Electron Beam Diagnostics and Feedback for the LCLS-II

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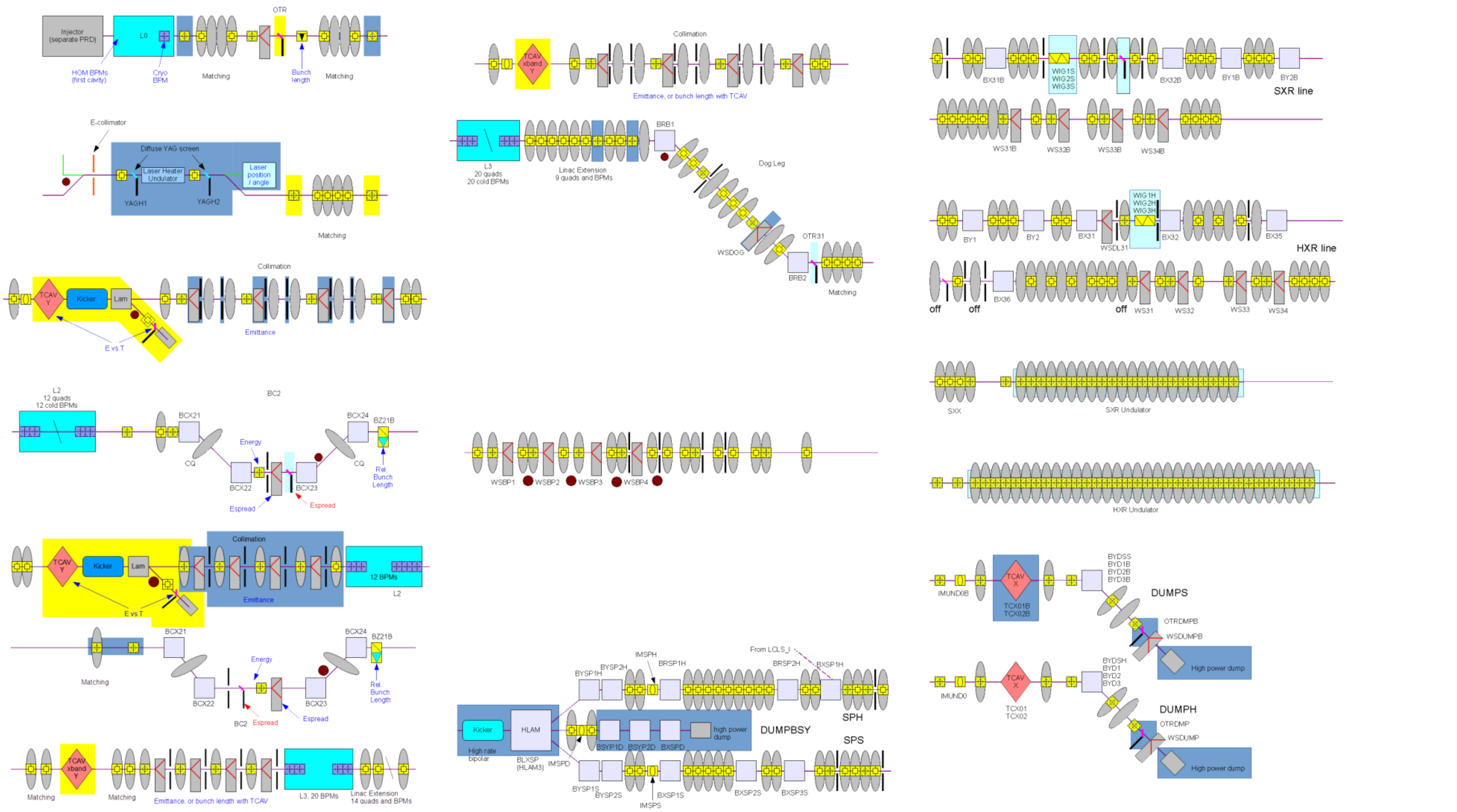
Diagnostics – What the Accelerator Physicists Want



Diagnostics – What the Project Can Afford

Some compromise is necessary!

Need to consider the minimum that will let the LCLS-II meet its design performance.

LCLS_II: CW superconducting LINAC driving two new variable gap undulators

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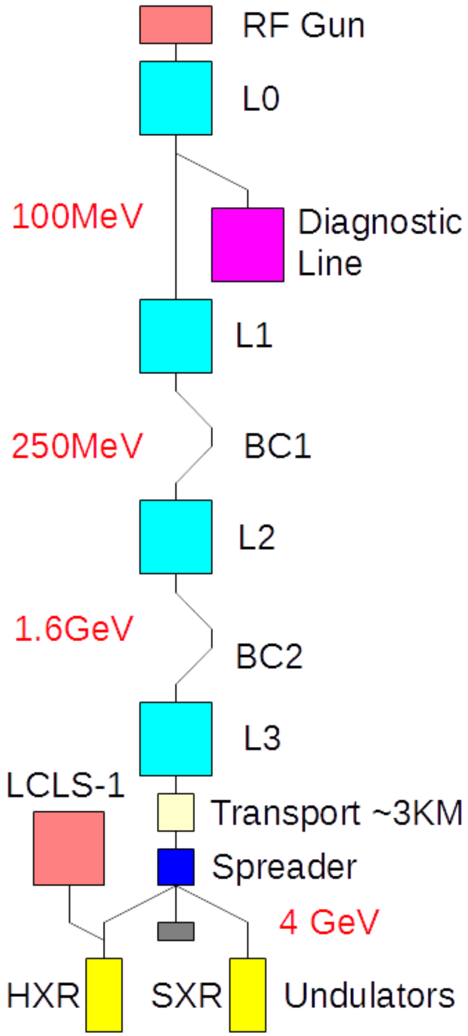


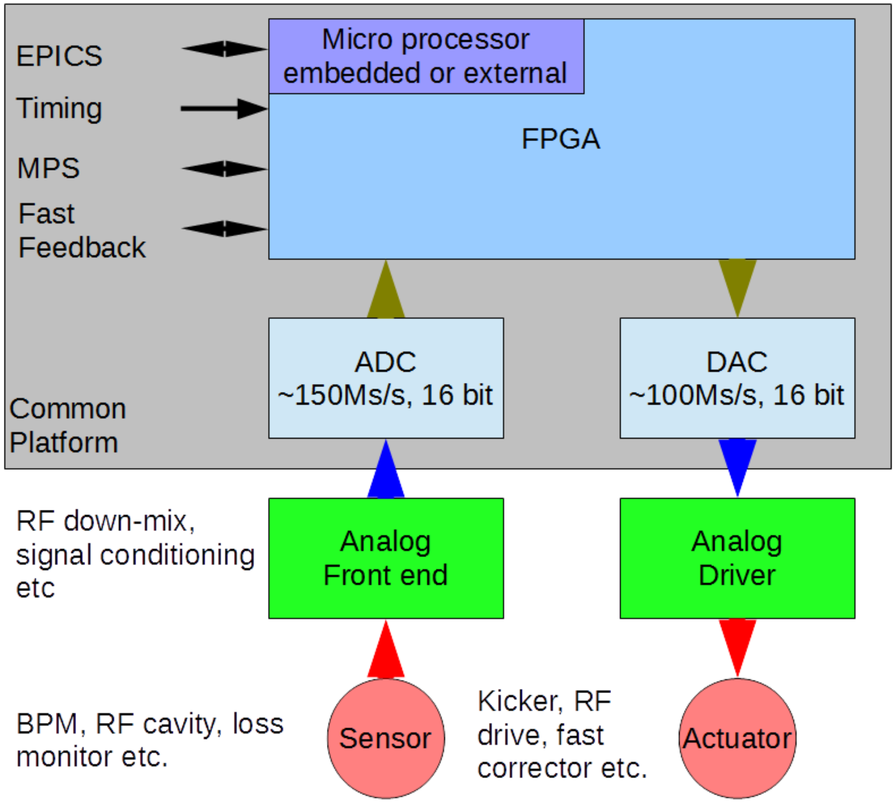
Beam energy	**4 GeV**
Bunch charge	10 – 300 pC
Bunch rate	< 0.93 MHz
Average beam power	<1.2 MW
Peak current	500-1500 A
Bunch length (RMS)	0.6 – 52 µm
Energy spread	125-1500 keV
Energy stability RMS	<0.01%
Emittance (at 100pC, normalized)	~0.3um

Differences from LCLS-I

- **High average beam power (up to 1.2MW)**
  - Intercepting devices need to be in low rate diagnostics lines or use short duration scans (flying wires)
  - Diagnostics needs to provide fast (<100μs) information to the Machine Protection System
- **High data rate, 1MHz beam**
  - Real time processing of data requires FPGAs to convert raw ADC data into "physics" data at 1MHz
  - Feedbacks and interlocks operate in FPGA logic
  - Circular data buffers to allow non-realtime data readout
- **Low Charge (10pC operation required)**
  - Need cavity BPMs in some locations for high resolution position measurement
- **Short bunches (600nm at 10pC)**
  - Bunch has temporal components in the optical: Coherent optical radiation will make imaging impractical on the fully compressed bunch.

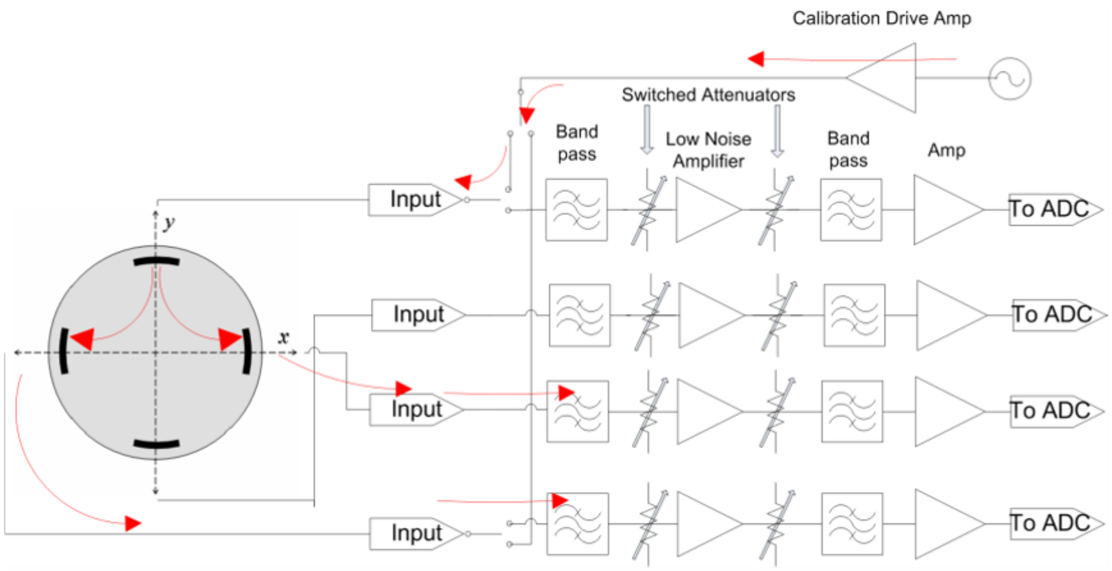
Common Platform for Diagnostics and LLRF

Hardware /Firmware / Software

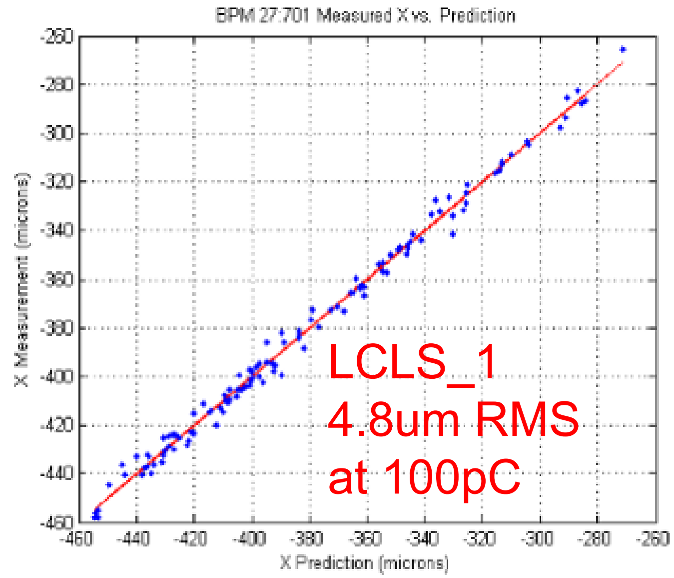


- For beam synchronous (1MHz) devices
- Analog front ends:
  - Downmix for cavity BPMs
  - Amplifiers for loss monitors
  - Others…
- Shared hardware and most firmware with LLRF
- Low rate devices (wire scanners, profile monitors) controlled directly through EPICS.

Beam Position: Stripline BPMs



Calibrator pulsing tone to the Y+ stripline. ADC digitize X+ anc X- signals.

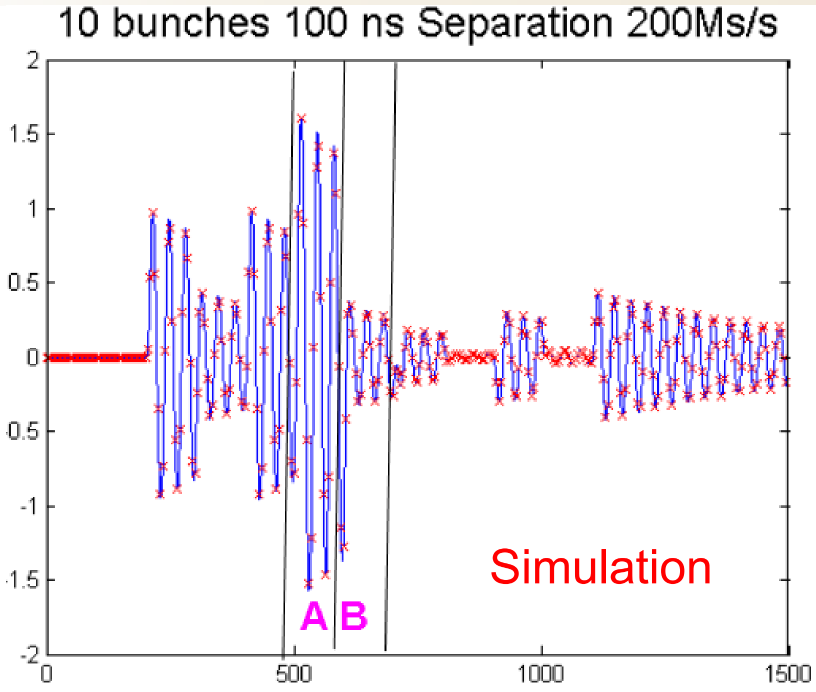


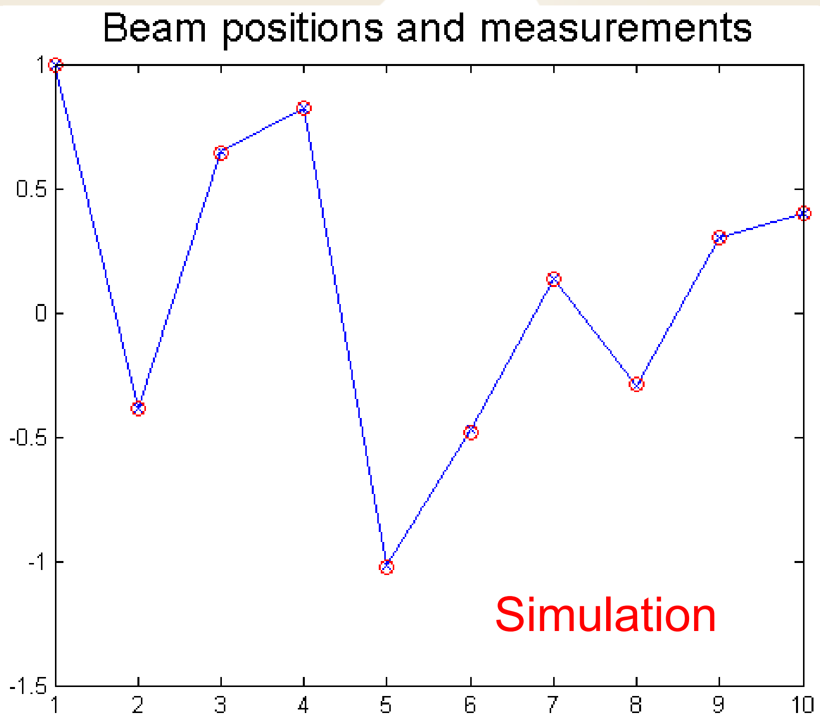
- Stripline BPMs will be similar to LCLS-I design
- Front end electronics:
  - Bandpass filters and variable gain amplifiers
  - Calibration pulse to correct for gain / cable drifts

Beam Position: Cavity BPMs

- Used where high resolution is required
  - Undulator BPMs (X-band)
  - BPMs used for feedback in the accelerator
    - C-band or S-band design
- Used for large aperture, high resolution BPMs in dispersive regions for energy measurement
  - Bunch Compressors, Doglegs and Dump
  - L-band for large aperture
- High Q cavities have decay times longer than inter-bunch spacing – need algorithm to separate bunches.

High Q Cavity BPMs and High Bunch Rates

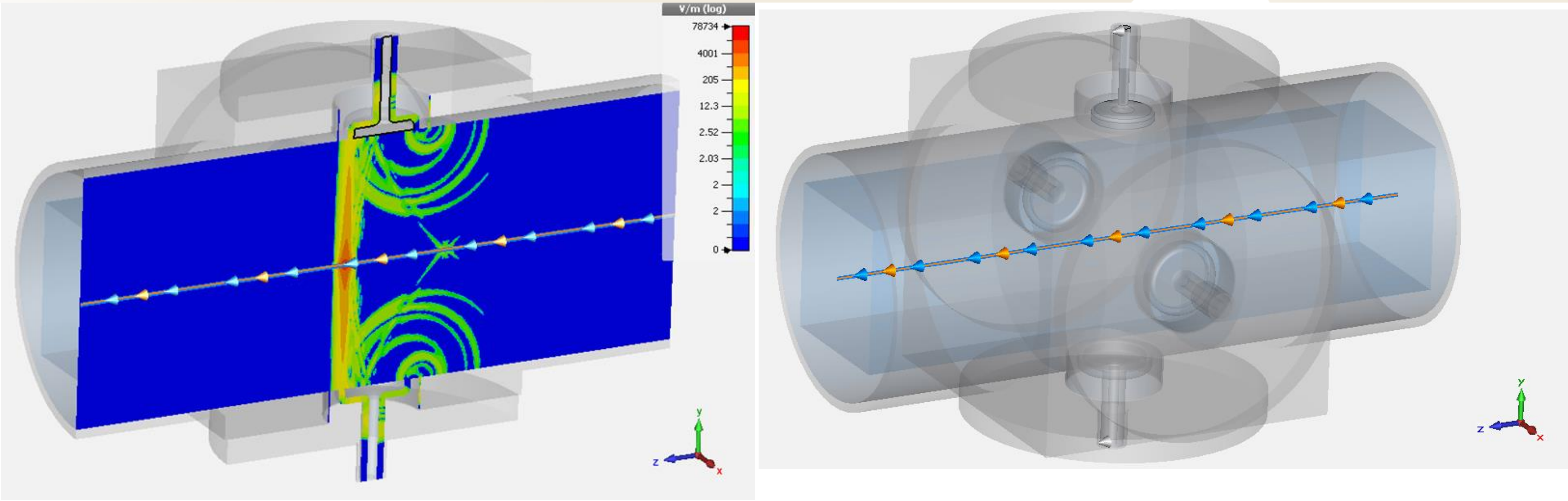




Can use high-Q cavity BPMS with a decay time longer than the bunch spacing:

- Measure the complex ratio of the RF fields at time B, from fields measured at A without bunch B present
- Subtract those amplitudes from the fields at B to measure the results from bunch B alone
- Demonstrated by Glen White at ATF2 (KEK),but not published.

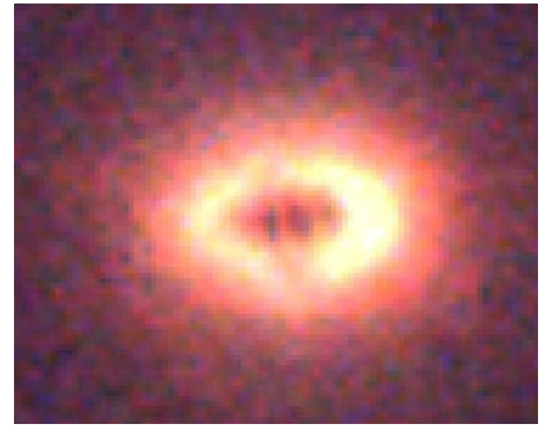
Beam Position: Cryo Button BPMs



- Cold BPM uses 20mm buttons in 70mm beam pipe
- European XFEL design
- Simpler, lower performance electronics than XFEL:
  - Signals processed at ~1GHz to remain below beampipe cutoff
  - Downmix signals for digitizing
- Expect 100um single bunch resolution at 10pC
- Signal averaging for high resolution on CW beam
- HOM BPMs used in first SC structure, and possibly others as needed for alignment.

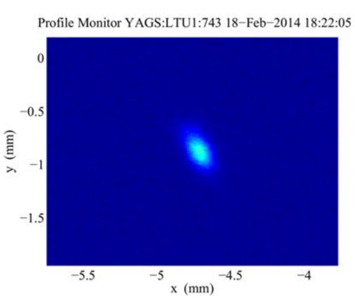
Transverse Profile Monitor

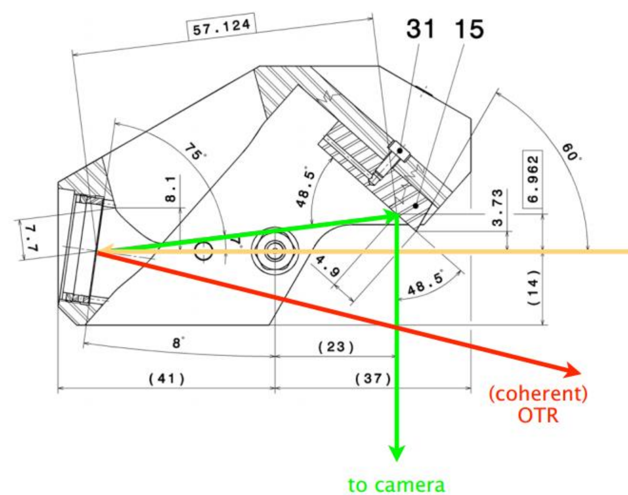
- Short bunch operating mode (0.6um RMS) will result in coherent emission at optical wavelengths from the bunch longitudinal form factor.
- Coherent emission from micro-bunching is also expected to distort the beam image at high compression.
- High average beam power prevents use of imaging devices in the main high rate beam
  - Injector diagnostic line (120Hz at 100MeV) will use profile monitors.

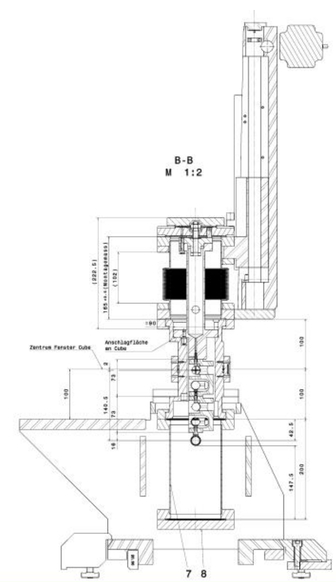


Coherent emission at LCLS at 20pC results in ring shape

Coherent emission resistant design from PSI is being considered for LCLS-II (Rasmus Ischebeck et. al)

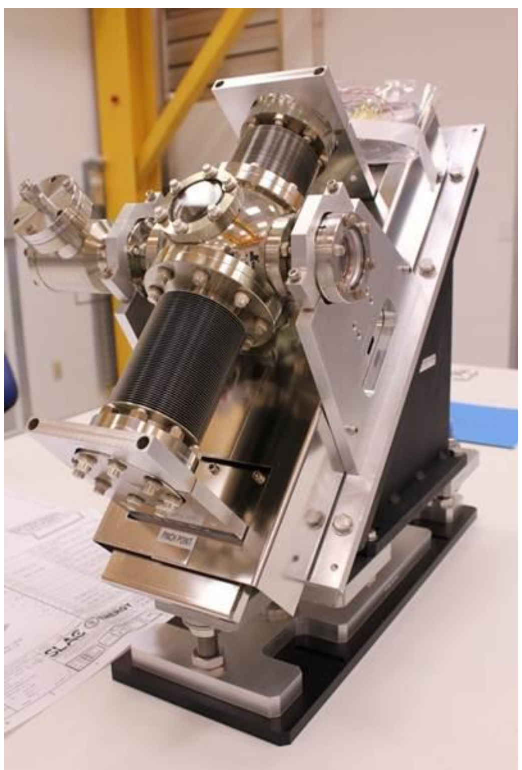


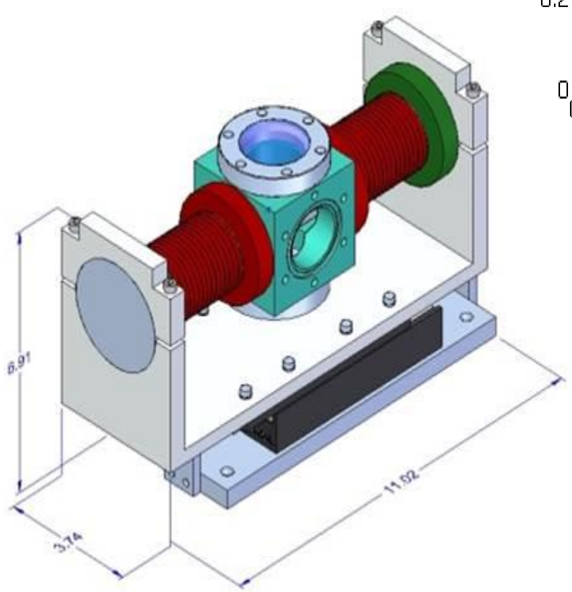


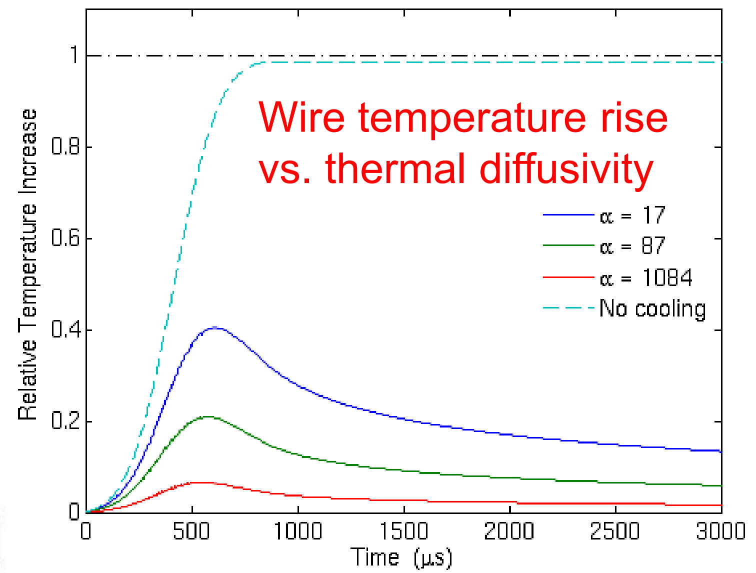


Transverse Profile: Wire Scanners

- Wire scanners are used in most locations for profile measurement
- High wire speeds allow scans of full rate beam
  - 34um Carbon wires (same as LCLS-I)
  - 100pC at 600kHz beam, 40um spots
  - Scan speed > 250mm/sec required for uncooled wires

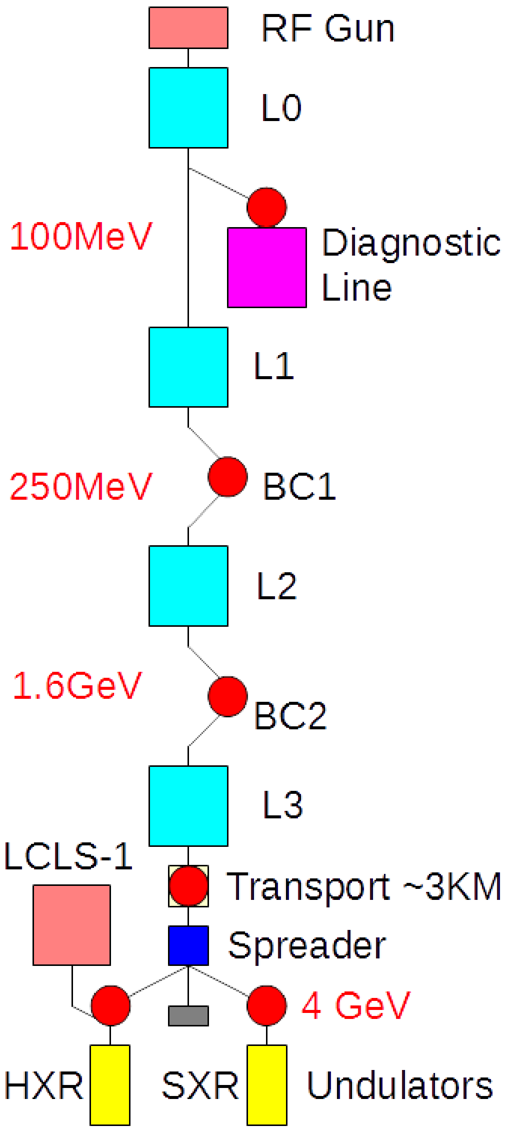






Beam Energy / Energy Spread

- Beam energy
  - BPMs in dispersive regions
  - Incoming orbit corrected with BPMS and optics model
  - Cavity BPMs used to obtain <0.01% energy resolution
- Energy Spread
  - Wire scanners in dispersive locations
  - Correct for jitter with nearby cavity BPMs



Relative Bunch Length

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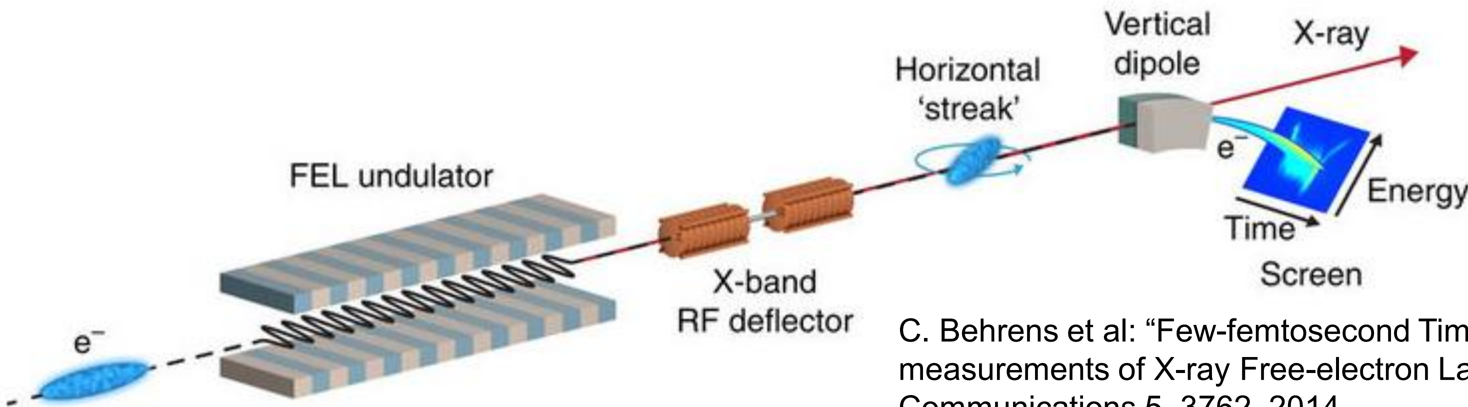
- Coherent emission monitors will be used to measure the (un-calibrated) bunch length for feedback.
- For BC2, the high average power of the coherent emission beam will require attenuation to prevent thermal damage to the detector.
  - Un-attenuated beam can be >10Watts average power.
  - Thermal limit for pyroelectric detectors is 25mW -> 25nJ pulse energy at 1MHz
  - Detector noise estimated at 5nJ so signal to noise is marginal
- R&D planned for improved detectors
  - Improved cooling for higher average power
  - Improved charge amplifiers for faster response and lower noise
  - Alternate (non-pyroelectric) detectors
- In BC1, the CSR pulse energy may be as low as 1.5nJ for low charge / long bunch operation
  - Plan to use millimeter wave diode detectors and a ceramic gap for long bunch operation
  - Tested at LCLS-I with good performance.

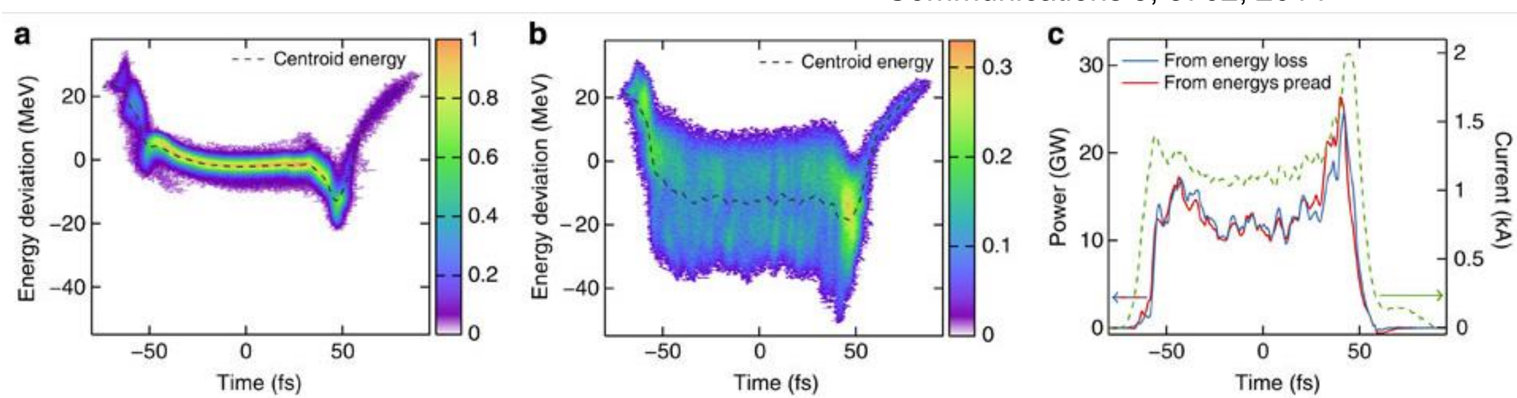
mm-wave diode

Bunch Profile Measurement – Transverse Cavity

- Transverse deflection cavities will be used to measure the longitudinal profile of the beam in the injector, after BC1, after BC2, and after each undulator.
- Room temperature (S-band at low energy, X-band at high energy) structures will be used.
  - 120Hz operation
  - Low fill time allows deflection of a single bunch without disturbing the rest of the 1MHz bunch train.

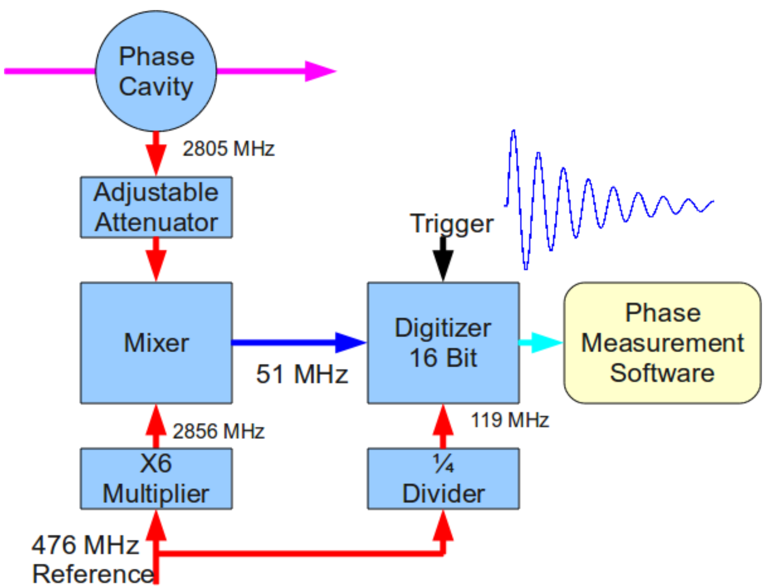


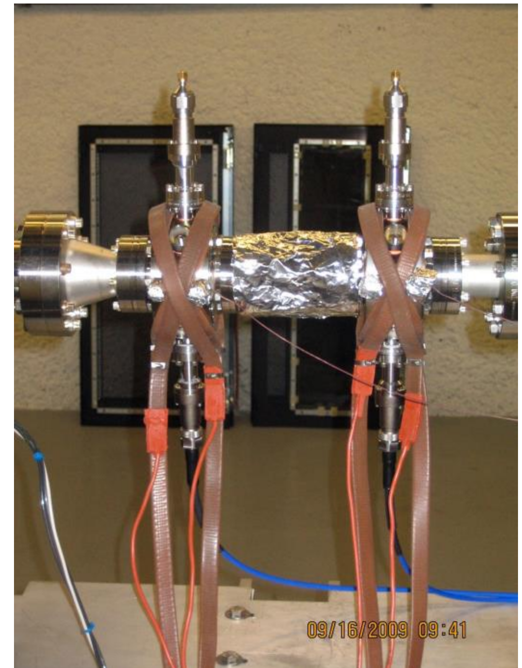
C. Behrens et al: "Few-femtosecond Time Resolved measurements of X-ray Free-electron Lasers, Nature Communications 5, 3762, 2014

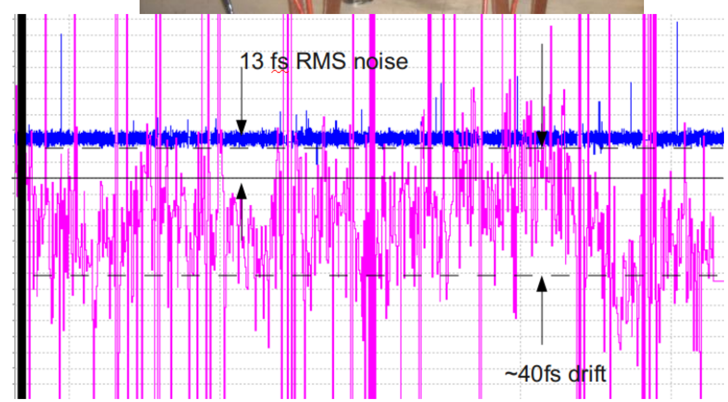


Beam Arrival Time Monitor

- Use RF phase cavities, similar in design to LCLS-I system
- Cavity temperature drifts corrected by algorithm that measures the cavity frequency on each pulse
  - Improved algorithm likely to give 7fs RMS noise
- Experiments use direct X-ray / optical cross correlator for precision (few femtosecond) timing







<10fs noise, 40fs drift over 4 days

Beam Feedbacks - Slow

- All measurements available to the EPICS control system
  - Data tagged by beam destination and pulse-ID
- Beam control through RF stations, corrector magnets and kickers
  - Fast device control can be set independently by pulse-ID / beam destination
  - Can use a single RF station operated off-frequency to provide an energy difference control for bunches to the two undulators for independent fine wavelength control
- Feedbacks written in Matlab, communicate through channel access – 5Hz rate

Beam Feedbacks - Fast

- LLRF expected to provide 0.01%, 0.01 degree short term RF stability
  - Drifts corrected by slow beam feedbacks
  - Sufficient to meet LCLS-II X-ray stability requirements
- Possibility of fast disturbances e.g.:
  - Interference in cavity probe signals from beam fields
  - Mechanical vibration of the SC structures
  - CSR instability causing temporal variations which result in variations in CSR energy losses
  - Variations in drive laser pointing
- Fast feedback system using low latency network
  - Estimate 5us latency + cable delays
  - All fast devices will be able to connect to the network
  - Fast feedback system to be designed / commissioned after first beam when the disturbances are understood

Challenges

- Profile monitors for ultra-short bunches
  - Coherent optical emission from micro-bunching and bunch form factor will distort the image
- Relative bunch length monitor for high average power
  - Pyroelectric detectors have marginal single bunch noise when attenuated to be safe for high beam rate
- Bunch Timing
  - With <1um bunches, experiments will want sub-femtosecond stability
- Cost and complexity
  - High rate processing -> complex firmware and high performance networks