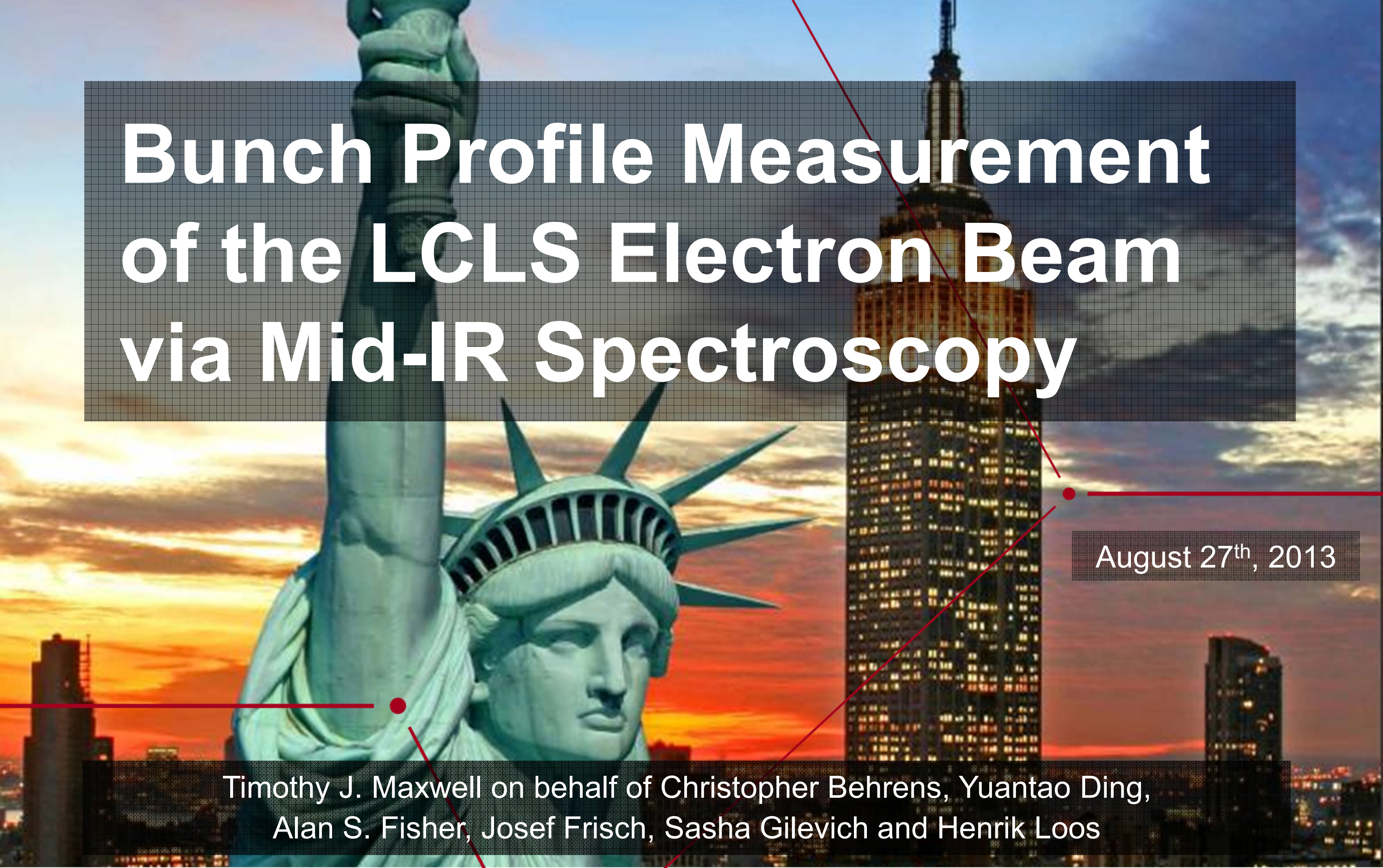


Bunch Profile Measurement of the LCLS Electron Beam via Mid-IR Spectroscopy

August 27th, 2013

Timothy J. Maxwell on behalf of Christopher Behrens, Yuantao Ding, Alan S. Fisher, Josef Frisch, Sasha Gilevich and Henrik Loos

U.S. DEPARTMENT OF ENERGY
Office of Science

FEL 2013
TUOANO03

SLAC NATIONAL ACCELERATOR LABORATORY

Outline

Coherent Beam Radiation Spectroscopy @ LCLS

- Background and requirements for an x-ray FEL linac bunch length monitor

Instrument Analysis

- The Middle-IR (MIR) Prism Spectrometer
- Design and key components
- Wavelength and transfer function calibration

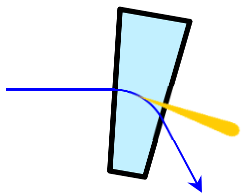
Signal Analysis

- Profile reconstruction (Spectral phase retrieval)
- *Measurements at LCLS*

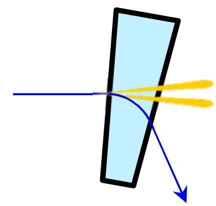
Summary

Coherent Beam Radiation Spectroscopy @ LCLS

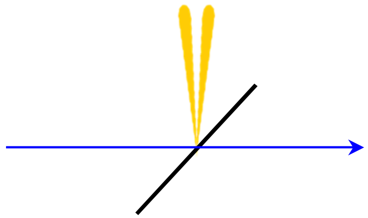
- Common sources of Coherent beam Radiation (CxR):



Synchrotron (CSR)



Edge (CER)



Transition (CTR)

- For $\lambda \gtrsim \sigma_z$ and $\sigma_r << \gamma\lambda/2\pi$ (CER and CTR), far field radiation longitudinally coherent
- First approx, spectrum $\propto$ FT^2 of current profile $\rho(z)$:

$$I(\vec{r}_\perp, k) = N_e^2\, I_e(\vec{r}_\perp, k) \left| \int \rho(z)\, e^{ikz}\, dz \right|^2$$

- CxR spectrometer → bunch length monitor

Coherent Beam Radiation Spectroscopy @ LCLS

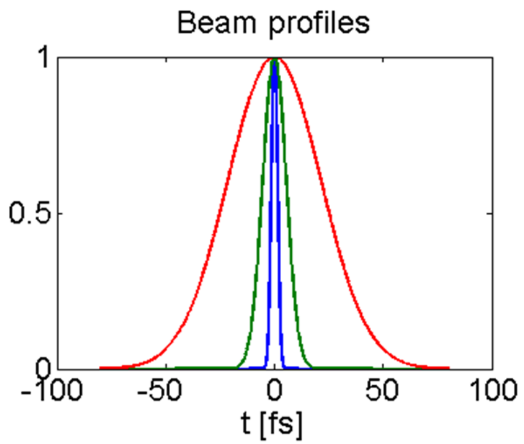
Spectra Fourier-related to bunch profile:

- Req'd λ range prop. to bunch duration range: $\lambda \propto c\Delta t$

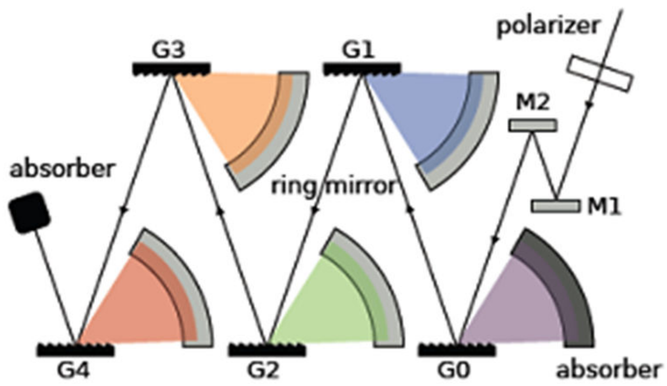
For LCLS: $Q =<$ 20 – 150 pC

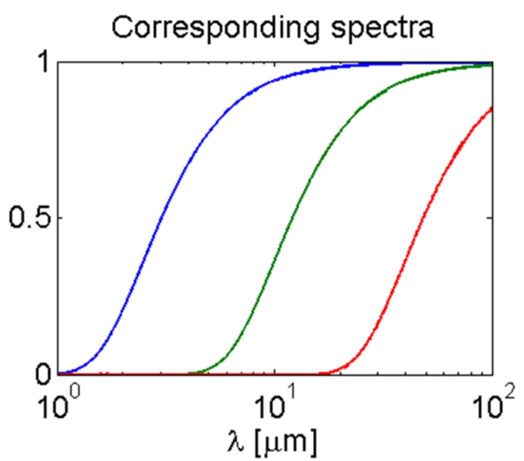
$\Delta t =<$ 3 – 50 fs

→ $\lambda \approx<$ 1 – 40 µm (mid-IR)



Excellent large BW, 1-shot, MIR *grating* spectro. at DESY:



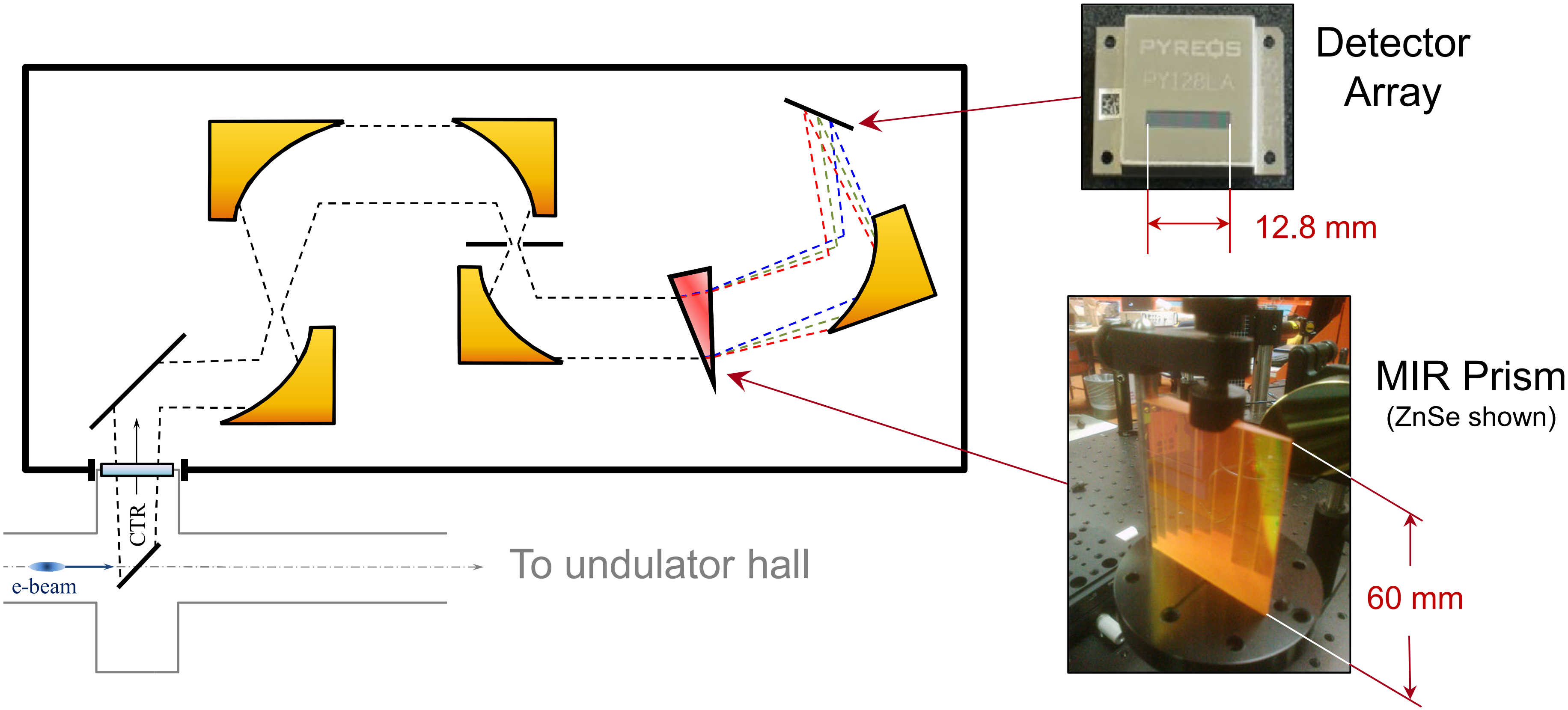


Our alternative solution:

MIR *prism* spectrometer for more robust, compact design

Wesch, *et al.*, Nucl. Instrum. Meth. A **665**, 40 (2011).

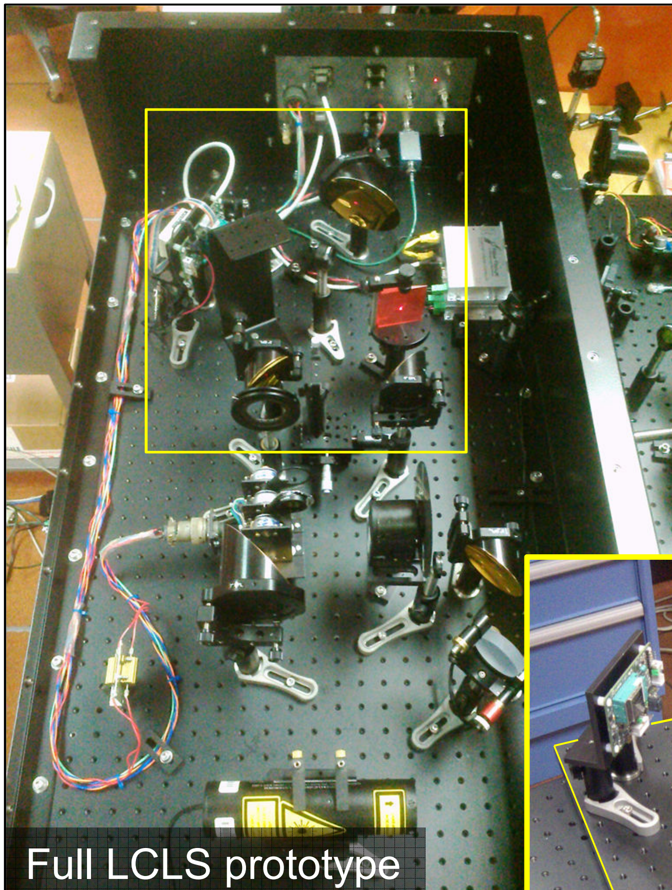
Instrument Analysis



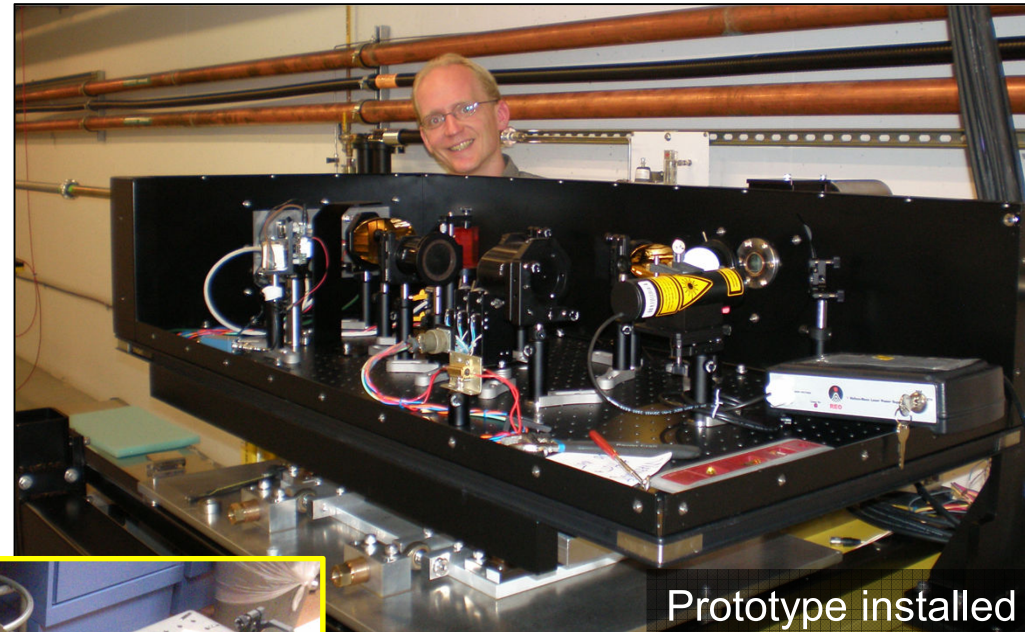
- Prism: 10º apex, KRS-5 (T = 0.6 – 40 μm) or ZnSe (T = 0.5 – 20 μm)
- Detector: Linear PZT pyroelectric array, 100 μm pitch
- Geometry: Design for 1-pix monochrom. illum. & 128-pix illum. w/ full BW

Further design details: *Int'l Beam Instrum. Conf. 2012*, Tsukuba, Japan, TUPA47

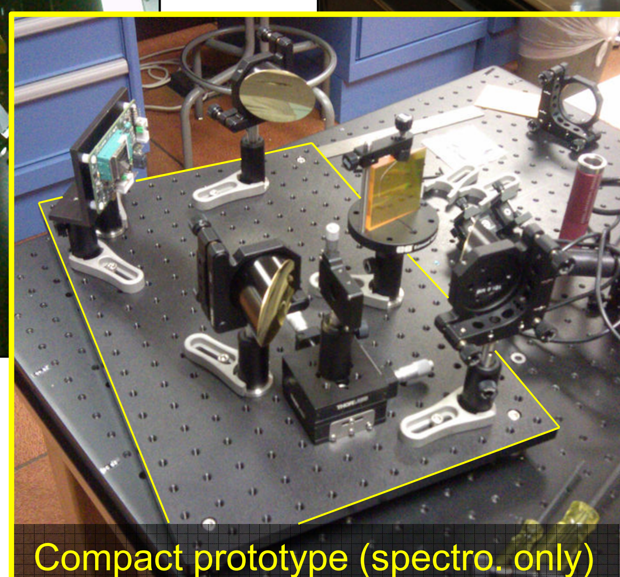
Instrument Analysis



Full LCLS prototype



Prototype installed



Compact prototype (spectro. only)

Compact unit:
300 mm x 450 mm

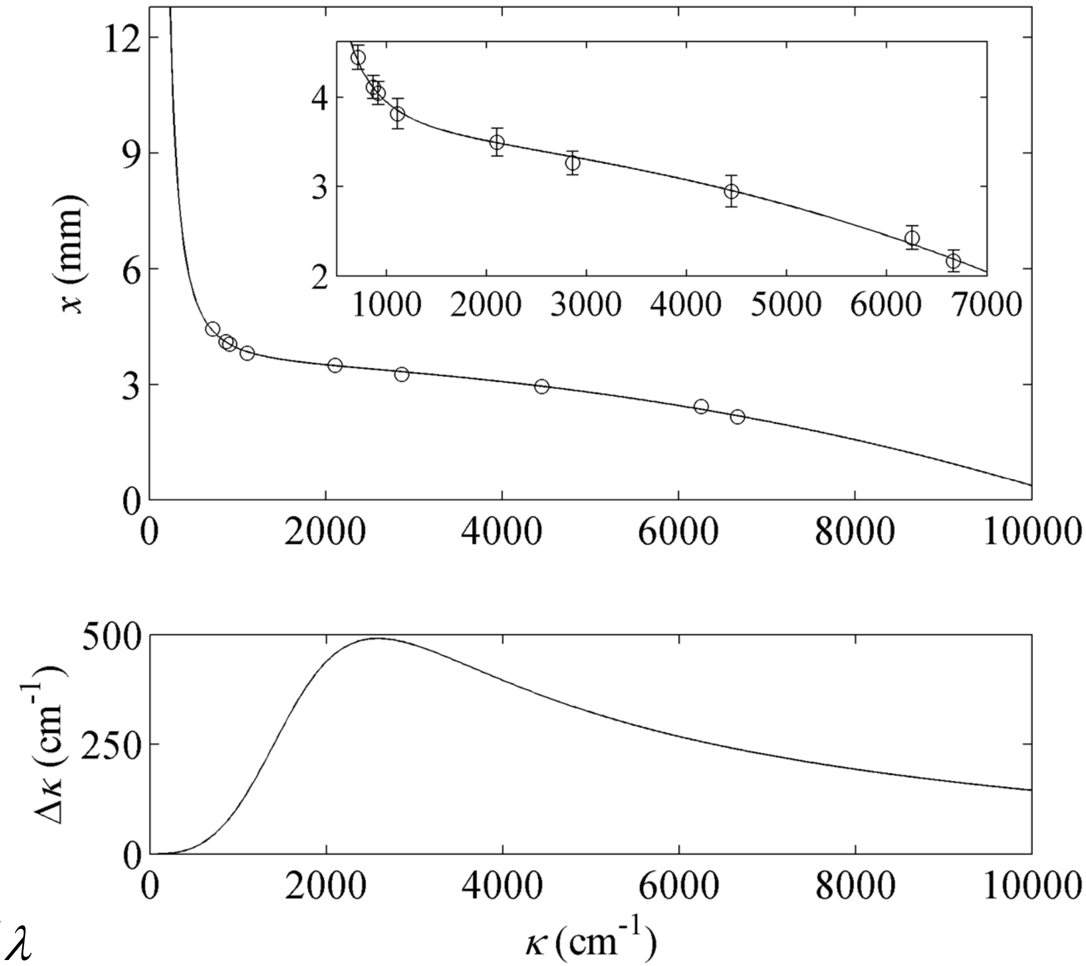
Practical Extras:

- Dried air enclosure (< 0.2% RH)
- Reverse-injected align. laser
- Remotely inserted MIR ND filters

Instrument Analysis

Dispersion $x(\kappa)$ characterization

- BB radiator + MIR BPFs
- Fit curve to nonlinear KRS-5 refractive index over broad bandwidth



- Spectral resolution est. by diff. limited spot size Δx and disp.

$$\Delta\kappa \approx \left(dx/d\kappa\right)^{-1}\Delta x$$

- Resolving power R = 5 - 40

Note spatial frequency $\kappa = k/2\pi = 1/\lambda$ *(MIR/Raman spectroscopy convention)*

Instrument Analysis

Amplitude Response $T(\kappa)$

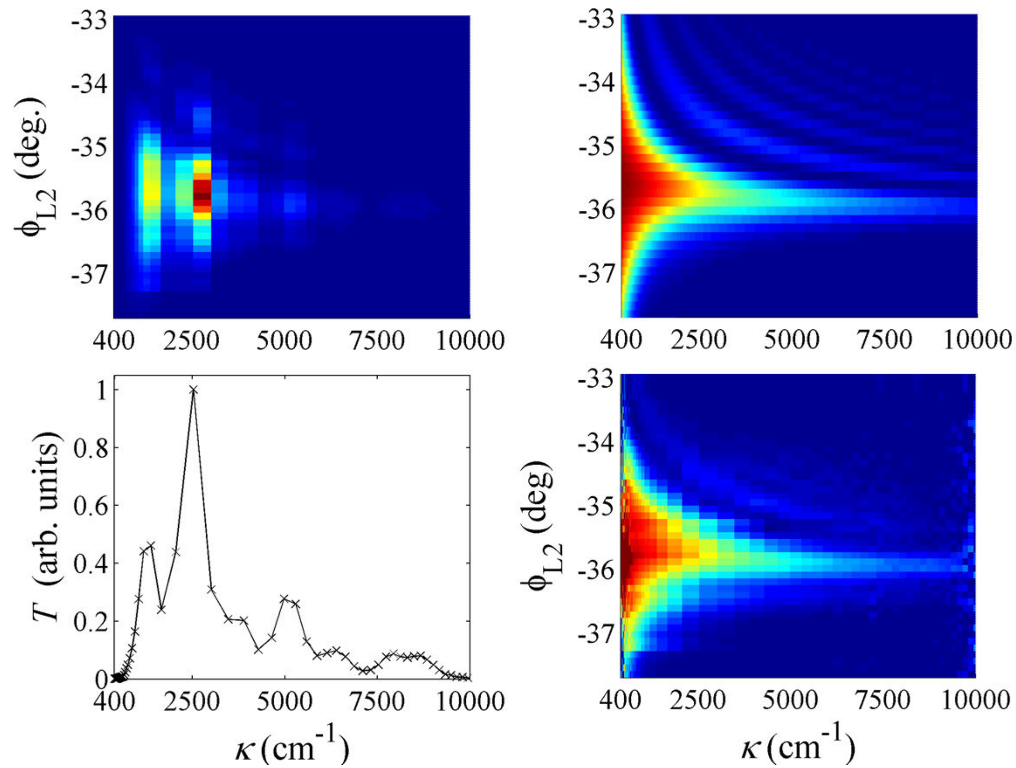
$$I[x(\kappa)] \approx \left[\frac{d\kappa}{dx}\right] T_{\text{det}}(\kappa) T_{\text{abs}}(\kappa) I_e(\kappa) |f(\kappa)|^2$$
$$= T(\kappa)|f(\kappa)|^2$$

1. Recon. $T(\kappa)$ by varying κ-independent param (φ_{L2})
2. Compare to *LiTrack* simulated φ_{L2} scans

$$I(\kappa;\phi_{L2}) = T(\kappa)|f(\kappa;\phi_{L2})|^2$$

3. Fit missing $T(\kappa)$ (and machine parameters)

1) Measured Spectra* 2) Simulated Spectra



3) Instrument Resp. 4) Corrected Measurement

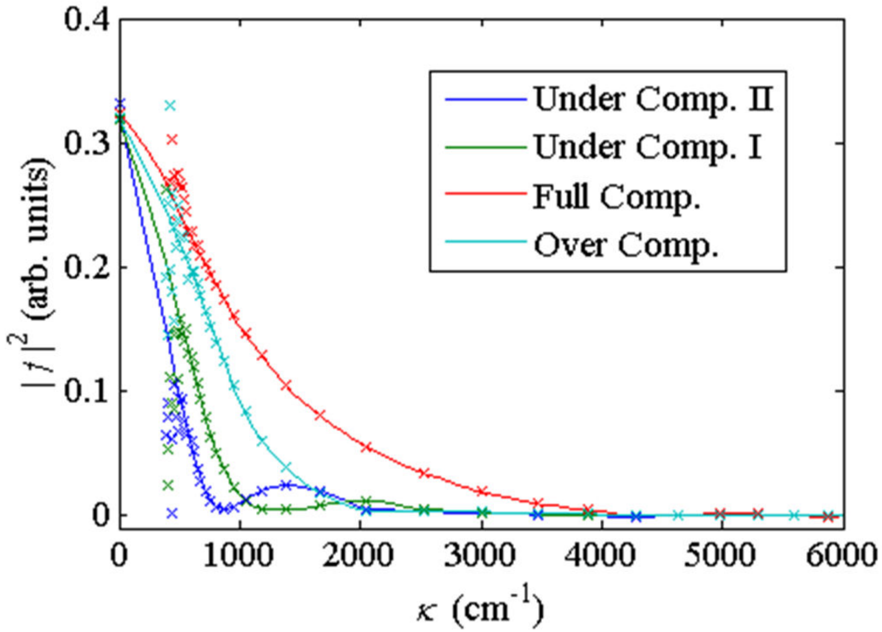
* LCLS BC2 chirp/phase scan, E = 13.4 GeV, Q = 40 pC

Signal Analysis

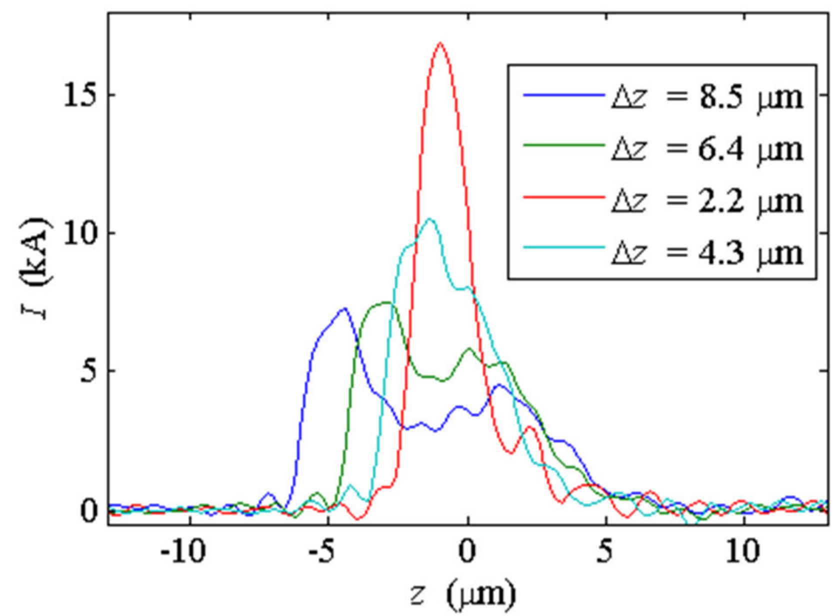
Bunch profiles estimated using Kramers-Kronig phase reconstruction

- R. Lai and A. Sievers, NIMA **397**, 221 (1997).

Corrected Spectra*



Bunch Profiles



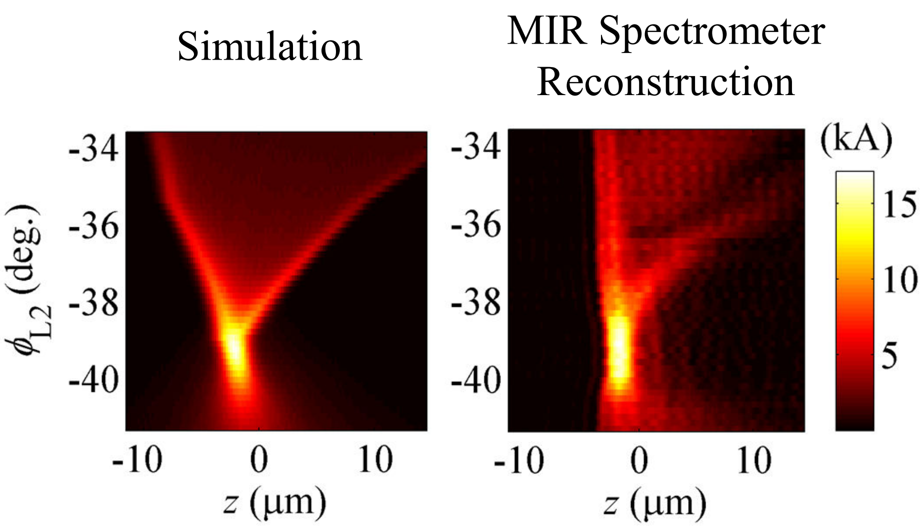
* E = 13.4 GeV, Q = 150 pC, BC2 chirp varied

Signal Analysis

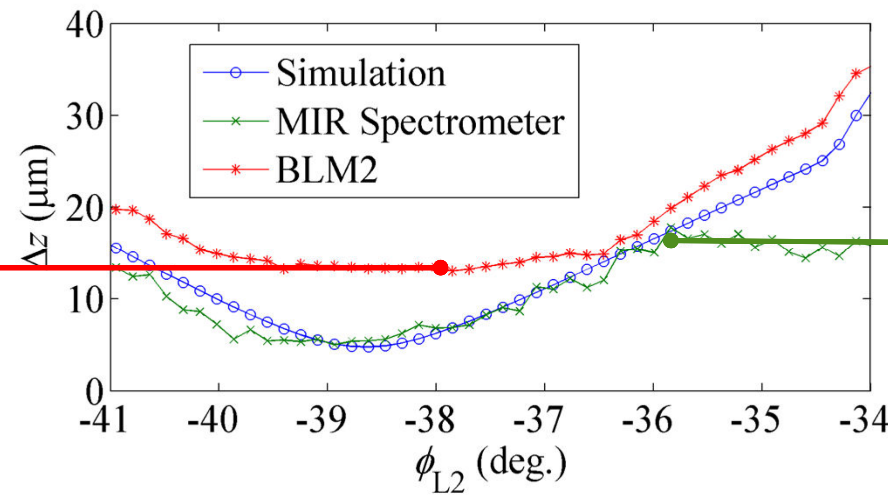
Full BC2 chirp scan analysis @ 150 pC and 13.4 GeV with

1. LiTrack simulation (no fitting)
2. Existing LCLS Bunch Length Monitor in BC2 (integrates CER from chicane)

Beam current profiles vs. BC2 compression phase



Δz, FWHM (*square-pulse fitting)



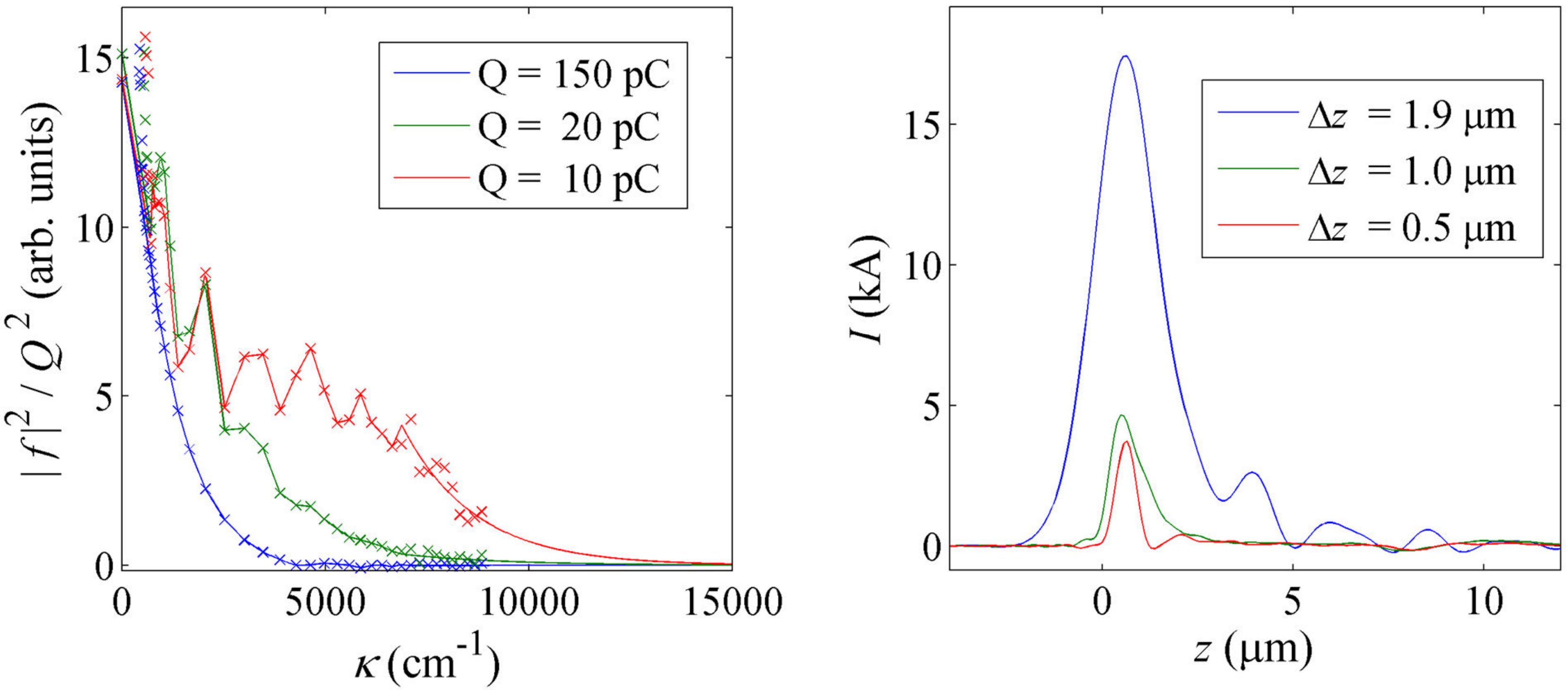
BLM2 flat for Δz < 15 μm
(30 μm LPF to block COTR)

Spectro. flat for Δz > 18 μm
(Strong signal @ 150 pC
ZnSe ND filter → 20 μm HPF)

Signal Analysis

Low-Q operation at LCLS: Shorter min. Δz with lower *Q*

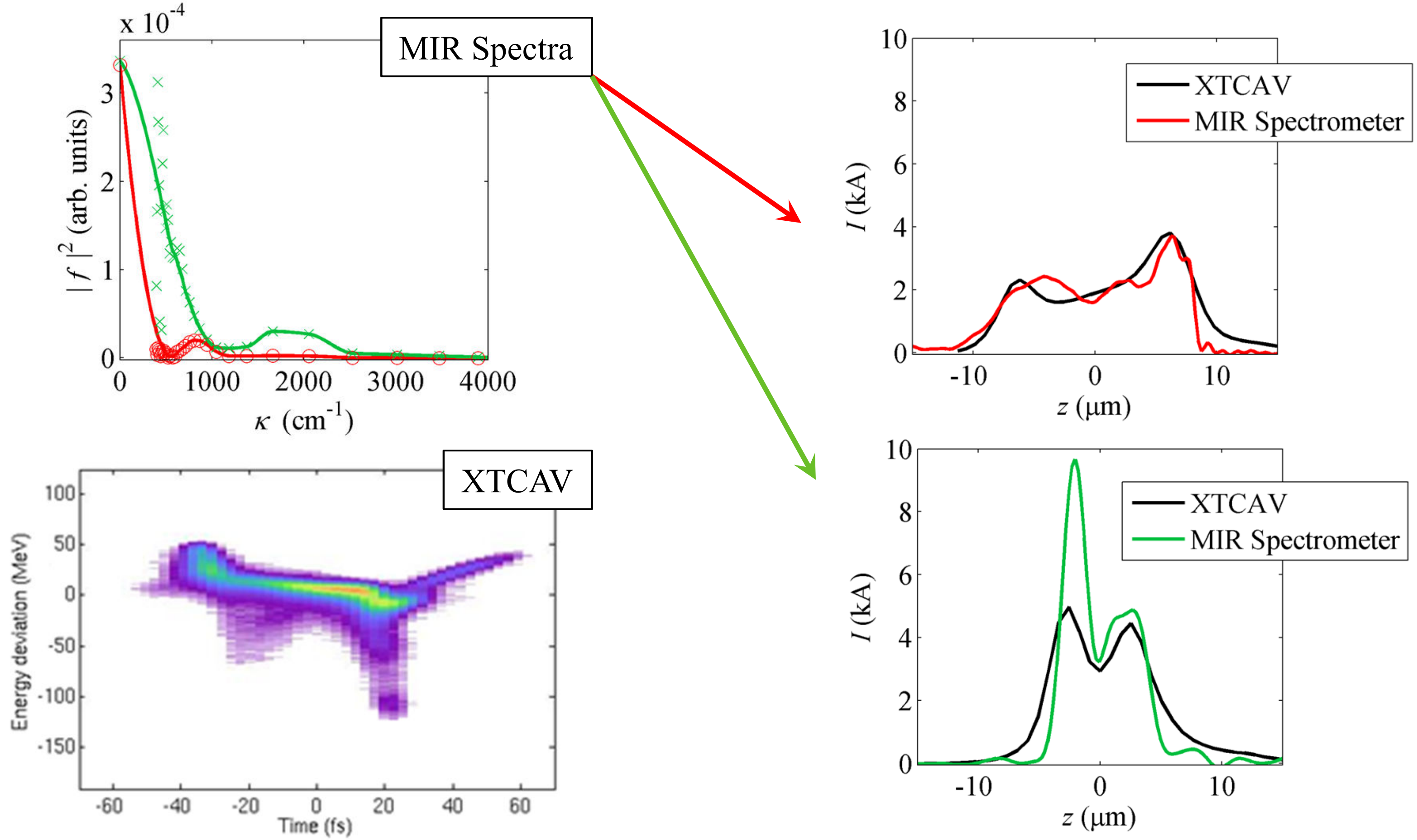
- Y. Ding, *et al.*, PRL **102**, 254801 (2009)



- At 10 pC, signal approaching detector noise level
- Strong hi-κ components beyond current range

Signal Analysis

Comparison to new LCLS X-band Trans. Defl. Cavity (XTCAV)



- *More great results from XTCAV in Y. Ding’s talk here at 12:15 pm!*

Summary

Word of warning/opportunity:

- μm-range spectrometer: Can see microbunching
- Can complicate σ_z measurement / New μBI measurements possible

Ongoing improvements

- Eventually: Detector improvement to remove hi-κ modulation
- Soon: ND Filter upgrade: For higher Q and σ_z
- Now: Detector upgrade: 2x higher sensitivity, ~2x higher κ
  (2x lower charge, ~2x shorter σ_z)
  Reach few pC, sub-μm (plasma wakefield accelerators)

MIR prism spectrometer as new σ_z diagnostic for x-ray FEL linacs

- Economical, compact, commercially available components
- Shorter bunches, lower charge (10-150 pC, < 1 – 20 μm fwhm)

Thank you!

Preprint of these results: SLAC-PUB-15692

Acknowledgments

- C. Behrens (DESY), A. Brachmann, J. Byrd (LBNL), F.-J. Decker, Y. Ding, A. S. Fisher, J. Frisch, T. Galetto, S. Gilevich, Z. Huang, R. Iverson, E. Johnson, E. Kraft, H. Loos, M. Martin (LBNL), M. Minitti, J. Robinson, B. Schmidt (DESY), G. Stupakov, J. Turner, J. Stieber

Work supported by US Department of Energy contract number DE-AC02-76SF00515.