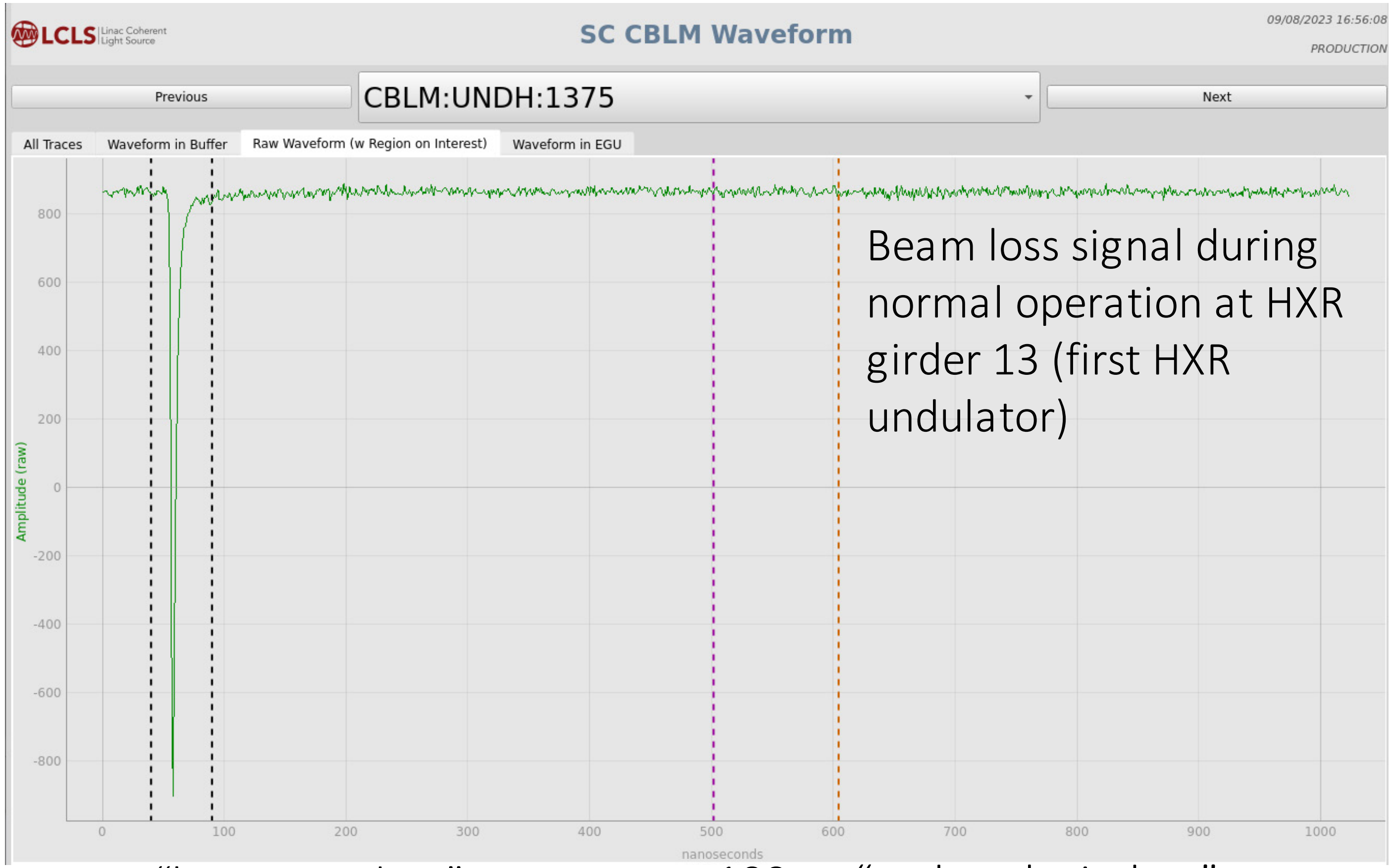
System designed with commissioning in mind

Commissioning happened in 3 phases:

1. Injector
   - Requires one central node
2. Linac
   - Requires two central nodes
3. Undulator Complex
   - Requires all central nodes

Goal is for MPS to stay out of the way unless it needs to intervene. When it intervenes, it must be able to tell operations why

Undulator Beam Loss Monitors



Beam loss signal during normal operation at HXR girder 13 (first HXR undulator)

50 ns "beam window"

100 ns "pedestal window"

Processed "beam loss" is the average value in the beam window minus the average value in the pedestal window

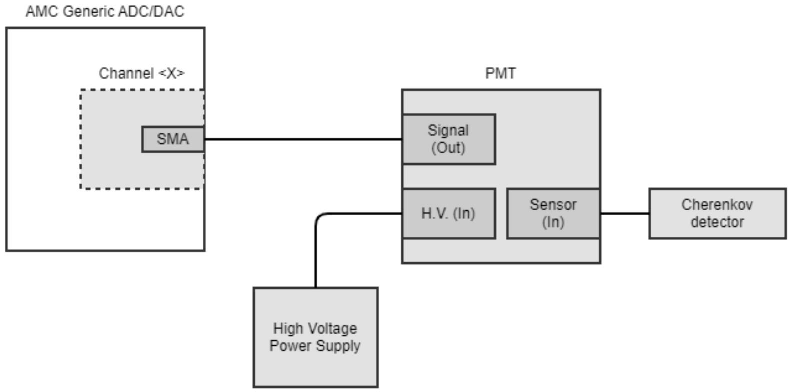
Every undulator girder has a beam loss monitor attached

- 34 Hard Undulators
- 22 Soft Undulators

Cherenkov detector with a PMT mounted

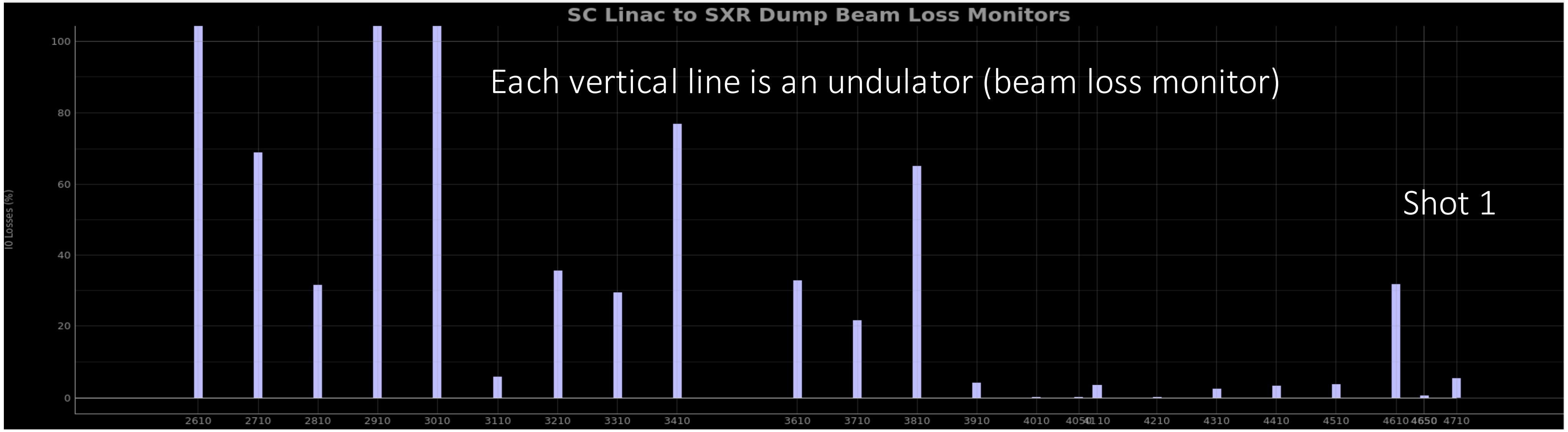
375 MHz digitizer in link node collects and processes PMT data at full machine rate (1MHz)

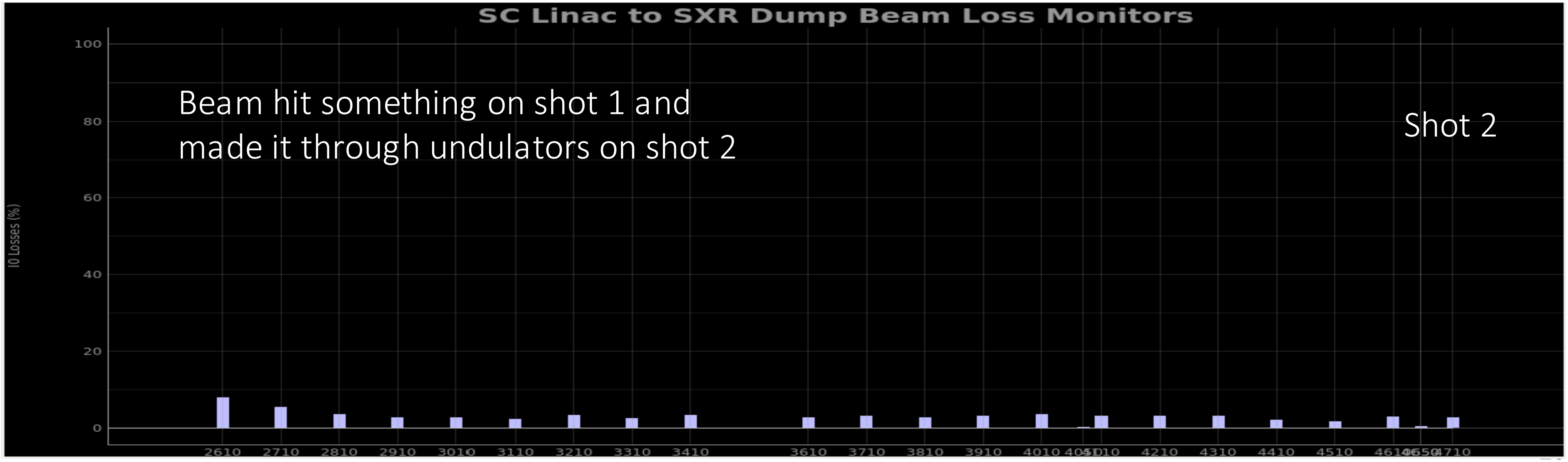
"Beam window" needs to be found for each beam loss monitor



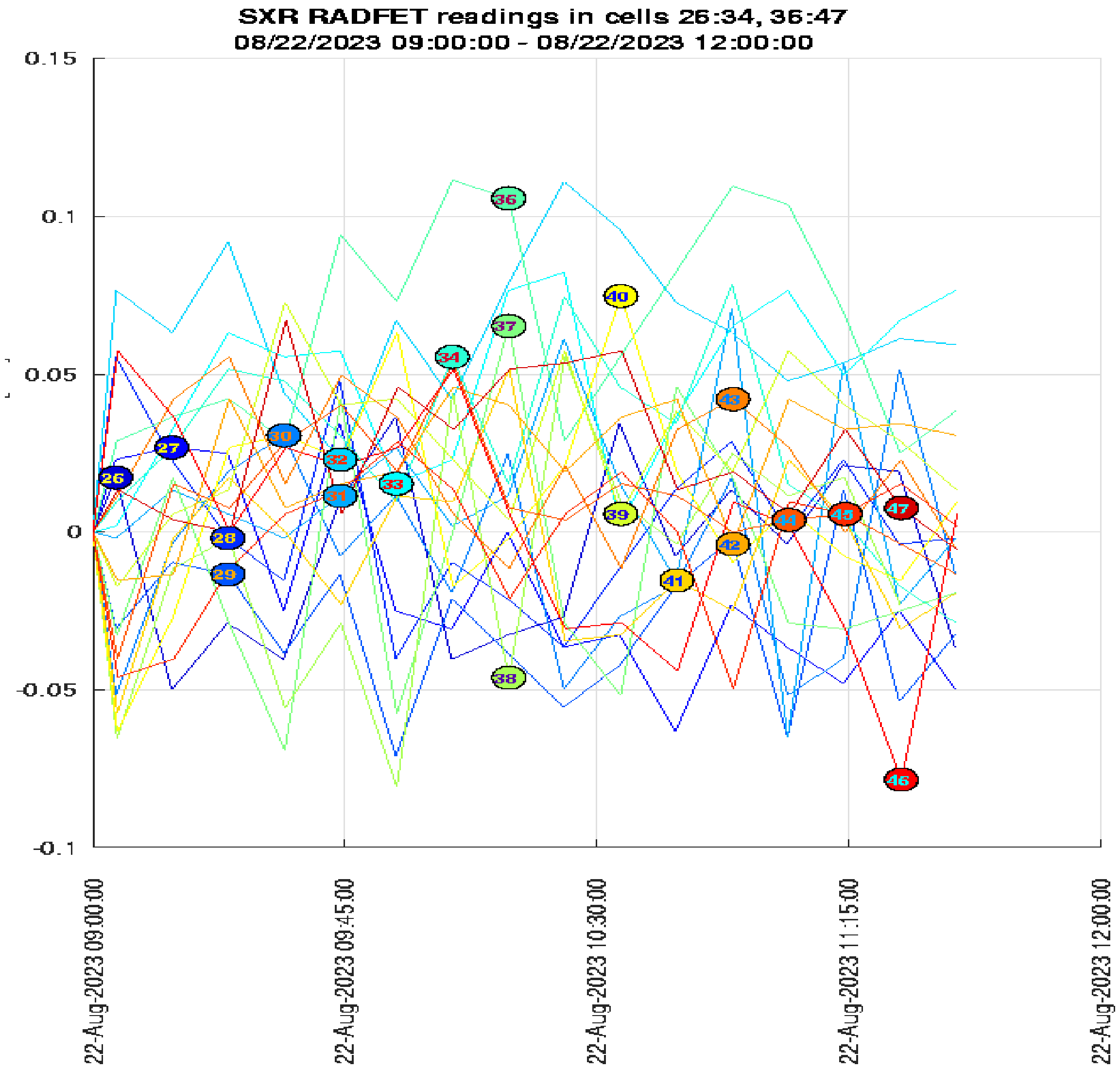
Utility of Undulator Beam Loss Monitors

Y axis is percent of trip threshold of processed beam loss value





RADFETs in undulator hall



Undulator girders have RADFETs

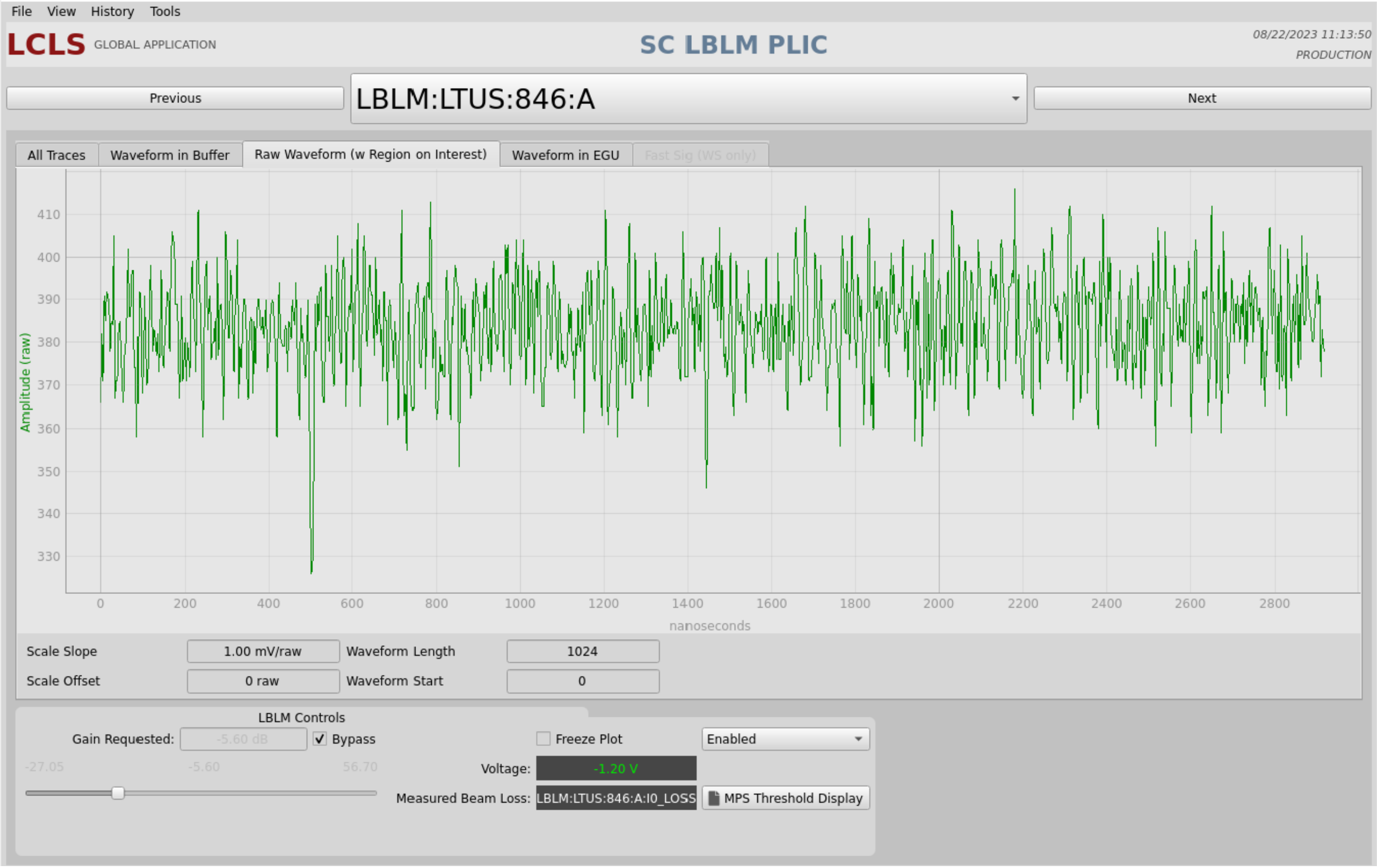
RADFETs not used for MPS

There as a diagnostic.

From the same time period as the previous plots, no significant accumulated dose observed at the RADFETs

Indicates the MPS beam loss monitors are not failing

General Beam Loss Monitors



Slow waveform view of general beam loss monitors as well. Can be used for beam loss localization

MPS and BCS Share

General beam loss monitoring scheme at LCLS complex described by Alan Fisher at TUP005

String of beam loss monitors that cover the entire 4 km extent of LCLS-II, instrumented as part of the Beam Containment System (safety system)

BCS processes the data and sends MPS the result as an analog signal → MPS can set tighter limits and trip first with the same beam loss signals

BPM Directionality

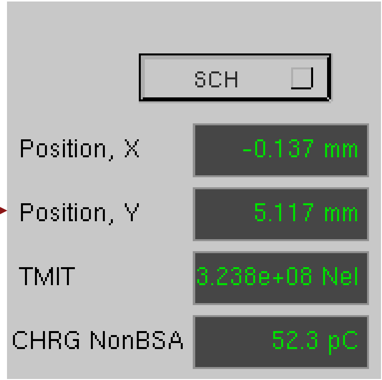
BPM orbit interlocks are used to pre-emptively reduce beam power when trajectory deviates from nominal

Certain BPMs near kicker magnets can detect beam straight ahead or kicked. Kicked beam shows up as a deviation from nominal

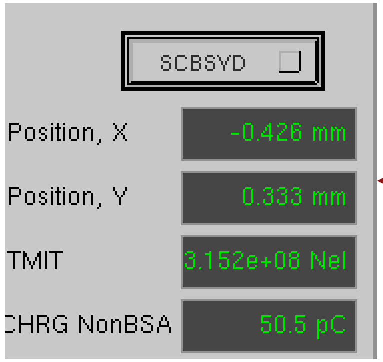
MPS is event driven and timing stream determines the beam destination, so thresholding is dependent upon destination

Kicked into HXR beamline

Kicked beam
Y required to be within
3 mm to 7 mm

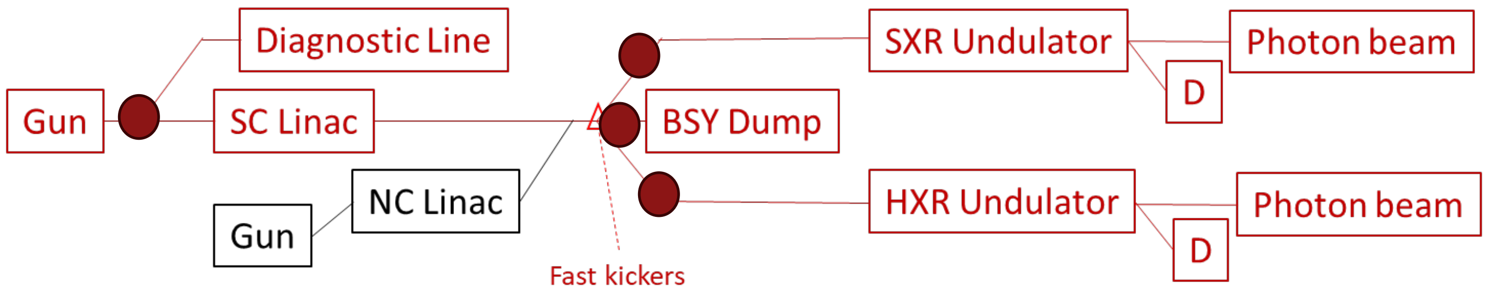


Straight ahead into BSY Dump



Straight ahead beam
Y required to be within
-2 mm to 2mm

Bunch Charge Monitor Interlock



Diagnostic toroids are installed in each beamline

Within SC linac, toroids installed in each warm beamline section

Bunch charge measurement feeds MPS interlock

Bunch Charge Monitors

- Diagnostic bunch charge monitor system measures bunch charge for each potential beam pulse
  - Either measures bunch or absence of bunch
- Timing system encodes destination information as part of the pattern
- MPS uses destination information to choose between 2 threshold tables
  1. Beam present
  2. No-beam
- Acts as a destination monitor and a measure of beam loss or power violation
  - Too little charge = loss
  - Too much charge = violation

Conclusions

- LCLS-II project at the SLAC Linear Accelerator Facility installed a new linear accelerator capable of producing 120 kW beams
- Precious components such as cryogenic RF cavities, beamlines, undulator permanent magnets, photon optics can be damaged by the electron beam
- LCLS SC MPS designed to keep people from damaging the accelerator
- LCLS SC MPS has been fully deployed and checked out. Commissioning underway
- LCLS SC MPS was designed to grow with the facility

Continuing work:

- Better understanding of shutoff time for the undulator complex needed
- MPS only affects photocurrent, but dark current can be a problem
  - Have observed that if some RF cavities in bad state MPS can be “tripped” but dark current can still be present
  - Considering a slow SW monitor to insert a stopper in the event of an MPS trip AND consistent beam loss