Feedback Requirements for SASE FELS

Henrik Loos, SLAC

IPAC 2010, Kyoto, Japan

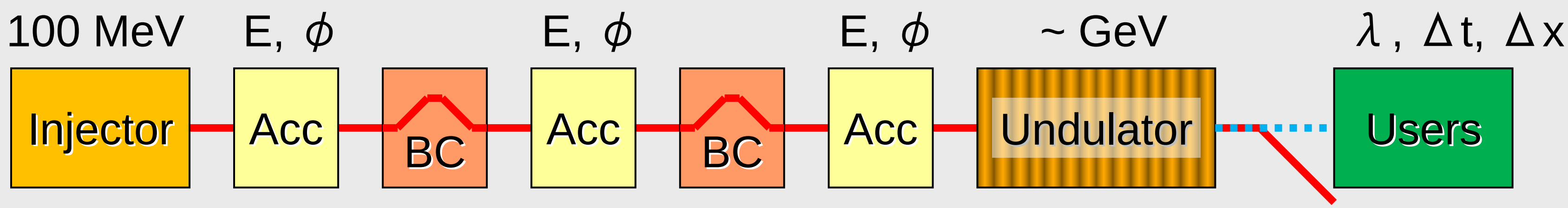
Outline

- Stability requirements for SASE FELs
- Diagnostics for beam parameters
  - Transverse: Beam position monitors
  - Longitudinal: Bunch length/compression/arrival monitors, synchrotron radiation monitors
- Feedback implementations
  - LCLS transverse feedback
  - XFEL orbit IBFB
  - LCLS longitudinal feedback
  - FLASH longitudinal IBFBs
- Summary

Henrik Loos
loos@slac.stanford.edu

SASE FEL Feedback

- Ensure electron beam quality for lasing
- Provide stable photon beam for users

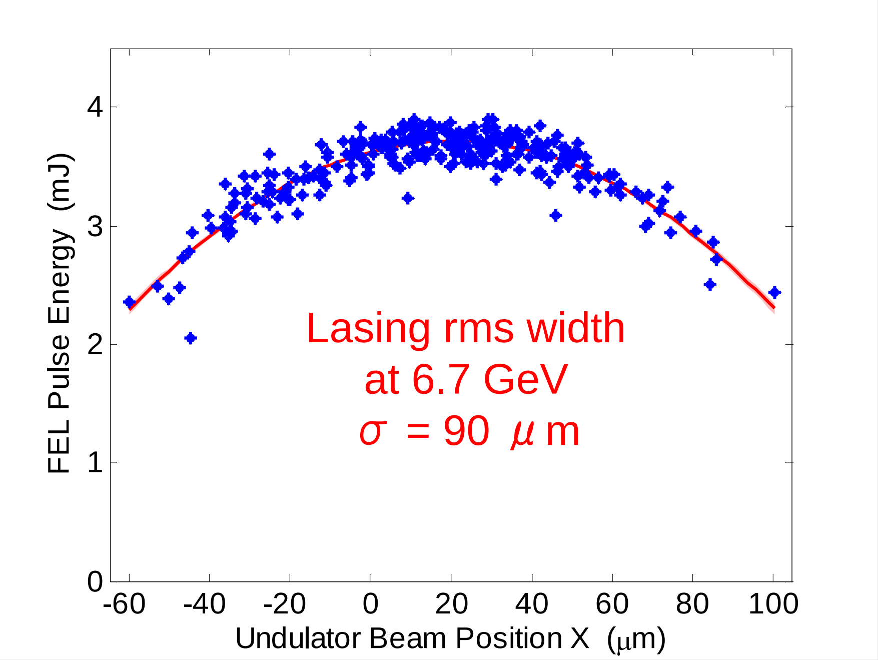


	Energy (GeV)	Wave length	Und. length	Bunch Charge	Peak Current	Gain length	Beam size	Rate (Hz)
LCLS	13.6	1.5 Å	100m	0.25-1nC	3kA	3.5 m	30 μm	120
SCSS	8	1 Å	100m	0.3nC	2.5kA	~10 m	35 μm	60
XFEL X-Ray Free-Electron Laser	17.5	1 Å	130m	0.1-1nC	5kA	3.7 m	45 μm	10/ 5E6

Henrik Loos
loos@slac.stanford.edu

SASE FEL Feedback Requirements

- Transverse requirements
  - Undulator orbit $x' < \sqrt{\lambda / L_G}$ for efficient SASE
  - L_G ~ 3 – 10 m, λ ~ 1 Å
    → x' < 5 μrad over several L_G
  - Beam position x < σ/10 for stable photon beam
  - β ~ 30 m, ε_n ~ 1 μm
    → x < 5 μm



LCLS example:
Transverse jitter in undulator
from leaked dispersion

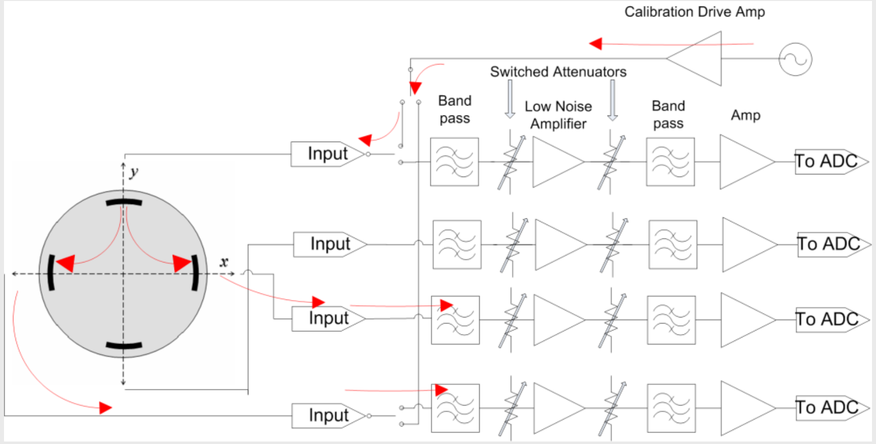
Henrik Loos
loos@slac.stanford.edu

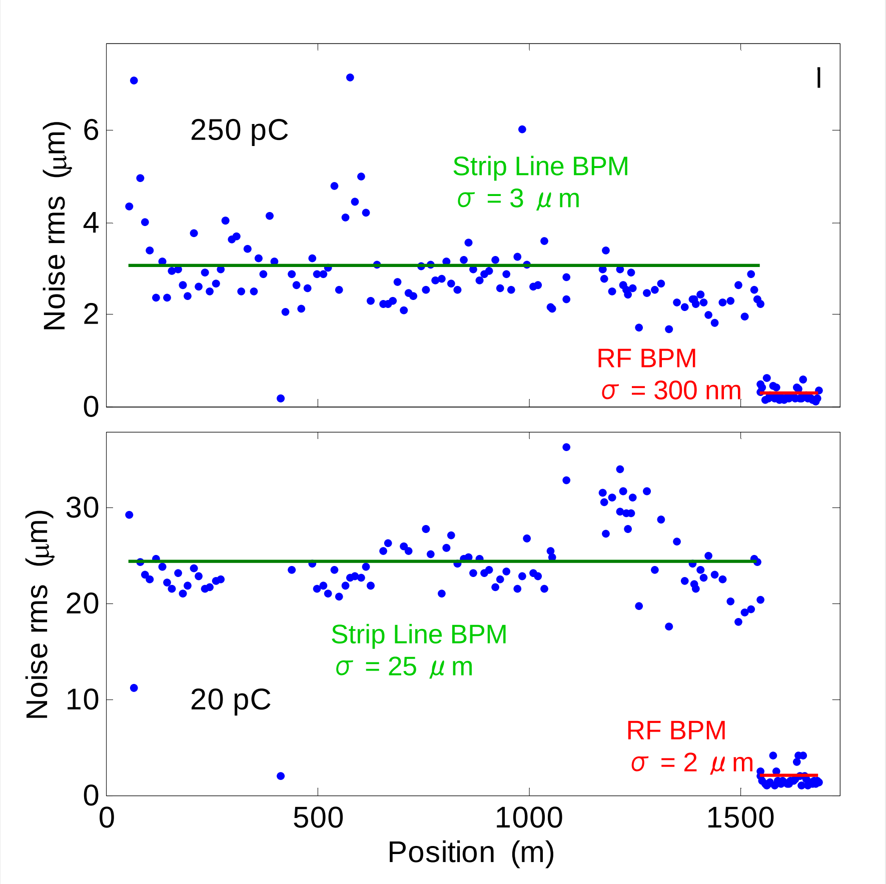
Feedback Requirements cont'd

- Longitudinal requirements
  - SASE process: ρ parameter ~ 10^{-4}
  - Photon BW ~ ρ → energy stability 10^{-4}
  - Bunch compressor R_{56} ~ 4 cm
    → timing jitter $\Delta t \sim R_{56}\,\rho/c$ ~ 10s of fs
  - Energy measurement R_{16} ~ 10 cm → $R_{16}\,\rho$ ~ 10 μm
  - Energy in BC from position measurement in BC or from TOF measurement with beam arrival monitors
- Bandwidth requirements
  - NC accelerator ~100 Hz rate → Feedback stabilizes slow drifts
  - SC accelerator bunch train MHz rate → Intra Bunch FB required

LCLS Strip Line BPM Performance

- Strip line BPMs
  - Continuous calibration with test pulse between beam triggers
  - 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
  - Average value for strip-line 3.5 μm, for RF cavity 250 nm at 250 pC





E. Medvedko et al., BIW 2008, TUPTPF037

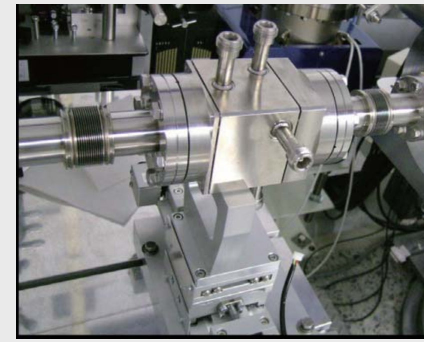
LCLS Undulator RF Cavity BPMs

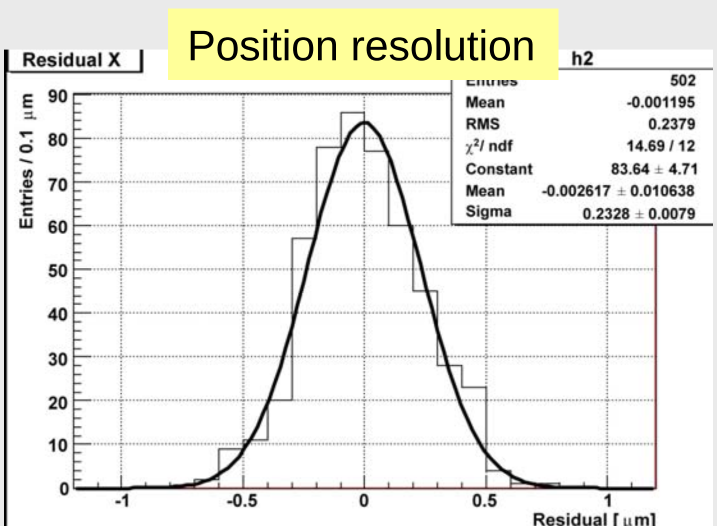
- Few micron beam orbit straightness in undulator required for FEL operation
- Sub-micron resolution met with RF cavity BPM design
- 11.4 GHz dipole cavity
- Reference cavity for normalization
- Calibration with beam signals
  - Move supporting girder of undulator
  - Induce known orbit oscillation upstream of undulator

Argonne NATIONAL LABORATORY

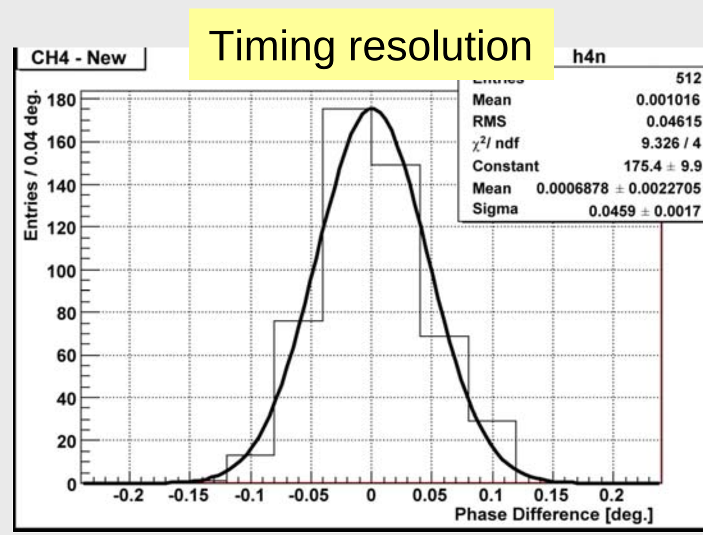
RF BPMs at XFEL/Spring-8

- Dipole mode cavity at 4.76 GHz + monopole cavity
- Shifted from main RF frequency to avoid dark current
- Measurements at SCSS test accelerator
- Position resolution < 200 nm
- Timing resolution from TM_{010} cavity < 25 fs



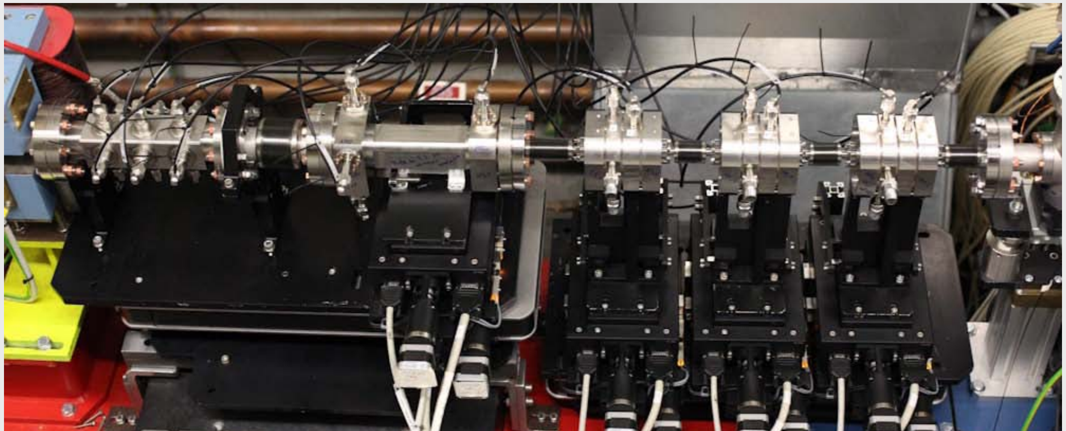


H. Maesaka et al., DIPAC09, MOPD07



See also H. Maesaka et al., MOPE003
S. Matsubara et al., MOPE004

RF BPMs for X-FEL



Test stand at FLASH

40 mm RF BPM for IBFB

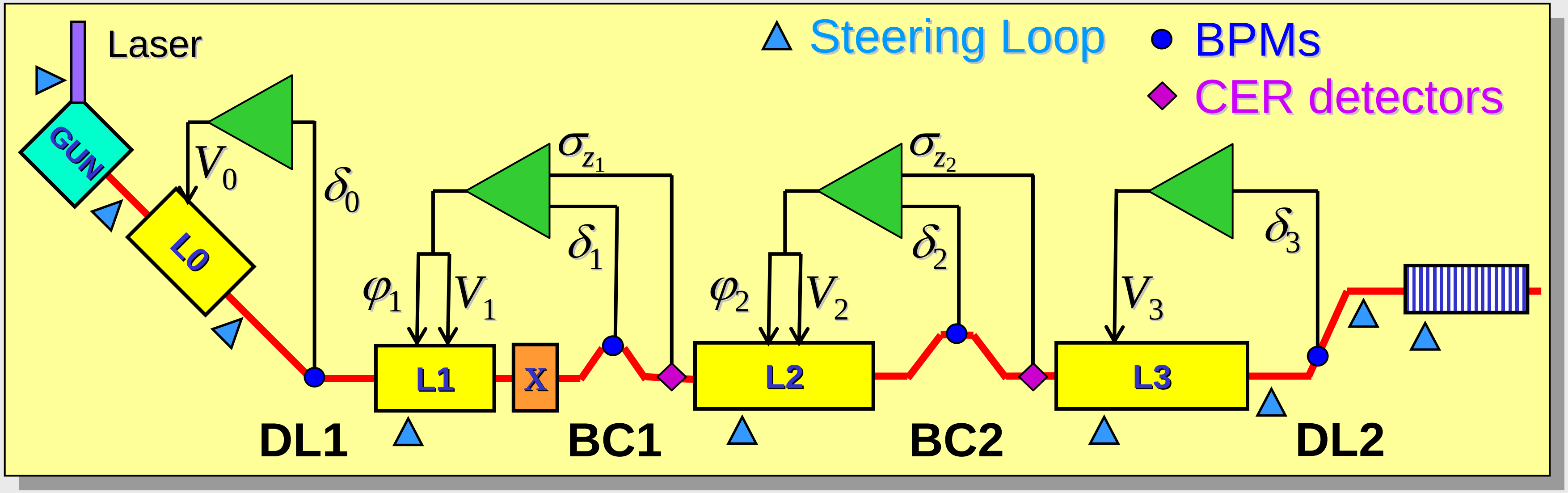
D. Noelle, BIW10, WECNB01

- Based on Spring-8 design
- Frequency 3.3 GHz
- Low Q to resolve bunch train at 5 MHz
- 10 mm high precision version for undulator
- 40 mm version for IBFB
- Designed for 1 μm resolution

European XFEL

See also B. Keil et al., MOPE064

- Launch FB for each linac section
- Loops for transport line and undulator
- FB are independent of each other
- Decoupling by use of different time scales
- FB response matrix from online model

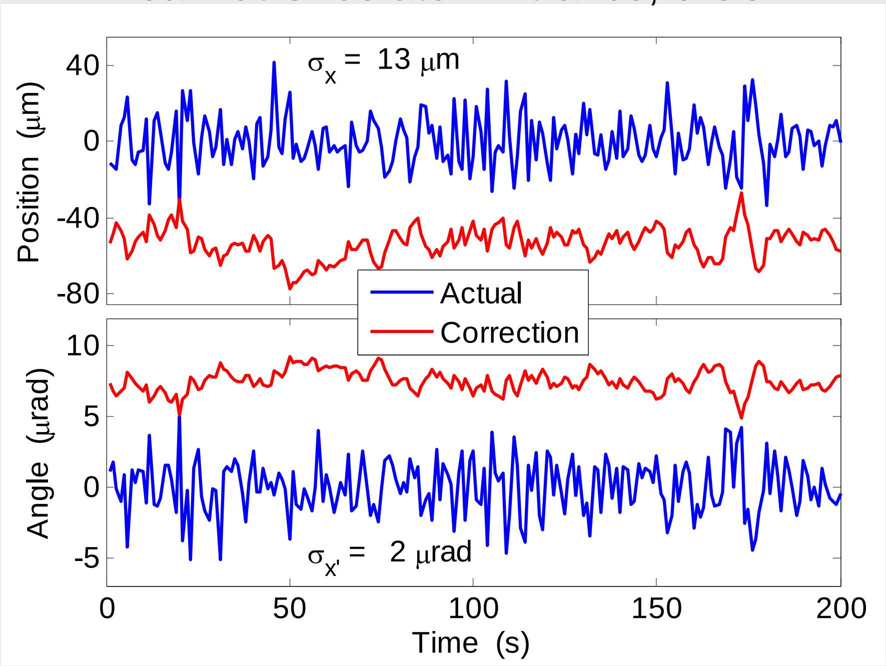


J. Wu et al., PAC 2009, WE5RFP046

Undulator Feedback Performance

- Upstream LTU FB runs at 10 Hz
- Undulator FB slower with 1 Hz
- Horizontal jitter 13 μm / 2 μrad
- 30 – 40% larger than vertical due to dispersion leakage
- Residual jitter ~ 25% of beam size

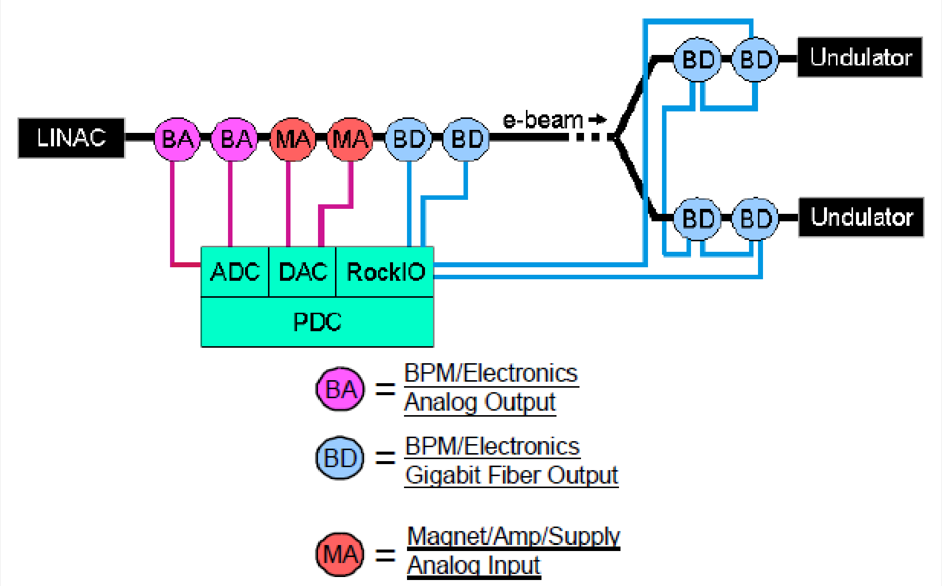
Beam at Undulator Entrance, 6 GeV



Henrik Loos
loos@slac.stanford.edu

XFEL/PSI Intra-Bunch Orbit Feedback

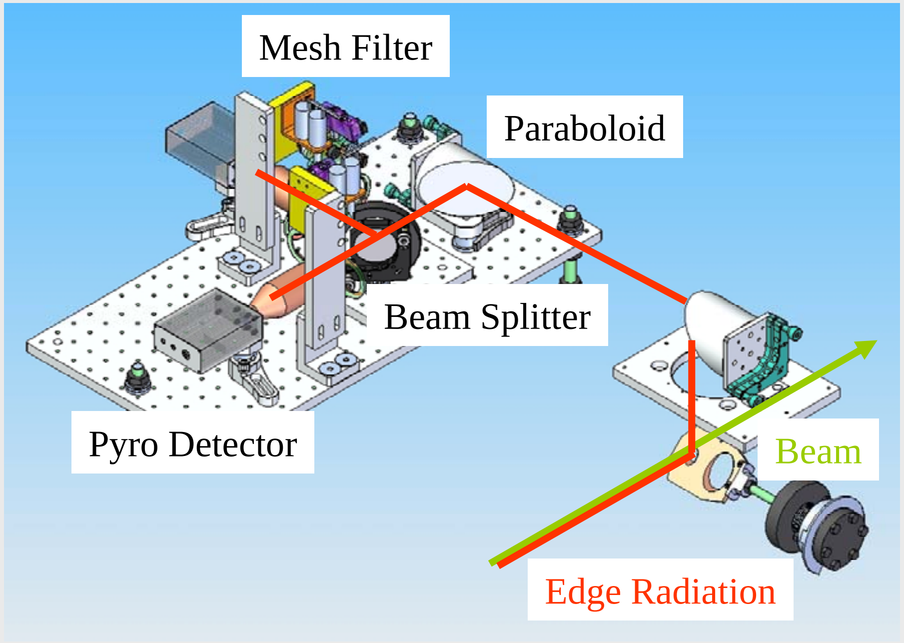
- Use downstream BPMs for feedback loop
- Latency ~ 1 μs bunch spacing
- FPGA for feedback calculation
- Fast strip-line kicker for orbit correction
- Use upstream BPMs for calibration
- BPMs in undulator for slow feedback

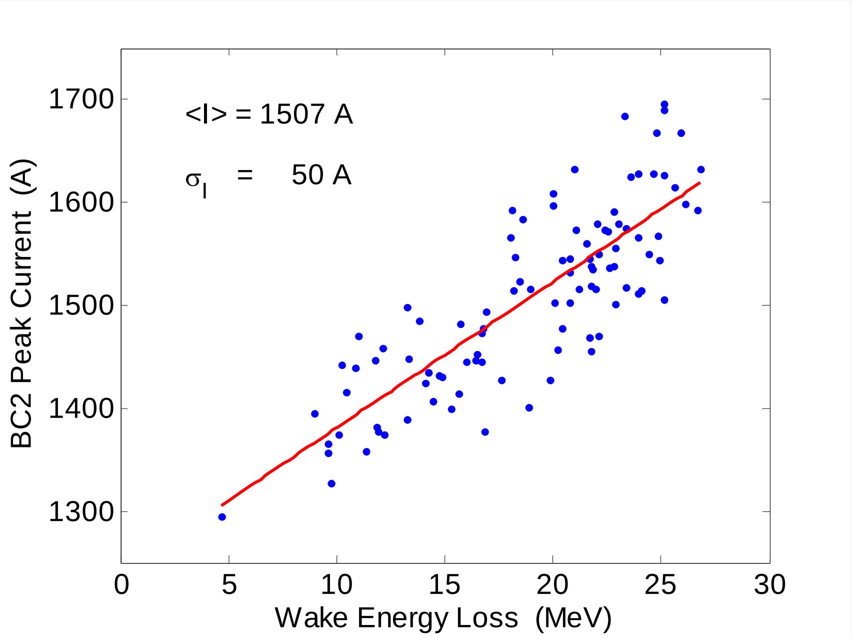


B. Keil et al., EPAC08, THPC123

LCLS Bunch Length Monitor

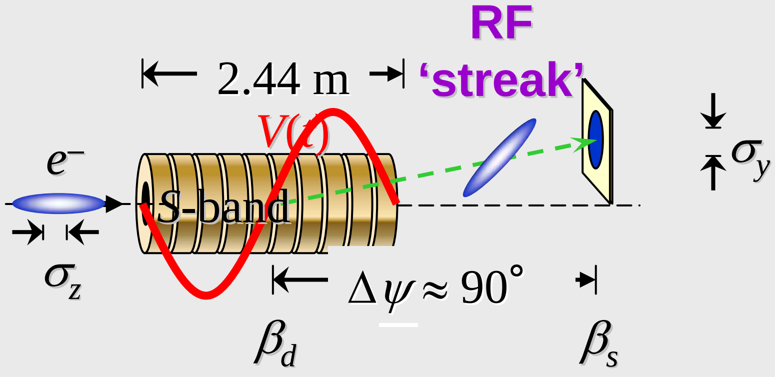
- Edge radiation from last dipole of each BC
- Integrated measurement sensitive from mm to 20 μm
- Block NIR radiation from bunching instability with filters
- 3% rms noise from correlation with bunch length dependent wake field energy loss in undulator

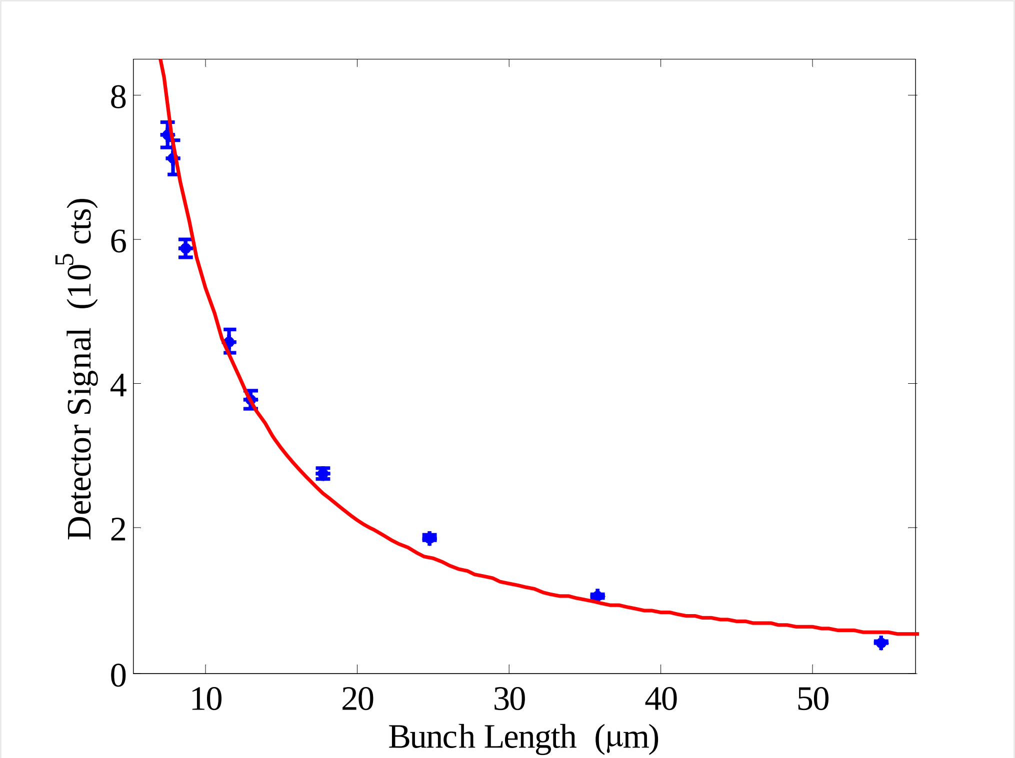




Henrik Loos
loos@slac.stanford.edu

- BPM provides only signal related to bunch length
- Calibration with absolute measurement from transverse deflecting cavity

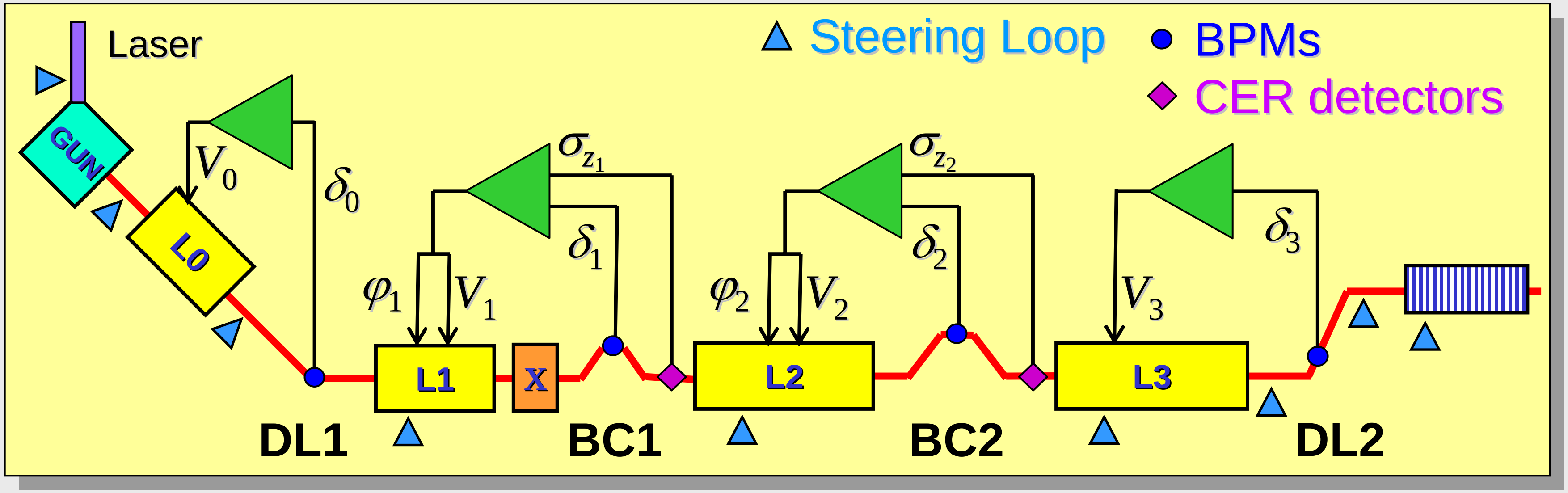




- Empirical fit of signal to $(\sigma_z)^{-4/3}$
- Use fit to calculate peak current

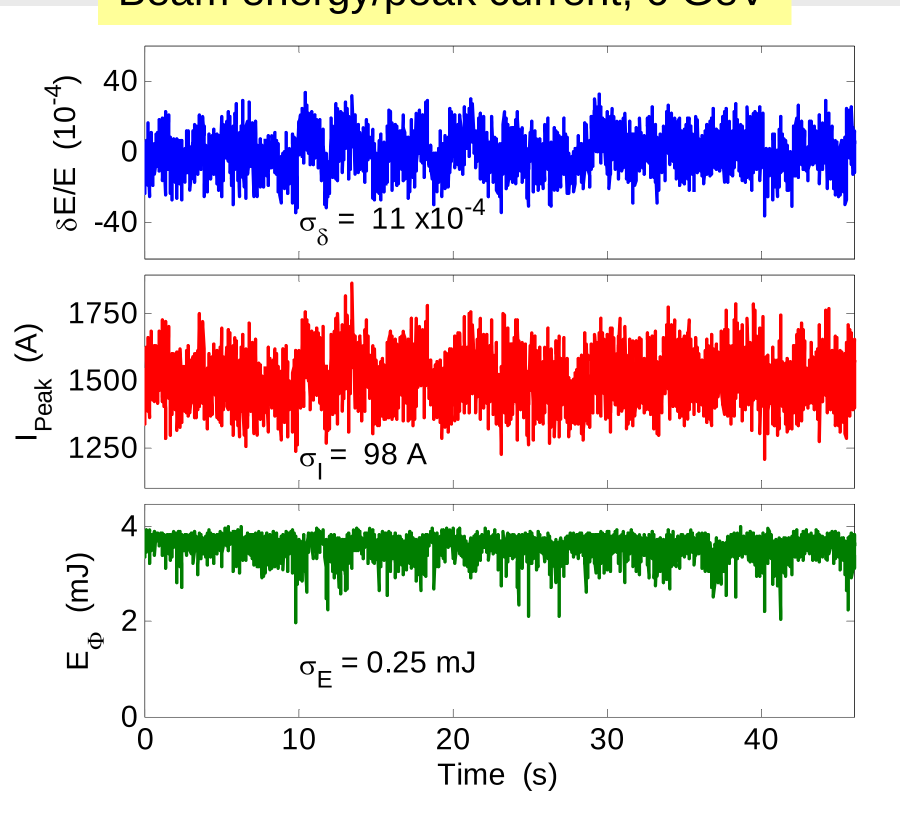
LCLS Longitudinal Feedback

- Cascaded FB at 5 Hz (Matlab implementation)
- Fixed energy gain in L2 & L3 klystrons
- Change global L2 phase
- Adjust L2 & L3 energy with several klystrons at opposite phases
- Feedback uses orthogonal actuators to separate energy gain and chirp of L2



Longitudinal Feedback Performance

Beam energy/peak current, 6 GeV



See also F.-J. Decker et al., TUPE071

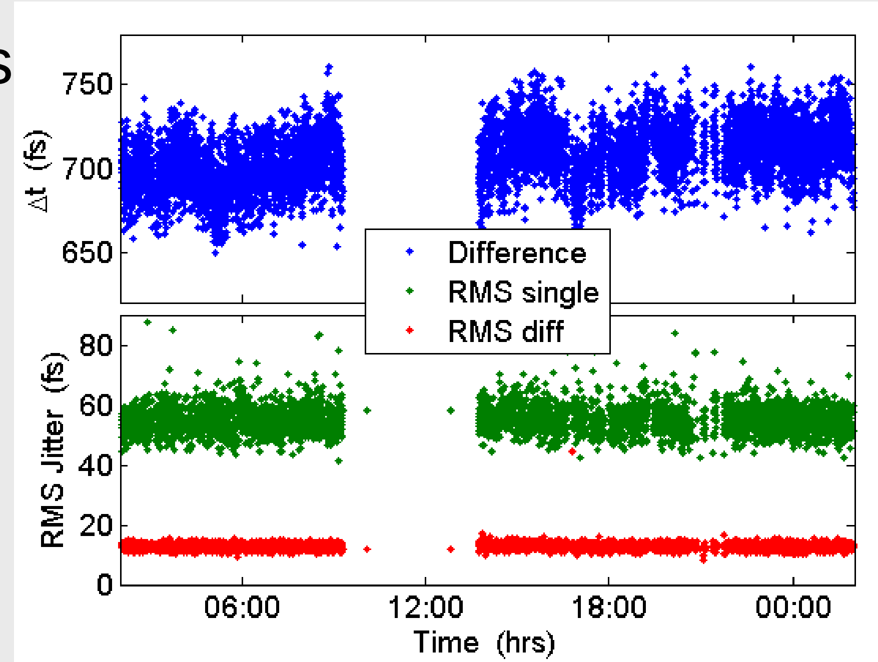
- 7% peak current jitter
- 6% X-ray pulse energy jitter (best 3%)
- Stability achieved over hrs
- Feedback controls enable bunch length & energy changes (few %) in 10s of seconds

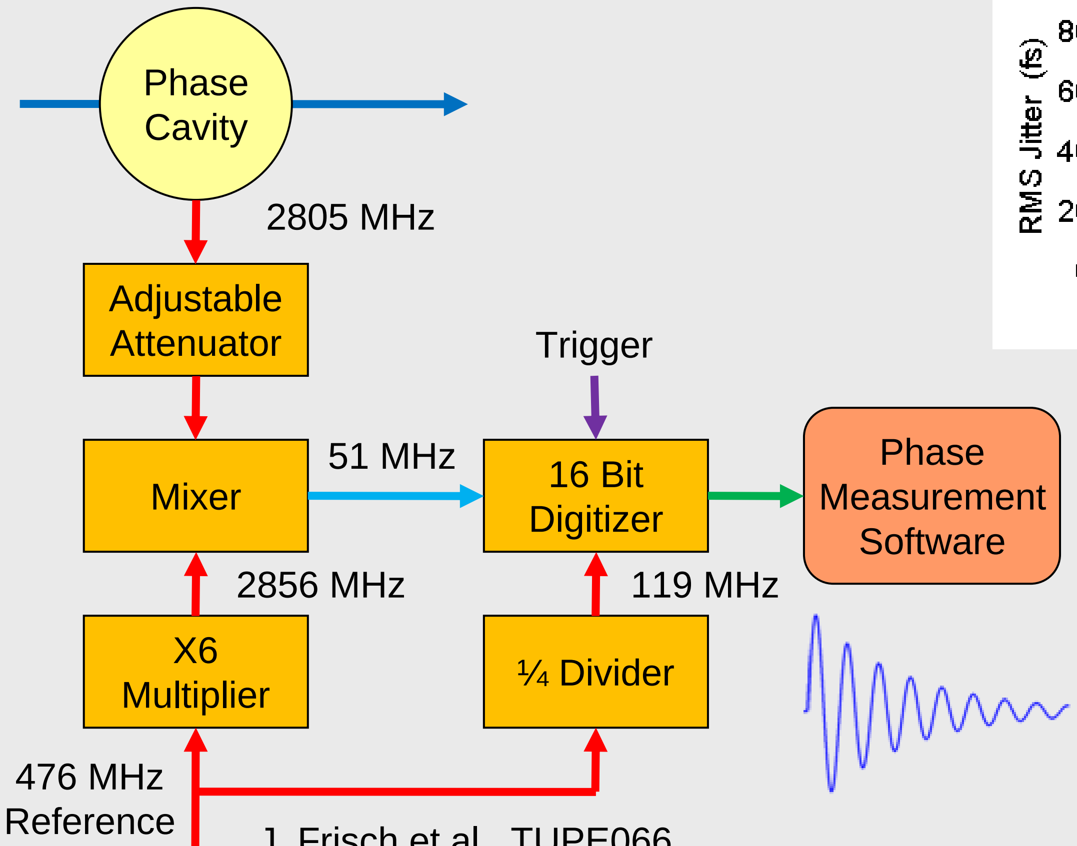
- Operation soon at 120 Hz
- Fast orbit and energy/phase feedback in development
- Time-slot aware control for different 60 Hz phases

Henrik Loos
loos@slac.stanford.edu

LCLS Phase Cavities

- Jitter between two cavities 15 fs
- Not used for e-beam FB
- Signal used for offline analysis





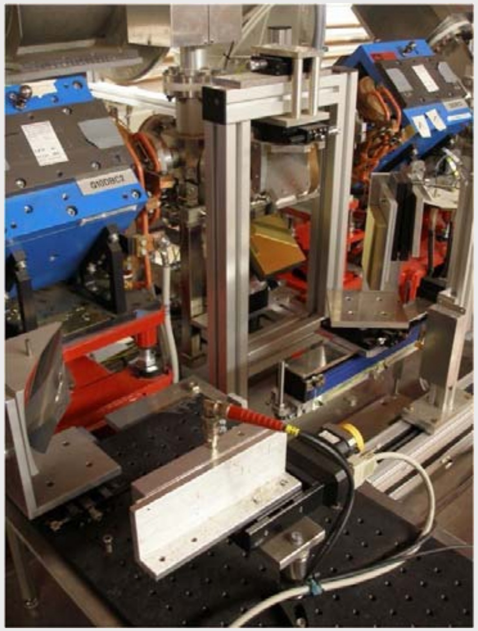
J. Frisch et al., TUPE066

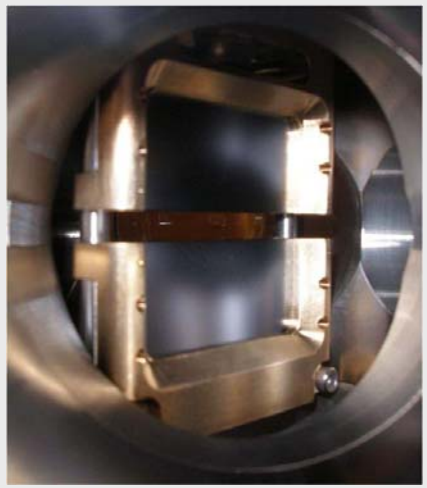
- Synchronize laser of user experiment to electron beam

J. Byrd et al., MOOCRA03

See also J. Byrd et al., TUPEA033
T. Ohshima et al., TUPEA030

FLASH Bunch Compression Monitor





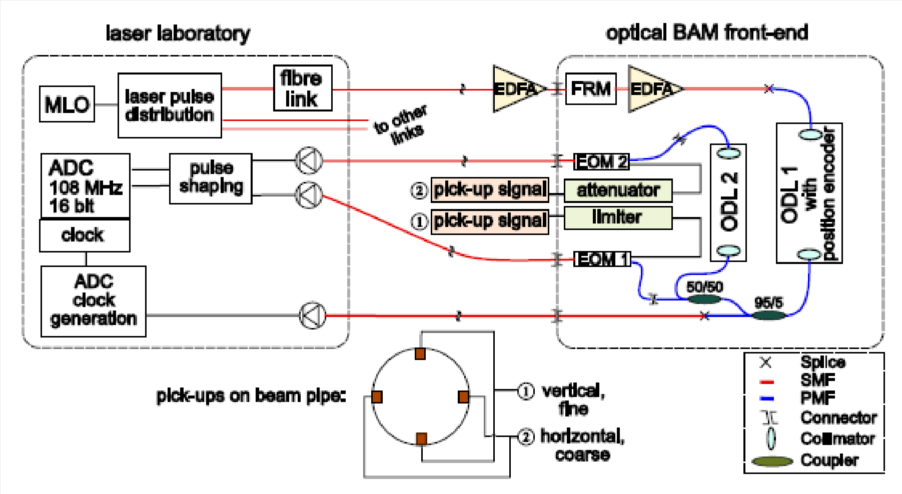
C. Behrens et al., MOPD090

- Coherent diffraction radiation detector
- Radiator is metal screen with slit
- Optical radiation transport with GHz to THz bandwidth
- Signal from pyroelectric detector
- Fast detection resolves bunch train

FLASH Beam Arrival Monitor

- Laser clock via length stabilized fiber with 6 fs stability
- Beam signal from 4 button pick-ups
- Electro-optic modulator encodes beam signal on laser amplitude
- Fast sampling with 108 MHz ADC
- Operate at zero-crossing of amplitude modulation
- Delivers arrival time of each bunch in bunch train with < 10 fs resolution

F. Loehl, TESLA-FEL2009-08

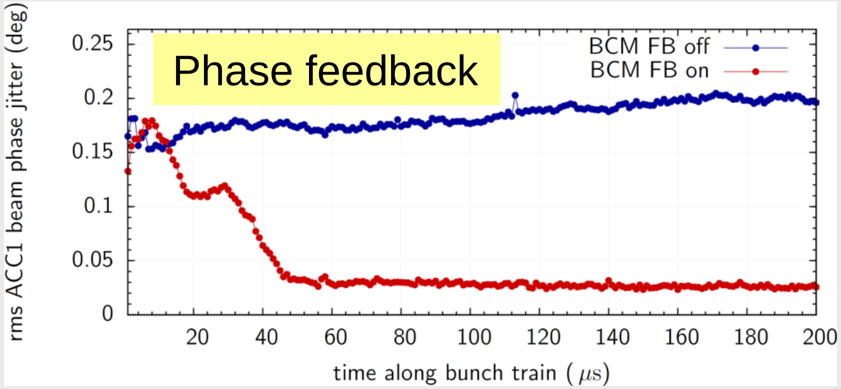


M. Bock et al., FEL09, WEPC66

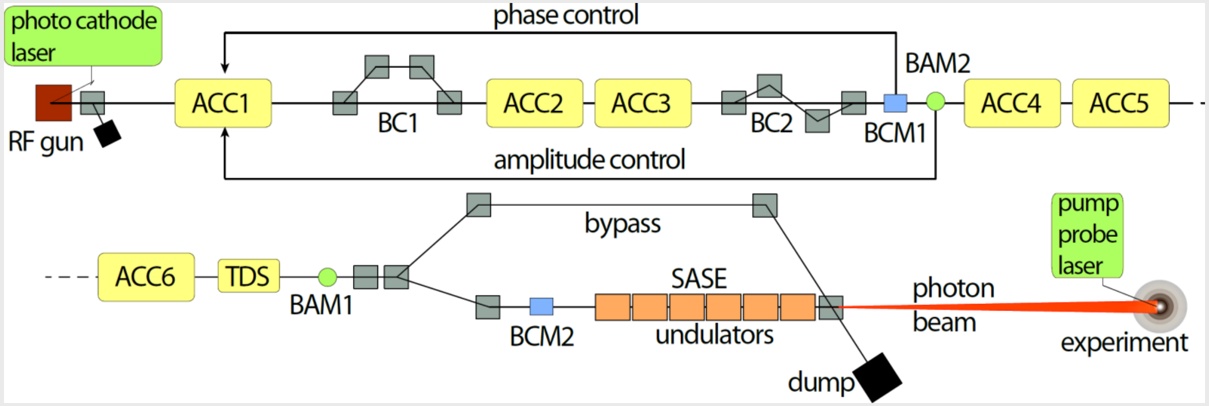
See also M. Bock et al., WEOCMH02

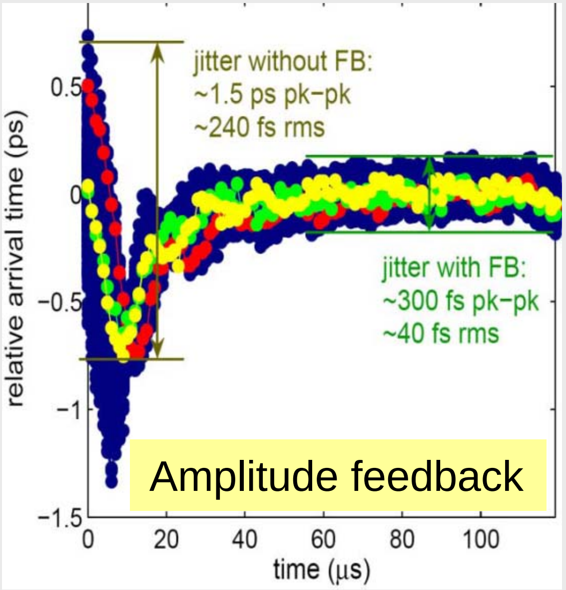
Longitudinal Intra-bunch Feedback

- FPGA based controller board
- PID controller for amplitude correction from BAM signal
- Phase control from BCM signal
- Rapid change at head of bunch train from beam loading
- Latency of 30 μs due to SC RF



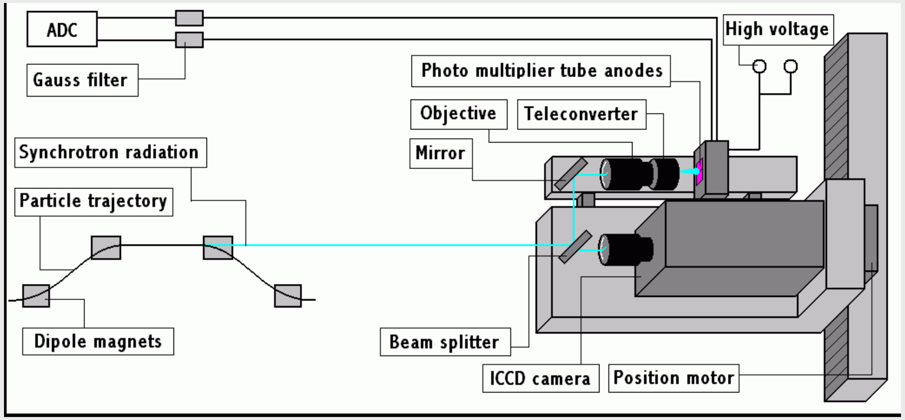
F. Loehl et al., FEL08, THBAU02



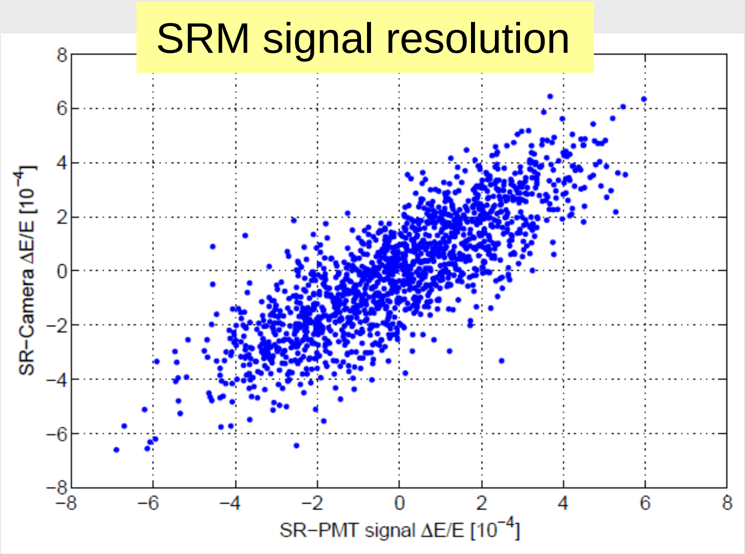


F. Loehl et al., EPAC08, THPC158

FLASH Synchrotron Radiation Monitor



A. Wilhelm et al., DIPAC09, TUPD43

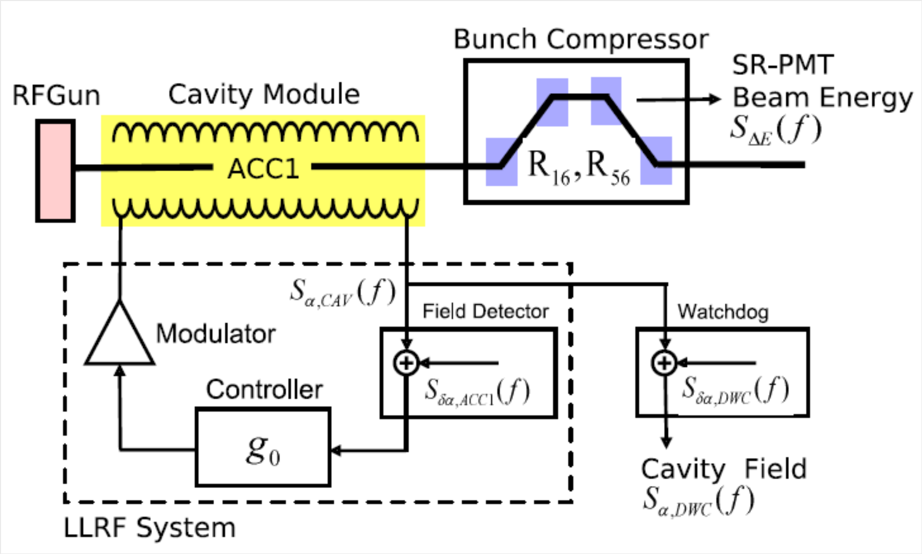


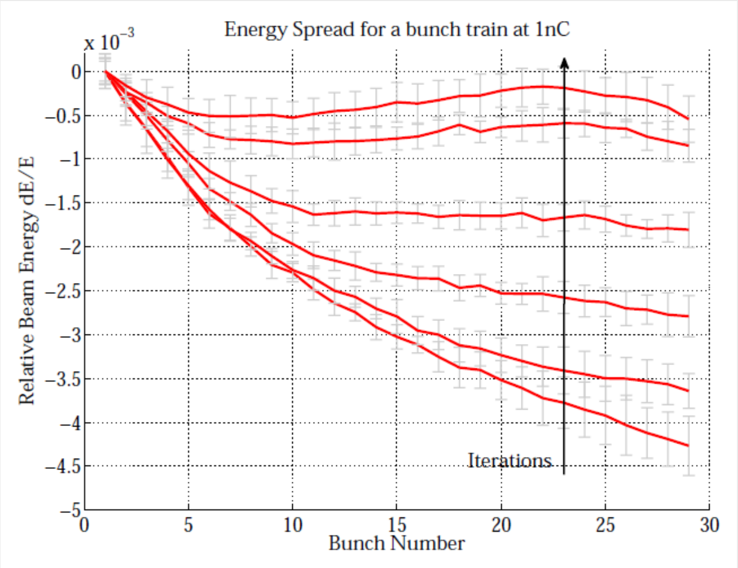
C. Gerth et al., DIPAC09, TUPD22

- Energy measurement with < 10^{-4} resolution
- ICCD for energy spread of single bunches
- Fast centroid readout with multi-anode PMT
- 14-bit ADC at 1 MHz for bunch train resolution

FLASH Energy Feedback using SRM

- Correct stochastic and deterministic disturbances with a learning FF algorithm
- Effect of beam loading at head of bunch train minimized after a few iterations of the FF algorithm





C. Gerth et al., DIPAC09, TUPD22

Summary

- Diagnostics available to meet resolution requirements for SASE FELs
- SASE FEL feedback systems achieve beam stability to do user experiments over many hours
- Optical synchronization schemes enable < 10 fs timing measurements and synchronization of user experiments
- Energy stability of ~ 10^{-3} still exceeds photon beam bandwidth

Acknowledgements

- Thanks to all the people working on X-ray laser facilities worldwide and to my colleagues from the LCLS commissioning team to make stable X-ray beams a reality

Henrik Loos
loos@slac.stanford.edu