Longitudinal Diagnostics for Short Electron Beam Bunches

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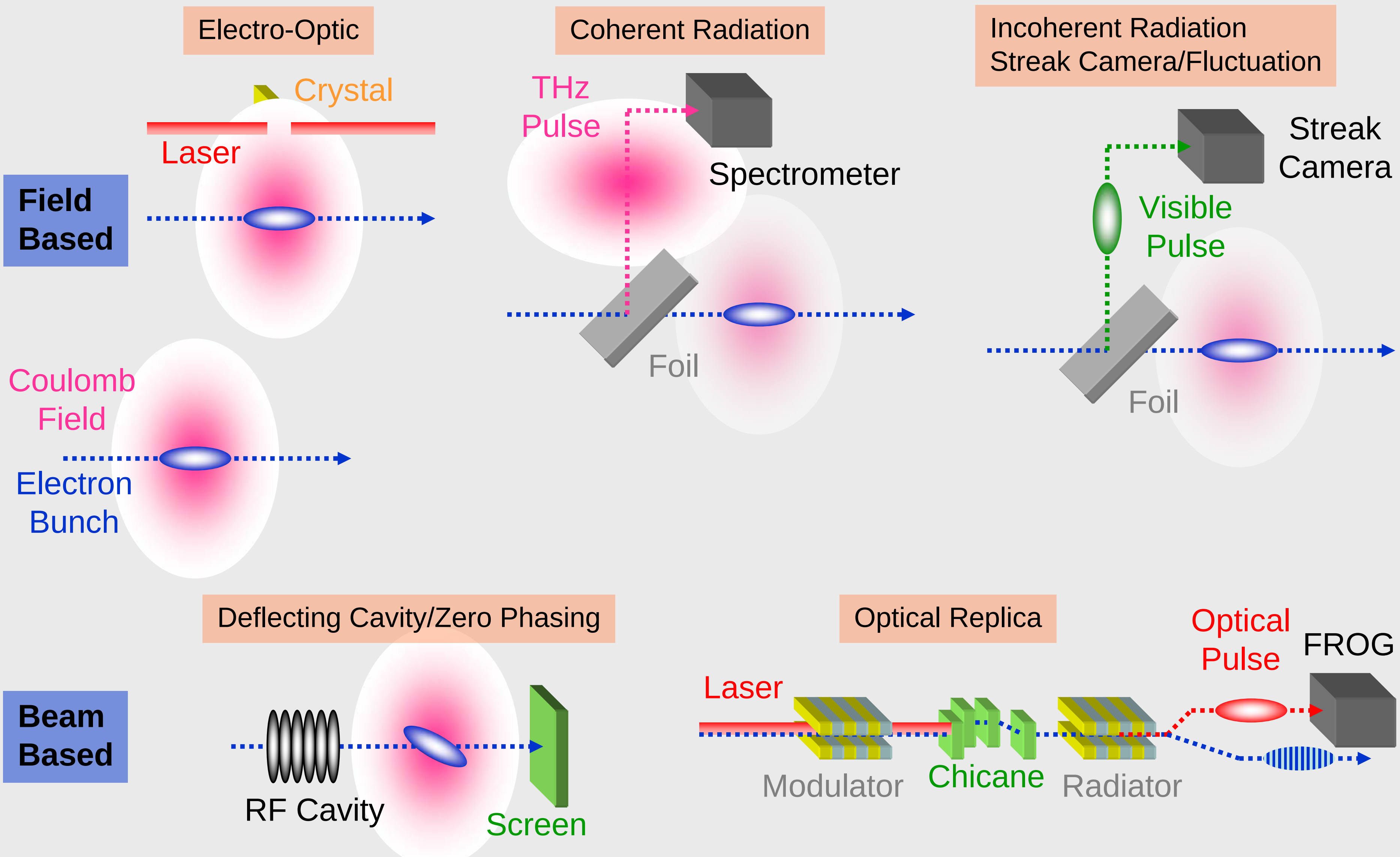
Motivation

- Bunch length diagnostic for X-Ray free electron lasers
- FEL gain scales with charge density
- X-Ray FEL saturation (1 Å) in < 100 m undulator needs kA of peak current at 1 μm norm. emittance
- For bunch charges of 1 nC or less, bunch lengths of sub-100 fs or 10s of μm are required and need diagnostics

	Energy (GeV)	Undulator length	Bunch Charge	Peak Current	Bunch Length
LCLS	13.6	100m	0.25-1nC	3kA	8-20μm
SCSS	6	100m	1nC	3kA	25μm
XFEL	17.5	130m	1nC	5kA	25μm

Bunch Length Measurement Principles



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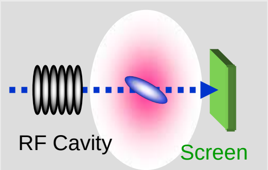
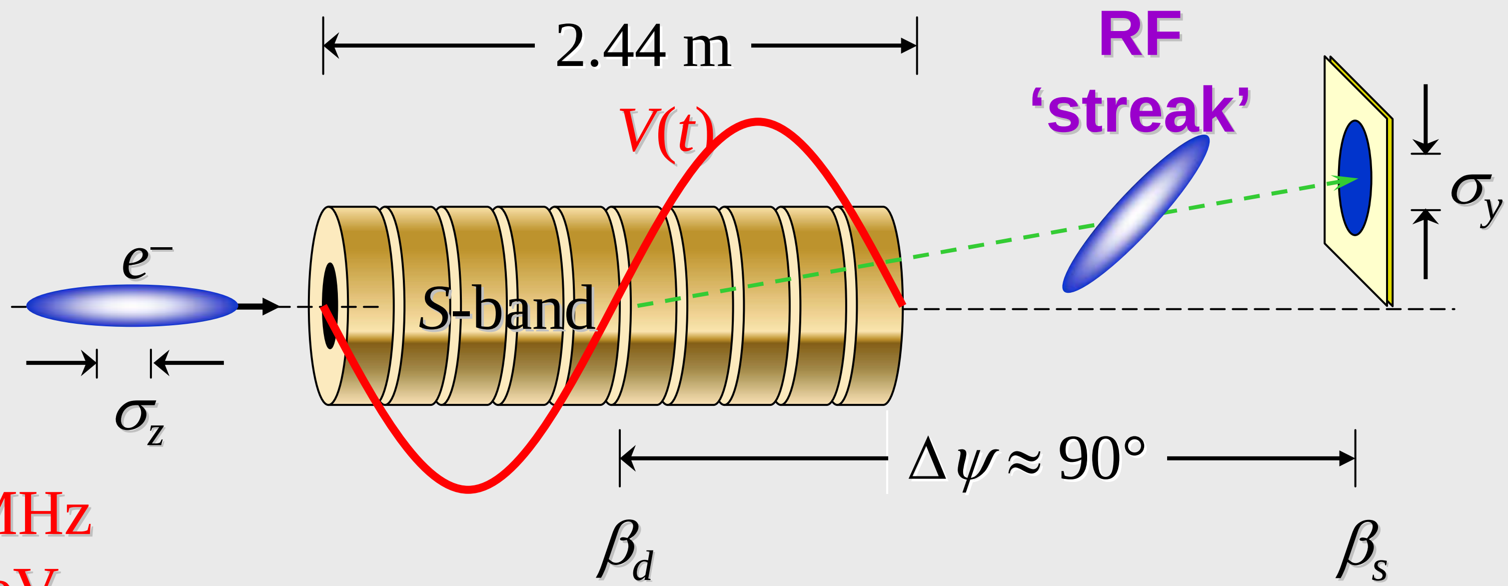
Bunch Length Overview

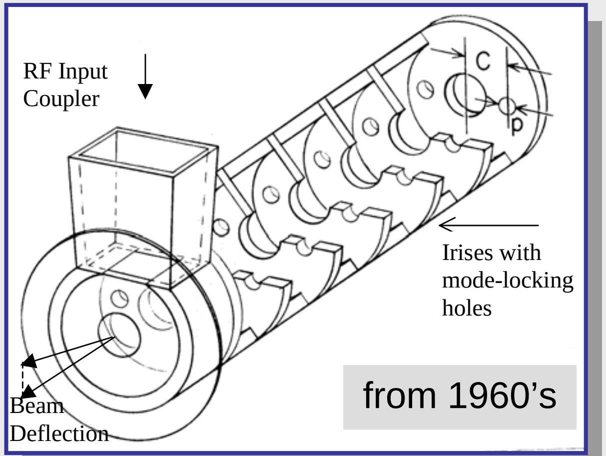
- Field based
  - Direct electro-optic field detection
    - Scanning and single shot methods
  - Coherent radiation generation
    - Transition, synchrotron, edge, diffraction, …
    - Power or spectrum measurement
  - Incoherent radiation
    - Transition, Cherenkov, undulator, synchrotron, …
    - Time based measurement with streak camera
    - Analysis of spectrum fluctuations
- Beam based
  - Phase space manipulation
    - Zero-phase acceleration and spectrometer
    - Transverse deflector cavity
- Beam & field based
  - Optical replica synthesizer
    - Optical phase space modulation
    - Coherent radiation generation

Transverse Deflector Cavity





$V_0 > 20$ MV
$f_{RF} = 2856$ MHz
$E_S = 13.6$ 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

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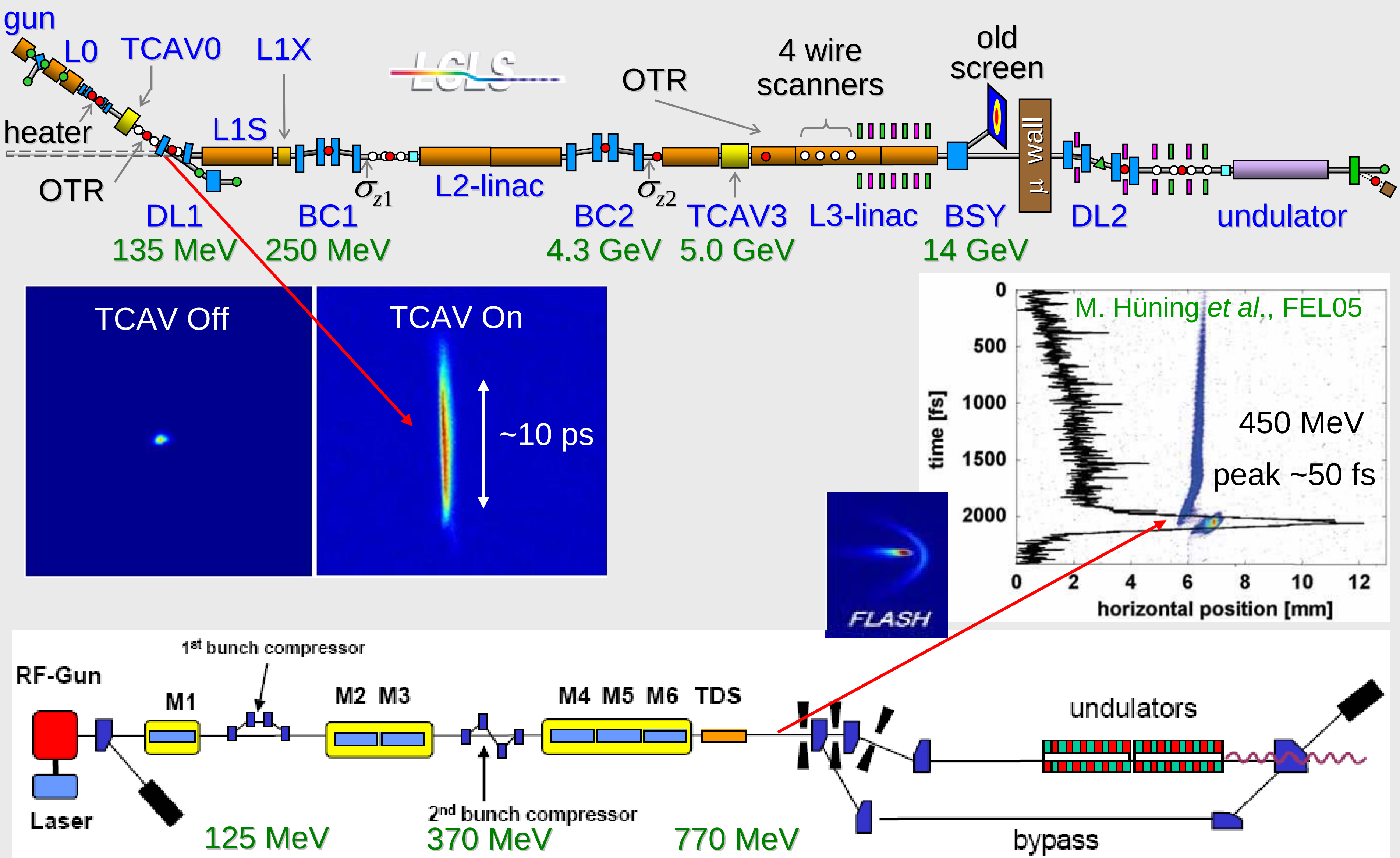
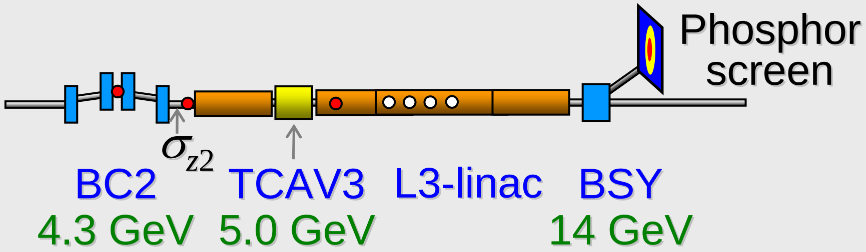
Transverse Deflector Cavity Setup

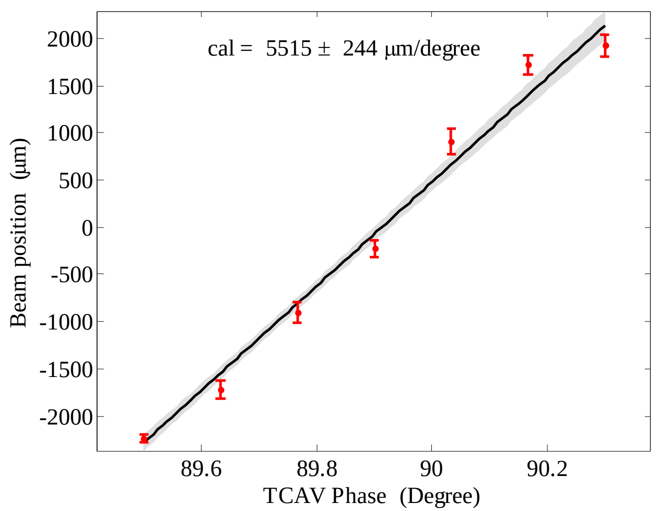


TCAV Measurements at LCLS

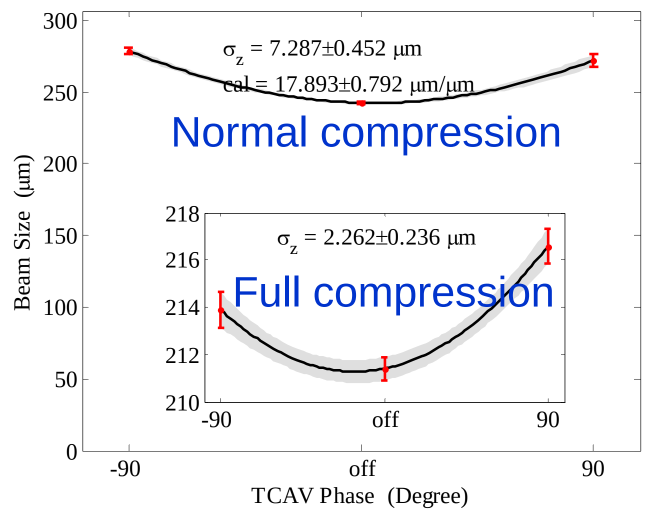


- Calibration by phase scan
- Shortest bunch is only 2% change in beam size
- Limited resolution from phosphor screen, only 1 Hz operation
- Phase jitter at full RF power
- Beam based FB implemented

Calibration



Bunch Length, 250 pC



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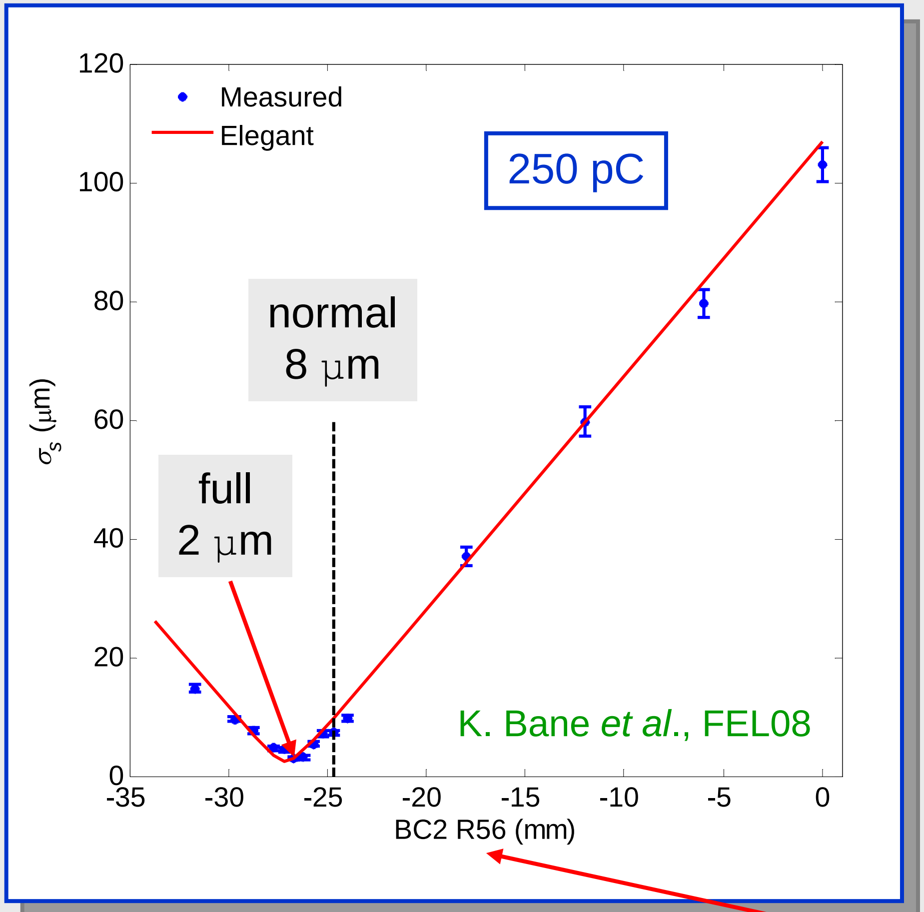
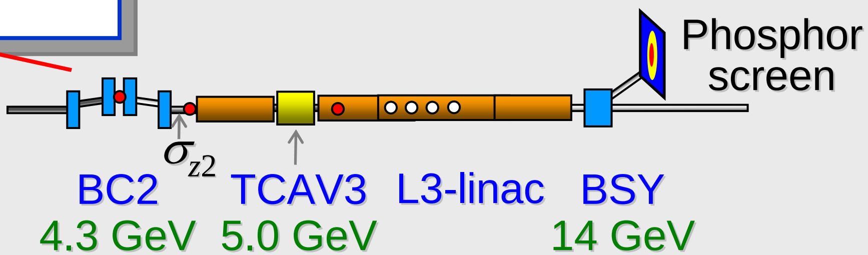
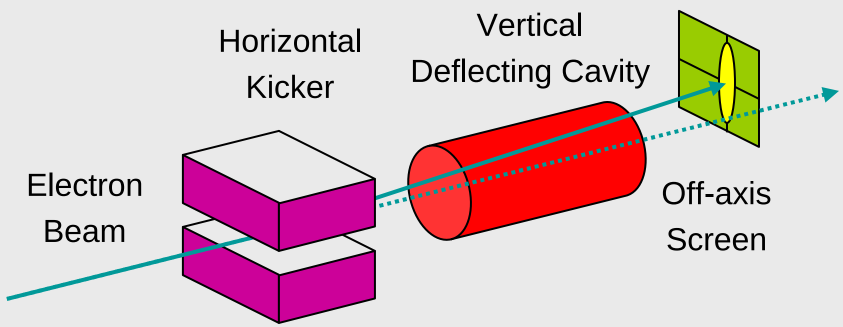
Bunch Length Measurement vs. Simulation



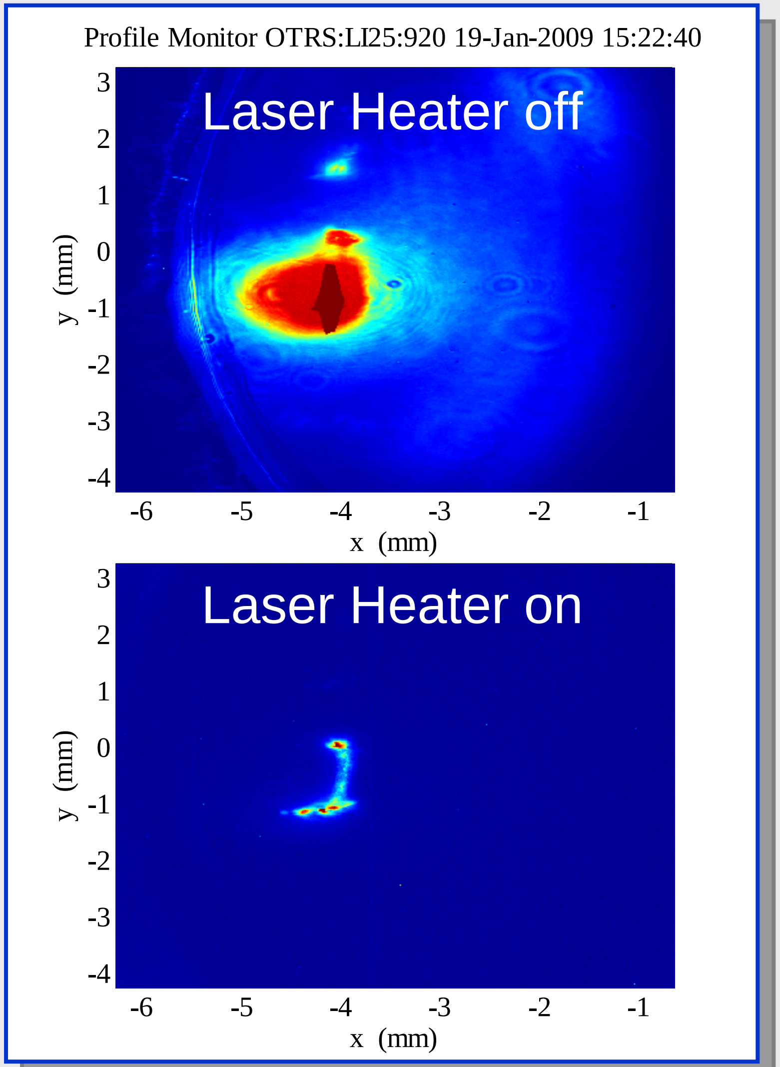
- Scan of BC2 bunch compressor strength
- Bunch length measurement with TCAV agrees well with Elegant simulation
- Shortest bunch of 2 µm supported by simulation



COTR Diagnostics Problem



- Planned pulse stealing mode for TCAV after 2nd BC
- Use horizontal kicker and off-axis OTR screen
- Camera saturated with coherent OTR from micro-bunching instability
- Increased energy spread from laser heater does not mitigate coherent radiation
- OTR diagnostics not usable for ultra-short bunch lengths near visible wavelengths



See Poster WE5RFP041 and talk R. Fiorito

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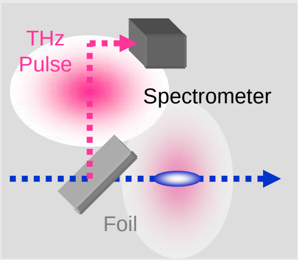
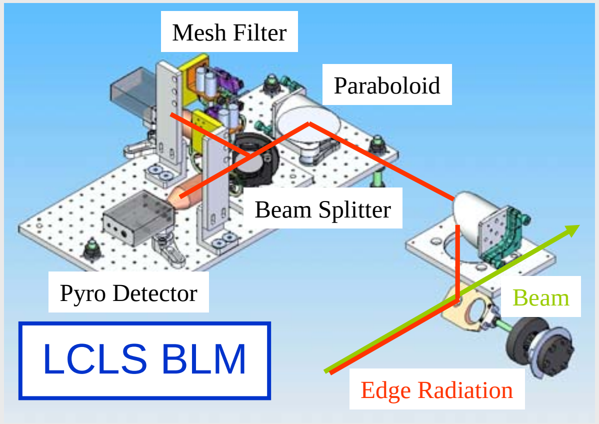
LCLS Transverse Deflector Summary

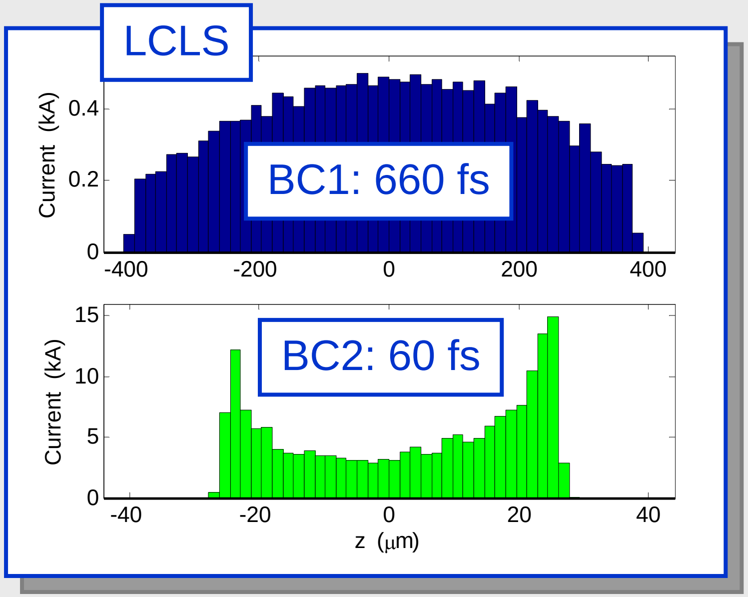
- TCAV at LCLS provides absolute bunch length measurement
- Injector TCAV used for
  - bunch length & slice emittance
  - longitudinal phase space
  - laser heater optimization
- Present TCAV use invasive to operation
  - Parasitic use on off-axis screen spoiled by COTR
  - Need to investigate alternative transverse diagnostics
  - Use of wire scanner with beam-based phase feedback tested
  - Wire scanner not single shot, at high compression profiles fluctuate due to CSR beam break-up
- Time resolution inadequate for shortest bunch operation
  - Implementation of X-band structure studied to improve time resolution

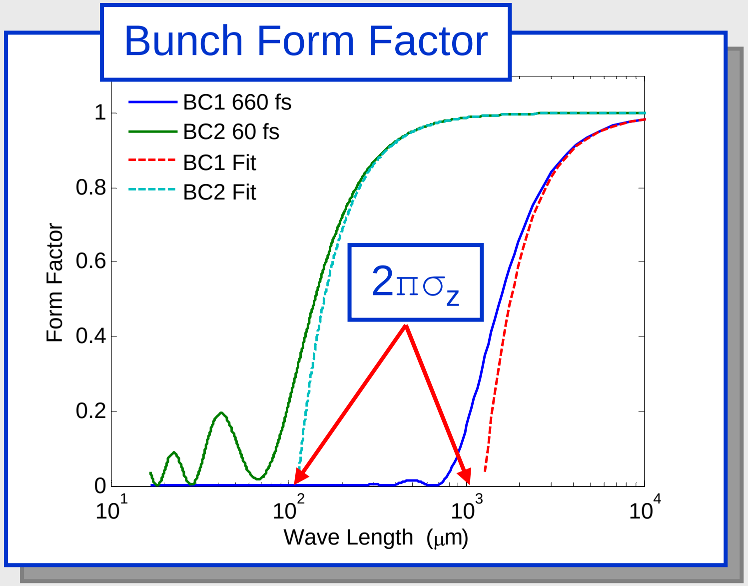
Coherent Radiation Detection





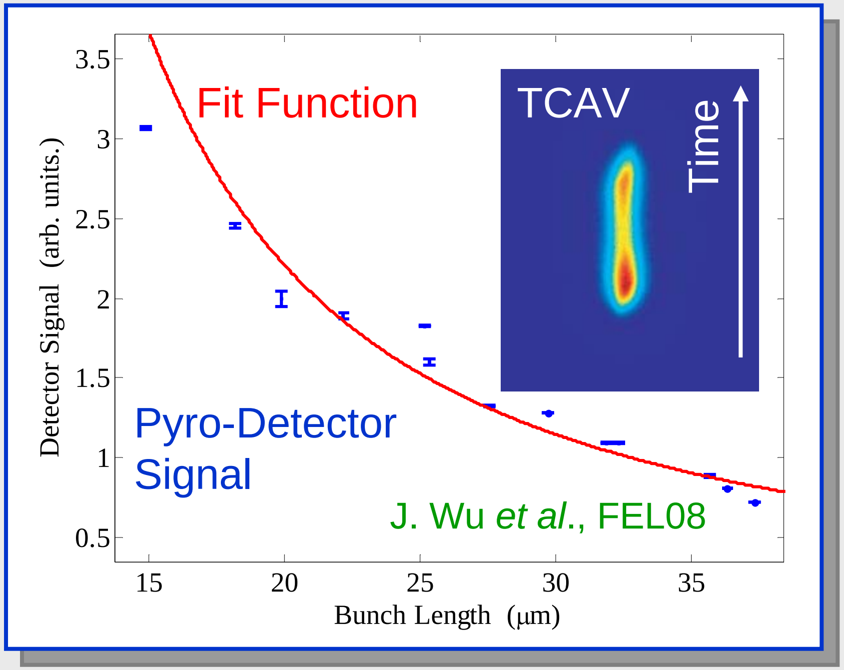
- Beam interaction with beam-line impedance (foil, iris, bend magnet,…)
- Used at many accelerator labs for ps and sub-ps bunch length diagnostics
- Depends on Fourier transform of temporal bunch shape
- Radiation spectrum
  - Low-frequency cut-off from apertures
  - High-frequency cut-off from bunch length
- Bunch length from spectrum $\lambda > 2\pi\sigma_z$

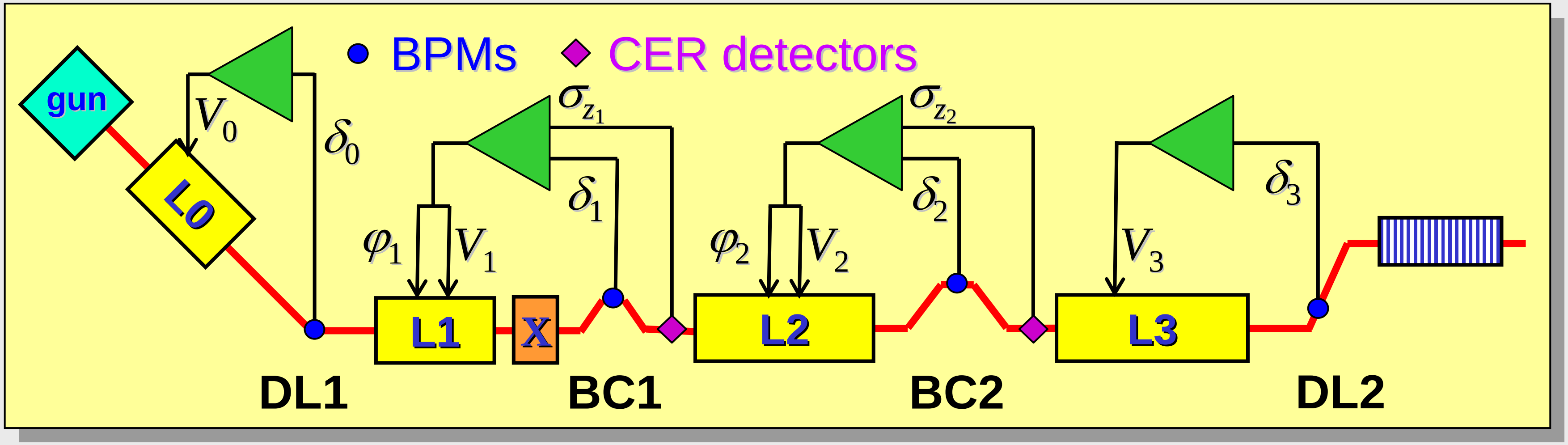




LCLS Relative Bunch Length Monitor

- BC2 Range 1 mm – 20 μm, broad-band pyro-detector & Si-window
- Best stability at BC2 with 100 μm low pass scattering filter
- Removes visible & NIR coherent μ-bunching radiation
- Calibration with TCAV
- Fit of empirical function of peak current to detector signal used for longitudinal feedback





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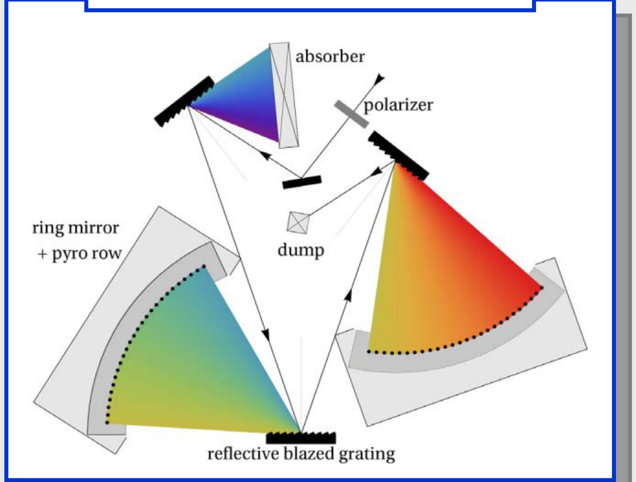
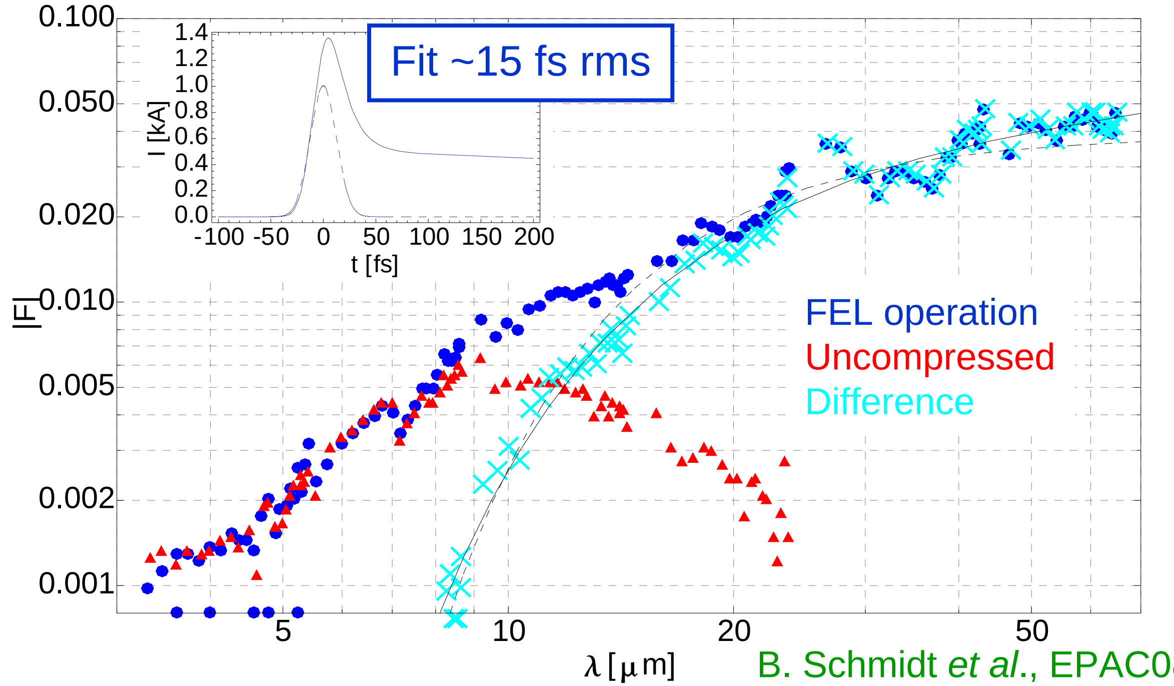
- Single-shot IR grating spectrometer at FLASH
- Wavelength range 3 µm to 65 µm accessible
- CTR transport over 20 m from linac to spectrometer
- NIR micro-bunching enhancement observed
- Form factor consistent with 15 fs bunch spike

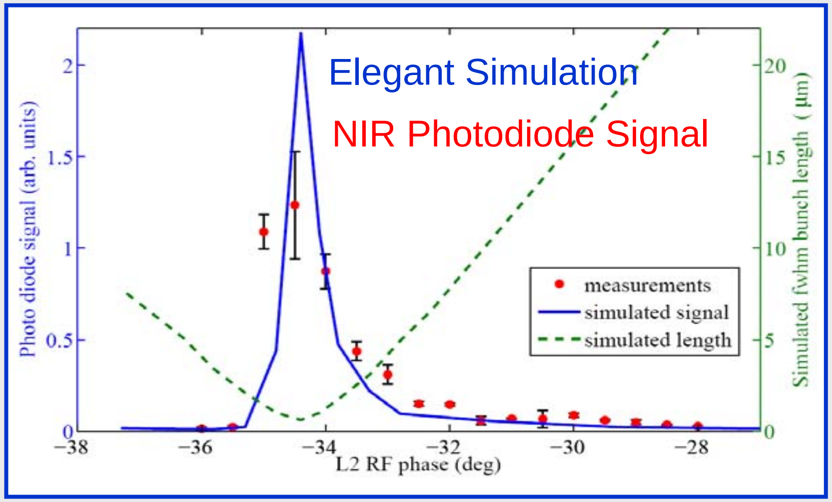
FLASH Spectrometer



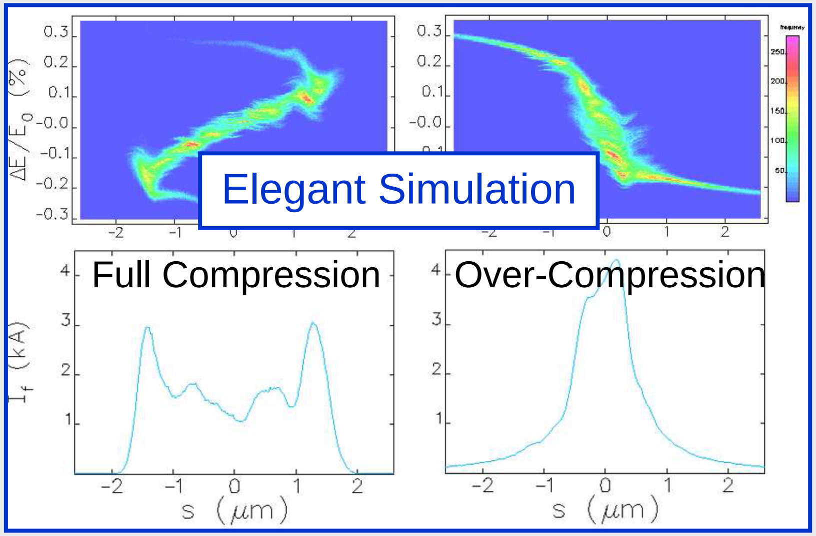


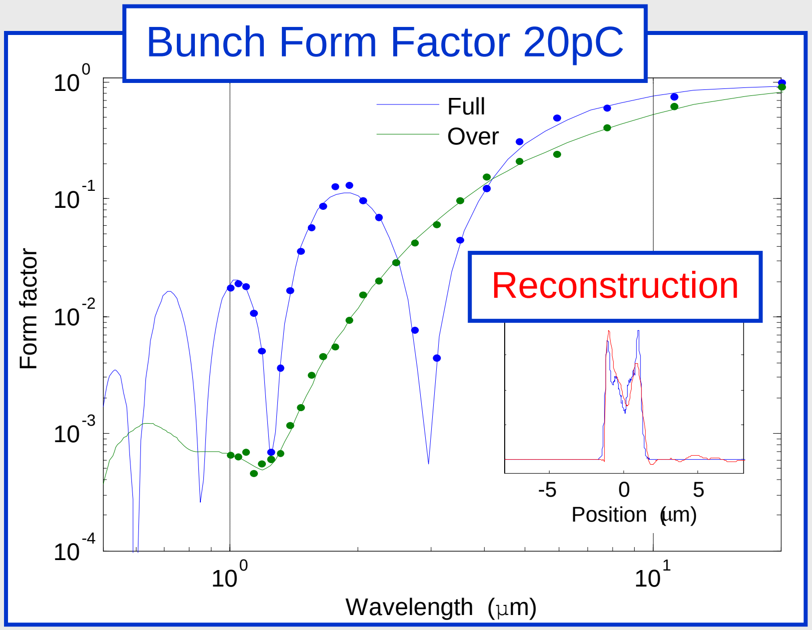
B. Schmidt *et al*., EPAC08

Ultra-Short Bunch Length Operation



See Poster WE5RFP040





- LCLS 20pC, 1μm bunch length?
- Only NIR photodiode signal
- NIR single-shot spectrum measurement needed
- Bunch shape reconstruction possible with 20 channel spectrum from 1-20 μm

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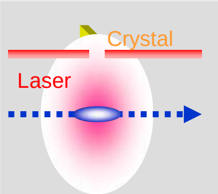
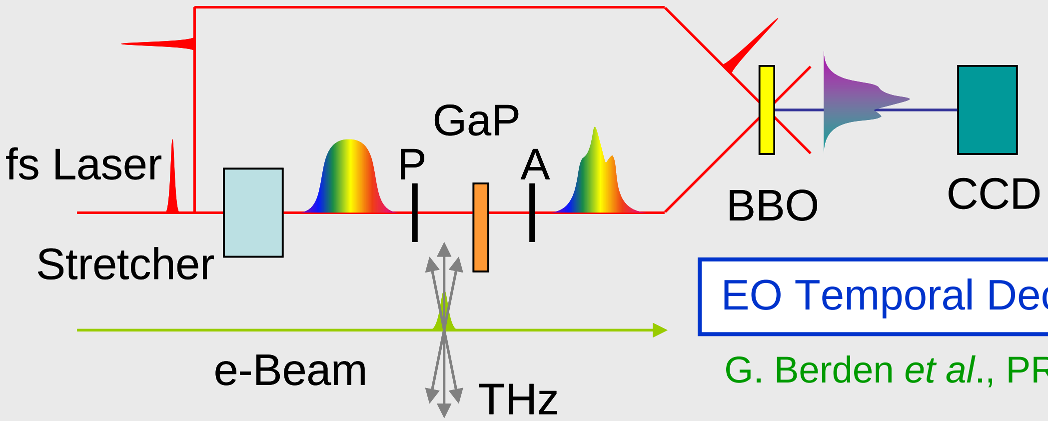
Coherent Radiation Summary

- Simple to implement as relative bunch length monitor
- Non-intercepting radiation sources available
  - Synchrotron, edge, diffraction radiation
- For absolute bunch length and shape measurement
  - precise knowledge of emission spectrum, transfer line and detector efficiency required
  - Calibration feasible from independent absolute measurement
  - Single-shot measurement needs multi-channel spectrometer with spectral range factor 10 or more in wavelength
- Single-shot device in use at FLASH and implementation at LCLS being studied

Electro-Optic Techniques



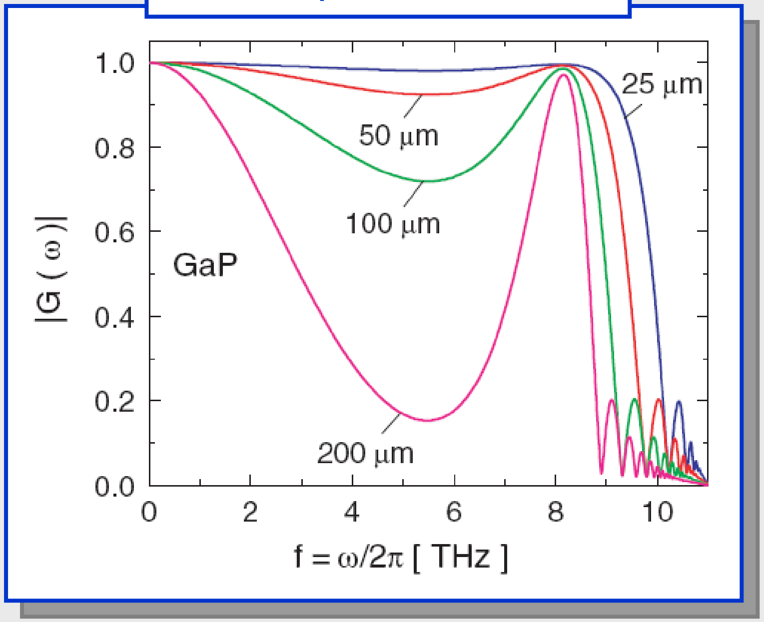


EO Temporal Decoding

G. Berden *et al*., PRL **93**, 114802 (2004)

- Transient birefringence in EO crystal induced by Coulomb field of beam
- Probe with laser beam and polarizer
- Scanning, spectral & spatial decoding
- Temporal decoding: retrieve temporal shape with SHG
- Requires amplified fs laser synchronized to RF
- Time resolution limited by phonon resonance in EO crystal, highest in GaP at 11 THz

EO Response Function



S. Casalbuoni *et al*., PRSTAB **11**, 072802 (2008)

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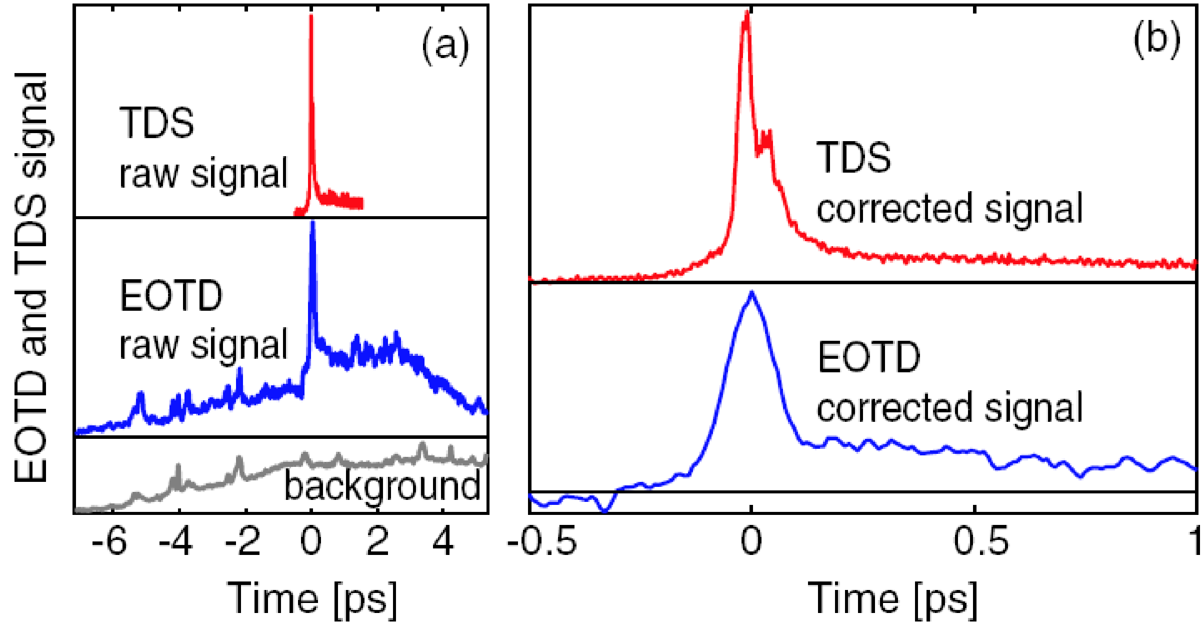
Electro-Optic Temporal Decoding

- EOTD and Deflector installed at FLASH
- Signals from same pulse train

Benchmark with Deflector Cavity



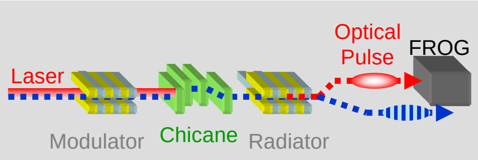
G. Berden *et al*., PRL **99**, 164801 (2007)

- TDS signal of 40 fs broadens to 60 fs in EOTD
- Good agreement between measured EOTD signals and simulation using bunch shape from deflector cavity
- Physics of detector response well understood

EO Detection Summary

- Non-interceptive single-shot absolute bunch length diagnostics
- Can be located anywhere in accelerator
- Needs transport of synchronized fs laser system to beam line
- Application to ultra-short bunches limited by available EO materials
- Simplified in future with fiber-laser based EO detection
- Shorter time scales may be accessible with new organic materials

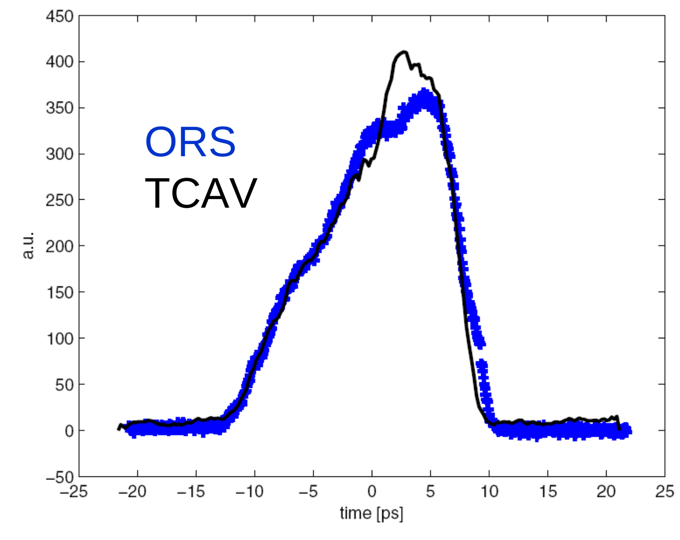
Optical Replica Synthesizer



E. Saldin *et al*., NIMA **539**, 499 (2005)

- Energy modulation with laser in first undulator
- Convert to density modulation in chicane
- Generate coherent light pulse at laser wavelength in second undulator
- Maps 3D electron beam distribution onto optical pulse
- Single shot laser temporal diagnostics, FROG, determines time resolution
- Principle demonstrated at FLASH for ps time scale
- Bunch form factor at laser wavelength to be incoherent

Benchmark with Deflector Cavity



G. Angelova *et al*., PRSTAB **11**, 070702 (2008)

Summary

- Matured bunch length diagnostics available for lengths > 20 fs
- Deflector cavities successfully implemented at LCLS & FLASH and provide absolute length
- Coherent radiation diagnostics at many accelerator labs
- Single-shot techniques for ultra-short fs long bunches need development
- Fluctuation analysis of x-ray spectra considered
- New materials (organic) for EO-method investigated

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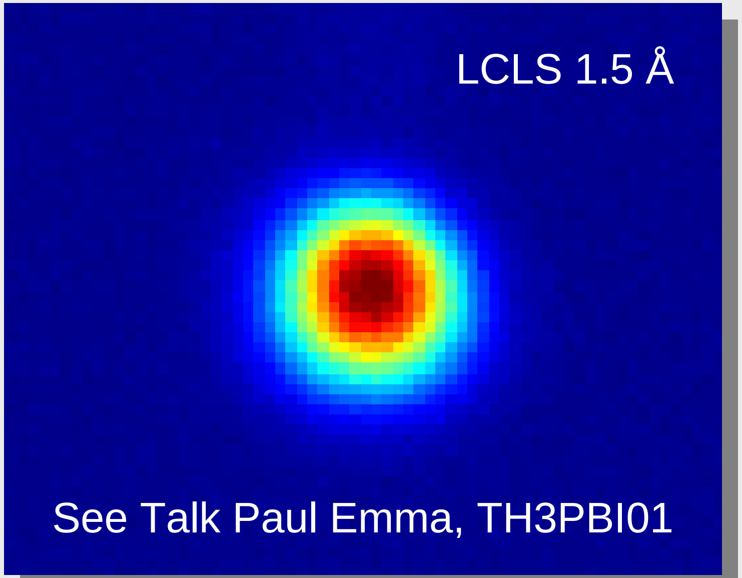
Thanks to the entire
LCLS Commissioning Team
for their many contributions!



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