Beam Instrumentation for X-ray FELs

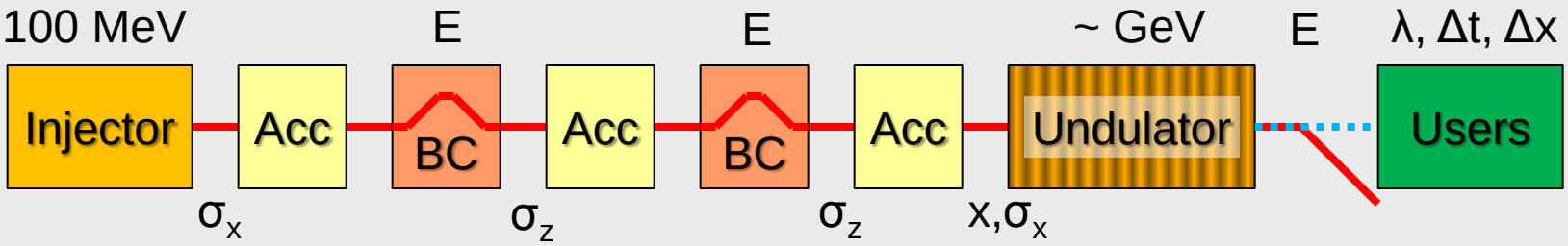
Henrik Loos

05/16/2011

Outline

- X-ray FEL overview
- Diagnostics requirements for X-ray FELs
- Transverse Diagnostics
- Longitudinal Diagnostics
- Summary

X-ray FEL Overview



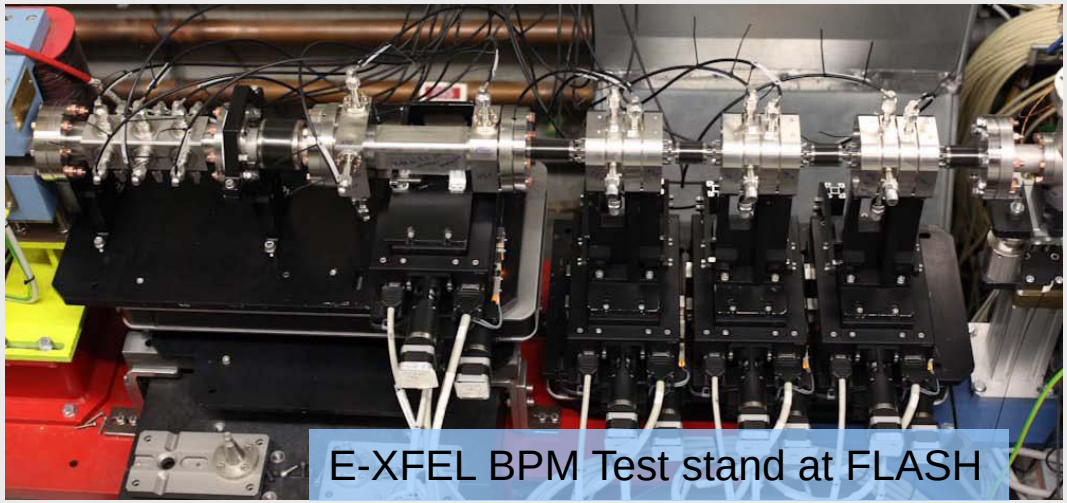
Energy (GeV)	Wave length	Bunch Charge	Peak Curr.	Emit-tance	Gain length	Und. length	Rate (Hz)
13.6	1.5 Å	0.02-1nC	3kA	.2-1 μm	3.5 m	100m	120
8	1 Å	0.2nC	4kA	.7 μm	~10 m	100m	60
17.5	1 Å	0.1-1nC	5kA	1-2 μm	3.7 m	130m	10/ 5E6

X-Ray FEL Diagnostics Requirements

- Work from MeV to GeV range, 10s of pC to nC
- Transverse
  - Typical $\beta \sim 10 - 100$ m, $\varepsilon_n \sim 1$ μm, beam size 10s μm
  - Need ~10 μm resolution for beam profiles
  - Beam position $x < \sigma/10$ for stable photon beam
  - Need few μm BPM resolution
  - Straight beam orbit in undulator within few μm
  - Need sub-μm cavity BPM
- Longitudinal
  - Typical 10^{-4} FEL bandwidth, energy resolution «10^{-4}
  - Need ~10 μm energy BPM resolution for ~10 cm dispersion
  - Bunch lengths 10s fs
  - Need timing and length resolution of few fs
- Non-intercepting/intra-bunch resolution for feedback systems

FLASH Beam Position Monitors

Courtesy N. Baboi



D. Noelle, BIW10, WECNB01

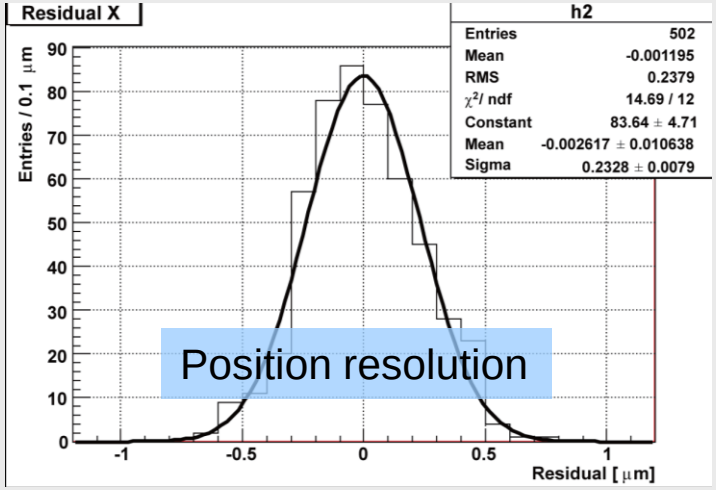
- ~70 BPMs, strip line
- 10 µm resolution
- Few button, cavity
- Electronics for 0.5 – 1 nC
- Upgrade to 50 pC beam

- E-XFEL BPM development
- Cavity BPM at 3.3 GHz
- 1 µm resolution
- Low Q to resolve intra-bunch train position
- Upgrade plan for FLASH undulator BPMs

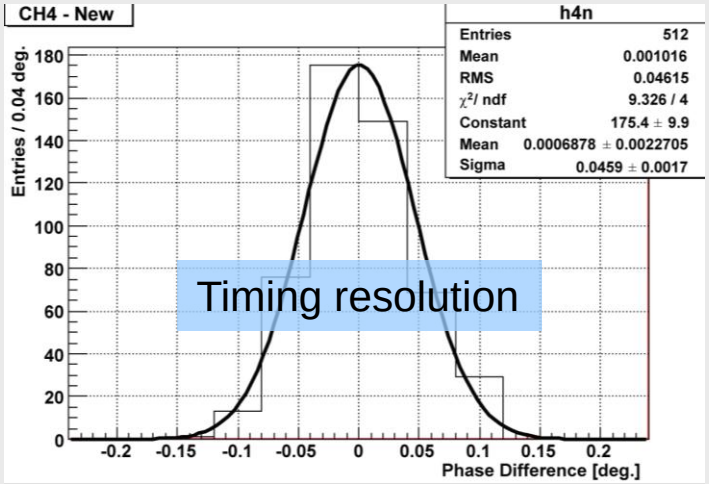
RF BPMs at XFEL/Spring-8

- 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

Matsubara, IPAC 2010 , MOPE004

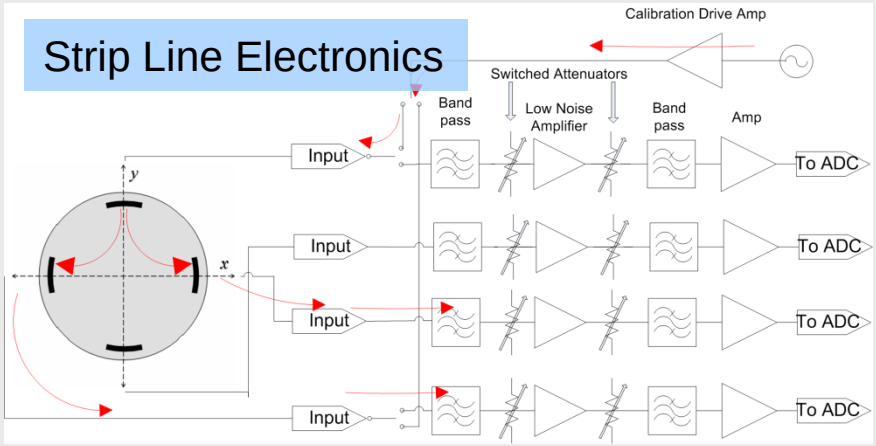


H. Maesaka et al., DIPAC09, MOPD07

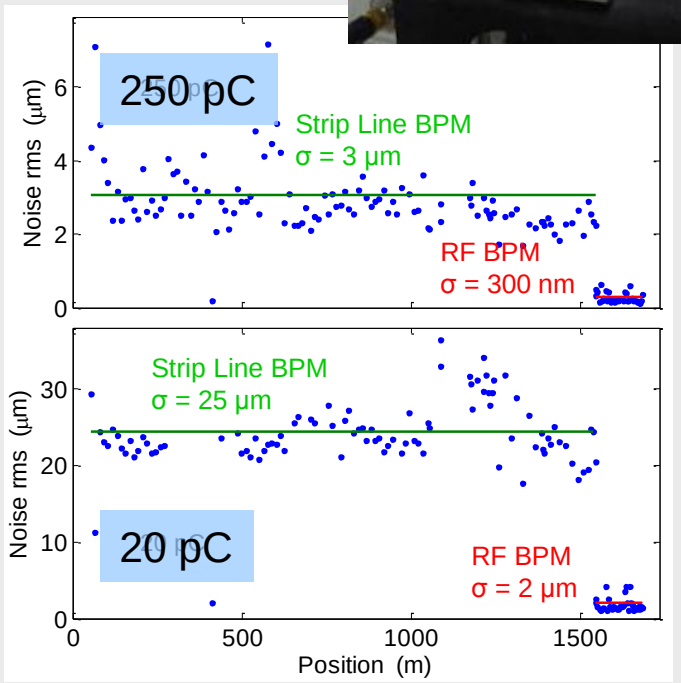


LCLS Beam Position Monitors

- 145 strip line type
  - Charge range ~10 pC to few nC with variable attenuators
  - Continuous calibration with test pulse between beam triggers
  - 3 μm resolution (25 μm at 20 pC)
- 35 cavity type between undulators
  - Dipole/monopole cavity at 11.4 GHz
  - < 300 nm resolution (2 μm at 20 pC)
  - Bi-weekly calibrate with girder motion & beam based alignment



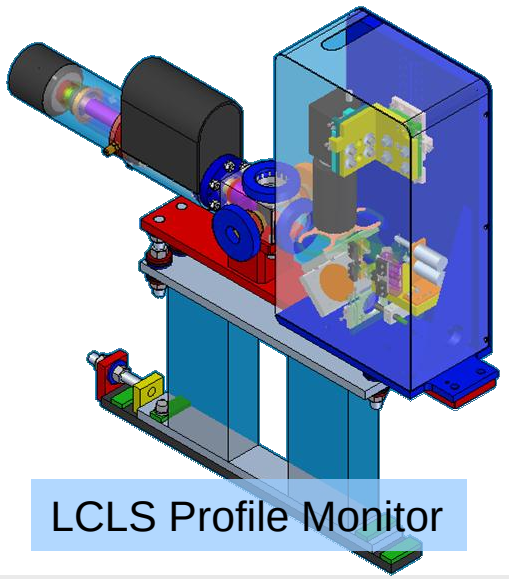
E. Medvedko et al., BIW 2008, TUPTPF037

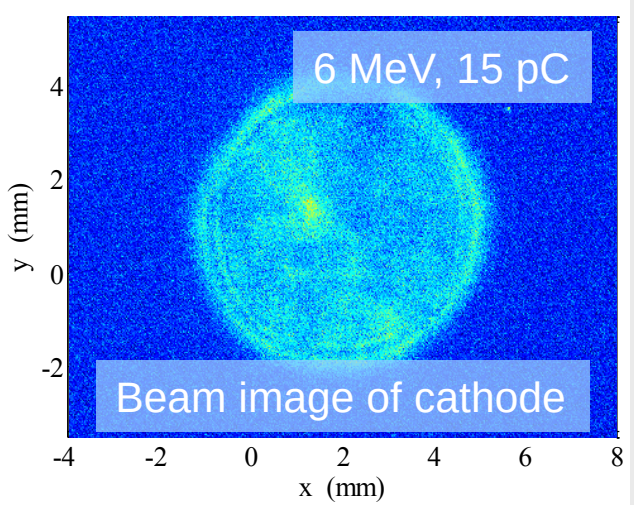


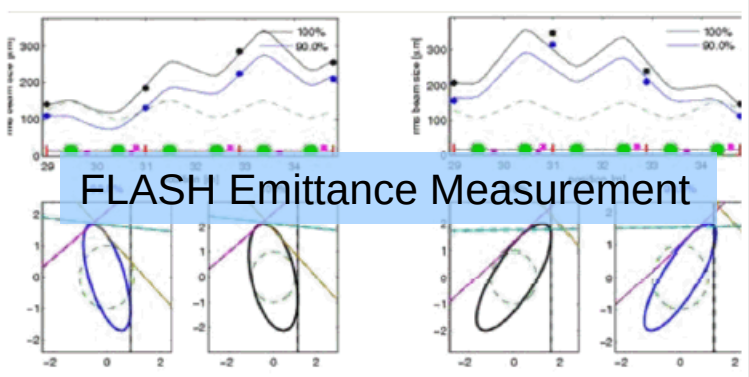
Henrik Loos
loos@slac.stanford.edu

Profile Monitors YAG/OTR

- YAG Screens
  - Powder or crystal
  - Saturate ~nC/mm^2
  - High sensitivity
- OTR Screens
  - Thin Al foil or Si wafer
  - Better resolution
- FLASH
  - 20 OTR with up to 10 μm resolution
  - Matching into BCs & undulator
  - COTR at high compression
- LCLS
  - 20 YAG & OTR, 50 – 10 μm resolution
  - Gun commissioning, injector tune-up

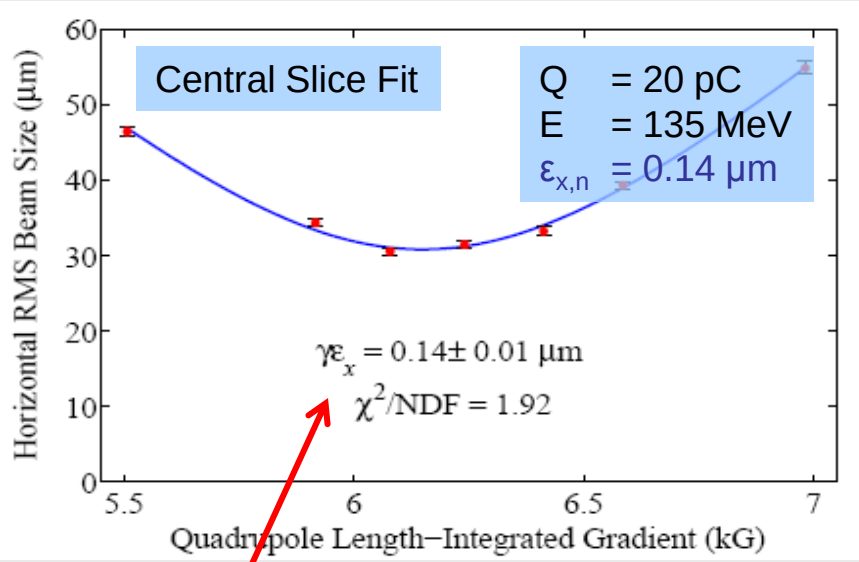

LCLS Profile Monitor

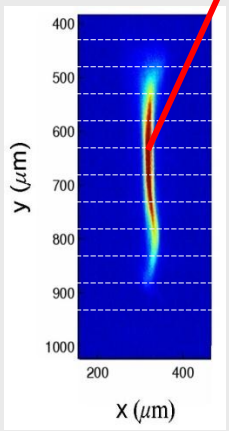


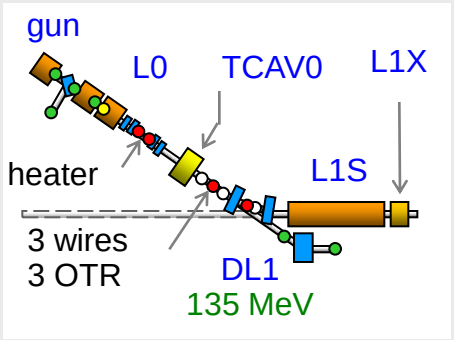

FLASH Emittance Measurement

Courtesy N. Baboi

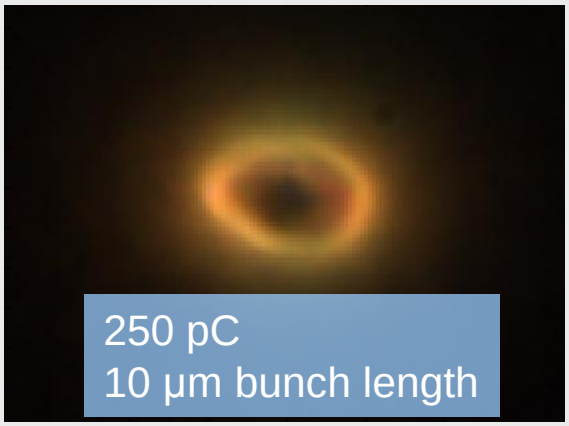
LCLS OTR Screens







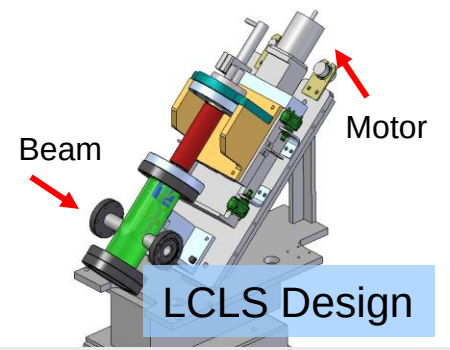
- Injector diagnostics
- Emittance of 10 slices at 20 pC
- COTR prevents use beyond injector
- Main dump OTR replaced with YAG

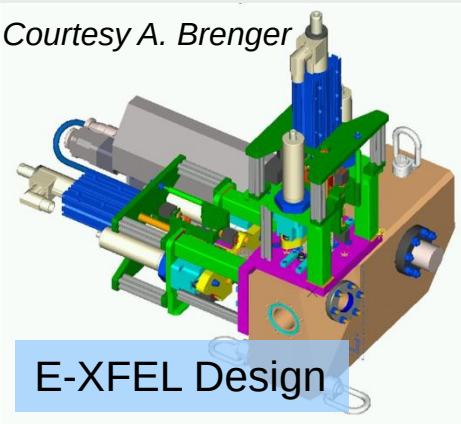


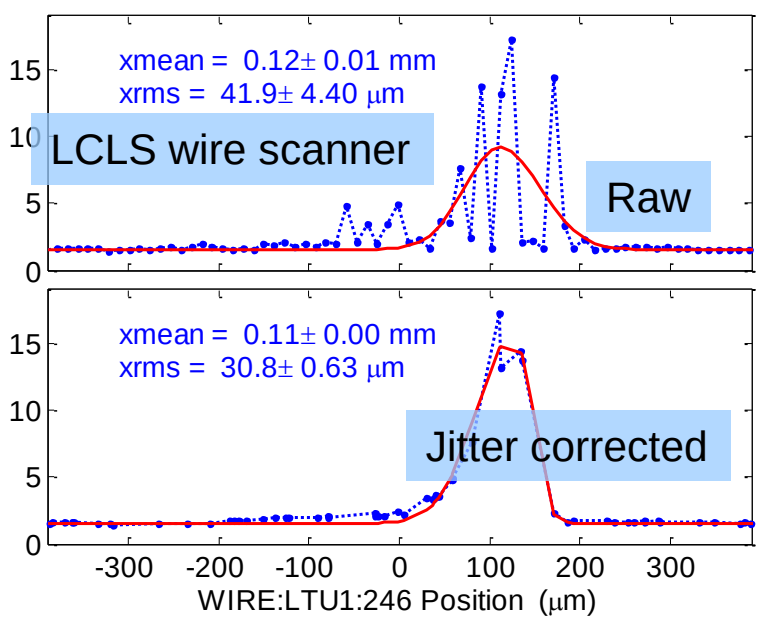
Also see S. Wesch & B. Schmidt, WEOA01

Wire Scanners

- Multi shot method
  - Intercept beam with thin wire
  - Use beam loss monitors to measure charge profile
- FLASH wire scanners
  - Agree well with OTR screens
  - Seldom used, slow scan at 10 Hz
- E-XFEL development
  - Scan with 1 m/s within bunch train
- LCLS wire scanners
  - Main method past injector (COTR)
  - Need to correct for beam jitter
  - Synchronous acquisition of beam orbit, wire position and PMT signal



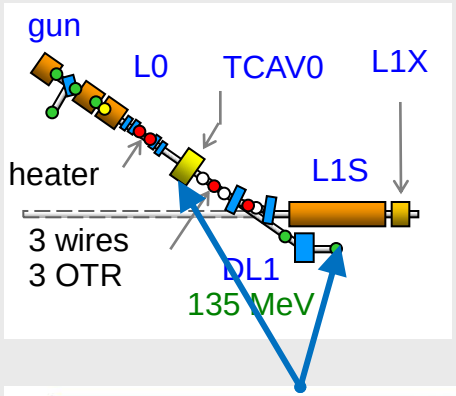


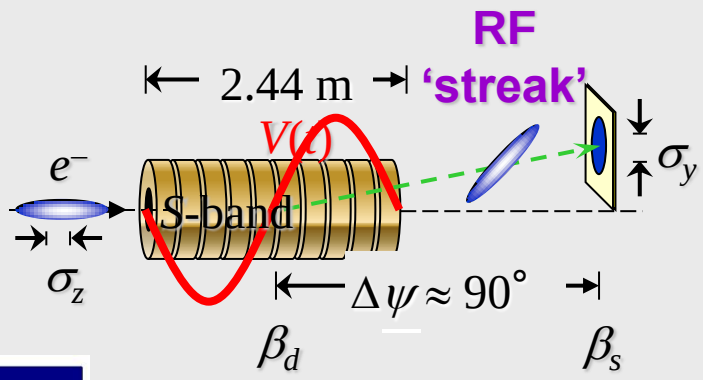


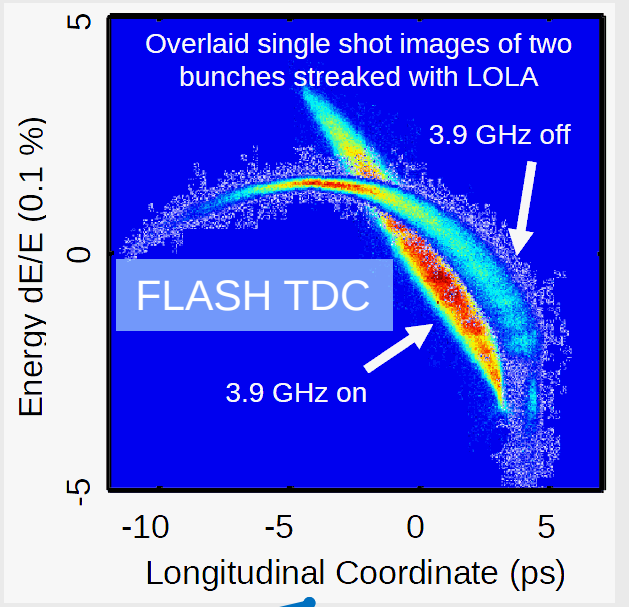
Transverse Deflecting Cavity

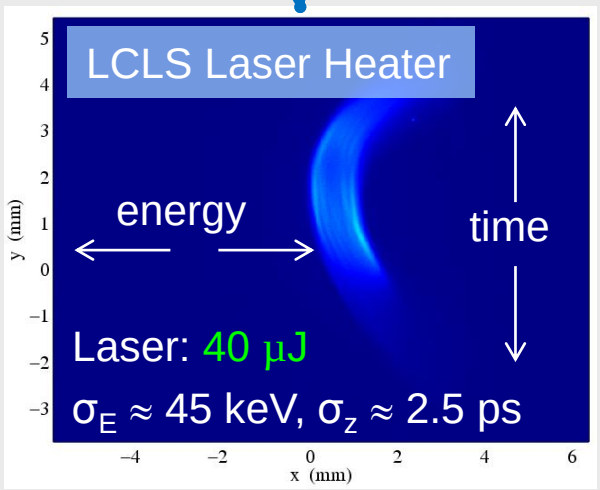
- Impose time dependent transverse kick on beam
- Phase advance 90º to screen
- Time calibration with phase scan

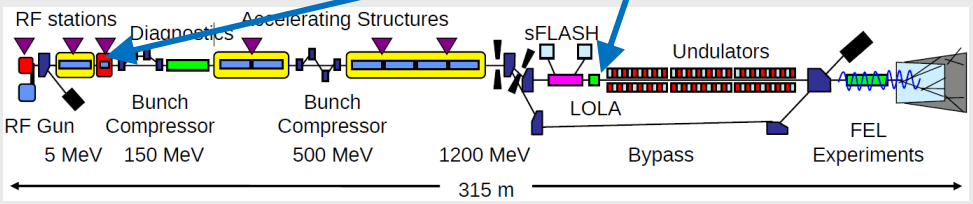
H. Edwards et al., LINAC10, MO304







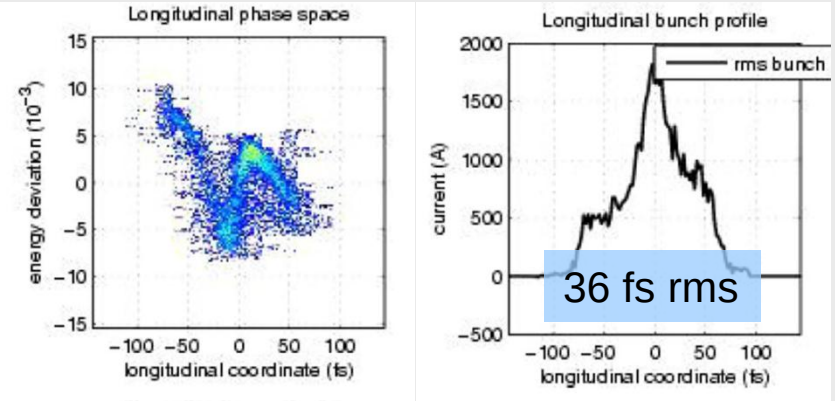




Henrik Loos
loos@slac.stanford.edu

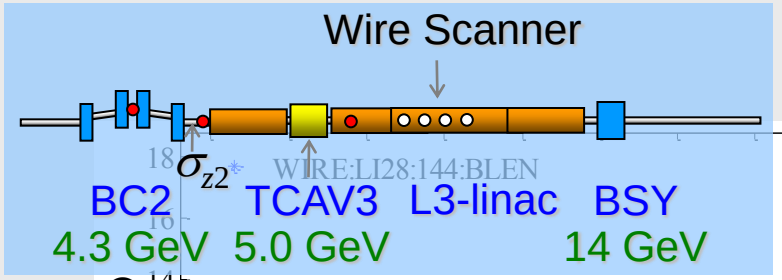
Compressed Bunch Measurements

- FLASH
  - Resolution 20 fs temporal, $1.4 \cdot 10^{-4}$ energy
  - Single bunch kicker
  - Straight ahead screen impeded by COTR
  - Mostly screen in spectrometer used

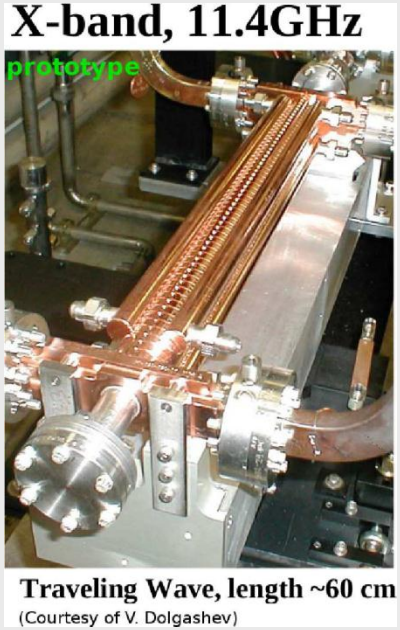


Courtesy C. Behrens

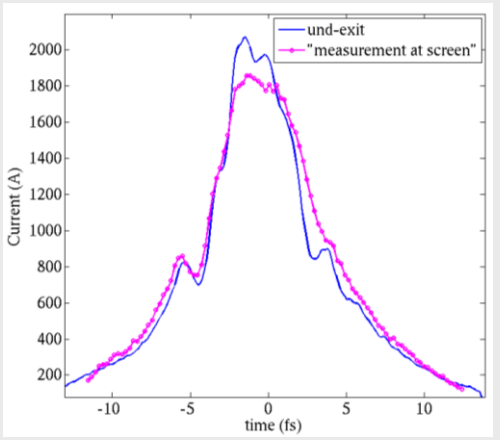
- LCLS
  - Wire scanner instead of OTR
  - Jitter correction imperative
  - Shortest bunches ~10 fs

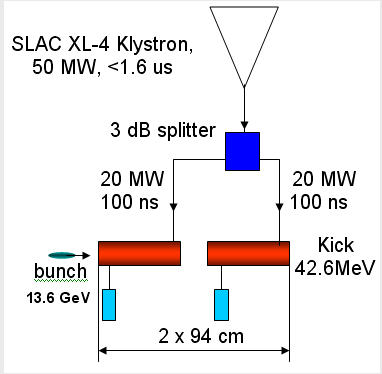


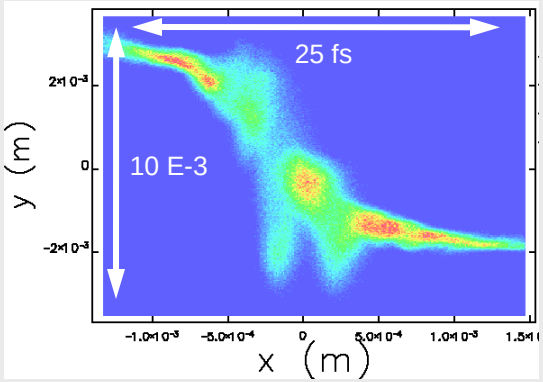
LCLS X-Band Transverse Deflector



- Planned after LCLS undulator
- Compared to S-Band Deflector
  - 4x frequency (11.424 GHz)
  - 2x voltage (43 MV)
  - 8x more kick
- Calibration factor of ~100 feasible
- Longitudinal phase space on main dump screen
- Obtain e-beam current profile
- Get x-ray pulse length from induced energy loss

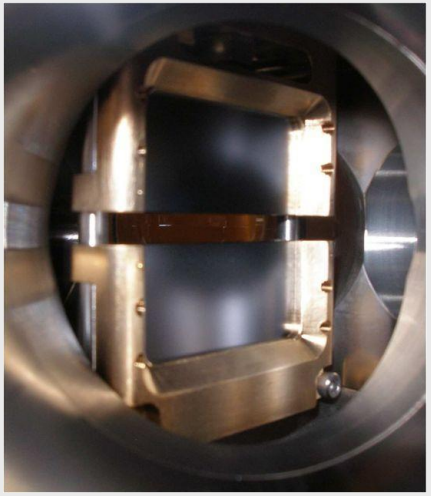


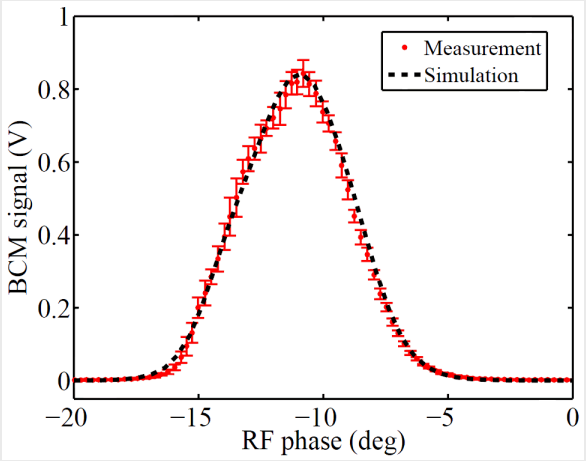


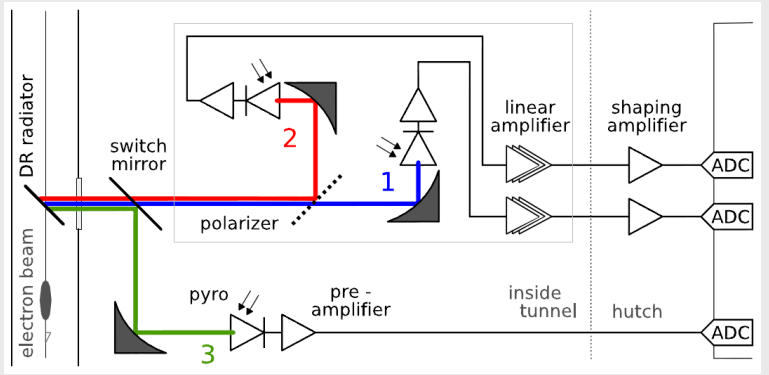


Courtesy Y. Ding

FLASH Bunch Compression Monitor

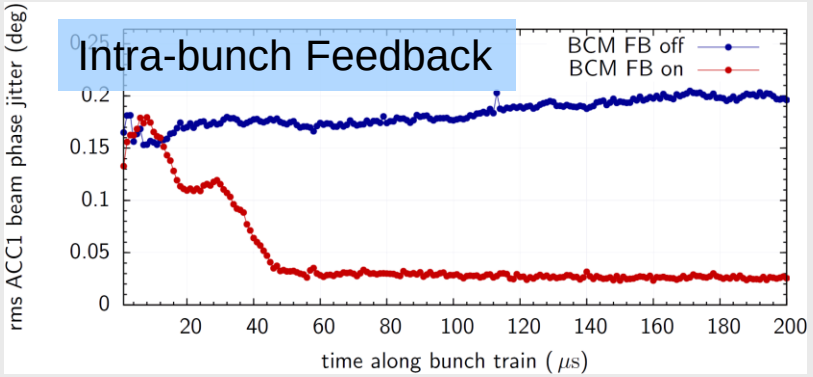






C. Behrens et al., IPAC10, MOPD090

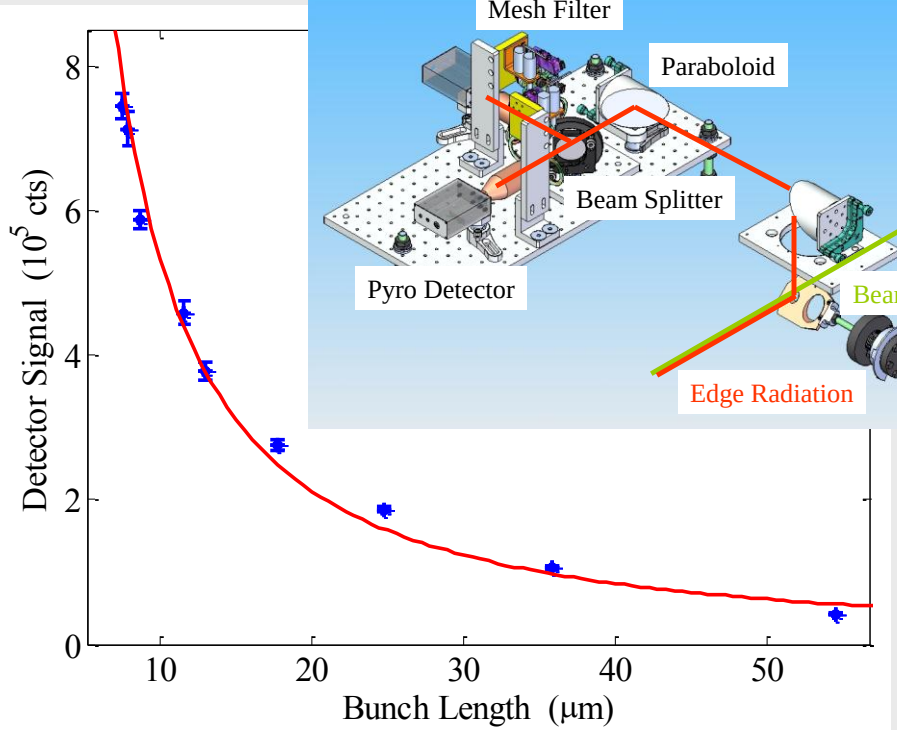
- Coherent diffraction radiation detector
- Radiator is slit metal screen
- Optical radiation transport with GHz to THz bandwidth
- Signal from pyroelectric detector
- Fast detection resolves bunch train
- Slow & fast phase feedback for upstream accelerator structures

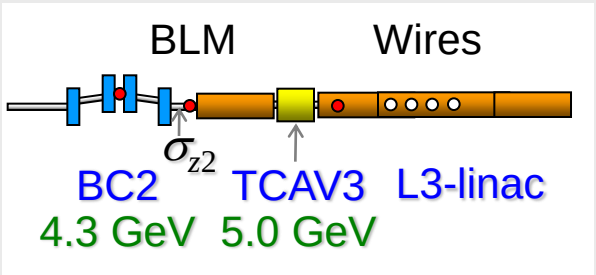


F. Löhl et al., PRL 104 (2010) 144801

LCLS Bunch Length Monitor

- Coherent edge radiation from last chicane bend
- Installed at BC1 & BC2
- BLM provides only signal related to bunch length
- Absolute measurement with transverse deflecting cavity for calibration
- Noise better than 3%



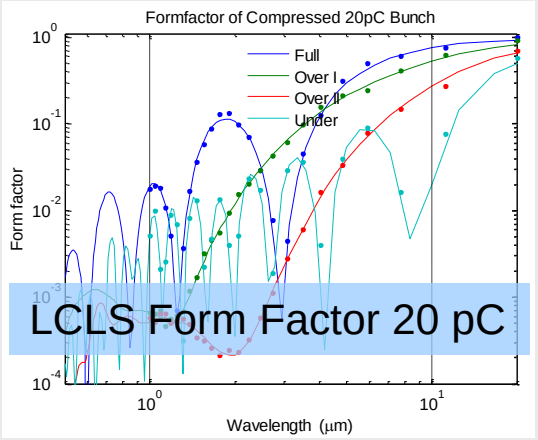


- Empirical fit of signal to $(\sigma_z)^{-4/3}$
- Calculate peak current for 120 Hz fast feedback system
- Regulate upstream linac phases

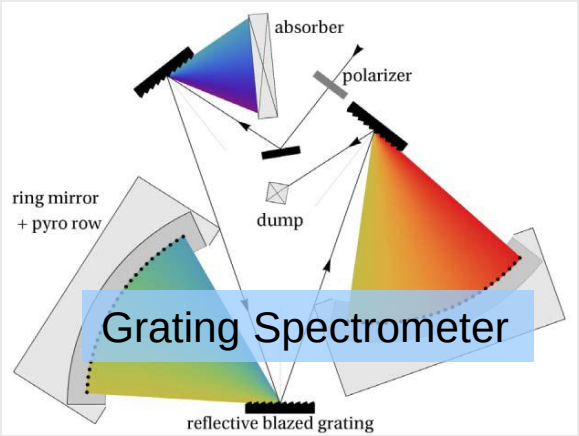
Henrik Loos
loos@slac.stanford.edu

Single Shot Spectrometer

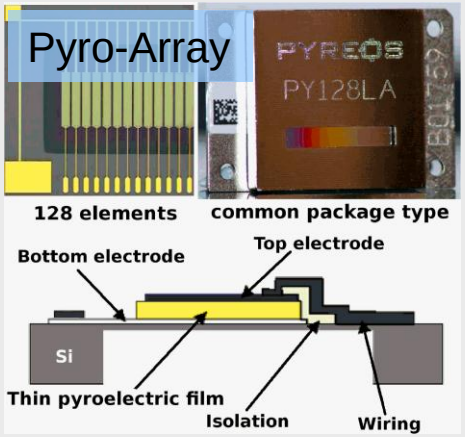
- FLASH grating spectrometer
  - Wavelength range 3 – 65 μm with multiple gratings
  - Bunch features of 15 fs resolved
- LCLS Prism spectrometer
  - From 0.8 – 39 μm with KRS-5 prism
  - Suitable for ≥1 μm bunch length



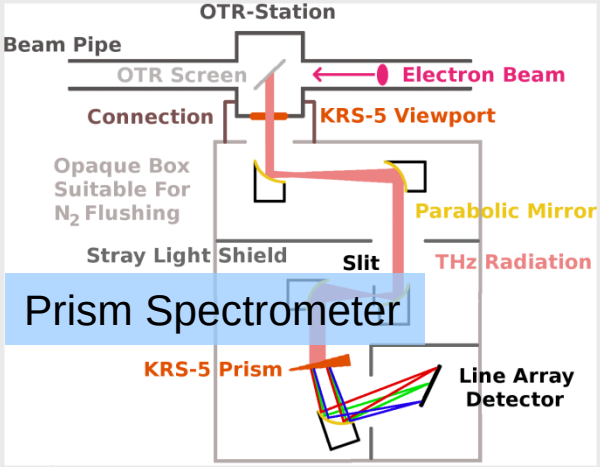
Elegant simulation courtesy Y. Ding



B. Schmidt et al., EPAC08, MOPC029



Pyreos Ltd, Edinburgh, UK

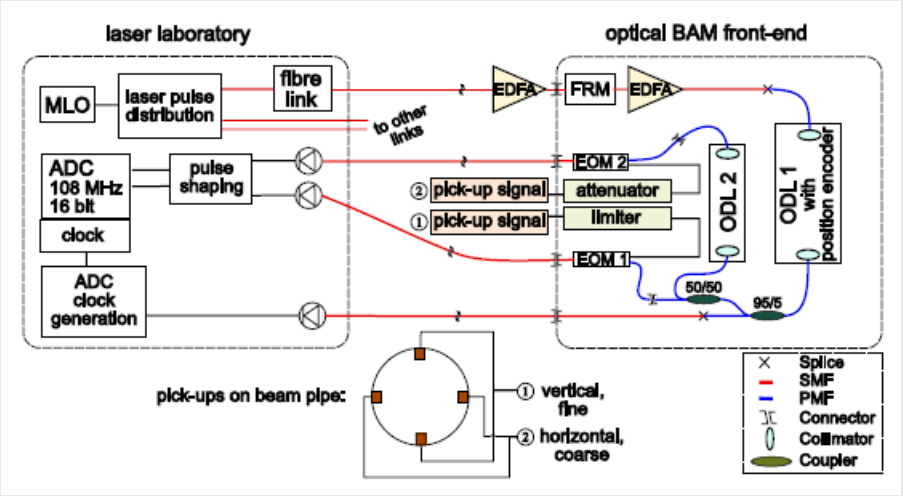


See C. Behrens et al., TUPD38

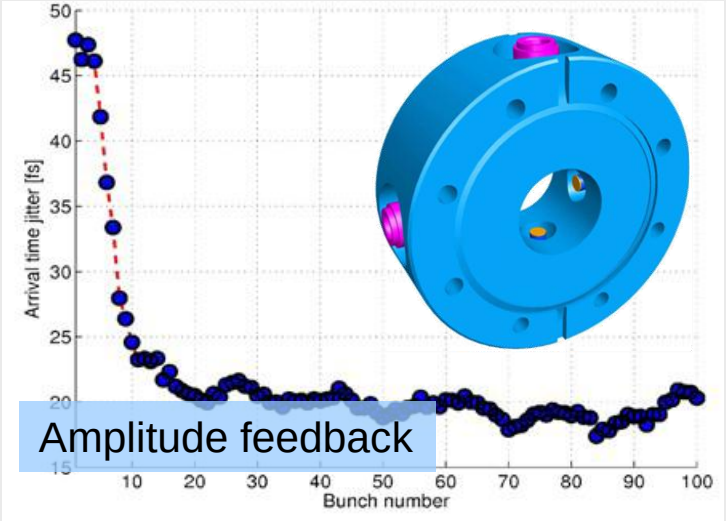
FLASH Beam Arrival Monitor

- Beam signal from 4 button pick-up
- Laser clock with 6 fs stability
- Electro-optic modulator encodes beam signal on laser amplitude
- Fast sampling for intra-bunch train feedback
- 5 BAM installed with 5 fs resolution

- FPGA based controller board
- PID controller for amplitude correction from BAM signal
- Latency of 30 μs due to SC RF



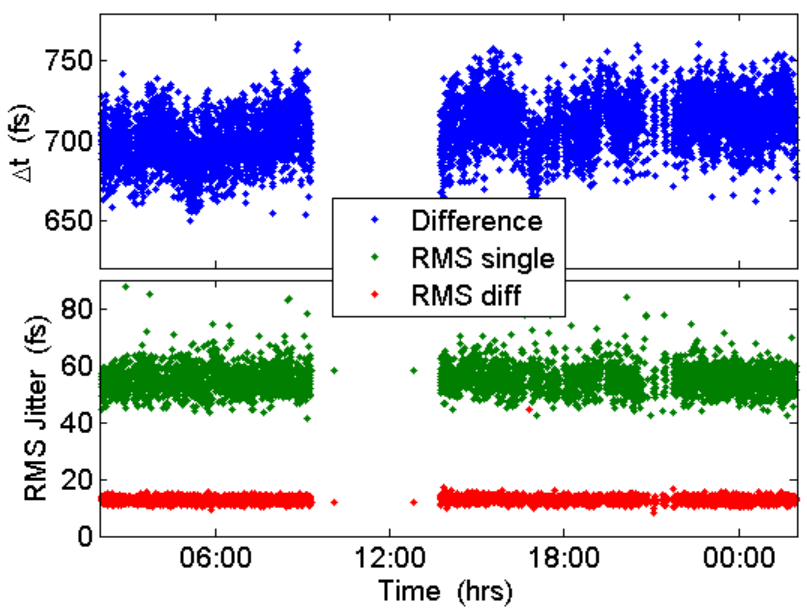
M. Bock et al., FEL09, WEPC66, IPAC10, WEOCMH02

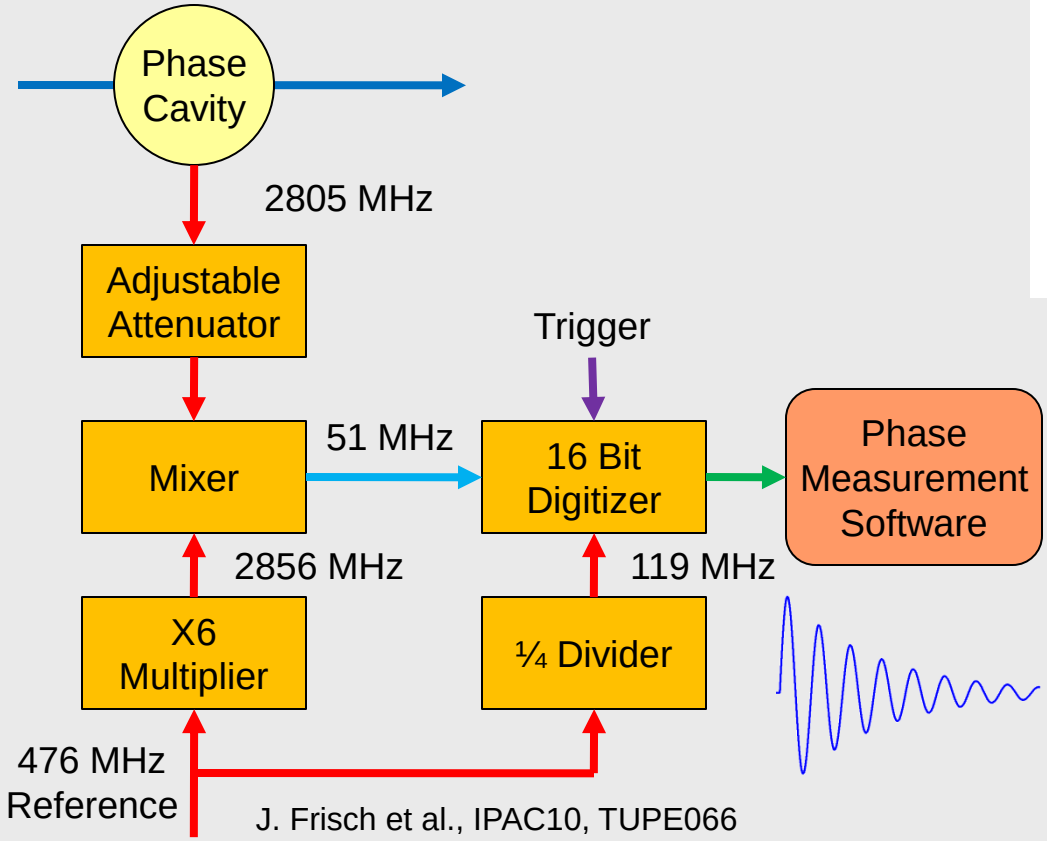


Courtesy C. Behrens

LCLS Phase Cavities

- Monopole mode cavity at 2805 MHz
- Down-mix with S-band 2856 MHz
- Beam jitter measured 50 fs rms
- Jitter between two cavities 15 fs



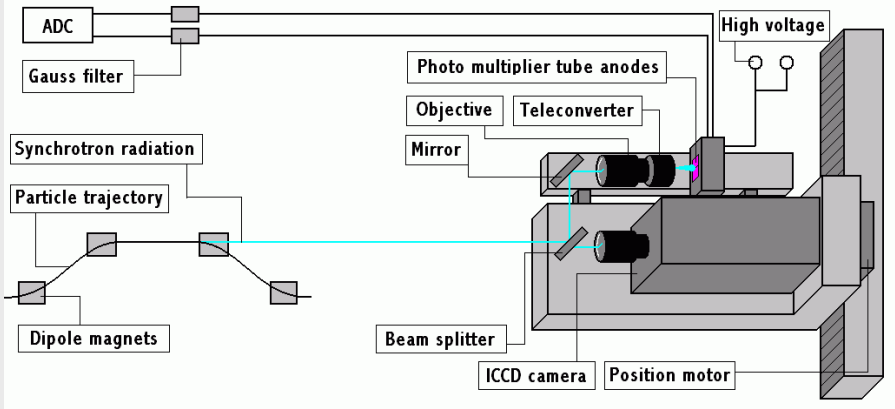


J. Frisch et al., IPAC10, TUPE066

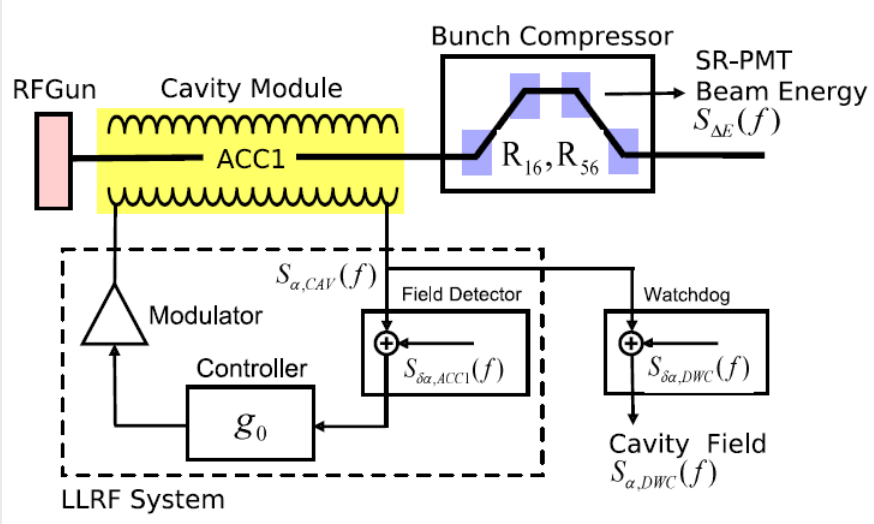
- Timing signals for user experiments
- Offline data analysis
- Synchronize lasers

Henrik Loos
loos@slac.stanford.edu

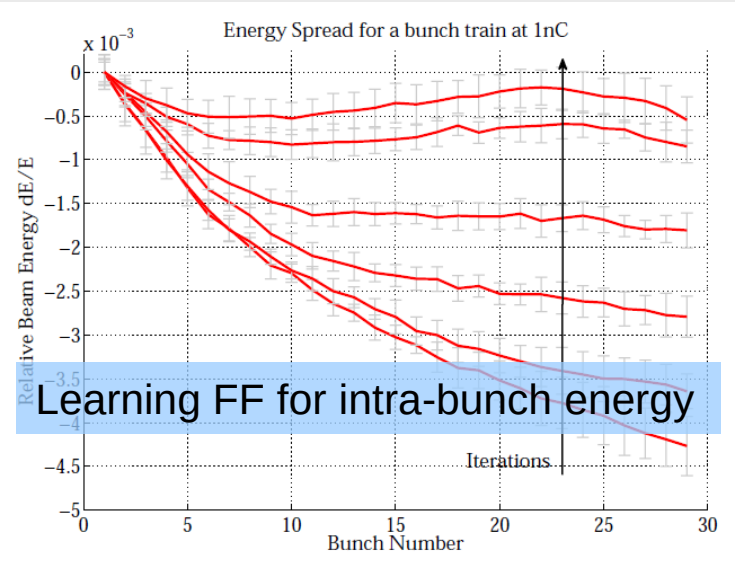
FLASH Synchrotron Radiation Monitor



A. Wilhelm et al., DIPAC09, TUPD43



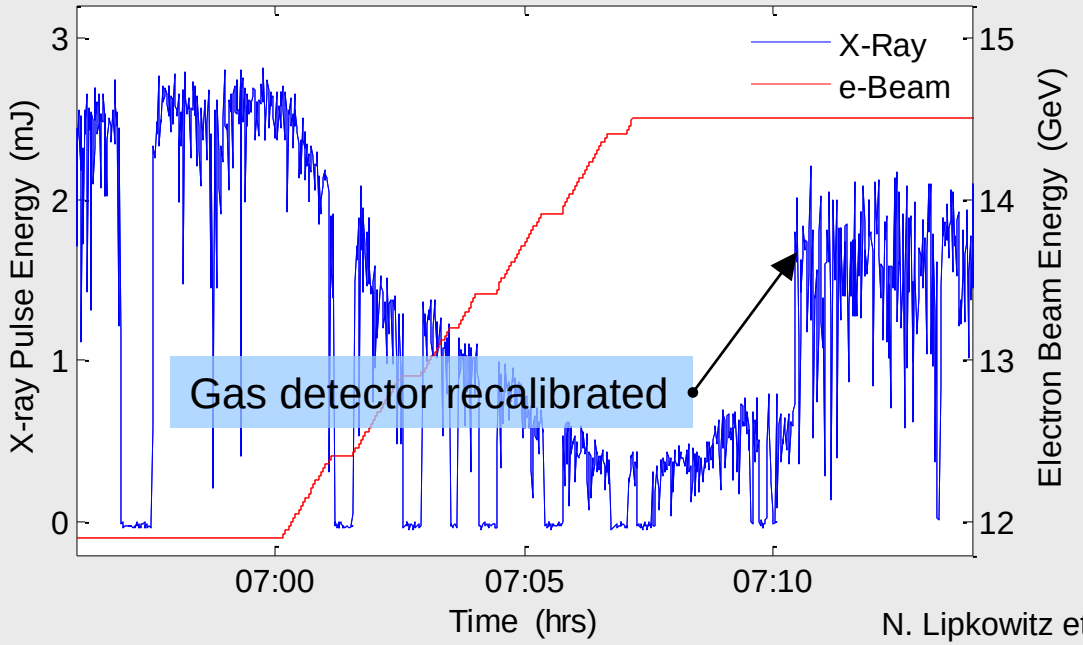
- Energy measurement with < 10^{-4} resolution
- ICCD for energy spread of single bunch
- Multi-anode PMT for centroid of bunch train
- 14-bit ADC at 1 MHz for bunch train resolution
- IBFB with a learning FF algorithm



C. Gerth et al., DIPAC09, TUPD22

Accelerator Configuration Change

- LCLS users request frequent energy changes
- Stable transverse & longitudinal feedbacks
- High level applications to integrate various diagnostics, feedback systems & controls
- Automatic energy change from 12 – 14.5 GeV with only 30% X-ray energy loss



N. Lipkowitz et al., PAC11, WEOBS4

Summary

- Diagnostics meets requirements to adequately measure beam parameters needed for X-FELs
- Reliable diagnostics available for daily operation of machine
- Commissioning tasks require more specialized diagnostics used by experts
- Issue is 2D spatial diagnostics for ultra-bright beams (COTR)
- Challenging task remains to measure <10 fs bunch lengths

Henrik Loos
loos@slac.stanford.edu

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