Laser assisted emittance exchange to reduce the X-ray FEL size

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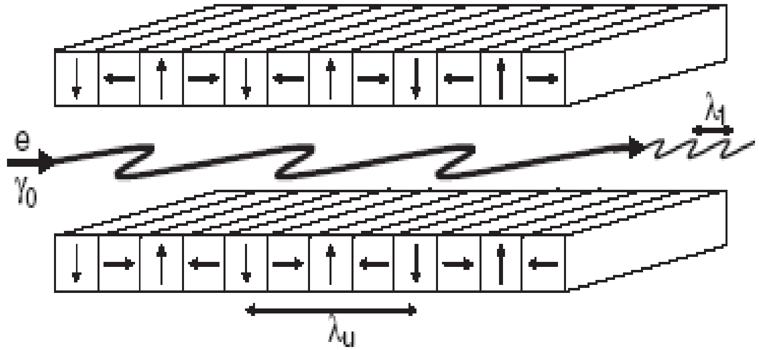
FLS 2010, SLAC

Outline

- Beam requirement for FELs
- Principles of emittance exchange
- Laser assisted emittance exchange (LAEE)
- An 1.5 Angstrom FEL driven by 3.8 GeV beam
- Timing and energy jitter

Beam requirement in x-ray FEL



Electron slips back by one radiation wavelength after it travels one undulator period

- **Low geometric emittance** $\frac{\varepsilon_n}{\gamma} \sim \frac{\lambda}{4\pi}$
- **Low energy spread** $\sigma_E / E < \rho$
- **High peak current** $L_G < L_R$

~10 GeV beam with ~1 MeV energy spread and ~kA peak current

- **LCLS: ~14 GeV; European XFEL: ~17.5 GeV**

Motivation for compact FEL

- **$$$**
  - **LCLS: 420 M $**
  - **European XFEL: 850 M Euros**
- **Space**
  - **SwissFEL, FEL at China, ……**

Path to a compact FEL

$$\lambda_r = \frac{1+K^2/2}{2\gamma^2}\lambda_u \qquad K = 0.934\times B(\mathrm{T})\times\lambda_u(\mathrm{cm})$$

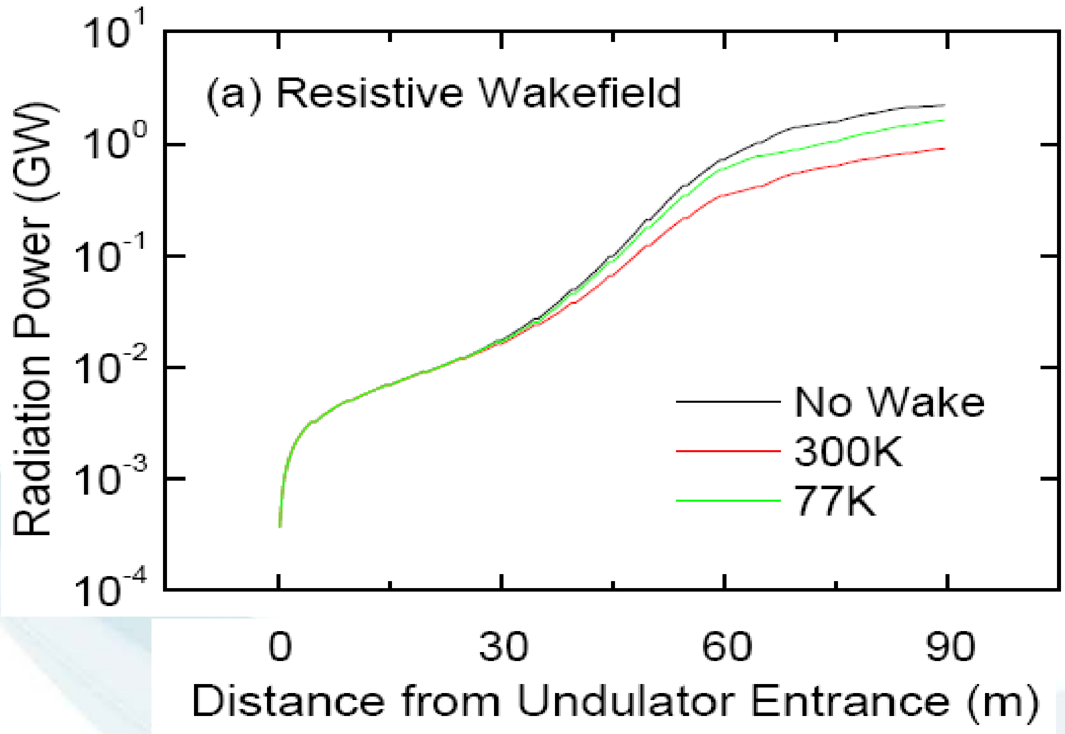
- **Electron-radiation coupling requires K ≥ 1**
- **Small λ_u , in-vacuum undulator**
- **Resistive wake field ~ a^{-2}**
- **Compact hard x-ray FEL with short period undulator**
  - **Moderate energy (~ 4 GeV)**
  - **Moderate peak current (< 500 A)**
  - ***Ultralow transverse emittance (~ 0.1 mm mrad)***
  - **Saturation length ~ 30 m (undulator period ~ 1 cm)**

Wake field effect in compact x-ray FEL

Spring-8 Compact Sase Source (SCSS)

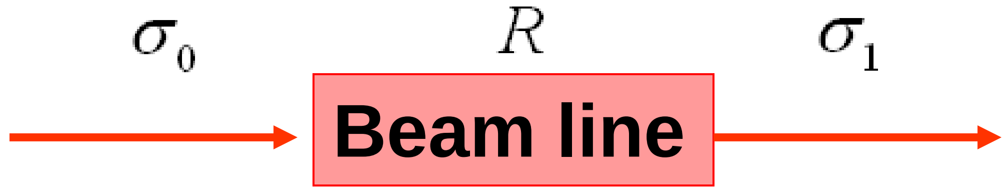
Undulator period: 15 mm

Undulator gap: 3.5 mm



SCSS X-FEL conceptual design report, 2005

Emittance exchange



$$\sigma_1 = R\sigma_0 R^T$$

Initial beam matrix

$$\sigma_0 = \begin{bmatrix} \sigma_x & \sigma_{xz} \\ \sigma_{xz}^T & \sigma_z \end{bmatrix} = \begin{bmatrix} \epsilon_{x0}\beta_x & -\epsilon_{x0}\alpha_x & <xz> & <x\delta> \\ -\epsilon_{x0}\alpha_x & \epsilon_{x0}\gamma_x & <x'z> & <x'\delta> \\ <xz> & <x'z> & \epsilon_{z0}\beta_z & -\epsilon_{z0}\alpha_z \\ <x\delta> & <x'\delta> & -\epsilon_{z0}\alpha_z & \epsilon_{z0}\gamma_z \end{bmatrix}$$

Transfer matrix of a beam line

$$R = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \qquad A = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \qquad B = \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix} \qquad \ldots\ldots$$

Emittance exchange

$$\sigma_1 = \begin{bmatrix} \sigma_{x1} & \sigma_{xz1} \\ \sigma_{xz1}{}^T & \sigma_{z1} \end{bmatrix}$$

with

$$\sigma_{x1} = \underline{A}\sigma_x A^T + B\sigma_{xz}^T \underline{A}^T + \underline{A}\sigma_{xz}B^T + B\sigma_z B^T$$

$$\sigma_{xz1} = \underline{A}\sigma_x C^T + B\sigma_{xz}^T C^T + \underline{A}\sigma_{xz}D^T + B\sigma_z \underline{D}^T$$

$$\sigma_{xz1}{}^T = C\sigma_x \underline{A}^T + \underline{D}\sigma_{xz}^T A^T + C\sigma_{xz}B^T + \underline{D}\sigma_z B^T$$

$$\sigma_{z1} = C\sigma_x C^T + \underline{D}\sigma_{xz}^T C^T + C\sigma_{xz}\underline{D}^T + \underline{D}\sigma_z D^T$$

Requirements for complete emittance exchange $A = D = 0$

$$\sigma_1 = \begin{bmatrix} B\sigma_z B^T & B\sigma_{xz}^T C^T \\ C\sigma_{xz}B^T & C\sigma_x C^T \end{bmatrix} \Rightarrow \begin{aligned} \epsilon_{x1}^2 &= |B\sigma_z B^T| = \epsilon_{z0}^2 \\ \epsilon_{z1}^2 &= |C\sigma_x C^T| = \epsilon_{x0}^2 \end{aligned}$$

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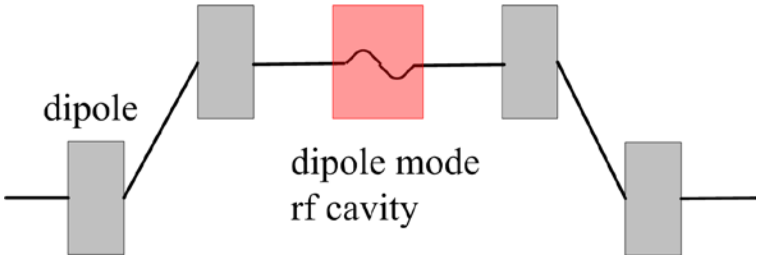
Emittance exchange

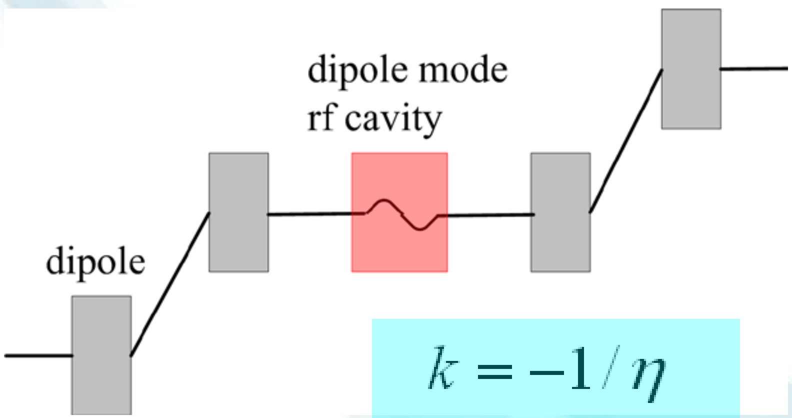
Chicane + rf dipole cavity (incomplete exchange)



$$\begin{pmatrix} 0 & 2L & kL & LkR_{56}-\eta \\ 0 & 2 & k & kR_{56} \\ kR_{56} & LkR_{56}-\eta & 0 & 2R_{56} \\ k & kL & 0 & 2 \end{pmatrix}$$

M. Cornacchia and P. Emma, Phy. Rev. ST-AB, 5, 084001 (2002)

Two doglegs + rf dipole cavity (complete exchange)



$$k = -1/\eta$$

$$\begin{pmatrix} 0 & 0 & kL & LkR_{56}+\eta \\ 0 & 0 & k & kR_{56} \\ kR_{56} & LkR_{56}+\eta & 0 & 0 \\ k & kL & 0 & 0 \end{pmatrix}$$

K.-J. Kim and A. Sessler, AIP Conf. Proc, 821, 115, (2006)

Limitations of the emittance exchange

- Longitudinal emittance is NOT small
  - LCLS beam: 250 pC

$$E = 6\text{MeV}$$

$$\sigma_z = 0.7\text{mm} \qquad \varepsilon_{n,z} = \gamma\sigma_z\sigma_\delta / E = 1.4\mu\text{m}$$

$$\sigma_\delta = 1\text{keV}$$

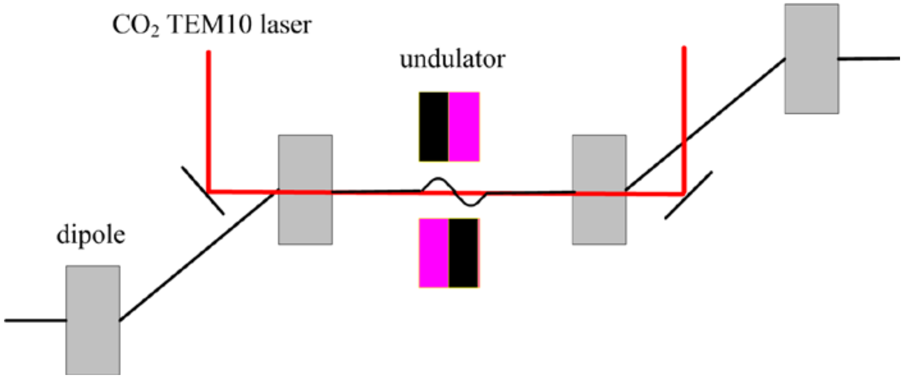
Transverse emittance is ~0.5 um

- Short bunch might have CSR problem

$$\sigma_z = 70\mu m \qquad \varepsilon_{n,z} = 0.14\mu m$$

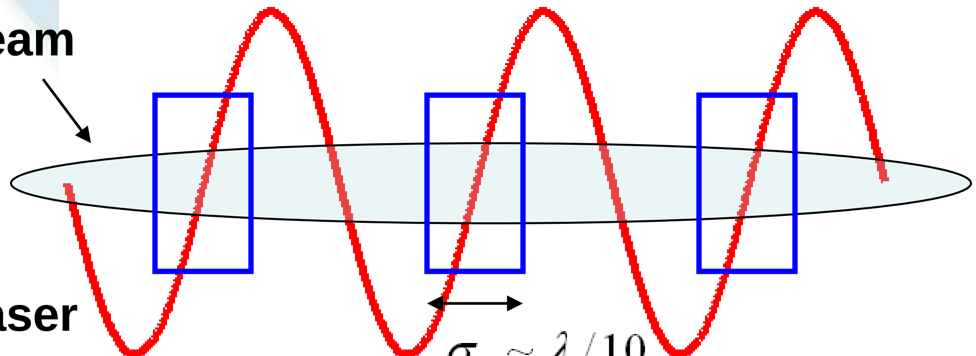
- Timing and energy jitter problem

Laser assisted emittance exchange (LAEE)



TEM$_{00}$ TEM$_{10}$

$$E_x = \frac{E_0}{1+(z/z_0)^2}\frac{2\sqrt{2}x}{w_0}\sin(2\pi(z-ct)/\lambda+\phi)\times\exp\left[-\frac{x^2+y^2}{w_0^2(1+(z/z_0)^2)}\right]$$



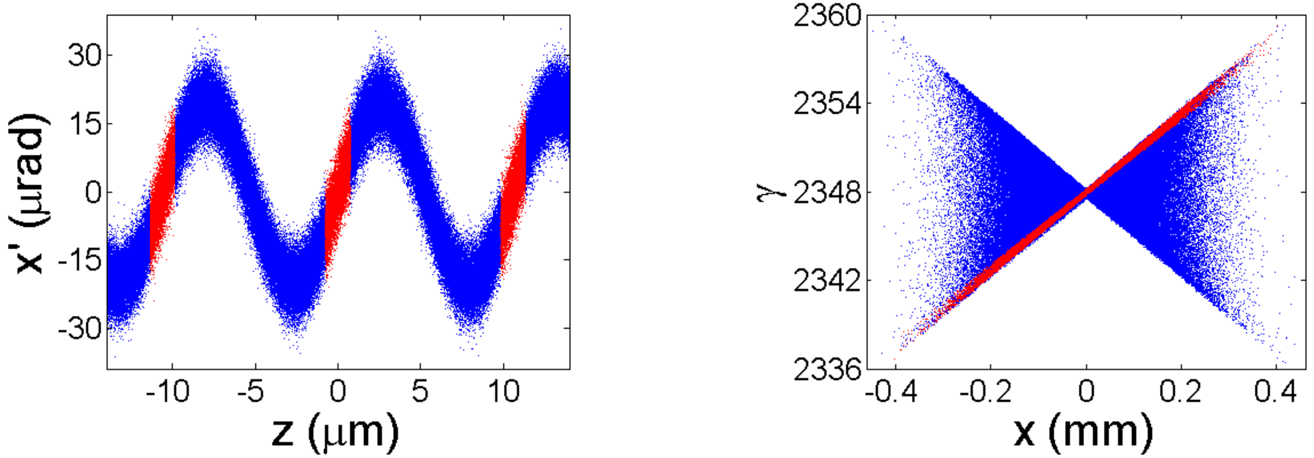
$s = 0$ ⇒

$$\Delta x'(x,y,s) \approx ks$$

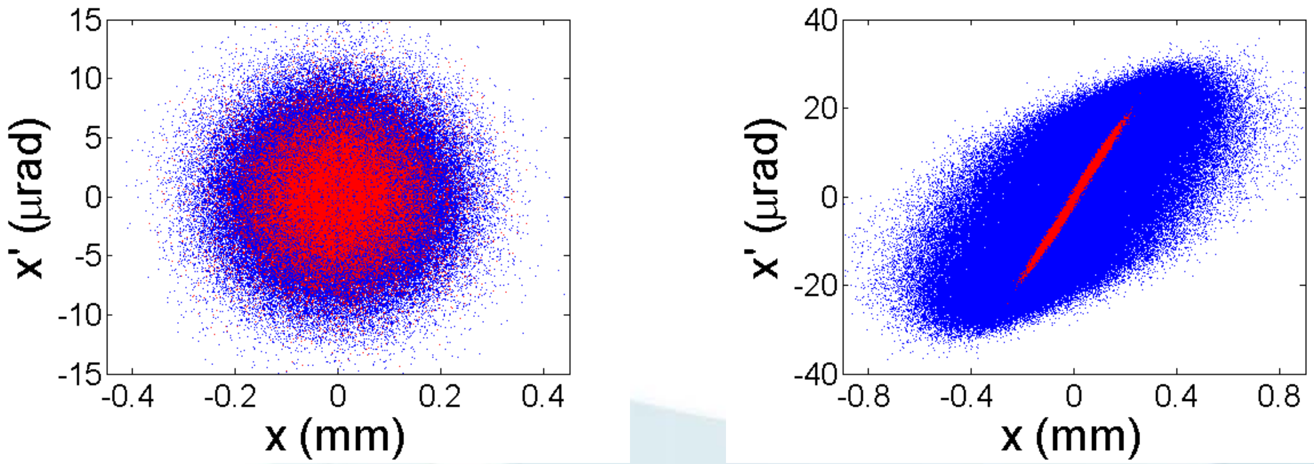
$$\Delta\gamma(x,y,s)/\gamma \approx kx$$

- TEM$_{10}$ laser is equivalent to rf dipole mode cavity for the particles at s~0

LAEE (Gold particles in red)

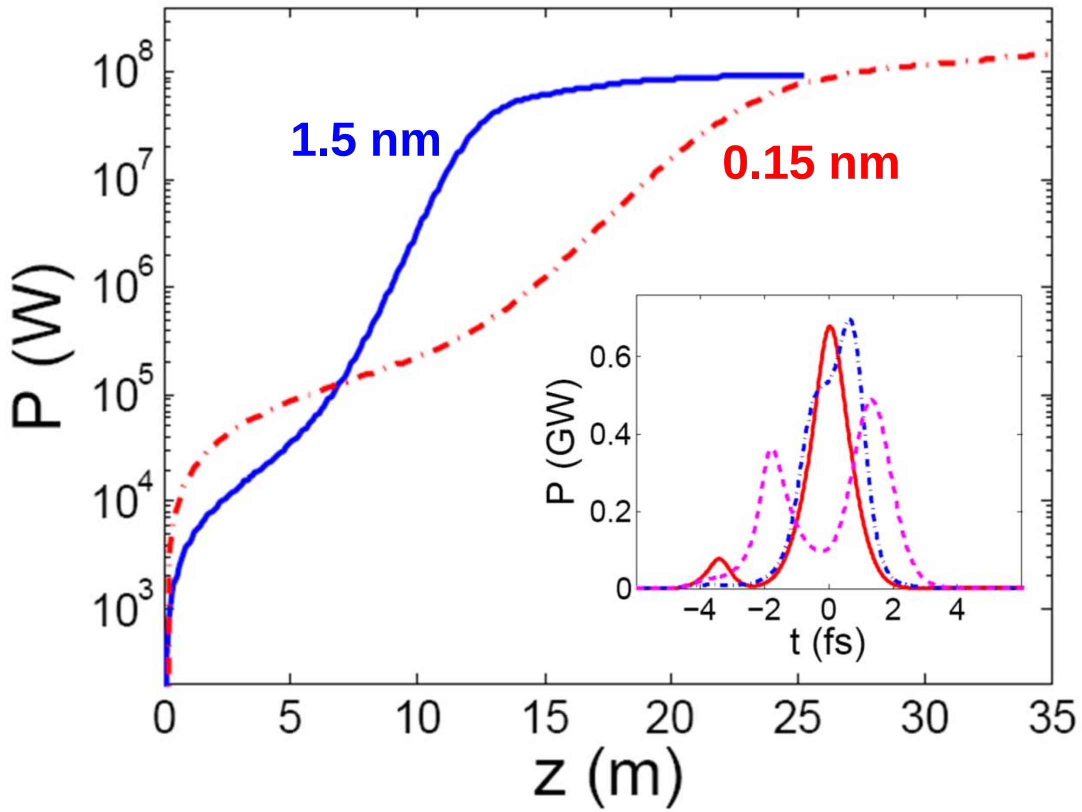


Phase space after interaction with the TEM_{10} laser



Before exchange **After exchange**

Compact x-ray FELs



- **Soft x-ray FEL at 1.5 nm**
  E=1.2 GeV; L_s=15 m; N_p=3*10^{11}
- **Hard x-ray FEL at 0.15 nm**
  E=3.8 GeV; L_s=30 m; N_p=5*10^{10}

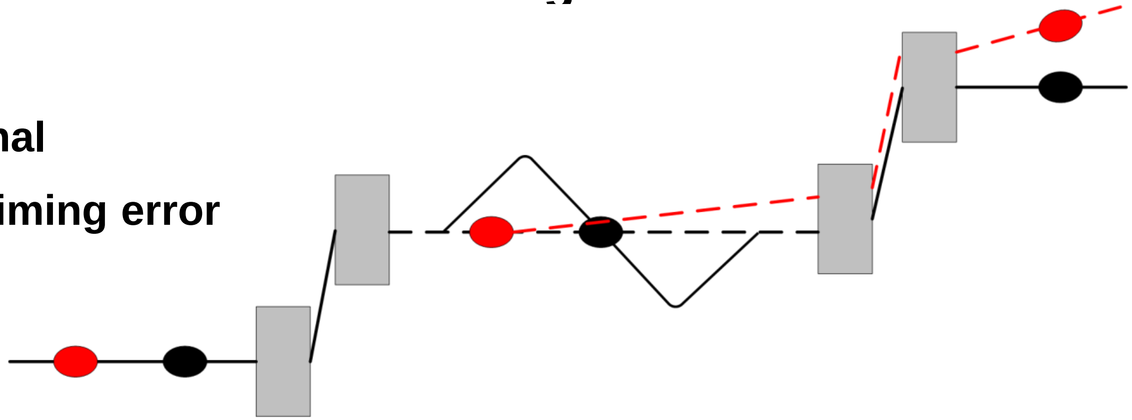
D. Xiang, Phys. Rev. ST-AB, 13, 010701 (2010)

Effects of energy and timing jitter

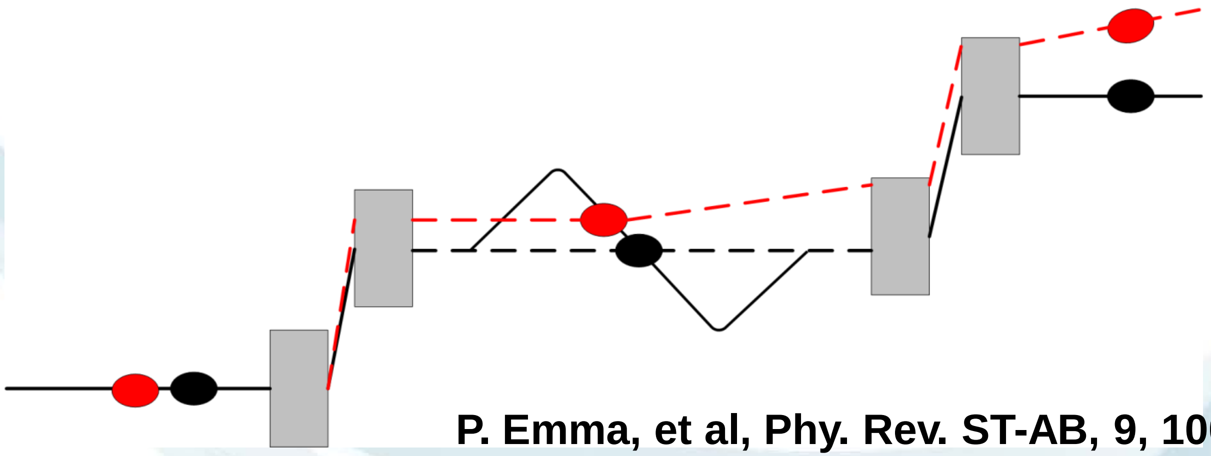
Standard emittance exchange scheme

nominal

with timing error



Timing jitter → wrong phase → non-zero kick → position jitter



P. Emma, et al, Phy. Rev. ST-AB, 9, 100702 (2006)

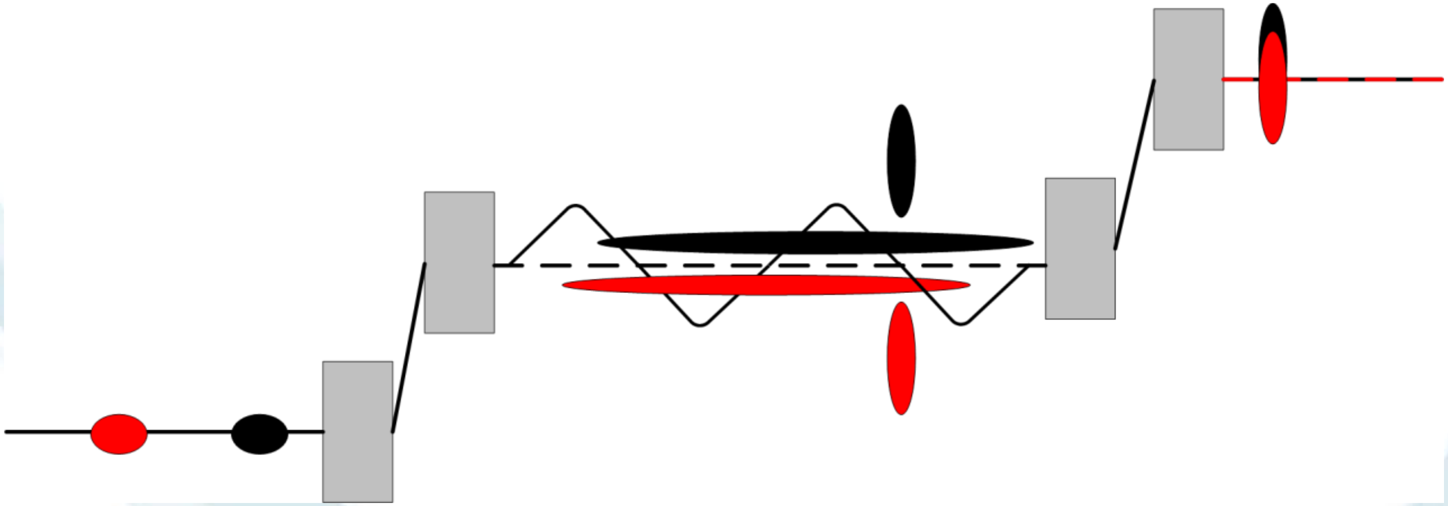
Energy jitter → wrong phase → non-zero kick → position jitter

Effects of energy and timing jitter

Traditional emittance exchange scheme

Timing/Energy jitter on the order of sigma_z and sigma_E will transform to transverse position/angular jitter on the order of sigma_x and sigma_x'

LAEE (timing jitter absorber)



Because the GOLD particles are defined by the laser, the timing and energy jitter of the beam will not affect the beam transverse position and divergence

Summary

- LAEE may allow one to generate beam with ultralow transverse emittance

- Help to realize an ultra-compact XFEL

- NOT sensitive to energy and timing jitter

Many thanks to:

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Thanks!