LCLS low-charge operation

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on behalf of *the LCLS commissioning team*

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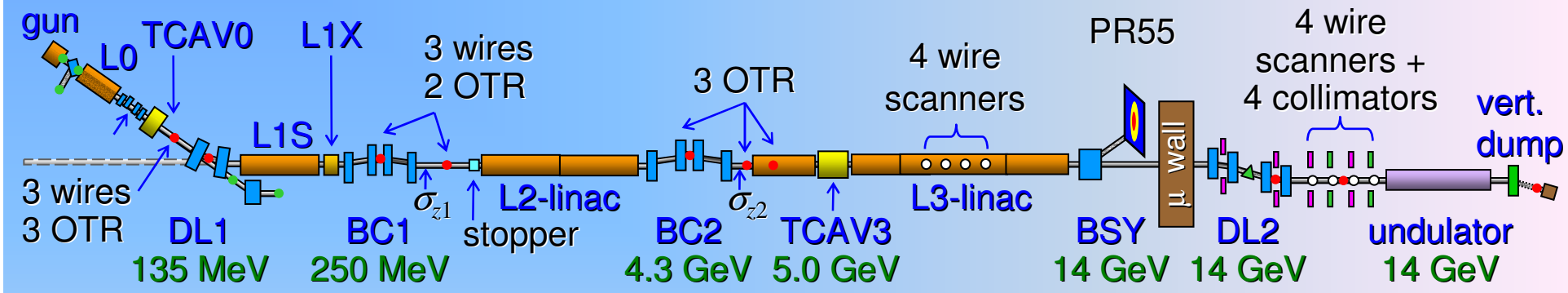
Berkeley Compact x-ray FEL workshop

Outline

- Introduction
  - Injector
  - Linac
- Low charge operation at soft x-ray
  - Measurements
  - Simulations
  - Slotted foil
  - Spectrum
  - Charge dependence
- Low charge operation at hard x-ray
  - Measurements
  - Gain length

LCLS layout



Impact-T ← Elegant → Genesis

- (Slice) emittance and bunch length measurements at OTR2;
- Measure emittance using wire scanners after BC1 and BC2;
- Measure bunch length signal after BC1, BC2 and PR55;
- Start-End simulations to evaluate FEL performance.

Typical Measured *LCLS* Parameters

Photon Beam Parameters	symbol	hard x-rays	soft x-rays	short pulse soft	short pulse hard	unit
Fundamental wavelength	λ_r	≥1.4	≤17	≤15	≥1.4	Å
Photon energy	$\hbar\omega$	9000	750-2000	800-2000	9000	eV
Final linac e^- energy	γmc^2	14.2	4.1	4.3	14.2	GeV
FEL 3-D gain length	L_G	3.3	1.5	~1.5	~3.3	m
Photons per pulse	N_γ	2	20	0.5	0.1	10^{12}
Peak brightness	B_{pk}	20	0.3	?	?	10^{32} §
Average brightness (30 Hz*)	$\langle B \rangle$	40	2	?	?	10^{20} §
Photon bandwidth	$\Delta\omega/\omega$	~0.2	~0.4	?	?	%
Bunch charge	Q	0.25	0.25	0.02	0.02	nC
Init. bunch length (rms)	σ_{z0}	0.65	0.65	0.23	0.23	mm
Final bunch length (rms)	σ_{zf}	7	20	~1	~1	μm
Final pulse duration (fwhm)	$\Delta\tau_f$	80	240	<10	<10	fs
Final peak current	I_{pk}	3.0	1.0	~3	~3	kA

P. Emma

20 pC operation condition

- Injector laser:

  spot size on cathode: 0.6 mm;

  temporal Gaussian shape, 1.5 ps rms;

  laser heater off.

- Bunch compressors (BC1 and BC2) fixed:

  BC1 R56 = -45mm; BC2 R56 = -24.7mm.

- L1 rf phase -22deg, tune L2 phase to adjust the compression factor.

  Bunch length monitor is used to determine the compression mode.

Emittance at injector : 20 pC

Transverse cavity and Quad-scan method are used to measure the slice emittance at OTR2 (1 um thick aluminum screen).

emittance at the central slice

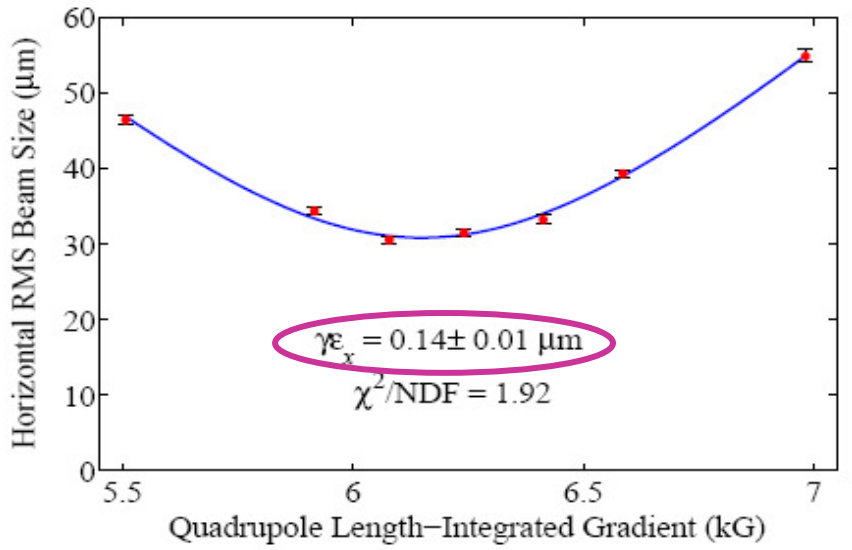
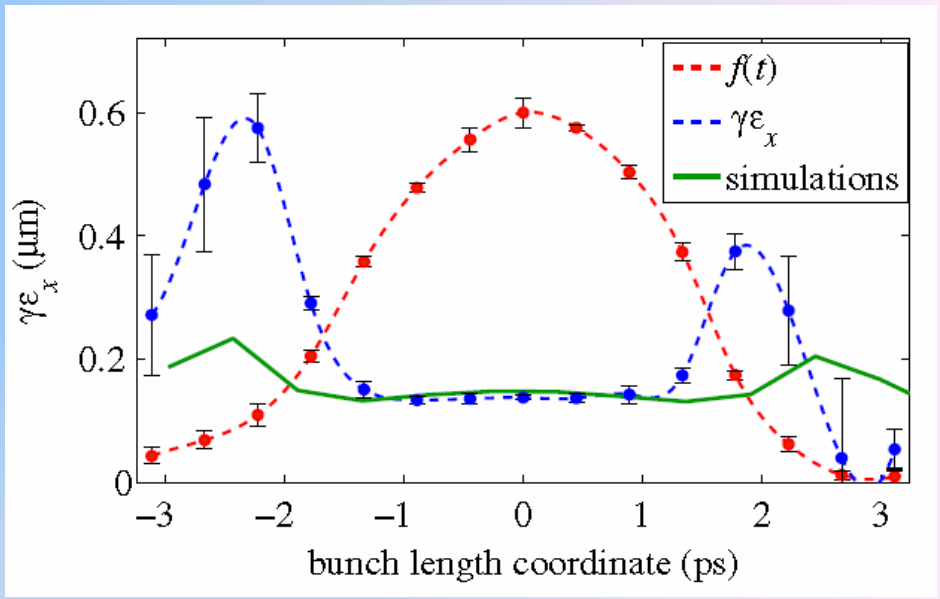


FIG. 2: Horizontal rms beam size (the center time-slice) on OTR2 versus an upstream quadrupole magnet strength. The curve is fitted to the data to calculate the emittance.

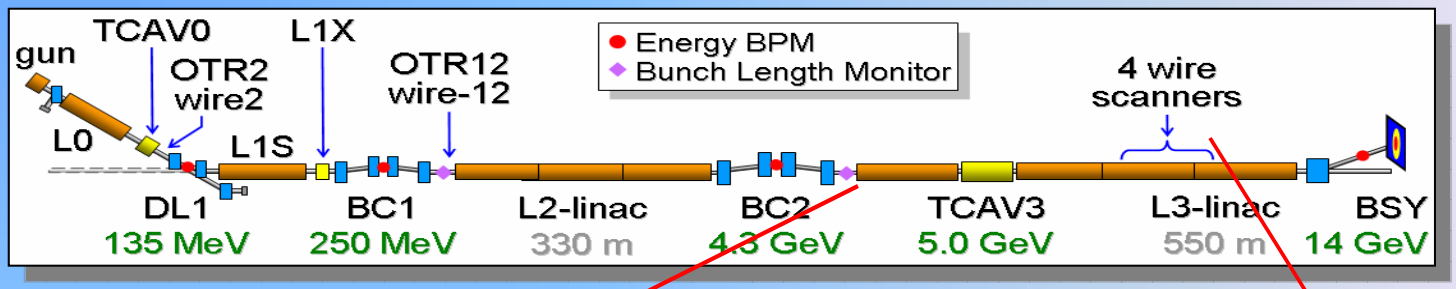
time-sliced emittance



Impact-T simulations are based on the measured thermal emittance.

laser phase: -30 deg,
laser spot 0.6 mm,
Gaussian temporal shape of 4 ps (fwhm).

Measurements and Simulations for 20-pC Bunch in linac



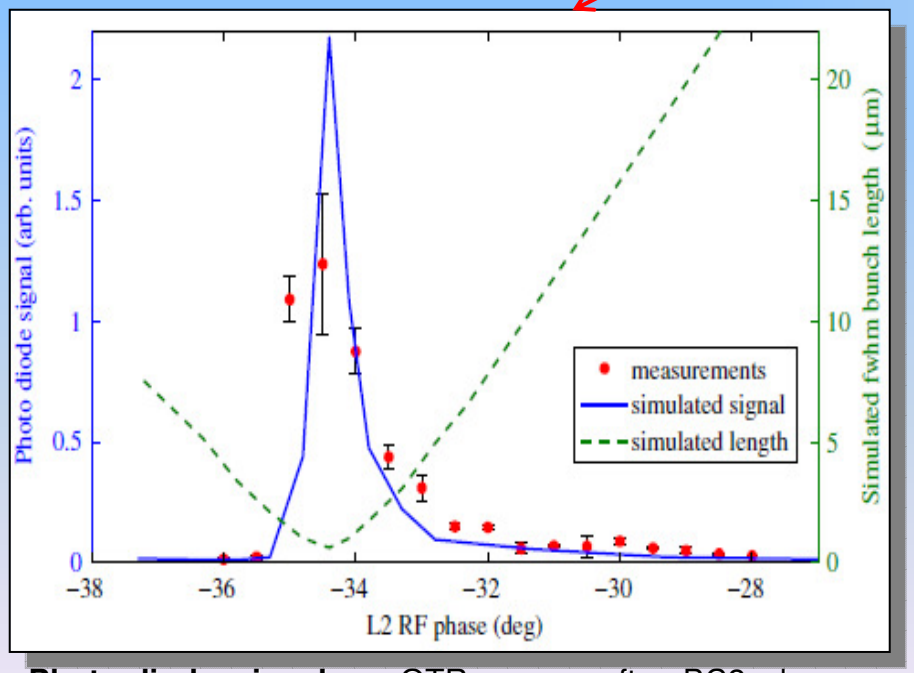
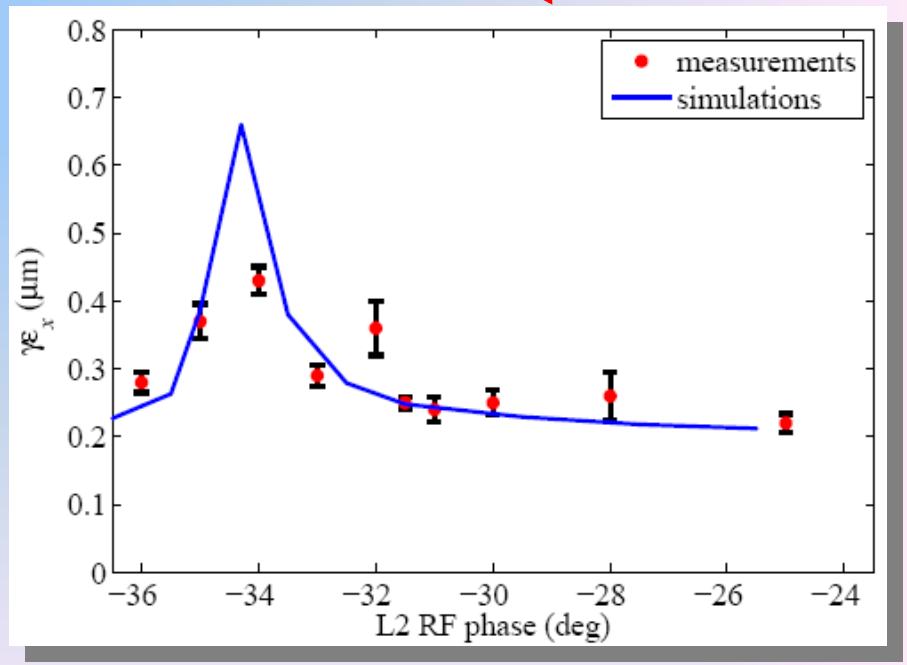


Photo-diode signal on OTR screen after BC2 shows minimum compression at L2-linac phase of -34.5 deg.



Horizontal projected emittance **measured** at 10 GeV, after BC2, using 4 wire-scanners.

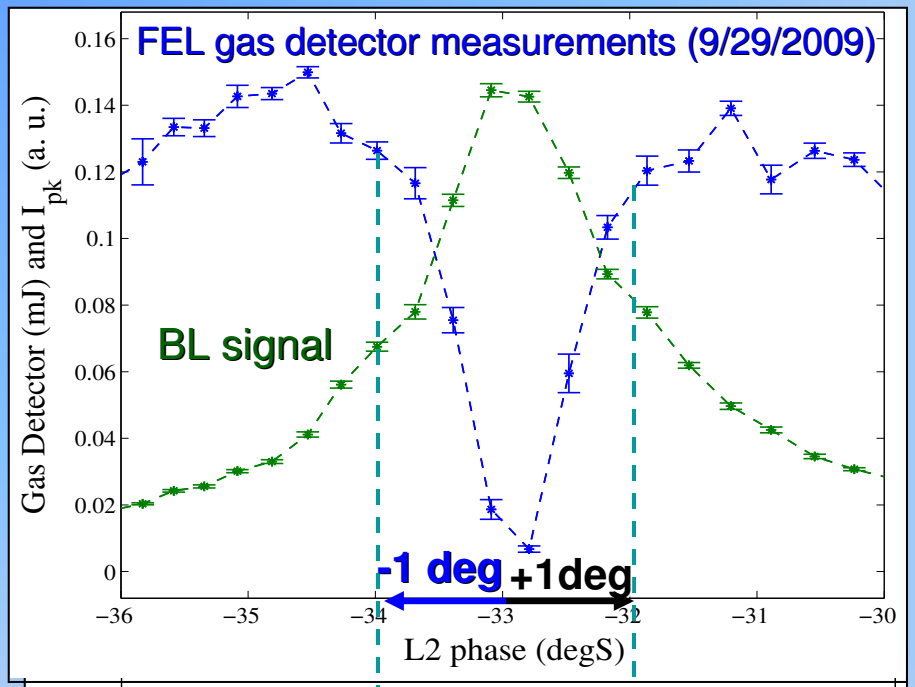
Y. Ding et. al, PRL 2009

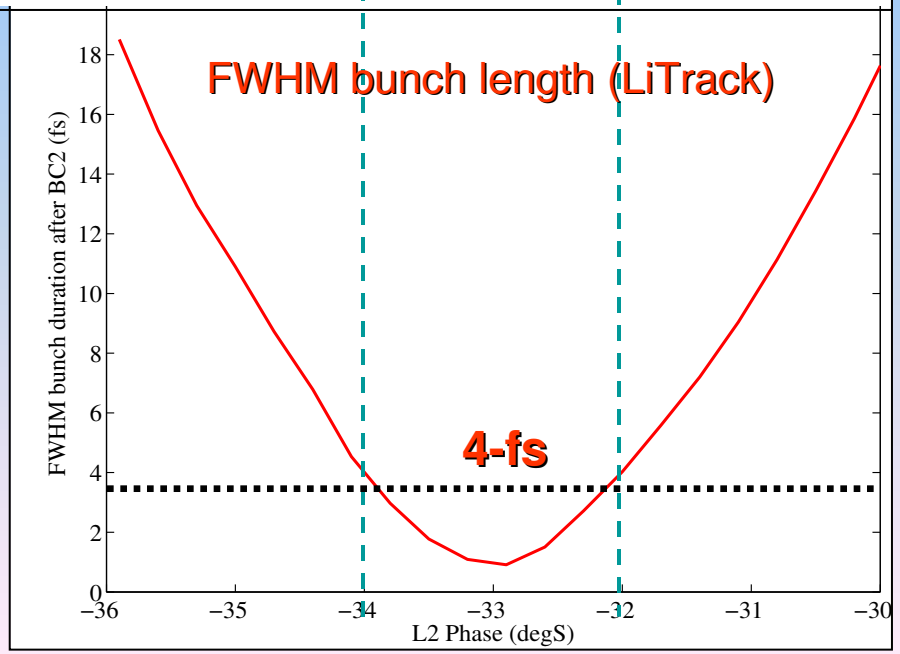
Soft x-rays

- Measurements
- Simulations
- Slotted foil
- Spectrum
- Charge dependence

photon energy @ 840 eV

20 pC Soft X-ray studies





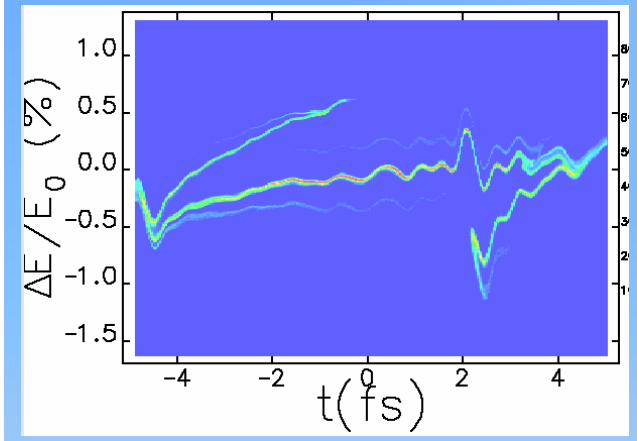
Half of undulators inserted (to prevent pulse lengthening due to slippage after FEL saturation)

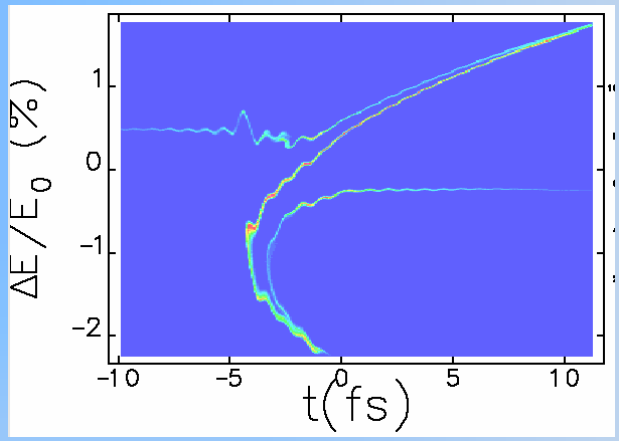
LiTrack simulation assumes
- 20 pC bunch charge
- 3 keV initial rms slice energy spread
- 0.23-mm initial rms bunch length

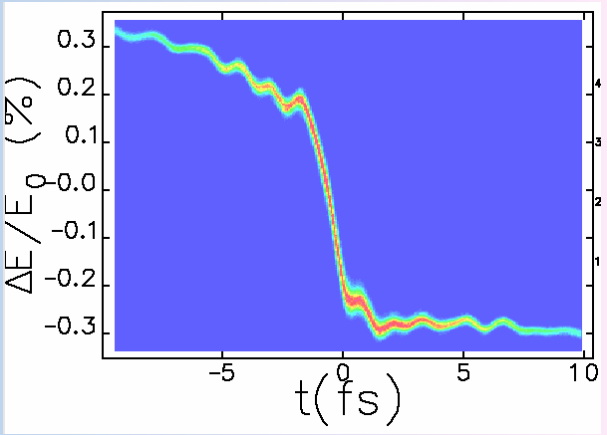
X-ray pulse duration should be <10 fs, but no direct measurement yet possible

Simulations: 1.5 nm (800eV)

At undulator entrance, 4.3 GeV, Laser heater off.



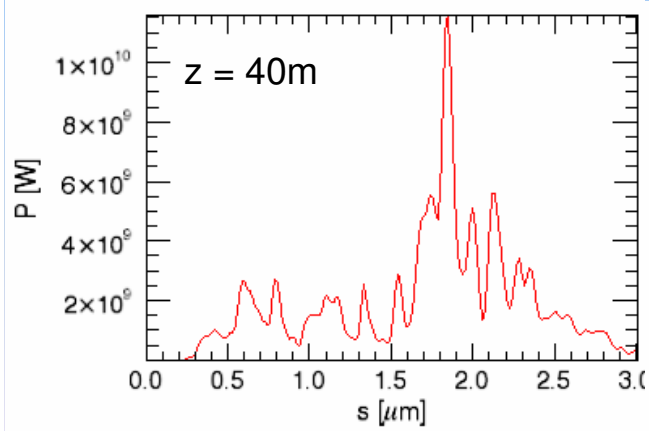


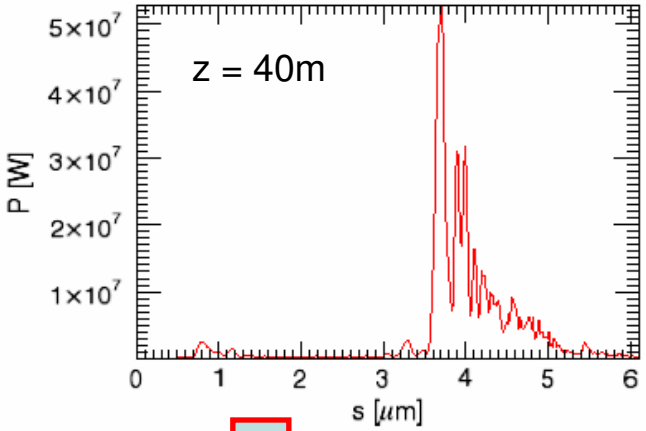


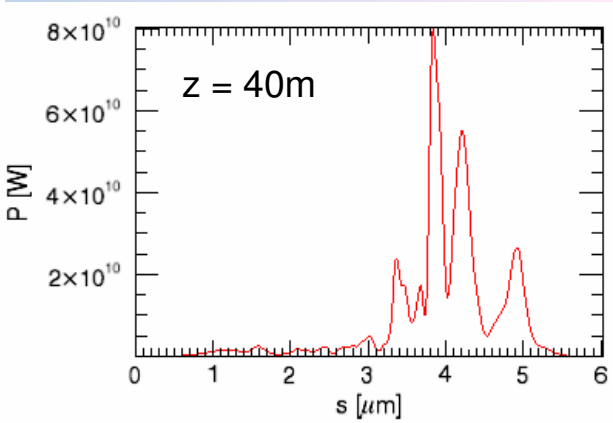
Under-compression: +1 deg off

Full-compression

Over-compression: -1 deg off

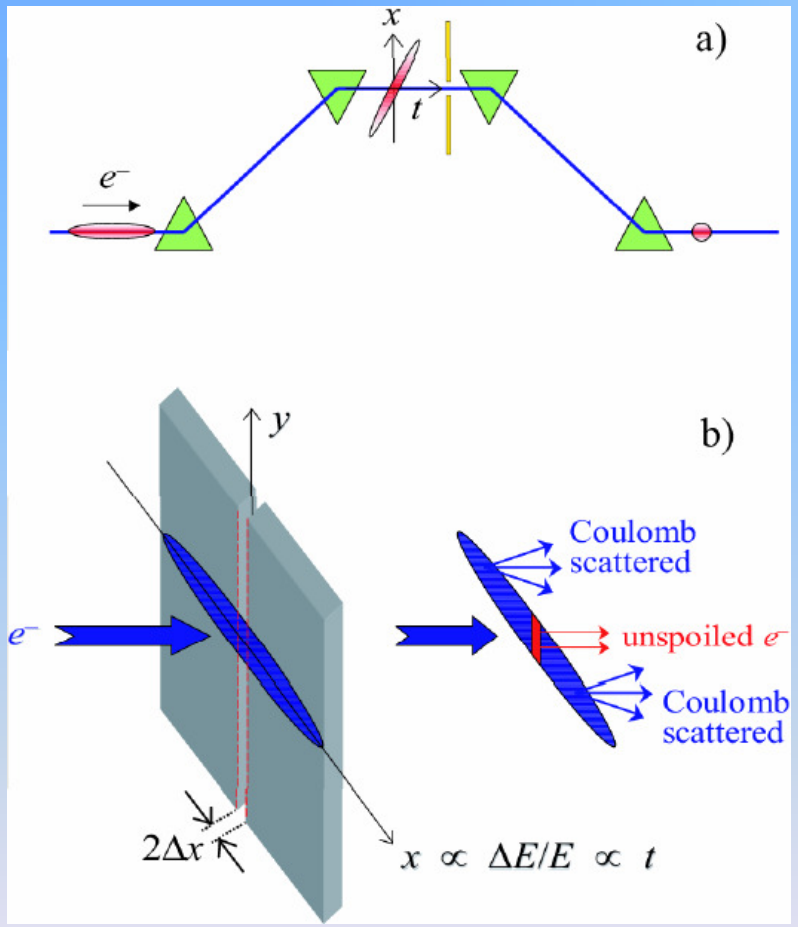






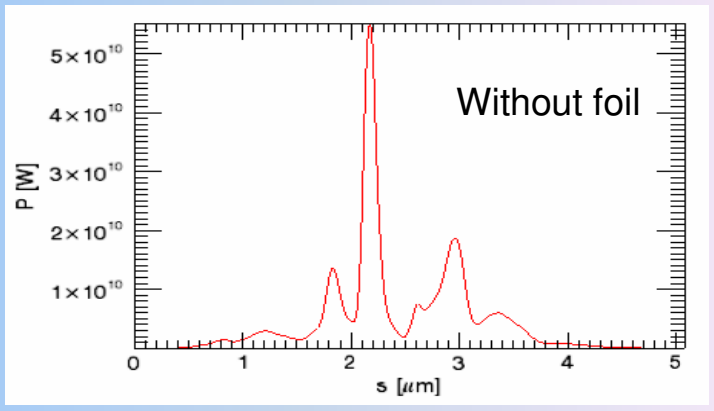
At full-compression, the FEL peak power is about 3 orders lower.

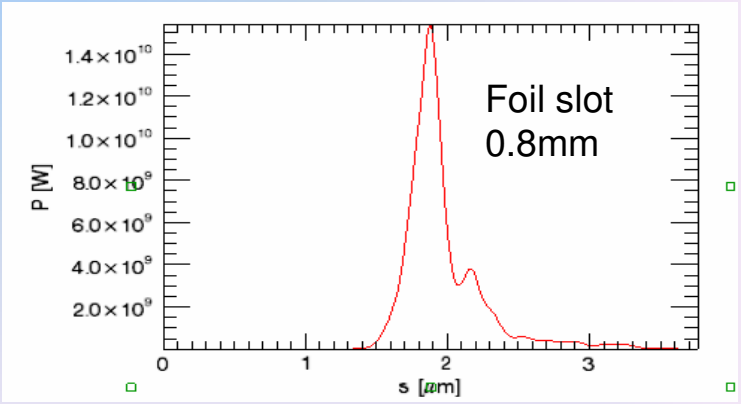
Slotted-foil at 20 pC



(P. Emma et al., PRL 2004)

Simulations: 4.3 GeV, 1.5 nm, Z = 35m.



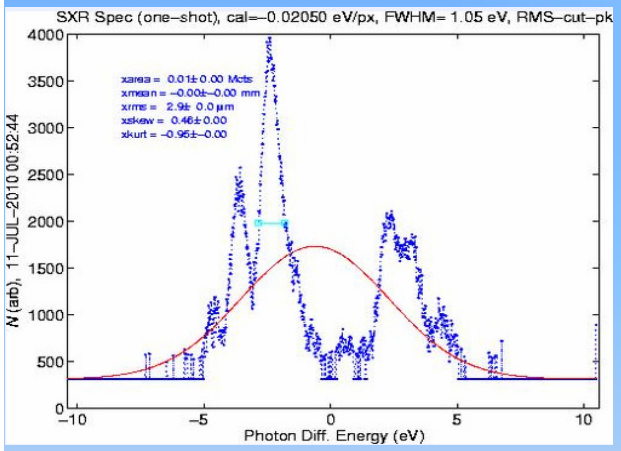


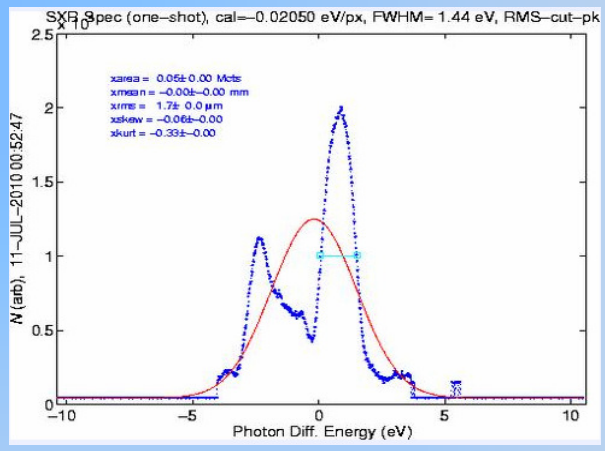
(Lanfa Wang)

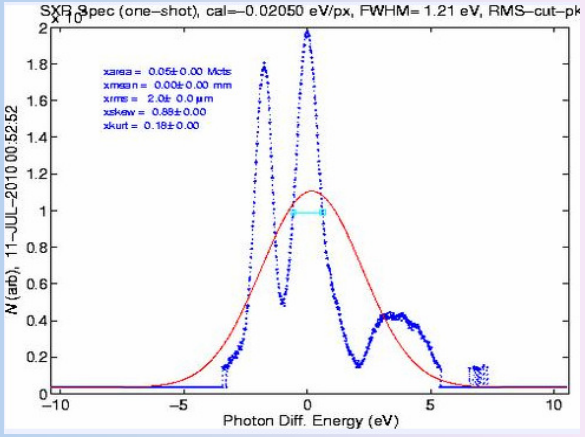
Spectrum measurements:

800eV, over-compression, und15-23 (~ z = 35m)

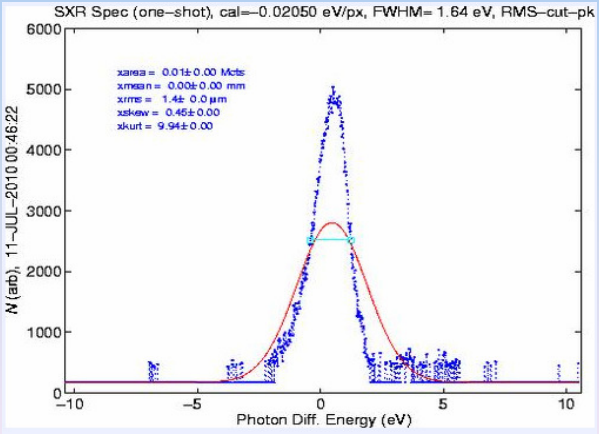
Without slotted-foil

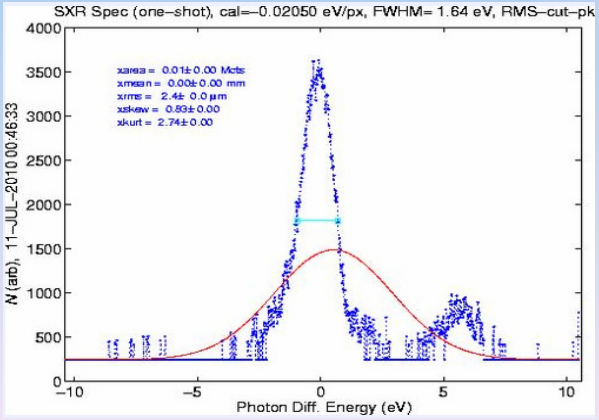


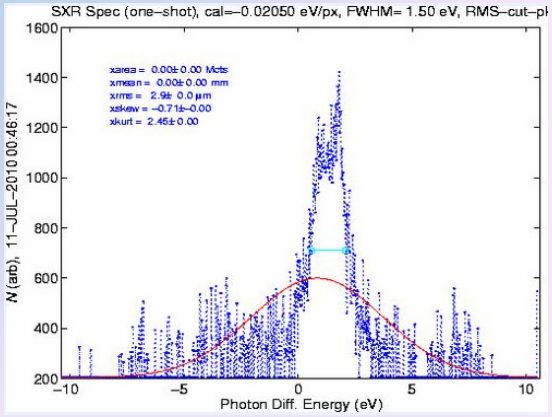




Slotted-foil width = 400um



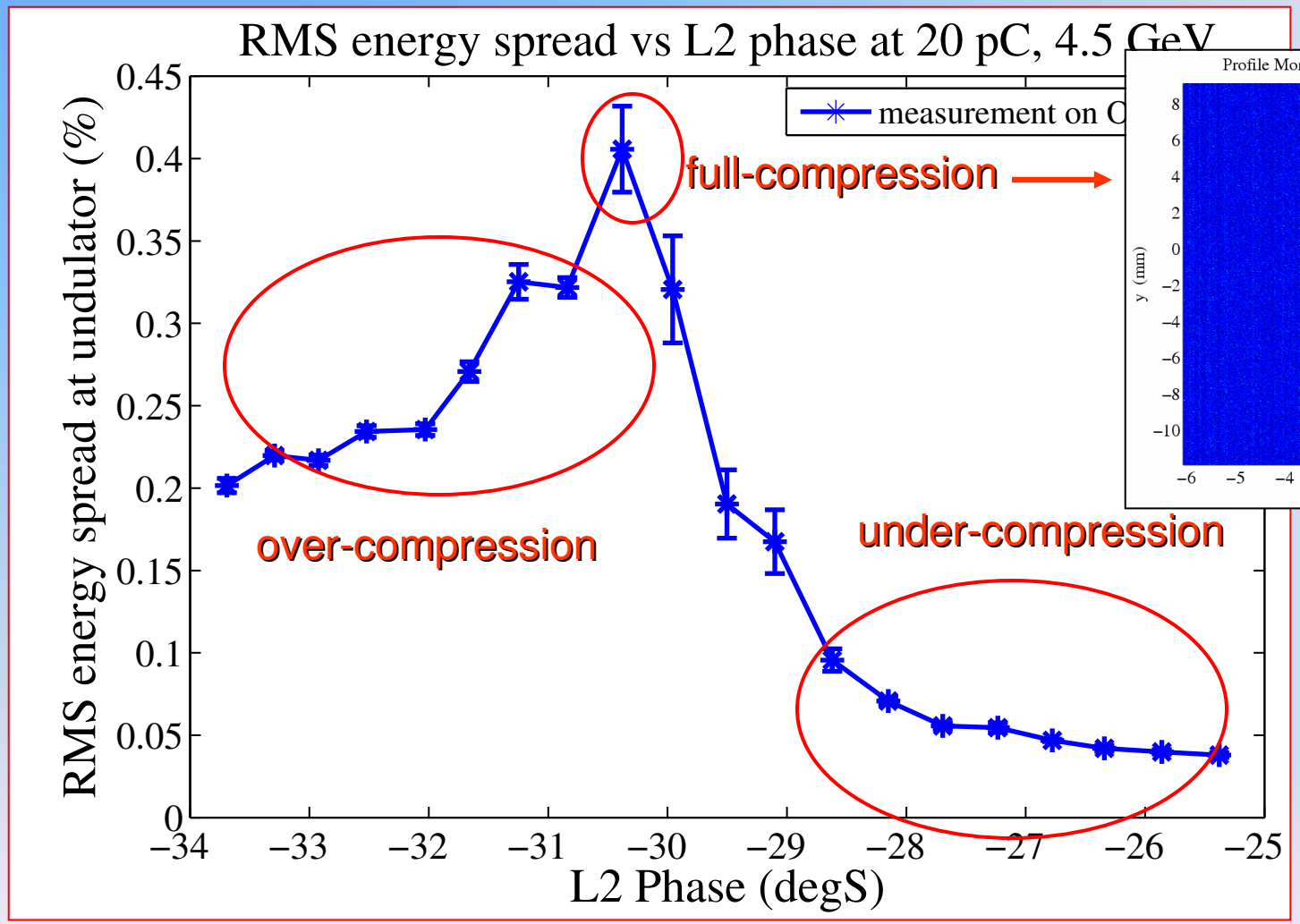


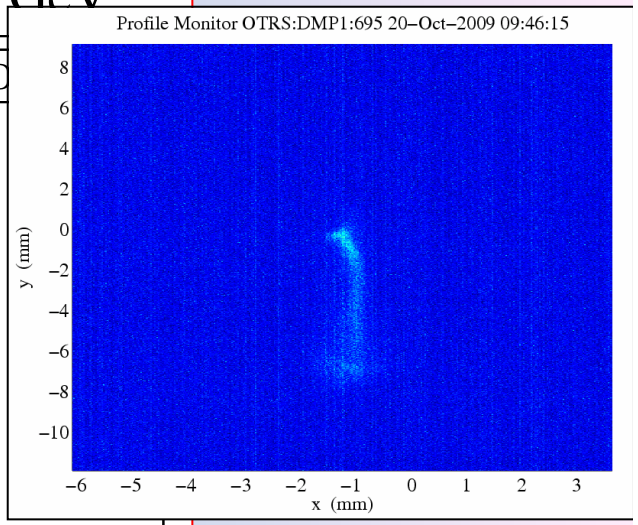


(G. Williams et al.)

Measured Energy spread (@ 4.5 GeV)

- Energy spread measured on the vertical dump OTR screen (FEL suppressed)

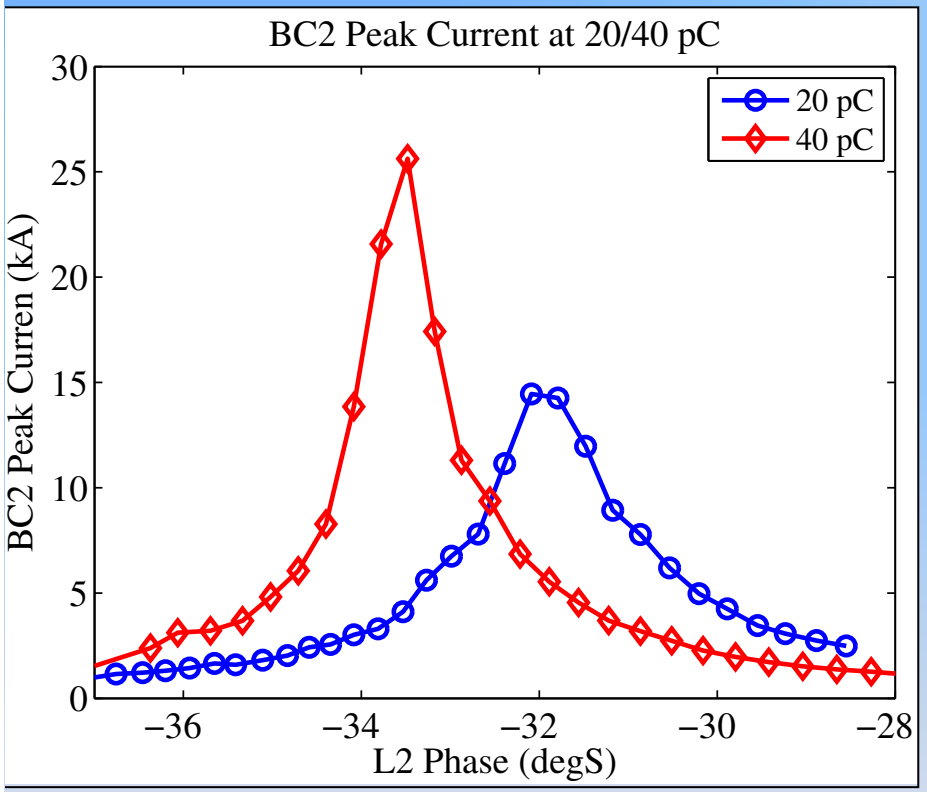


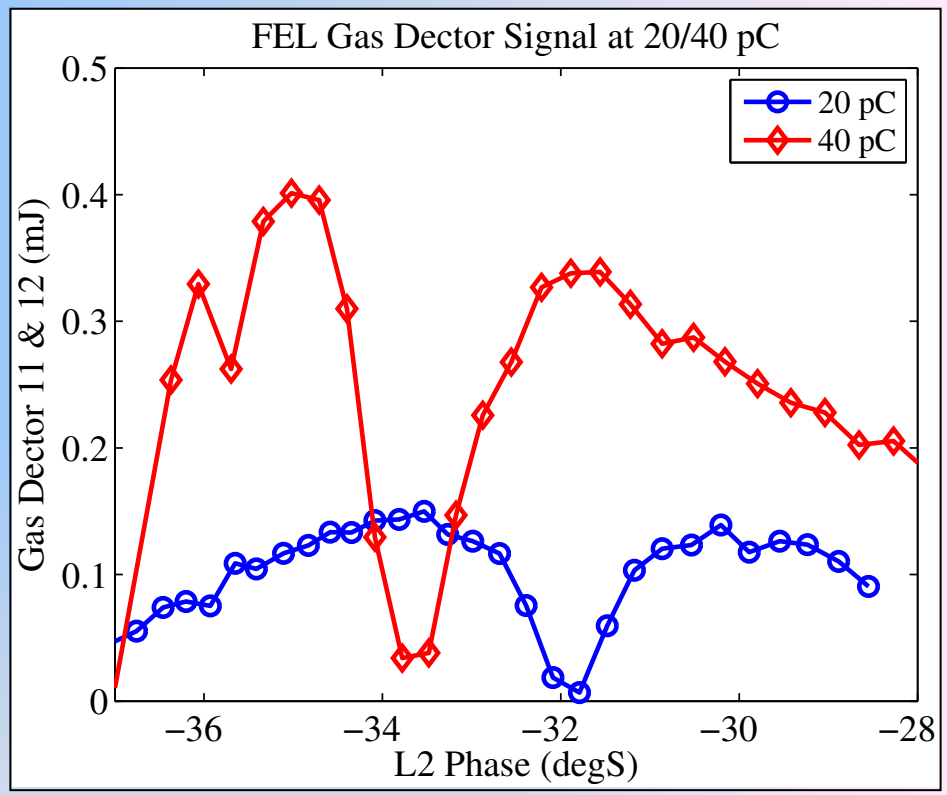


- Difference in under/over-compression shows up in FEL bandwidth

Charge dependence

- Can easily go to 40 pC (laser iris diameter 0.8 mm) or 10 pC (laser iris diameter 0.5 mm)





- FEL energy is approximately proportional to charge
- X-ray pulse length probably also increases with charge (no direct measurement yet)

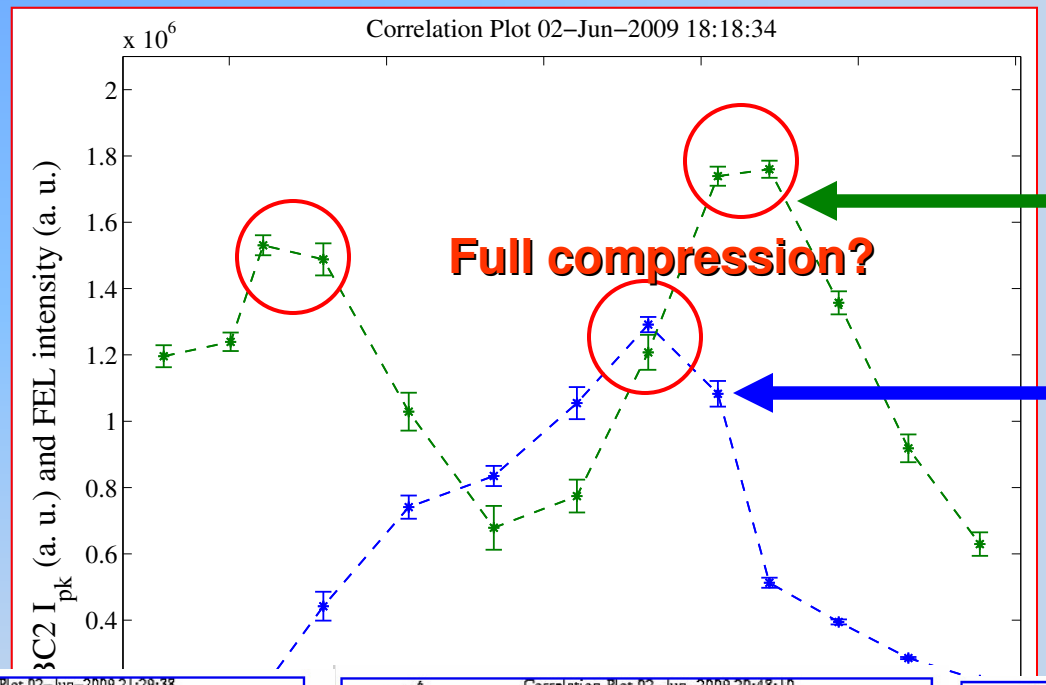
Hard x-rays

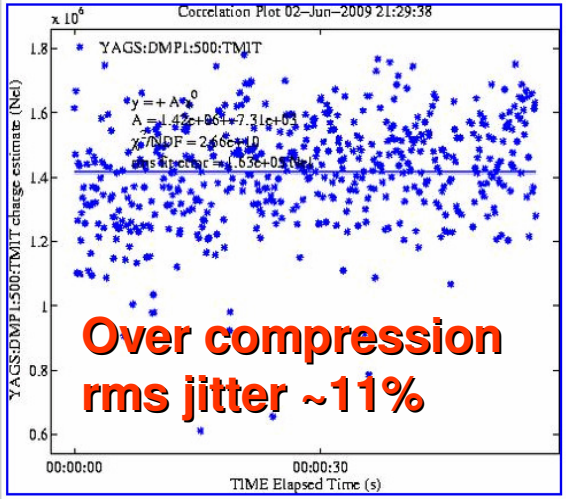
(13.6 GeV, 1.5 Å)

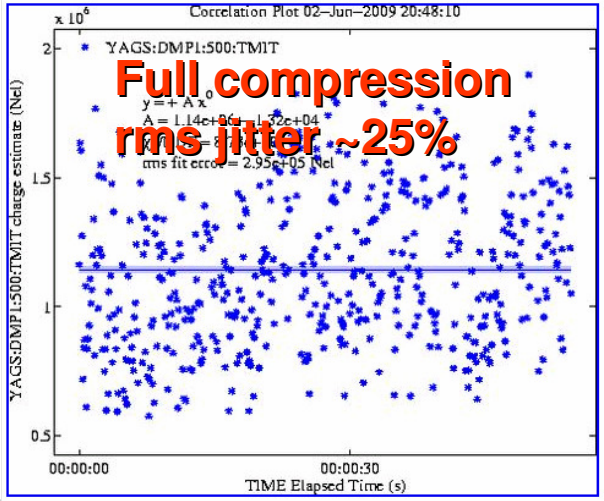
- Measurements
- Gain length
- Full compression

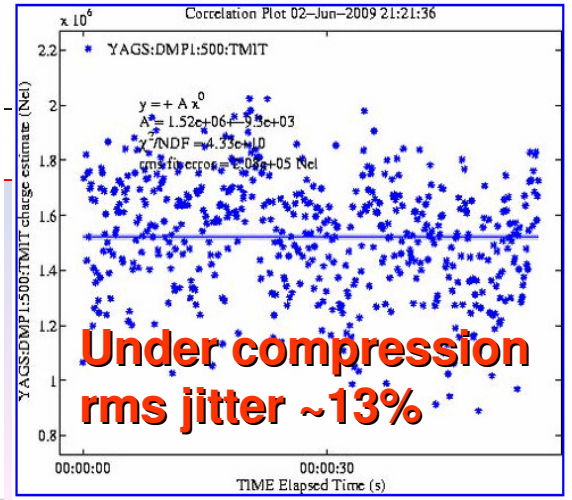
20 pC hard X-ray measurements

- Results shown here from June 2009.
- Full 33 undulator with fixed und. taper (13.6 GeV, 1.5 Å)



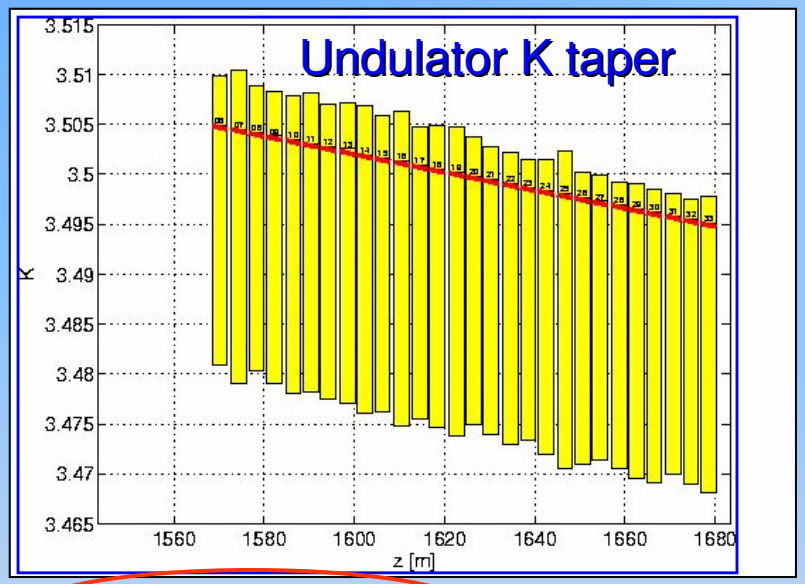


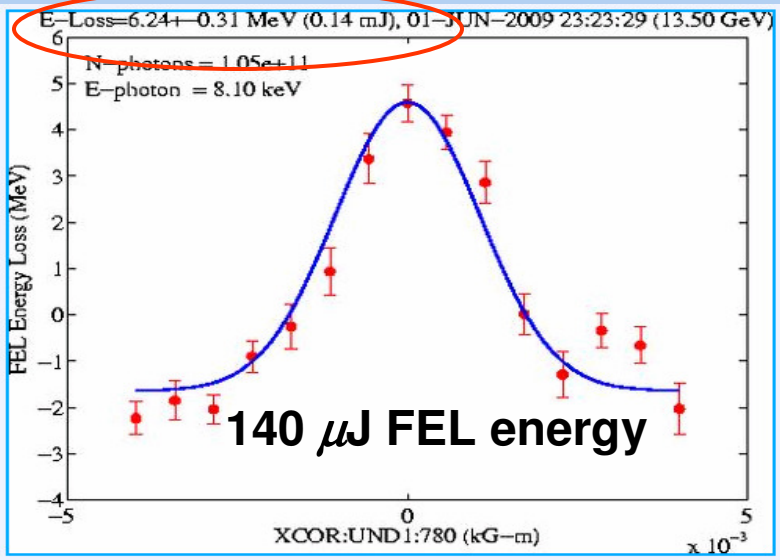


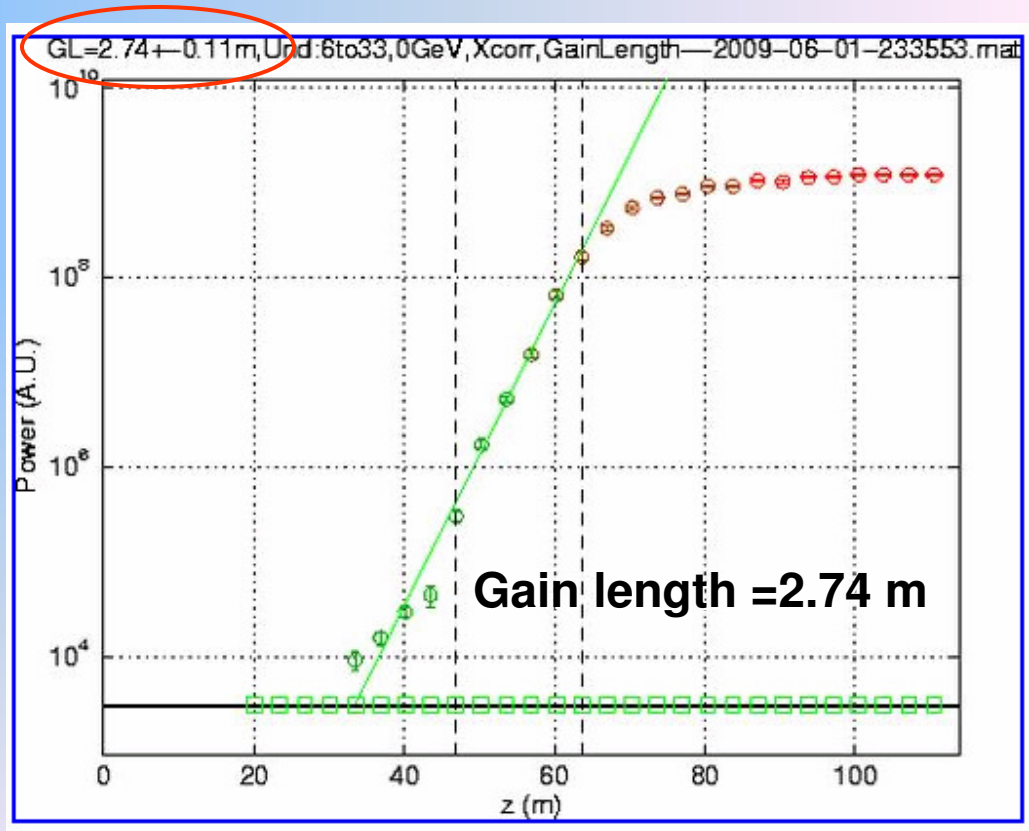


Gain length and FEL energy at Full compression

- Unlike soft x-rays, FEL can perform well @ full-compression for the hard x-ray case (~140 μJ with 25% fluctuation)

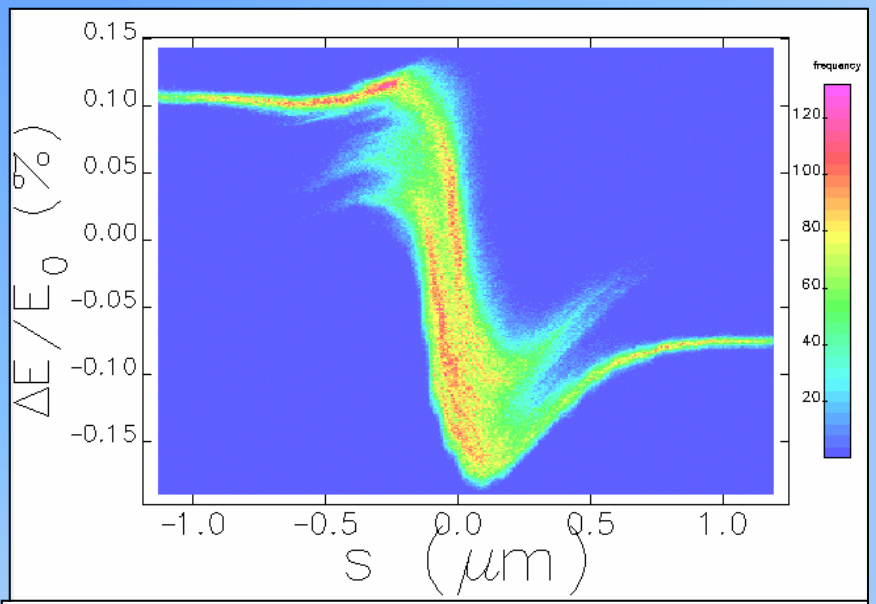


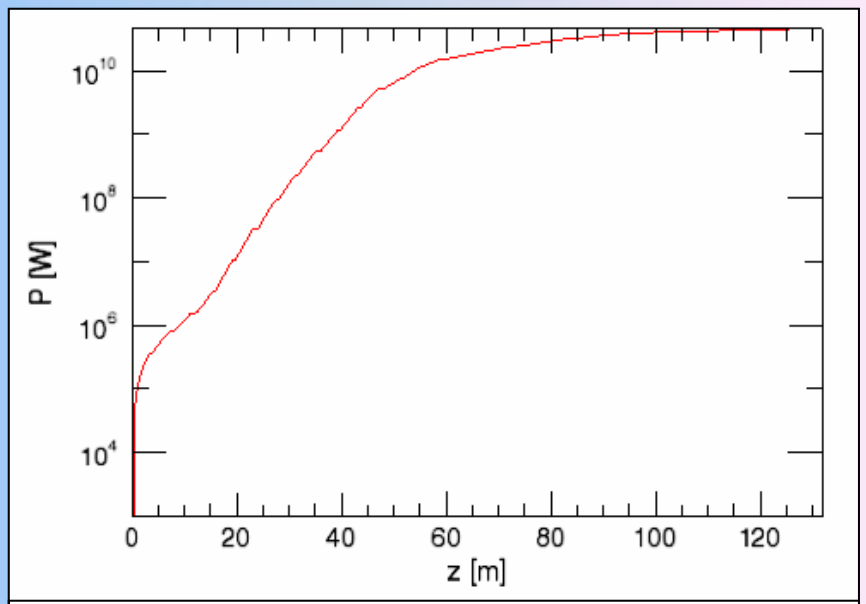


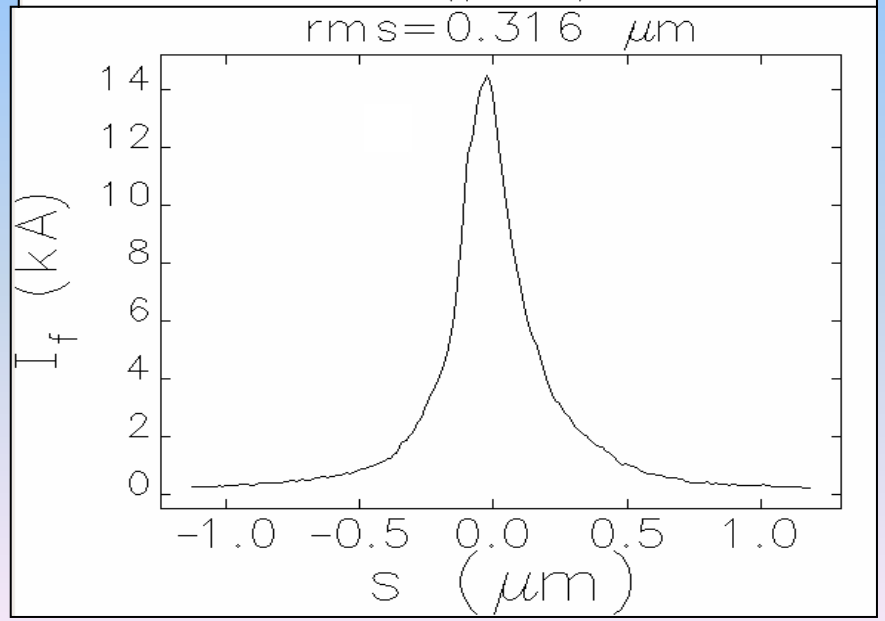


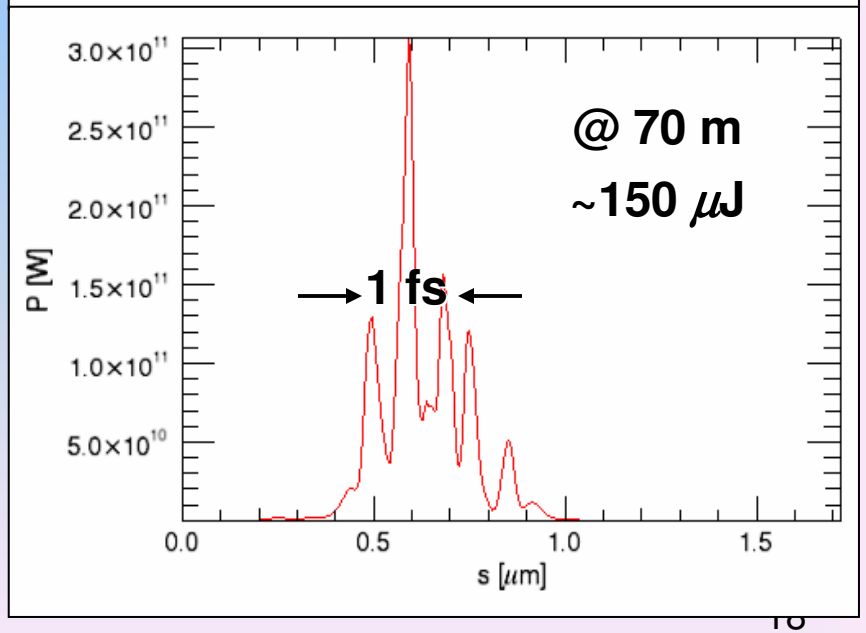
- (13.6 GeV, 1.5 Å)

Simulations: BC2 full compression, 13.6 GeV









L1 = -22 deg.

Summary & discussions

- LCLS low charge beams deliver short x-ray pulses (<10 fs) to soft x-ray users (hard x-rays also available)
- Future x-ray FEL designs may benefit from low charge configurations
  - Smaller emittance ➔ lower beam energy for the same λ_{FEL}
  - Less charge ➔ less wake, more compact accelerators (x-band?) and more bunches
- Much diagnostic challenge, especially the need for reliable bunch length measurements with fs resolution
- Can we do better on the present LCLS machine?
- How to improve the LCLS-II design considering the <20pC?