Recent Advances and New Techniques in Visualization of Ultra-short Relativistic Electron Bunches

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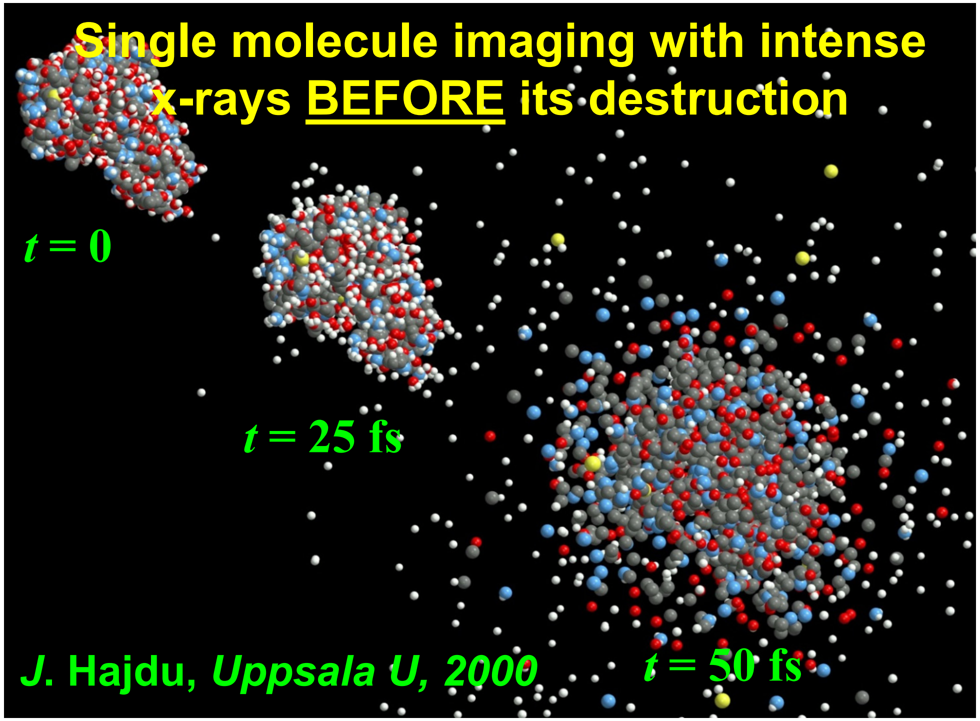
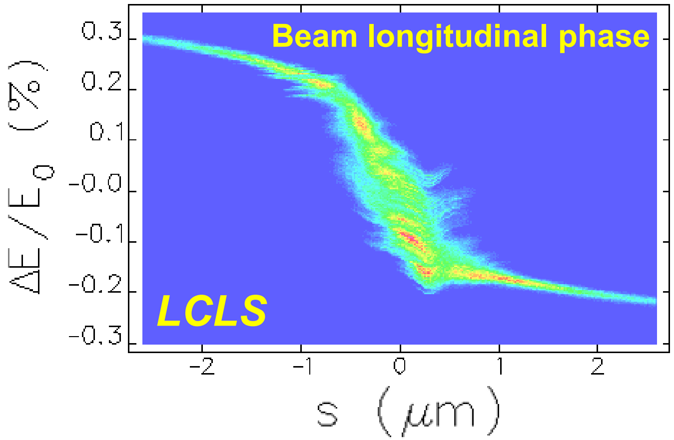
05/23/2012

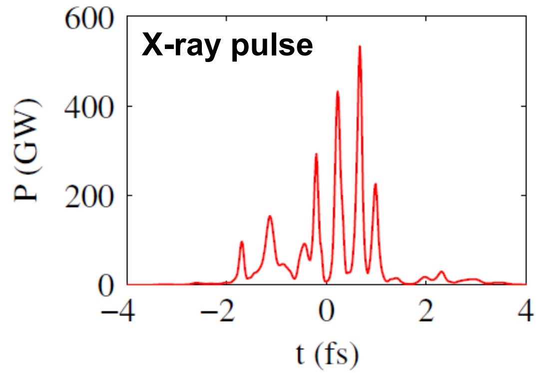
IPAC12, New Orleans

Need for ultra-short bunches

- Ultra-short x-rays in free-electron lasers (FELs)







Diffraction before destruction

Chapman et al., Nature, 470, 73 (2011)

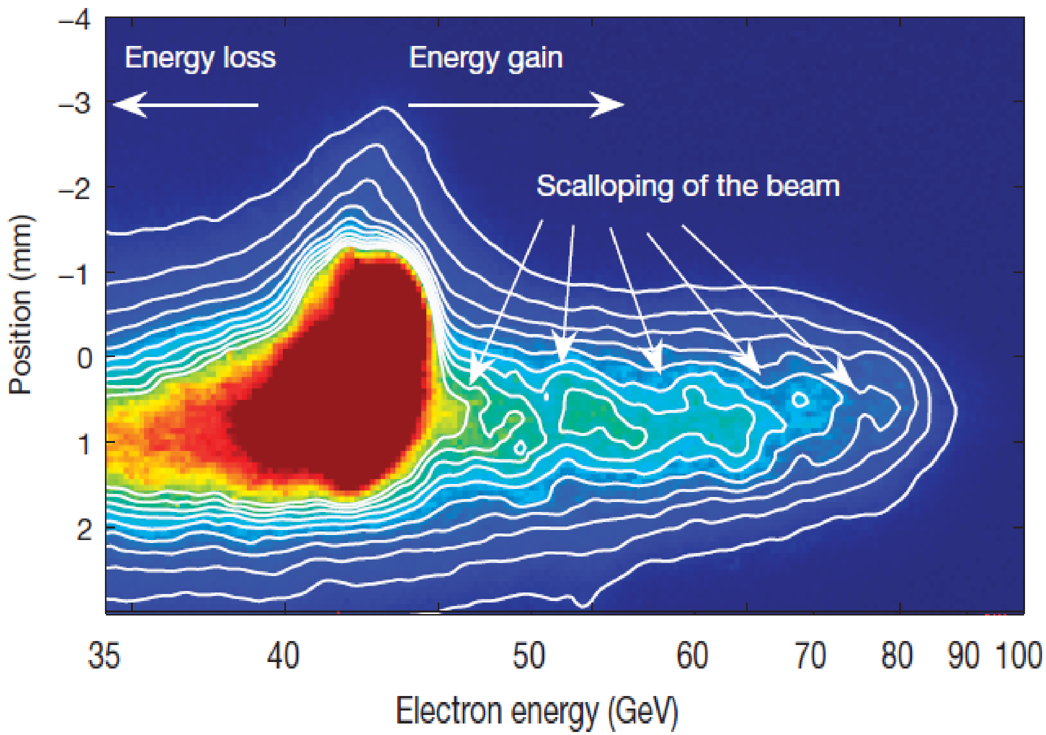
Seibert et al., Nature, 470, 78 (2011)

Ding et al., PRL, 102, 254801 (2009)

Emma et al., Nature Photon., 4, 641 (2010)

Need for ultra-short bunches

- Plasma wake-field acceleration and high field physics



$$E_z \sim \frac{Q}{\sigma_t^2}$$

E167 $Q = 3\text{nC}$ $\sigma_t = 50\text{fs}$

$E_z \approx 50\text{GeV/m}$

LCLS $Q = 20\text{pC}$ $\sigma_t = 1\text{fs}$

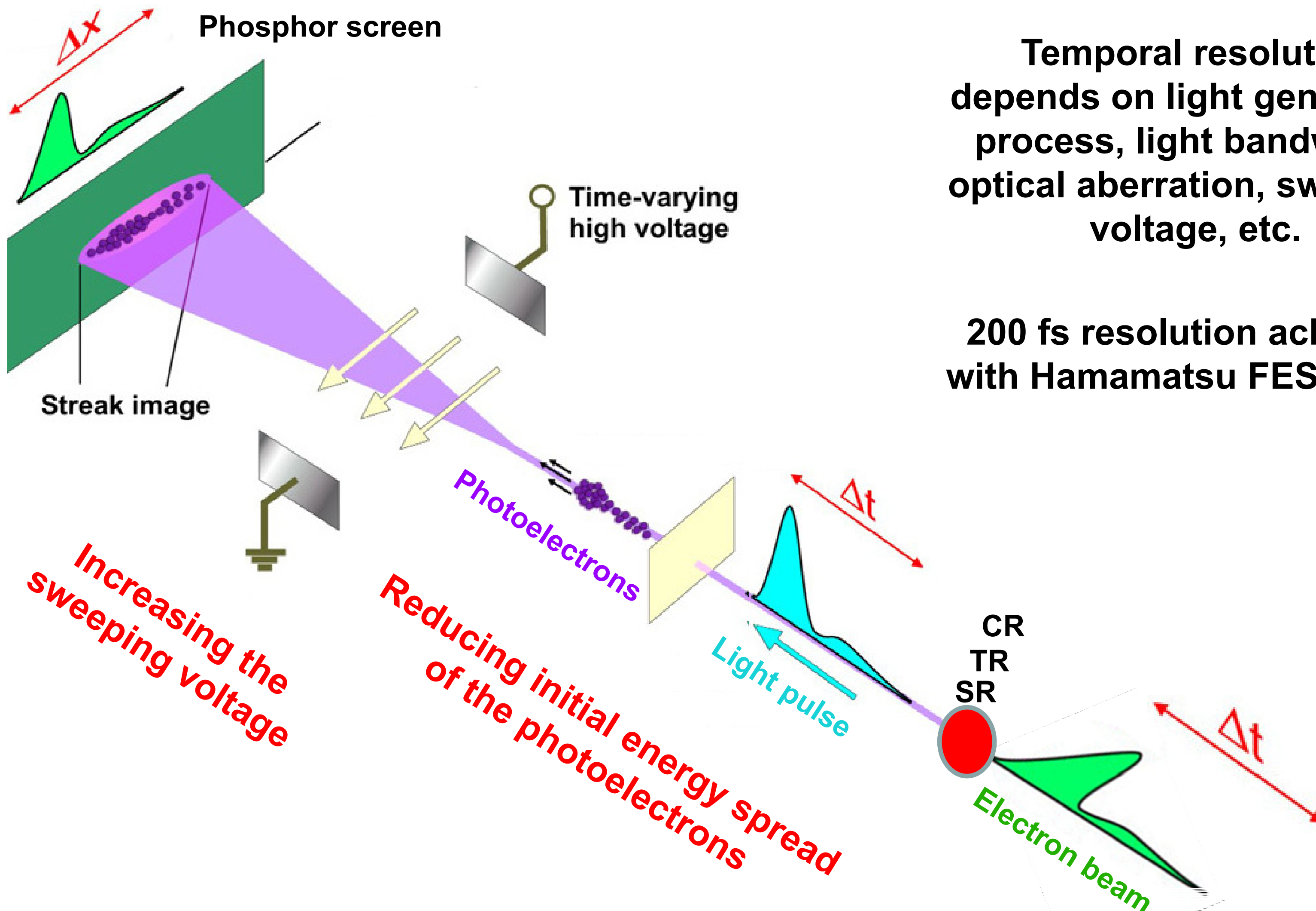
$E_z \approx 1\text{TeV/m}$

Energy doubling of a 42 GeV beam

Blumenfeld et al., Nature, 445, 741 (2007)

Rosenzweig et al., NIM A, 653, 98 (2011)

Streak camera

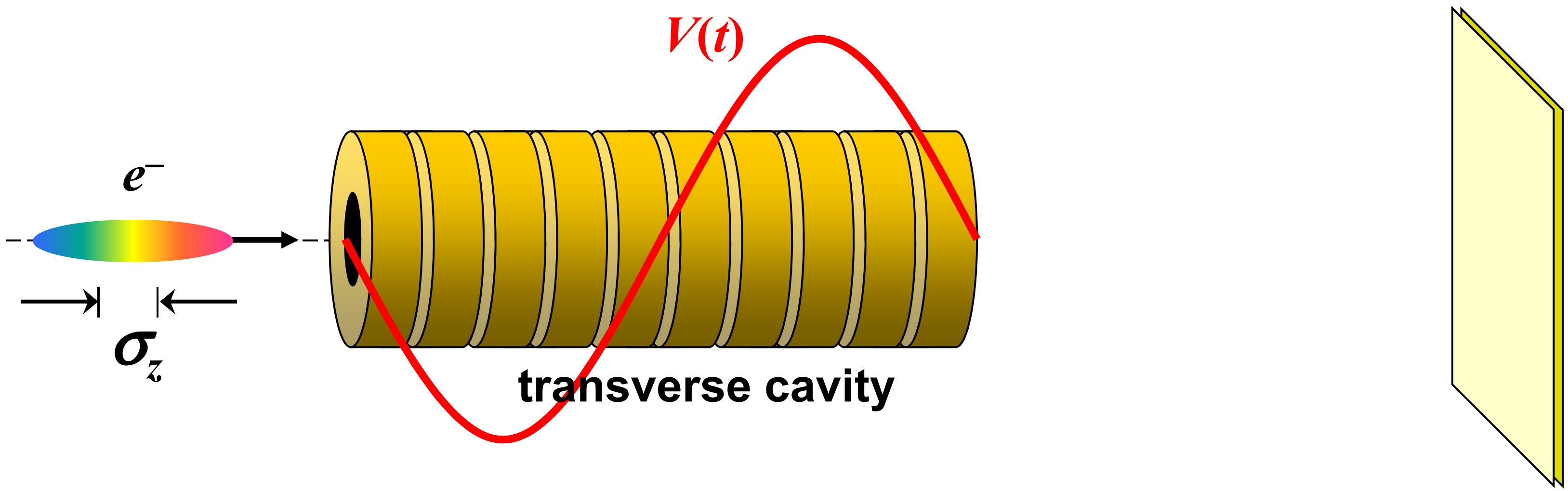


Temporal resolution depends on light generation process, light bandwidth, optical aberration, sweeping voltage, etc.

200 fs resolution achieved with Hamamatsu FESCA-200

Transverse cavity

- Deflecting cavity ~ crab cavity
- Developed at SLAC in 1960's for particle separation



P. Emma

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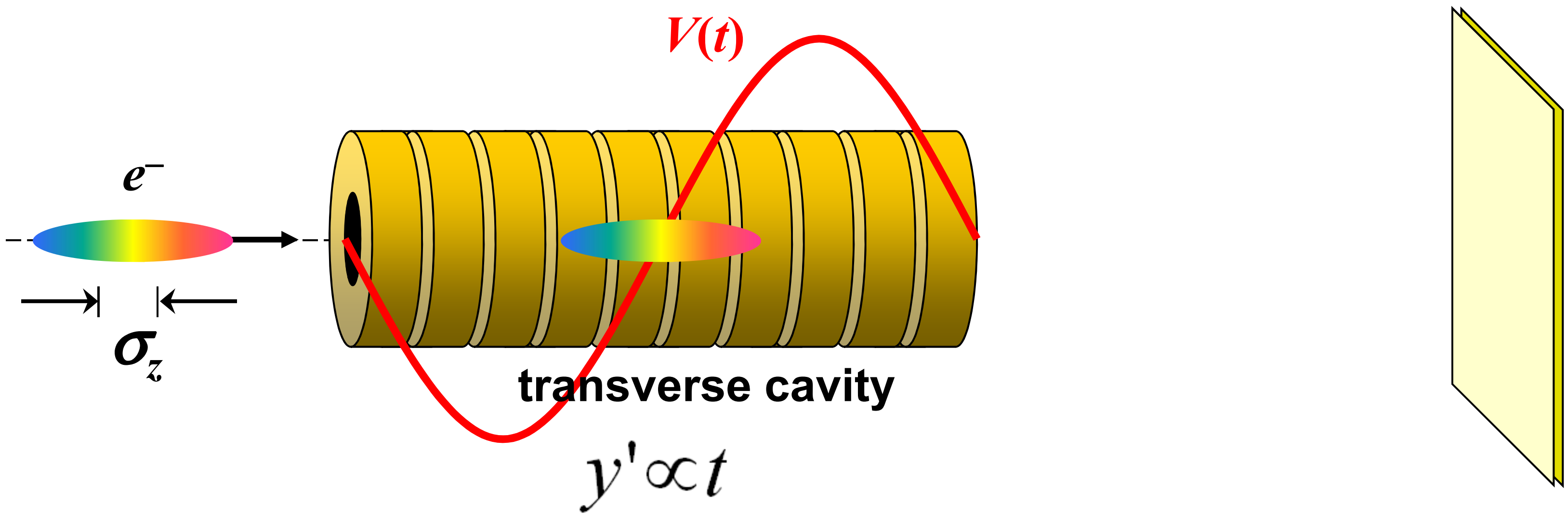

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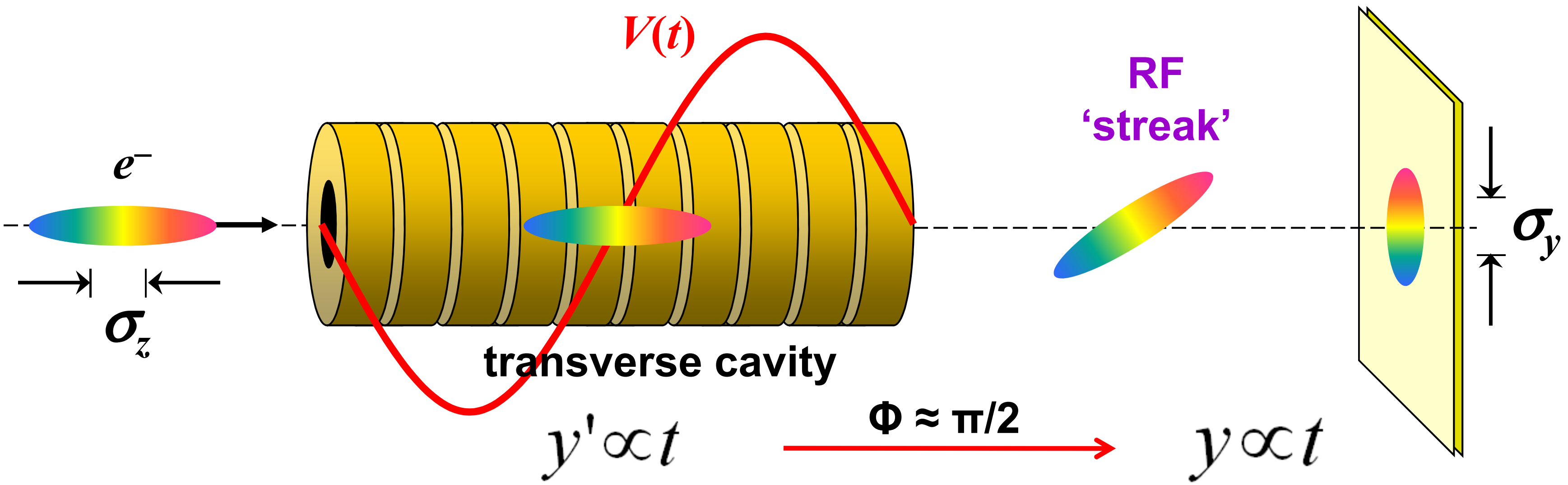
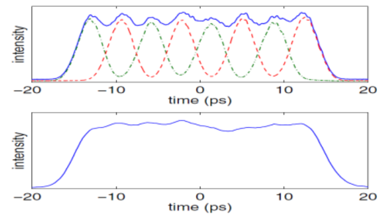


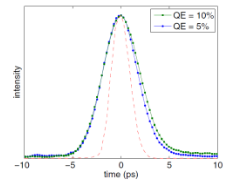
P. Emma

- Transverse cavity used to measure:
  - Absolute bunch length and temporal profile
  - Beam arrival time jitter
  - Beam slice parameters

Measure beam temporal profile

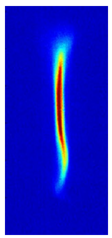
- L-band



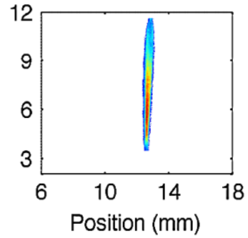


Cornell University

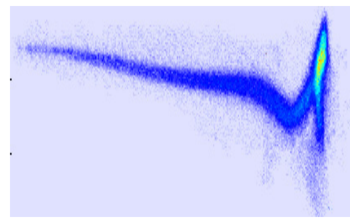
- S-band



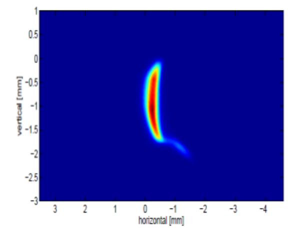
LCLS



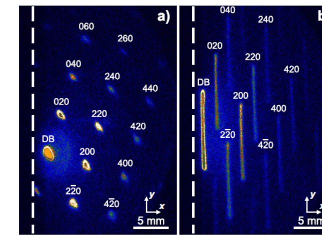
SPARC



FLASH

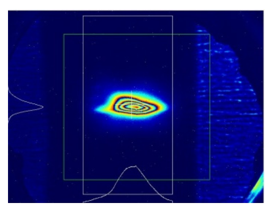


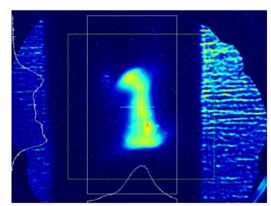
PSI



Tsinghua University

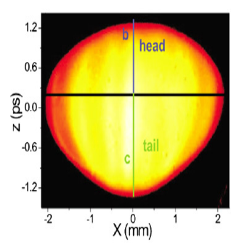
- C-band

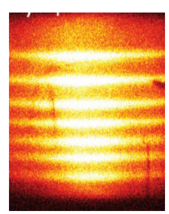




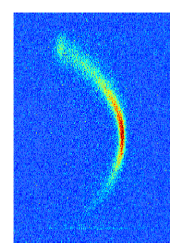
SACLA

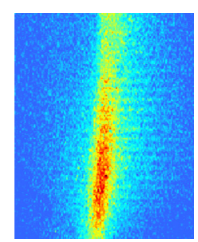
- X-band

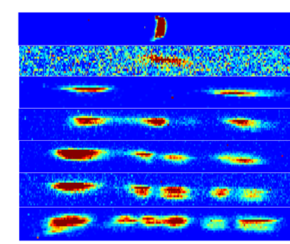




UCLA

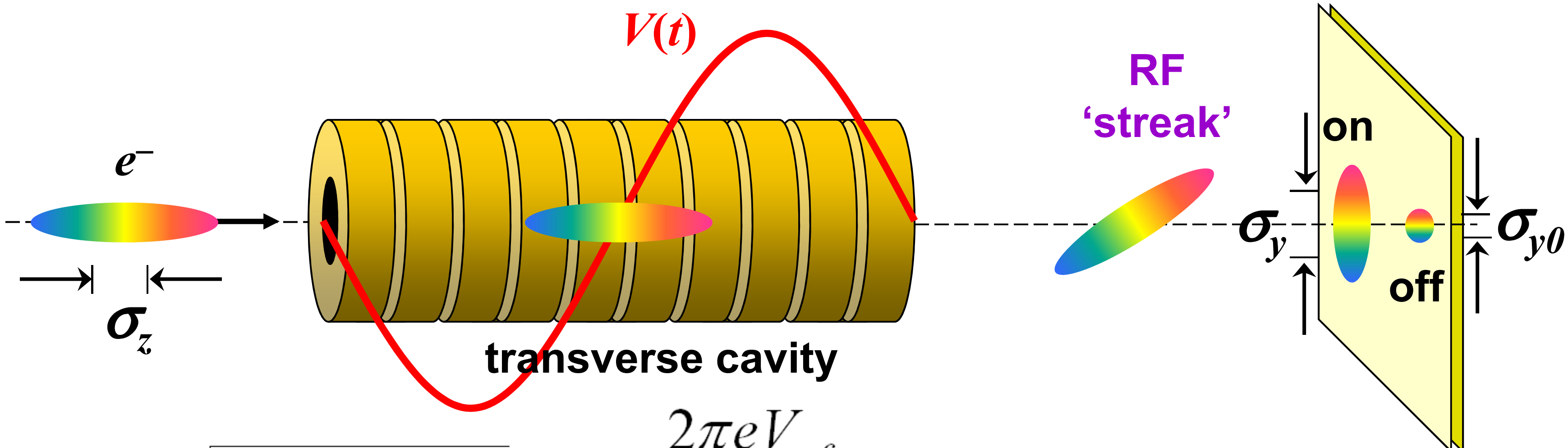






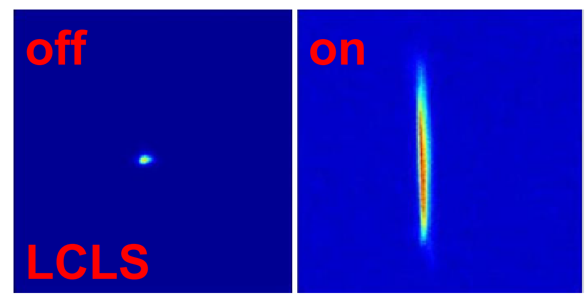
NLCTA, SLAC

Transverse cavity resolution limit



$$\sigma_y = \sqrt{\sigma_{y0}^2 + r_{34}^2 k^2 \sigma_z^2} \qquad k = \frac{2\pi e V_{rf}}{\lambda_{rf} E}$$

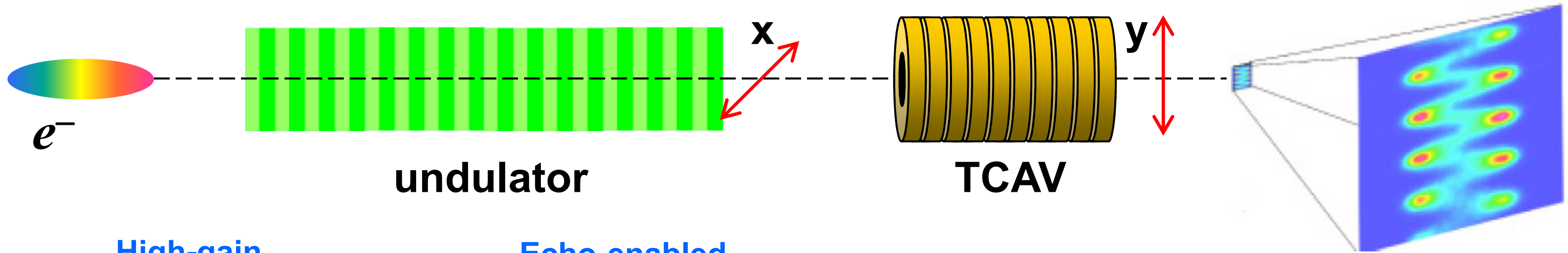
$$\Delta t \approx \frac{\sigma_{y0}}{\sigma_y}\sigma_z \approx \frac{\sigma'_y}{k}$$



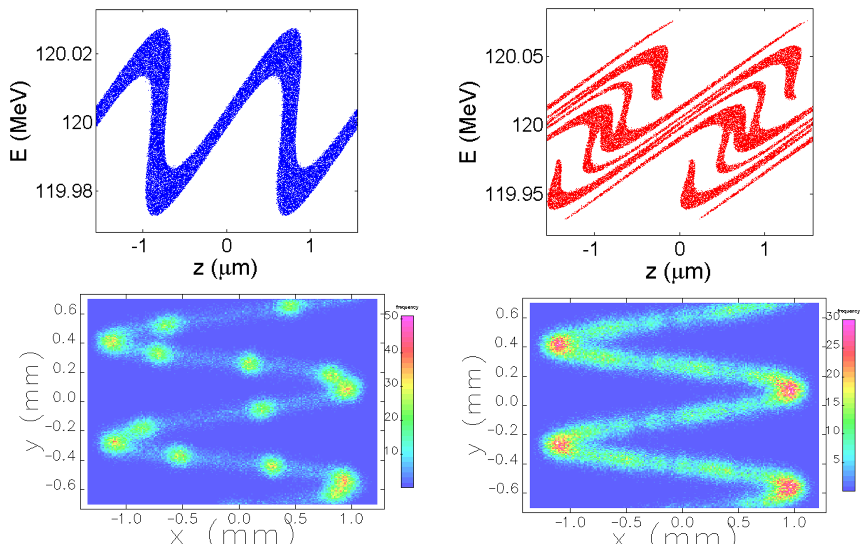
- **Improving resolution:**
  - Increasing k (increase V_{rf} or reduce λ_{rf})
  - Reduce σ'_y (or preferably remove the term σ_{y0})

Optical oscilloscope

- Replacing transverse cavity with TEM_{10} mode laser ($\div$1000 in λ)



High-gain Harmonic Generation | **Echo-enabled Harmonic Generation**



~200 as resolution

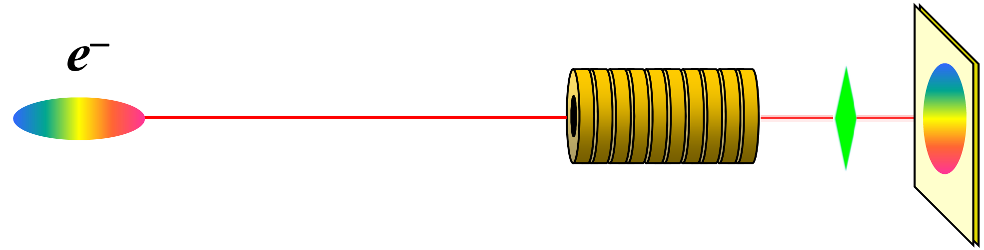
Xiang et al., PRL, 105, 114801 (2010)

- TCAV for overall bunch shape
- Laser for fine structure
- Sub-femtosecond resolution
- High power CO_2 laser
- Proof-of-principle experiment being planned in BNL ATF

Andonian et al., PRST-AB, 14, 072802 (2011)

Longitudinal-to-transverse mapping

$$\sigma_y = \sqrt{\sigma_{y0}^2 + r_{34}^2 k^2 \sigma_z^2}$$



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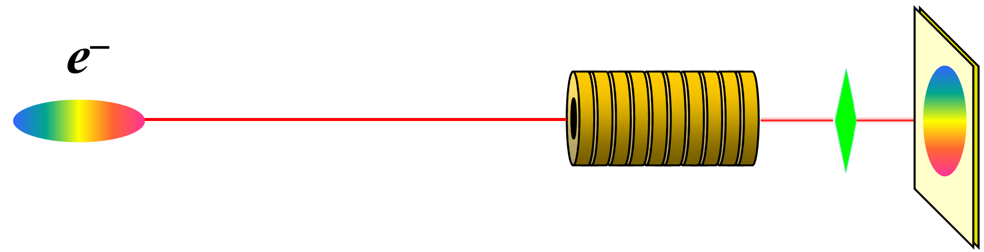

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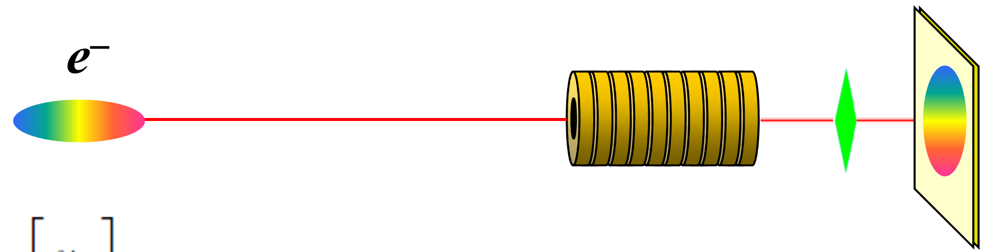

$$\begin{bmatrix} y_1 \\ y_1' \\ z_1 \\ \delta_1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & k & 0 \\ 0 & 0 & 1 & 0 \\ k & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} y_0 \\ y_0' \\ z_0 \\ \delta_0 \end{bmatrix}$$

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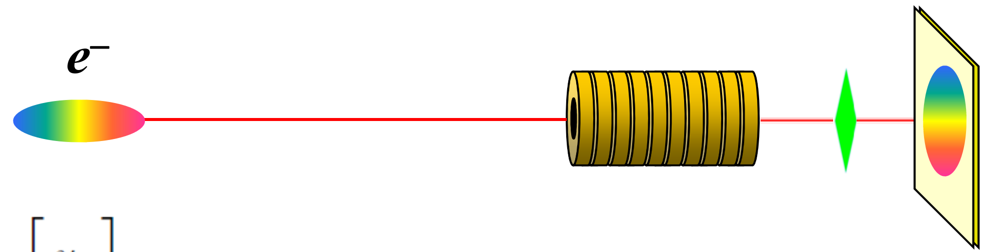

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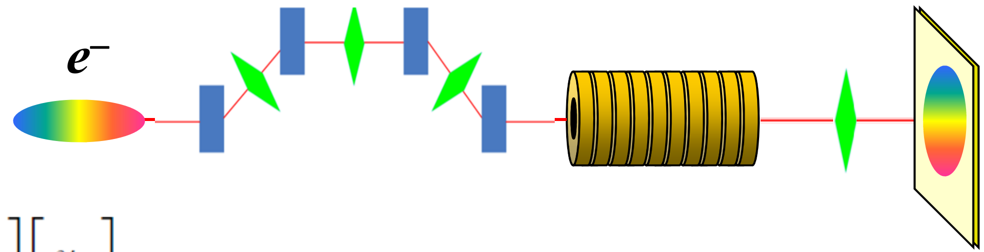

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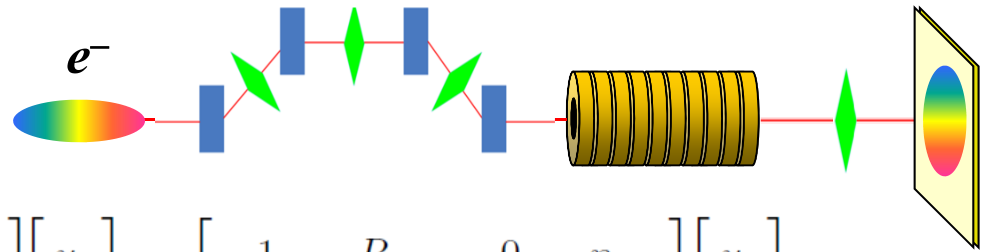

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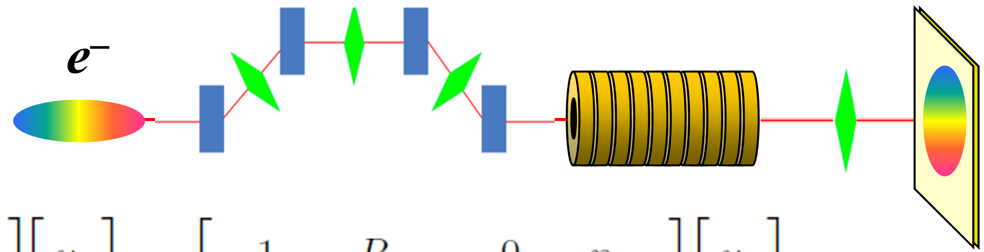

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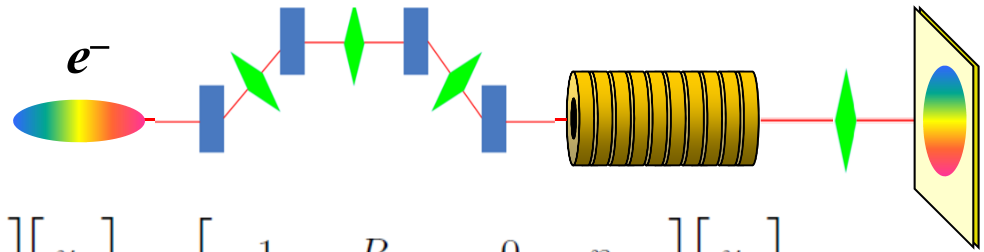

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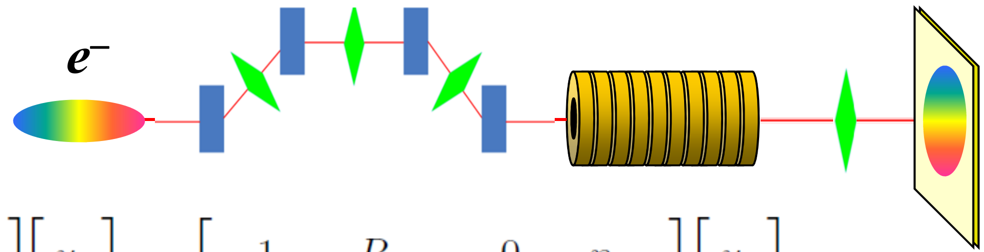

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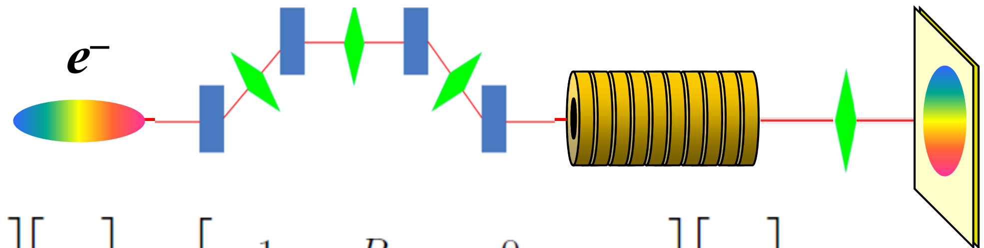

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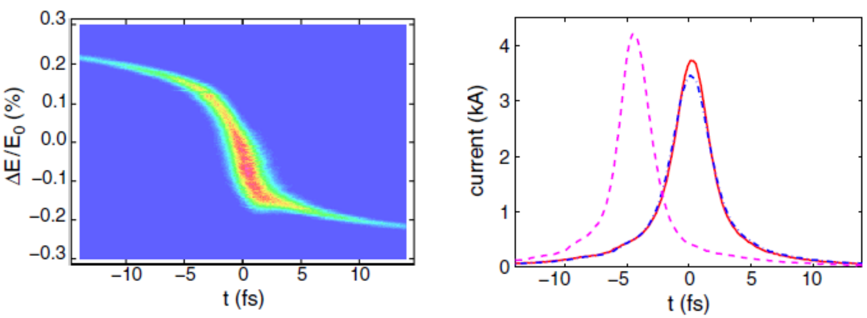
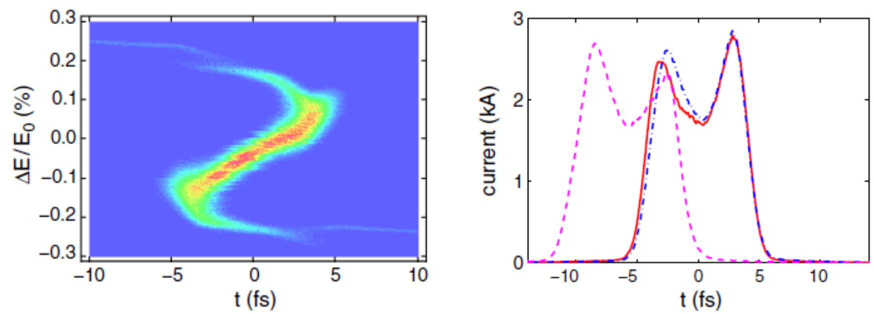
- Z exactly mapped to y; sub-fs resolution



LCLS over-compression

Xiang and Ding, PRST-AB, 13, 094001 (2010)

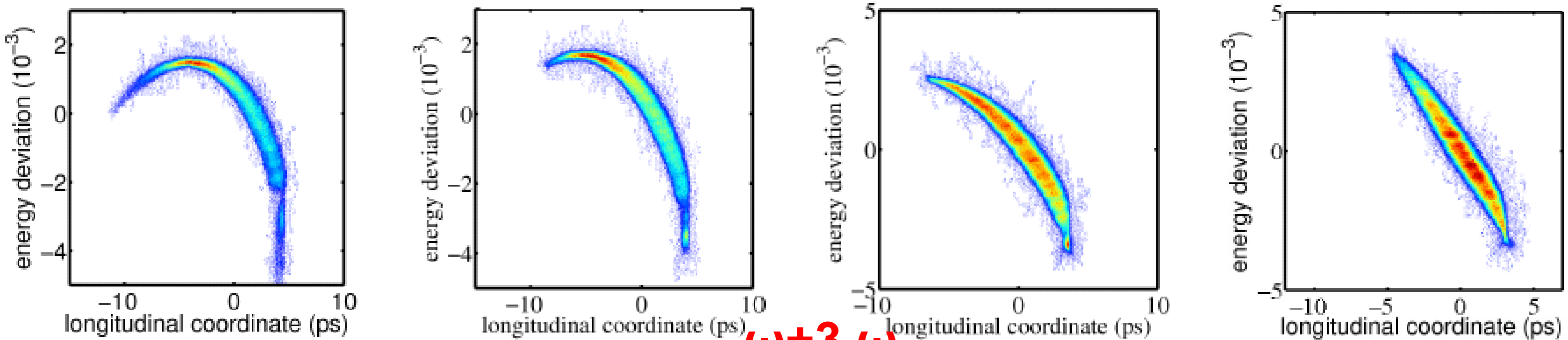


LCLS under-compression

Xiang and Chao, PRST-AB, 14, 114001 (2011)

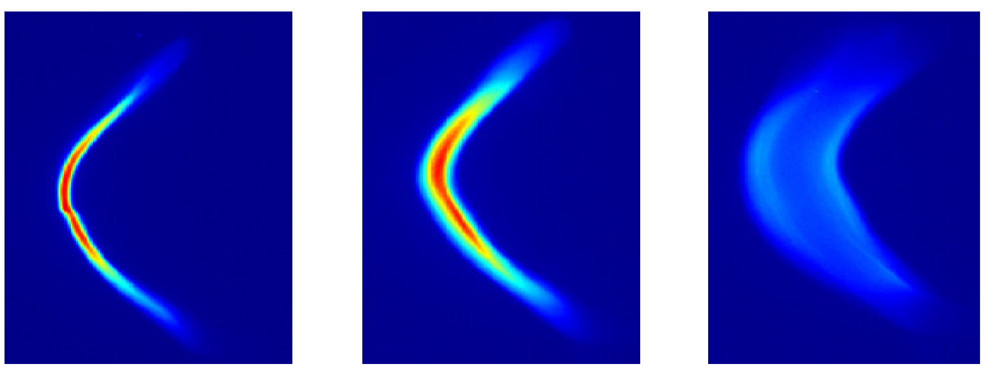
Measure beam longitudinal phase space

- **A transverse cavity + an energy spectrometer**



ω+3 ω

Linearized beam longitudinal phase spaces at FLASH **C. Behrens**



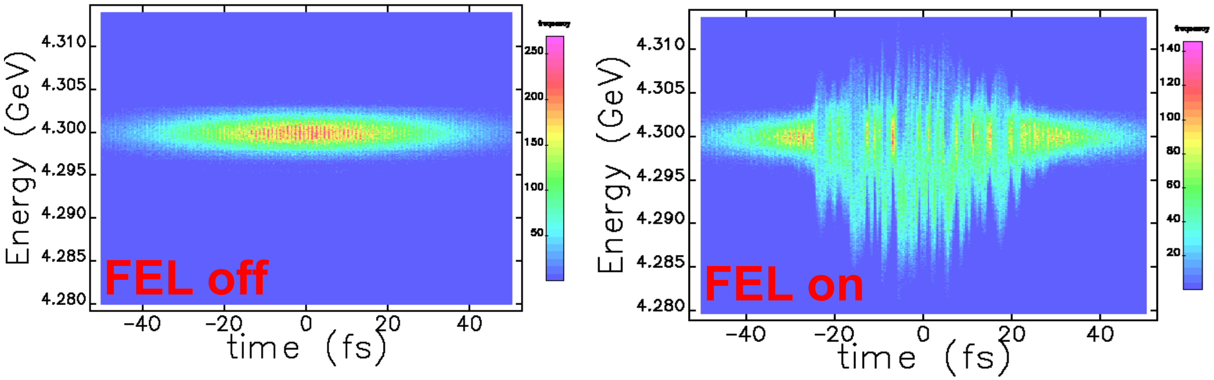
Beam longitudinal phase spaces at LCLS with a 'laser heater'

Huang et al., PRST-AB, 13, 020703 (2010)

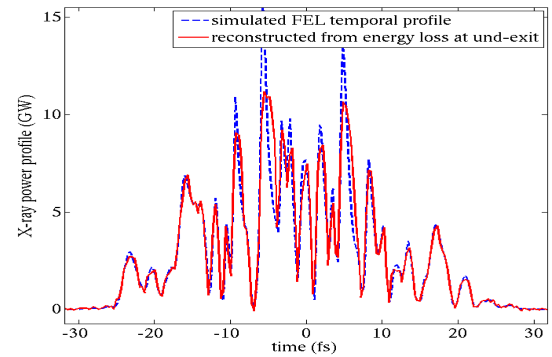
- **The transverse accelerating field in a transverse cavity increases beam slice energy spread, as dictated by Panofsky-Wenzel theorem**
- **Degrade energy resolution**

Measure x-ray pulse shape

Measuring beam longitudinal phase space after an FEL undulator



Beam longitudinal phase spaces



X-ray pulse shape

Parameter	Symbol	Value	Unit
rf frequency	f	11.424	GHz
Deflecting structure length	L	2×1	m
rf input power	P	40	MW
Deflecting voltage (on crest)	V_0	48	MV
Soft x-ray (e-beam 4.3 GeV)			
Calibration factor	S	400	
Temporal resolution (rms)	$\sigma_{t,r}$	~ 1	fs
Energy resolution (rms)	$\sigma_{E,r}$	56	keV
Hard x-ray (e-beam 14 GeV)			
Calibration factor	S	128	
Temporal resolution (rms)	$\sigma_{t,r}$	~ 2	fs
Energy resolution (rms)	$\sigma_{E,r}$	100	keV

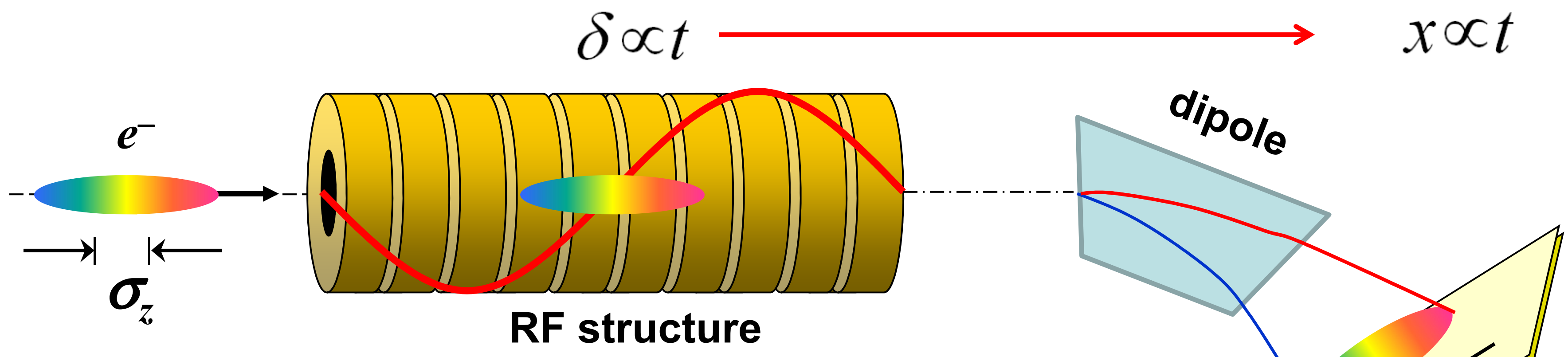
- **High resolution (1~2 fs)**
- **Measure both e-beam and x-ray**
- **Large dynamic range (1~200 fs)**
- **Applies to any x-ray wavelength**
- **No interruption with user's experiments**

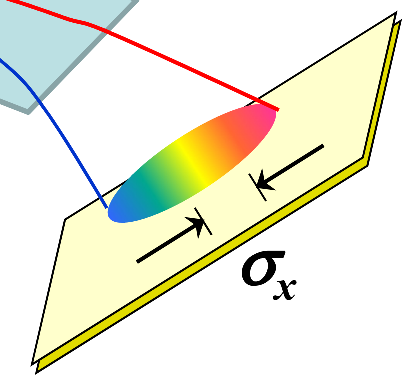
First results expected in Spring 2013

Ding et al., PRST-AB, 14, 120701 (2011)

Zero-phasing

- An accelerator-based streak camera



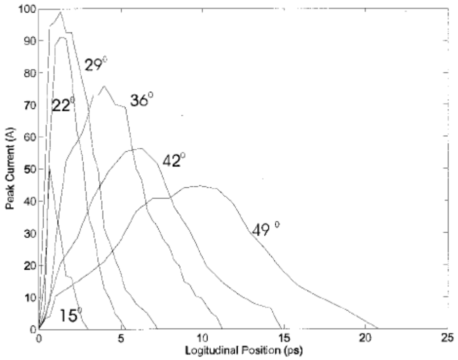


- Zero-phasing method used to measure:
  - Absolute bunch length and temporal profile
  - Beam slice parameters
  - Beam arrival time jitter

Resolution $$\Delta t = \max\left[\frac{E_0 \lambda_{rf} \sigma_{x0}}{2\pi V \eta}, \frac{E_0 \lambda_{rf} \sigma_{\delta}}{2\pi V}\right]$$

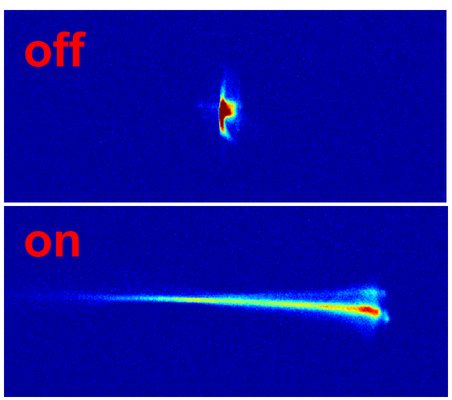
Wang et al., PRE, 57, 2283 (1998)

Zero-phasing



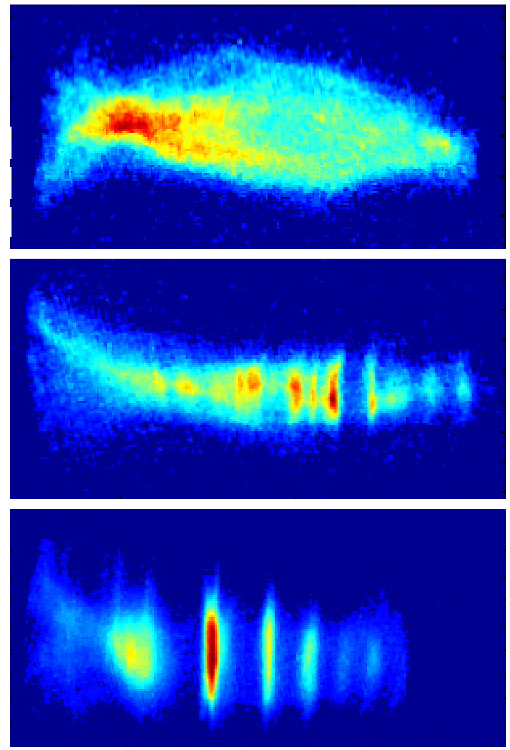
Velocity bunching

Wang et al., PRE, 54, R3121 (1996)



Bunch length

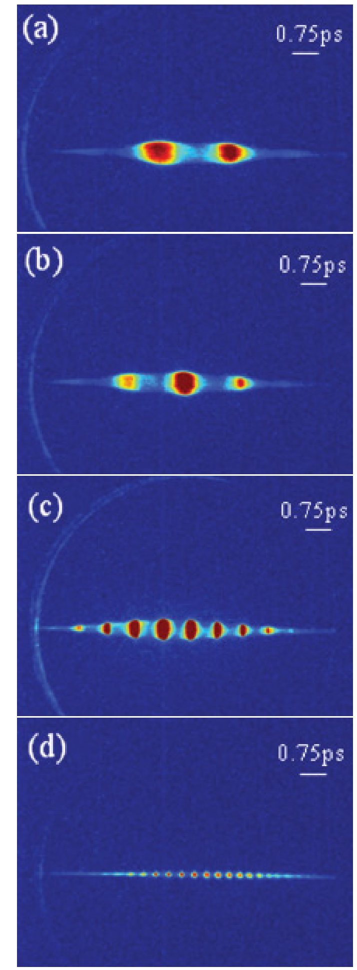
Xiang et al., IPAC10 (2010)



Micro-bunching in magnetic bunch compression

Graves et al., PAC01 (2001)

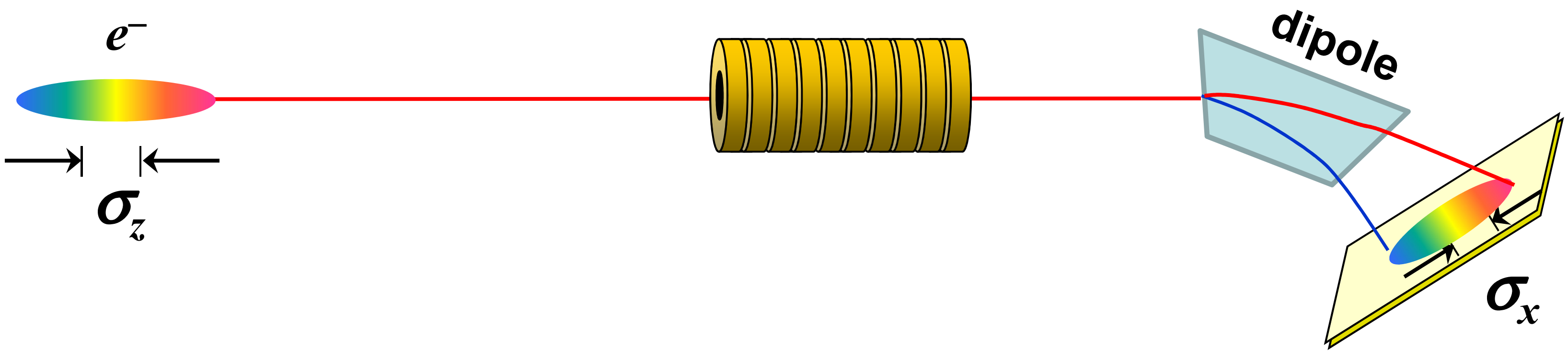
Shaftan et al., PAC03 (2003)



THz modulation

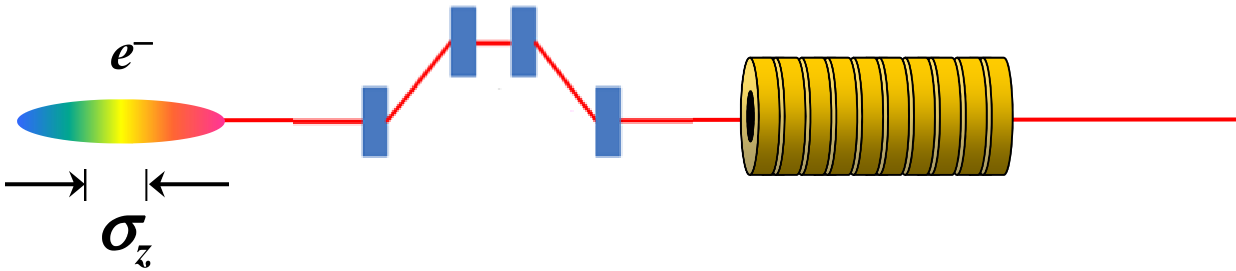
Shen et al., PRL, 107, 204801 (2011)

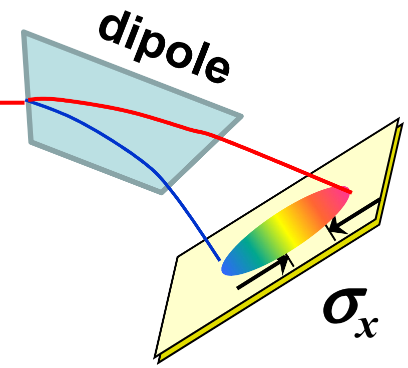
Longitudinal-to-energy mapping



Crosson el al., AIP Conf. Proc., 367, 397 (1996)

Longitudinal-to-energy mapping

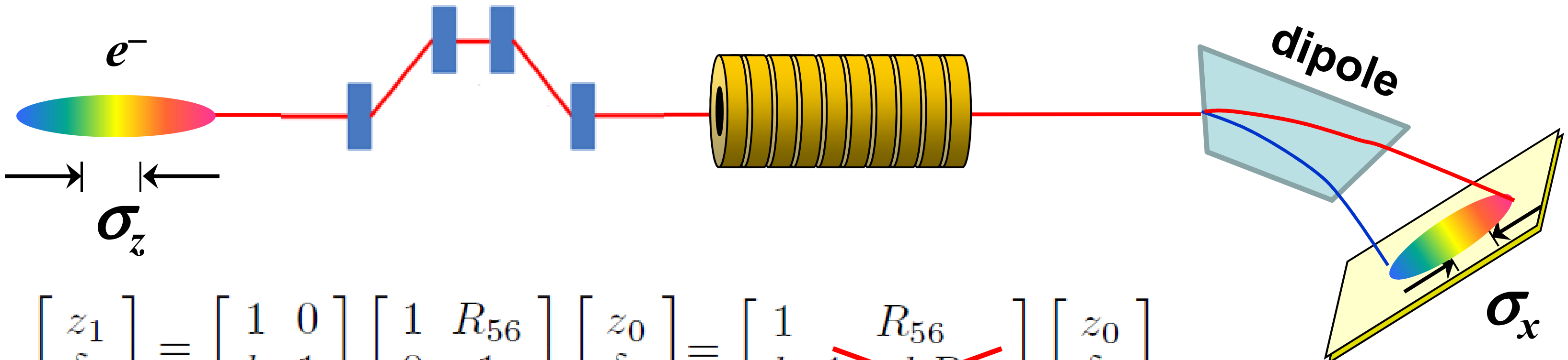




$$\begin{bmatrix} z_1 \\ \delta_1 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ h & 1 \end{bmatrix} \begin{bmatrix} 1 & R_{56} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} z_0 \\ \delta_0 \end{bmatrix} = \begin{bmatrix} 1 & R_{56} \\ h & \cancel{1+hR_{56}} \end{bmatrix} \begin{bmatrix} z_0 \\ \delta_0 \end{bmatrix}$$

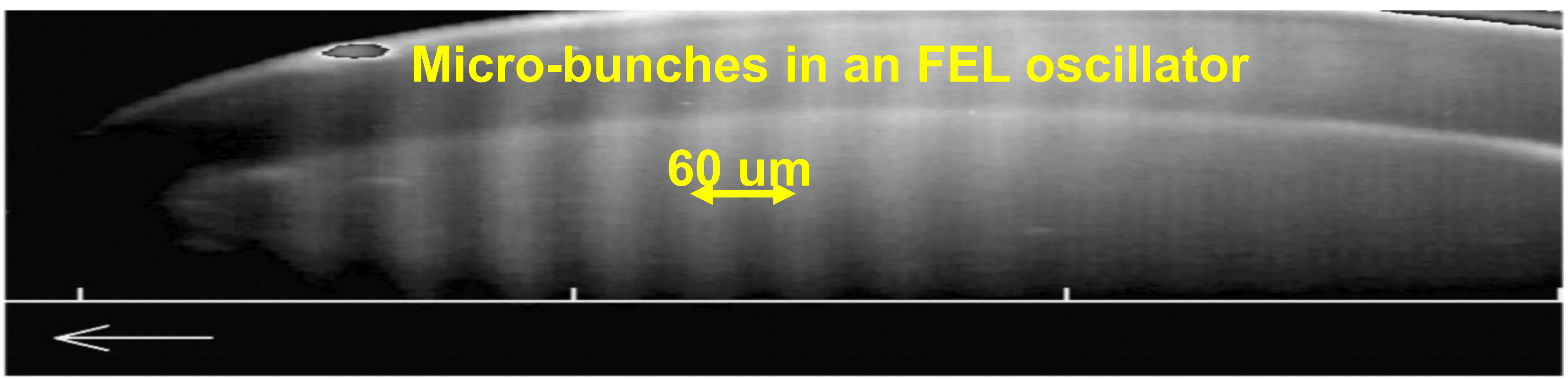
Crosson el al., AIP Conf. Proc., 367, 397 (1996)

Longitudinal-to-energy mapping



$$\begin{bmatrix} z_1 \\ \delta_1 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ h & 1 \end{bmatrix} \begin{bmatrix} 1 & R_{56} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} z_0 \\ \delta_0 \end{bmatrix} = \begin{bmatrix} 1 & R_{56} \\ h & \cancel{1 + hR_{56}} \end{bmatrix} \begin{bmatrix} z_0 \\ \delta_0 \end{bmatrix}$$

- **Map z exactly to δ; Similar to longitudinal-to-transverse mapping**

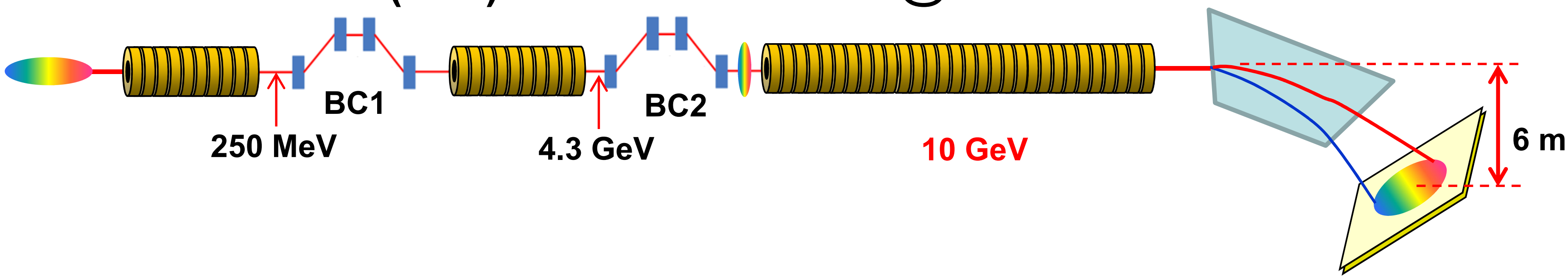


Crosson el al., AIP Conf. Proc., 367, 397 (1996)

Ricci and Smith, PRST-AB, 3, 032801 (2000)

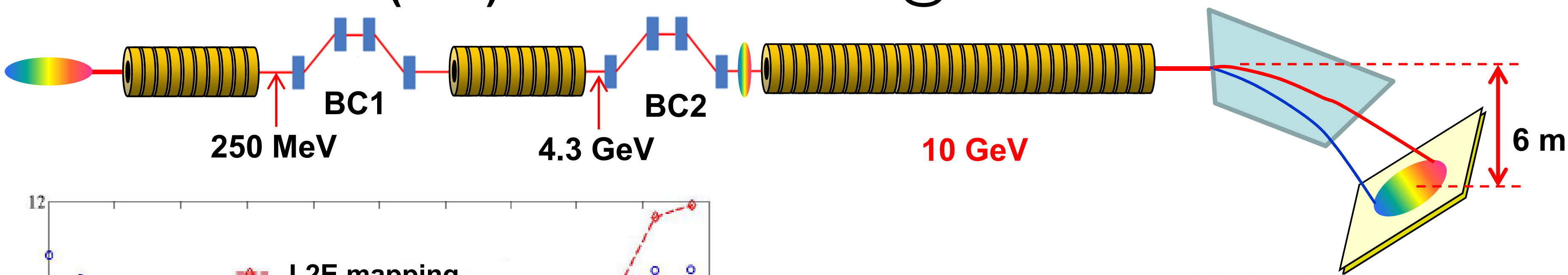
Longitudinal-to-energy mapping

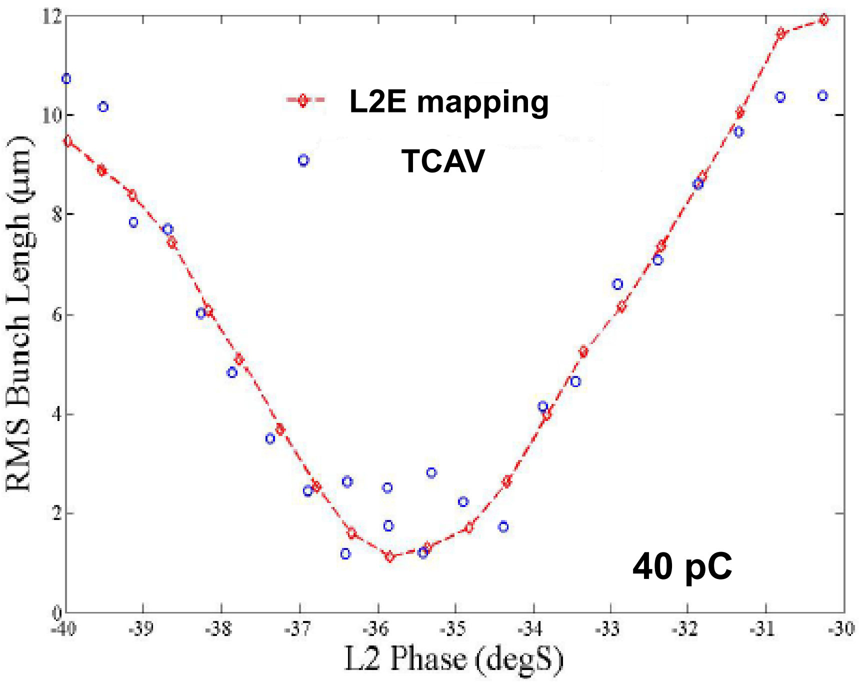
- Measure 1 fs (rms) ultra-short bunch @ LCLS



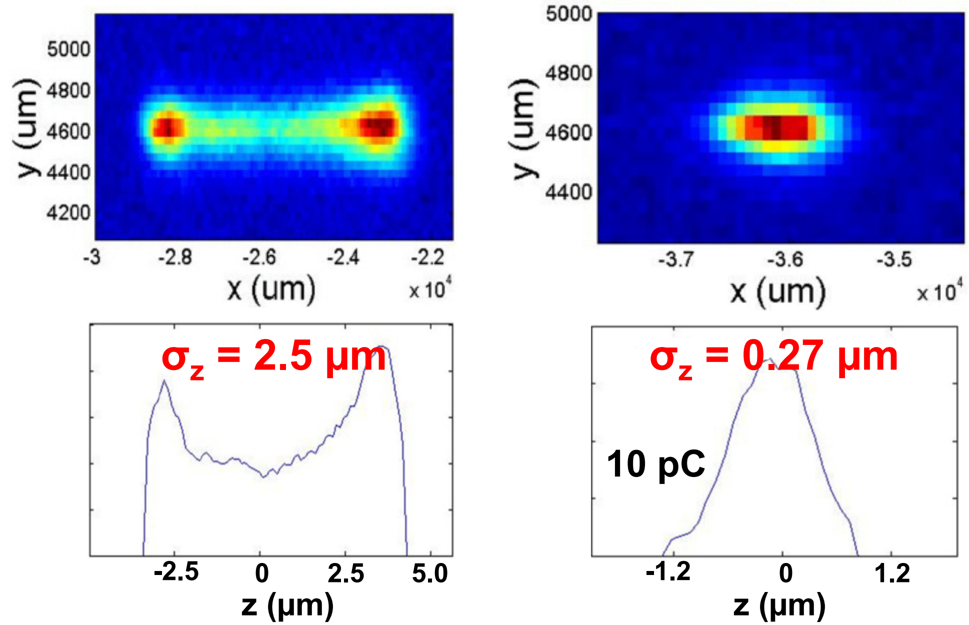
Longitudinal-to-energy mapping

- **Measure 1 fs (rms) ultra-short bunch @ LCLS**





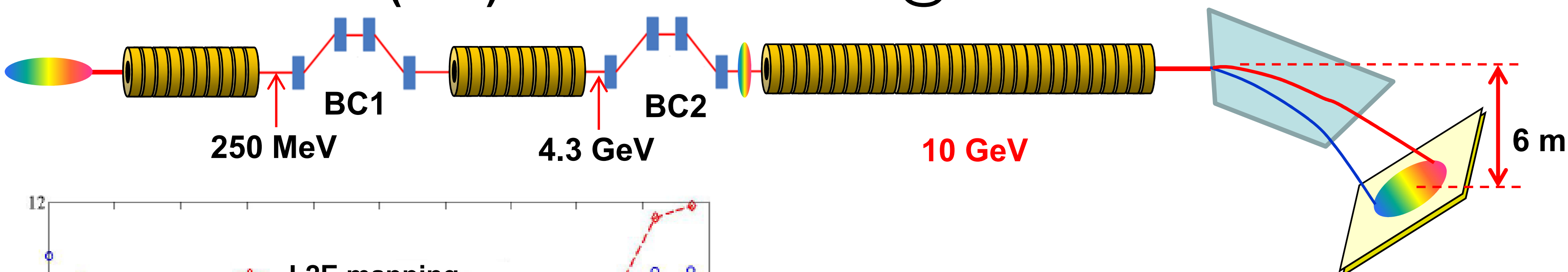
Huang et al., PRST-AB, 13, 092801 (2010)

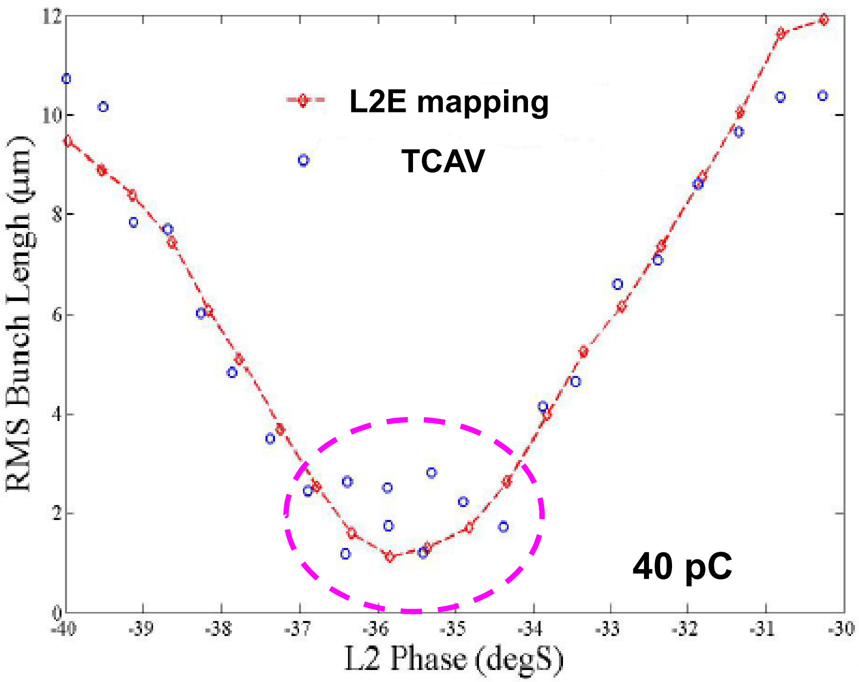


Huang et al., PAC11 (2011)

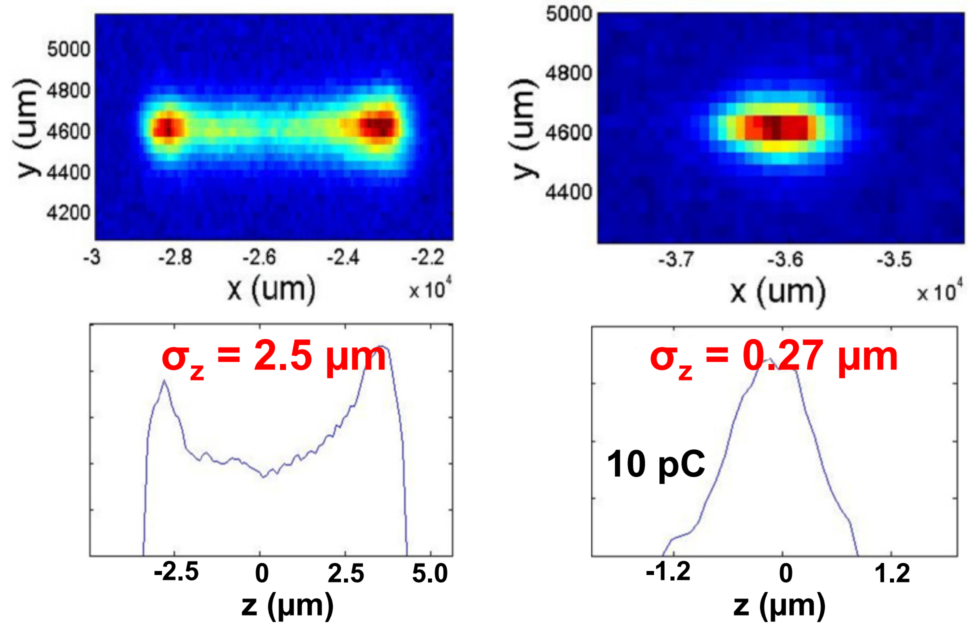
Longitudinal-to-energy mapping

- **Measure 1 fs (rms) ultra-short bunch @ LCLS**





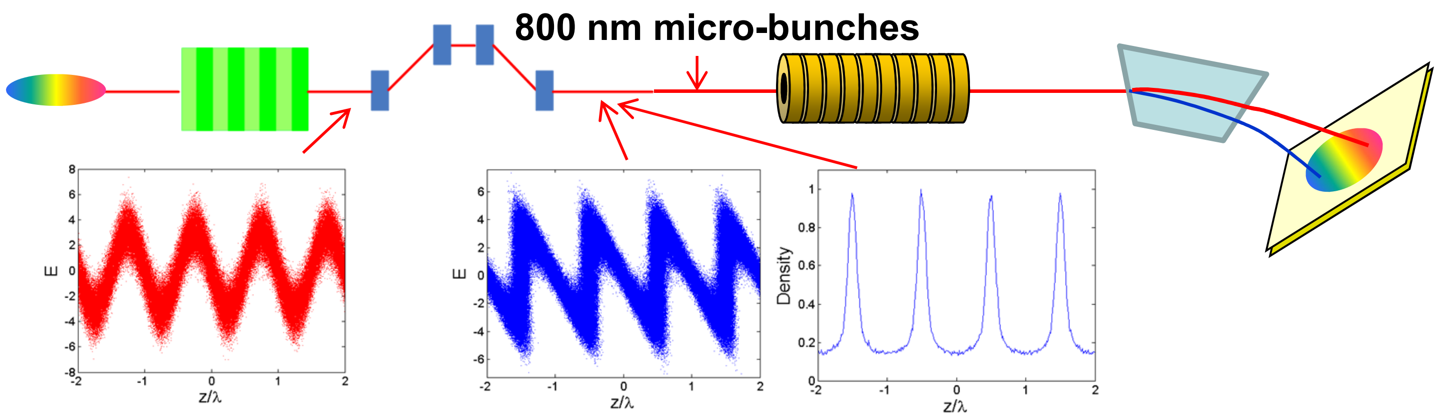
Huang et al., PRST-AB, 13, 092801 (2010)



Huang et al., PAC11 (2011)

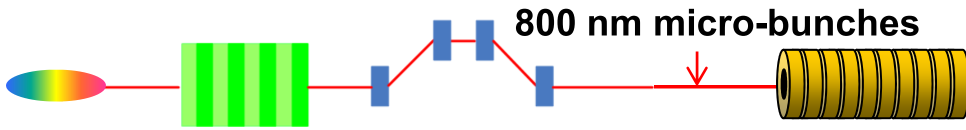
L2E mapping: old tricks, new games

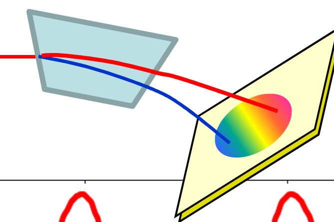
- Visualizing optical micro-bunches @ SLAC's NLCTA



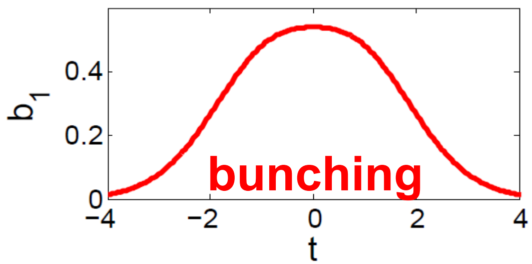
L2E mapping: old tricks, new games

- Visualizing optical micro-bunches @ SLAC's NLCTA

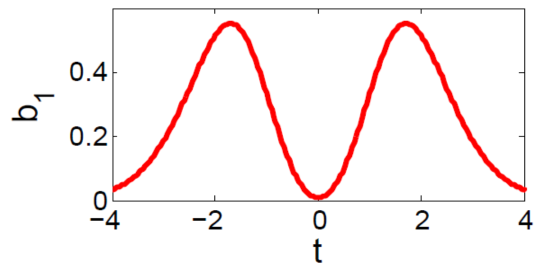




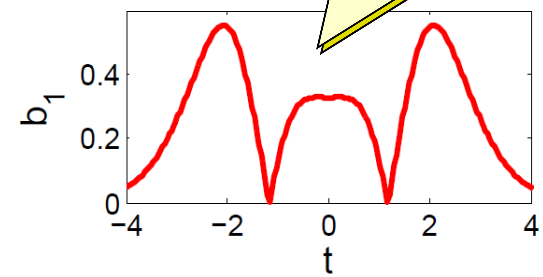
$$b_n = |J_n(nkR_{56}\Delta E/E)|e^{-(1/2)n^2k^2R_{56}^2\sigma_E^2/E^2}$$



ΔE = 5 keV



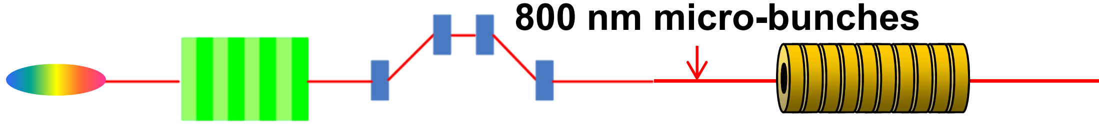
ΔE = 12 keV

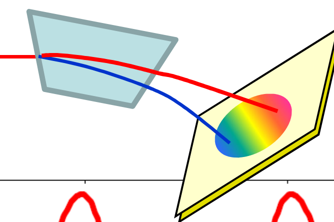


ΔE = 17 keV

L2E mapping: old tricks, new games

- **Visualizing optical micro-bunches @ SLAC's NLCTA**





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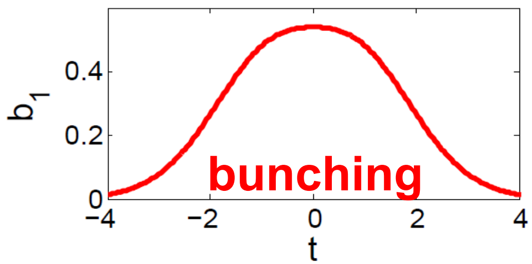
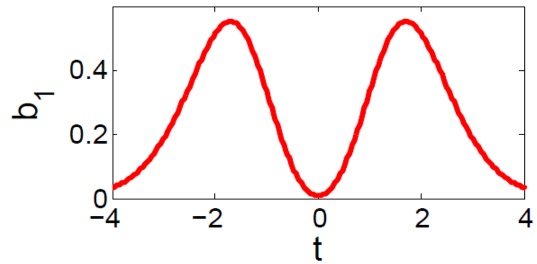
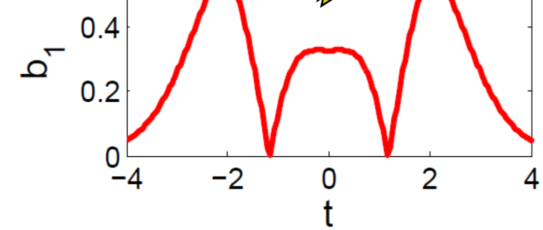


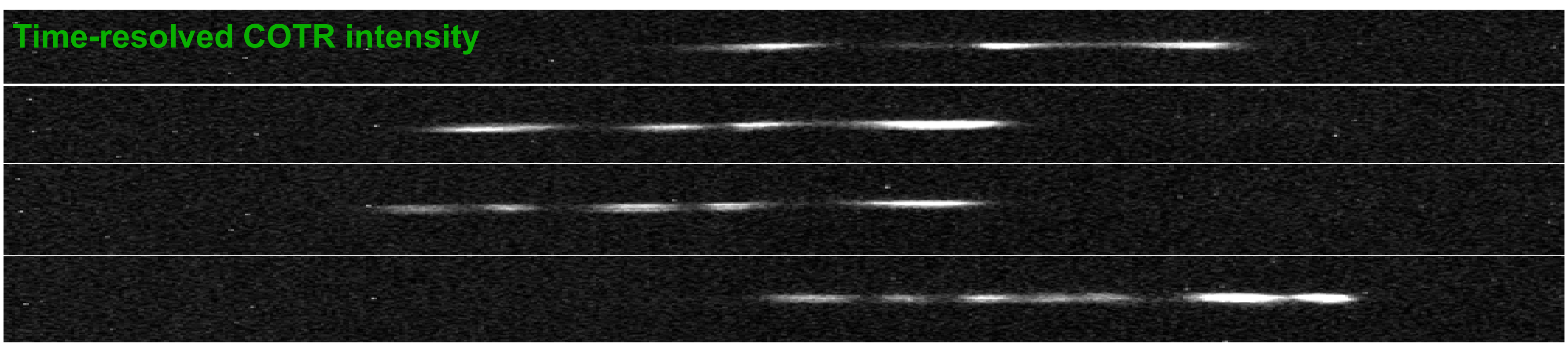
ΔE = 5 keV



ΔE = 12 keV



ΔE = 17 keV

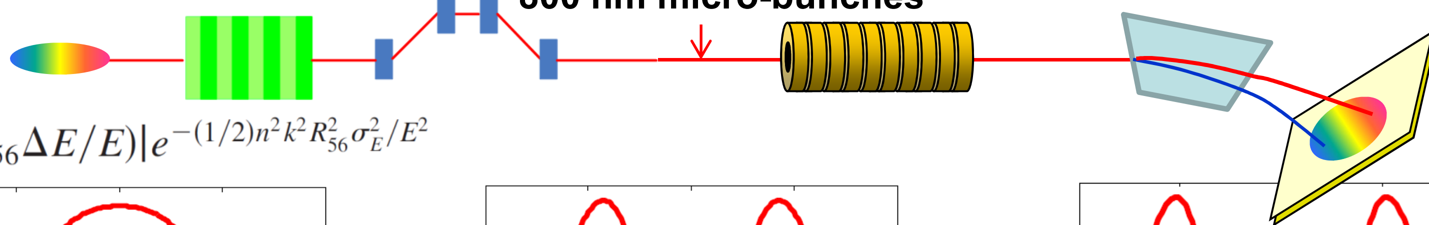


Xiang et al., PRST-AB, 14, 112801 (2011)

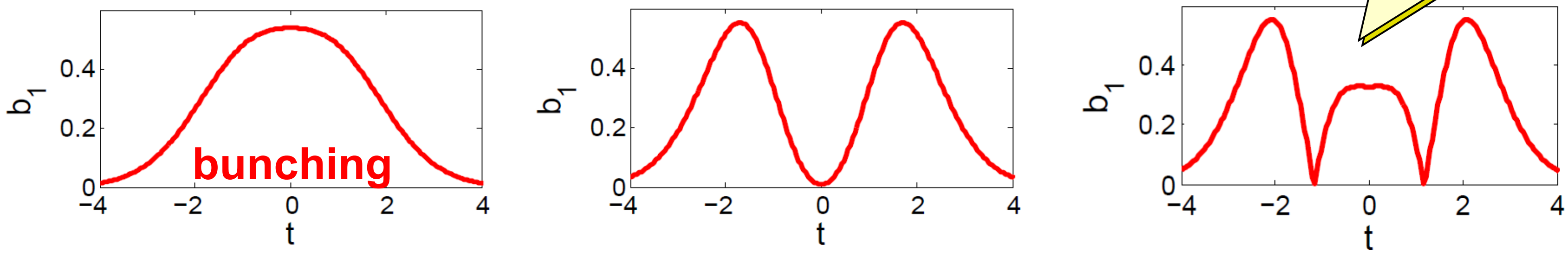
First results expected in Spring 2013

L2E mapping: old tricks, new games

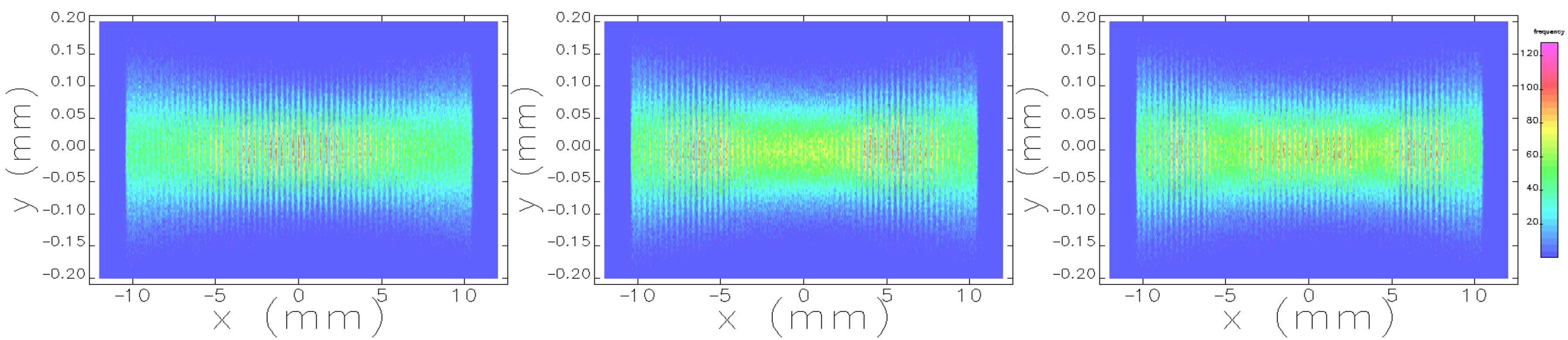
- **Visualizing optical micro-bunches @ SLAC's NLCTA**



$$b_n = |J_n(nkR_{56}\Delta E/E)|e^{-(1/2)n^2k^2R_{56}^2\sigma_E^2/E^2}$$



ΔE = 5 keV **ΔE = 12 keV** **ΔE = 17 keV**



Xiang et al., PRST-AB, 14, 112801 (2011)

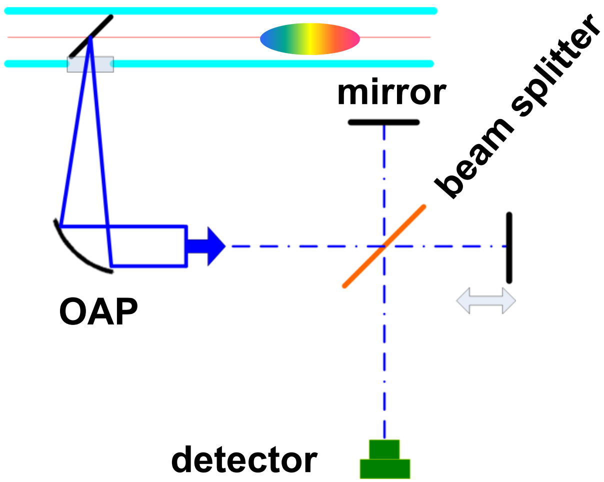
First results expected in Spring 2013

Measuring ultra-short bunches

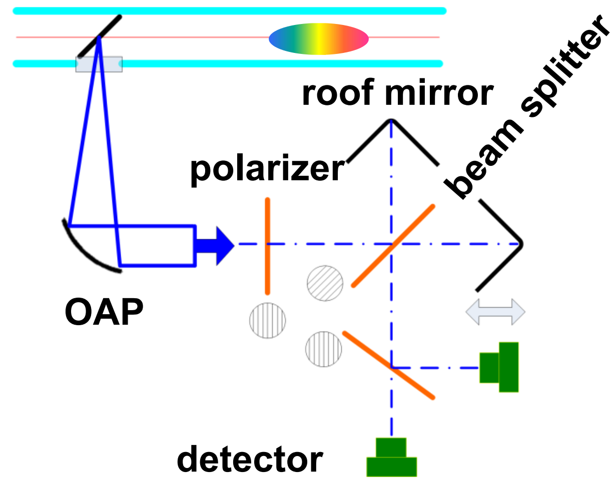
- Time domain
  - Streak camera
  - RF transverse cavity
  - Zero-phasing
- Frequency domain
  - Interferometer
  - Spectrometer
- Laser based methods
  - Electro-optical sampling
  - Optical replica synthesizer
- … …

Interferometer

- Michelson interferometer



- Martin-Puplett interferometer



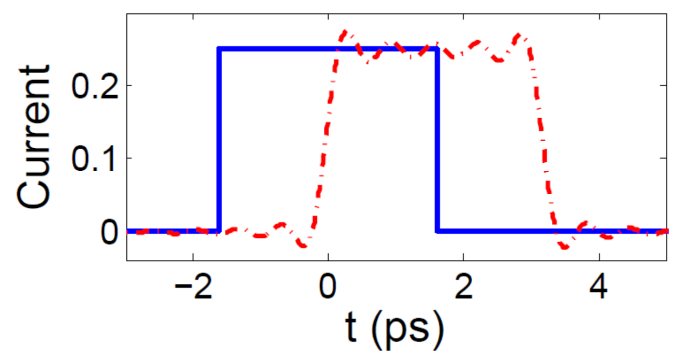
Autocorrelation function $$I_M(\tau) = \int_{-\infty}^{+\infty} |E(t) + E(t-\tau)|^2 dt$$

- Temporal profile reconstruction

$$\Phi(\lambda) = \frac{2}{\pi\lambda} \int_0^\infty \frac{\ln[|F(\lambda')|/|F(\lambda)|]}{1-(\lambda'/\lambda)^2} d\lambda'$$

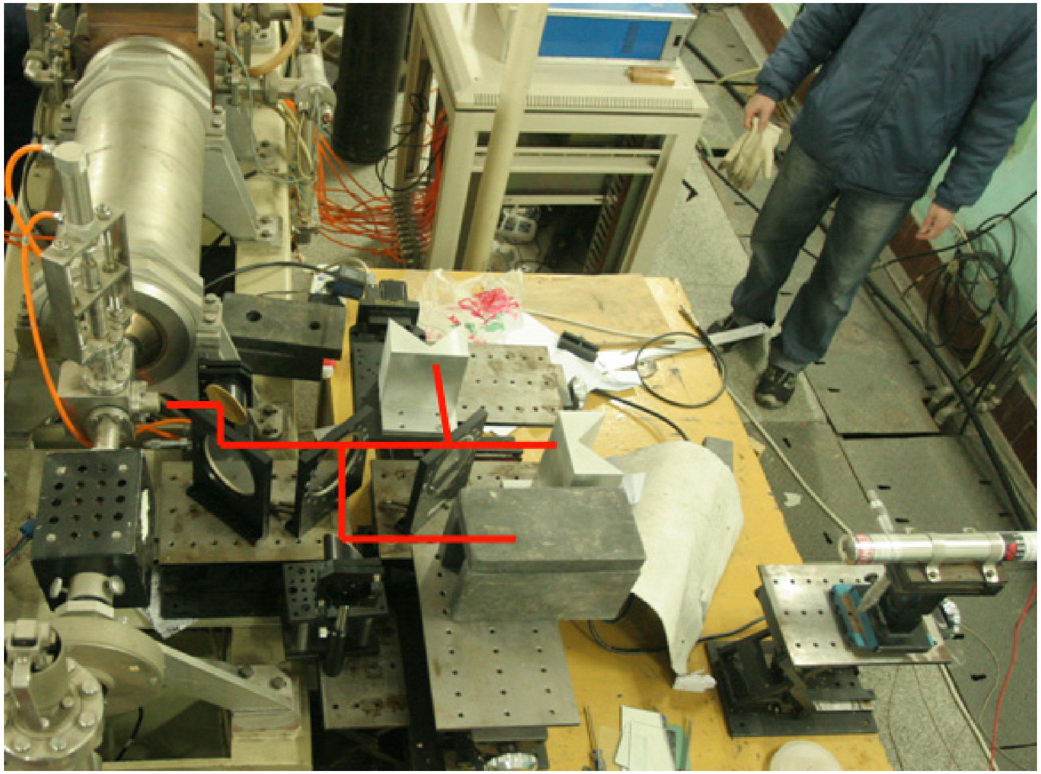
Kramers-Kronig relation

Lai and Sievers, Phys. Rev. E 50, R3342 (1994)

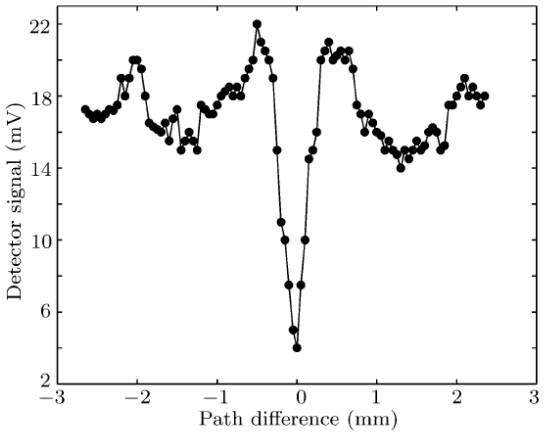


Interferometer

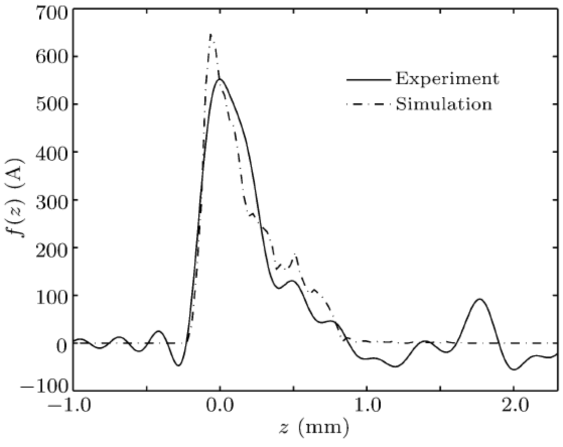
- Cost effective
- Can be non-invasive



Xiang el al., Chin. Phy. Lett. 25, 2440 (2008)



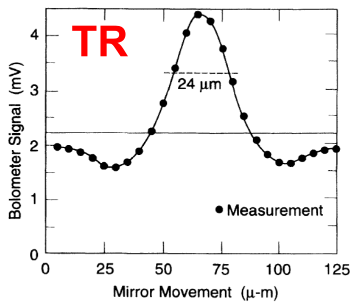
Autocorrelation curve



Reconstructed beam profile

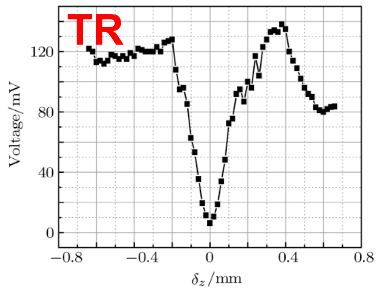
Interferometer

- Used world-wide to measure short bunch (0.05 ~ 1 ps)



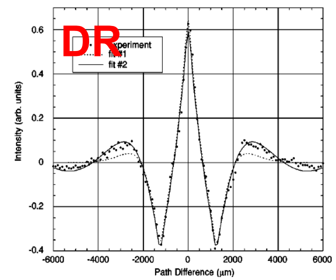
SLAC

PRL, 73, 967 (1994)



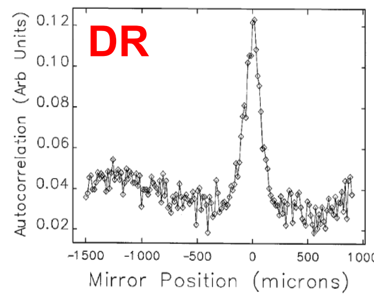
Tsinghua University

Chin. Phy. B 20, 074102



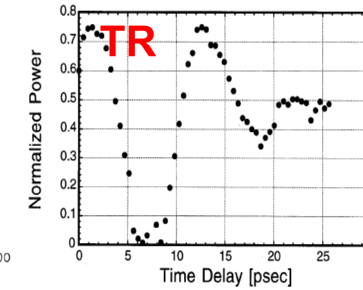
INFN

PRE, 63, 056501 (2001)



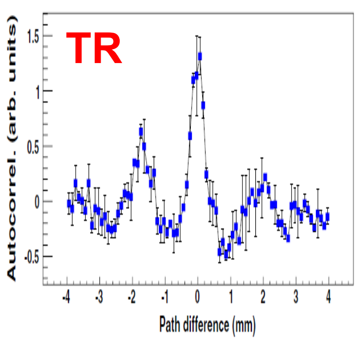
ANL

NIM A, 475, 470 (2001)



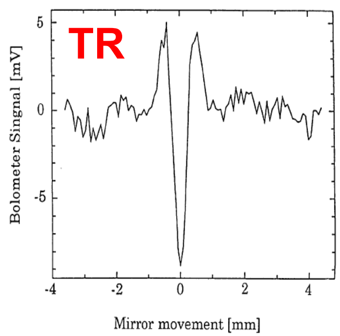
UCLA

NIM A, 410, 452 (1998)



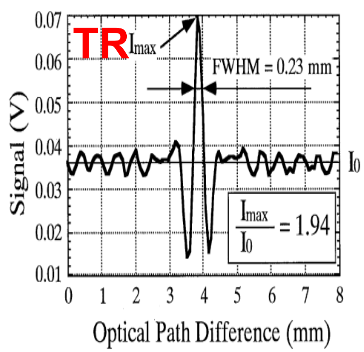
FNAL

PRST-AB, 9, 082801 (2006)



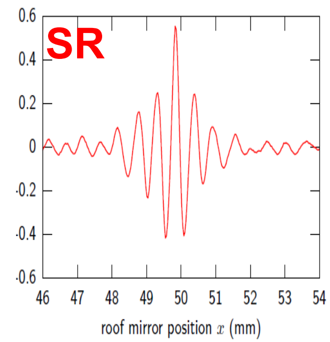
Uni. of Tokyo

NIM A, 410, 424 (1998)



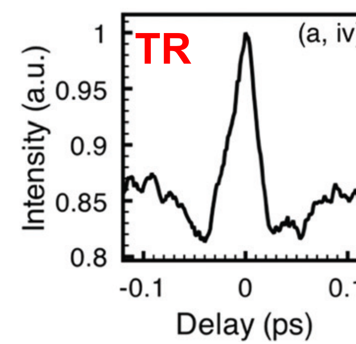
BNL

NIM A, 437, 1 (1999)



DESY

TESLA-FEL 2005-02

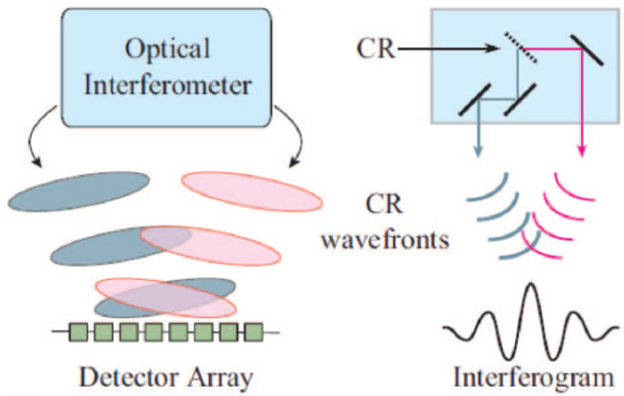


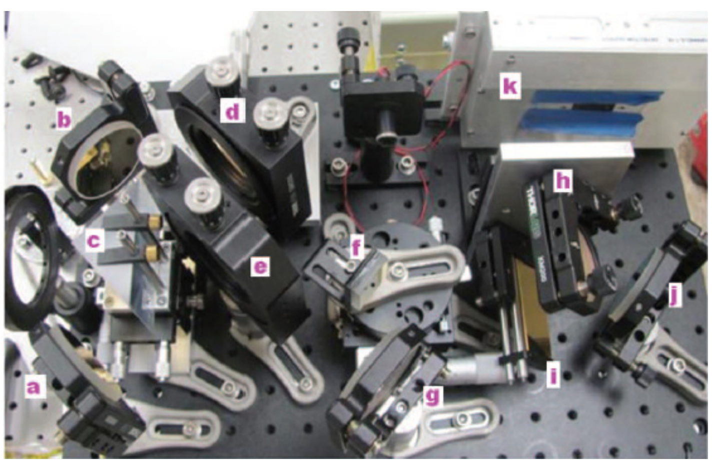
SLAC

APL, 99, 141117 (2011)

Interferometer

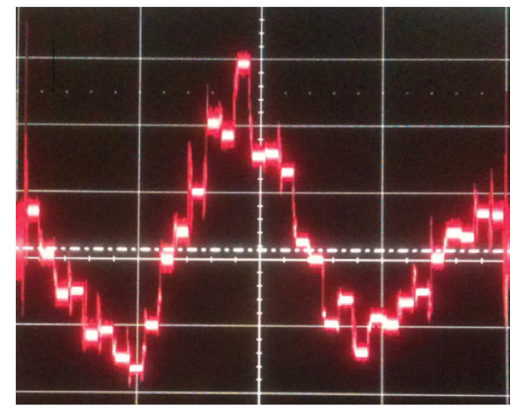
❑ Single-shot interferometer

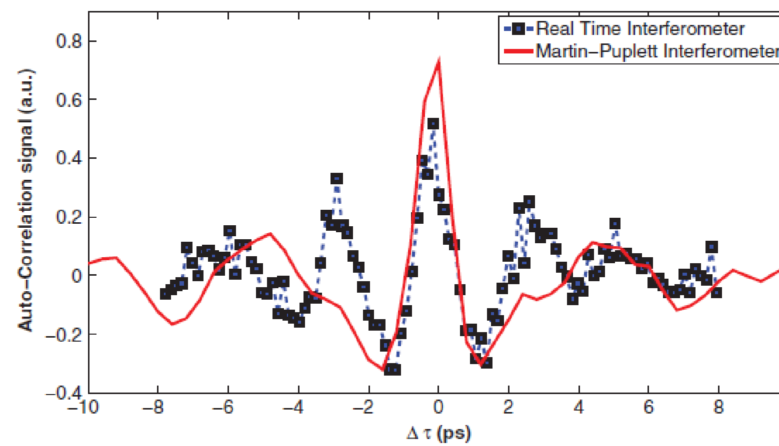




Andonian et al., IPAC10 (2010)

Tested in A0 photoinjector @ FNAL

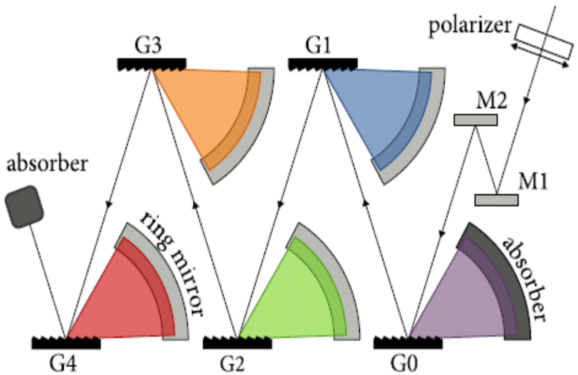


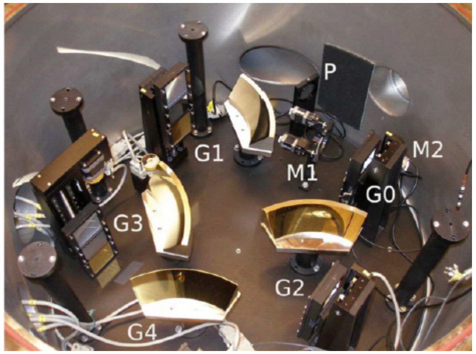


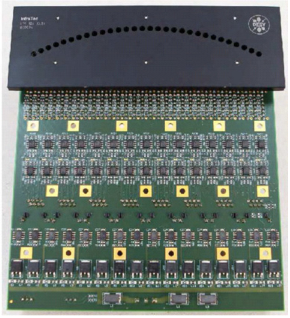
Thangaraj et al., Rev. Sci. Instru. 83, 043302 (2012)

Spectrometer

- Dispersive element + detector array

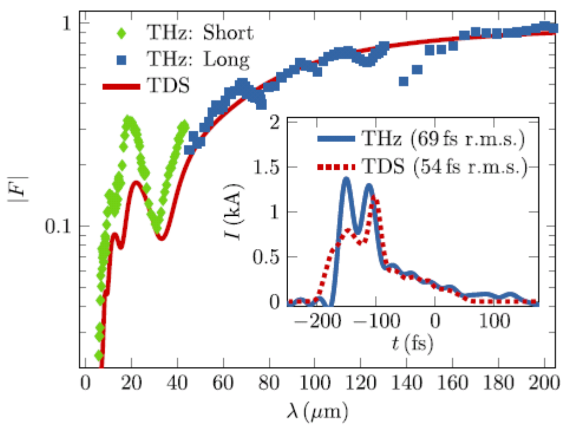


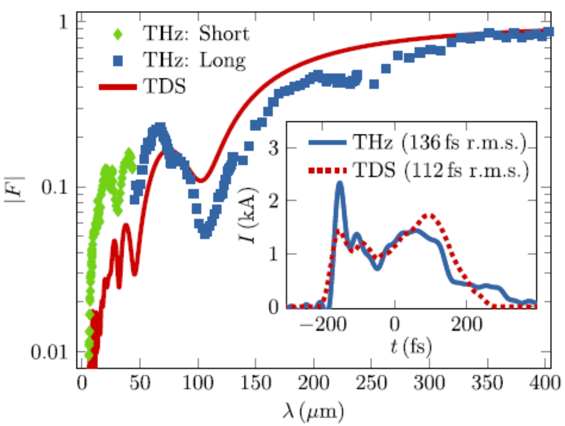




Detector array

5 consecutive gratings cover 4~40 um; 2 sets of gratings cover 4 ~ 400 um



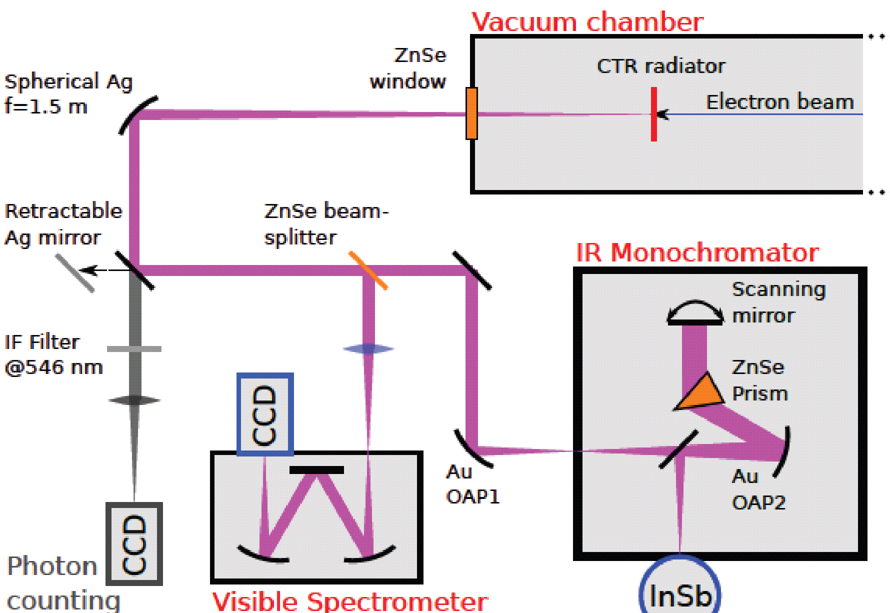


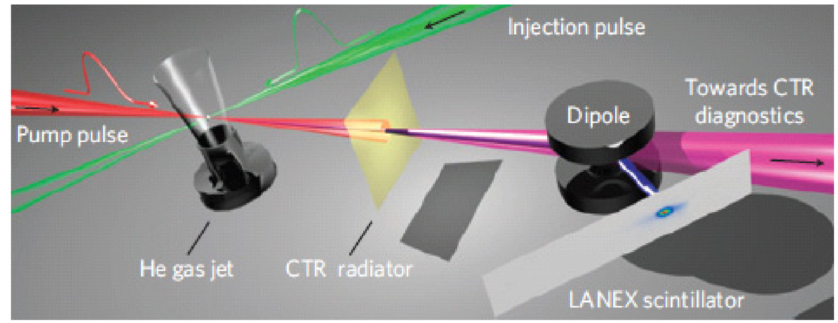
Delsim-Hashemi, Ph.D thesis (2008) *Wesch et al., NIM A 665, 40 (2011)* *Behrens et al., PRST-AB 15, 030707 (2012)*

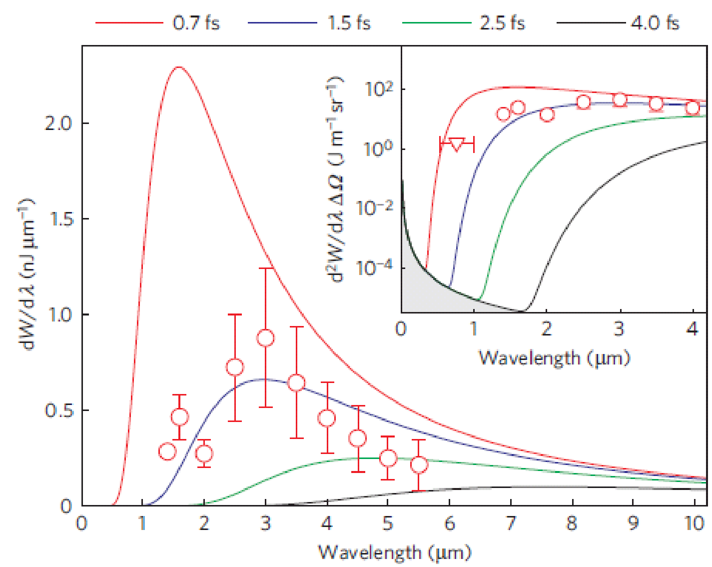
Spectrometer

- Measure ~1.5 fs ultra-short bunch from a LWFA

Use a grating and a prism to measure CTR spectrum from 0.5 um to 5.5 um







Lundh et al., Nature Phys, 7, 219 (2011)

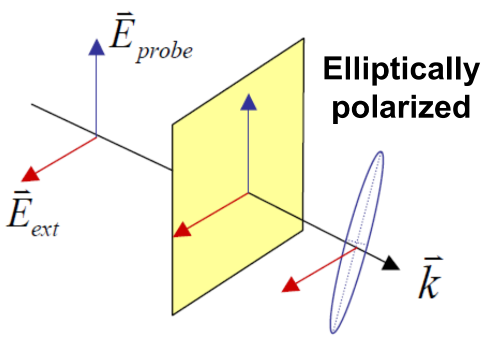
Measuring ultra-short bunches

- **Time domain**
  - Streak camera
  - RF transverse cavity
  - Zero-phasing
- **Frequency domain**
  - Interferometer
  - Spectrometer
- **Laser based methods**
  - Electro-optical sampling
  - Optical replica synthesizer
- … …

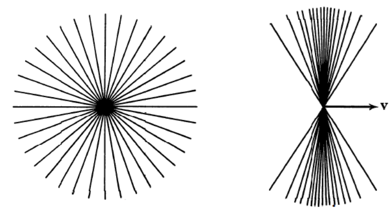
Laser based methods

❑ Electro-optical sampling

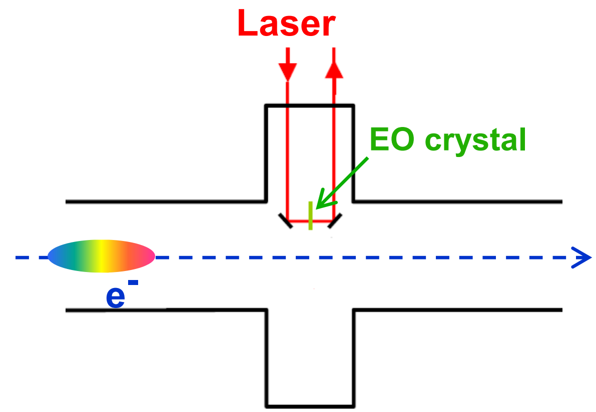
Polarization change ~ E



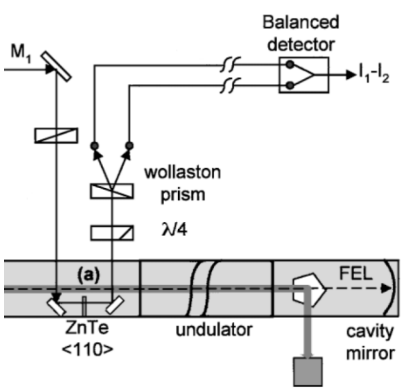
E ~ I



$$E_r(r) = -\frac{Ne}{2\pi\epsilon_0 L_b}\frac{1}{r}$$

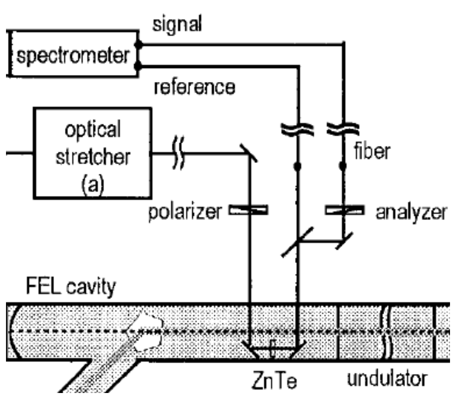


Multi-shot



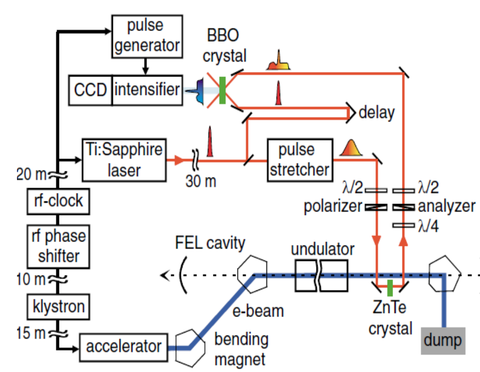
PRL, 85, 3404 (2000)

Single-shot



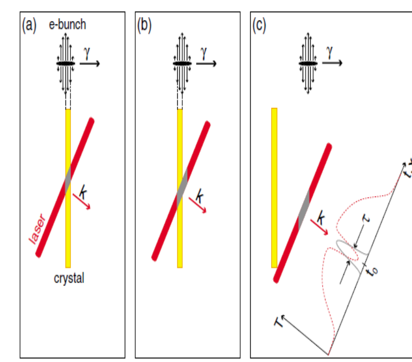
PRL, 88, 124801 (2002)

Temporal decoding



PRL, 93, 114802 (2004)

Measure jitter

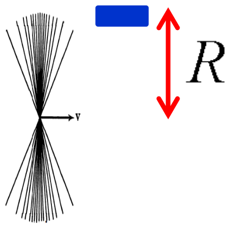


PRL, 94, 114801 (2005)

Electro-optical sampling

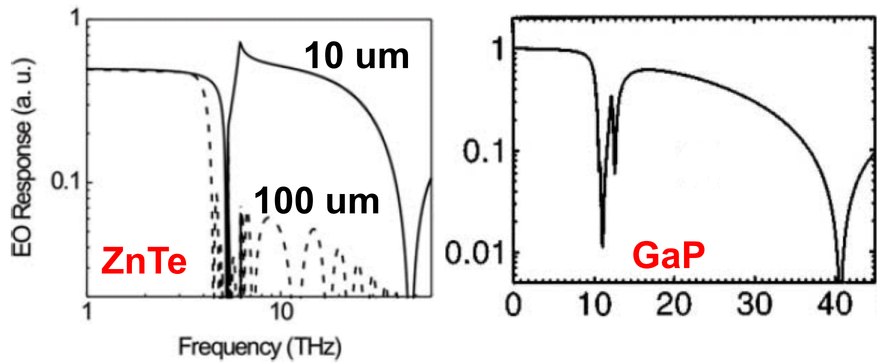
Resolution

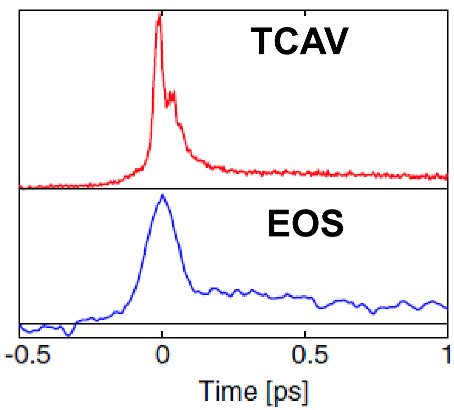
Finite opening angle of E-field



$$\Delta t \approx \frac{2R}{\gamma c}$$

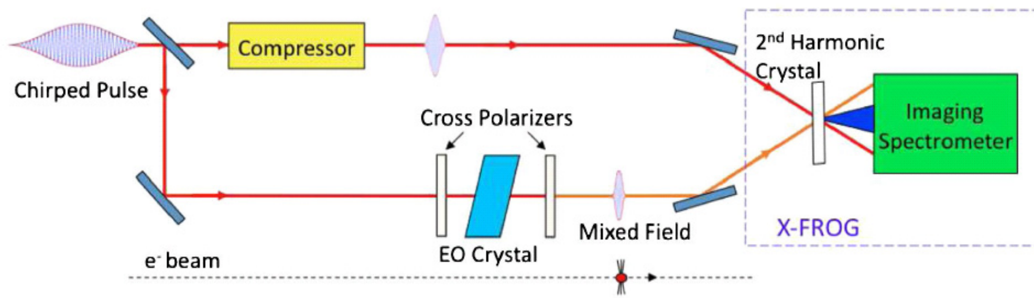
Frequency response of the crystals





Benchmarking with TCAV indicates ~50 fs resolution

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

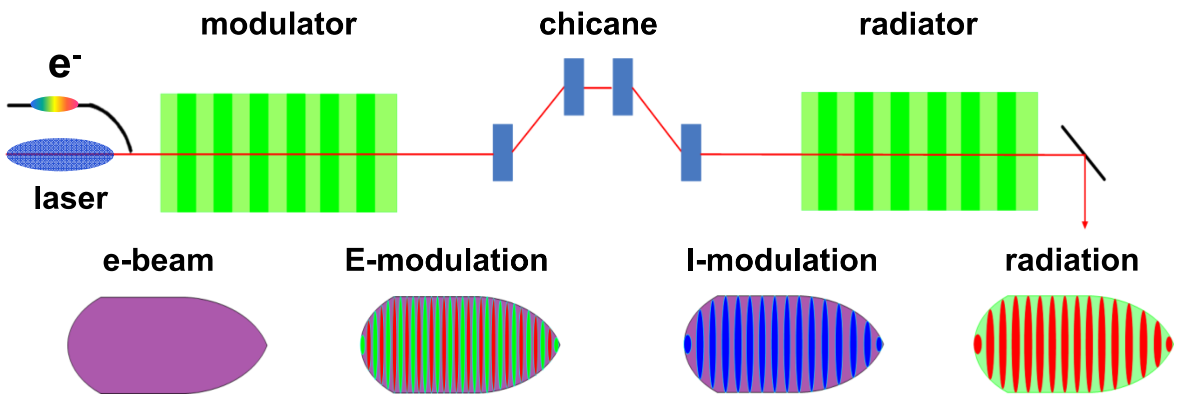


Bandwidth mixing FROG ~10 fs resolution

Helle et al., PRST-AB, 15, 052801 (2012)

Optical replica synthesizer

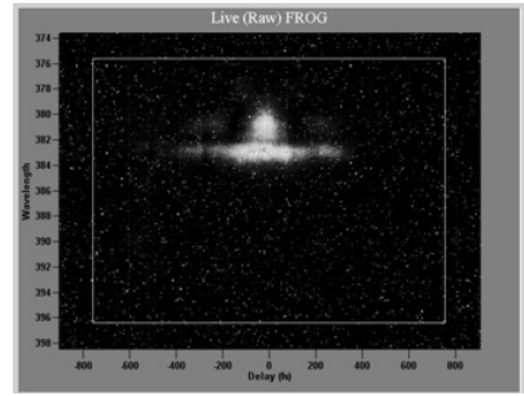
- Convert e-beam to coherent light



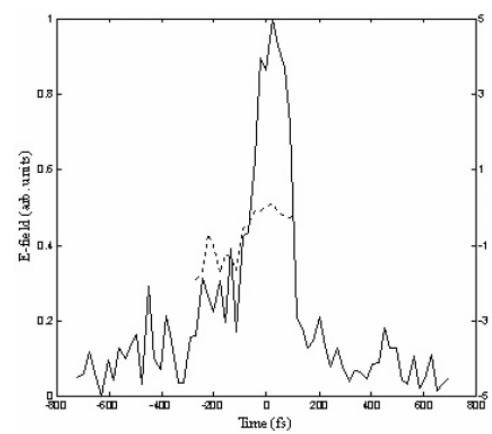
The field of the radiation is a replica of the beam temporal profile

- 6-D phase space characterization
- Resolution limited by slippage length
- NOT apply to Low and moderate current beam

Saldin, Schneidmiller, Yurkov, NIM A, 539, 499 (2005)



FROG trace obtained @ FLASH



Retrieved E-field

Salen et al., FEL09 (2009)

Summary

- Increasing interest in generation of ultra-short e-bunch
- Various techniques are being developed
  - Time-domain: transverse cavity, zero-phasing
  - Frequency-domain: single-shot interferometer and spectrometer
  - Laser based: electro-optical sampling, optical replica synthesizer
- Measuring e-beam parameters provide more information than expected: x-ray temporal profile
- Temporal resolution of ~1 fs has been achieved @ LCLS
- Expect more measurements with sub-fs resolution to come soon

Thank you!