The 40th JKPS:

Longitudinal-to-transverse mapping for femtosecond electron bunch length measurement

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A longitudinal-to-transverse mapping technique is proposed to measure the length and temporal profile of ultrashort electron bunches. In this scheme a special chicane and a radio-frequency deflecting cavity are used to transform the beam's longitudinal distribution into angular distribution which is further converted to transverse distribution after a parallel-to-point imaging beam line. With this technique, the temporal profile of the electron beam is exactly mapped to the transverse profile. This makes it possible to measure ultrashort electron bunch length with a resolution well beyond 1 femtosecond.

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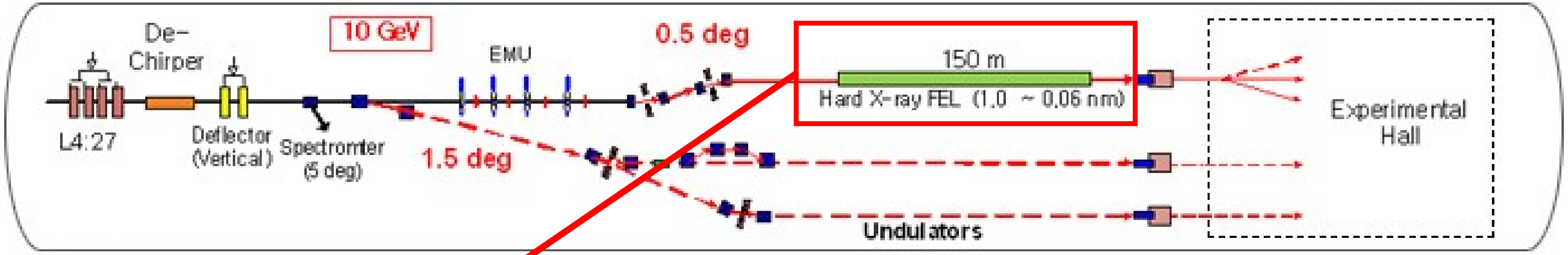
26. 01. 23

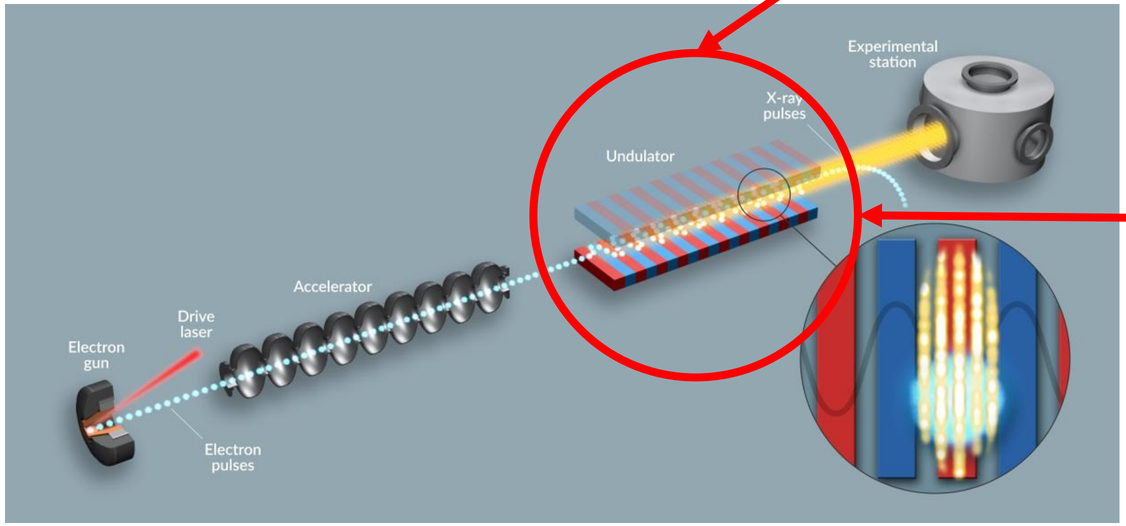
Geunwoo Kim

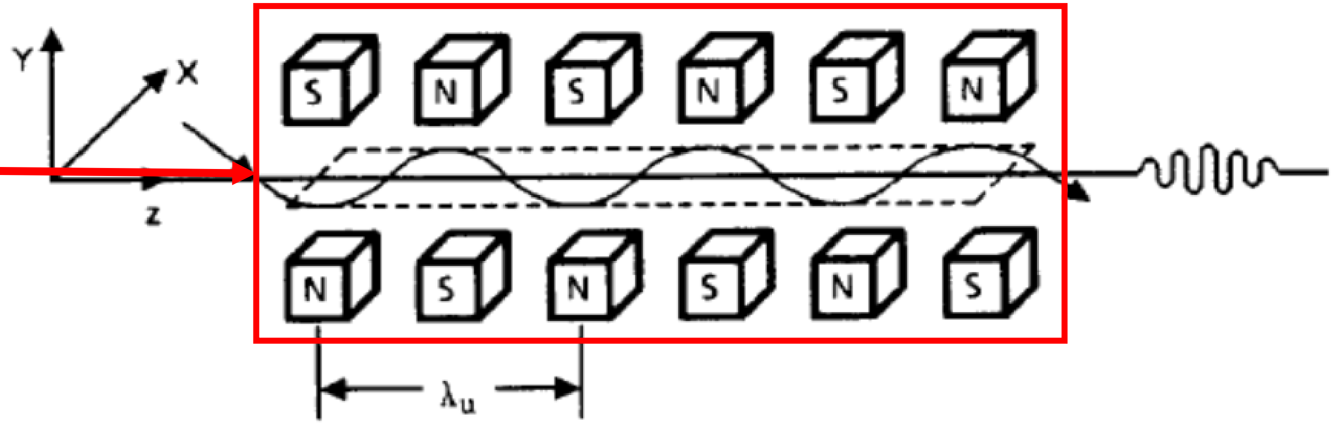
POSTECH

Background: Free Electron Laser (FEL)

- **Schematic of FEL beamline**

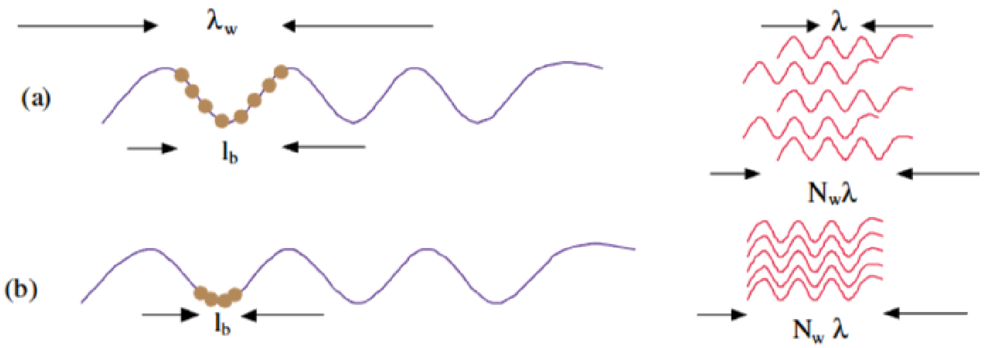






Background: Free Electron Laser (FEL)

- **Requirements for FEL performance**
  1. *<u>Short pulse (=short length beam): High peak current</u>* → interests in this paper (How to measure it?)
  2. Low energy spread is essential for stable FEL gain.



Gain length: $L_g = \frac{\lambda_u}{4\pi\sqrt{3}\cdot\boldsymbol{\rho}}$

Pierce parameter: $\rho^3 = \frac{\boldsymbol{I}}{4I_A}\frac{\gamma K_u^2[JJ]^2(K_u^2)}{\left(1+\frac{K_u^2}{2}\right)^2(k_r\boldsymbol{\sigma_x})^2}$, → $\boldsymbol{\rho^3} \propto \boldsymbol{I}/\boldsymbol{\sigma_x^2}$

"Increasing the peak current shortens the gain length."

Background: Free Electron Laser (FEL)

- **Application**

	3^{rd} Gen.	SASE-FREE-ELECTRON LASER	Short pulse SASE-FREE-ELECTRON LASER
Wavelength range, nm	1-0.1		
Emittance, nm rad	2	0.03	0.03
Pulse length, ps	15-30	0.06	0.01
Average brightness	10^{20}	10^{22}	10^{21}
Peak brightness	10^{23}	10^{33}	10^{33}
Peak power, W	10^{3}	10^{10}	10^{10}

3^{rd} gen. beam line

coherence volume 1 x 5 x 50μm

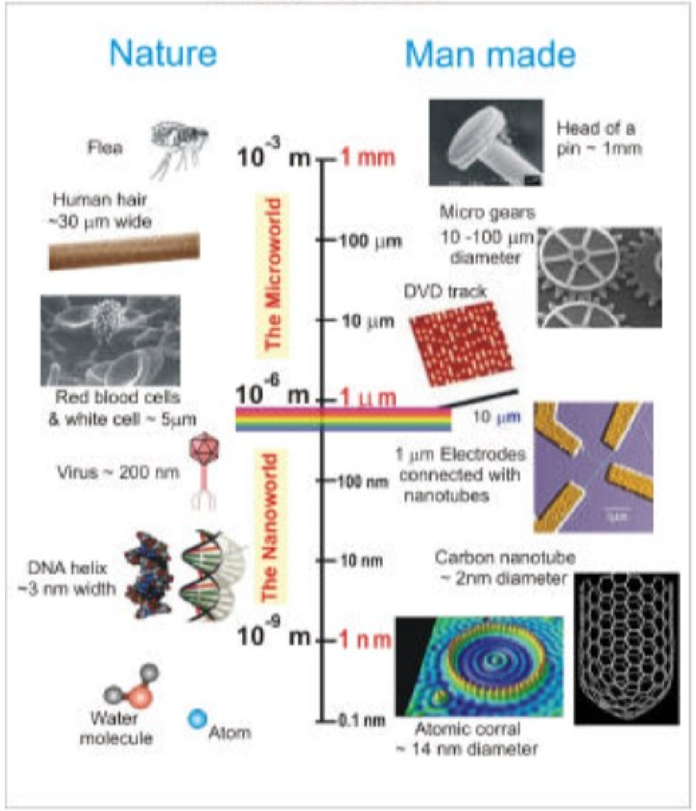
contains < 1 photon

LCLS source

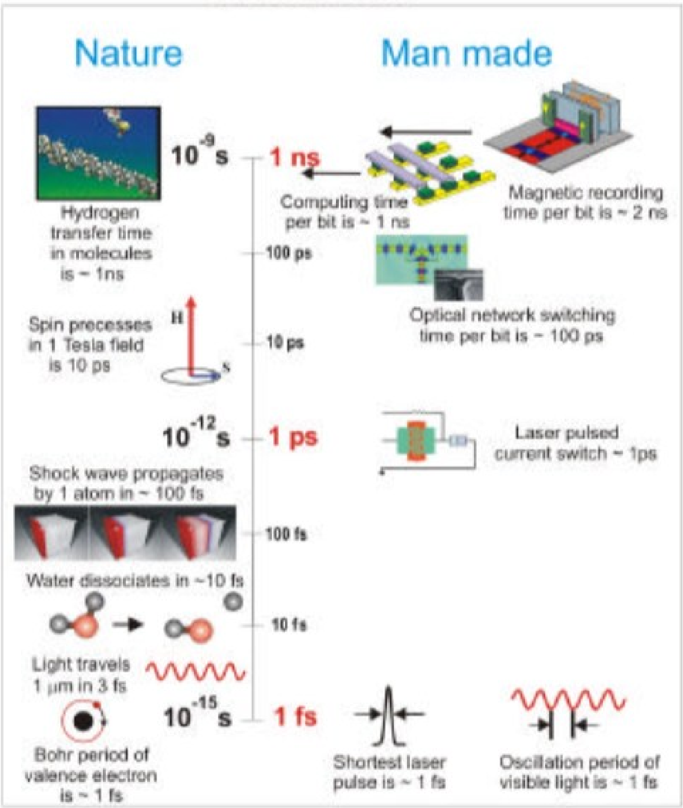
coherence volume 0.1 x 100 x 100μm

contains 10^9 photons

Ultra-Small



Ultra-Fast

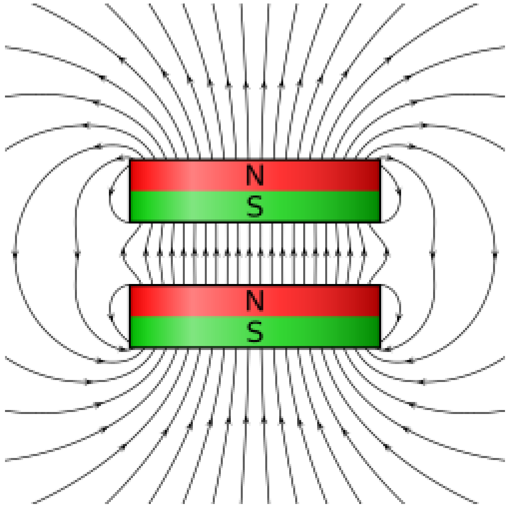


Background: Dipole Magnet

Main feature

- Generates a uniform magnetic field to bend charged particles.
- Bending angle θ depends on momentum → energy-dependent dispersion.

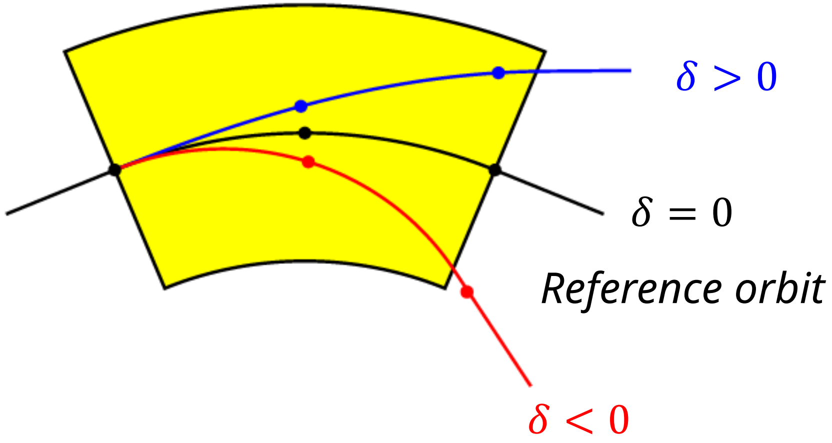
$$\theta \approx 0.3 \cdot \frac{B\ [\mathrm{T}] \cdot L\ [\mathrm{m}]}{E\ + \boldsymbol{\Delta E}\ [\mathrm{GeV}]}$$



- Maps energy deviation (δ) into horizontal position.

$$\boldsymbol{\delta} = \frac{\boldsymbol{p} - p_0}{p_0}$$

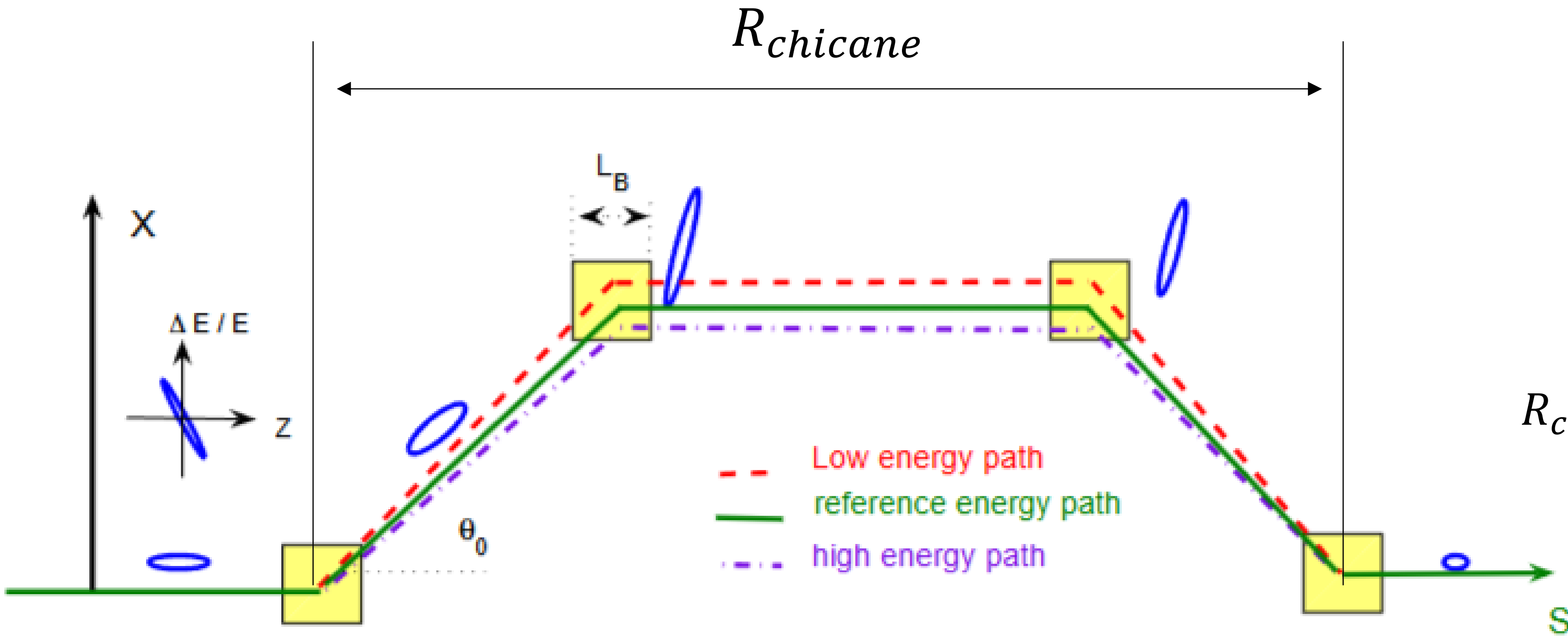
$$x(s) = x_{\beta(s)} + \boldsymbol{D}(\boldsymbol{s})\boldsymbol{\delta}$$



Background: Chicane (usually bunch compressor)

Main feature

- Made of 4 dipole magnets.
- *Used to shorten the electron bunch length* by exploiting $\delta - x$ coupling.
- $z_f = z_i + \boldsymbol{R_{34}}\delta$ where $R_{56} = \int \frac{D(s)}{\rho(s)} ds$

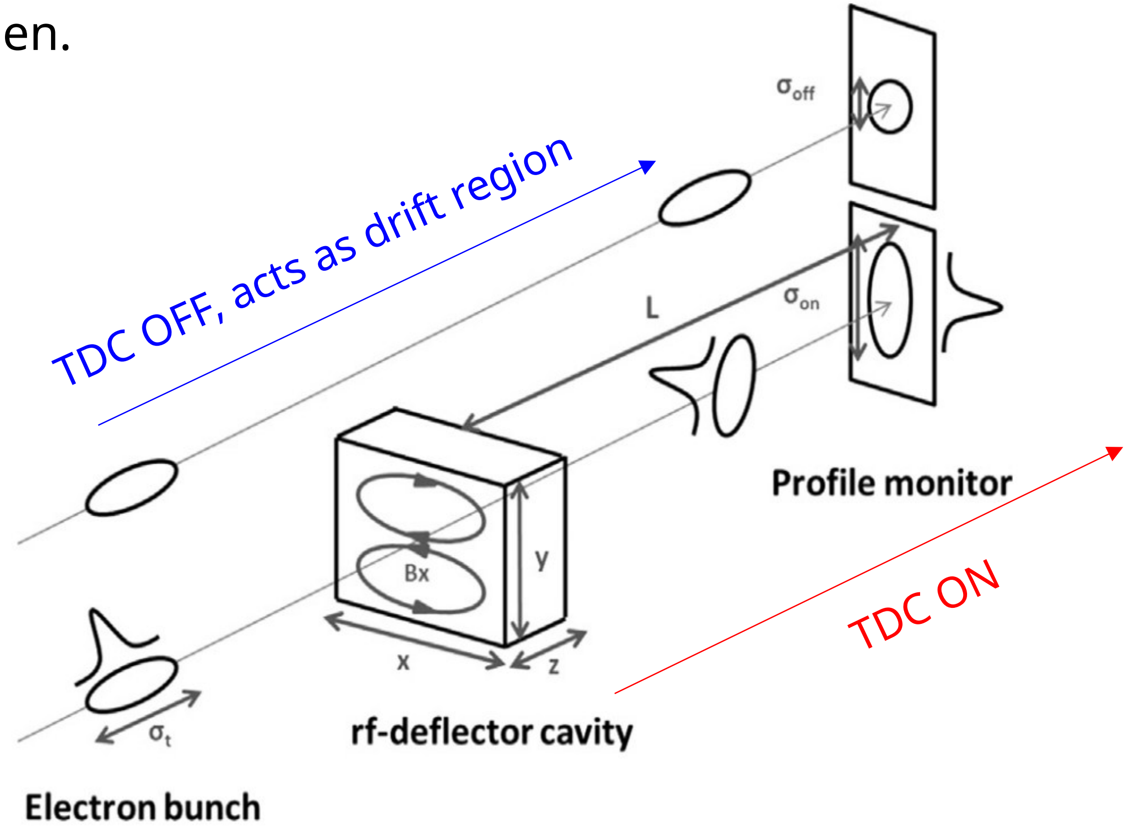


$$\overrightarrow{g_0} = (x, x', z, \delta)^T$$

$$R_{chicane} = \begin{bmatrix} 1 & L & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & \boldsymbol{R_{34}} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

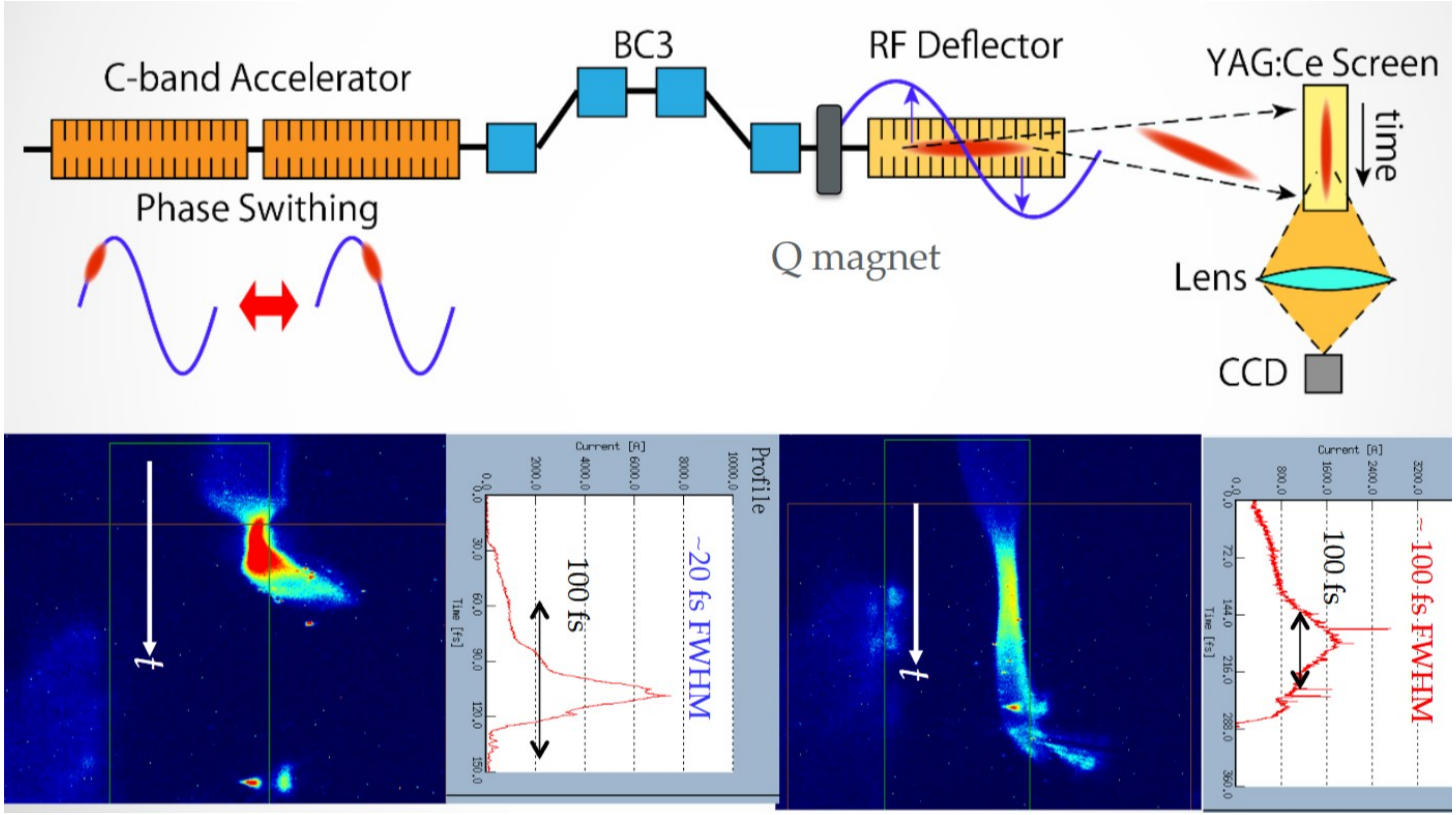
Background: Transverse Deflecting Structure (TDS)

- **Basic principle of TDS**
  - A type of the longitudinal beam profile monitor.
  - Provides a transverse kick via RF fields ($\vec{\boldsymbol{F}} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$.
  - Map $z \rightarrow x \; or \; y$ on screen.



Existing Method: Bunch Length Measurement

- RF deflector + YAG screen measure bunch length (~10–20 fs).



Introduction: Reported Bunch Length at LCLS

Motivations

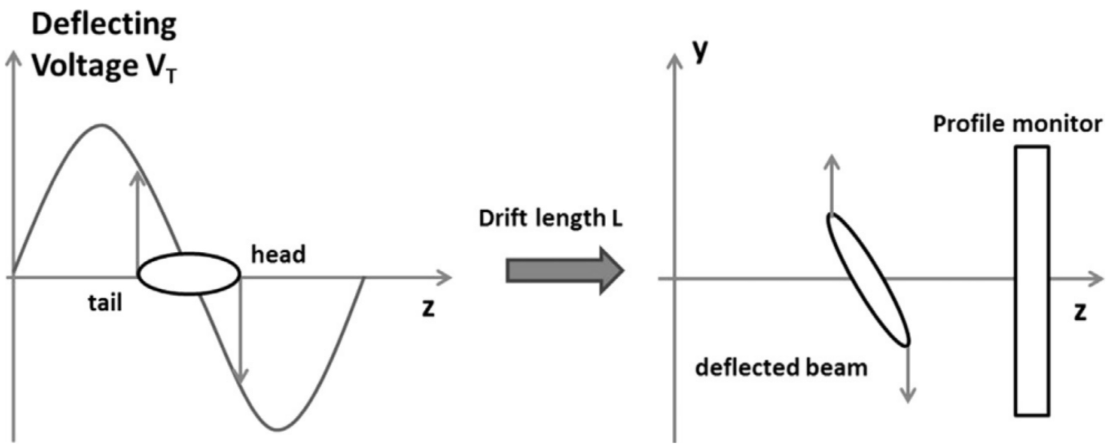
- LCLS achieves bunch lengths of ~ 3 fs.
- Achieved 10-20 fs resolution through TDS (2010).
- Such short pulses are beyond TDS diagnostics.
- Plus, all proposed method depends on $\sigma_{intrinsic}$.

→ *How to measure sub-fs scale beam length?*

Parameter[a]	20 pC	250 pC	1 nC	Unit
UV laser energy on cathode	1.5	20	250	μJ
UV spot diameter on cathode	0.6	1.2	2	mm
UV pulse duration (fwhm)	4.0	6.5	10	ps
Injector bunch length (rms)	1.3	2.5	2.8	ps
Initial peak current	5	30	100	A
Injector slice emittance	0.14	0.6	1.0	μm
Injector projected emittance	0.20	0.7	1.2	μm
Final bunch length (rms)	~3	~30	80	fs
Final peak current	~3	~3	3.4	kA
Final projected emittance	0.4	1.0	1.5	μm
FEL pulse duration (fwhm)[b]	~2	~60	230	fs
FEL peak power[b]	~400	~20	~10	GW

Resolution Limit of TDS

- **Temporal resolution of TDS**
  - $\sigma_{t,res} = \frac{p_z c}{e} \cdot \boldsymbol{\sigma_{x0}} \cdot \frac{1}{V_T \omega_{RF} L}$
  - $R_D R_{\mathrm{TDS}} = \begin{bmatrix} 1 & L & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & k & 0 \\ 0 & 0 & 1 & 0 \\ k & 0 & 0 & 1 \end{bmatrix}$ for $\beta \approx 1$
  - $R_{final} = \begin{bmatrix} 1 & L & kL & 0 \\ 0 & 1 & k & 0 \\ 0 & 0 & 1 & 0 \\ k & 0 & 0 & 1 \end{bmatrix}$

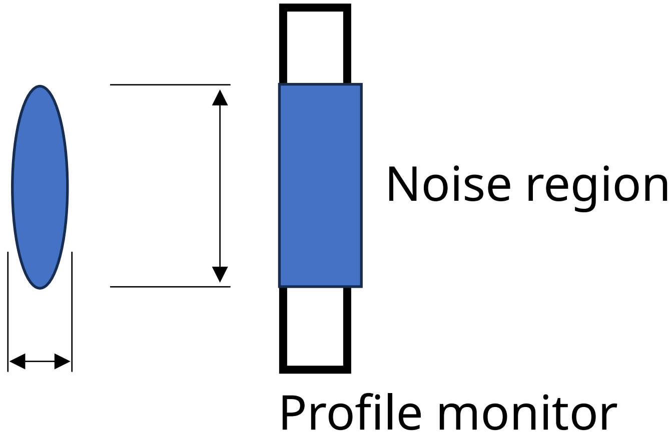


Noise ***Signal***

$\rightarrow\ \boldsymbol{x_f = x_i + L x_i' + kLz_i}$

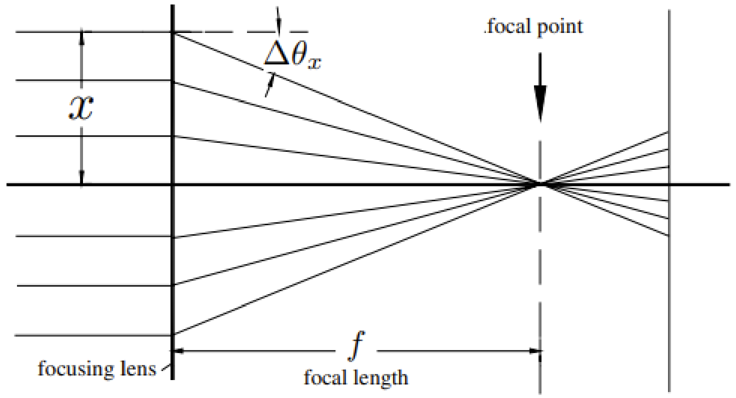
$\rightarrow\ \boldsymbol{\sigma_x^2 = \sigma_{x0}^2 + L^2 k^2 \sigma_{z0}^2}$

If $\sigma_x > \sigma_z$ ...



Method: elimination x_i

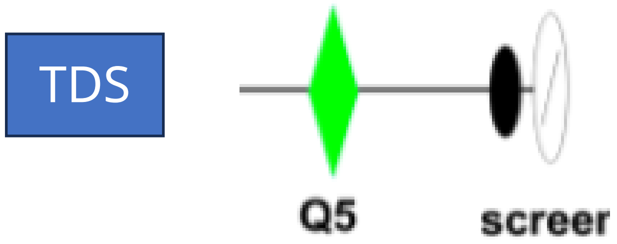
$$\vec{F}_{QM} = q\vec{v} \times \vec{B} = qv_z K \begin{bmatrix} -x \\ y \\ 0 \end{bmatrix}$$



Parallel-to-Point optics

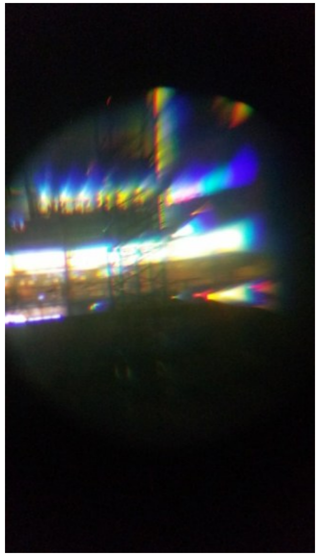
- D-Q-D setup enables removal of x_i.
- Setting the focal length to $f = L$ yields $R_{11} = 0$
- Transfer map:

Drift QM Drift



$$R_D R_{QF} R_D = \begin{bmatrix} 1 - \frac{L}{f} & L(2 - \frac{L}{f}) \\ -\frac{1}{f} & 1 - \frac{L}{f} \end{bmatrix}$$

$$R_{PtP} = \begin{bmatrix} 0 & f \\ -\frac{1}{f} & 0 \end{bmatrix} \text{ for } f = L.$$



$$R_{PtP} R_{TDS} = \begin{bmatrix} 0 & f & 0 & 0 \\ -\frac{1}{f} & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & k & 0 \\ 0 & 0 & 1 & 0 \\ k & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} \mathbf{0} & f & kf & 0 \\ 0 & 1 & k & 0 \\ 0 & 0 & 1 & 0 \\ k & 0 & 0 & 1 \end{bmatrix}$$

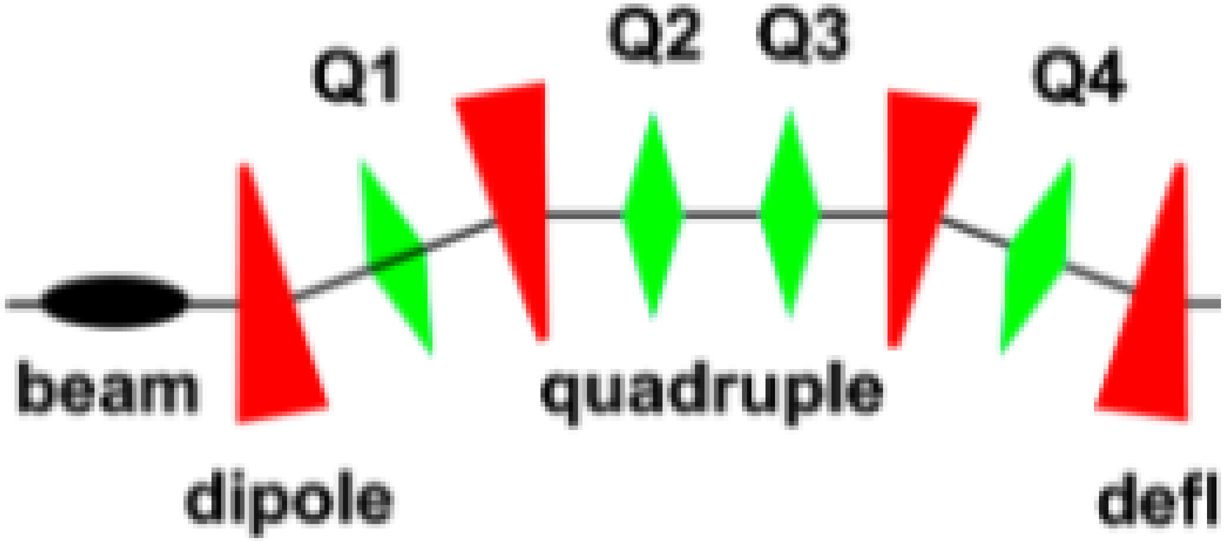
→ *Removal of R_{11}*

$$\boldsymbol{x_f = \overset{0}{\cancel{x_i}} + Lx_i' + kLz_i}$$

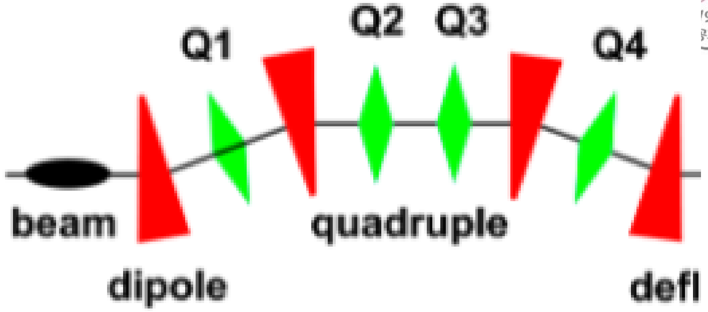
Method: Special chicane to remove x_i'

Special chicane for eliminating x_i'

- Insert symmetric QM inside the chicane.
- *Control the dispersion* and match with the TDS strength k.
- Using –*I transformer* (mirror-symmetric lattice with $\Delta\phi = \pi$)



Method: Special chicane to remove x_i'



Special chicane with D≠0, D'=0

- –I transformer sets $\mathrm{R}_{11} = -1$, $\mathrm{R}_{22} = -1$
- Constraint via QM
    1. $\mathrm{R}_{31} = 0$ (Independent between $\mathrm{x} - \mathrm{z}$)
    2. $\mathrm{R}_{33} = 1$ (No bunch compression)
    3. $\mathrm{R}_{34} = 0$ (Isochronous chicane)

D≠0

$$\begin{bmatrix} x_c \\ x_c' \\ z_c \\ \delta_c \end{bmatrix} = \begin{bmatrix} -1 & R_{12} & 0 & \eta \\ R_{21} & -1 & 0 & 0 \\ 0 & R_{32} & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} x_i \\ x_i' \\ z_i \\ \delta_i \end{bmatrix}$$

- Symplectic condition $R^T S R = S$ where $S = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \end{bmatrix}$ → $(R_{12}R_{24} - R_{22}R_{14}) + (R_{32}R_{44} - R_{42}R_{34}) = 0$

$$(0 + \eta) + (R_{32} \cdot 1 - 0) = 0$$

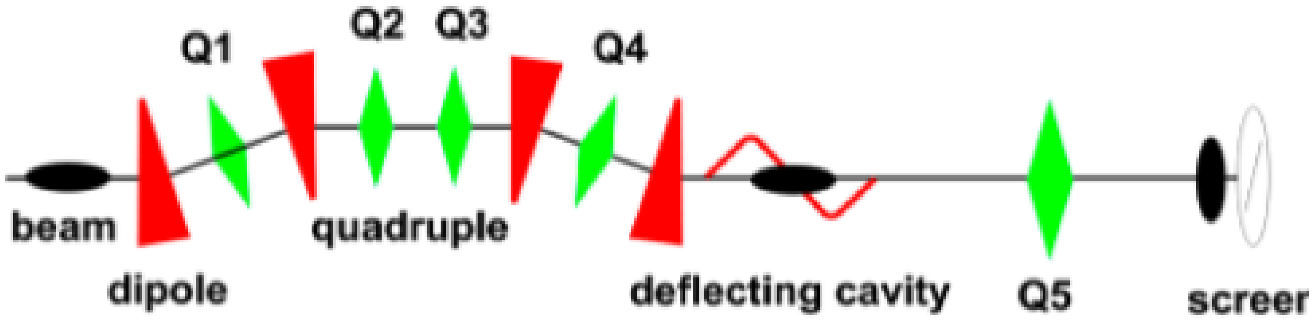
$$\therefore R_{32} = -\eta,\ R_{21} = 0$$

    - $R_{32} = -\eta$, $R_{21} = 0$

Method: Special chicane to remove x_i'

Calculation whole transfer map

- If one sets to dispersion $k = 1/\eta$, possible to remove initial x_i'.



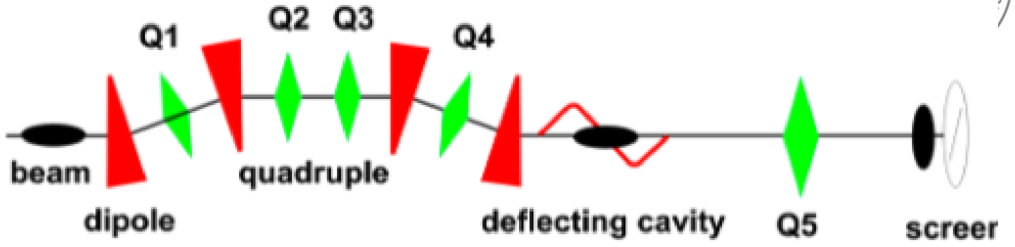
$$R_{TDS}R_c = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & k & 0 \\ 0 & 0 & 1 & 0 \\ k & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} -1 & R_{12} & 0 & \eta \\ 0 & -1 & 0 & 0 \\ 0 & -\eta & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} -1 & R_{12} & 0 & \eta \\ 0 & -(1+\eta k) & k & 0 \\ 0 & -\eta & 1 & 0 \\ -k & kR_{12} & 0 & 1+\eta k \end{bmatrix}$$

$$R_{total} = R_{PtP}R_{TDS}R_c = \begin{bmatrix} 0 & 0 & fk & 0 \\ 1/f & -R_{12}/f & 0 & 1/fk \\ 0 & 1/k & 1 & 0 \\ -k & kR_{12} & 0 & 0 \end{bmatrix} \text{for } k = 1/\eta.$$

$$\boldsymbol{x_f = \cancelto{0}{x_i} + L\cancelto{0}{x_i'} + kLz_i}$$

Effective magnification ratio $\boldsymbol{M = kL}$

Verification: ELEGANT simulation



ELEGANT simulation for 2nd –order effects

- Higher-order terms (T_{266}, T_{566}) must be considered.
- They leave a residual σ_{x0}.
  - Nonlinear effects cause additional spread and worse resolution.

$$x_1' \approx kz_1 + T_{266}\delta_0^2$$

$$z_1 \approx z_0 + T_{566}\delta_0^2$$

$$\Delta t \approx \sqrt{\frac{2T_{266}^2}{k^2} + 2T_{566}^2} \cdot \frac{\delta_0^2}{c}$$

Simulation parameters

Arc length of the dipole	0.5 m
Bending angle of the dipole	20 mrad
Strength of Q1 and Q4	0.330 33 m^{-2}
Strength of Q2 and Q3	−0.916 51 m^{-2}
Length of the quadruples	0.3 m
Frequency of the deflecting cavity	11.424 GHz
Length of the deflecting cavity	1.5 m
Voltage of the deflecting cavity	29 MV

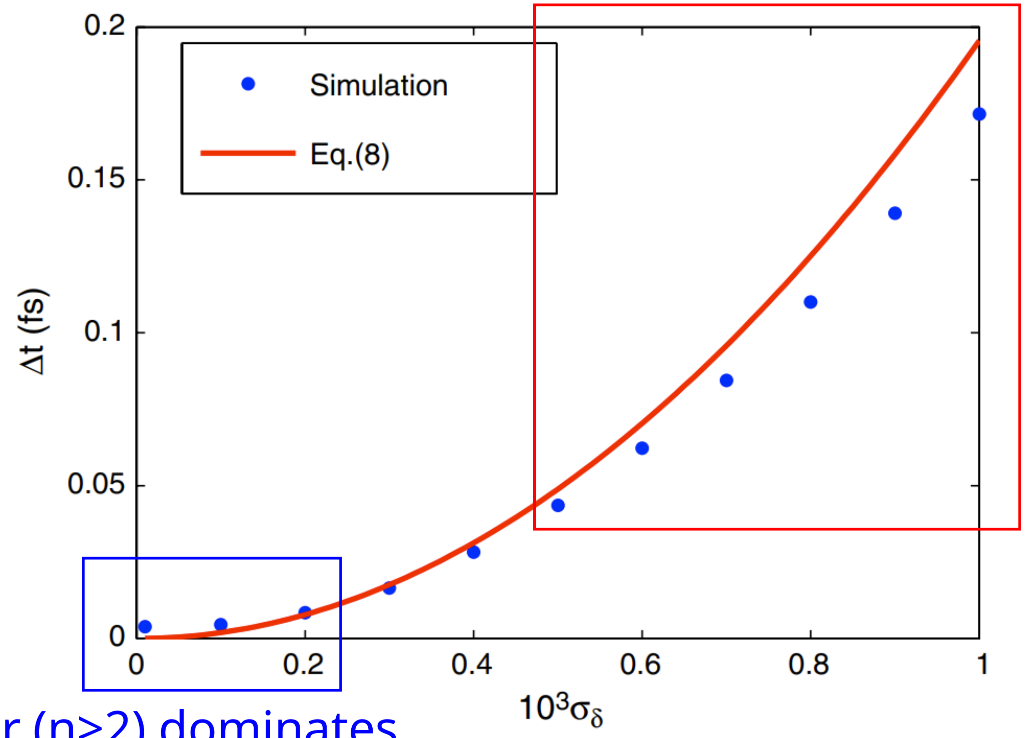
- Initial transverse parameters are optimized to reduce 2nd geometric factor.
  - No focusing in y direction in the PtP method.

Verification: ELEGANT simulation

Resolution sweep result

- Distance of chicane: 4 m
- $E = 4.3\ GeV$
- $\varepsilon_{project,n} = 0.6\ mm \cdot mrad$
- $T_{266} = 0.058$ m, $T_{566} = 0.021$ m
- f = 12.4 m
- $M = 20$

2nd order dominates



higher-order (n>2) dominates

FIG. 2. Resolution in bunch length measurement: blue dots are the resolution determined from the beam size on the screen using ELEGANT simulation and the red curve is the results from Eq. (8).

→ $\Delta t = 0.2$ fs for $\sigma_p \sim 10^{-3}$

Verification: Simulation using LCLS beam

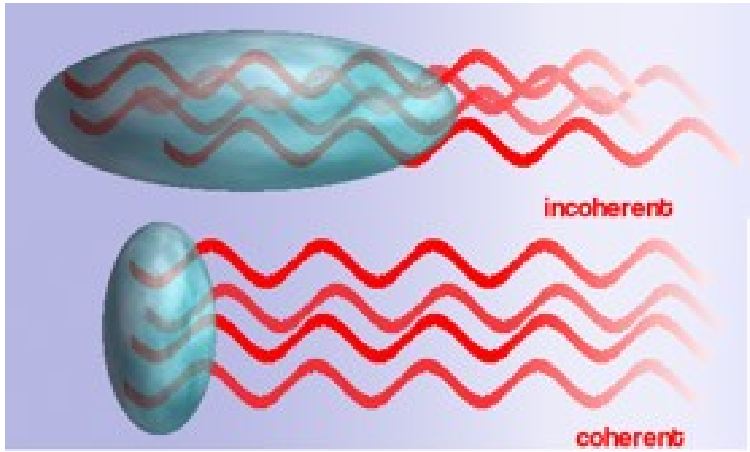
Coherent Synchrotron Radiation (CSR) effects

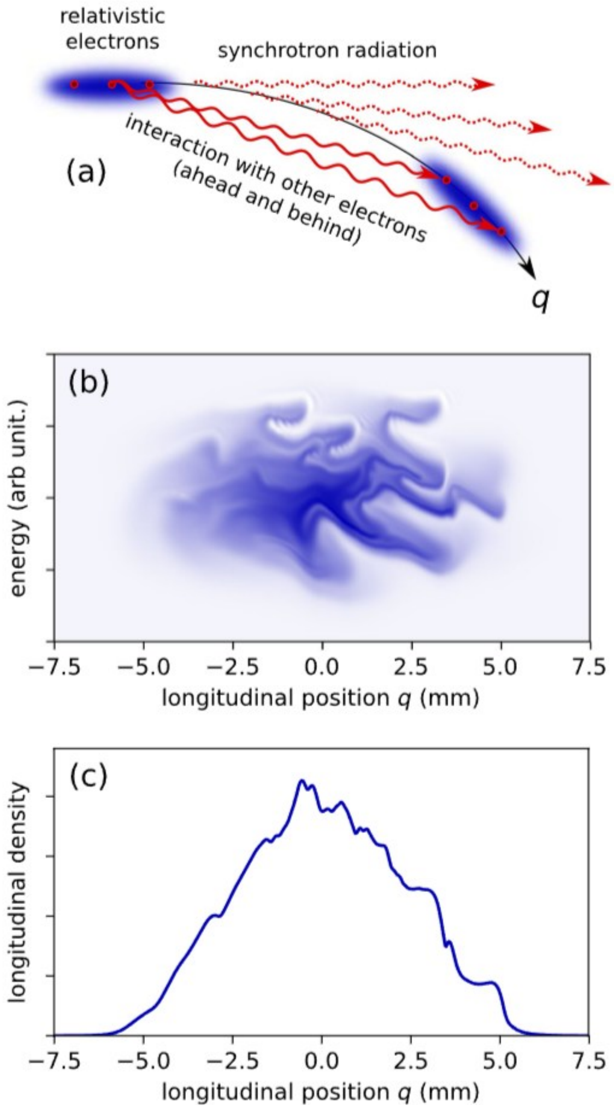
- SR emitted from the tail electrons catches up with the head electrons.
- Tail electrons lose energy due to CSR.
- Head electrons gain energy from the radiation.

→ Worse ε, causing micro-bunching instability (MBI)

$$\begin{bmatrix} x_c \\ x_c' \\ z_c \\ \delta_c \end{bmatrix} = \begin{bmatrix} -1 & R_{12} & 0 & \eta \\ 0 & -1 & 0 & \color{red}{R_{24}} \\ 0 & -\eta & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} x_i \\ x_i' \\ z_i \\ \delta_i \end{bmatrix}$$

$$\boldsymbol{x_f = x_i} + \color{blue}{\boldsymbol{Lx_i'}} + \boldsymbol{kLz_i}$$





Verification: Simulation using LCLS beam

$\sigma_p = 1.1 \times 10^{-3}$

$\sigma_{t,res} \sim 0.2$ fs

Overcompressed beam: ISR and CSR effect

- Ground truth: 3.52 fs
- predicted: 3.07 fs w/ CSR, ISR

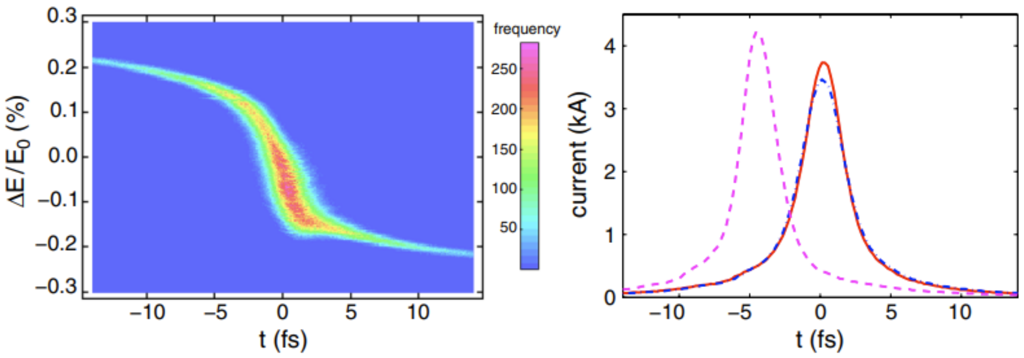


FIG. 3. (left) Longitudinal phase space for the overcompressed beam (bunch head to the left). (right) Temporal profiles: true temporal profile (red solid line); predicted temporal profile without considering ISR and CSR effect (blue dash-dotted line); predicted temporal profile with ISR and CSR taken into account (magenta dashed line).

Undercompressed beam: ISR and CSR effect

- Ground truth: 8.50 fs
- Predicted: 8.55 fs w/ CSR, ISR

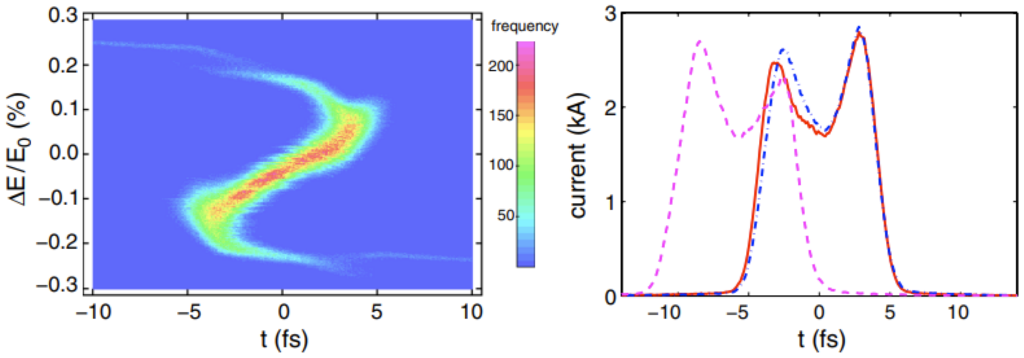


FIG. 4. (left) Longitudinal phase space for the undercompressed beam (bunch head to the left). (right) Temporal profiles: true temporal profile (red solid line); predicted temporal profile without considering ISR and CSR effect (blue dash-dotted line); predicted temporal profile with ISR and CSR taken into account (magenta dashed line).

Discussion

- Removing the core-beam chirp reduces global energy spread and improves resolution.
- With full chirp compensation (ideal LCLS case):
  - Energy spread ≈ 1.5 MeV.
  - Resolution improves to ~20 as.
- Increasing dipole spacing and reducing θ / k_{QM} helps mitigate 2nd order effects.

XTCAV optimization (2016)

		Non-SLED	SLED
Klystron power	MW	50	40
Klystron pulse length	µs	0.2	1
XTCAV kick amplitude	MV	45	85
Effective streak at 6 GeV	mm per °X-band	4.12	8.45
Temporal resolution HXR (10kV)	fs	4	2
Temporal resolution SXR (1kV)	fs	1	0.5

Double-horn structure

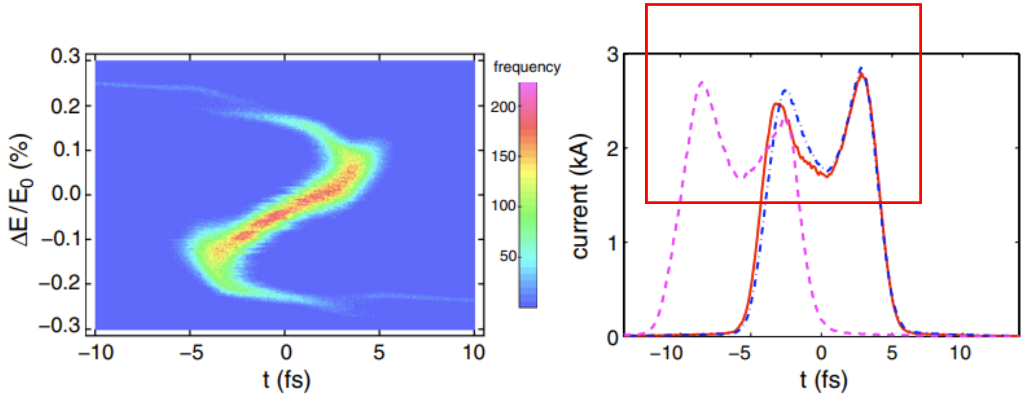


FIG. 4. (left) Longitudinal phase space for the undercompressed beam (bunch head to the left). (right) Temporal profiles: true temporal profile (red solid line); predicted temporal profile without considering ISR and CSR effect (blue dash-dotted line); predicted temporal profile with ISR and CSR taken into account (magenta dashed line).