ICALEPCS2017

Barcelona · Spain, October 8-13 · Palau de Congressos de Catalunya

Diagnostic and Instrumentation Challenges at LCLS-II

Patrick Krejcik

SLAC National Accelerator Laboratory

SLAC NATIONAL ACCELERATOR LABORATORY

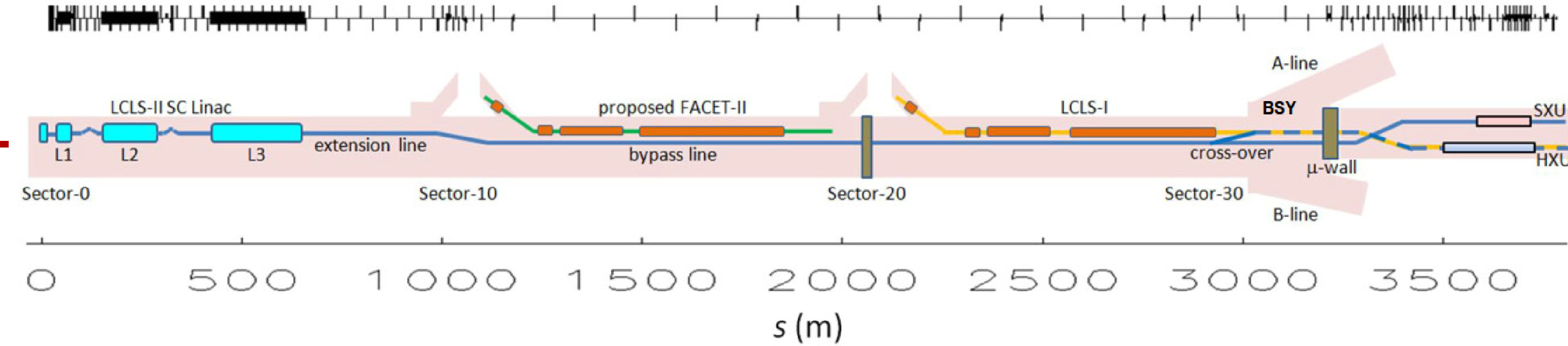

Remove 1 km of
Linac from
Sectors 0-10
New LCLS-II Injector and
New Superconducting Linac
SLAC
New Cryoplant
SLAC NATIONAL ACCELERATOR LABORATORY
BERKELEY LAB
Argonne NATIONAL LABORATORY
Fermilab
Jefferson Lab
Existing Bypass Line
New Transport Line
Expected
First Light
August 2020
Two New Undulators
And X-Ray Transport
Exploit Existing
Experimental Stations

Key accelerator* diagnostic and instrumentation challenges at X-ray FELs

- High brightness, high peak current beams
  - Requires measurement of very small transverse beam sizes
  - And ultra short bunch length measurements
  - Single-pass machine requires bunch-by-bunch measurement

- Add to this the requirements for new generation of superconducting CW linacs
  - High average beam power needs minimally invasive diagnostics
  - High repetition rates require **high data acquisition rates**
  - Diagnostics and instrumentation must be fully integrated with the **timing system** and **machine protection system**

* for LCLS-II photon controls see Dan Flath's talk MODPL06

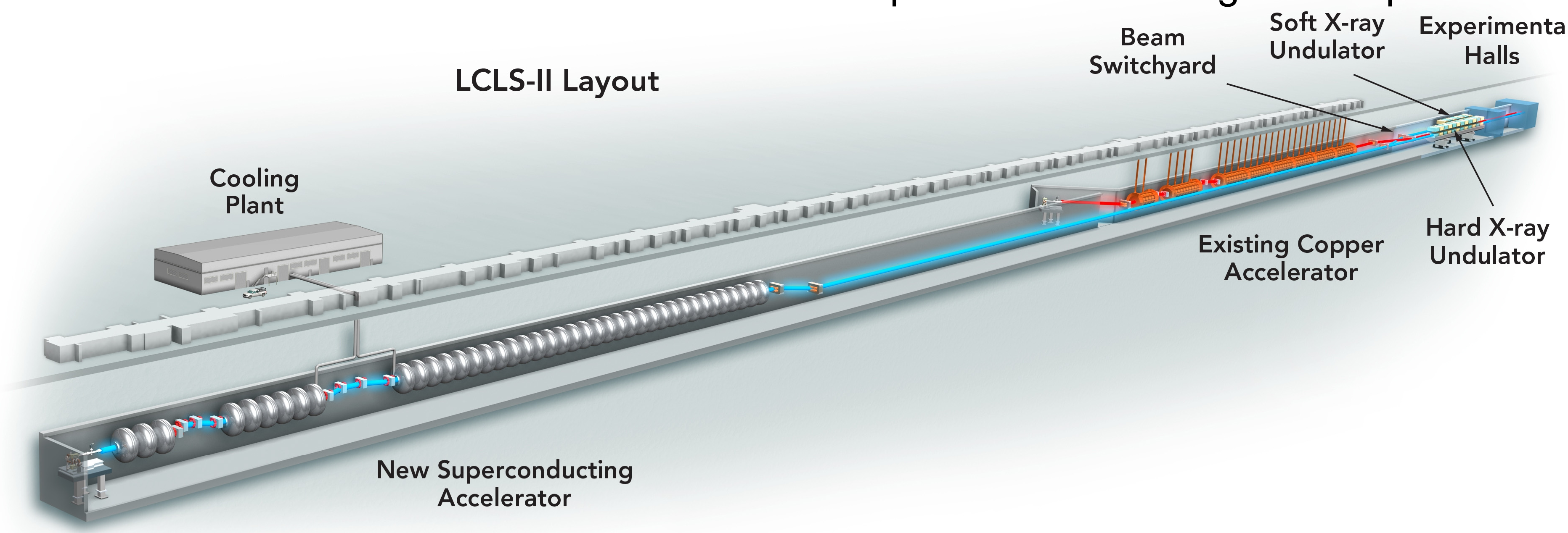


LCLS-I

- Warm, copper S-band pulsed linac
- 120 Hz single bunch repetition rate
- 3.5 to 14 GeV

LCLS-II

- Superconducting 1300 MHz CW linac
- Nominal 1 MHz bunch repetition rate
- 4.5 GeV
- Up to 250 kW average beam power



Shopping List of diagnostics for LCLS--II

- **Beam Position Monitors (BPMs)** – (255, strip-lines, cavity, and cold-buttons)
- **YAG Screens** (6, *x* & *y* beam profile – thick screen)
- **OTR Screens** (14, *x* & *y* beam profile – sensitive to μ-bunching)
- **Wire-Scanners** (31, *x* or *y* beam profile – fast scans needed at ~0.3 m/s)
- **Transverse RF Deflectors** (1-3, allow time-resolved bunch measurements)
- **Rel. Bunch Length Monitors** (4, measures relative bunch length for feedback)
- **Beam Loss Monitors** (BCS and MPS loss detection)
- **Micro-Bunching Detector** (not in baseline yet)
- **Beam Toroids** (< 2 MHz only – does not see gun dark current)
- **Average Current Monitors** (BCS, cavity based, new)
- **Faraday Cups** (2, absolute bunch charge – FC after gun temporary)
- **Bunch Arrival Time Monitors** (cavities, not in baseline yet)
- **RADFETs** (long term undulator loss management)

Major Control System Differences

LCLS-I

- 120 Hz data acquisition rate
- Buffered single bunch beam synchronous acquisition from all devices for all consecutive bunches
- VME crate with EPICS IOC processors
- Distributed event-based timing system with discrete timing receivers
- Machine protection over a dedicated network with single bunch 8.3 ms response latency

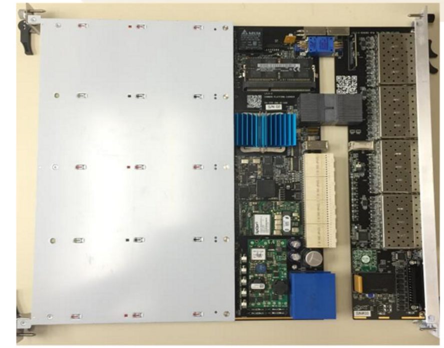
LCLS-II

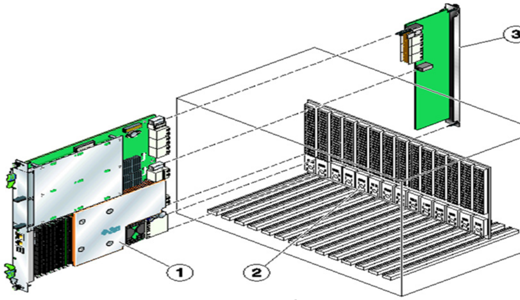
- 1 MHz data acquisition rate
- Buffered single bunch beam synchronous acquisition from all devices for all consecutive bunches
- Common platform for high-performance systems based on ATCA crates and board-level FPGA processing
- Distributed pattern-based timing system with embedded timing receivers
- Machine protection over a dedicated network with 100 µs response latency

SLAC NATIONAL ACCELERATOR LABORATORY

Status – Common Platform

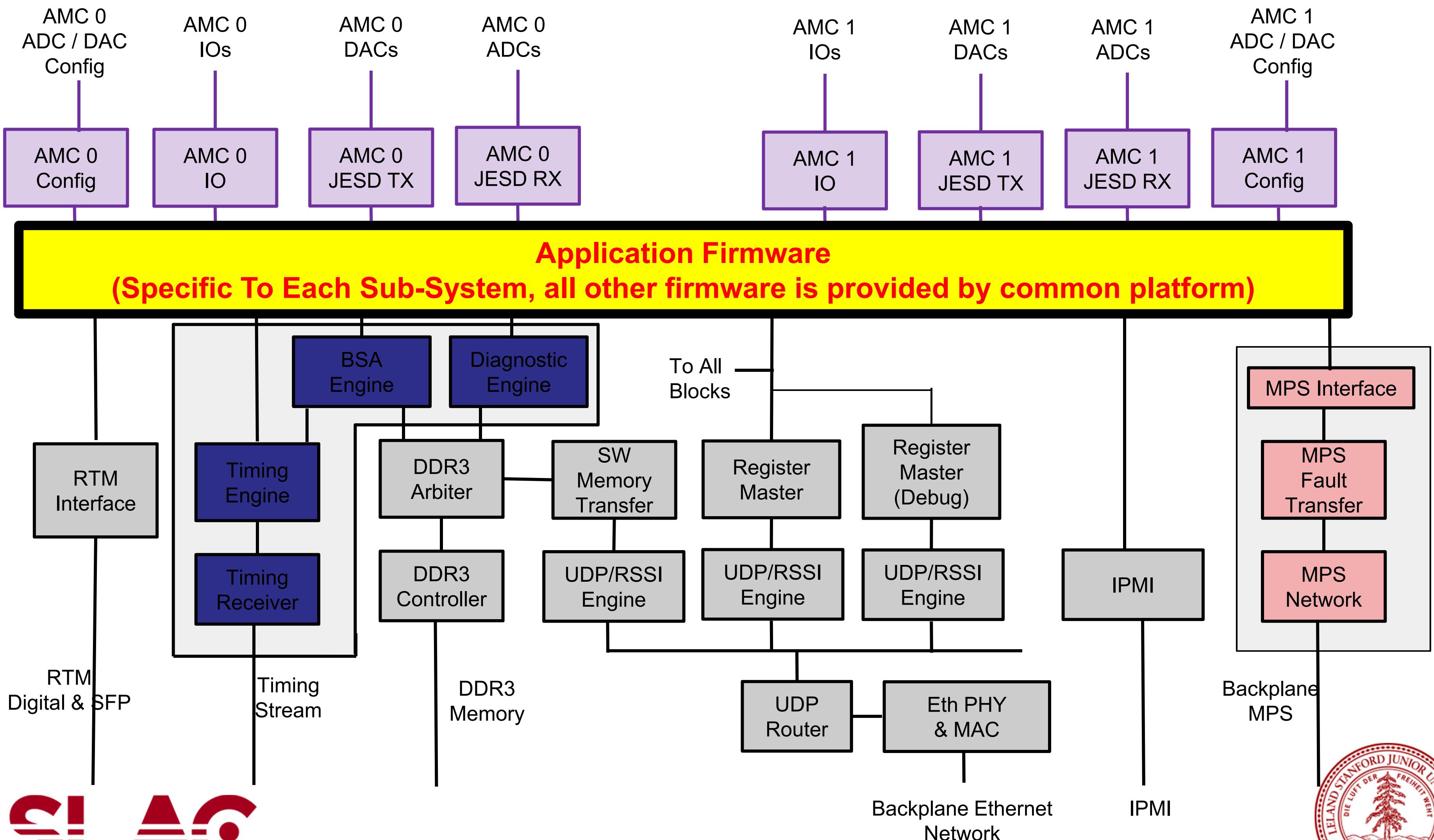
- Hardware
  - Final ATCA AMC carrier completed and being used by sub-systems for sub-system development. Hardware being used by projects outside LCLS-II at SLAC.
- Firmware
  - Base firmware in place and being used for sub-system development
  - Timing system & MPS base firmware integrated
- Software
  - Software released and being used for sub-system development
- Procurement
  - Production underway for Early injector Gun Commissioning (EIC)





SLAC NATIONAL ACCELERATOR LABORATORY

HPS Common Platform: Firmware: Block Diagram



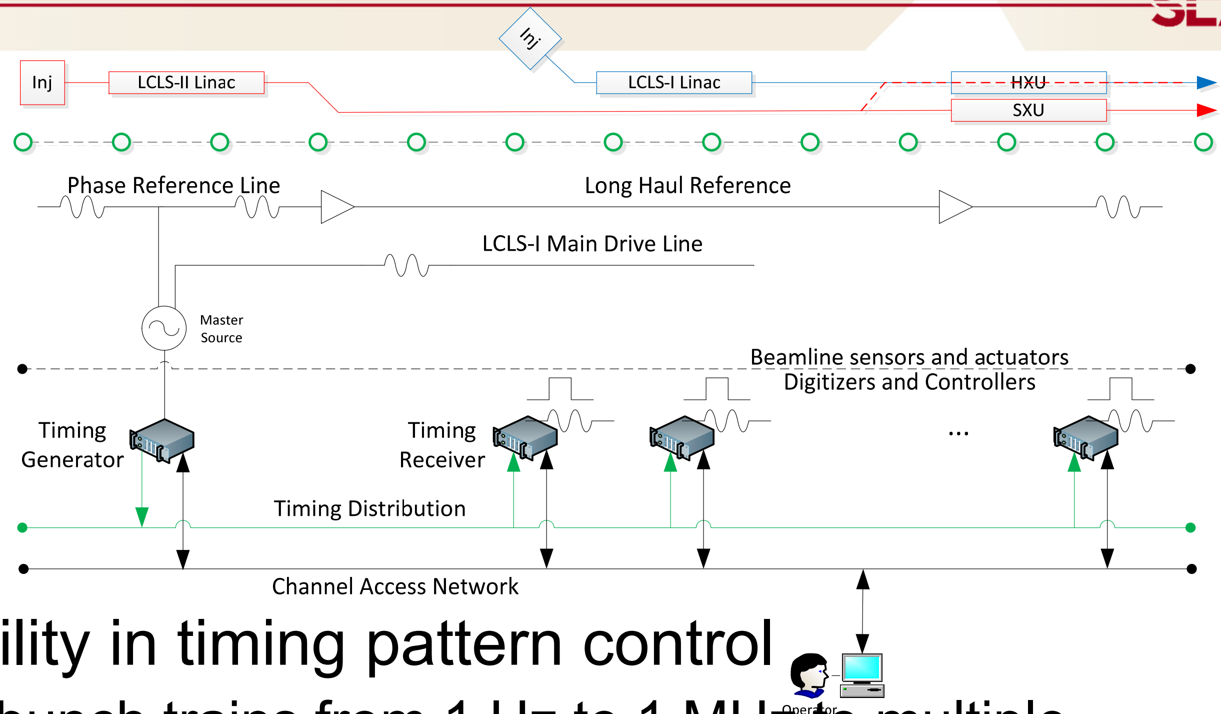
SLAC NATIONAL ACCELERATOR LABORATORY

LCLS-II Timing System

Accelerator

Phase Reference

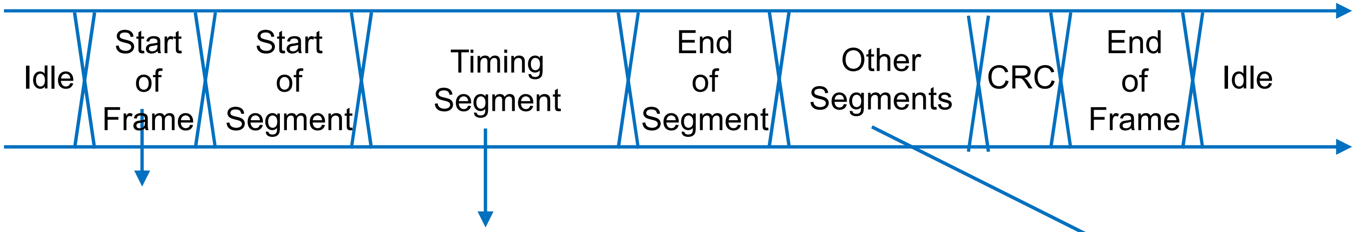
Timing Distribution



- Need flexibility in timing pattern control
  - arbitrary bunch trains from 1 Hz to 1 MHz to multiple destinations
  - Beam synchronous data acquisition of single bunch data at 1_MHz
- Timing data now also includes expected bunch charge and other beam parameters - metadata

Timing Pattern and Fast "Beam Loss" Measurement

Frame data is serialized as 186MHz of 16-bit words (+8b/10b encoding = 3.71Gbps)
Recovered clock is beam synchronous



Field	Size	Description
PulseID	64	Unique, monotonic. Increments at base rate.
TimeStamp	64	Time since 1990 epoch. Increments at programmed step size
FixedRates	10	Fixed rate markers 0-9; one bit for each.
ACRates	6	Power line synchronized markers 0-5, one bit for each.
TimeSlot	3	360Hz timeslot 1-6, persistent. Computed from TS1 input.
BeamRequest	1	Beam is requested from the injector.
Destination	4	Beam destination {HXL,SXL,D10,DL,InjSpec}.
ChargeInj	16	Bunch charge.
BeamEnergy	4x16	Beam energy at 4 locations.
BSA Control	4x64	For each buffer, initialize, average, acquire, finalize.
ControlSeq[0:17]	288	16b control step data for each of 18 sequences.
+others		

Possibilities include:
Fast feedback,
DAQ Control,
LCLS-I Timing.

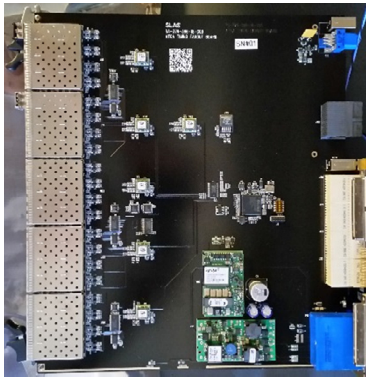
Fast control, acquisition commands, beam meta-data

INNOVATION: diagnostic devices can immediately flag if the measured charge on a single bunch does not agree with expected value for MPS

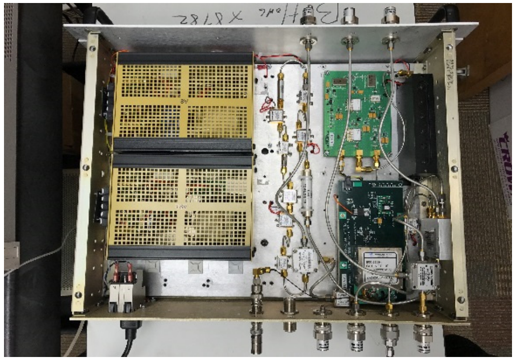
NATIONAL ACCELERATOR LABORATORY

Status - Timing

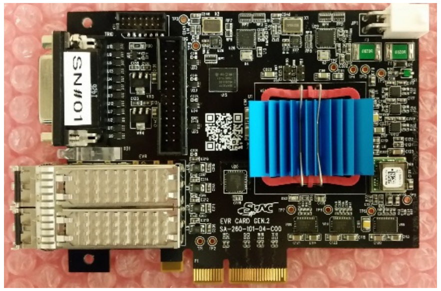
- Timing Pattern Generator (TPG, aka EVG)
  - Hardware and firmware complete. Integrated with EPICS IOC software.
  - TPG IOChas been run few months for testing
- Fanout
  - Hardware Fabricated and Tested
- Non HPS Timing Patter Receiver (TPR)
  - Hardware Fabricated and Tested
- Phase Reference Line (PRL)
  - Hardware Tested.
  - Performance Validate with LLRF and MO/LO
- Software
  - TPG Software prepared for Production Standards
  - Beam Sync Acquisition EPICs support module and TPG SW near completion
- Procurement EIC
  - Complete and in assembly



ATCA Fanout



MO Prototype



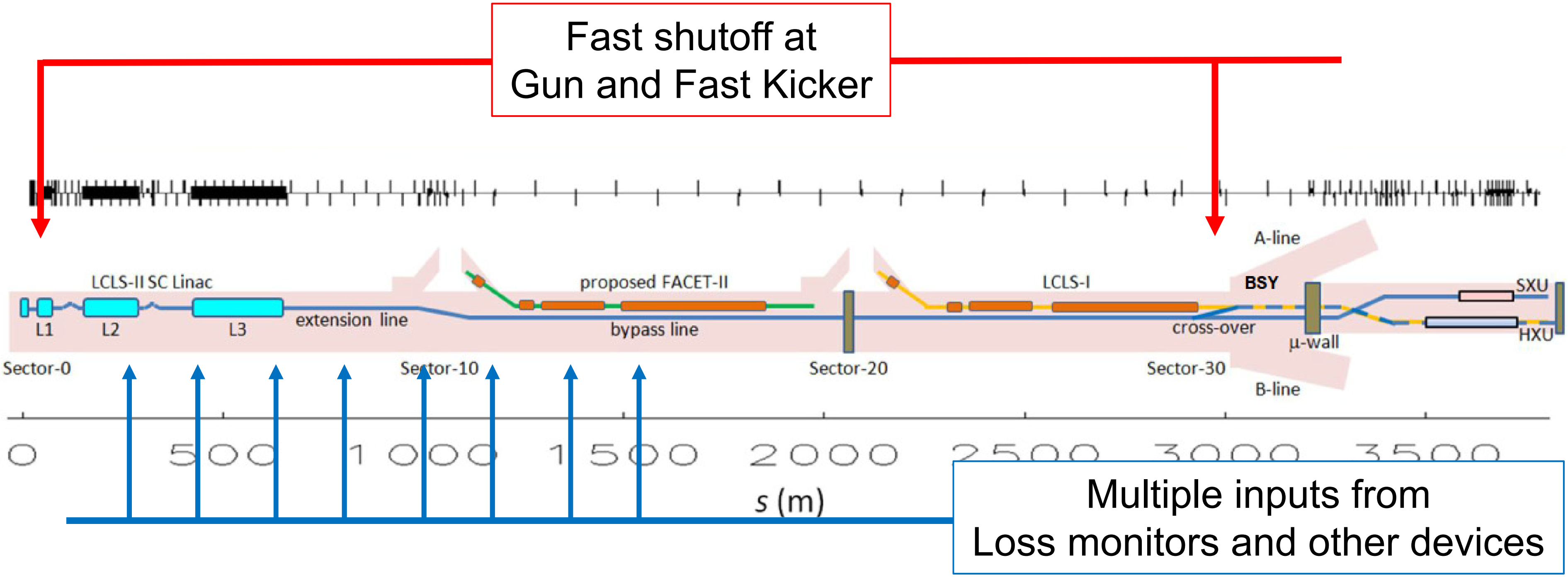
Non HPS TPR (PCIe EVR)

Phase Reference Line Testing

M. Weaver

Machine Protection Requirements

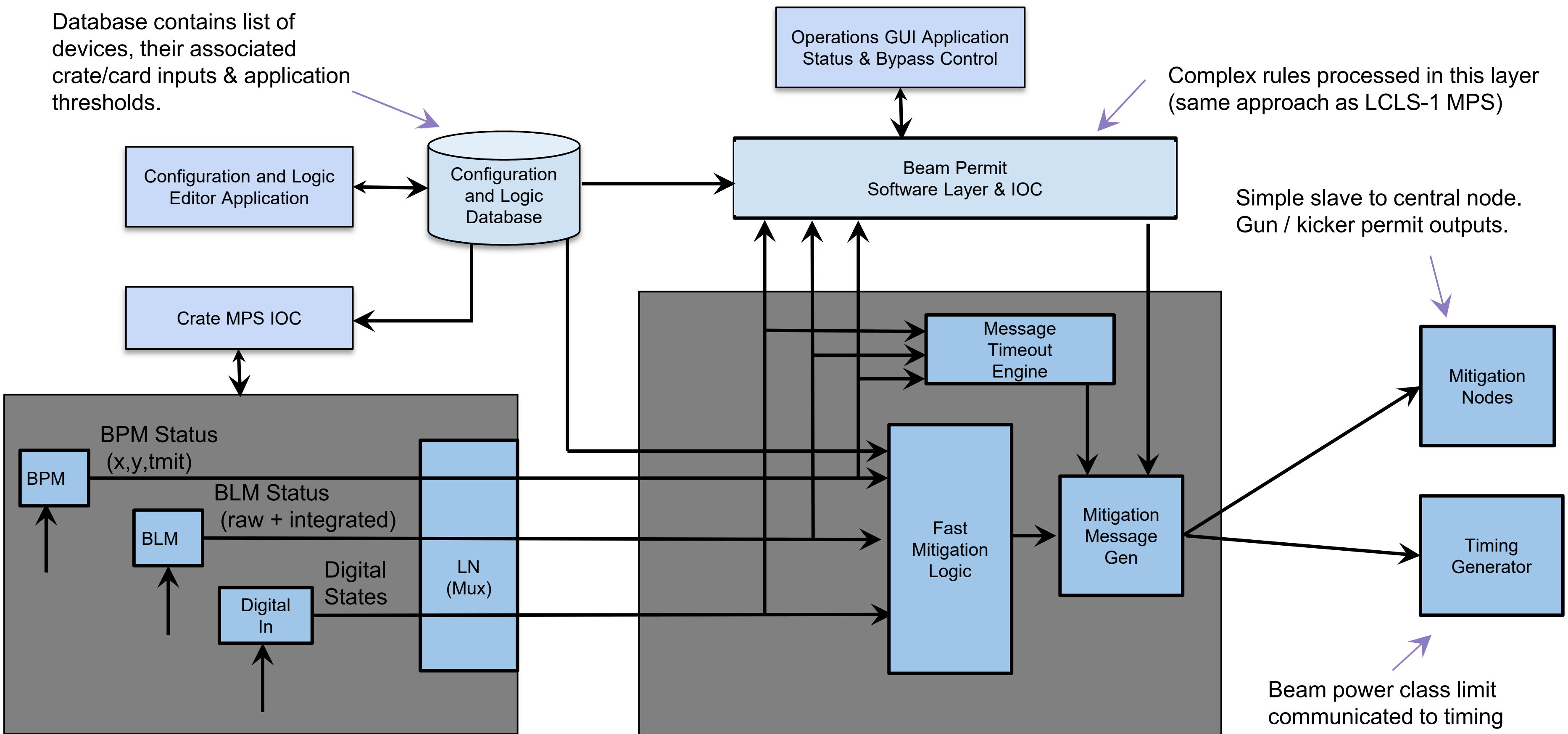
- 250 kW av. beam power at 1 MHz rep rate needs fast abort



- At 1 MHz there are already ~14 bunches in the pipe
- Design for <100 µs shutoff time

SLAC NATIONAL ACCELERATOR LABORATORY

MPS Overview - R. Herbst



Crates

- Application MPS logic applies a set of pre-defined thresholds to application inputs. Threshold results are sent in messages to central node.
- Digital inputs are optionally debounced and sampled values are sent to central node.
- Link node (slot 2 card) forwards messages to central node.

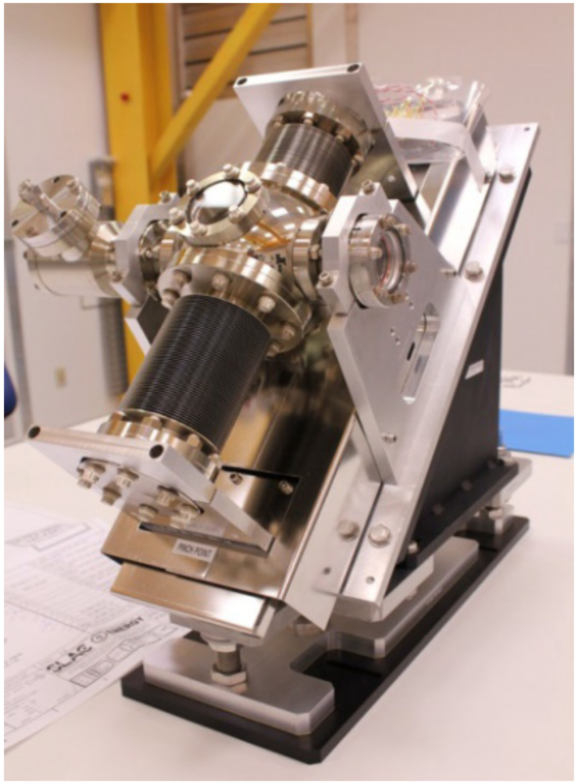
Central Node

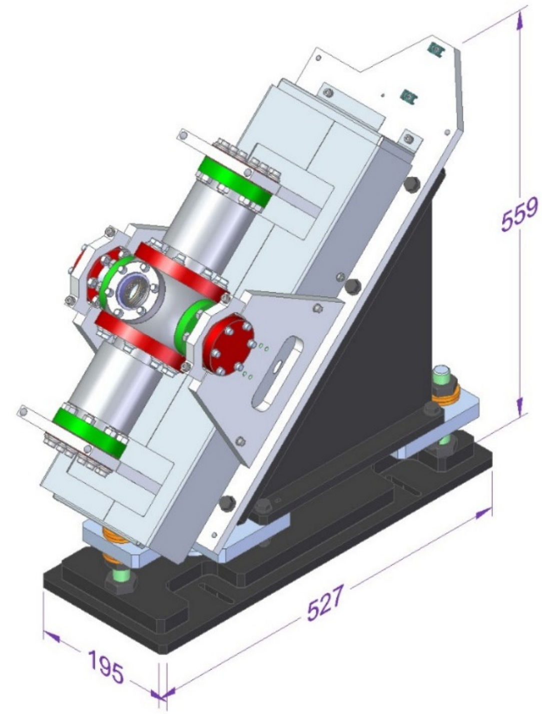
- Central node processing threshold comparison results and digital inputs.
- Fast mitigation logic compared threshold & digital input state against permitted values for each power class.
- Slow processing logic in software compares combinations of threshold results and digital inputs.
- Resulting power class limits and mitigation states are generated.

Select just two examples of diagnostic challenges

- Transverse beam size measurement
  - Profile monitor screens won't tolerate high rep rate
  - And are susceptible to coherent radiation from microbunching instabilities
  - Therefore rely on FAST WIRE SCANNERS
    - Complex trajectory and speed control to acquire profile without destroying wire
- Longitudinal, temporal bunch profile
  - Need sub-femtosecond resolution for both electrons and photons
  - Non-invasive measurement
  - Use X-band RF transverse deflecting cavity to streak the beam
    - XTCAV

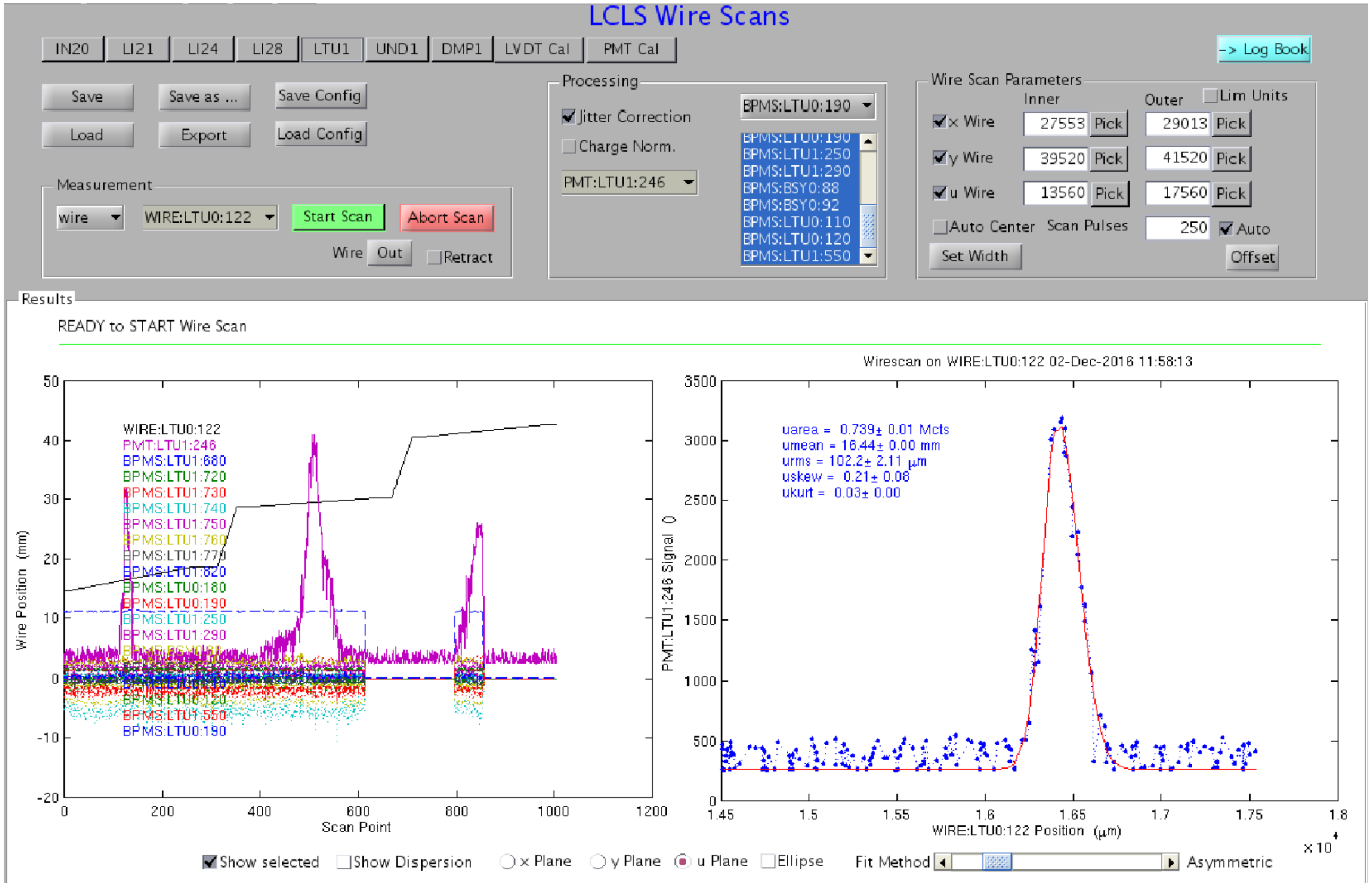
Fast Wire Scanners developed at LCLS-I





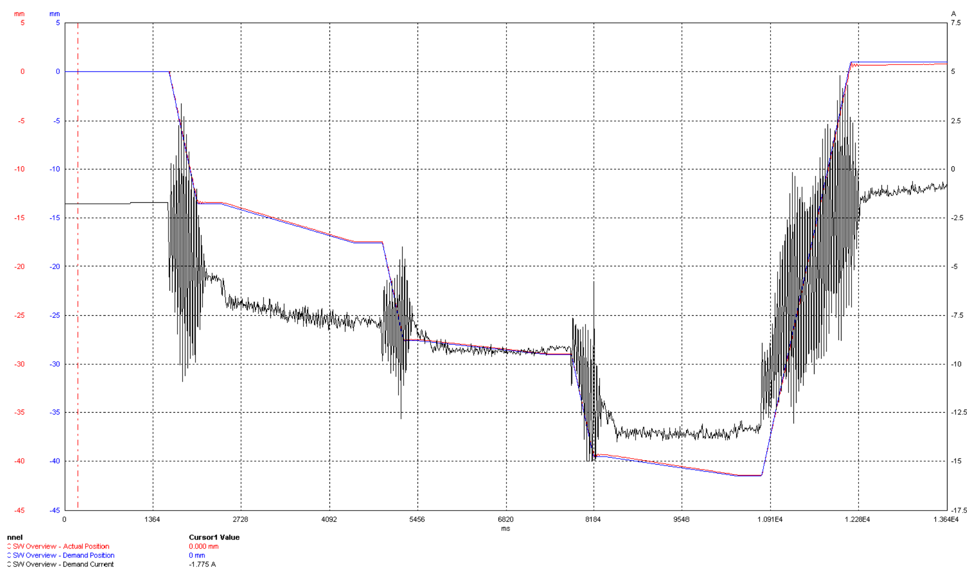
- Linear dc servo motor acting through dual bellows at 45°
- High speed significantly reduces emittance measurement and tuning time
- 1 MHz beam at LCLS-II requires 0.5 m/s wire speed

Slow speeds are also required depending on beam rate

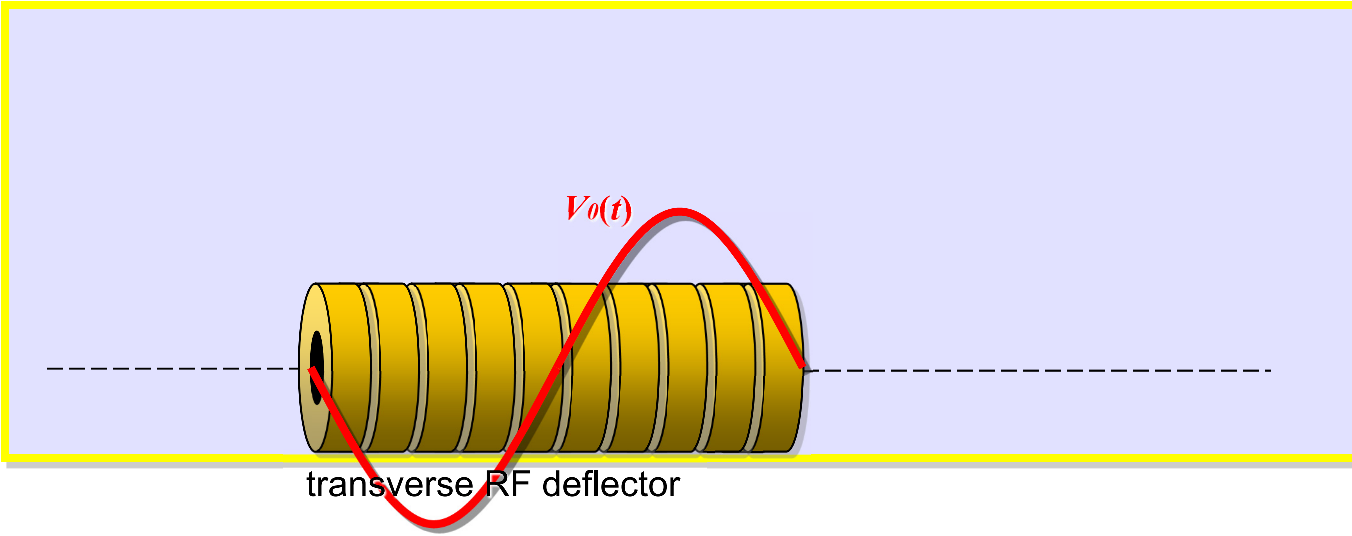


Operational lessons learned

- Complex trajectory and speed control is required
- Position encoder is read back synchronously with the beam
    - But also need to monitor motor current
    - PID servo loop can be unstable in regard to motor current



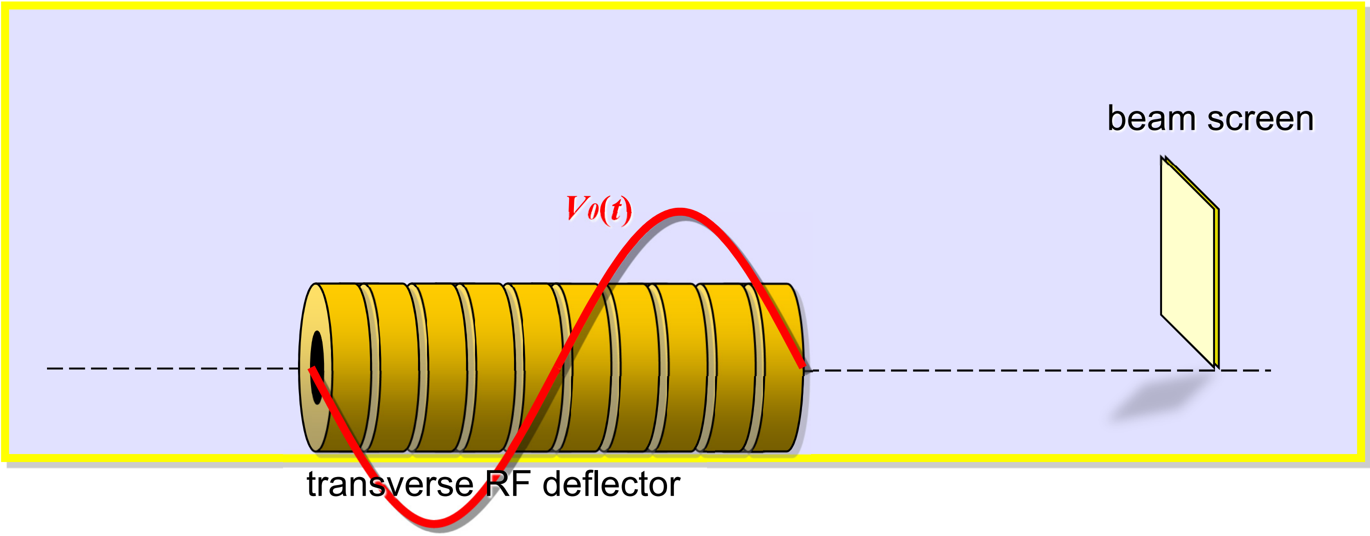
Transverse Cavities are now a well-established longitudinal diagnostic



$$\sigma_{t,R} \propto \frac{\lambda_{rf}}{V_0}\sqrt{E\,\frac{\varepsilon_{N,x}}{\beta_x(s_0)}}$$

Temporal resolution
improves with higher RF frequency

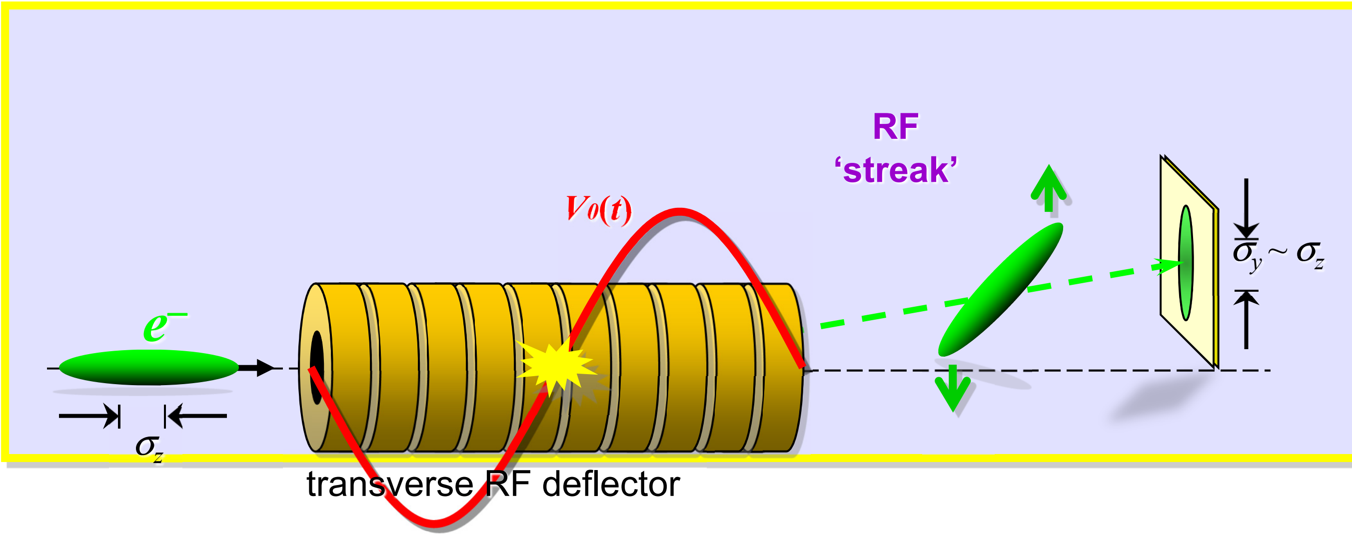
Transverse Cavities are now a well-established longitudinal diagnostic



$$\sigma_{t,R} \propto \frac{\lambda_{rf}}{V_0}\sqrt{E\frac{\varepsilon_{N,x}}{\beta_x(s_0)}}$$

Temporal resolution
improves with higher RF frequency

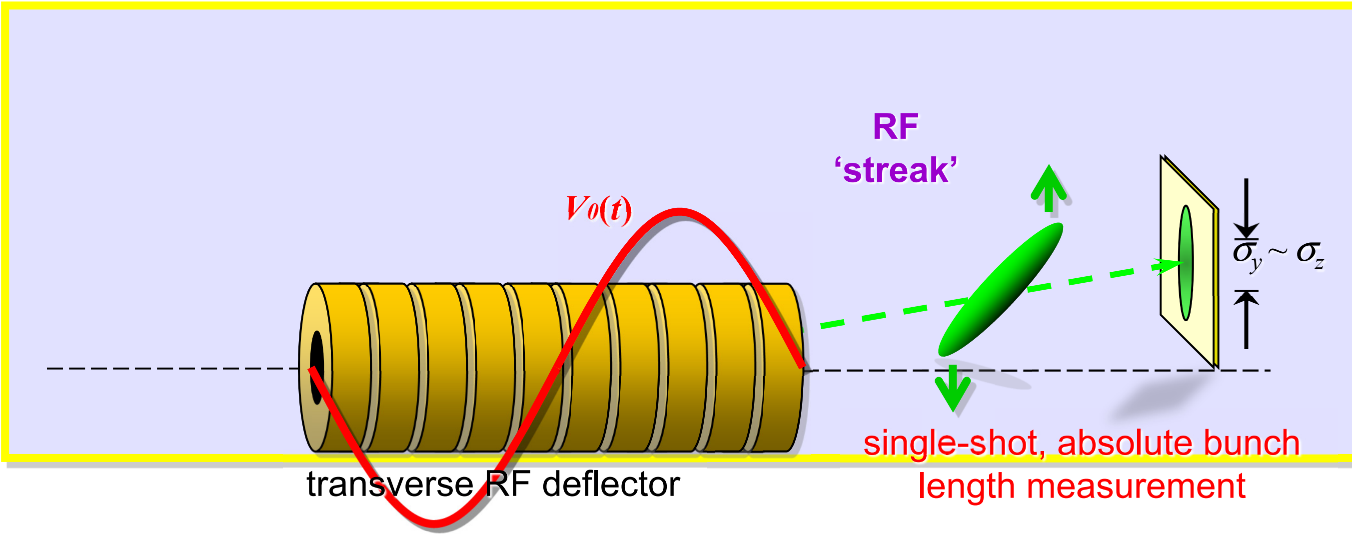
Transverse Cavities are now a well-established longitudinal diagnostic



$$\sigma_{t,R} \propto \frac{\lambda_{rf}}{V_0}\sqrt{E\,\frac{\varepsilon_{N,x}}{\beta_x(s_0)}}$$

Temporal resolution
improves with higher RF frequency

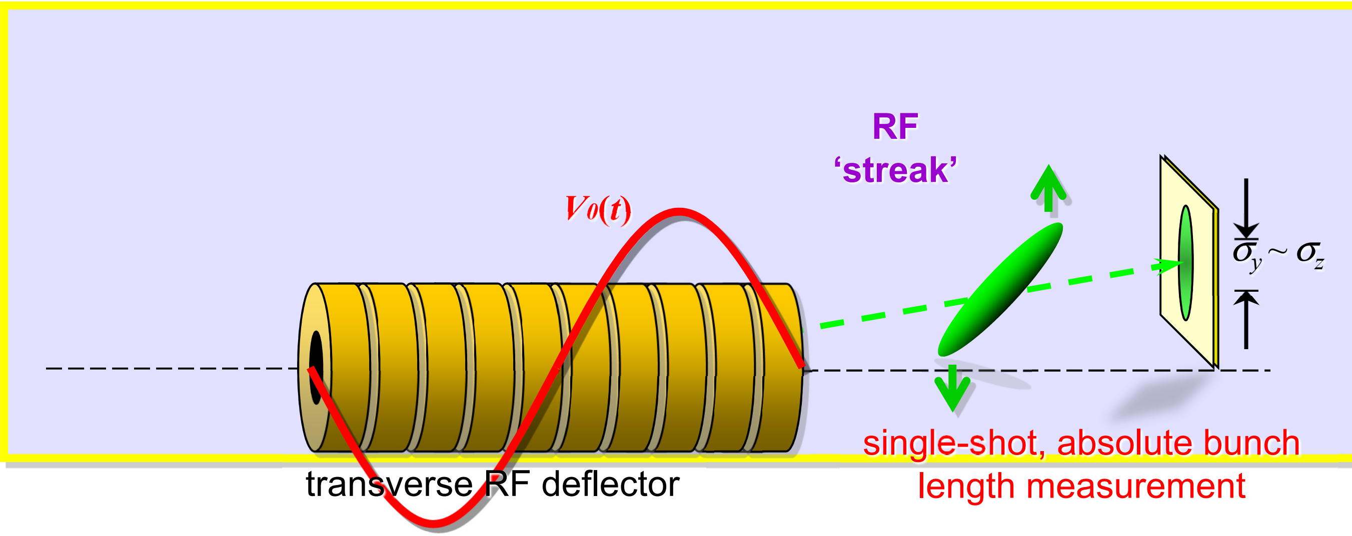
Transverse Cavities are now a well-established longitudinal diagnostic



$$\sigma_{t,R} \propto \frac{\lambda_{rf}}{V_0}\sqrt{E\,\frac{\varepsilon_{N,x}}{\beta_x(s_0)}}$$

Temporal resolution
improves with higher RF frequency

Transverse Cavities are now a well-established longitudinal diagnostic



$$\sigma_{t,R} \propto \frac{\lambda_{rf}}{V_0}\sqrt{E\frac{\varepsilon_{N,x}}{\beta_x(s_0)}}$$

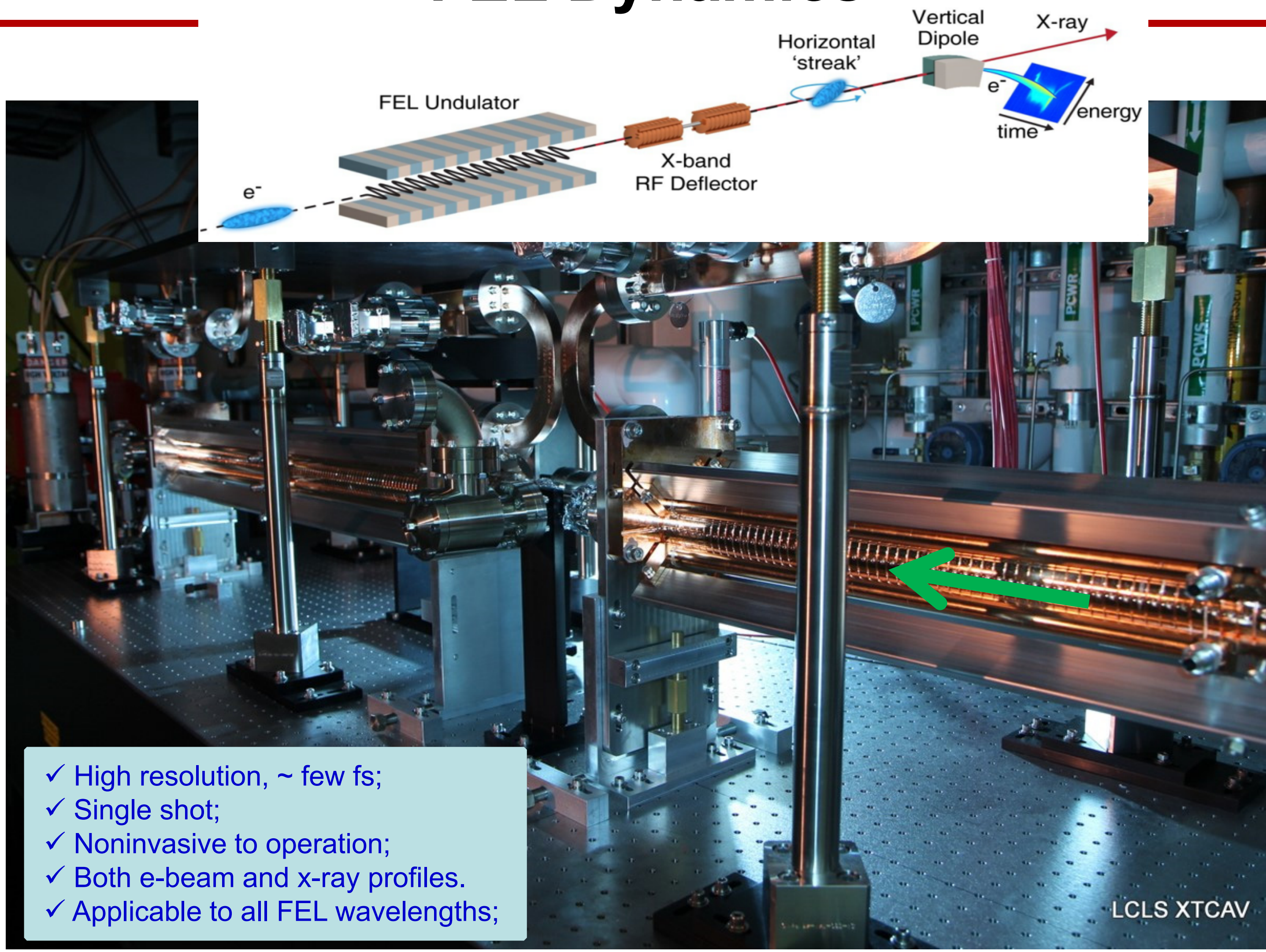
Temporal resolution improves with higher RF frequency

X-band TCAV: (before SLED)	
Frequency	11.424 GHz
Maximum kick	45 MV@35MW

HXR: *(14GeV)*	***SXR:*** *(4.3GeV)*
Calib.factor ~40, $\sigma_{t,R} \sim$ ***4 fs****;*	*Calib. factor ~120,* $\sigma_{t,R} \sim$ ***1 fs****;*

SLAC NATIONAL ACCELERATOR LABORATORY

XTCAV downstream of Undulator reveals complex FEL Dynamics



- ✓ High resolution, ~ few fs;
- ✓ Single shot;
- ✓ Noninvasive to operation;
- ✓ Both e-beam and x-ray profiles.
- ✓ Applicable to all FEL wavelengths;

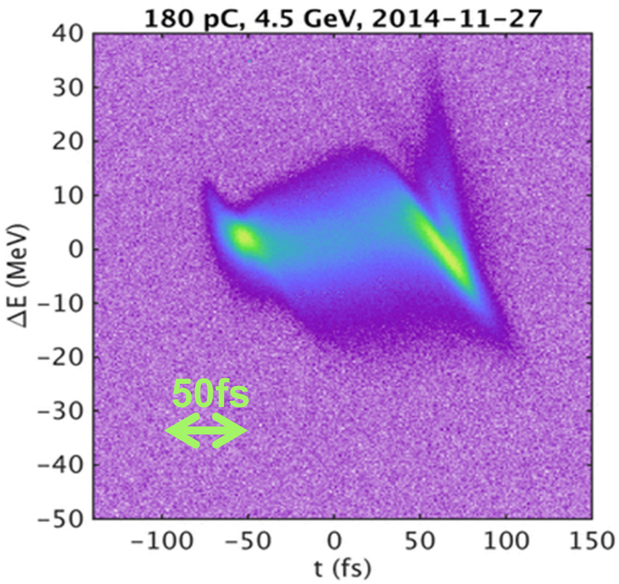
A Most Versatile Diagnostic!

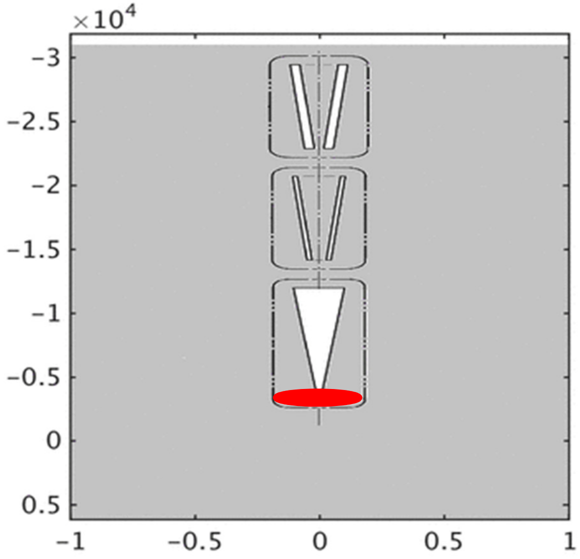
- The XTCAV system is

  a  diagnostic tool

  at a $ $ $ $ $ price
- Not in everyone's budget, but pays for itself in the long run
- Uses every aspect of accelerator control systems
  – LLRF, timing, imaging, MPS….
- Downstream of the undulator it is the only single-shot diagnostic that can reconstruct the x-ray photon beam temporal profile
- And allow a number of exotic pump-probe set ups for users

Measurements with foil-scan at LCLS





There are many new challenges with ultrafast attosecond bunches!

Thank You!

And please consider joining us to meet these new and exciting challenges in

Electronics, controls, software and engineering …

https://careers.slac.stanford.edu/

ICALEPCS2017

Barcelona · Spain, October 8-13

Palau de Congressos de Catalunya

www.icalepcs2017.org

SLAC NATIONAL ACCELERATOR LABORATORY