$\sim fs$

Measurement of <u>ultrashort</u> electron and x-ray beams for x-ray free-electron lasers

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Outline

- Motivation and background;
- Overview of ultrashort diagnostics;
- **Experimental study of longitudinal mapping with a high-resolution spectrometer at LCLS;**
- **An X-band transverse deflector for e-beam and x-ray pulse measurement;**
- Discussions on optical streaking techniques.

Motivation/background

- Growing interests in a few fs or even sub-fs x-ray pulses.
- LCLS operating at ~20 pC or using slotted-foil has delivered x-rays to the users, with estimated duration of a few fs.
- However, the resolution of the present e-beam diagnostics at LCLS is about 10 fs rms.
- The characterization on the x-ray pulse duration is also very challenging, even at 100s fs scale.
- Need techniques with1-fs resolution, for both e-beams and x-rays.

Overview: e-beams (I)

Existing methods of e-beam longitudinal diagnostics

- S-band/C-band transverse deflector:

  ~10 fs rms resolution at LCLS, time-domain, direct measurement; (LCLS, FLASH, Spring-8, …)

- Single-shot spectrometer:

  frequency-domain; (FLASH, LCLS (under construction), …)

- Relative bunch length monitor (BLM) from coherent edge radiation or diffraction radiation:

  (LCLS, FLASH, …)

- Electro-optic (EO) method: (FLASH, …)

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Overview: e-beams (II)

New techniques have been proposed/developed*:

- longitudinal-to-transverse mapping:

  chicane + deflector (Xiang and Ding, PRSTAB13 094001 (2010))

- optical streaking or deflecting
- RF + optical deflecting:

  two orthogonally oriented deflecting (Andonian et al.,PRSTAB14 072802 (2011))

- optical replica synthesizer: Saldin et al.
- **<u>longitudinal mapping: time→ energy</u>** (this talk)

* Just pick a few examples here.

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Overview: x-ray pulses*

- X-ray auto-correlation

  Difficult due to vanishingly small cross-sections in nonlinear processes

  Geloni et al., two undulators + fresh bunches

- x-ray gas interaction + laser or THz fields streaking

  next talk, A. Maier

- Statistical analysis

  J. Wu et al. FEL10; A. Lutman et al. WEOA2, FEL11.

- Optical afterburner

  N. Stojanovic, WEOA4, FEL11

- **X-band transverse deflector** (this talk)

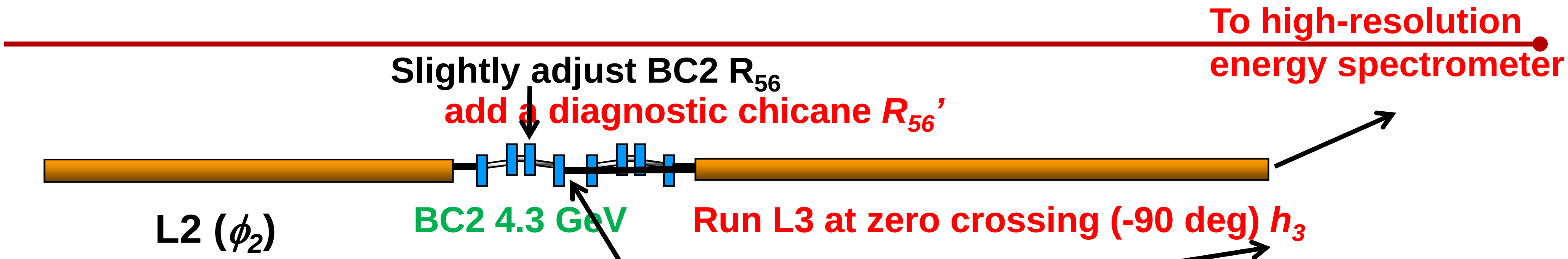
* Just pick a few examples here.

Longitudinal mapping with a high-resolution energy spectrometer*:

- Review of the method
- Experimental setup and results

**Z. Huang et al., PRSTAB 13, 092801 (2010),*
Presented at FEL10.
** Z. Huang et al.,PAC11, THP183*

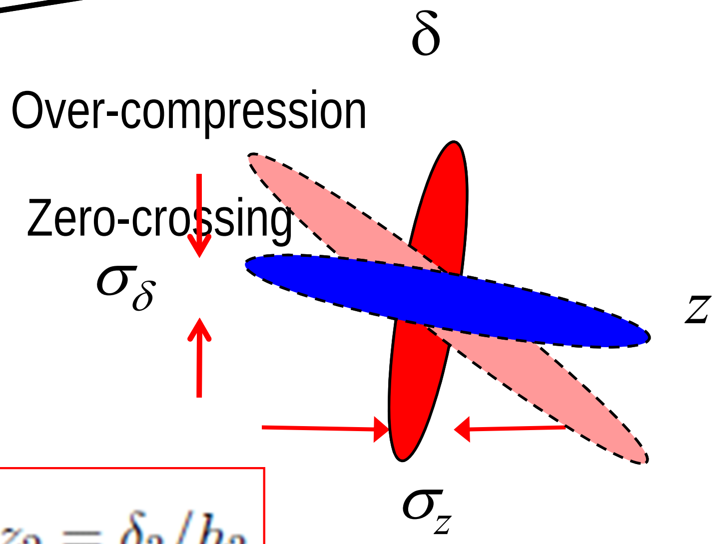
Apply this method to measure fs bunches



$$\begin{pmatrix} z_3 \\ \delta_3 \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ h_3 & 1 \end{pmatrix} \begin{pmatrix} 1 & R'_{56} \\ 0 & 1 \end{pmatrix} \begin{pmatrix} z_2 \\ \delta_2 \end{pmatrix}$$

$$= \begin{pmatrix} 1 & R'_{56} \\ h_3 & 1 + h_3 R'_{56} \end{pmatrix} \begin{pmatrix} z_2 \\ \delta_2 \end{pmatrix}$$

=0 ⇒ $z_2 = \delta_3 / h_3$



- Diagnostic chicane can be part of BC2
- Final energy spread/profile corresponds to short bunch length/profile
- Wakefield of long linac must be taken into account

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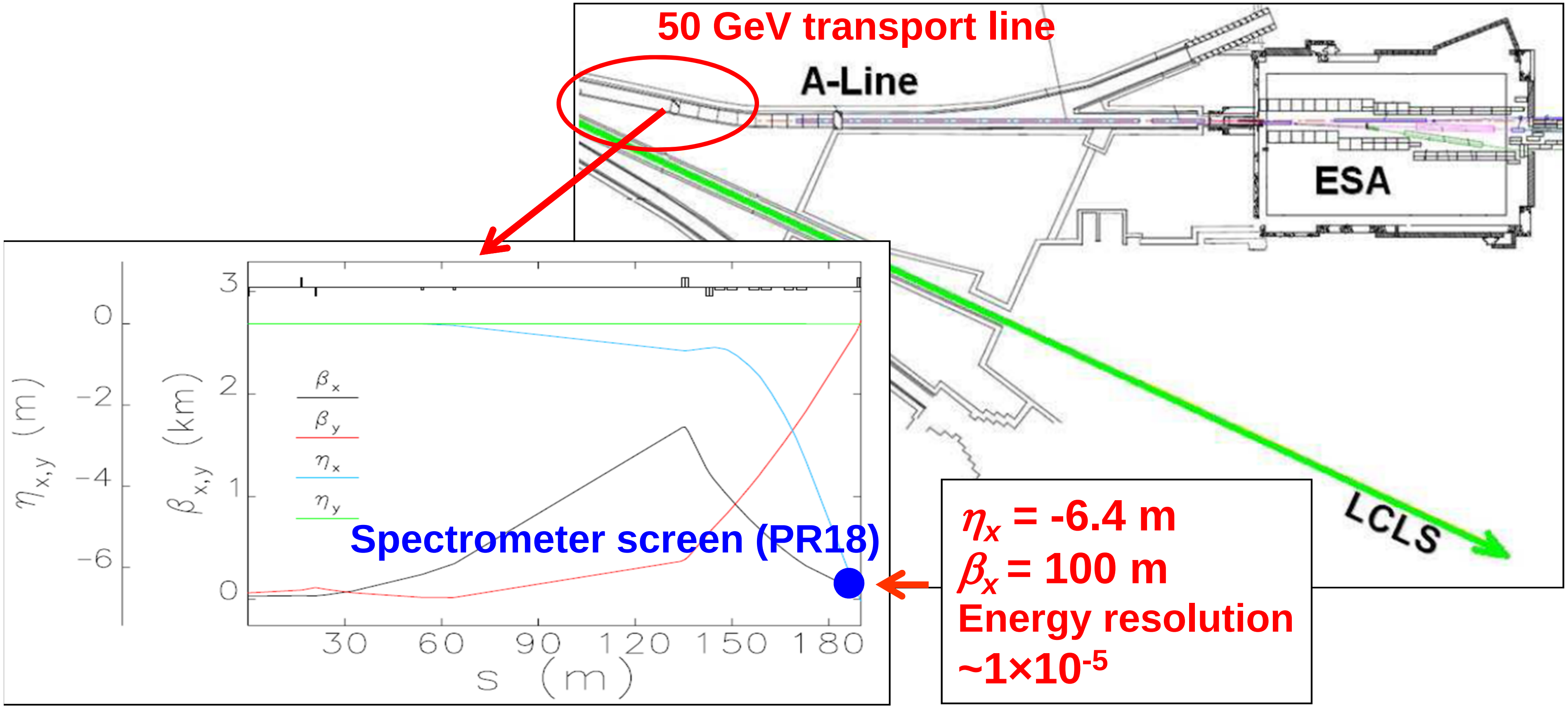
A-line as a high-resolution spectrometer



Updated the screen from aluminum to ZnS (Zinc Sulfide), ~0.1 mm thickness.
Measured resolution of 250 μm in σ_x with the new screen.

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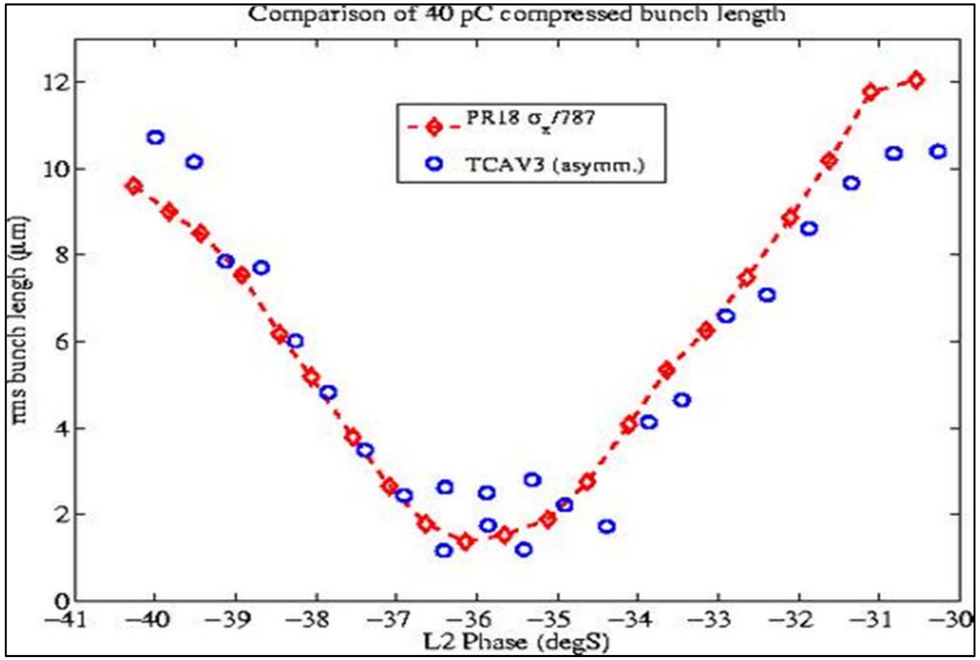
Calibration and Benchmark

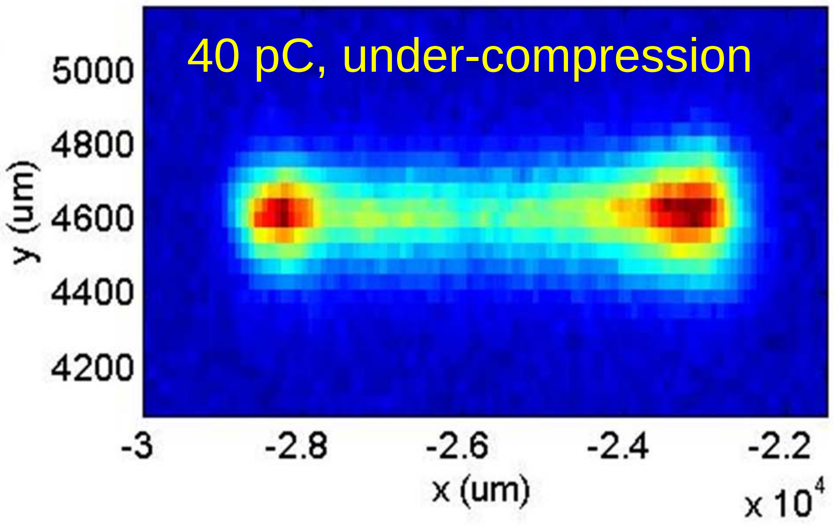
- Calibration factor: ➔~ 770-840 μm/μm bunch length
  - ❖ Measure PR18 horizontal central position vs L3 phase;
  - ❖ OR, use measured dispersion and chirp.
- TCAV3 runs out of resolutions at about ~3 μm (10 fs) bunch length level

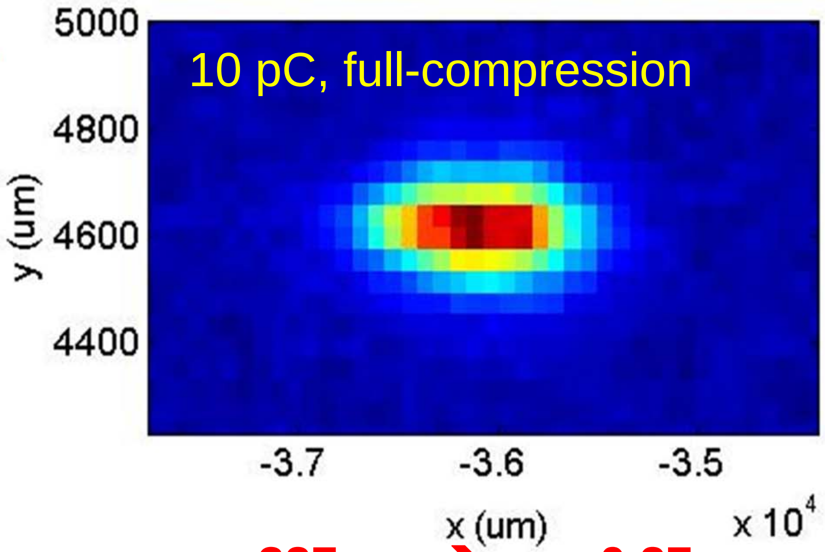
40 pC measured data*



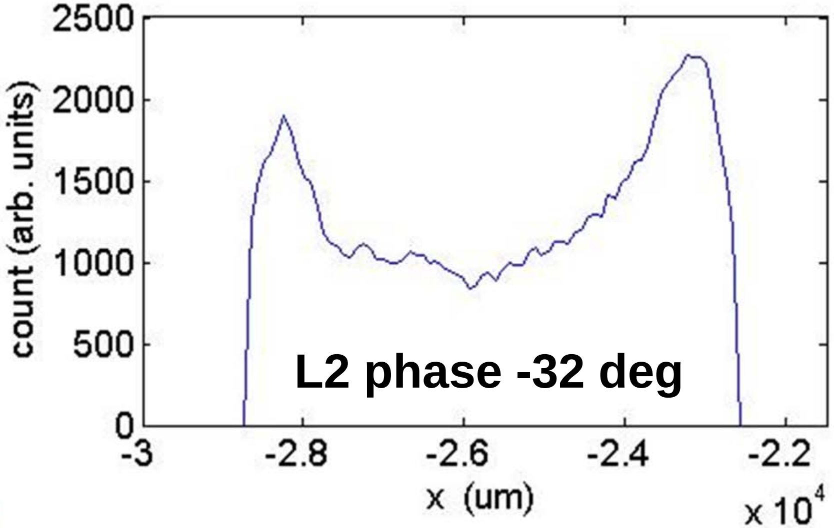
* With an old aluminum screen.

Measurement examples on PR18 (new screen)



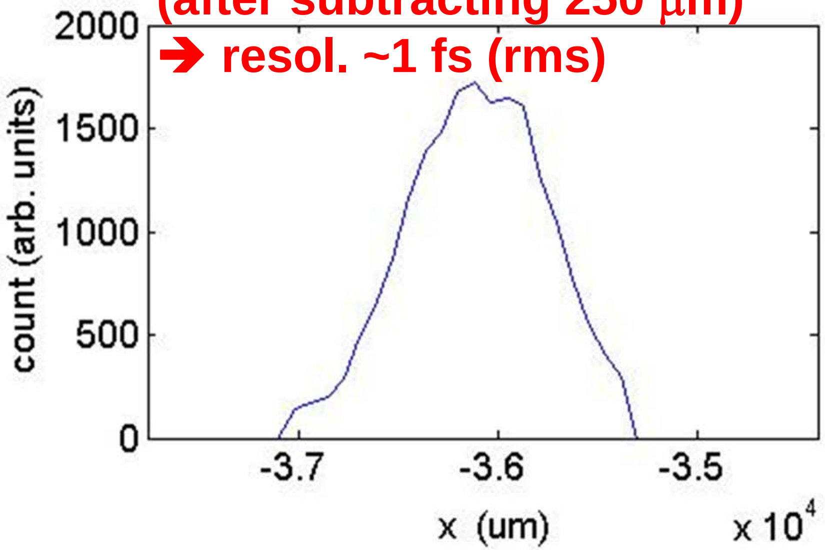


σ_x = 1908 μm ➔ σ_z = 2.47 μm



σ_x = 327 μm ➔ σ_z = 0.27 μm (after subtracting 250 μm)

➔ resol. ~1 fs (rms)



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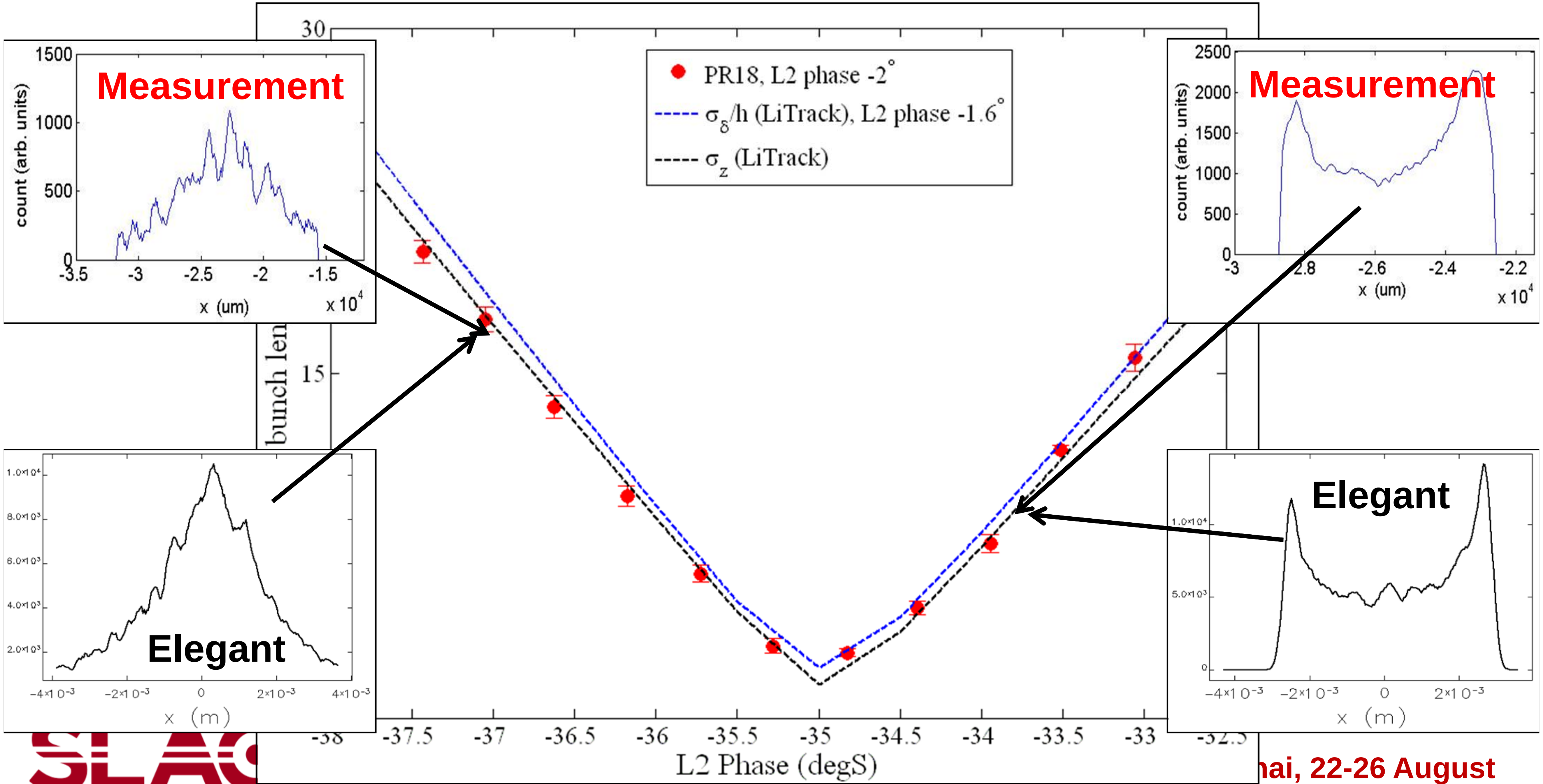
Measurement vs. simulation (40 pC)

- BC2 R56=-24.7mm to get σ_z, and R56=-35 mm and L3 -90 deg to get σ_δ
- Shifted L2 phase to compare measurement with simulations (5% cut area)



X-band transverse deflector for both e-beam and x-ray pulse measurement*:

- Basic principle
- System layout and requirements
- Resolution
- simulation examples

****** Y. Ding et al., SLAC-PUB-14534, submitted to PRSTAB.*

** Poster WEPB14, FEL11.*

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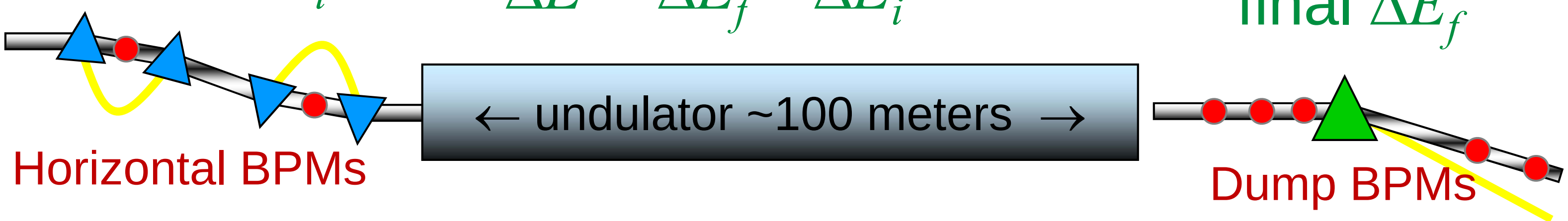
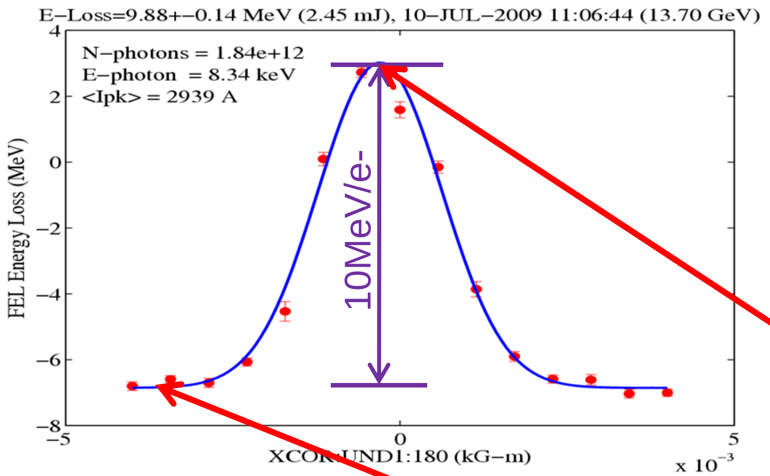
How to get the x-ray temporal profile

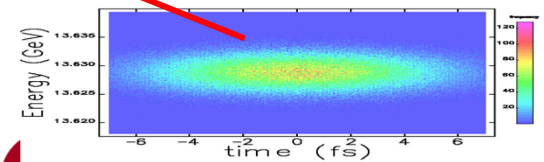
- The E-loss scan for measuring x-ray pulse energy:

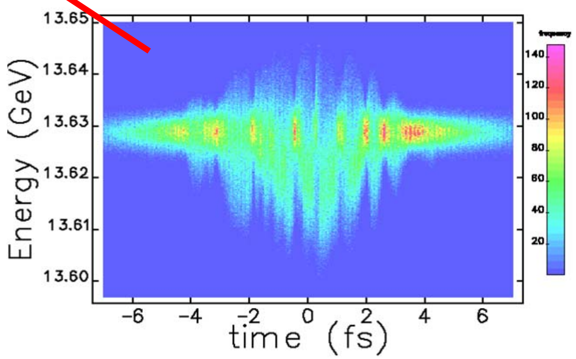


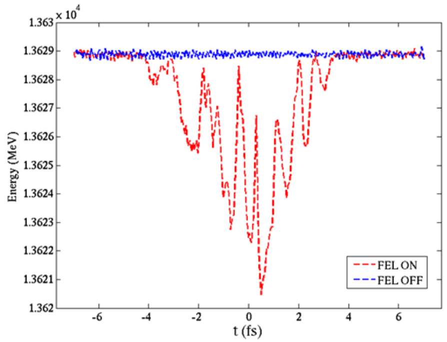
vary FEL power with oscillations & record *e*⁻ energy loss



We propose to streak the beam in time using a transverse deflector to measure the ***time-resolved*** energy loss, and energy spread, where the x-ray profile has been imprinted in the e-beam time-energy phase space.







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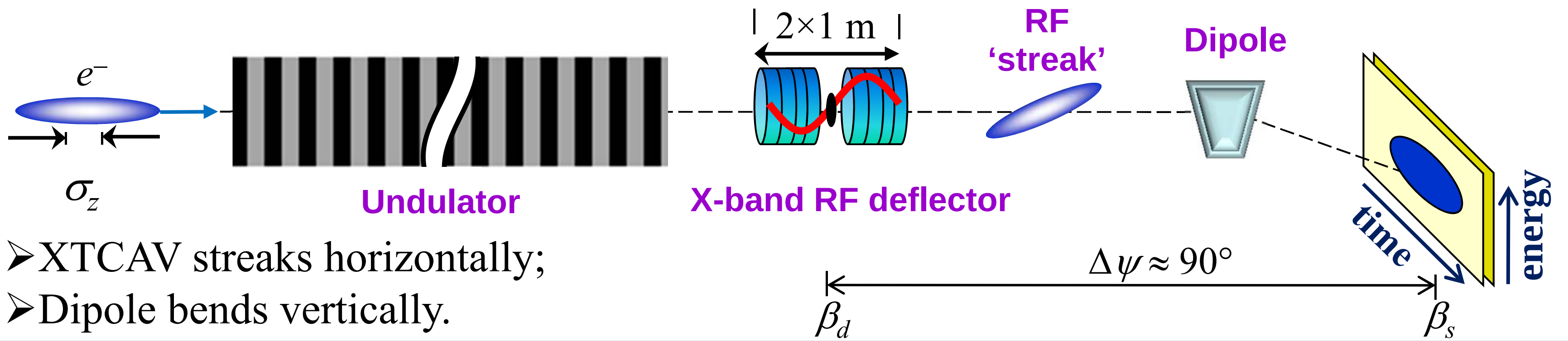
Layout and deflector parameters



➢XTCAV streaks horizontally;
➢Dipole bends vertically.

Deflector Parameters	
Structure length	2 x 1 m
Frequency	11.424 GHz
Maximum kick	48 MV@40MW
Max rep. rate	120 Hz
Phase stability	<0.1 deg rms
Amplitude stability	<1%

(Juwen Wang)

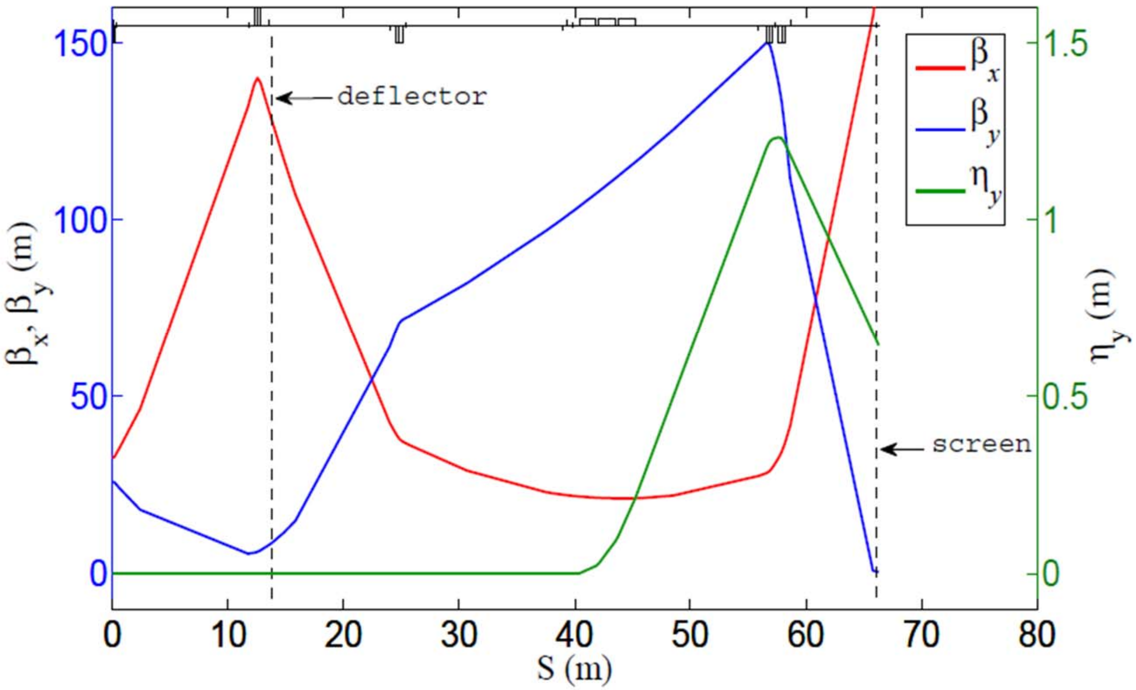
Resolution and optics optimization

$$\text{Temporal resol.} = \frac{\sigma_{x0}}{cS} \propto \frac{\lambda_{rf}}{V_0}\sqrt{E\frac{\varepsilon_{N,x}}{\beta_{xd}}}$$

$$\text{Energy resol.} = \frac{\sigma_{y0}}{\eta_y} \propto \sqrt{\frac{\beta_{ys}\ \varepsilon_{N,y}}{E\ \eta_y}}$$

***S** is the calibration factor:*

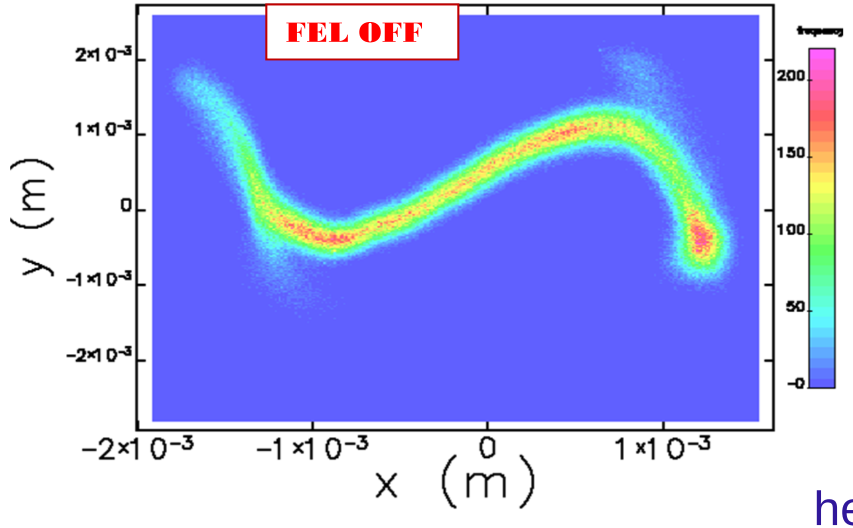
$$S = \frac{\sigma_x}{c\sigma_t} = \frac{eV_0}{pc}\sqrt{\beta_{xd}\beta_{xs}}|\sin\Delta\Psi|\frac{2\pi}{\lambda}.$$

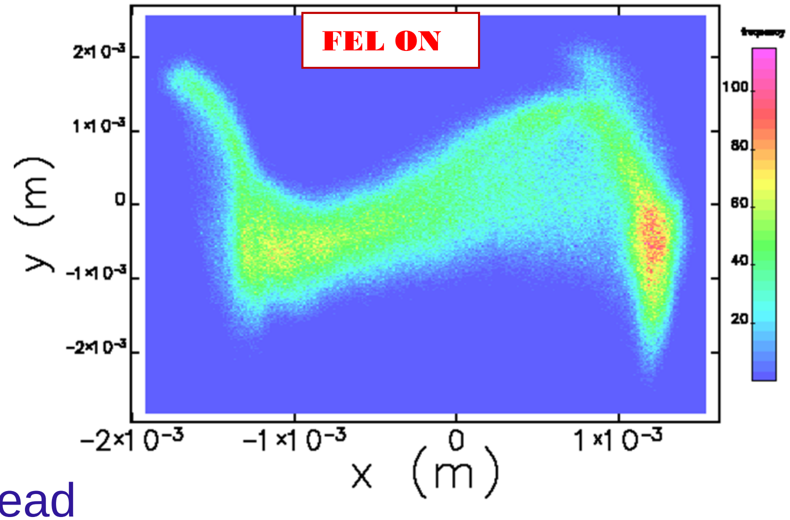


HXR: *(14GeV)*	***SXR:*** *(4.3GeV)*
$\varepsilon_{N,x} = 0.6\mu m$	$\varepsilon_{N,x} = 0.6\mu m$
S =128,	*S =400,*
$\sigma_{t,R}$ ~**2 fs**;	$\sigma_{t,R}$ ~**1 fs**;
$\sigma_{\delta,R}$ =7.3e-6 (100keV);	$\sigma_{\delta,R}$ =1.3e-5 (56keV);

Simulation example: hard x-ray S2E beam, 250pC

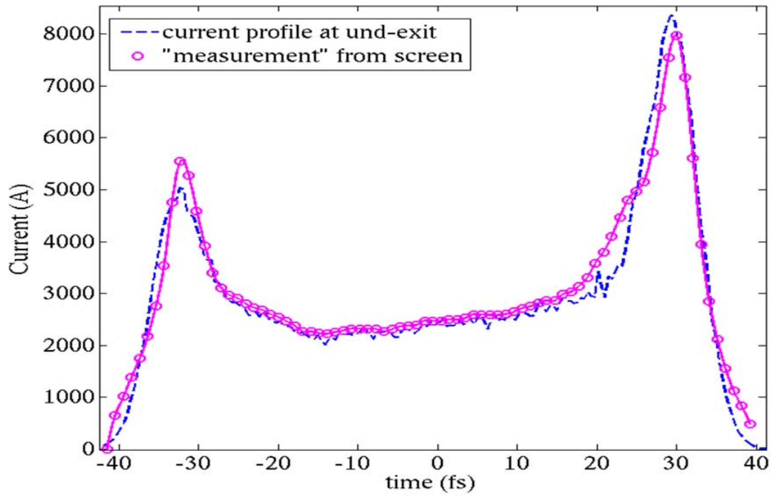
Screen



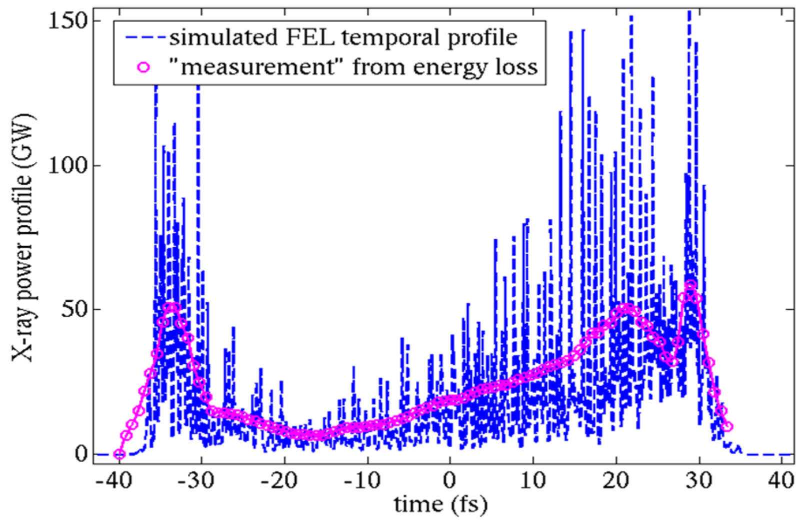


head

Reconstruction e-beam profile

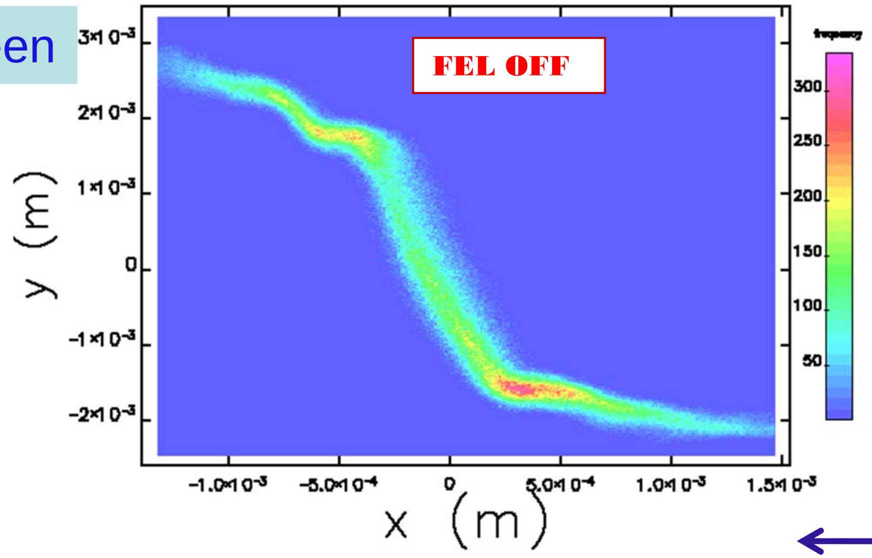


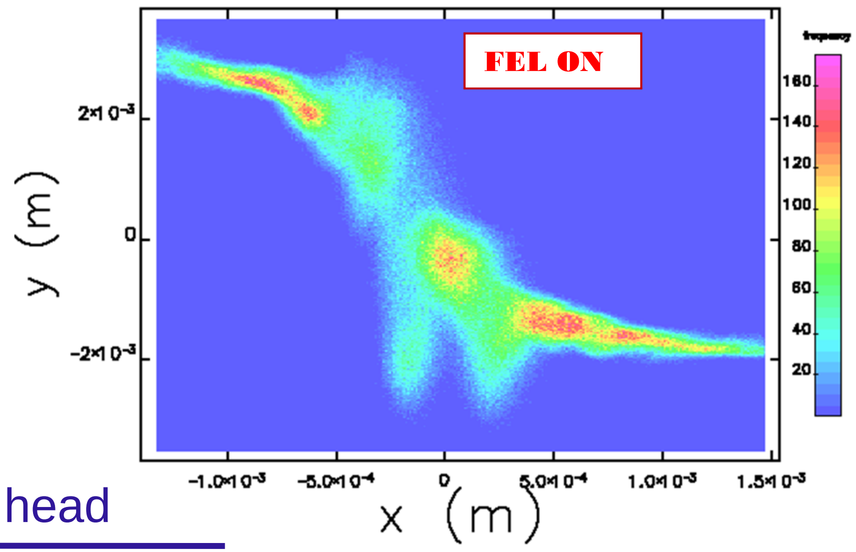
Reconstruction x-ray profile



Simulation example: soft x-ray S2E beam, 20pC

Screen





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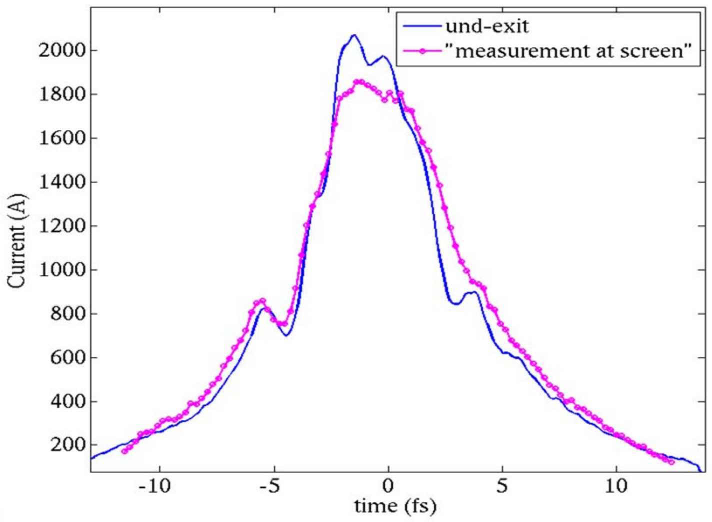
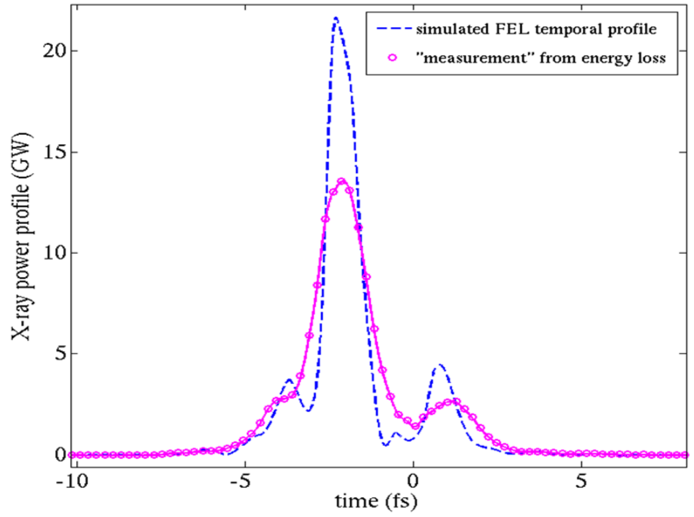
Reconstruction e-beam profile



Reconstruction x-ray profile



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Advantages of the X-band deflector method

- ✓ High resolution, ~ few fs;
- ✓ Applicable for all radiation wavelength;
- ✓ Wide diagnostic range, few fs to few hundred fs;
- ✓ Profiles, single shot possible;
- ✓ No interruption with LCLS operation;
- ✓ **Both** e-beam and x-ray profiles.

Generally applicable to other FEL facilities…

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Jitter discussions …

- Calibration requires small arrival time and X-band deflector rf phase jitters:
  - use larger dump screen;
  - use phase cavity signal to correct;
- Electron energy jitter correction with BPMs:
  - energy correction with BPMs;
  - using energy spread is less sensitive than E-loss ;
- Current (bunch length) jitter correction:
  - cause difference on wake loss;
  - correction by correlation (same as E-loss scan).

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Streaking at optical frequencies?

- Optical streaking with a Ti:Sa laser
  - use the slope of the intensity envelope to distinguish the different modulation periods.
  - calibrated with the laser wavelength. ***Poster WEPB22***.
- Optical deflecting of the ionized low-energy electron beam with a circularly-polarized long-wavelength laser (~10 μm)
  - No synchronization problem;
  - calibrated with the laser wavelength.

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Thanks all my SLAC colleagues for helps and supports;

Thanks C. Behrens for X-band transverse deflector work;

Thanks the support from DOE Early-Career Award Program.

We have postdoc position open at SLAC on this ultrashort diagnostic topic.

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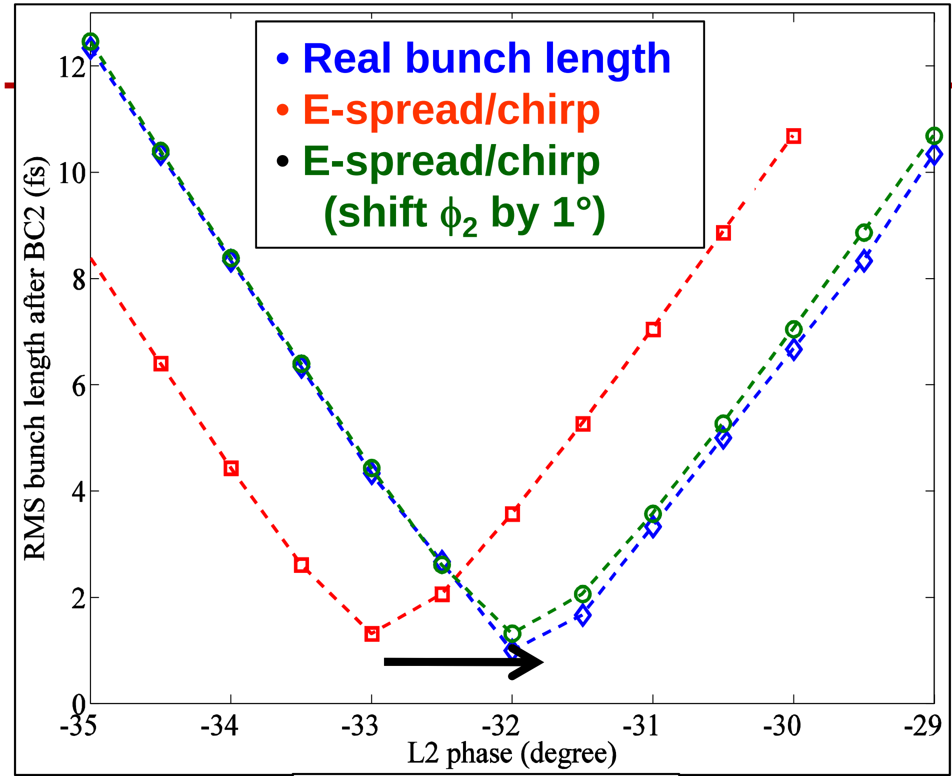
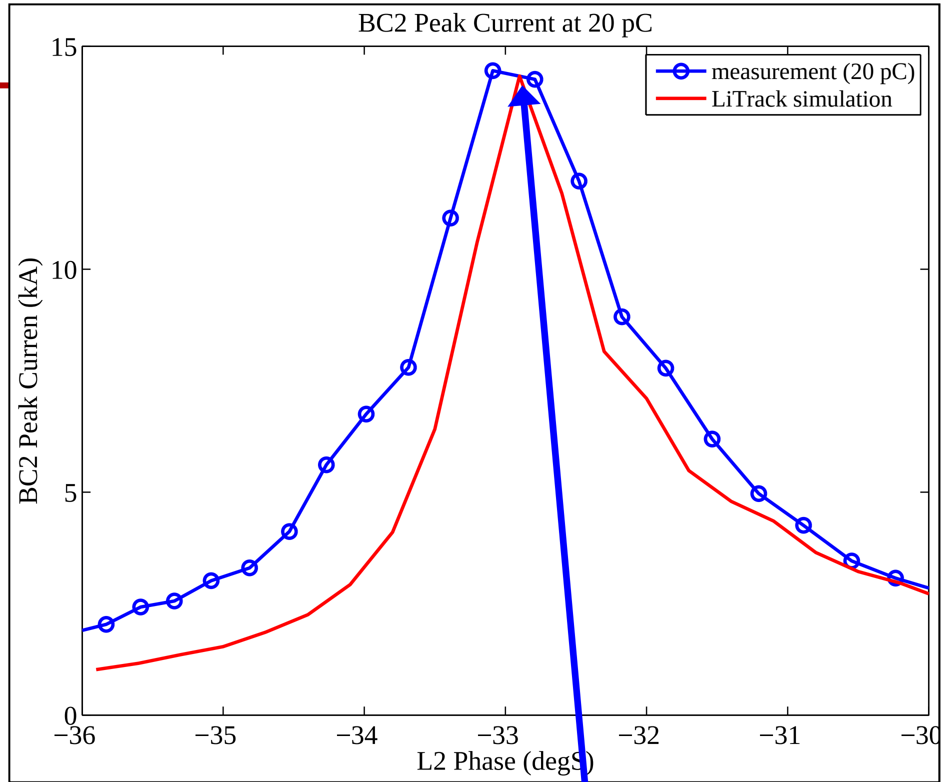
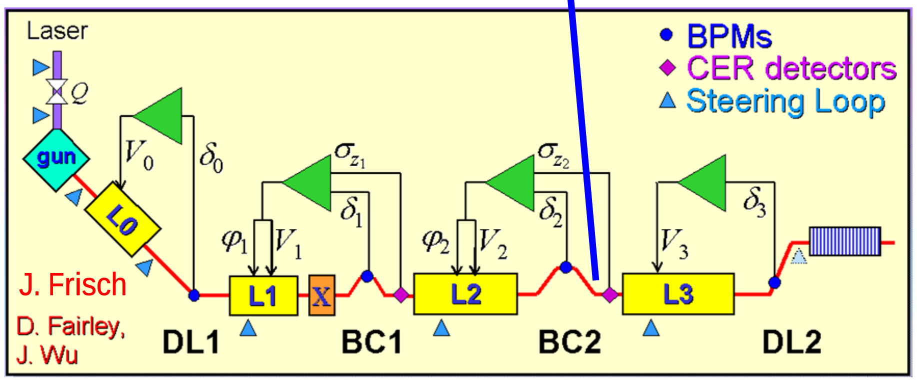
Wakefield compensation by shifting L2 phase





$R_{56}' = -7.18$ mm

- **Phase shift agrees with theory**
- **Wake effect can be corrected empirically by identifying full compression phase through CSR bunch length monitor**



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