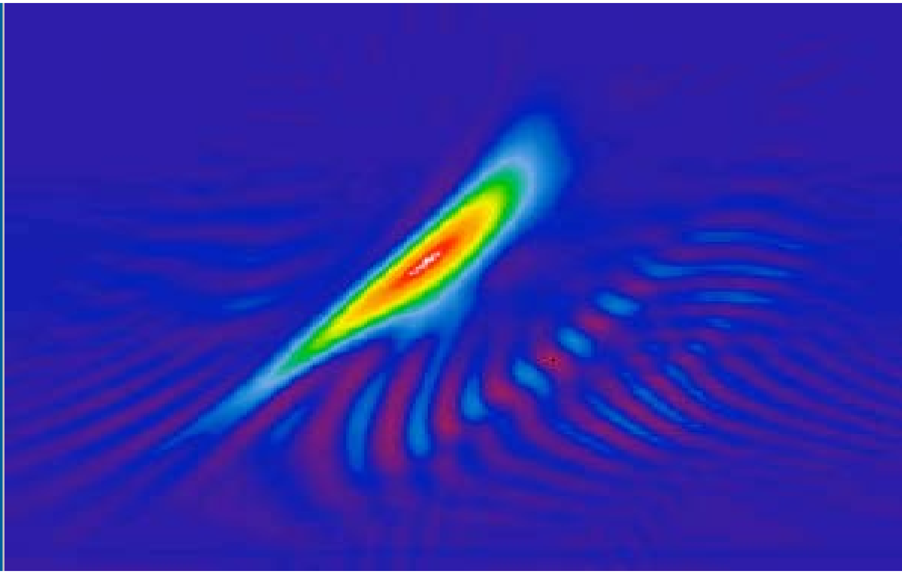
BEAM BY DESIGN

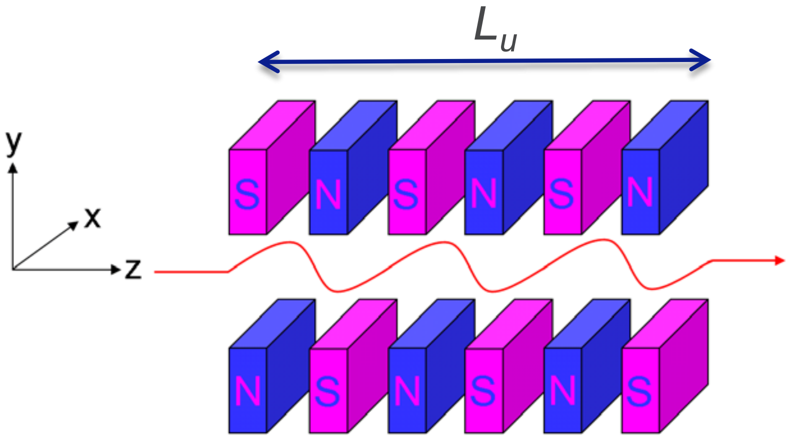


ALEXANDER ZHOLENTS
Argonne National Laboratory

Workshop on nonlinear dynamics and collective effects in particle physics
Arcidosso, September 18, 2017

BASICS OF THE LASER BEAM INTERACTION WITH THE ELECTRON BEAM

LASER E-BEAM INTERACTION IN UNDULATOR



Undulator/Modulator

$$B_y(z) = B_0 \cos(k_u z)$$

$$k_u = 2\pi/\lambda_u$$

Undulator parameter

$$K = \frac{eB_0}{k_u mc^2}$$

Electron motion in undulator

$$\beta_x(z) = -\frac{K}{\gamma}\sin(k_u z),$$

$$\beta_z(z) \approx \underbrace{1 - \frac{1}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)}_{\bar{\beta}_z} + \frac{K^2}{4\gamma^2}\cos(2k_u z)$$

LASER E-BEAM INTERACTION IN UNDULATOR (CONT'D)

Laser field (plane wave approximation)

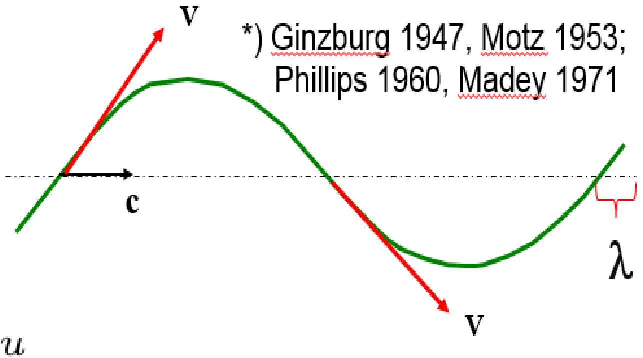
$$E_x(z,t) = E_0 \sin\left[k_L(z-ct)\right]$$

$k_L = 2\pi/\lambda_L$ laser wave vector

Energy gain or loss by the electron

$$\frac{d\gamma}{dz} = \frac{e}{mc^2} E_x \beta_x$$

$$\frac{d\gamma}{dz} = -\frac{eKE_0}{\gamma mc^2} \sin(k_u z) \sin\left[k_L(z-ct)\right]$$



*) Ginzburg 1947, Motz 1953; Phillips 1960, Madey 1971

FEL resonant energy $\gamma_r^2 = k_L\left(1+K^2/2\right)/2k_u$

$$k_L(z-ct) = k_L s/\bar{\beta}_z - k_u z \frac{\gamma_r^2}{\gamma^2} + \frac{\xi}{2}\sin(2k_u z)$$

where
$$\begin{cases} s = z - c\bar{\beta}_z t \\ \xi = K^2/(2+K^2) \end{cases}$$

After averaging over the undulator period

$$\frac{d\gamma}{dz} = -\frac{eKE_0\mathcal{J}}{2\gamma mc^2}\cos(k_L s/\bar{\beta}_z)$$

where $\mathcal{J} = J_0(\xi/2) - J_1(\xi/2)$

$$\boxed{\Delta\gamma(s) = \sqrt{\frac{P_L}{P_0}}\frac{2KL_u\mathcal{J}}{\gamma w_0}\cos(k_L s)}$$

where

- P_L is the laser peak power
- P_0 = 8.7 GW

BEAM MANIPULATION USING TWO MODULATORS

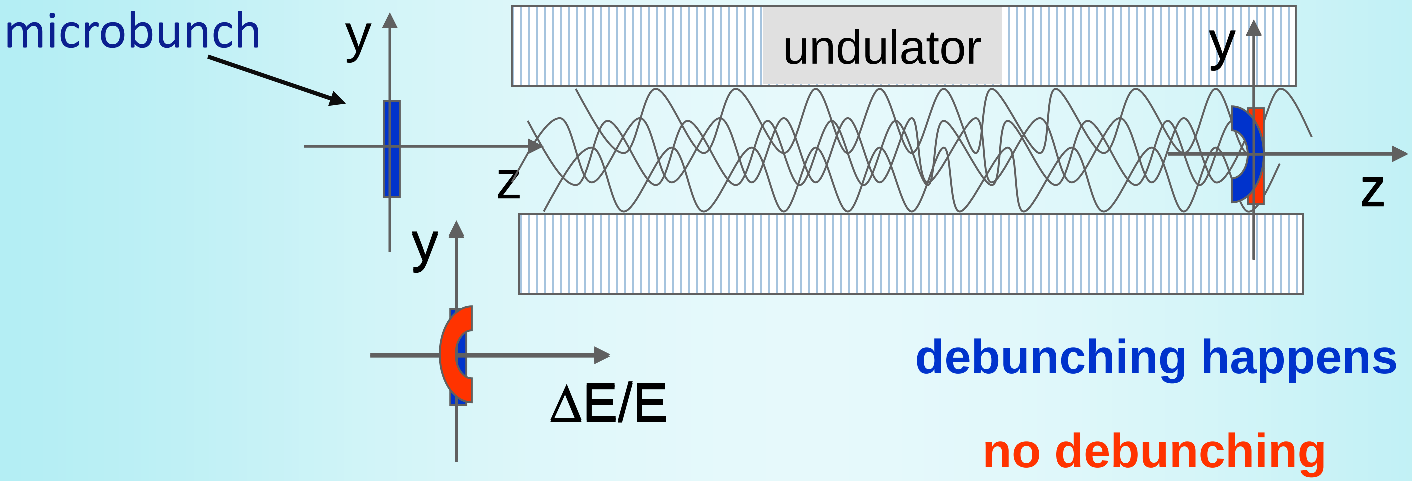
BEAM CONDITIONING FOR FREE-ELECTRON LASERS*

MODIFYING BEAM PROPERTIES BY IMPOSING USEFUL CORRELATIONS ON A MICROSCALE

*) Sessler, Whittum, Yu, *Phys. Rev. Lett.*, **68**, 309 (1992).

What “beam conditioning” does

Addresses the problem of de-bunching due to electron transverse oscillations in FEL



debunching happens

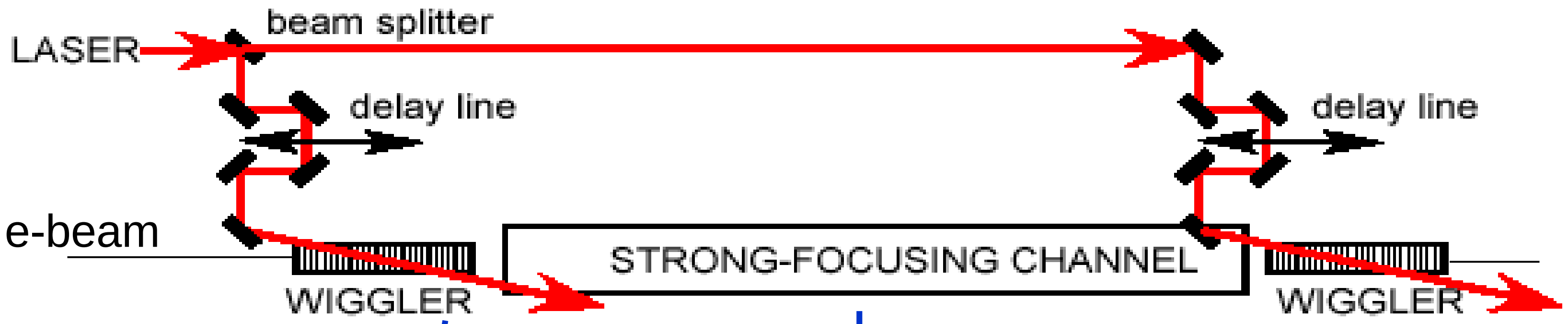
no debunching

Solution of the problem:
Provide correlation between the amplitude of electron transverse oscillation and electron energy to speed up the electron

Beam conditioning relaxes requirements on the beam emittance in FELs

Laser-assisted electron beam conditioning*

(extension of a time delay method proposed by Vinokurov)



$$\Delta\gamma_1 \sim \sin(k_L z_1)$$

$$\Delta\gamma_2 \sim -\sin(k_L z_2)$$

$$z_2 = z_1 + \frac{1}{2}\underbrace{\int \left(x'^2 + y'^2\right) ds}_{\sim\, J_x + J_y}$$

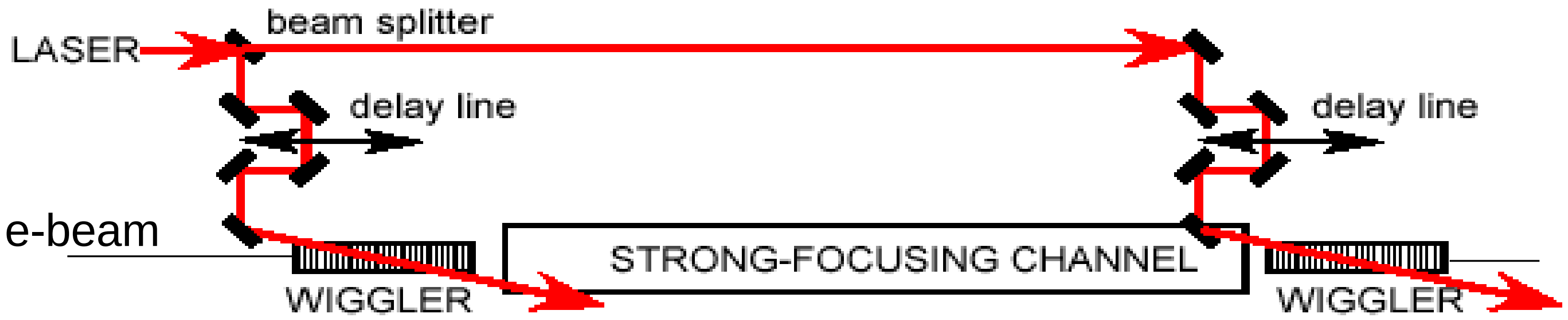
$$\delta\gamma = \Delta\gamma_1 - \Delta\gamma_2 \sim \left(J_x + J_y\right) k_L \cos\left(k_L z_1\right)$$

By utilizing laser and wiggler for electron energy modulation this scheme gives a factor of 10^5 better conditioning than equivalent scheme based on RF cavities:

$$k_L / k_{RF} \sim 10^5 \quad !!!$$

*) Zholents, Phys. Rev. ST–Acc. and Beams, **8**, 050701, (2005)

Laser-assisted electron beam conditioning cont’d



$$\delta\gamma \sim \left(J_x + J_y\right) k_L \cos\left(k_L z_1\right)$$

Caution:

approximately one half of electrons have wrong sign of correlations

Best choice of parameters to achieve conditioning

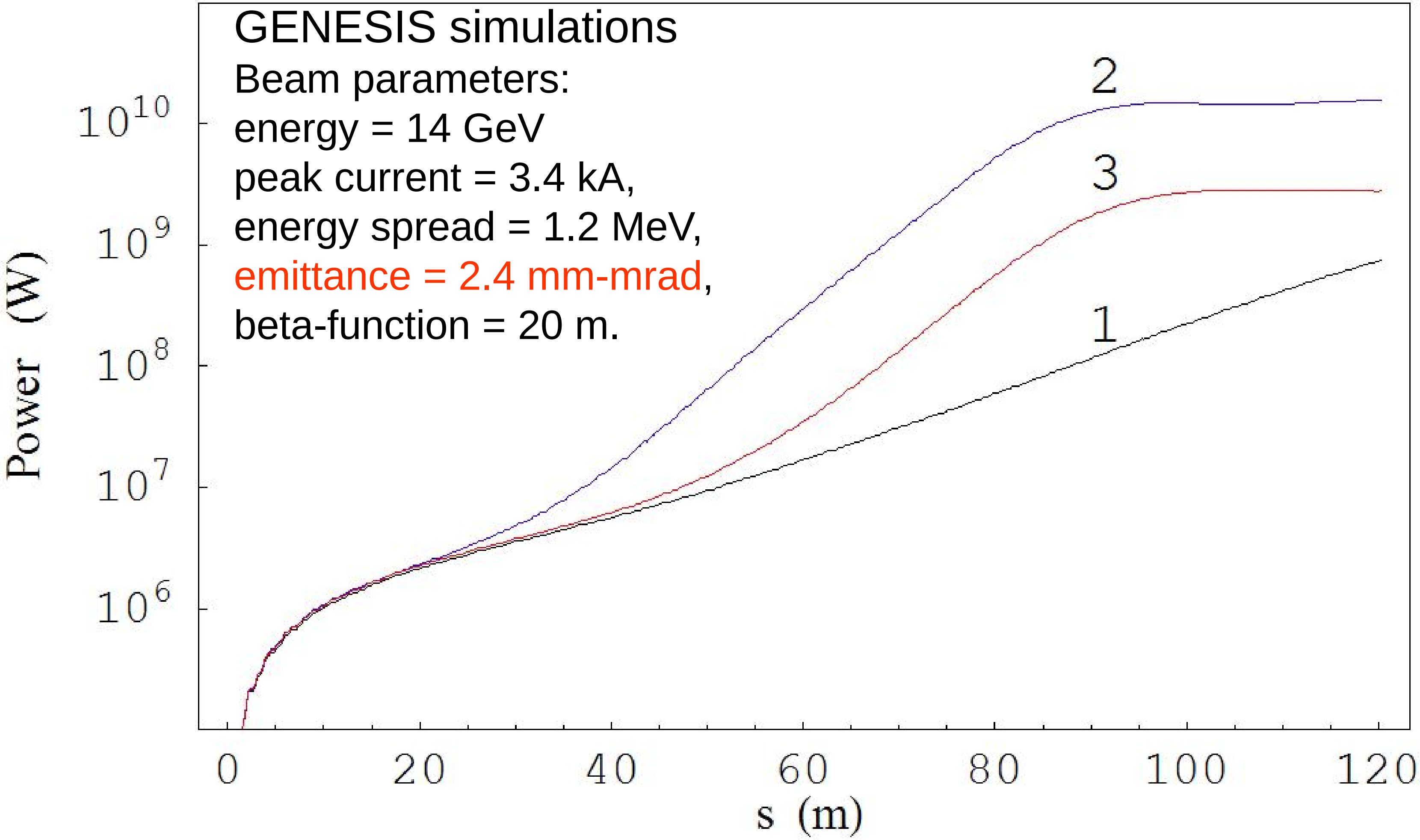
- short ~ 20 μm electron bunch,
- *single cycle* 1.5 THz, ~15 mJ light pulse*) to chirp and de-chirp the electron bunch
- one period wiggler

$$\boxed{\delta\gamma \sim \left(J_x + J_y\right) k_L}$$

*) feasible with the accelerator-based coherent emission THz source, i.e, like TeraFermi

Laser-assisted electron beam conditioning cont'd

Example: LCLS-like FEL with ~5 times of LCLS emittance



GENESIS simulations

Beam parameters:

energy = 14 GeV

peak current = 3.4 kA,

energy spread = 1.2 MeV,

emittance = 2.4 mm-mrad,

beta-function = 20 m.

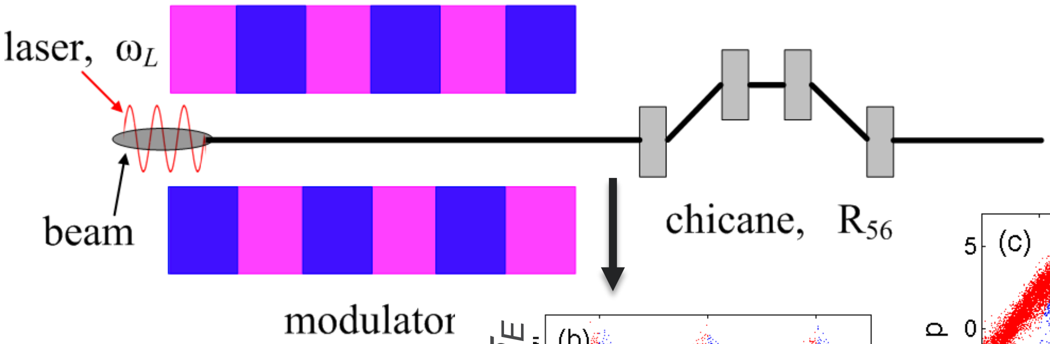
1 - no conditioning, 2 - ideal conditioning (all electrons),

3 - partial conditioning.

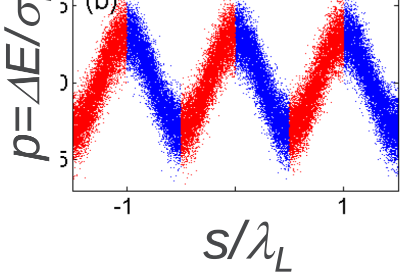
BEAM MANIPULATION USING MODULATOR- MAGNETIC CHICANE MODULES

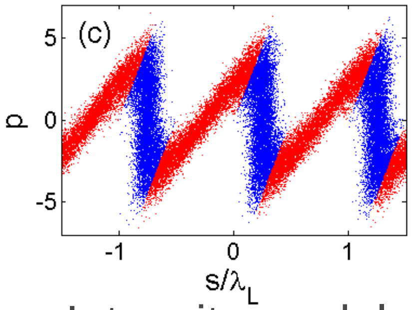
COMBINATION OF ONE MODULATOR AND ONE MAGNETIC CHICANE

Coherent Harmonic Generation[1]
High Gain Harmonic Generation[2]



$$p = A\sin(k_L s)$$

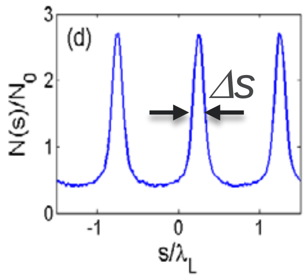




for A>>1

$$\Delta s \approx 0.5\frac{\lambda_L}{A}$$

$$\frac{N_{\max}}{N_0} \approx 1.5A^{2/3}$$



$$\left\{\begin{array}{lcl} B & = & R_{56}k_L\sigma_{\mathcal{E}}/\mathcal{E}_0 \\ \zeta & = & k_L s \end{array}\right.$$

J_n is Bessel function of order n

Intensity modulation

$$\boxed{\frac{N(\zeta)}{N_0} = 1 + \sum_{n=1}^{\infty} 2b_n\cos(n\zeta)}$$

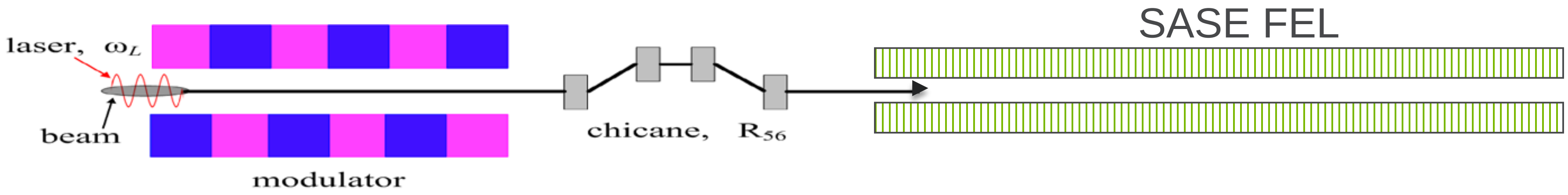
Bunching

$$\boxed{b_n = e^{-\frac{1}{2}B^2n^2}J_n(-ABn)}$$

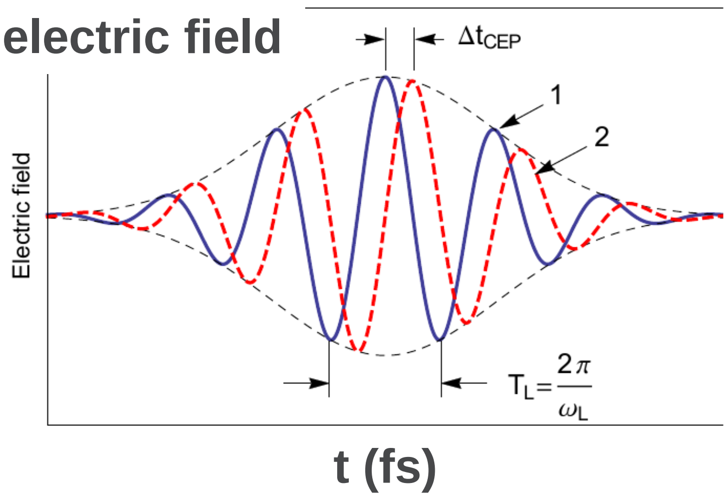
1) Girard *et al*., 1984; Kinkaid *et al*., 1984

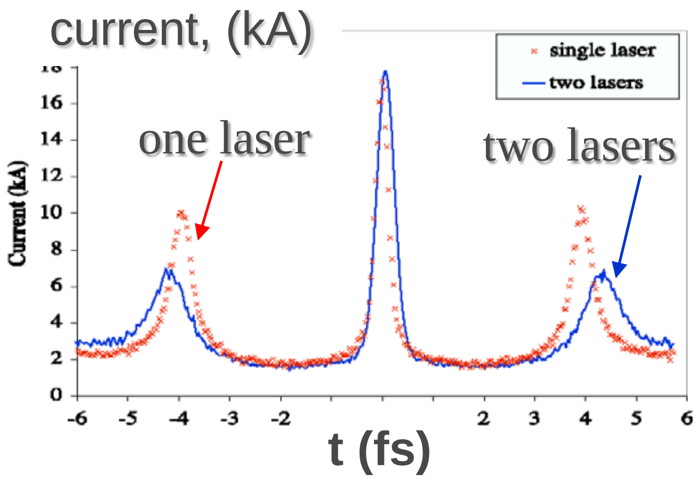
2) Ben-Zvi *et al*., 1991; Yu *et al*., 1991; Allaria *et al*., 2013

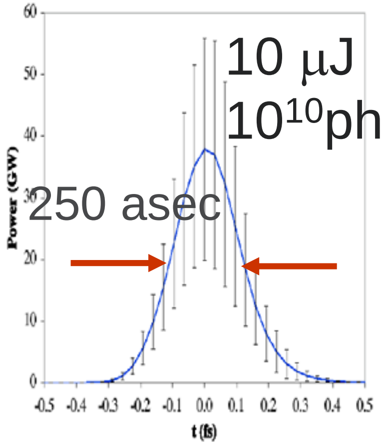
EXAMPLE: GENERATION OF ATTOSECOND X-RAY PULSES



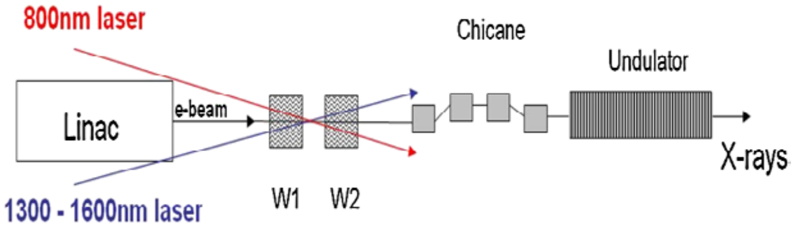
Current Enhanced Self Amplified Spontaneous Emission (ESASE)*







Carrier-envelop phase stabilized few cycle laser pulse



Nearly Fourier transform limited x-ray pulse

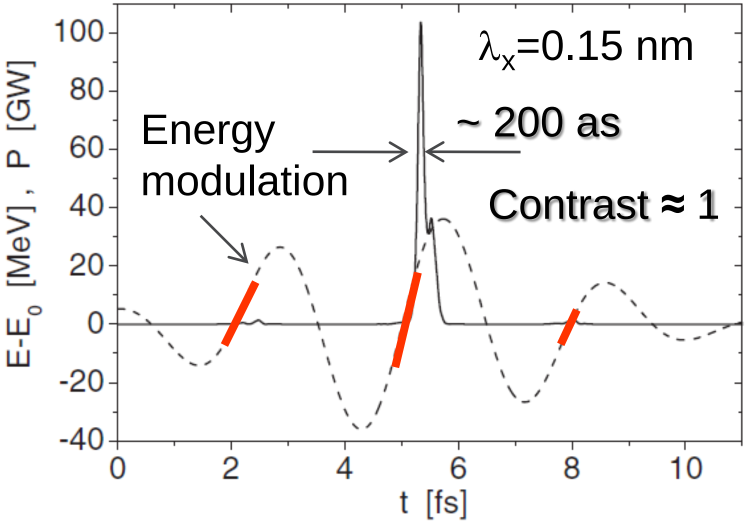
*) Zholents, 2005; Zholents and Penn, 2005; Y. Ding et al., 2009; Marinelli, 2016.

GENERATION OF ATTOSECOND X-RAY PULSES (CONT'D)

Tapered undulator method*

Hard x-rays

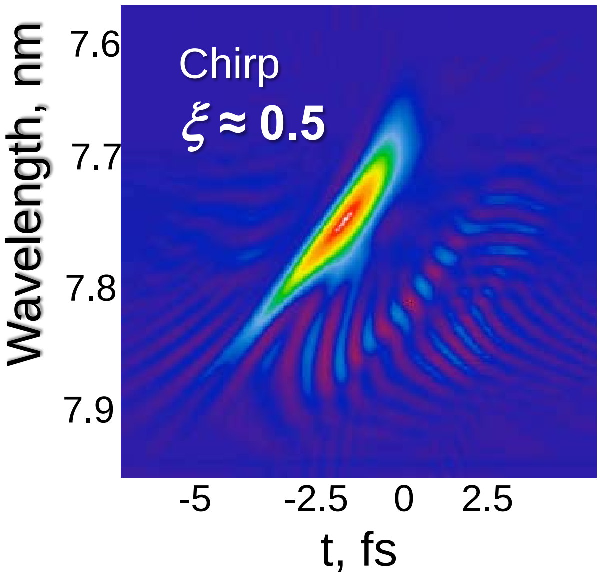
Energy chirp is compensated by the undulator taper in the central slice



$$\frac{d\ln K}{dz} = -\frac{\lambda_x}{\lambda_u}\frac{1+K^2/2}{K^2/2}\frac{d\ln\gamma}{cdt}$$

Soft x-rays

Wigner transform of the on-axis far field



Frequency chirp definition

$$\varphi = \xi(t/\sigma_t)^2$$

Fourier transform limited pulse ~ 1.5 fs (FWHM)

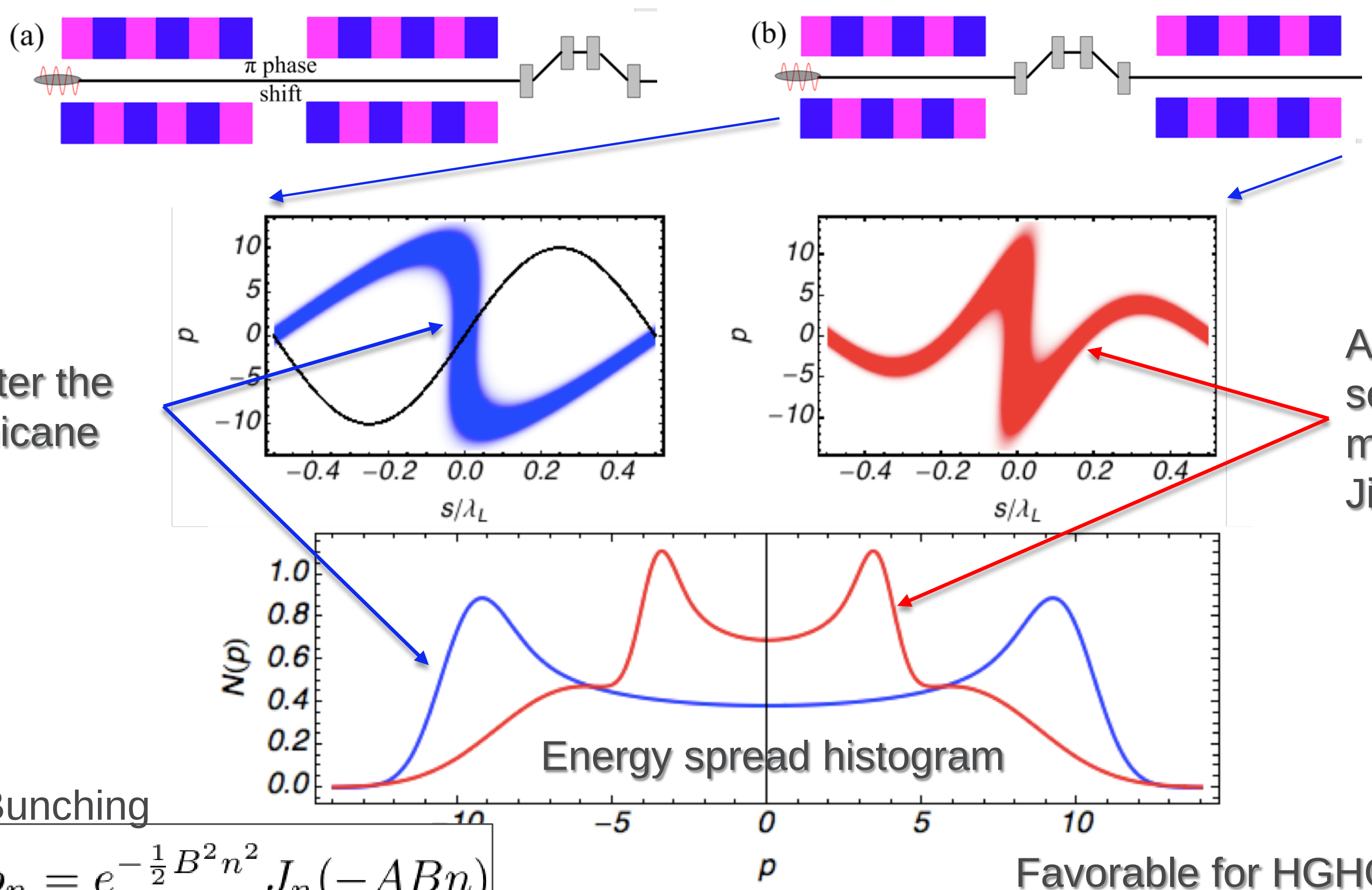
W.M. Fawley, Nucl. Inst. and Meth. A 593, 111(2008).

With two lasers one can manipulate the energy chirp and, thus, the frequency chirp

*) E.L. Saldin, E.A. Schneidmiller, M.V. Yurkov, Phys. Rev. ST-AB 9, 050702 (2006).

COMBINATION OF TWO MODULATORS AND ONE MAGNETIC CHICANE*

Partial reduction of the energy spread induced by first modulator



After the chicane

After second modulator Jia et al.

Energy spread histogram

Favorable for HGHG

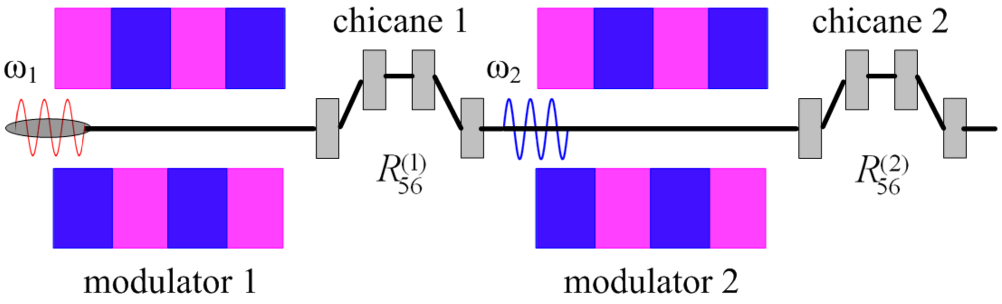
Bunching

$$b_n = e^{-\frac{1}{2}B^2n^2} J_n(-ABn)$$

*) McNeil *et al*., 2005; Allaria and De Ninno, 2007; Jia, 2008

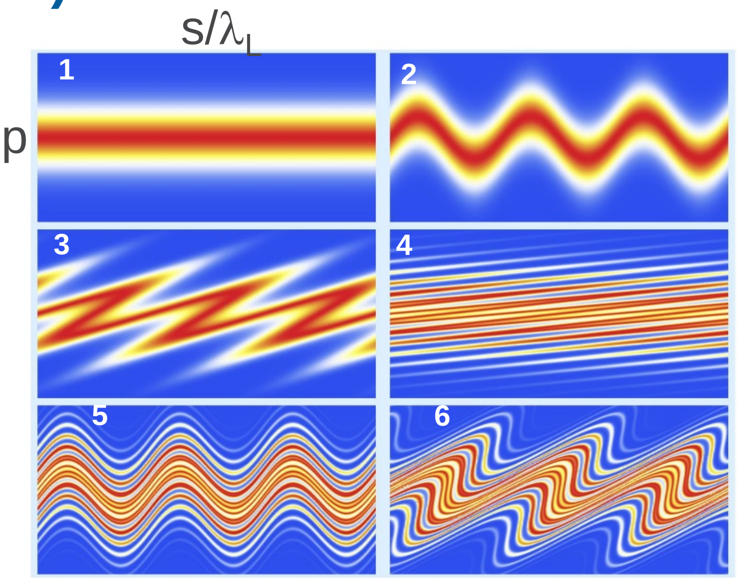
COMBINATION OF TWO MODULATORS AND TWO MAGNETIC CHICANES*

Echo Enabled Harmonic Generation (EEHG)



$$\frac{N(s)}{N_0} = \sum_{n,m=-\infty}^{\infty} 2b_{n,m}\cos[(nk_1 + mk_2)s + \psi_{n,m}]$$

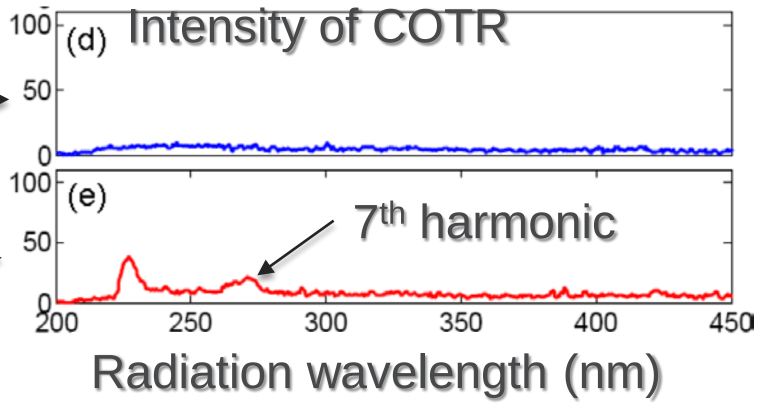
Efficient bunching $b_{-1,m} \approx \frac{0.36}{m^{1/3}}$



Evolution of the longitudinal phase space through an EEHG system

Only 1590 nm modulation, ω_1

Both 1590 nm and 795 nm modulations, ω_2

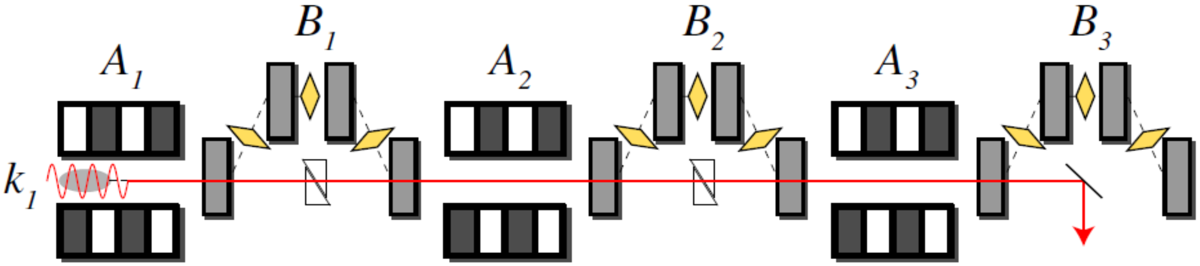


experimental results

*) Stupakov, 2009; Xiang and Stupakov, 2009; Xiang *et al*., 2012; Zhao *et al*., 2012

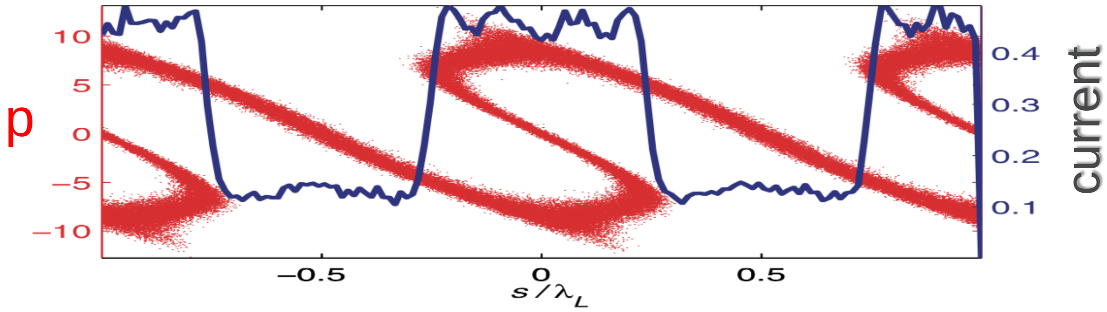
SYNTHESIS OF RADIATION WITH AN ARBITRARY WAVEFORM*

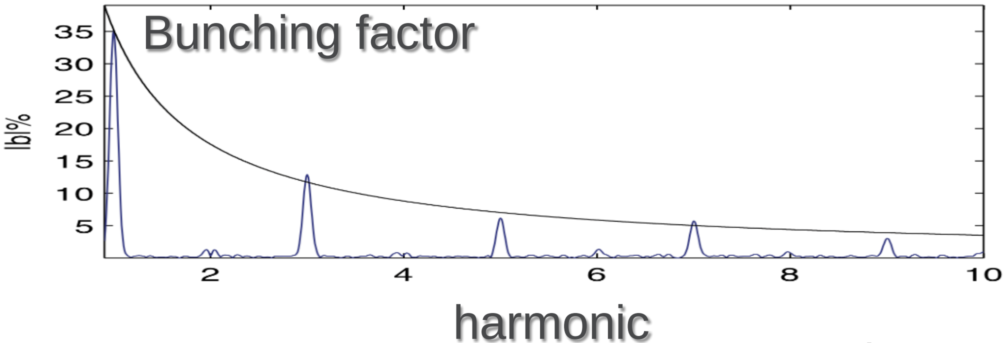
Cascaded laser manipulations for tailoring the harmonic content of the radiation



Quadrupoles are used in chicanes to control the sign of R_{56}

Generation of odd-harmonic bunching for emission of square waveform fields





Deleterious effects:

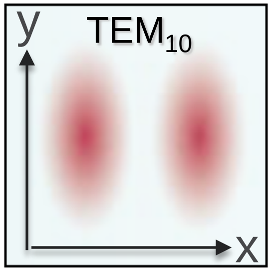
- Incoherent synchrotron radiation
- Intrabeam scattering
- Coherent synchrotron radiation

*) Hemsing and Xiang, 2013

BEAM ANGULAR MODULATION USING THE LASER

USING TEM$_{10}$ LASER FIELD MODE

Second order solution of paraxial wave equation can be used to impart an optical-scale angular kick to the electrons*



$$E(x,y,z,t) = \frac{E_0}{1+(z/z_R)^2}\frac{2\sqrt{2}\,x}{w_0}e^{-(x^2+y^2)/w(z)^2}$$
$$\times\sin\left(k_L z - \omega_L t + \psi_G^{(1)} + k_L\frac{x^2+y^2}{2R(z)} + \psi_0\right)$$

Gouy phase

$$\psi_G^{(1)} = -2\arctan(z/z_R)$$

energy modulation

electron horizontal offset

$$\frac{\Delta\gamma}{\gamma}(s) = \frac{2K}{\gamma^2}\sqrt{\frac{P_L}{P_0}}\mathcal{J}k_L x\cos(ks+\psi_0)$$

applying Panofsky-Wenzel theorem

$$\frac{\partial\Delta x'}{\partial s} = \frac{\partial}{\partial x_0}\left(\frac{\Delta\gamma}{\gamma}\right)$$

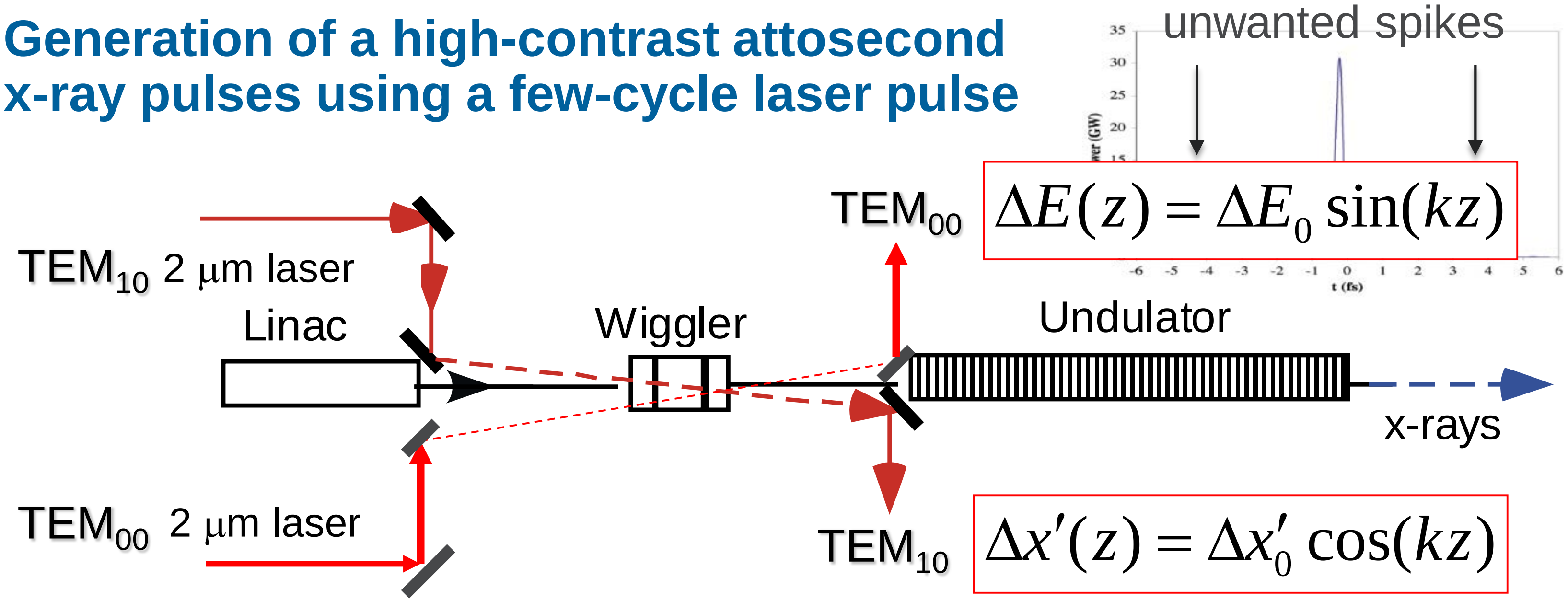
obtain angular modulation

$$\boxed{\Delta x'(s) = \frac{2K}{\gamma^2}\sqrt{\frac{P_L}{P_0}}\mathcal{J}\sin(ks+\psi_0)}$$

*) Zholents and Zolotorev, 2008

APPLICATION OF ANGULAR MODULATION

Generation of a high-contrast attosecond x-ray pulses using a few-cycle laser pulse



$$\Delta E(z) = \Delta E_0 \sin(kz)$$

$$\Delta x'(z) = \Delta x'_0 \cos(kz)$$

Due to transverse oscillations electrons acquire additional phase shift:

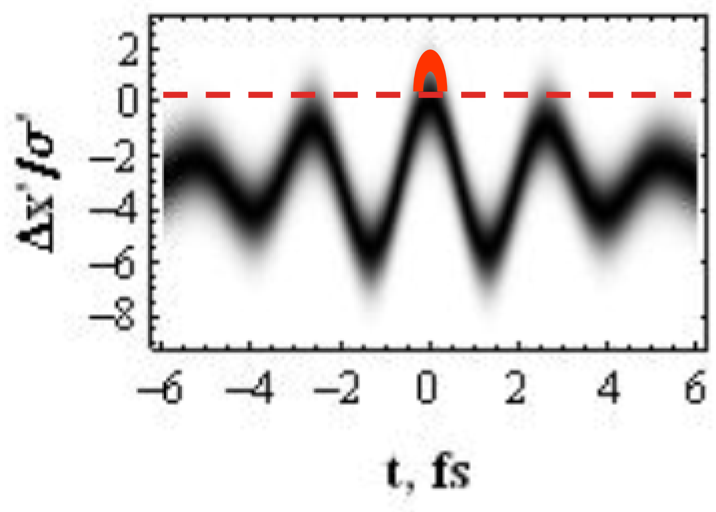
$$\Delta\phi \approx k_x (\Delta x')^2 L_G/2$$

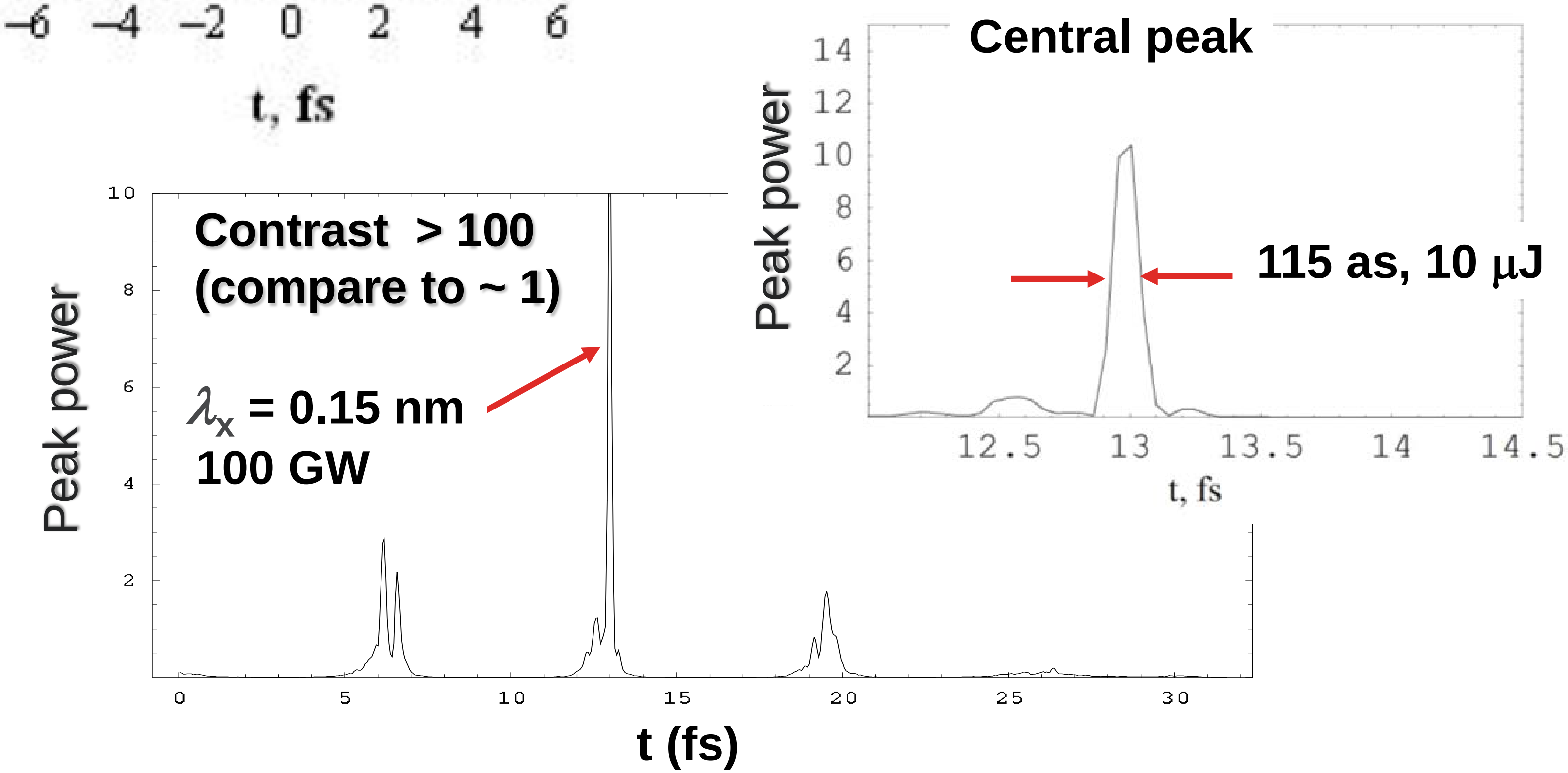
- L_G is the FEL gain length
- k_x =$2\pi/\lambda_x$ is the x-ray wave number

Slippage caused by transverse oscillations can increase or even “kill” the FEL gain

$$\frac{\Delta L_G}{L_G} \approx \frac{\Delta\phi/4}{1-\Delta\phi/4}$$

APPLICATION OF ANGULAR MODULATION (CONT'D)





Contrast > 100 (compare to ~ 1)

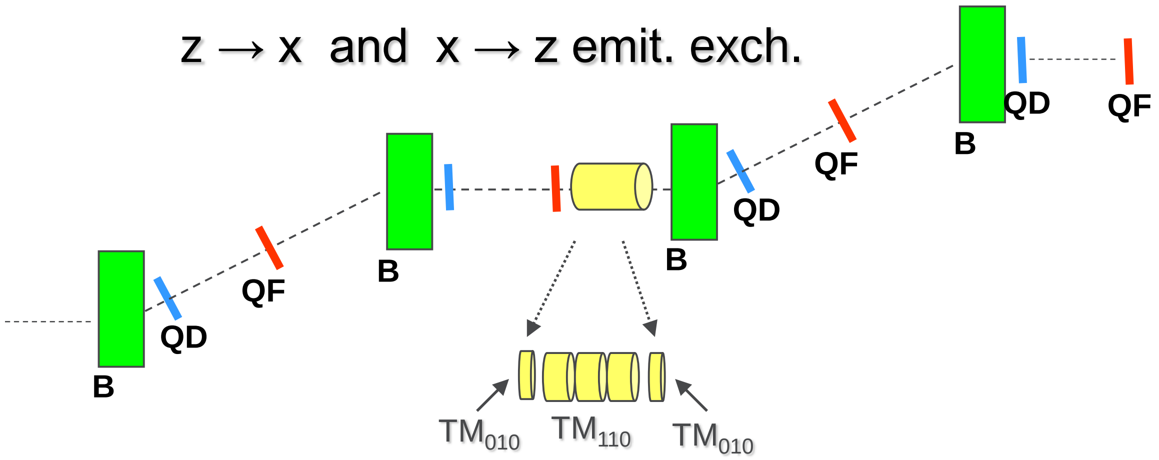
λ_x = 0.15 nm
100 GW

Central peak

115 as, 10 μJ

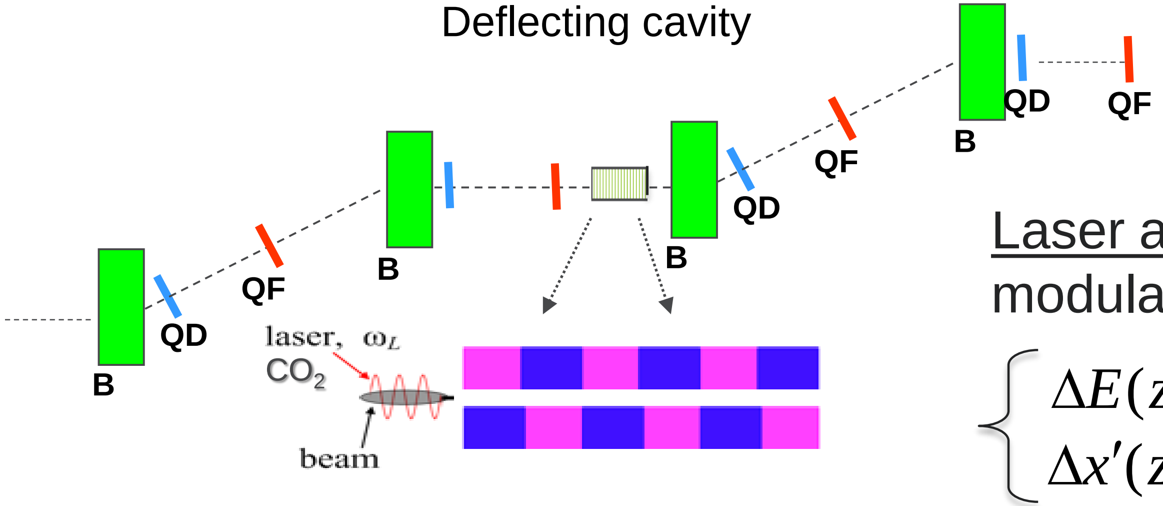
APPLICATION OF ANGULAR MODULATION (CONT'D)

z → x and x → z emit. exch.



Deflecting cavity

Emittance exchange (EEX) beamline with deflecting cavity*



Laser assisted EEX with angular modulation by the laser**

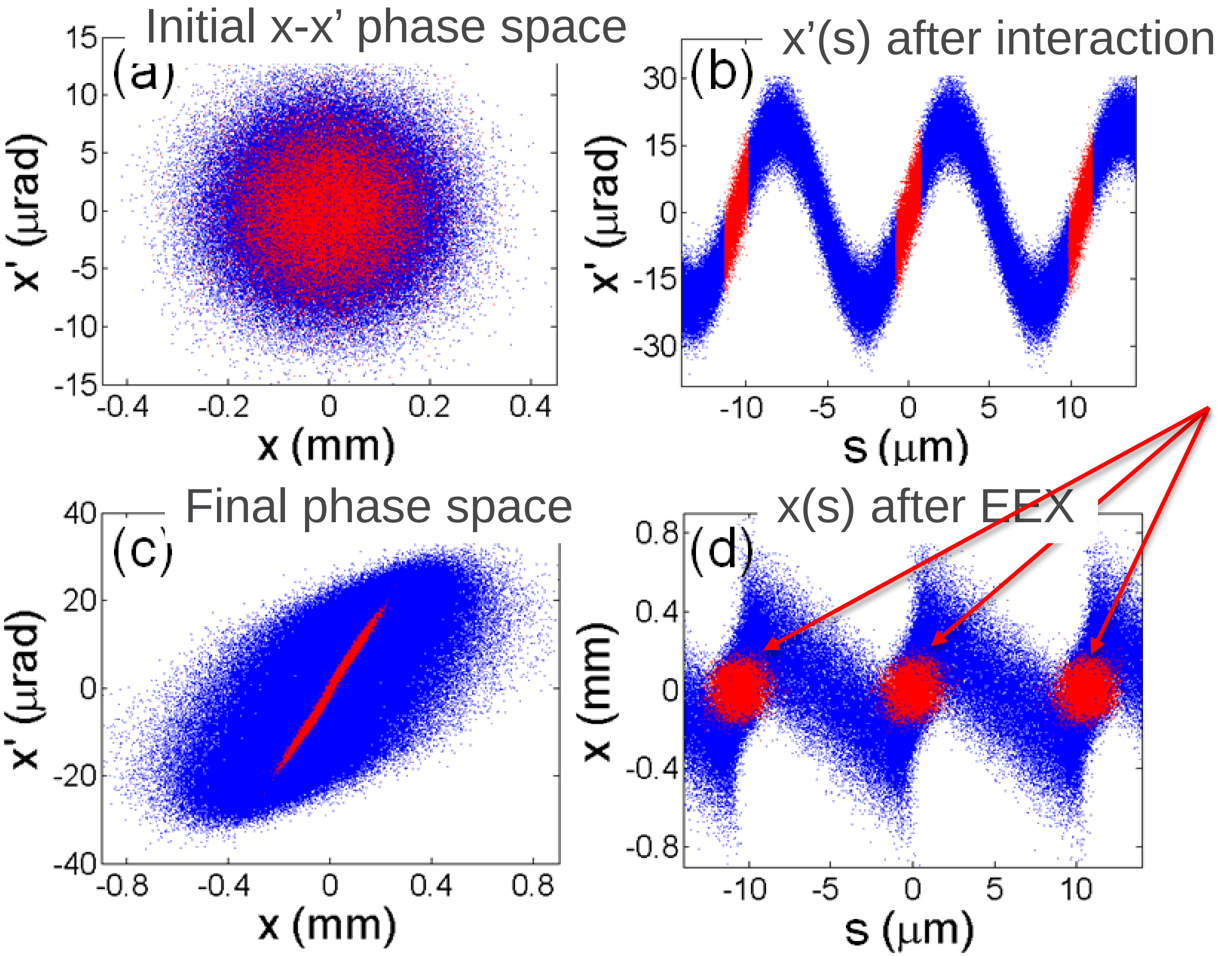
$$\begin{cases} \Delta E(z) = \Delta E_0 \sin(kz) \\ \Delta x'(z) = \Delta x_0' \cos(kz) \end{cases}$$

*) Cornacchia and Emma, 2002; Emma *et al*., 2006; Sun *et al*., 2010; Xiang and Chao, 2011; Zholents and Zolotorev, 2011.

**) Xiang, 2010

APPLICATION OF ANGULAR MODULATION (CONT'D)

EEX for regular spaced clusters of electrons



Initial x-x' phase space

x'(s) after interaction with laser

Final phase space

x(s) after EEX

High brightness electron clusters

Energy chirp before EEX and collimator after EEX can be used to select a single cluster

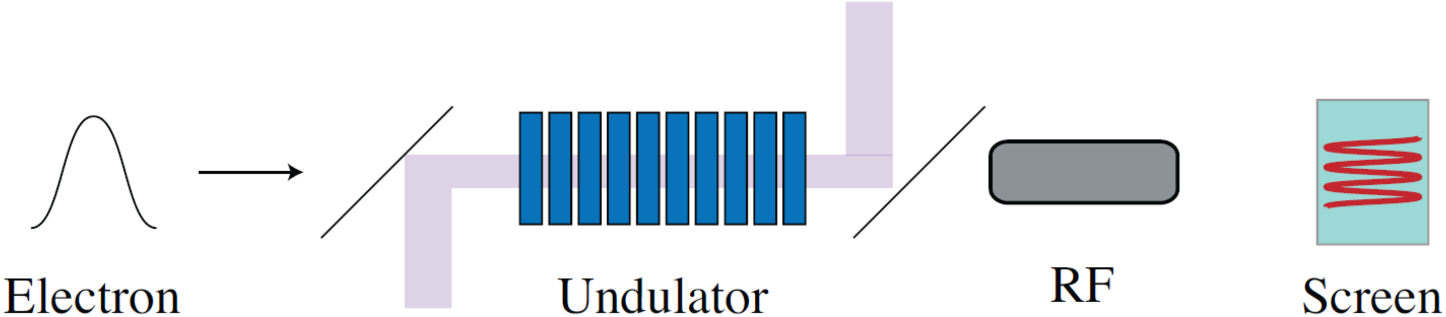
Representative beam phase space evolution in EEX with a laser

*) Xiang, 2010

DIAGNOSTICS WITH LASERS

APPLICATION OF ANGULAR MODULATION (CONT’D)

Optical oscilloscope: combination of the rf deflector and laser deflector*



Electron Bunch

Laser, (TEM$_{10}$) mode

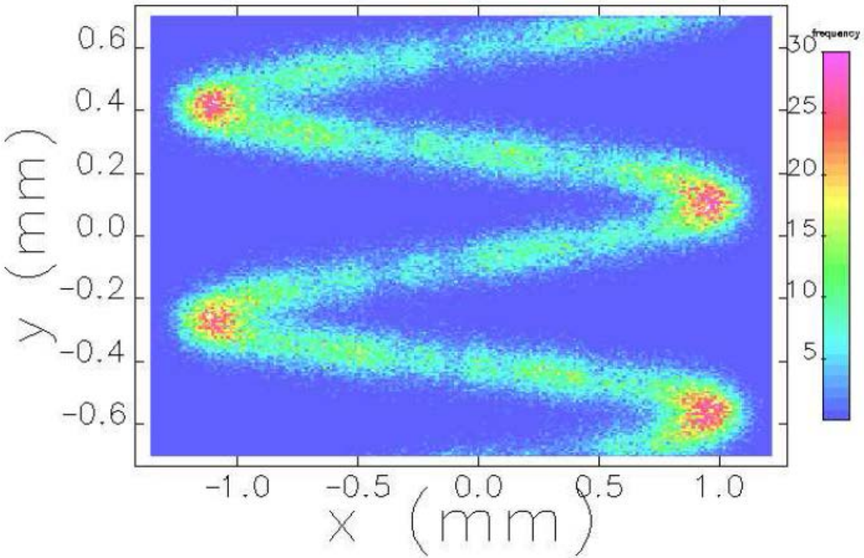
Undulator

RF Deflector

Screen

Simulation: a fragment of the electron bunch on the YAG screen

RF streaking

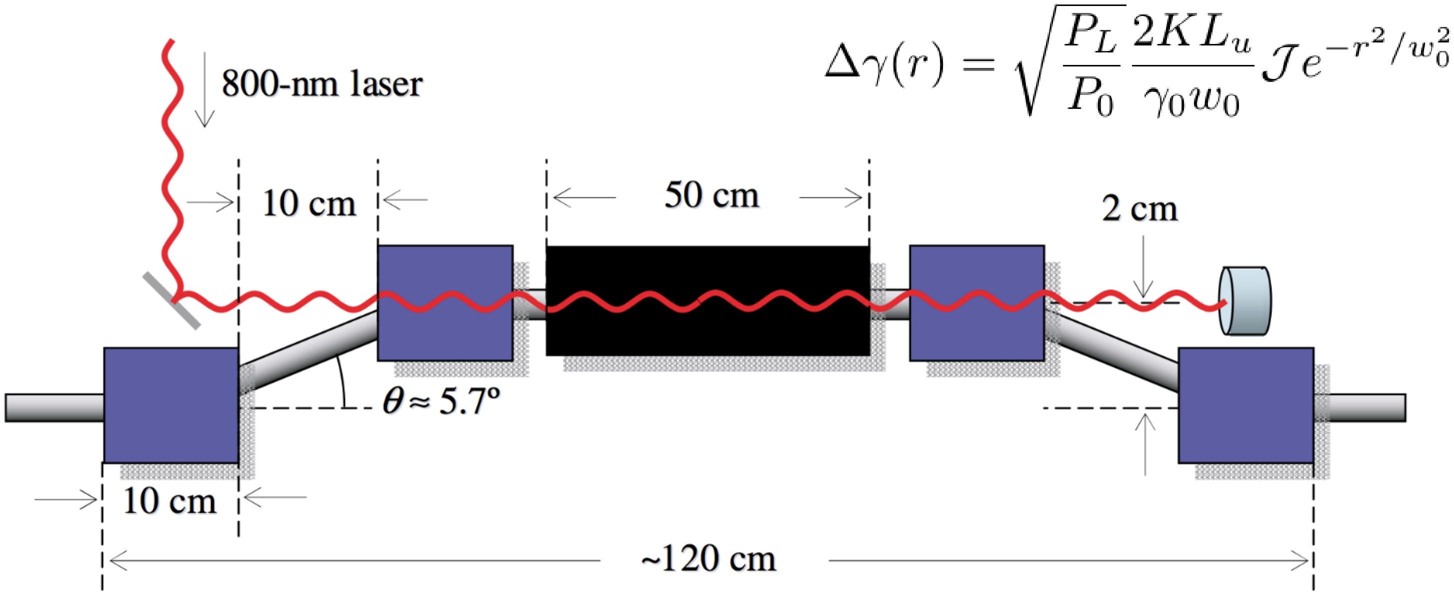


Laser streaking

*) Andonian *et al*., 2011

LASER HEATER*

An effective tool to suppress microbunching instability

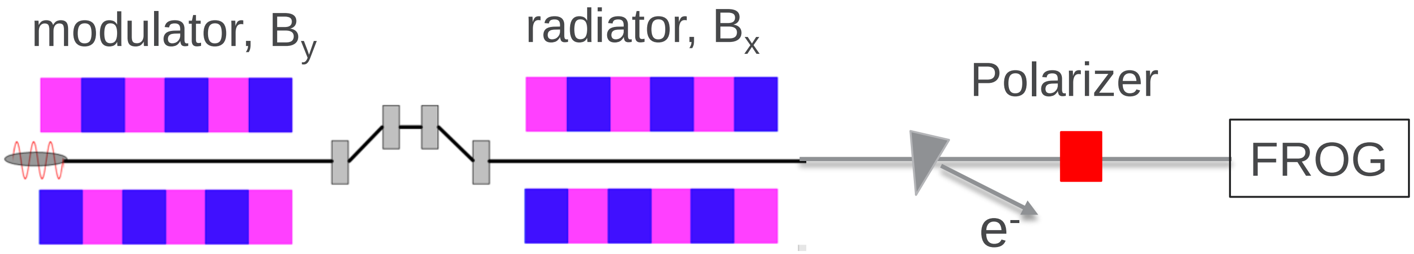


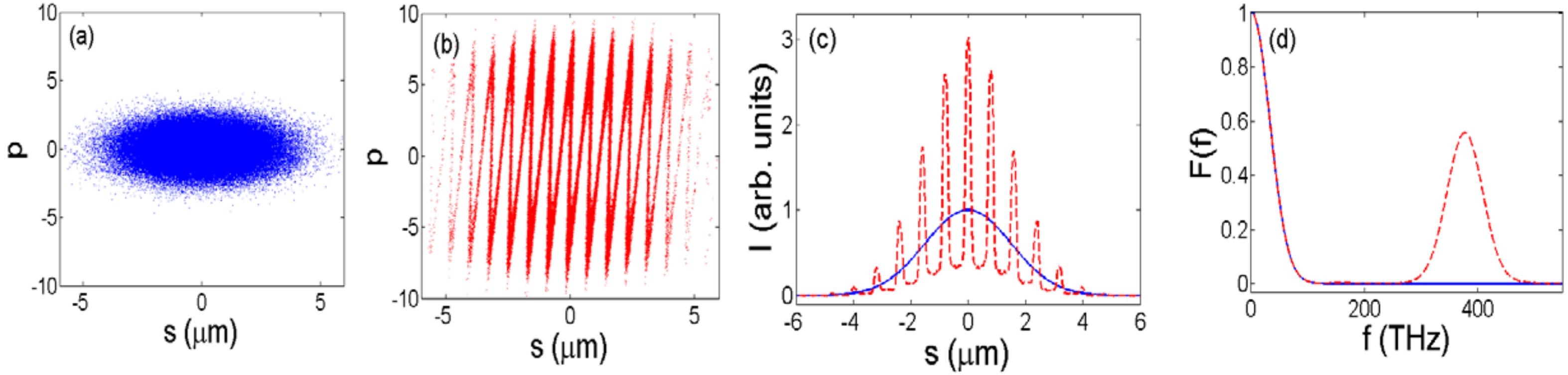
$$\Delta\gamma(r) = \sqrt{\frac{P_L}{P_0}}\frac{2KL_u}{\gamma_0 w_0}\mathcal{J}e^{-r^2/w_0^2}$$

The laser heater works by introducing a correlated microstructure in the phase space of the beam on the scale of the laser wavelength that is effectively washed out through transport, resulting in an increase in the uncorrelated energy spread.

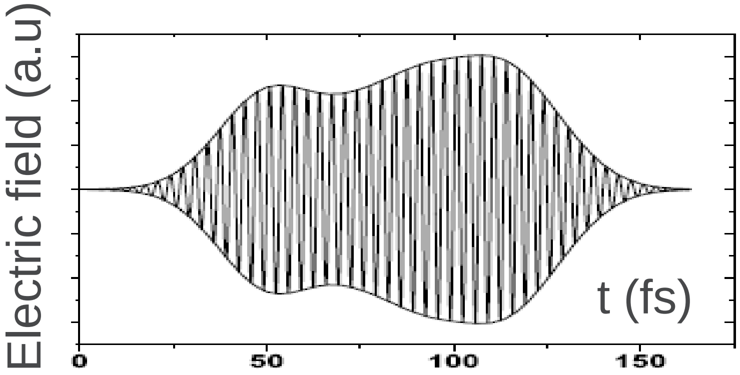
*) Saldin, Schneidmiller, Yurkov, 2004; Huang *et al*., 2004; Huang *et al*., 2010

OPTICAL REPLICA SYNTHESIZER*





Evolution of the longitudinal phase space in a simplified ORS scheme



FROG trace maps bunch shape:

$$|E(t)| \propto |I(t)b(t)| = I(t)\ J_1(kR_{56}\delta_m)e^{-k^2R_{56}^2\sigma_\delta{}^2/2}$$

energy modulation

slice energy spread

*) Saldin *et al*., 2005; Salén *et al*., 2011;

ACKNOWLEDGEMENT

Many examples given in the presentation are taken from the paper: "*Beam by design: Laser manipulation of electrons in modern accelerators*" published in Rev. of Modern Phys., V. 86, p.897, (2014). And I benefited from many fruitful discussions with Erik Hemsing, Gennady Stupakov and Dao Xiang during the work on the paper.

OTHER PRESENTATIONS AT THIS WORKSHOP ON THE “BEAM BY DESIGN” TOPIC

- Yuantao Ding (SLAC), "Beam shaping to improve the FEL performance at LCLS"
- James MacArthur (SLAC), "Towards attosecond science at LCLS and LCLS-II with sub-fs beam length manipulations“
- Paolo Craievich (PSI), "Beam manipulations in FEL linacs using self-induced fields"
- Tim Maxwell (SLAC), "Dechirpers design and experimental results“

CONCLUSION

- Beam manipulations on the microscale, in particular those using the laser, have shown a tremendous potential for preparing the better beams

- Many techniques have been adapted in practice and the number of newly proposed techniques continue to grow

- The outlook for a future is very bright as new possibilities like transverse laser modulation and beam shaping are awaiting further explorations

THANK YOU FOR YOUR ATTENTION