A single-shot method for measuring fs bunches in LCLS

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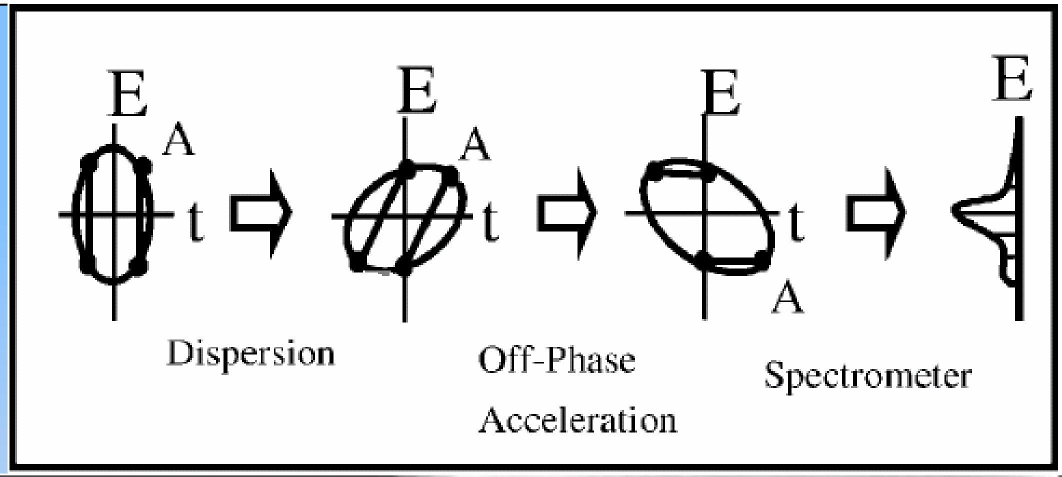
Compact XFEL workshop
August 5-6, 2010, LBL

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS, VOLUME **3**, 032801 (2000)

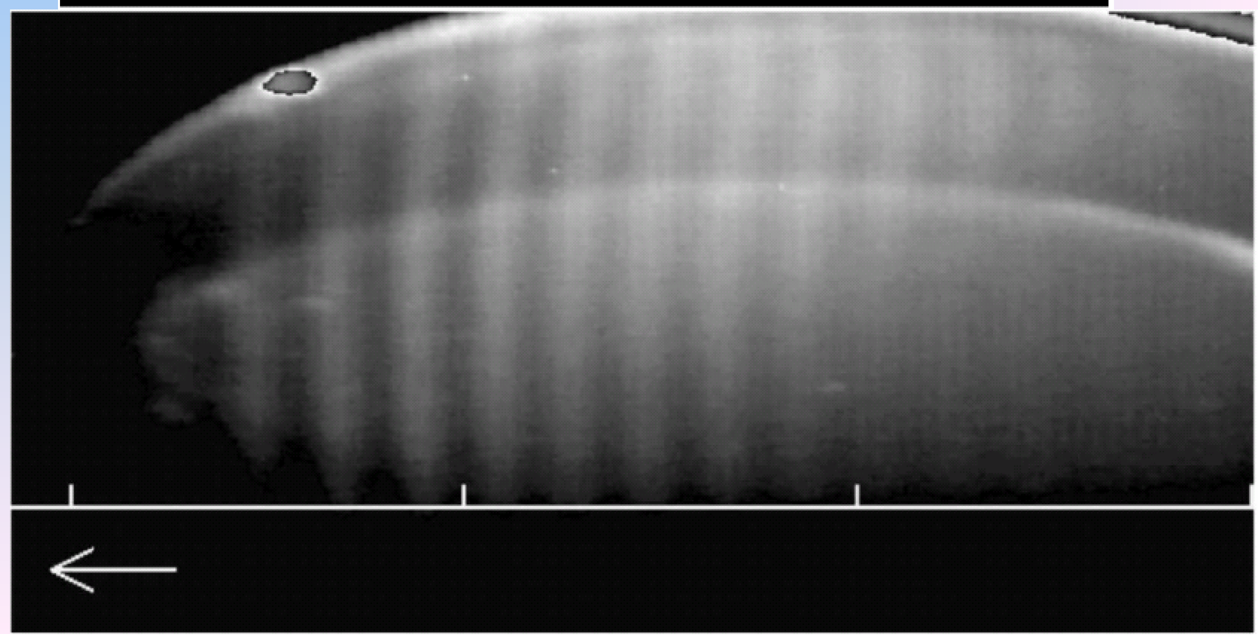
Longitudinal electron beam and free electron laser microbunch measurements using off-phase rf acceleration

Kenneth N. Ricci* and Todd I. Smith

Initially proposed by E. Crosson et al., 1995



Measurement of 60-μm FEL microbunching at stanford, 2000



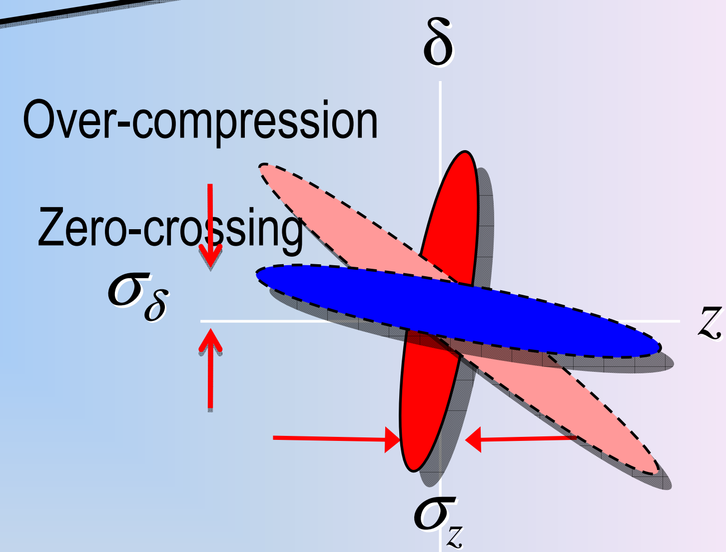
Apply this method to measure fs bunches*

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

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

=0

$$\Rightarrow \quad z_2 = \delta_3 / h_3$$

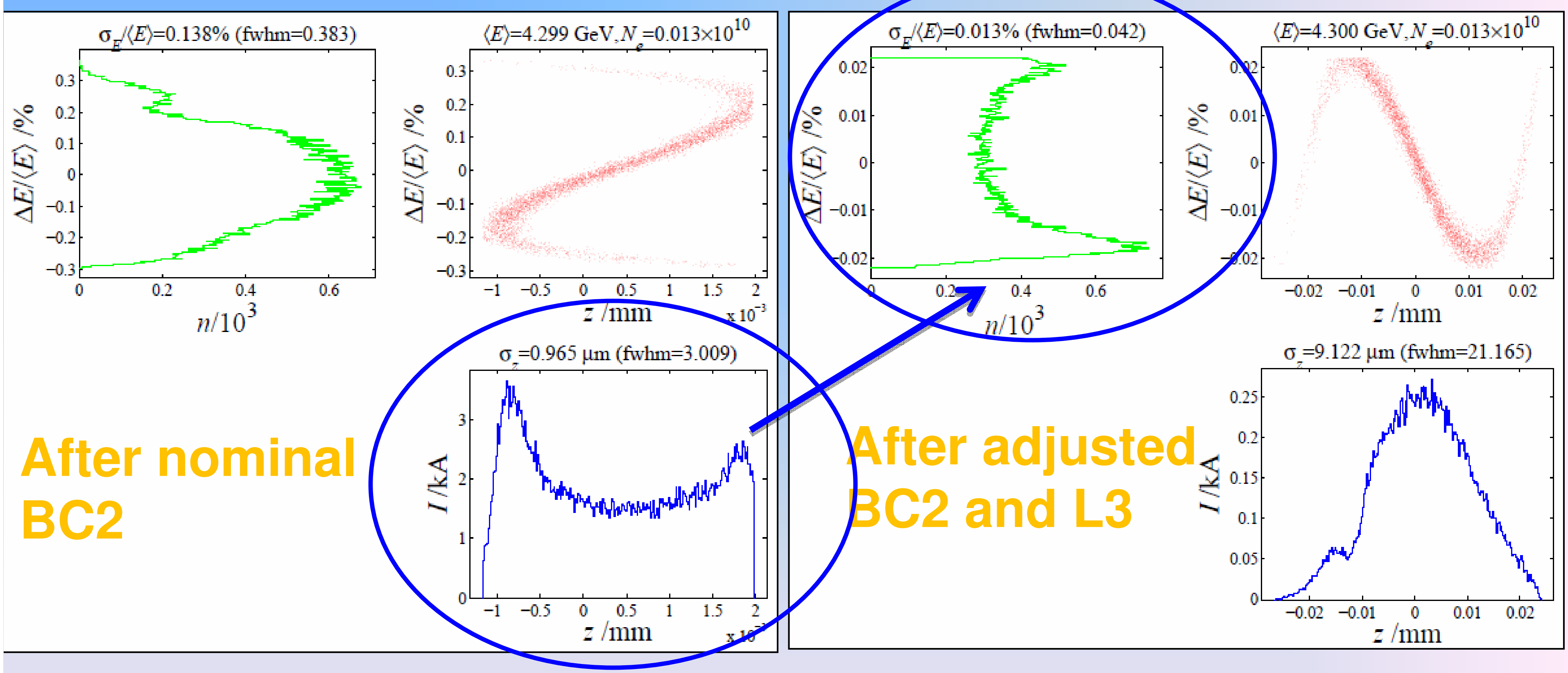


- Final energy spread/profile corresponds to short bunch length/profile
- Wakefield of long linac must be taken into account

** Z. Huang, K. Bane, Y. Ding, P. Emma, SLAC-PUB-14104, 2010*

LCLS low charge

- Run LiTrack with 20 pC setup (L2 phase at -31 deg, under-compression)
- Run L3 at -90 deg (10 GeV over 553 m leads to h_3 = 139 m^{-1})
- Increase BC2 R56 by R_{56}' = -1/ h_3 = -7.18 mm
- **Turn off Linac-3 wake (discussed in next slides)**



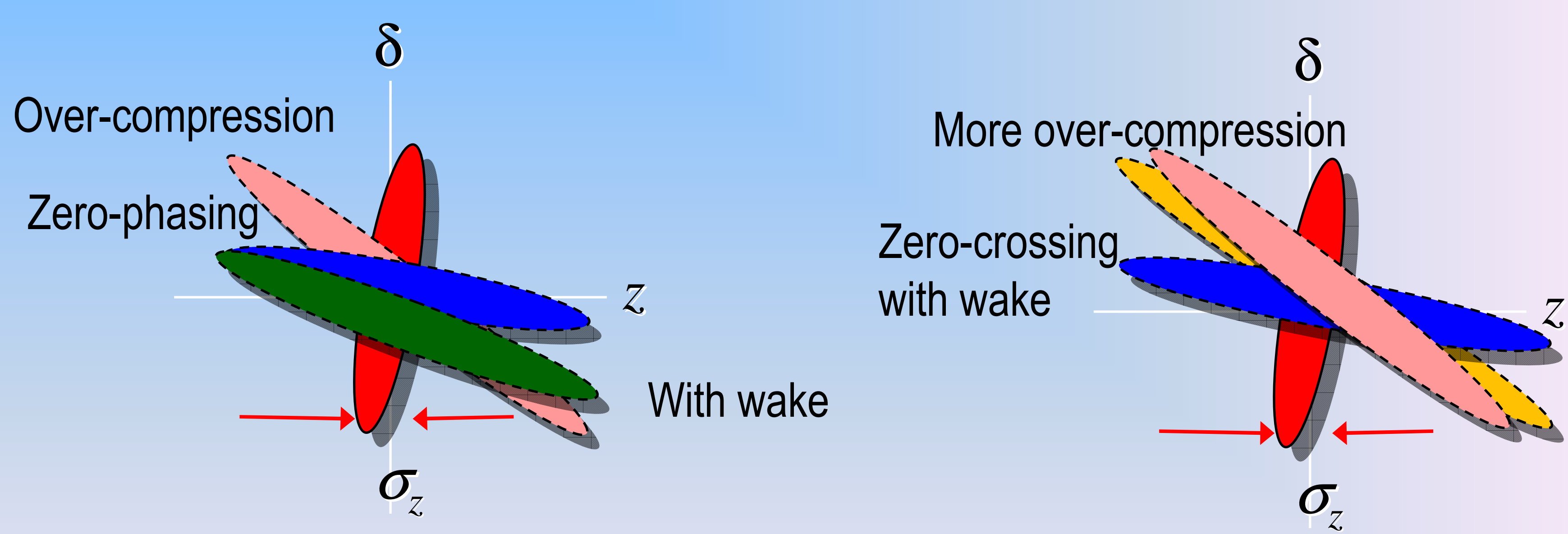
- Conventional RF zero-phasing has no chance here (*induced E-spread << initial E-spread*)
- This technique is insensitive to initial E-spread or chirp

Linac Wakefield

- L3 wake introduces an additional energy spread to the measurement
- For very short bunches (<10 μm), wake-induced energy spread (primarily a linear chirp) is independent of bunch length

$$\sigma_{\delta_w} = \left[\frac{1}{N}\int_{-\infty}^{\infty}(\delta_w(\bar{z}_3) - \bar{\delta}_w)^2 n(\bar{z}_3)d\bar{z}_3\right]^{1/2} = \frac{2}{\sqrt{3}}\frac{N r_e L}{\gamma_2 a^2}$$

N: # of e^-
L: L3 length
a: iris radius



Wakefield un-corrected **Wakefield corrected**

- This simple wake-correction scheme works for almost arbitrary (short) bunch length we want to measure!

Wakefield compensation

- Linac-3 wake can be corrected by a bit more over-compression
  - Using stronger chirp in Linac-2

$$\Delta\phi_2 \approx \sqrt{\frac{8\pi}{3}\frac{I_2}{I_A}\frac{\lambda_{rf}\cos^2(\phi_2)L}{2\pi\gamma_2 a^2 R_{56}|h_3|}}$$

  - Or using stronger R56 in BC2

$$\Delta R_{56} \approx \sqrt{\frac{8\pi}{3}\frac{I_2}{I_A}\frac{R_{56}L}{\gamma_2 a^2|h_3|}}$$

I_2 is peak current in L2 (same for all BC2 compression settings)
I_A=17 kA,
h_3 is L3 chirp by RF zero-phasing

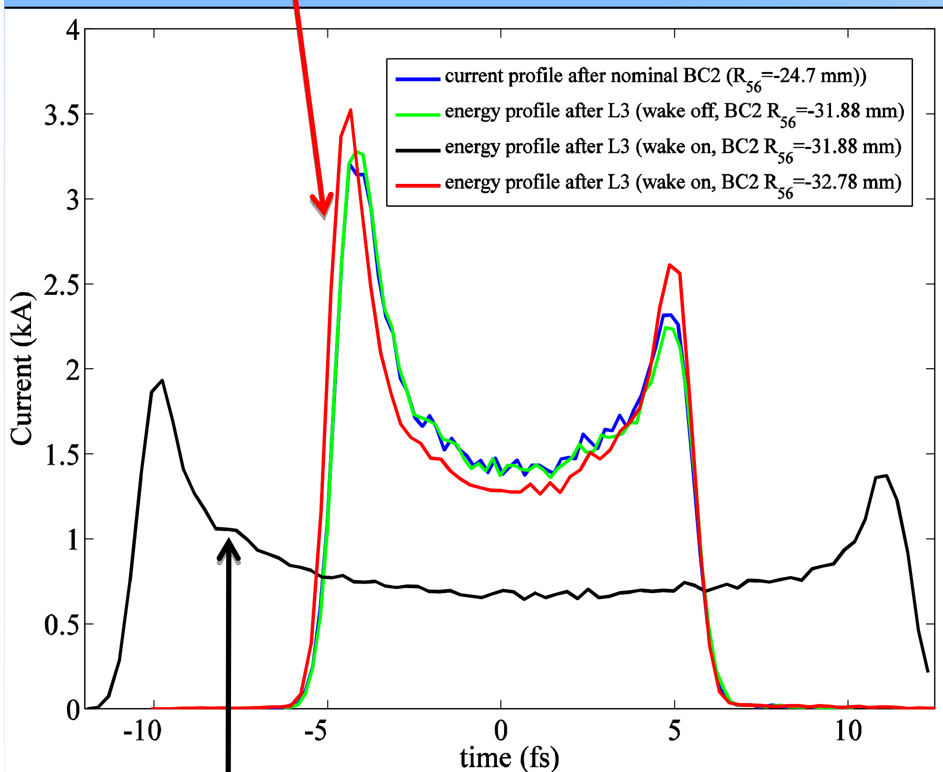
- Preferred wake-correction method is by shifting R_{56} of BC2, which needs to be increased by ~8.08 mm
  - R_{56}' (= -7.18 mm = -1/ h_3) and
  - ΔR_{56} (≈ -0.9 mm for wake compensation)

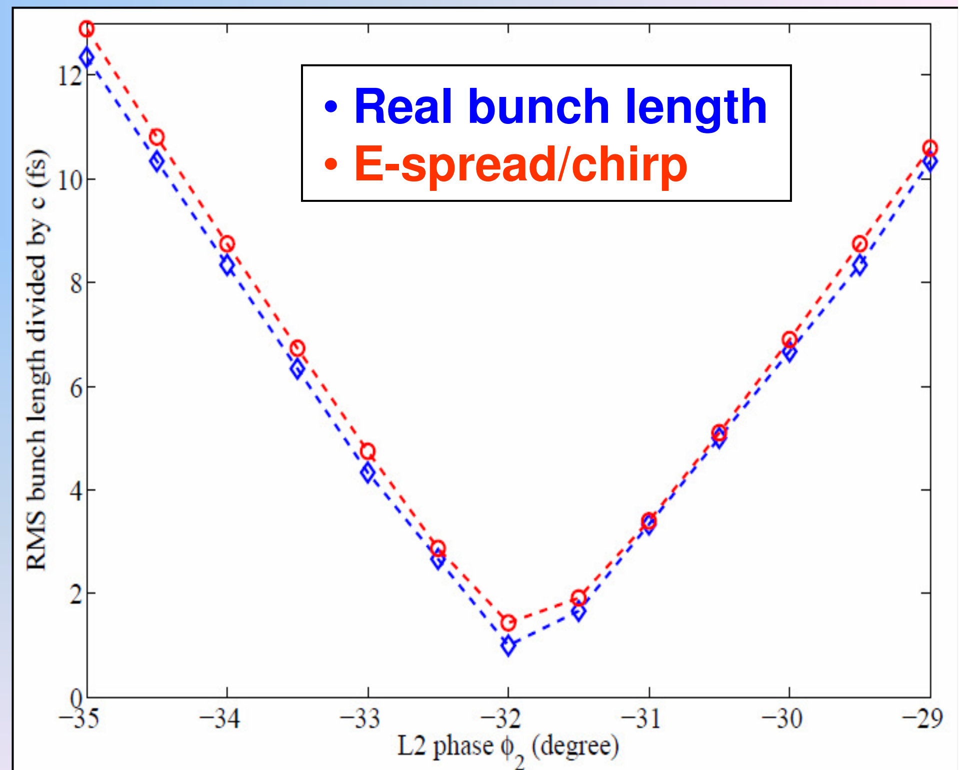
Wakefield compensation by changing R_{56}

- Run LiTrack with 20 pC (L2 phase at -31 deg, under-compression)
- Run L3 at -90 deg (10 GeV over 553 m leads to h_3 = 139 m^{-1})
- **Turn on Linac-3 wake**

Increase BC2 R56 by $R_{56}' + \Delta R_{56}$ = -8.08 mm

Wakefield corrected



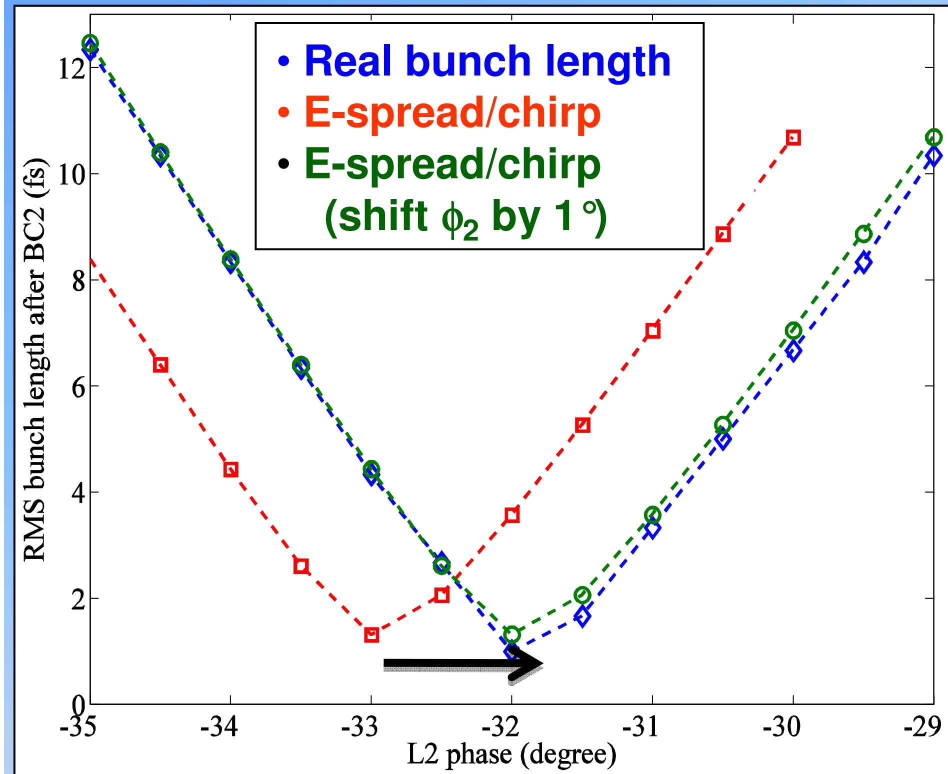


Increase BC2 R56 by $R_{56}' = -1/\ h_3 = -7.18$ mm

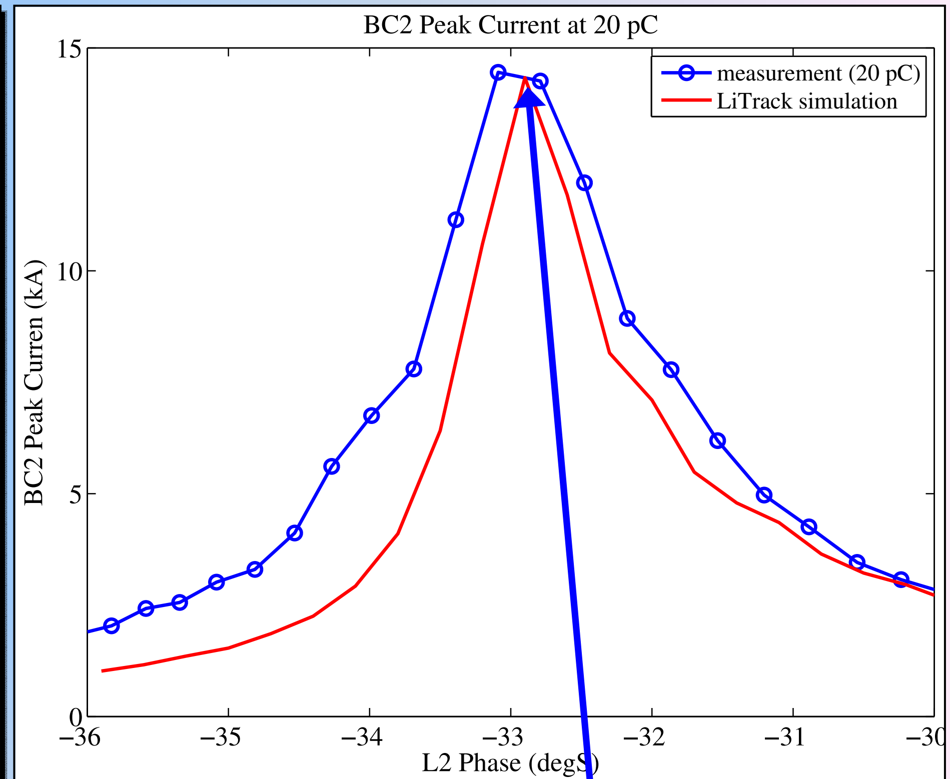
Wakefield un-corrected

R_{56}' = -8.08 mm

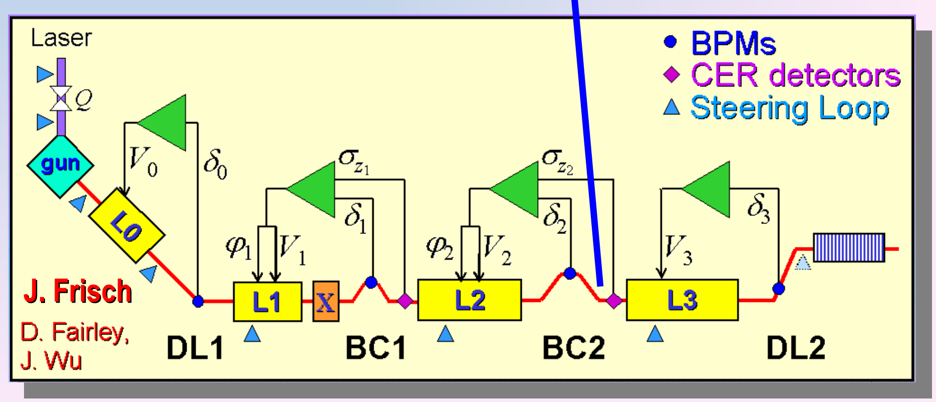
Wakefield compensation by shifting L2 phase



$R_{56}' = -7.18$ mm

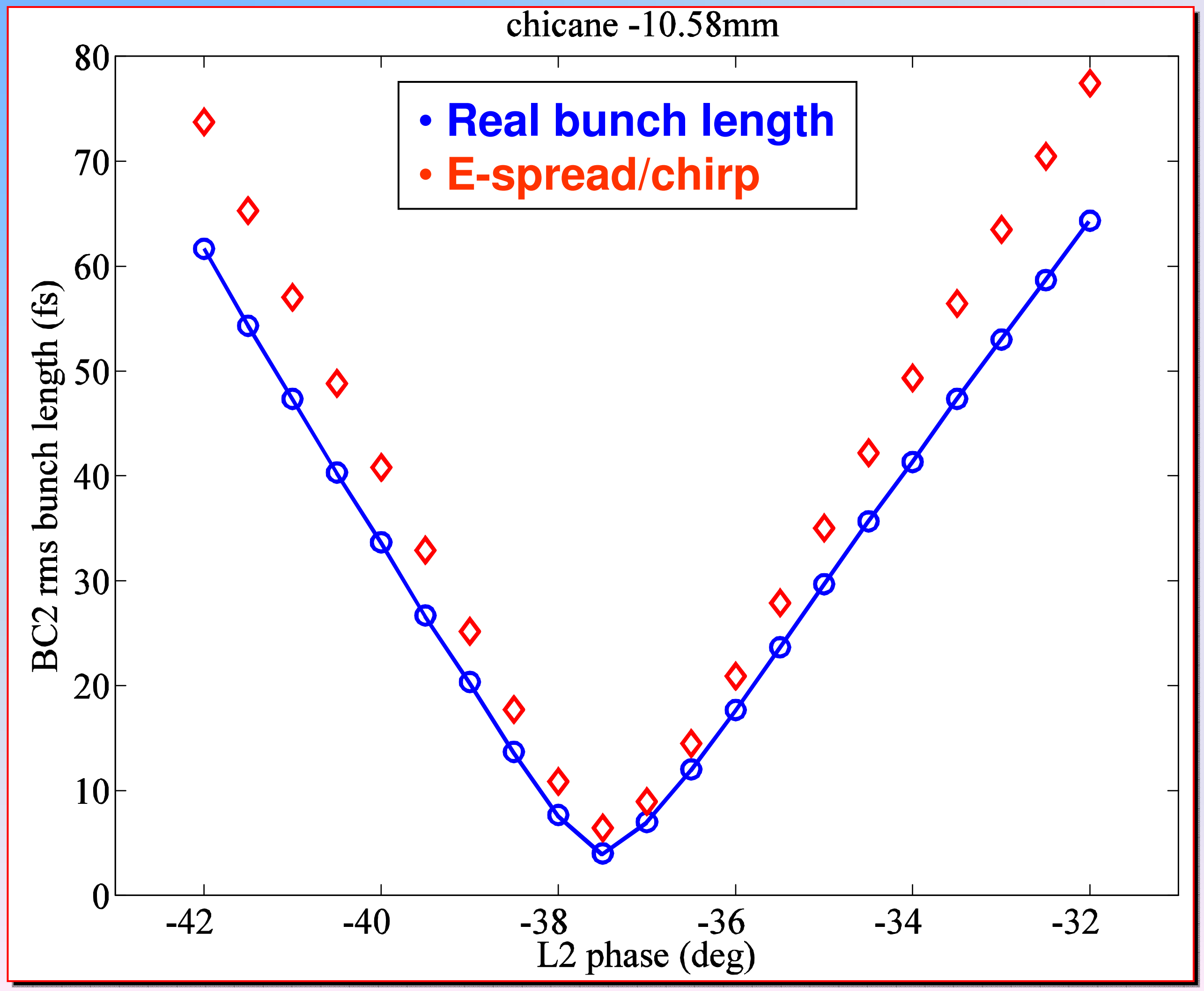


- Phase shift agrees with theory
- Wake effect can be corrected empirically by identifying full compression phase through CSR bunch length monitor

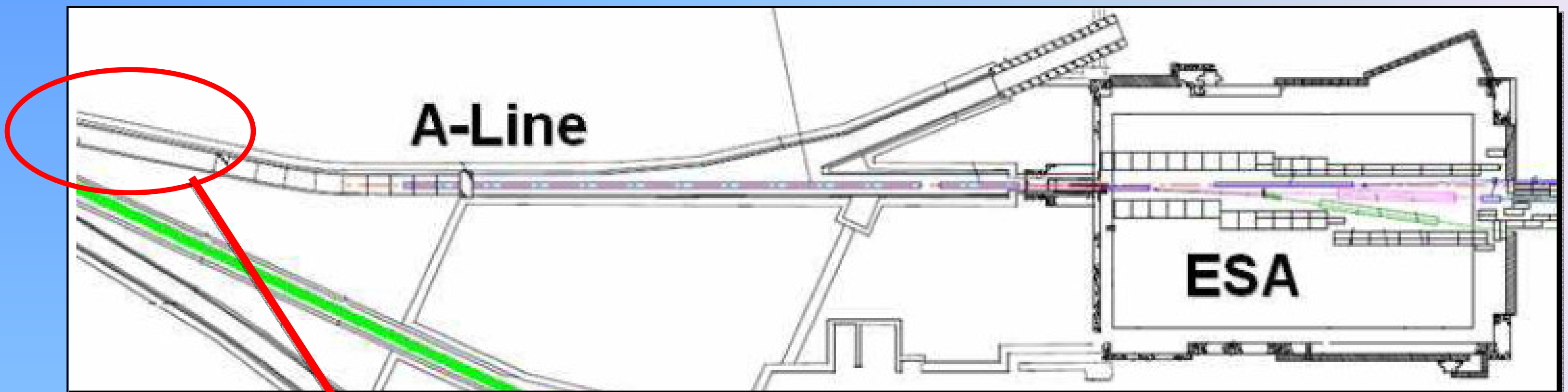


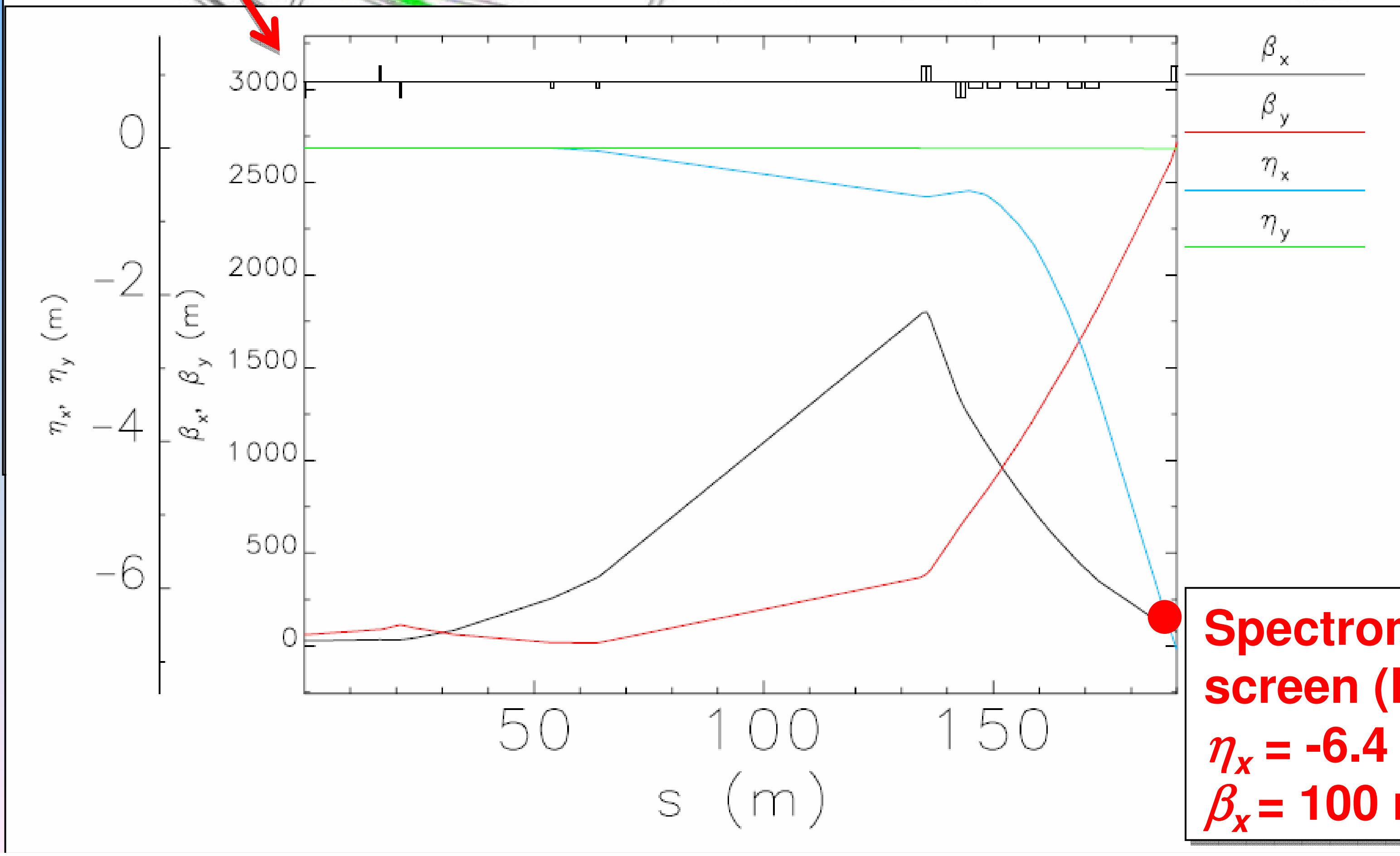
High charge case (250 pC)

- Wakefield E-spread for a longer bunch depends on bunch length
- Run LiTrack with 250 pC, increase BC2 R56 by 10.58 mm, run L3 at -90 deg zero-crossing
- Wakefield compensation still works (not as well as low charge case)



A-line as a high-resolution spectrometer





Spectrometer screen (PR18)
η_x = -6.4 m
β_x = 100 m

Resolution estimate

- For 0.5 um emittance, beam size limits the energy resolution of A-line spectrometer at the level of $\sim 1\times 10^{-5}$

- Divided by h_3 ~ 100 m^{-1}, temporal resolution is 0.1 um or 0.3 fs

- Other issues that limit the resolution:

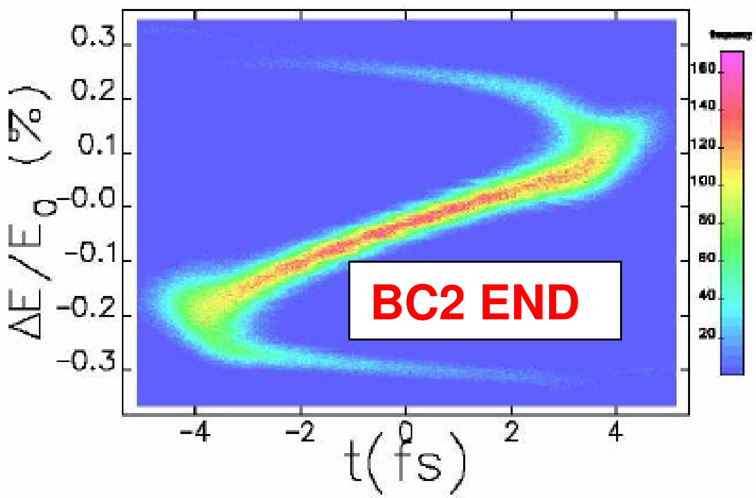
  - Linac wake adds some nonlinear energy chirp that distorts measurements
  - CSR/LSC must be taken into account in bends and linacs (addressed in ***elegant*** simulations next)

- Practical issues:

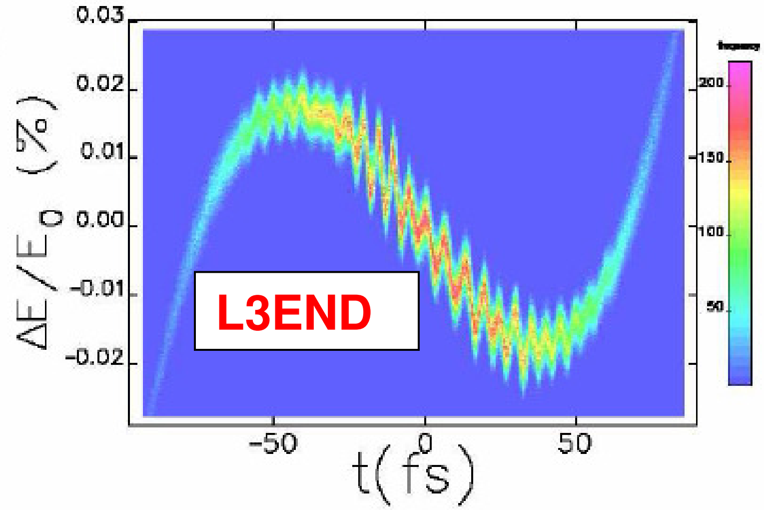
  - A-line is an old high-energy line that used to transport 50 GeV beams (power supply stability at 4 GeV is a concern)
  - L3 phase jitter (~50 fs) will make beam position jitter at the screen (need energy feedback)

- We hope to test this method at A-line soon.

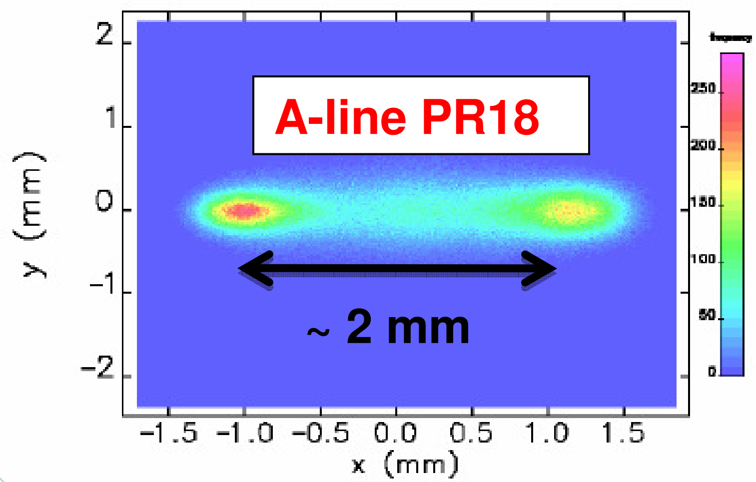
Under-compression (20 pC, L2 at -31.5 deg)



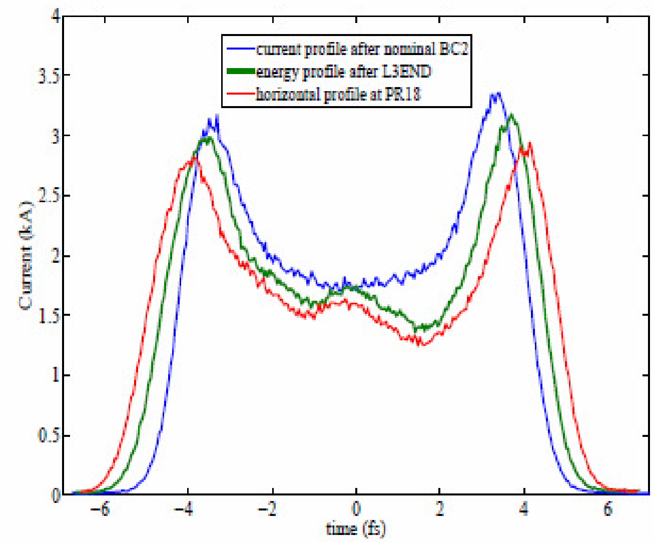
(a)Long. phase space after nominal BC2



(b)Long. phase space after L3

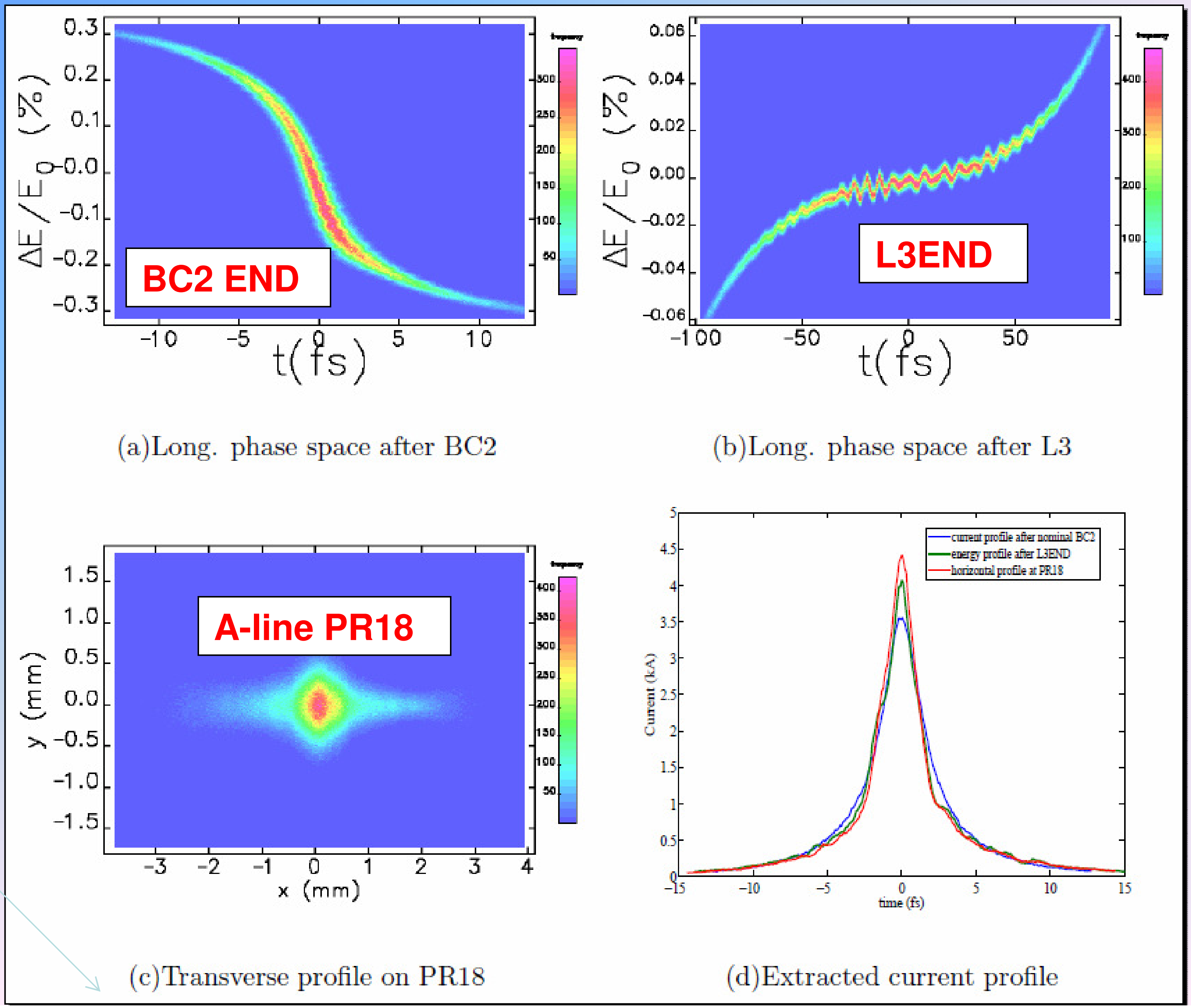


(c)Transverse profile on PR18



(d)Extracted current profile

Over-compression (20 pC, L2 at -33 deg)



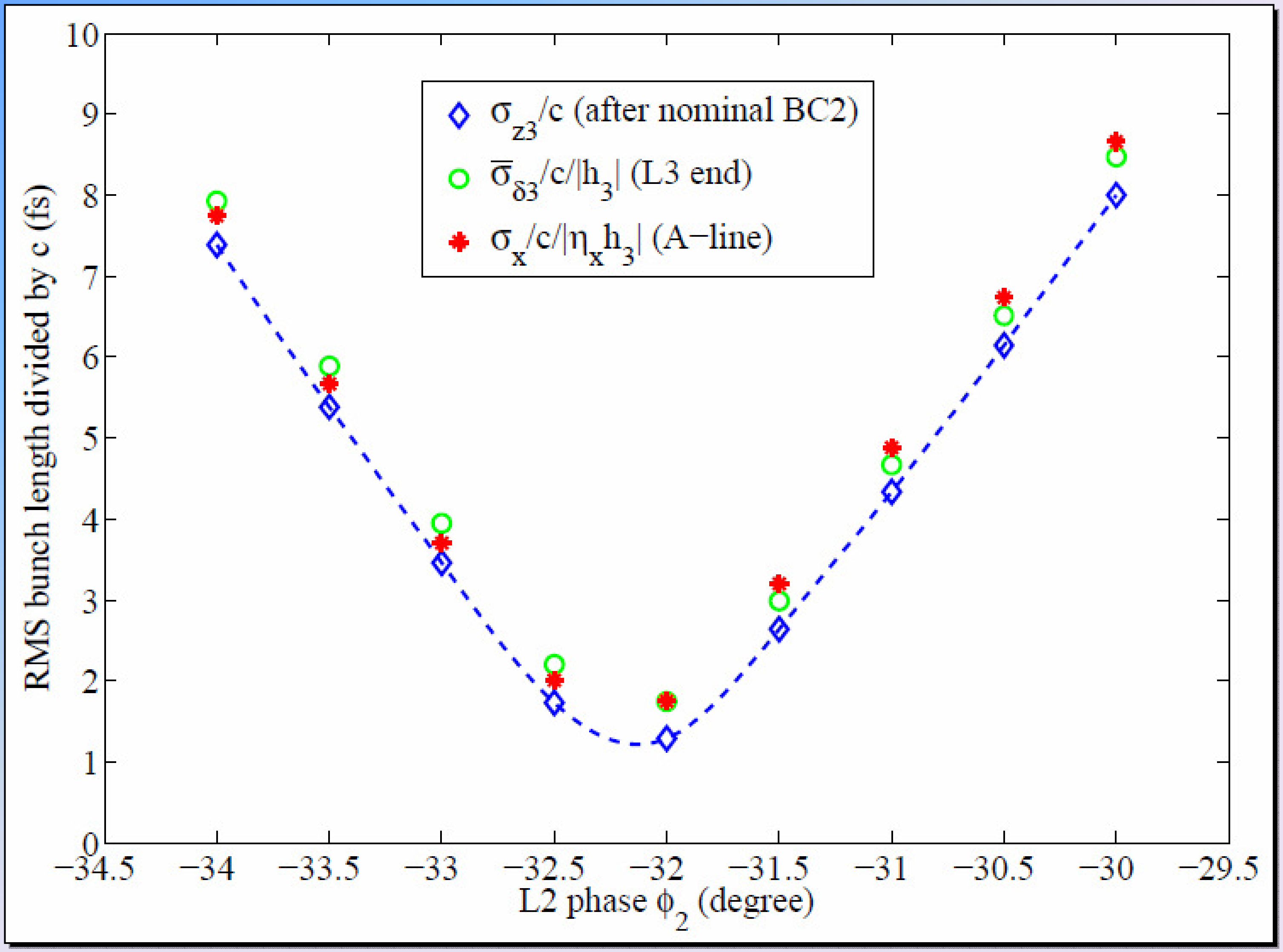
(a)Long. phase space after BC2

(b)Long. phase space after L3

(c)Transverse profile on PR18

(d)Extracted current profile

RMS bunch length (*Elegant* simulations)



- Turning on and off 2nd order optics (in elegant) has no effect on "measured" bunch length/profile
- Wakefield/CSR/LSC add a systematic error ~0.4 fs

Summary

- A single-short method for measuring fs LCLS bunches is studied
- The method will be tested using the SLAC A-line spectrometer
- The method requires no extra hardware (besides a high-resolution spectrometer) and may be applicable to other XFEL facilities