LCLS bunch length monitor utilizing coherent radiation

Juhao Wu, Apr. 03, 2006

- Purpose of this study
- Current status
- What to improve

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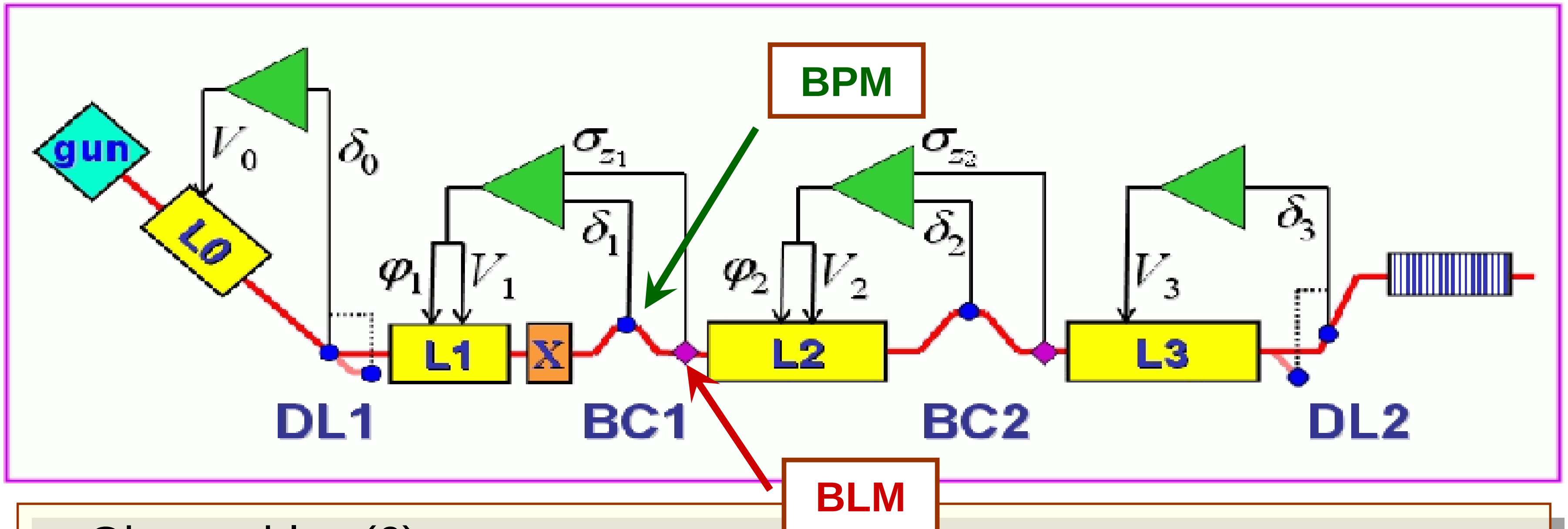
LCLS BLM utilizing coherent radiation

- LCLS feedback system schematic



- Observables (6):
  - Energy: E_0 (at DL1), E_1 (at BC1), E_2 (at BC2), E_3 (at DL2)
  - Coherent Radiation energy → bunch length: $\sigma_{z,1}$ (at BC1), $\sigma_{z,2}$ (at BC2)
- Controllables (6):
  - Voltage: V_0 (in L0), V_1 (in L1), V_2 (effectively, in L2)
  - Phase: φ_1 (in L1), φ_2 (in L2), φ_3 (in L3)

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LCLS BLM utilizing coherent radiation

- Coherent Radiation (CR) as nondestructive diagnostic tool
  - Synchrotron (magnet), Edge, and Diffraction Radiation
- For a group of N_e electrons
  - CR spectrum

$$\frac{d^2 I}{d\omega d\Omega} = \left| \sum_{j=1}^{N_e} e^{i\omega t_j} e^{-i\omega \frac{\hat{\vec{n}} \bullet \vec{R}_j}{c}} \right|^2 \frac{d^2 I_0}{d\omega d\Omega} \equiv N_e^2 \left| F \right|^2 \frac{d^2 I_0}{d\omega d\Omega}$$

- Form factor → bunch length information

Single e^-

$$\left| F \right|^2 = \left| \int n(x,y,z) e^{-ikz} e^{-ik\hat{\vec{n}} \bullet \vec{R}} dxdydz \right|^2$$

$$\approx \left| \int n(x,y,z) e^{-ikz} dxdydz \right|^2$$

with

$$\int n(x,y,z) dxdydz = 1$$

"thin" beam approximation

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LCLS BLM utilizing coherent radiation

- Let us start with "ideal" calculation
- ISR power spectrum from a bending magnet
  - Far field, infinite long bending magnet
  - For an azimuthal milliradian of the electron orbit (θ) and integrated over all the vertical angles

$$P_{\text{isr}}(\lambda)[\text{W/mrad}\,\theta\text{/mm}] = 8.42\times10^{-8}\rho^{1/3}[\text{m}]I[\text{Amp}]\lambda^{-7/3}[\text{mm}]$$

for $\lambda >> \lambda_c \equiv \dfrac{4\pi\rho}{3\gamma^3}[\overset{o}{A}];$

Hence, $P_{\text{csr}}(\lambda)[\text{W/mrad}\,\theta\text{/mm}] = N_e|F|^2 P_{\text{isr}}(\lambda).$

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LCLS BLM utilizing coherent radiation

- Parameters at BC1 and BC2

	Q (nC)	ρ (m)	σ_z (mm)	λ (mm)	f (THz)
BC1	1	2.3	0.2	1.2	0.24
	0.2	2.2	0.06	0.38	0.80
BC2	1	14	0.02	0.12	2.4
	0.2	17	0.008	0.05	6.0

- CSR pulse energy can be as much as μJ

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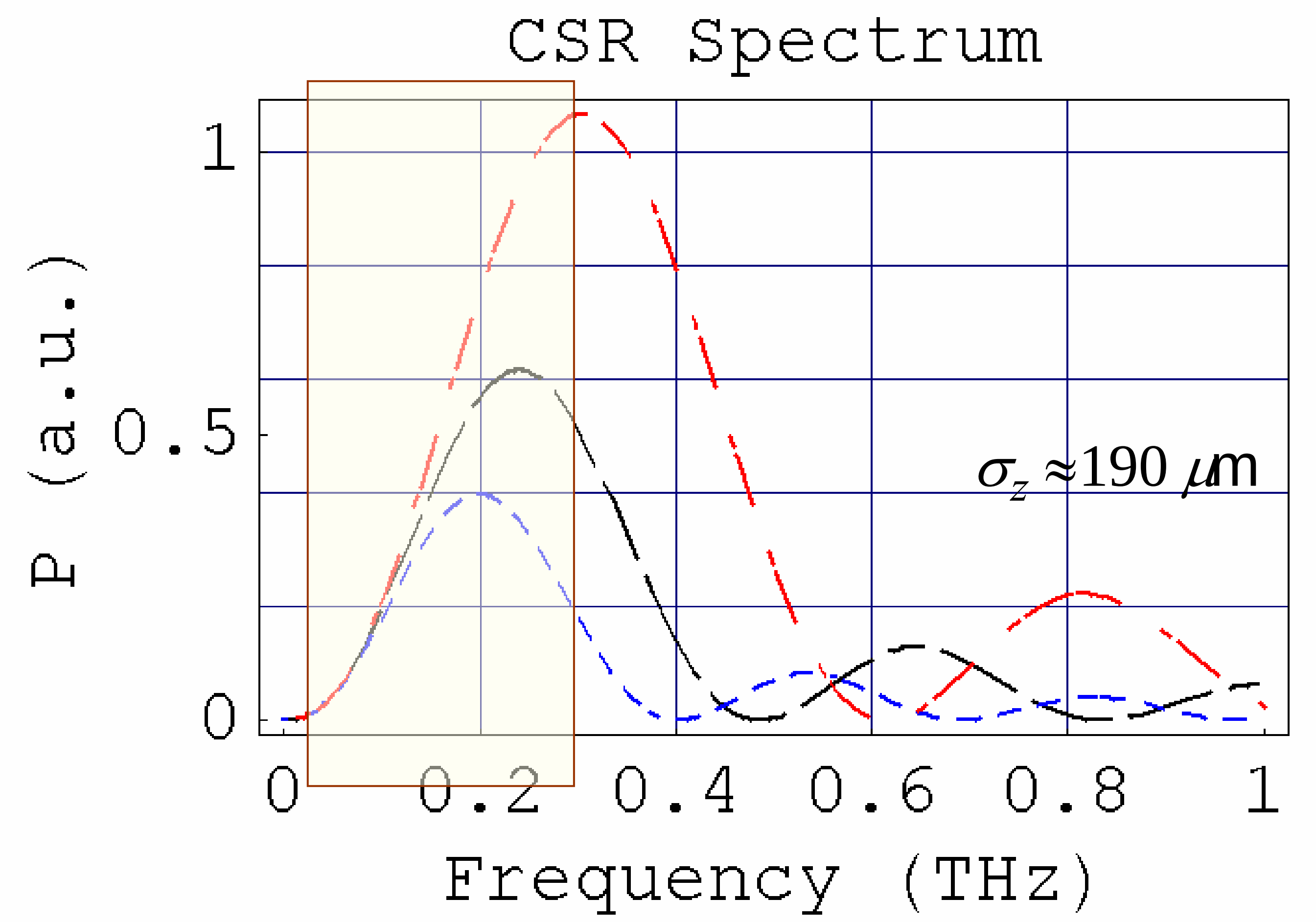
- Phase jitter affects CSR spectrum after BC1
  - Density distribution — parabolic



Black: Nominal

Blue: $\Delta\phi_1 = 2.1^o$

Red: $\Delta\phi_1 = -2.1^o$

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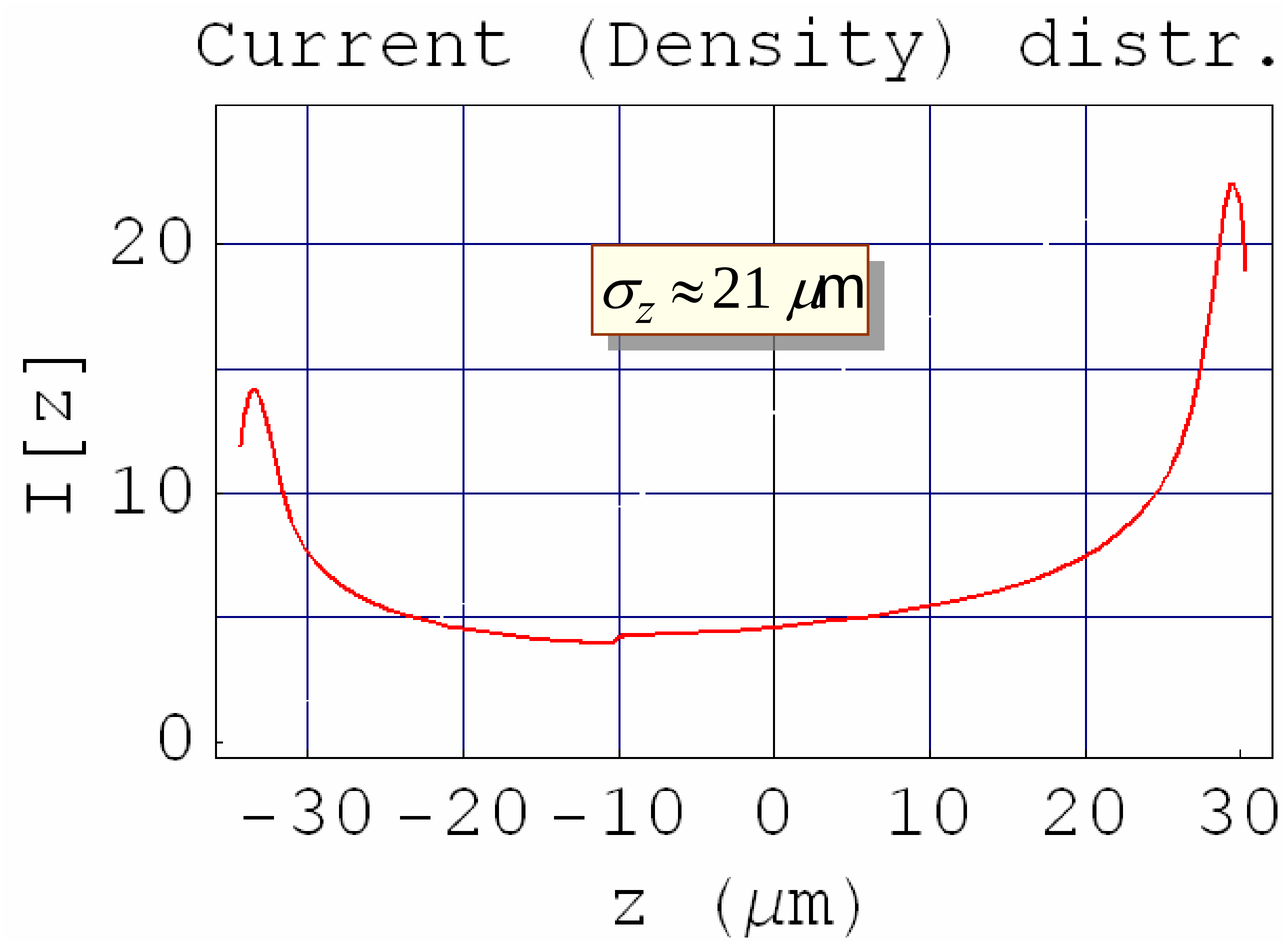
LCLS BLM utilizing coherent radiation

- Wake-induced double-horn structure after BC2



With Laser-Heater

($\sigma_E = 47$ keV)

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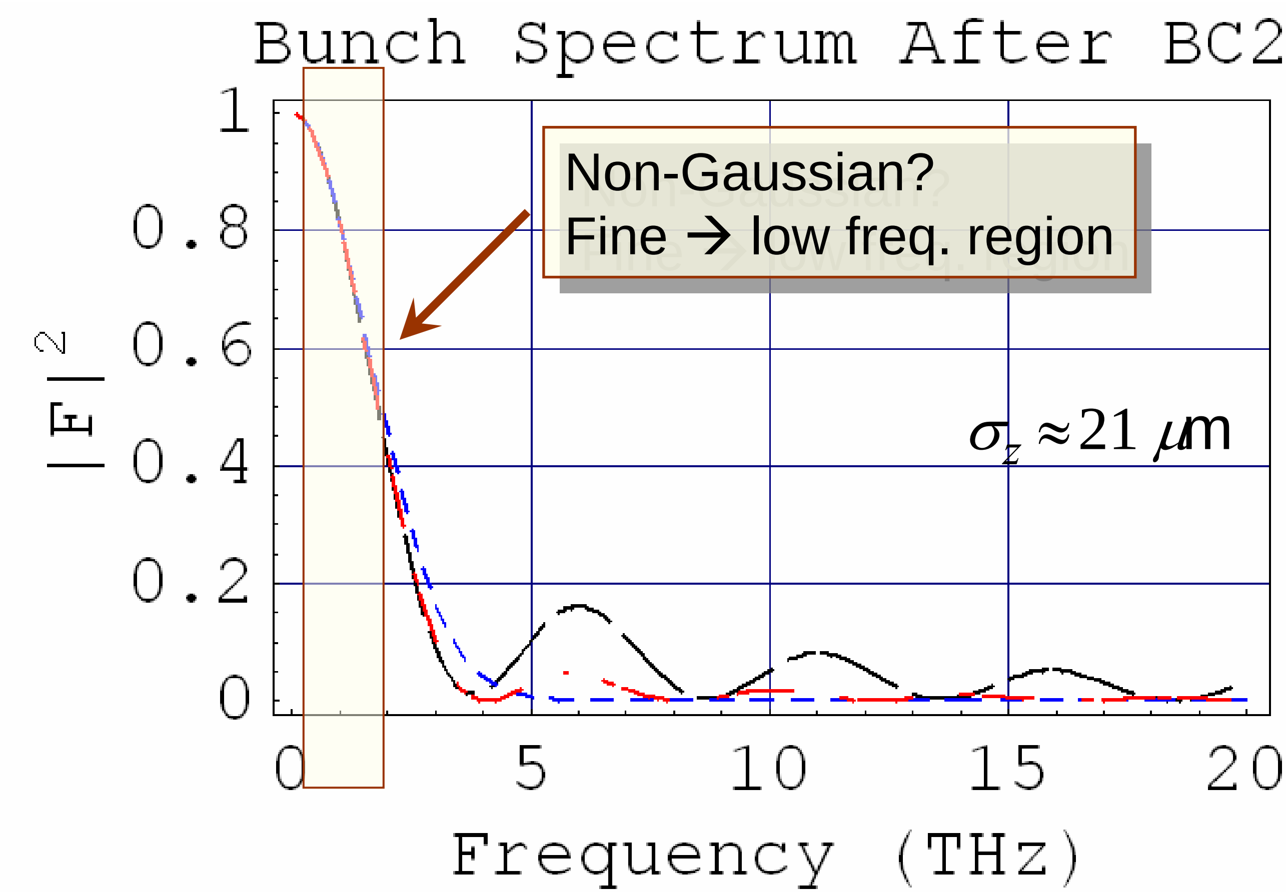
LCLS BLM utilizing coherent radiation

- Sharp-edge induces high freq. component after BC2.
- However, low freq. region independent of shape



Black: double-horn

Blue: Gaussian with same σ_z

Red: Step with same σ_z

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LCLS BLM utilizing coherent radiation

- Stay in the low frequency regime
- Pyroelectric detector, diode detector?
- Detector with fixed Δλ, the integrated power
  - Gaussian — density distribution
  - Detected power

$$F(\lambda) = e^{-\frac{2\pi^2\sigma_z^2}{\lambda^2}}$$

$$P_{\rm det}(\lambda, \Delta\lambda) = \frac{3.63\times 10^{-10} N \rho^{1/3} I}{\sigma_z^{4/3}} \left\{ \Gamma\left[\frac{2}{3}, \xi_+\right] - \Gamma\left[\frac{2}{3}, \xi_-\right] \right\} \quad \left[\frac{\mathrm{W}}{\mathrm{rad}}\right]$$

with $\xi_\pm \equiv \dfrac{4\pi^2\sigma_z^2}{\left(\lambda \pm \dfrac{\Delta\lambda}{2}\right)^2}$

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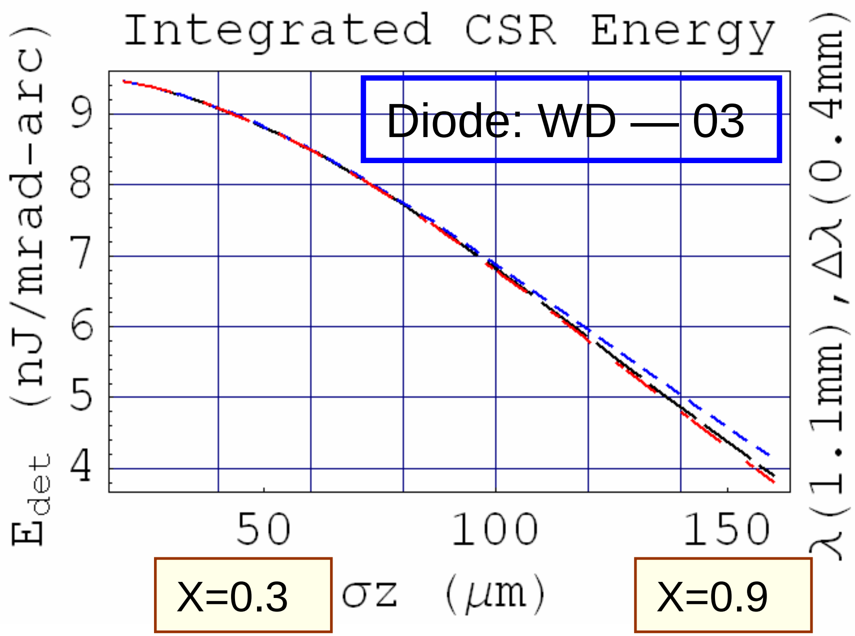
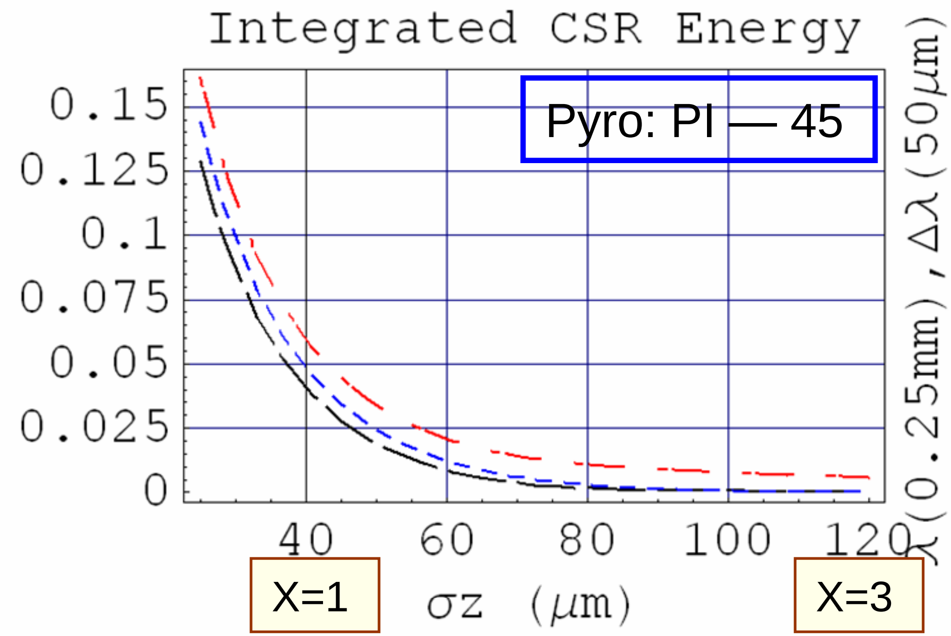
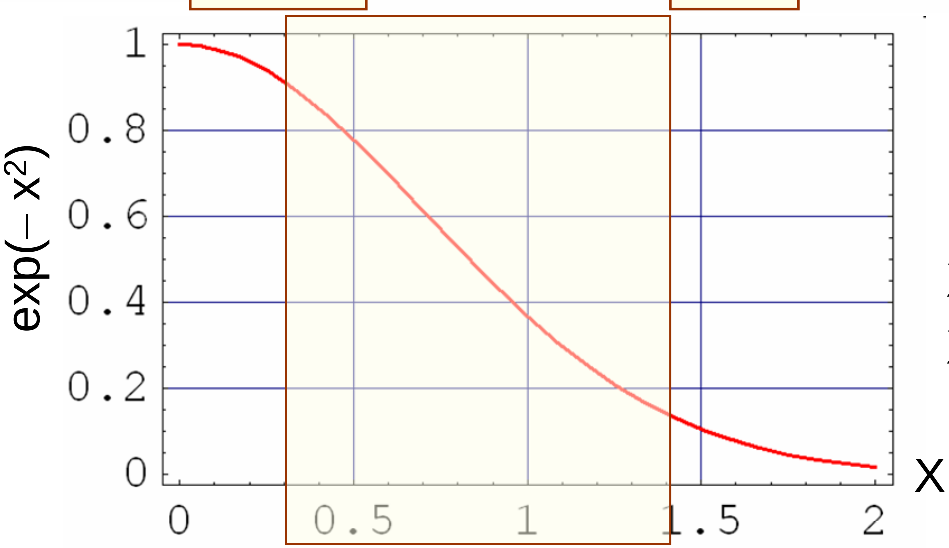
- Low charge case (0.2 nC) at BC1







$X \equiv 2\,\pi\,\sigma_z\,/\,\lambda$

$X \in (0.3, 1.4)$

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LCLS BLM utilizing coherent radiation

- So much for the "ideal" calculation
- Let us now study the real experimental setup
  - Near-field, far-field
  - Finite magnet length
  - Edge radiation
  - Diffraction radiation
  - Finite aperture

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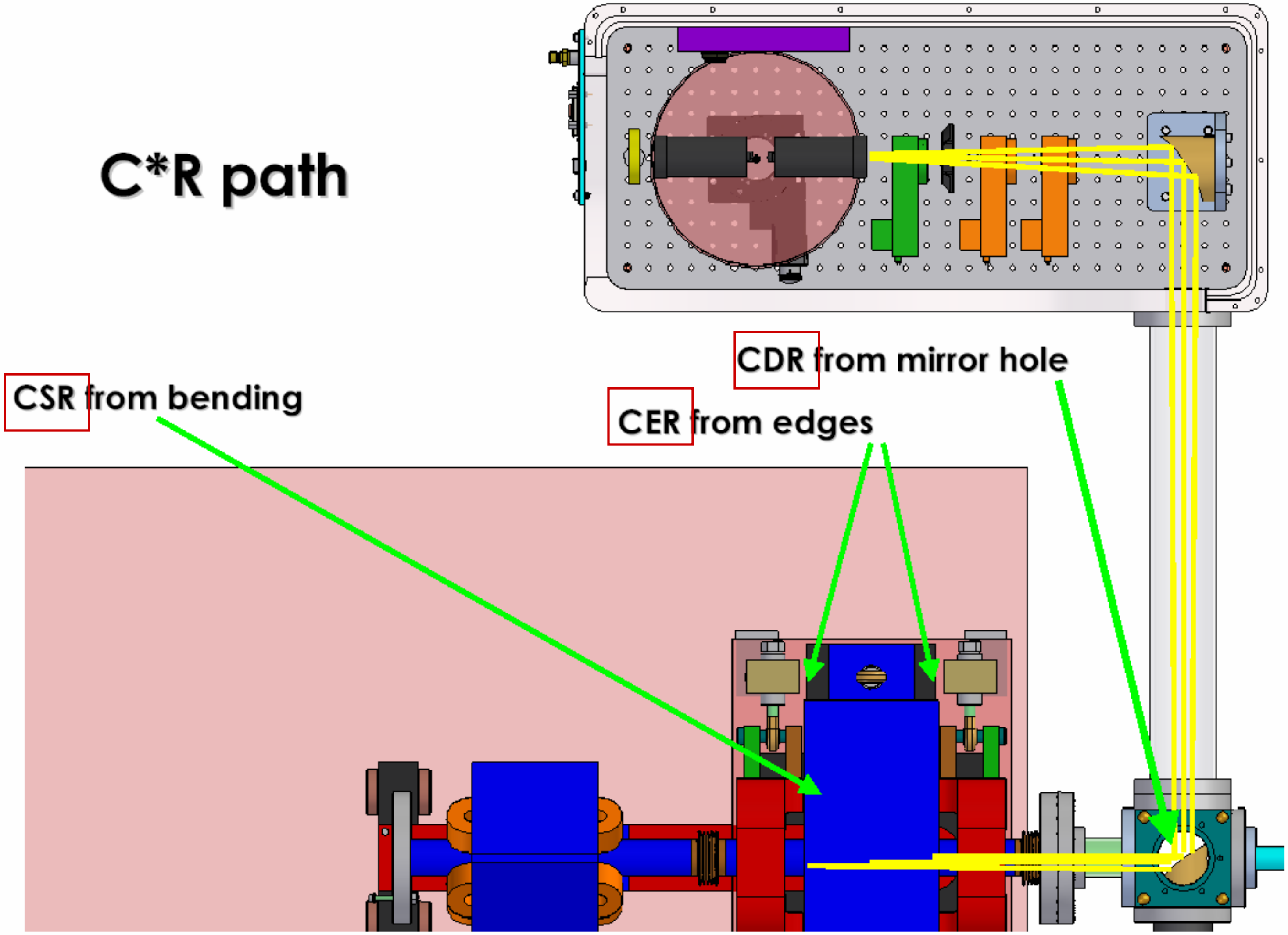
LCLS BLM utilizing coherent radiation

Proposed Design

- UCLA design

C*R path



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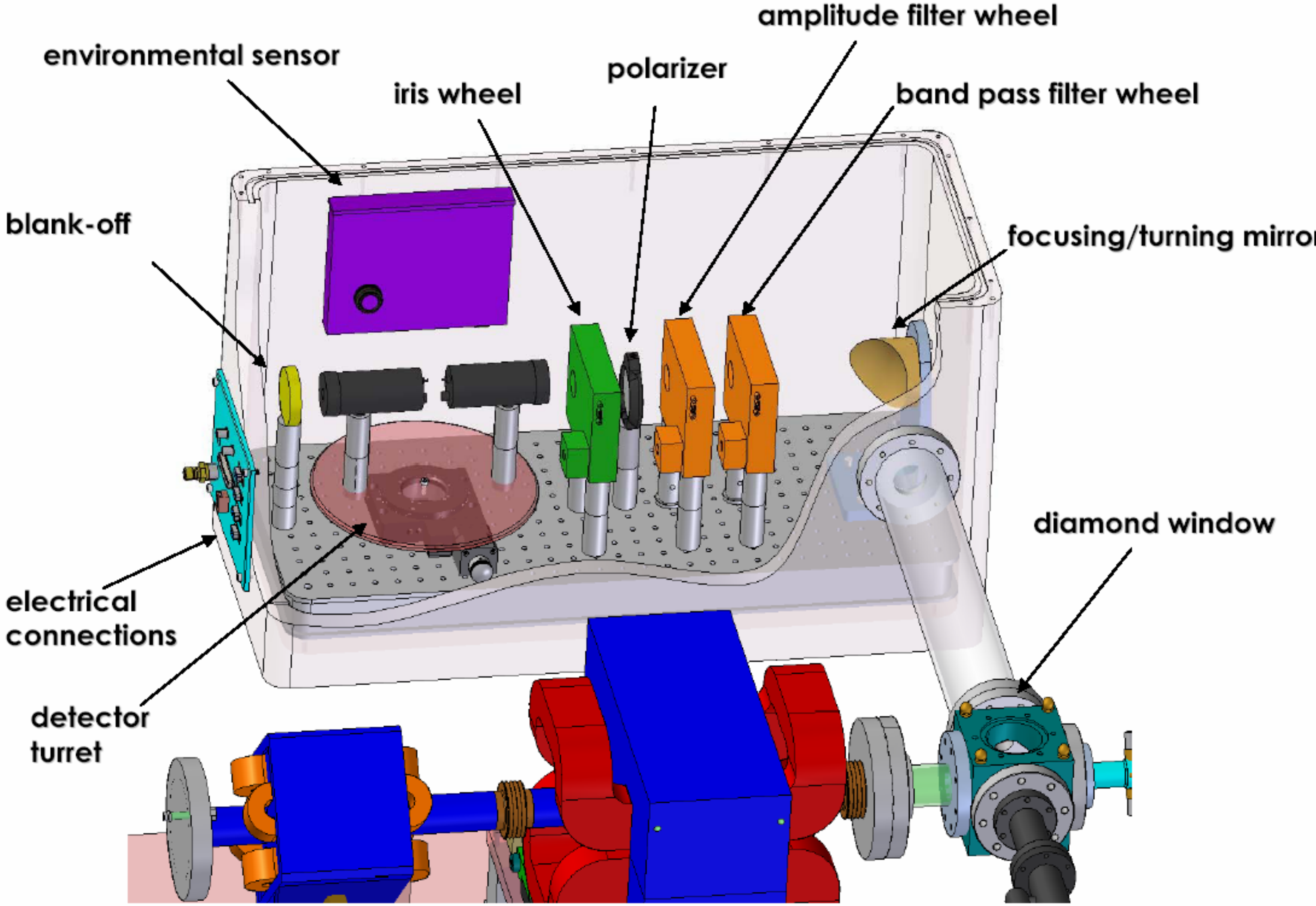
Proposed Design

- UCLA design



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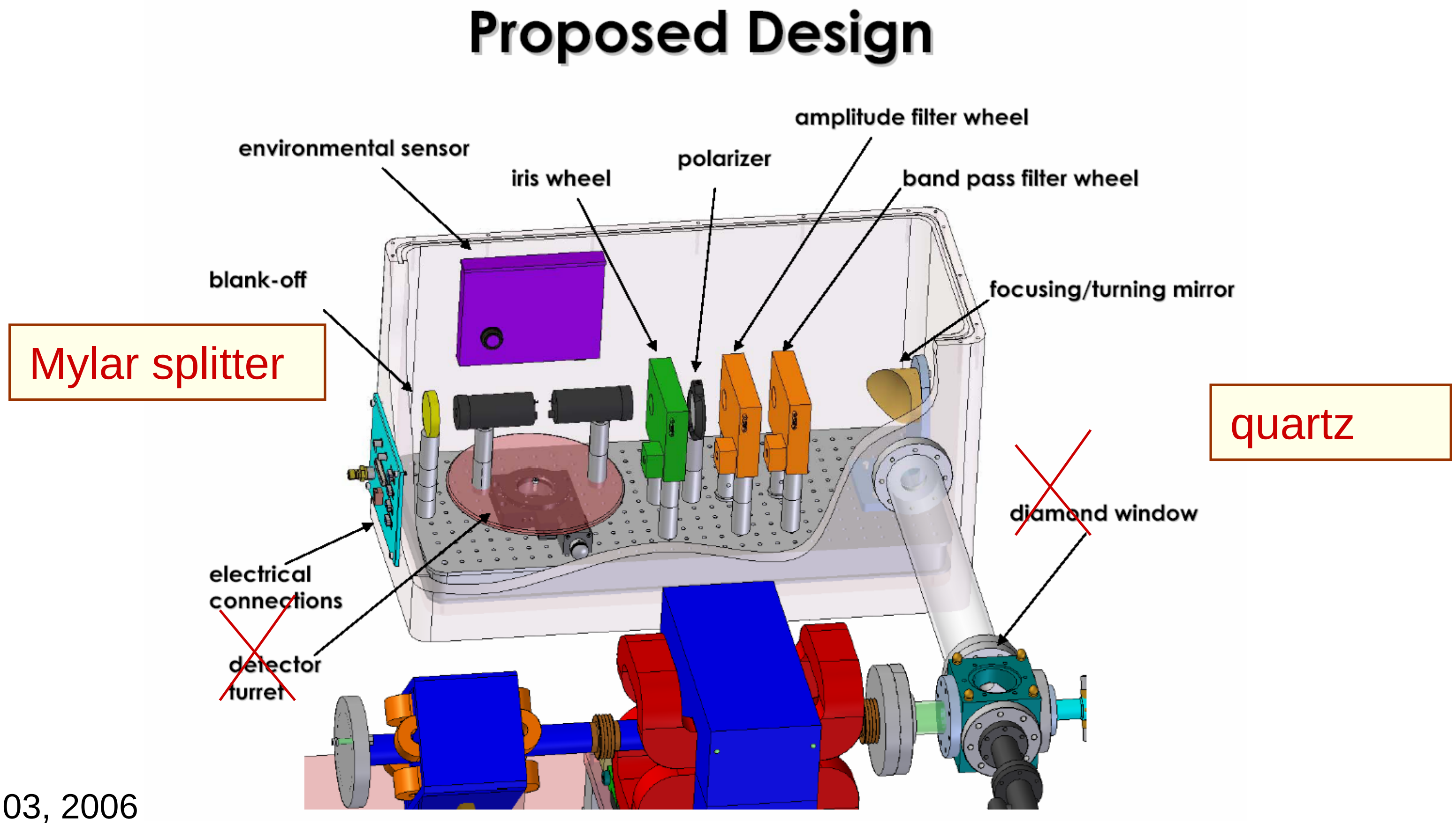
LCLS BLM utilizing coherent radiation

- SLAC modification
  - No turret
  - Diamond → quartz
  - Mylar splitter → two detectors (pyro & diode?)
  - Add camera



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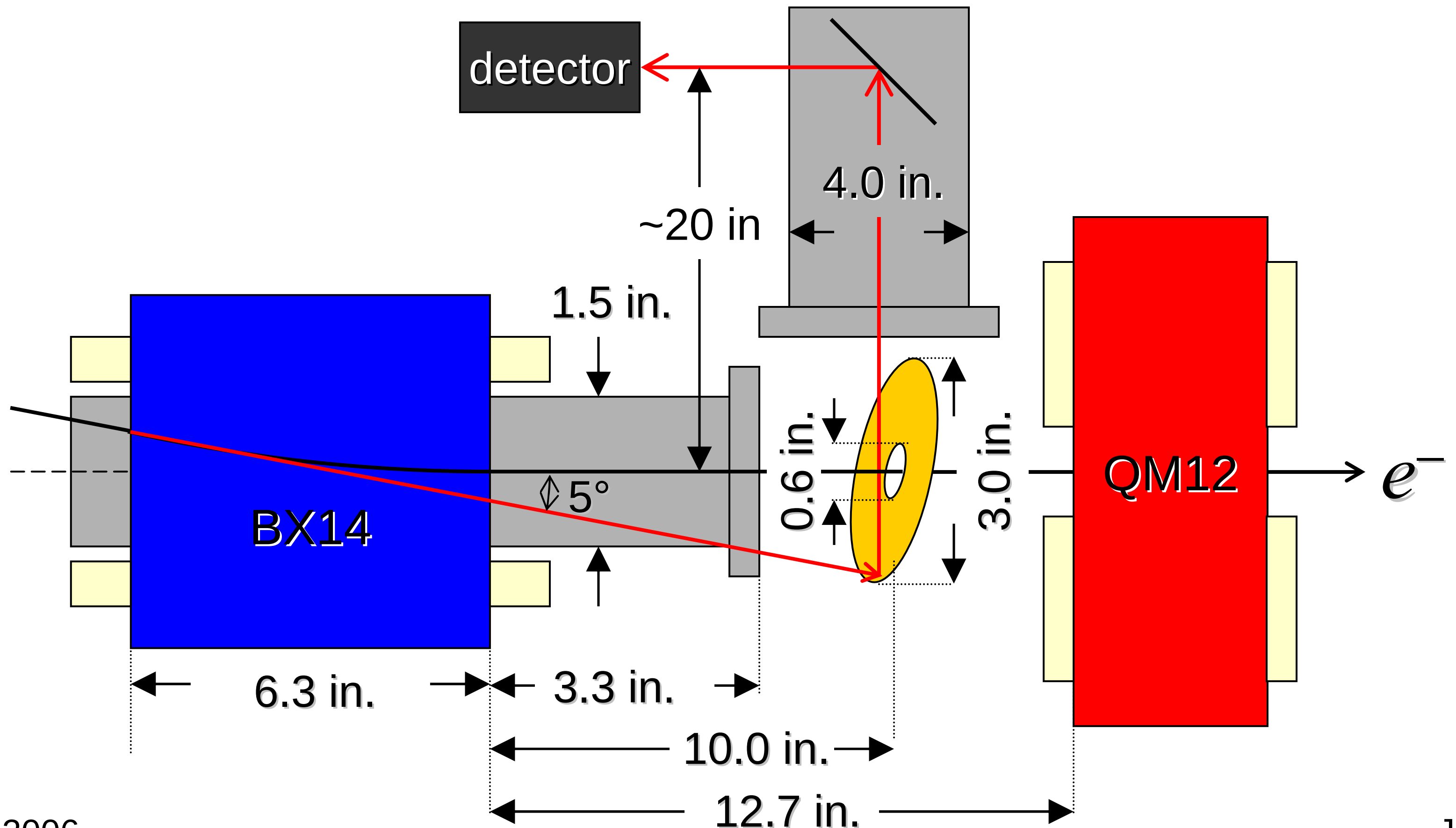
LCLS BLM utilizing coherent radiation

- Schematic plan view
  - Aperture allows CSR to couple out
  - Mirror with hole collects arc of 1.7° to 5°



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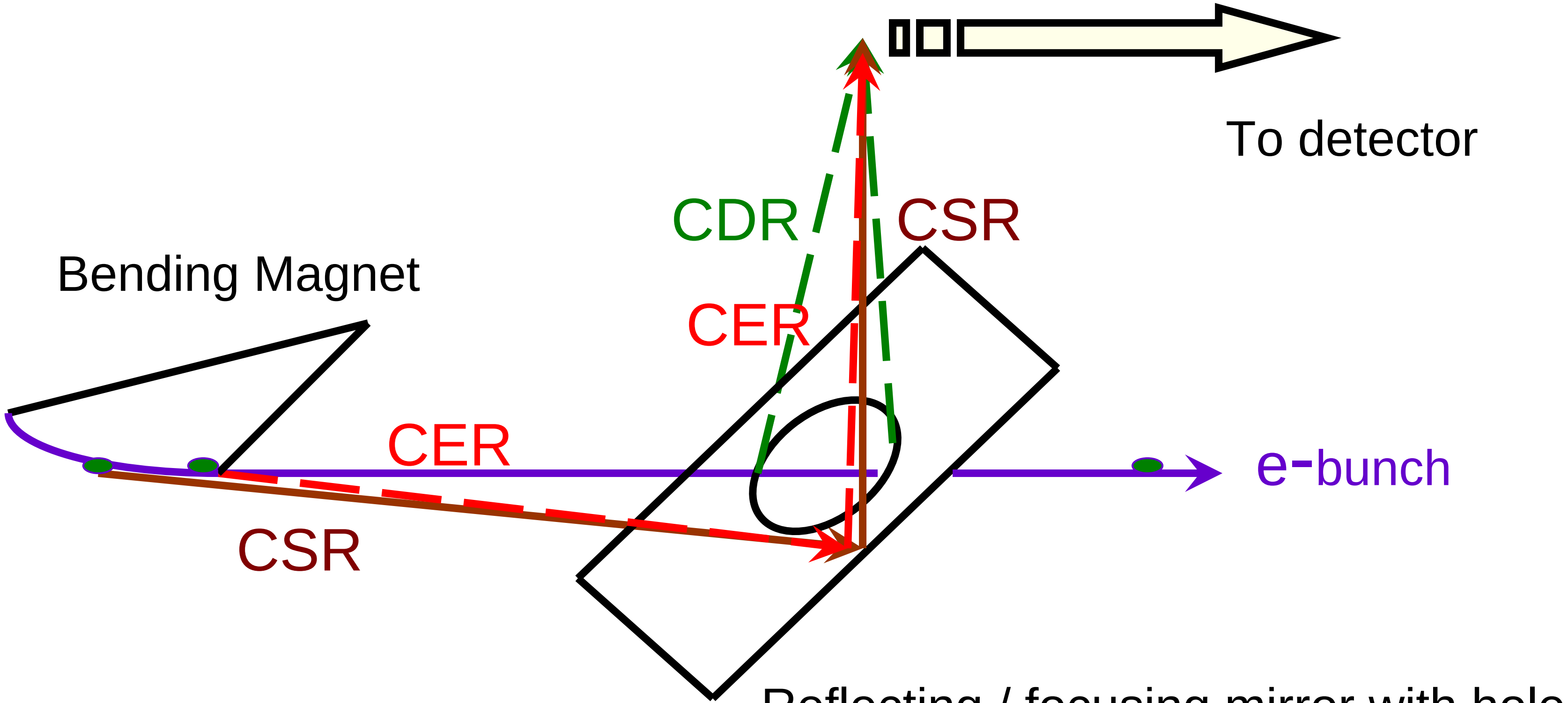
LCLS BLM utilizing coherent radiation

Schematic optics setup



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LCLS BLM utilizing coherent radiation

- Edge Radiation (ER)
- "Zero-edge length" model

R.A. Bosch, *Il Nuovo Cimento*, **20**, 483(1998)

- For γ >>1, radially polarized
- Photon flux per unit solid angle (in photons / s-relative bandwidth $\Delta\omega/\omega$-steradian)

$$\frac{dF}{d\Omega} = \begin{cases} \alpha \dfrac{\Delta\omega}{\omega} \dfrac{I}{e\pi^2} \dfrac{\gamma^4\theta^2}{\left(1+\gamma^2\theta^2\right)^2} & \text{for} \quad R >> \lambda\gamma^2 \\ \alpha \dfrac{\Delta\omega}{\omega} \dfrac{4I}{e\pi^2} \dfrac{\sin^2\left(\dfrac{\pi R \theta^2}{2\lambda}\right)}{\theta^2} & \text{for} \quad R << \lambda\gamma^2 \end{cases}$$

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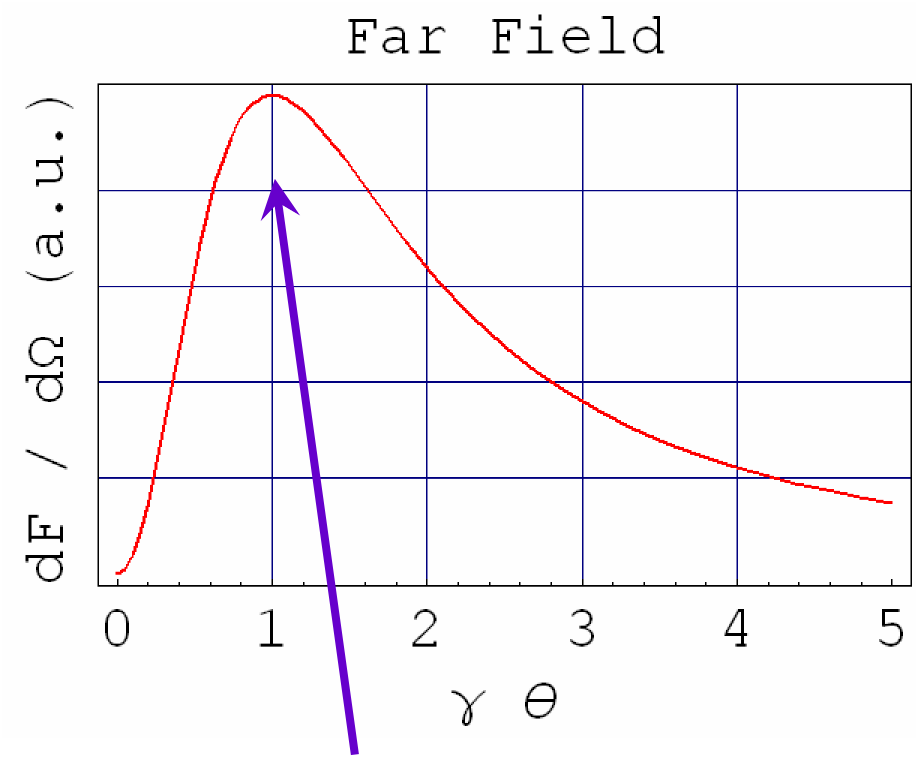
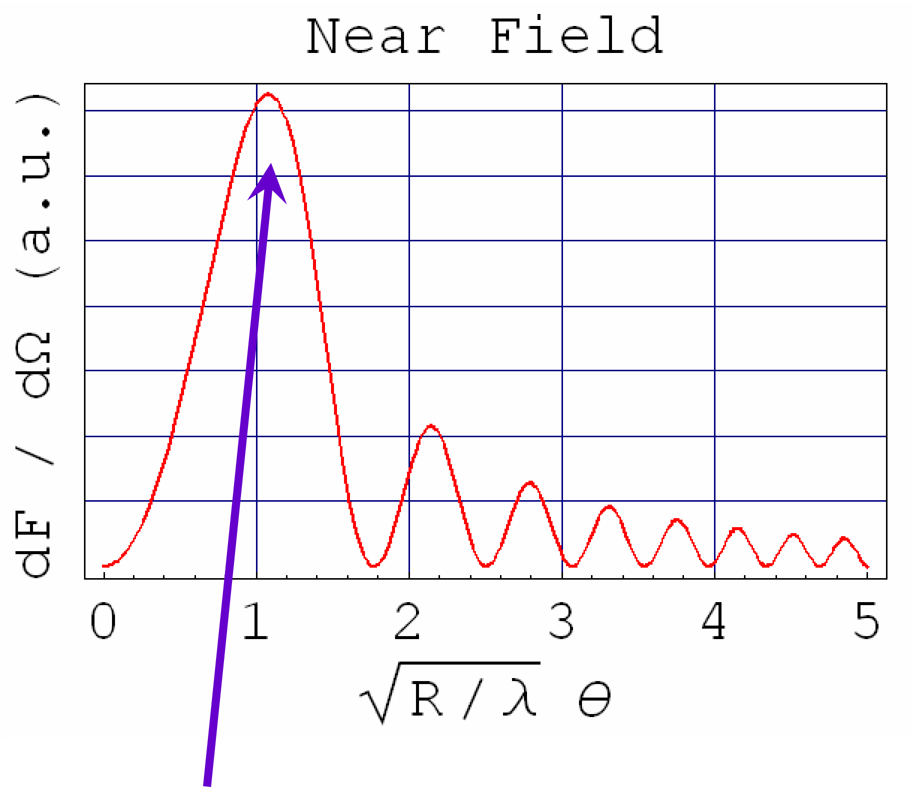
LCLS BLM utilizing coherent radiation

Far field & near field





$$\theta \approx 1/\gamma$$

$$\theta \approx \sqrt{\lambda / R}$$

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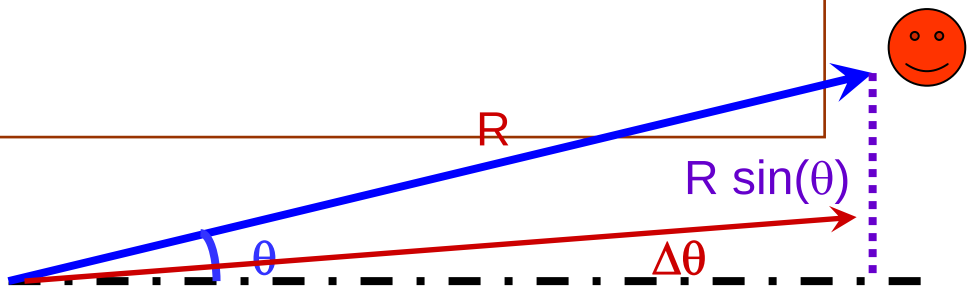
LCLS BLM utilizing coherent radiation

- Far field & near field

	ρ (m)	σ_z (mm)	λ (mm)	E (GeV)	$\lambda\gamma^2$ (m)	$R(\lambda/R)^{1/2}$(cm)
BC1	2.4	0.19	1.2	0.25	286	1.7
BC2	14.5	0.021	0.13	4.3	9,343	0.6

- In Near field regime
- R = 25 cm
- Reflecting part aperture 0.8 cm => $\Delta\theta = 1.7^o$
- Reflecting part is 3.8 cm off-axis => $\theta = 8.5^o$
  - Will capture the peak of ER
  - SR interferes with ER



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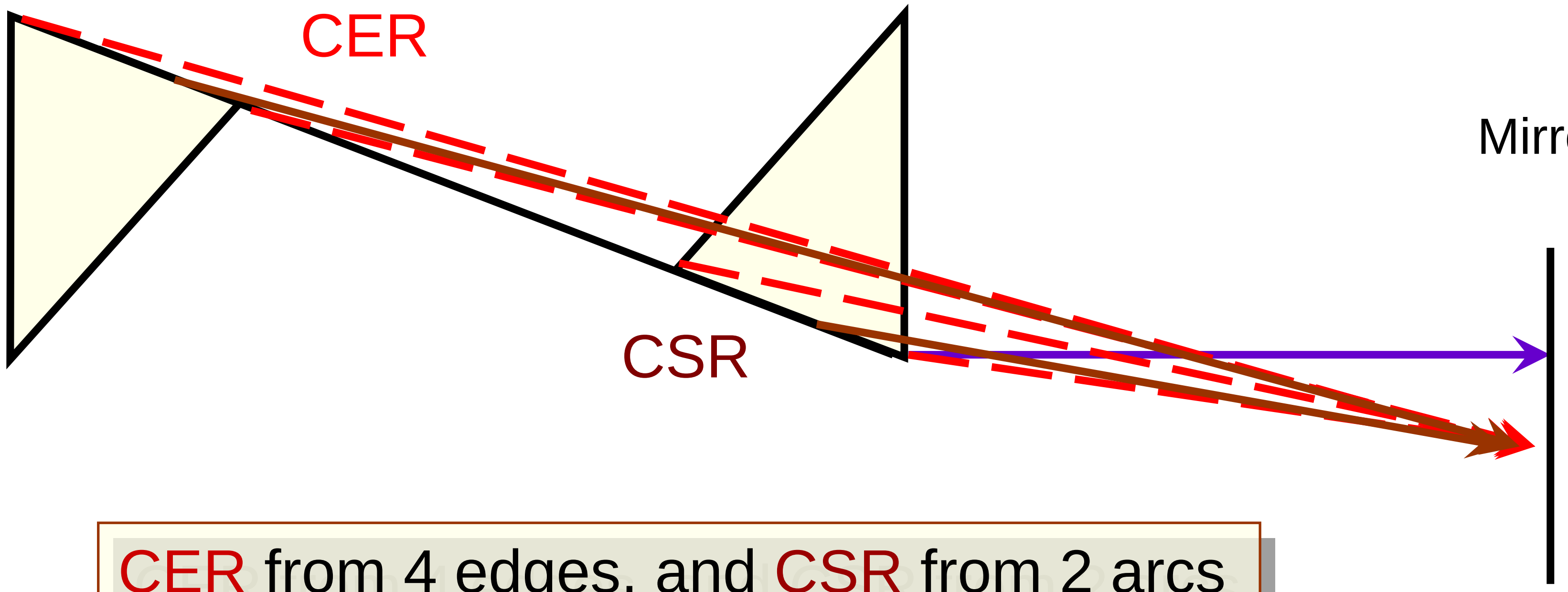
Possible situation



CER from 4 edges, and CSR from 2 arcs

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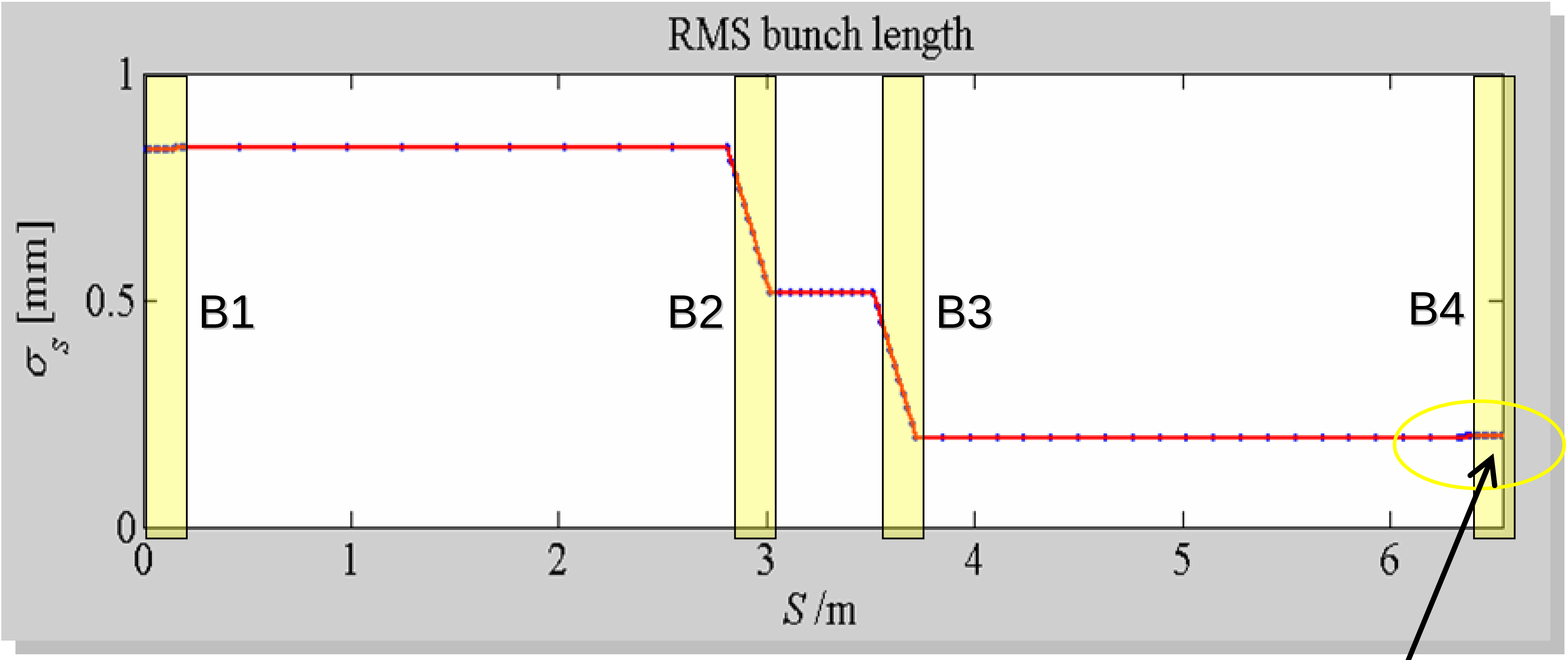
LCLS BLM utilizing coherent radiation

- Evolution of RMS Bunch Length Through BC1
  - CSR from B4
  - CER from B4 and B3 (with proper bunch length)



constant 200-μm rms bunch length through final bend

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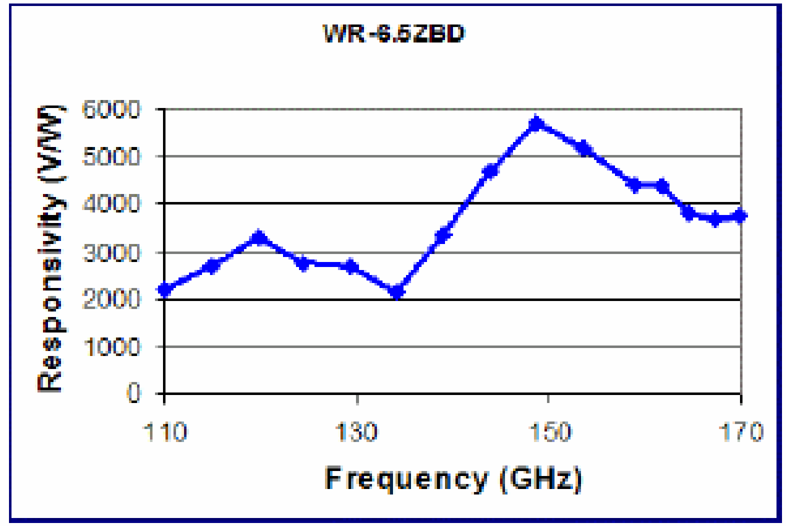
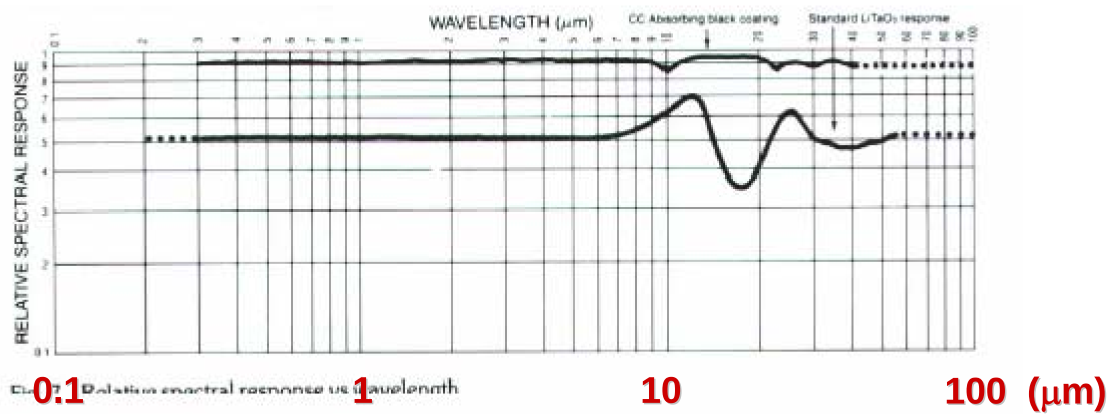
LCLS BLM utilizing coherent radiation

- Response function
  - Signal detection
    - Diode detector
    - Pyrodetector





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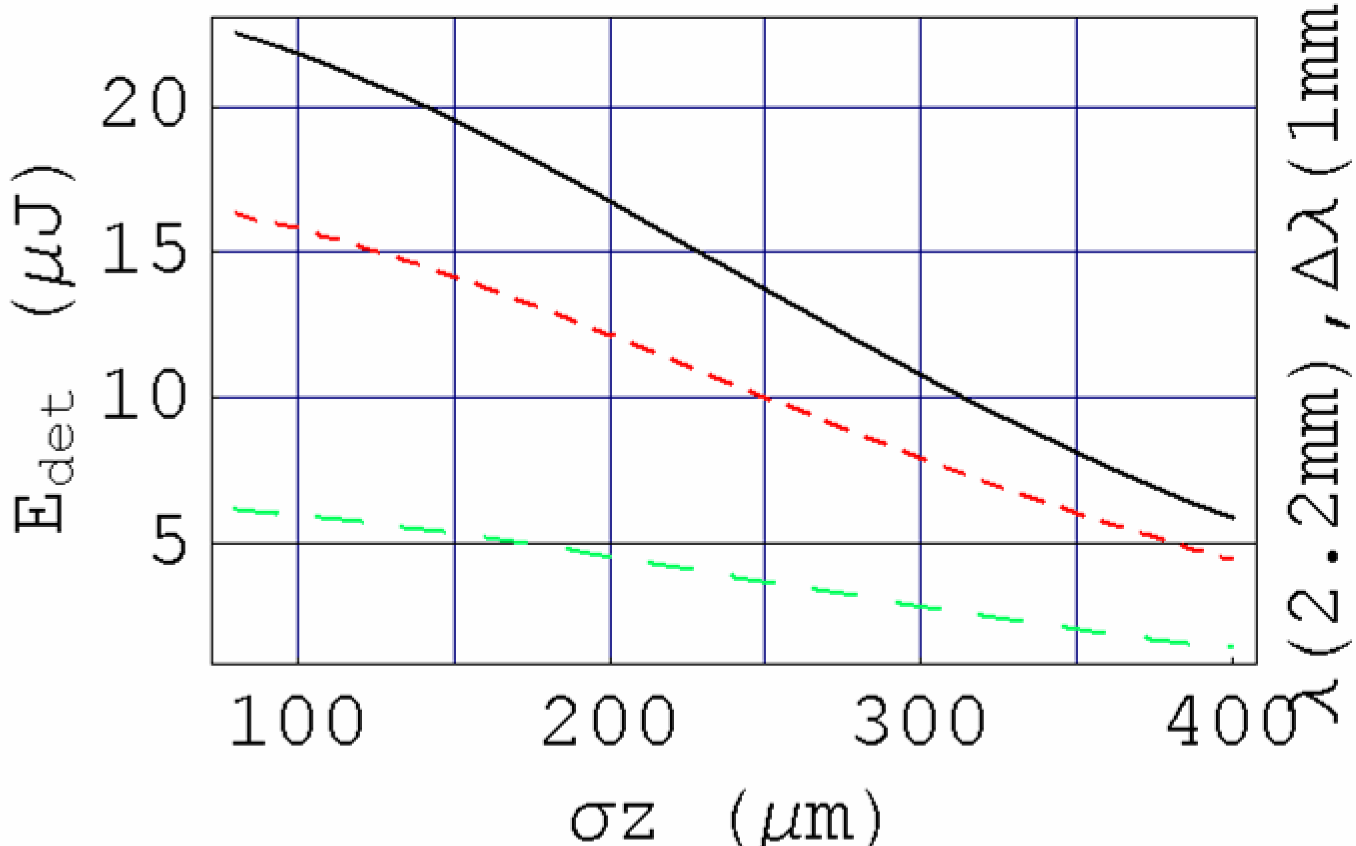
LCLS BLM utilizing coherent radiation

- CER: Calculate E-field at four edges, sum up with proper phase difference→ then power
- Do not calculate interference between CSR and CER
- Diode: WD — 06 detector



CSR (green)
CER (red)

The black solid curve is simply the sum

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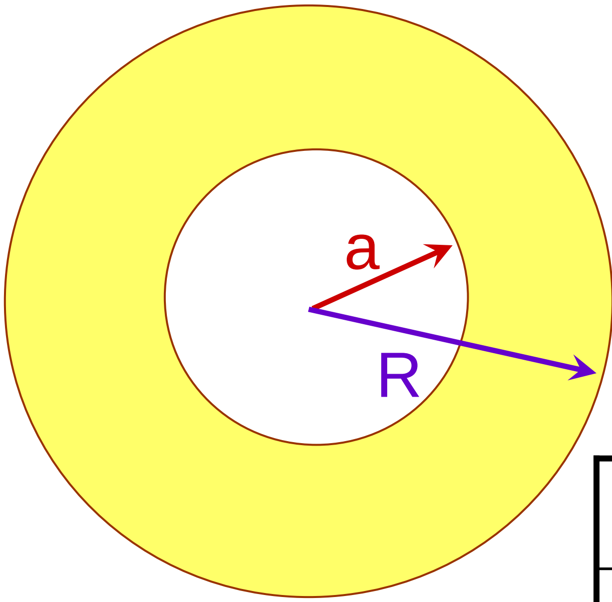
LCLS BLM utilizing coherent radiation

- Diffraction radiation concentrates for

$$\frac{a}{\gamma} \le \lambda \le \frac{R}{\gamma}$$



	λ (mm)	γ	λ γ (m)
BC1	1.2	489.2	0.59
BC2	0.13	8414.9	1.1

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LCLS BLM utilizing coherent radiation

- Transition Radiation
  - Infinite Plate

$$\left.\frac{d^2 I}{d\omega d\Omega}\right|_{Ti} \equiv W_0 \approx \frac{Z_0 e^2}{16\pi^3}\left(\frac{\sin(2\theta)}{1-\cos^2(\theta)}\right)^2$$

  - Finite Plate

$$W_T \equiv W_0\left[1-\frac{\omega R}{\gamma c}K_1\left(\frac{\omega R}{\gamma c}\right)J_0(kR\sin\theta) - \frac{\omega R}{\gamma^2 c\sin\theta}K_0\left(\frac{\omega R}{\gamma c}\right)J_1(kR\sin\theta)\right]^2$$

S. Reiche *et al.*, PAC2001, p. 1282

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LCLS BLM utilizing coherent radiation

- Diffraction Radiation — Finite Plate with Hole

$$W_D \approx W_T \left[J_0\left(\frac{\pi a \sin\theta}{\lambda} \right) \frac{\pi a}{\gamma\lambda} K_1\left(\frac{\pi a}{\gamma\lambda} \right) \right]^2$$

Y. Shibata *et al.*, Phys. Rev. E 52, p. 6787 (1995)

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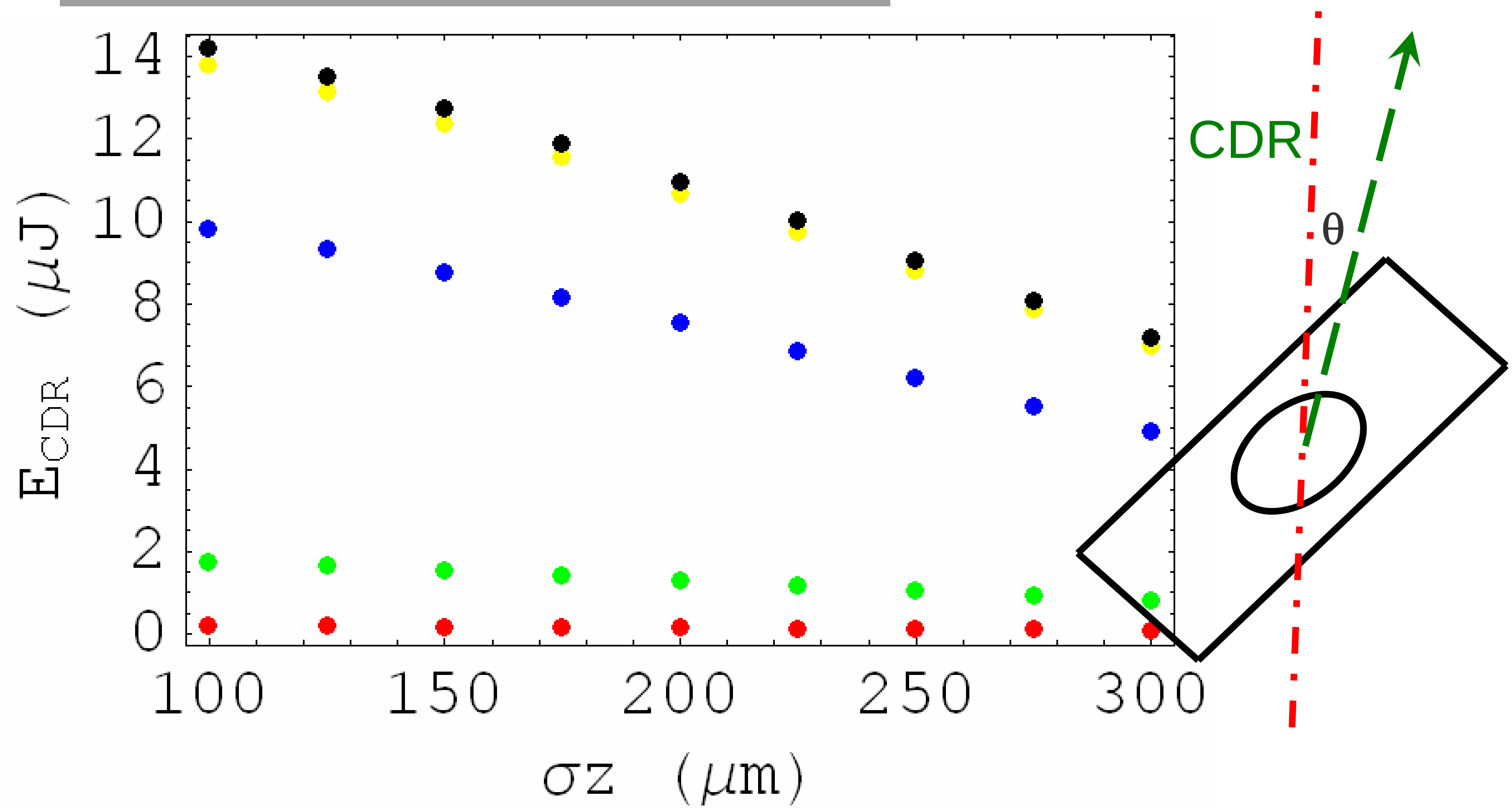
LCLS BLM utilizing coherent radiation

- Coherent Diffraction Radiation
  - Diode: WD-06 detector



$\theta \Rightarrow$ (0.01;0.02;0.05;0.2;0.5)

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LCLS BLM utilizing coherent radiation

- Signal strength (at birth)
  - Ceramic gap (optical diffraction model)

$$\Delta E \approx 1/\pi\Gamma(1/4)Q_b^2 Z_0 c/(4\pi R)\sqrt{g/(\pi\sigma_z)}$$

	aperture	σ_z (mm)	Q_b (C)	E_{rad} (μJ)
SLC	5%	2	5	0.75
LCLS	5%	0.2	1	0.1

- CR

$$E_{CSR} + E_{CER} + E_{CDR} > 30(\mu J)$$

>100

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LCLS BLM utilizing coherent radiation

- Current mechanical design would collect CER, CDR along with CSR

- Further improvement
  - CSR near-field, far-field calculation
    - O. Chubar and P. Elleaume → Synchrotron Radiation Workshop
  - Power loss on the mirror
    - Reflectivity — p–polarization, and s–polarization
  - Transmission of the system in general

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