Operational Performance of LCLS Beam Instrumentation

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Linac Coherent Light Source at SLAC

X-FEL based on last 1-km of existing linac

1.5-15 Å

Existing 1/3 Linac (1 km)
(with modifications)

New e⁻ Transfer Line (340 m)

X-ray Transport Line (200 m)

Undulator (130 m)

Near Experiment Hall

Far Experiment Hall

Injector (35°) at 2-km point
2 Transverse RF cavities (135 MeV & 5 GeV)

180 BPMs and 13 toroids

7 YAG screens (at $E \leq 135$ MeV, one at 14 GeV)

13 OTR screens at $E \geq 135$ MeV

17 wire scanners (each with x & y wires)

CSR/CER pyroelectric bunch length monitors at BC1 & BC2

5 beam phase monitors (2856 – 51 MHz)

Gun spectrometer line + injector spectrometer line
Strip Line BPM Performance

- Strip line BPMs
  - 60+ new ones for LCLS, 80+ upgraded from SLC with new electronics
  - Continuous calibration with test pulse between beam triggers
  - Two variable attenuators for charge range 50 pC – several nC
  - Beam synchronous data acquisition system at 120 Hz
- Noise level measurement
  - Measure beam orbits at ~150 BPMs for 500 shots in main linac through undulator
  - SVD eigenvalues to determine orbit jitter and intrinsic BPM noise level
  - Average value for strip-line 3.5 \(\mu\)m, for RF cavity 250 nm at 250 pC
  - Noise at 20 pC ~10 times higher
Few micron beam orbit straightness in undulator required for FEL operation
Sub-micron resolution met with RF cavity BPM design
11.4 GHz dipole cavity
Reference cavity for normalization
Calibration with beam signals
  Move supporting girder of undulator
  Induce known orbit oscillation upstream of undulator
Beam Based Undulator Alignment

- Measure undulator orbit at energies from 4.3 – 13 GeV
- Fit yields quad + BPM offsets
- Apply correction to get dispersion free orbit
- After several iterations, average orbit rms few μm
- Mainly incoming orbit jitter

![Graph showing orbit measurements at different energies]

- 4.30 GeV, $\sigma_x = 7.3$ μm
- 7.00 GeV, $\sigma_x = 4.0$ μm
- 9.25 GeV, $\sigma_x = 3.7$ μm
- 13.64 GeV, $\sigma_x = 3.8$ μm

- 4.30 GeV, $\sigma_y = 5.3$ μm
- 7.00 GeV, $\sigma_y = 4.0$ μm
- 9.25 GeV, $\sigma_y = 6.8$ μm
- 13.64 GeV, $\sigma_y = 3.1$ μm
Wire card with x, y, 45° wires
- 20 – 40 μm tungsten wires
- Stepper motor driven in open loop, LVDT readback
- Fast ion chambers + PMTs for beam loss detection
- Synchronous acquisition of beam orbit, wire position and PMT signal
- Beam jitter correction
- Use beam jitter to sample beam size with fixed wire

Wire in DL2 with orbit jitter > beam size

- xmean = 0.12±0.01 mm
- xrms = 41.9±4.40 μm

- xmean = 0.11±0.00 mm
- xrms = 30.8±0.63 μm
Emittance measured with 4 wires at 45° phase advance

Accurate beam size measurement for good beta matching
Common design
- 100 μm YAG crystal
- 1 μm OTR foil (Al)

Fixed magnification
- 50 mm telecentric lens
- ~10 – 20 mm FOV
- 10 um resolution (OTR)

CCD Camera
- Mega pixel
- 12 bit

Insertable filters
- OD1 + OD2
- Total system dynamic range > $10^5$
YAG Screen Performance

- YAG screens at low energy in injector
- High sensitivity for low charge beam
- Image cathode emission on YAG at 15 pC

![Image of electron density plot](image-url)

- Saturation limits beam size
  - 130 μm at 250 pC
- Beam size significantly smaller at most locations
OTR Low Charge Slice Emittance

Individual Slice Fit

Lower limit on OTR slice emittance $\sim 10$ pC

$Q = 20$ pC
$E = 135$ MeV
$\sigma_z = 400$ $\mu$m
$I = 5$ A
$\gamma \varepsilon_x = 0.14$ $\mu$m

$Laser Spot \ Ø 0.6$ mm

$\chi^2$/NDF = 1.92
- Linear OTR response in injector
- Coherence effects after bend magnets
- Factor 2 change in OTR size for % change in beam size
- Highly compressed beam light intensity x10^5
- Distribution fractured or ring shaped
Coherent effects visible on dump OTR foil
Recently replaced with YAG crystal
YAG fluorescence $10^3$ higher than OTR from crystal
Small crystal tilt to steer COTR away from camera
COTR speckle pattern gone in YAG image
Tolerable energy loss in dump area, but concern elsewhere
$V_0 > 20 \text{ MV}$

$f_{RF} = 2856 \text{ MHz}$

$E_S = 13.6 \text{ GeV}$

$\sigma_y^2 = \sigma_{y0}^2 + \beta_d \beta_s \sigma_z^2 \left( \frac{k_{RF} e V_0}{E_s} \sin \Delta \psi \cos \phi \right)^2$

- Map time axis onto transverse coordinate
- Simple calibration by scan of cavity phase
Laser heater effect on slice energy spread can be studied

Timing between heater laser & electron beam adjusted
Bunch length as small as 3.5 \(\mu\)m rms measured for 250 pC beam

- Double-horn structure of undercompressed beams visible
- BPM noise too large for jitter correction at 20 pC and \(~1\ \mu\)m bunch length

![Graph showing bunch length vs. compression](image)

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![Graph showing PMT signal vs. z position](image)

- Jitter uncorrected
- Corrected

\[ z_{rms} = 382.5 \pm 38.02 \ \mu\text{m} \]

\[ z_{rms} = 23 \pm 0.00 \ \mu\text{m} \]
Pulse Stealing Bunch Length Scan

- Trigger TCAV at 1 Hz to steal diagnostic bunch
- 50 fs phase jitter $\rightarrow$ 100 $\mu$m orbit jitter
- Place wire off beam axis, TCAV kicks beam there

\[ \sigma_y = 60.2 \pm 0.00 \mu m \]  
\[ \sigma_y = 44.0 \pm 0.00 \mu m \]  
\[ \sigma_y = 61.3 \pm 0.00 \mu m \]

Use 3 positions 0.5 mm apart
Let jitter sample profile
Insufficient jitter when TCAV off
Relative Bunch Length Monitor

- Single shot non-interceptive bunch length diagnostics
- Coherent edge radiation from chicane bend
- Broadband pyroelectric detector for far infrared
- Wavelengths 1 mm – 20 μm

Detector calibration with absolute measurement from TCAV

Empirical fit of signal to \((\sigma_z)^{4/3}\)

Use fit to calculate peak current
X-Ray Energy Measurements

- Determine X-ray beam energy from electron beam loss due to lasing
- Compare energy in main dump with energy upstream of undulator
- Also loss from wake fields in undulator vacuum chamber and spontaneous emission
- Kick orbit to suppress lasing as base line
- Absolute measurement to calibrate others
Gas Detectors

- Part of gas attenuator system located between differential pumping stations
- N₂ gas at 0.1 – 2 Torr
- Pressure depends on X-ray wavelength
- X-rays create Auger e⁻, trapped in magnetic field
- Generate secondary e⁻, and N₂ fluorescence, detect with PMTs

Signal saturates at too much pressure
Calibrate with energy loss scan
Routinely done when X-ray wavelength changed
X-Ray YAG Screens

- Dump area X-Ray YAG Screen
- Direct imager cooled 16 bit CCD
- Measure X-ray beam size
- Use intensity for FEL gain length

Main X-ray beam with diffraction pattern from C-wire at last undulator
- Spontaneous background with shadow from undulator vacuum chamber
- Visible light CER ring from dump bend

FEE Direct Imager
Summary

- Diagnostics meets all requirements necessary for successful FEL operation
- Highly integrated into EPICS control system
- High level Matlab applications to automate measurements
- COTR issue of profile monitors offset by use of wire scanners
- New 2D diagnostics needed for time resolved emittance measurements for compressed bunches
- Sub-micron bunch length in 20 pC mode poses diagnostics challenge, new methods being discussed
- Single shot X-ray spectrum measurement soon available
- X-ray pulse length measurement in development
## Acknowledgements

**LCLS Commissioning Team**

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