Status of Electron Beam Diagnostics
January 19, 2004

- Review of electron beam diagnostics in the context of undulator commissioning
- Electron beam commissioning in readiness for undulator tests
- Electron beam diagnostics during FEL tuning
Electron beam characterization

- Measurement of 6D phase space
  - Transverse emittance
  - $x$, $y$ only - no special effort made to measure coupling
    - round beams and no intentionally rolled beam lines
  - Bunch length and energy spread

- Beam centroid measurements
  - Energy
    - Is absolute energy calibration essential?
    - Only as good as bend field strength calibration, e.g. in the dump line.
  - Beam orbit
    - Requirement for absolute position measurement
    - Versus relative orbit – use beam based alignment
Electron beam monitoring

- Electron beam changes due to FEL
  - Beam energy due to ISR
  - Energy spread from SASE
  - Microbunching not directly observable, except through x-ray spectrum

- Beam drifts due to upstream changes

- Minimize changes with feedback
  - Changes are never zero,
  - even with perfect feedback in a dynamic system

- Monitor pulse-to-pulse jitter in the beam

- Monitor instabilities in the beam
  - Diagnose CSR microbunching
**Status of beam position monitors**

- **Injector-Linac-LTU**
  - Stripline bpms
  - 0.2 – 1 nC
  - 5 μm resolution
  - Requires new modules
    - To be designed.
  - New stripline BPMs to be fabricated for chicanes
    - 20 um res. for 1 - 0.2 nC in a 3 cm x 10 cm chamber
  - New stripline BPMs to be fabricated for the LTU in addition to existing FFTB BPM
  - Last 8 LTU BPMs redundant with undulator-style cavity BPMs
    - 1 um resolution at 0.2 nC

- Aligned to mechanical center of quadrupoles
- Systematic offsets from variations in d
Cavity beam position monitors in the undulator and LTU
R&D at SLAC – Steve Smith

- Raw digitizer records from beam measurements at ATF

- X-band cavity shown
- Dipole-mode couplers
SLAC X-band cavity BPM – Steve Smith

Mechanical center of RF BPM well correlated to electrical center – more accurately than for stripline BPMS
Cavity BPM R&D at SLAC – Steve Smith
preliminary beam calibration data from a C-band cavity at ATF

- cavity BPM signal versus predicted position
- bunch charge 1.6 nC

- plot of residual deviation from linear response
- << 1 µm LCLS resolution requirement
BPM Controls issues

- **Timing pulse identification**
  - Allows all BPMs to be read on the same beam pulse
    - Single pass machine each pulse is different
- **120 Hz readback**
- **Ring buffer for all BPM readings extending back last ~1000 pulses**
  - MPS trips can be traced to orbit excursion
  - RMS orbit jitter can be historied every ~1000 pulses
- **Application software linked to optics model**
  - Real-time orbit fitting displays
Beam size monitors

Wire scanners

- Used throughout SLC, essentially noninvasive
- Technical challenges are
  - Small beam size dictates small wire
  - Range of beam charge 0.2 – 1 nC,
    - compromise between signal to noise and saturation
    - Signal to noise from linac dark current
  - Low beam charge operation dictates high Z wire material
  - Beam loss considerations in front of undulator dictates low Z
- Groups of 4 wire scanners for emittance reconstruction
- Measure average, projected emittances in x and y
- Matching section at end of LTU verifies emittance and beta match at undulator entrance
- However, no room in the dump beam line for zero dispersion location
Beam size monitor locations

![Diagram of beam size monitor locations with labels such as L0, L1, L2, L3, LTU, Dump, and sigma notation (\(\sigma_E\)) with specific values and equations for \(\gamma_\varepsilon_{x,y}\) and \(\gamma_\varepsilon_y = 1.5 \mu m\).]

4-wire emittance reconstruction example from linac sector 2

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Beam size monitors

Profile monitors

- Except for injector, use thin foil OTR screens
- Technical challenges are
  - Small beam size requires precision, remote optics + digital video ($’s)
  - Stretching a thin, low Z foil flat
- Measure single pulse x & y beam profiles
- Acts as emittance spoiler, but beam still transported to dump
- Energy spread profile in high dispersion locations
  - Injector inflector, chicanes, LTU dogleg, dump line
- Single pulse slice emittance diagnostic (invasive)
  - in conjunction with transverse RF deflecting cavity
Slice parameters from transverse RF deflecting cavity

- OTR screen down stream of the Tcav. can be used in conjunction with a quadrupole scan to measure horizontal slice emittance

- OTR screen down stream of the Tcav. At a horizontal dispersion location, large $\eta_x$, small $\beta_x$, can measure slice energy spread
Profile Monitors

**Technical challenges**

- Small beam size requires precision, remote optics + digital video ($'s)
- Stretching a thin, low Z foil flat
- Avoiding punctures
- Block synchrotron radiation from bends bends bends with polarizers

SPPS BC chicane measured energy spread

SR background
Profile Monitors for Synchrotron Radiation

- single shot projected energy spread
- Generated from vertical chicane wiggler in a horizontal dispersion region
- ISR strikes an off-axis screen
- Optical resolution set by divergence of x-rays, filter out low energy x-rays with foil and use thin fluorescent crystal

Also serves as CSR monitoring port
Synchrotron Radiation:

- Lattice optimized for high $\Delta E$
  resolution: low $\beta_x$, high $\eta_x$
- real-time, noninvasive energy spread monitor
- single shot projected energy spread

Compared to energy spread at dump spectrometer
Conventional diagnostics and their upgrades

**Beam Phase Monitors**
- Use linac style S-band monitor cavities
- Measure pulse-to-pulse phase jitter
- Subject to thermal drift so can’t use for feedback control of phase
  - Thermal stabilization technology (as required for the undulator) may make this possible in the future.
- Beam phase can be measured w.r.t.
  - RF distribution
  - Laser from injector or at experiment
Collimation and Machine Protection System

**Collimation**
- Movable energy collimator in each chicane
  - Diagnostic, and later for foil slits
- Pair of adjustable energy collimators in the dog-leg bend of the LTU
- Three x & y adjustable collimators in the matching section of the LTU
  - Two betatron phases and one clean-up in each plane

**Beam Loss Monitors**
- PLIC cables along the length of the undulator
- Protection Ion Chambers at
  - collimation section in LTU
  - Between undulator modules
Linac To Undulator beamline diagnostic & collimation section

- Linac To Undulator beamline diagnostic & collimation section
- Single Bunch Beam Dumper
- Insertable Tune-Up Dump
- 3 betatron collimators per plane

Highlighting:
- $\beta_x$ (black)
- $\beta_y$ (green)
- $\eta_x$ (blue)
- $\eta_y$ (red)
**Beam Rate Limiting**

- **Single bunch beam dumper (SBBD)**
  - Linac beam up to the dog-leg bend in the LTU can be maintained at 120 Hz
    - Favorable for upstream stability and feedback operation
  - Pulsed magnet allows
    - Single shot, 1 Hz, 10 Hz, 120 Hz down the LTU line
    - Failure in pulsed magnet will turn off beam at gun

- **Tune-up dump at end of LTU**
  - Optional second stopper at end of dummy line (radiation?)
  - Max. 10 Hz to tune-up dump
  - Stopper out will arm MPS for stopping beam with the SBBD
Conditions that will stop the beam at the SBBD

- Tune-up dump at end of LTU is out, and:
- Beam loss at detected by either by PLIC along the undulator chamber, or by the PIC’s between the undulator modules
- Invalid readings from undulator
  - Vacuum
  - Magnet movers
  - BPMs
- Energy error in the LTU
- PIC’s at the collimators
- Launch orbit feedback failing
- Magnet power supplies for some key elements
Bunch Length Measurement

**Absolute** bunch length profile measurements
- RF transverse deflecting cavity
  - 1 Hz pulse stealing
  - 3 pulse measurement
- Electro optic longitudinal profile and timing measurement
  - Single pulse
- Autocorrelation measurement from CTR
  - Average, 2\textsuperscript{nd} moment

**Relative** measurements of rms bunch length
- THz power level measurements from Coherent TR, DR, SR
  - Prompt, single pulse
- Longitudinal wakefield energy loss
  - Invasive, fast scan
Relative bunch length measurement at SPPS based on wakefield energy loss scan

Energy change measured at the end of the linac

as a function of the linac phase (chirp) upstream of the compressor chicane

Shortest bunch has greatest energy loss

Predicted wake loss \( V_{\text{RTL}} = 42.0 \text{ MV}, V_{\text{sim}} = 42.0 \text{ MV}, N = 1.85 \times 10^{10} \)

Predicted shape due to wake loss plus RF curvature

Energy Loss (MeV)

pre-chicane rf phase, \( \langle \phi \rangle \) (degrees S-band)

Rms bunch length (\( \sigma_z \))
Far-Infrared Detection of Wakefields from Ultra-Short Bunches

- Wakefield diffraction radiation
- Wavelength comparable to bunch length
- Pyroelectric detector
- GADC

Comparison of bunch length minimized according to wakefield loss and THz power

- Linac phase
- Wake energy loss
- THz power

Pyrometer signal [arb. units]
- Linac phase offset from crest [deg. S-Band]

- Linac Wake Loss
- FFTB Pyrometer Signal
Absolute bunch length determination

- **Average bunch length from CTR autocorrelation**
  - Radiation from the OTR screen is focused into an interferometer
  - One arm of interferometer is movable, so two profiles are swept through each other
  - Measured bunch length is calibrated in microns of arm motion
  - Averaged over many pulses, so integrates any bunch length jitter

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**Graphical Illustration**

- Diagram showing interferometer setup with OAP, S1, S2, M1, M2, D1, and D2.
- Mylar window indicated.
- Scatter plot showing D2/D1 ratio with fitted line.
- Text: M. Hogan, P. Mugli, SPPS, 48 fs rms.
**CTR Measurements**

**Technical challenges**

- Intercepting thin foil (OTR) versus foil with hole (ODR)

- **Wavelength response of vacuum window**
  - Fused silica
  - Mylar foil vacuum window
  - Window diameter

- **Wavelength response of water vapor**
  - Dry nitrogen blanket

- **Detecting power at several wavelengths**
  - Tune to arbitrary bunch length, not the minimum bunch length
CSR THz radiation from diagnostic chicane

- THz spectral power diagnoses relative bunch length
- CSR spectrum reveals spikes in bunch length distribution
- Spikes due to microbunching instability arising in the BC chicanes also seen in CSR spectrum

Z. Huang: expect to observe microstructure at $\lambda_0/\text{comp.fact}$
Bunch Length Measurements with the RF Transverse Deflecting Cavity

Bunch length reconstruction
Measure streak at 3 different phases

\[
\sigma_y^2 = A \phi_{rf}^2 + B, \quad \sigma_z = \frac{\lambda_{rf} \sqrt{A}}{4C}
\]

Asymmetric parabola indicates incoming tilt to beam

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Calibration scan for RF transverse deflecting cavity

Beam centroid [pixels]

Cavity phase [deg. S-Band]

\[ A = 3.848 \quad \text{STD DEV} = 8.818 \quad \text{RMS FIT ERROR} = 3.116 \]

- Bunch length calibrated in units of the wavelength of the S-band RF
- Further requirements for LCLS:
  - High resolution OTR screen
  - Wide angle, linear view optics
Bunch length and timing diagnostics

**Absolute bunch length determination**

- **Single shot electro optic pump probe measurement**
  - Transforms the problem of measuring short electron bunch length to measuring a short pulse of laser light.
  - Electro-optic process is inherently fast, < 2 fs
  - Time resolution is dependant on crystal geometry and laser BW
  - Investigating two geometries at SPPS
  - Femtosecond laser systems are complex
  - Innovation at SPPS is transport a compressed beam to the e- beamline with a long fiber
Electro Optic Bunch Length Measurement

Geometry chosen to measure direct electric field from bunch, not wakefield
Modelled by H. Schlarb
Resolution limit in temporal-to-spectral translation

\[ T_{\text{res}} = \sqrt{T_0 T_C} \]

However, recent work shows this limit can be overcome with noncollinear cross correlation of the light before and after the EO crystal

*S.P. Jamison, Optics Letters, 28, 1710, 2003*
Temporal to spatial geometry under test at SPPS

- **Elevation view**
  - Electrons
  - EO Xtal

- **End view**
  - EO Xtal

- **Plan view**
  - Polarizer
  - Analyzer
  - Xtal

Principal of temporal-spatial correlation

Line image camera analyzer

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SPPS Electro Optic bunch length measurements – Adrian Cavalieri et al

Spatial profile of beam focused along time axis, total sweep only several picoseconds

Principal of temporal-spatial correlation

- polarizer
- analyzer
- xtal
- Line image camera

6 ps

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SPPS - EO signal vs time and single bunch – Adrian Cavalieri et al

- 0.5 mm ZnTe crystal

Principal of temporal-spatial correlation

- multiple peaks indicate multiple rotations of polarization vector

0.3 mm ZnTe crystal
SPPS - time sequence of multiple EO images

Principal of temporal-spatial correlation

EO xtal
Line image camera
Analyzer
Polarizer

Optical delay

E_t
SPPS - time sequence of multiple EO images

Principal of temporal-spatial correlation

Line image camera

EO xtal

Wollaston prism

Polarizer

Optical delay

Note wakefields after passage of the bunch
EO resolution limit due to wakefields – H. Schlarb

- Apparent change in $\sigma_z$ when measured at increasing radii relative to the aperture from the edge of the laser mirror.
- Negligible perturbation if EO crystal is closer to beam than mirror edge.
Feedback implementation

- **Pulse-to-pulse control of**
  - Orbit position & angle, energy
    - as in SLC
  - beam phase,
    - Necessary, for example, to measure orbit after RF deflecting cavity to maintain cavity at zero phase crossing
  - bunch length
    - Use relative signal strength from OTR THz spectral power measurement
    - Demonstrated at SPPS with dither feedback to minimize bunch length
    - Needs power measurement at several THz wavelengths to tune to arbitrary bunch lengths
    - Decouple longitudinal feedback requirements
      - Energy feedback maintains constant energy at the BC chicane
      - Bunch length feedback controls the linac phase (energy chirp)
Energy feedback at SPPS chicane responding to a step energy change

Energy measured at a dispersive BPM, Actuator is a klystron phase shifter

Energy jitter measured from chicane feedback system 5.6 MeV rms 0.06%
Dither feedback control of bunch length minimization - L. Hendrickson

Bunch length monitor response

Feedback correction signal

Dither time steps of 10 seconds

Linac phase

Jitter in bunch length signal over 10 seconds ~10% rms
Conclusions

- Upgrades to conventional diagnostic instrumentation
- We rely on several new and complex bunch length and timing diagnostics
  - Development work on these has started at SPPS
- Feedback is an essential part of maintaining stable tuning
- MPS is integrated into diagnostics and feedback requirements