

Coherent X-Ray Cherenkov Radiation (CXCR) Produced by Microbunched Beams

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1. Introduction

The density distribution of the Gaussian e-beams of FELs is microbunched according to

$$f(r, z) = \frac{N_b}{2\pi\sigma_r^2} \frac{\exp(-r^2 / 2\sigma_r^2)}{(2\pi)^{1/2} \sigma_z} \frac{\exp(-z^2 / 2\sigma_z^2)}{[1 + b_1 \cos(k_r, z)]}, \quad (1)$$

with form factor

$$F(\omega, \theta) = \exp(-(k\sigma_r\theta)^2) \left[\exp\left(\frac{-\omega^2\sigma_z^2}{2V^2}\right) + b_1 \exp\left(-\left(\frac{\omega}{V} - k_r\right)^2 \frac{\sigma_z^2}{2}\right) + b_1 \exp\left(-\left(\frac{\omega}{V} + k_r\right)^2 \frac{\sigma_z^2}{2}\right) \right]^2 \quad (2)$$

where $\lambda_r = 2\pi / k_r = 2\pi c / \omega_r = L_{und} (1 + K^2 / 2) / 2\gamma^2$ and b_1 are the microbunching wavelength and the modulation depth, N_b , L_{und} and $K \dots$

The coherent radiation of microbunched beams has been studied: in [1]-COTR; in [2]-CXTR; in [3]- CXDR; in [4]- CChR; in [5]- CPXR in [6]-CCUR; in [7]-a review of all.

- 1. J. Rosenzweig, G. Travish, A. Tremaine, Nucl. Instr. and Meth. A 365 (1995) 255.**
- 2. E.D. Gazazian, K.A. Ispirian, R.K. Ispirian, M.I. Ivanian, Nucl. Instr. and Meth. B173 (2001) 160.**
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Theoretically substituting the calculated values of χ' and χ'' into X-ray transition radiation (XTR) formulae (see [8]) and experimentally using $E=1.5$ GeV [9] and 5-10 MeV [10-12] electrons it has been shown that at K-. L- edges in narrow regions where $n(\omega)>1$, X-ray Cherenkov radiation (XCR) is produced.

This work is devoted to the theoretical study of coherent X-ray Cherenkov radiation (CXCR) in water window region ($\hbar\omega=285$ -550 eV) which can be produced and used at DESY FLASH2 with $E=1.2$ GeV [13] and at Japan SACLA [14] and DESY EuroFEL [15] with $E=8$ and 10 GeV electrons.

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- 10. W. Knulst et al, Appl. a) Phys. Lett. 79 (2001) 2999; b) 83 (2003) 4050; c)Proc. SPIE, 5196 (2004) 393. d) W. Knulst, Dissertation, Eindhoven University of Technology, 2004.**
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- 12. K.A. Ispirian, Lecture “X-Ray Cherenkov Radiation”, in Proc. of NATO ARW 2004, Vol. 199, p. 217**
- 13. a) V. Ayvazyan et al, Eur. Phys. J. D37 (2006) 217; b) K. Honkavaara et al, Proc. of IPAC2012, TUPP052, 1715, 2012; c) M. Vogt et al, Proc. IPAC 2013, TUPEAO04.**
- 14. T. Ishikawa et al, Nature Photonics, 6, 540, 2012.**
- 15. TESLA Technical Design Report 2001 DESY 011.**

2. The Calculation of CXCR

Using the well known relation (see [16])

$$\frac{d^2 N_{CXCR}}{d\omega d\theta} \cong N_b^2 F(\omega, \theta) \frac{d^2 N_{XCR}}{d\omega d\theta}, \quad (3)$$

Where the form-factor is given by (2) and $\frac{d^2 N_{XCR}}{d\omega d\theta}$

by the XTR formula (1.59) of [8] which can be used also for XCR

$$\frac{d^2 N_{XTR}}{d\hbar\omega d\theta} = \frac{d^2 N_{XCR}}{d\hbar\omega d\theta} = \frac{2\alpha\theta^3}{\pi\hbar\omega} \frac{(\chi'^2 + \chi''^2)}{(\theta^2 + \gamma^{-2})^2 [(\theta^2 + \gamma^{-2} - \chi')^2 + \chi''^2]} \cdot (4)$$

Substituting (4) and (2) into (3) one derives for the spectral-angular distribution of CXCR

$$\frac{d^2 N_{CXCR}}{d\omega d\theta} \cong N_b^2 b_1^2 \frac{2\alpha\theta^3}{\pi\omega} \frac{(\chi'^2 + \chi''^2)}{(\theta^2 + \gamma^{-2})^2 [(\theta^2 + \gamma^{-2} - \chi')^2 + \chi''^2]} \exp\left(-(k\sigma_r\theta)^2\right) \exp\left(-\left(\frac{\omega}{V} - k_r\right)^2 \sigma_z^2\right) \cdot (5)$$

16. N. A. Korkhmazian, L.A. Gevorgian, M. L.Petrosian, Zh. Techn. Fiz. 47, 1583, 1977.

The angular distribution of CXCR photon number is obtained integrating (5) over ω

$$\frac{dN_{CXCR}}{d\theta} \cong N_b^2 b_1^2 \frac{2\alpha \theta^3 V}{\sqrt{\pi} \sigma_z \omega_r} \frac{(\chi'^2 + \chi''^2)|_{\omega=\omega_r}}{(\theta^2 + \gamma^{-2})^2 [(\theta^2 + \gamma^{-2} - \chi'|_{\omega=\omega_r})^2 + \chi''^2|_{\omega=\omega_r}]} \exp(-(k_r \sigma_r \theta)^2). \quad (6)$$

The spectral distribution of CXCR is obtained by integration of (5) over θ

$$\frac{dN_{CXCR}}{d\omega} \cong N_b^2 b_1^2 \frac{2\alpha(\chi'^2 + \chi''^2)}{\pi \omega} I(\omega, \theta_0) \exp\left(-\left(\frac{\omega}{V} - k_r\right)^2 \sigma_z^2\right), \quad (7)$$

where

$$I(\omega, \theta_0) = \int_0^{\theta_0} \frac{\theta^3}{(\theta^2 + \gamma^{-2})^2 [(\theta^2 + \gamma^{-2} - \chi')^2 + \chi''^2]} \exp(-(k\sigma_r \theta)^2) d\theta \quad (8)$$

The upper limit of integration in (8) must be taken $\theta_0 \gg 1/\gamma$ since the radiation intensities decrease sharply after these angles

For $\gamma \gg 1$ one obtains

where

$$I(\omega, \infty) = \frac{j}{2\chi''} (A - A^*) + B$$

$$A = \frac{1}{2} \frac{e^{-(k\sigma_r)^2(\chi' - j\chi'')}}{\chi' - j\chi''} \Gamma\left(0, -(k\sigma_r)^2(\chi' - j\chi'')\right), \quad B = \frac{1}{2} \frac{1 + C + 2 \ln(k\sigma_r/\gamma)}{\chi'^2 + \chi''^2} \quad (9)$$

$$\Gamma(a, z) = \int_z^\infty t^{a-1} e^{-t} dt, \quad C = 0.577216 \quad (10)$$

The total number of CXCR photons per bunch obtained by integration of (6) over θ , or of (7) over ω is equal to

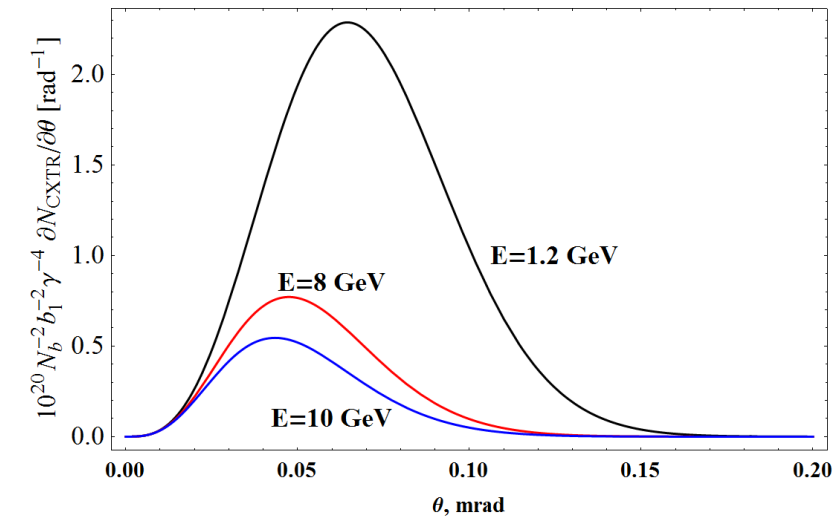
$$N_{CXCR} = N_b^2 b_1^2 \frac{2\alpha V(\chi'^2 + \chi''^2)|_{\omega=\omega_r}}{\sigma_z \sqrt{\pi} \omega_r} I(\omega_r, \theta_0). \quad (11)$$

3. Numerical Results

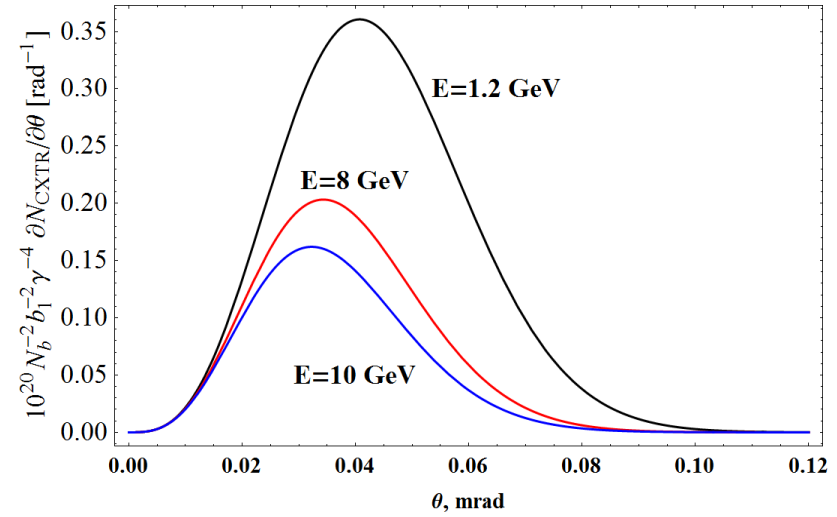
Obtained with the help of (6) - (11) for C are calculated for $\hbar\omega_r=284$ eV (FLASH2) with $E=1.2$ GeV [13], and SACLA [14] and EuroFEL [15] with $E=8$ and 10 GeV, respectively, by “tuning” the parameters. The results for Ti are calculated for SACLA [14] and EuroFEL [15] at $E=8$ and 10 GeV, respectively. In all the cases it is taken $b_1=1$, $\sigma_r = 13 \mu m$ $\sigma_z = 15 \mu m$

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3a. The Angular Distributions of CXCR



a)

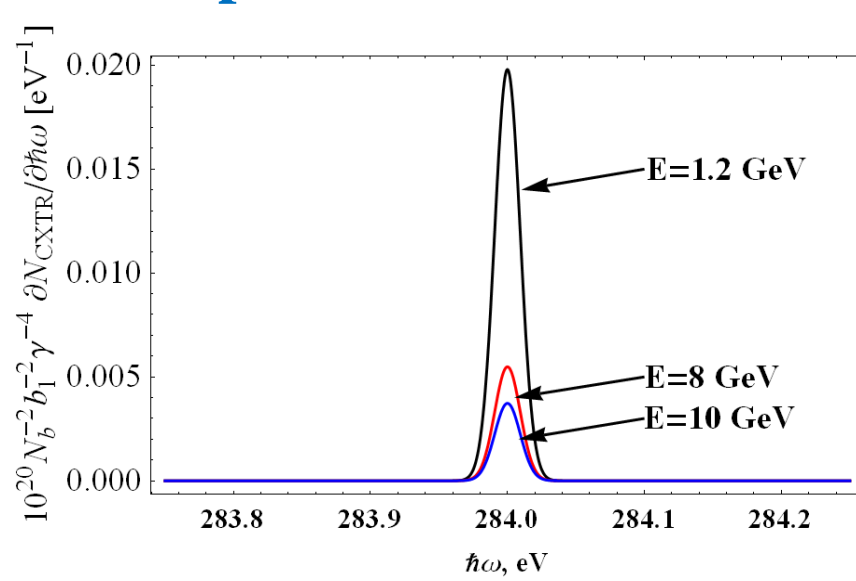


b)

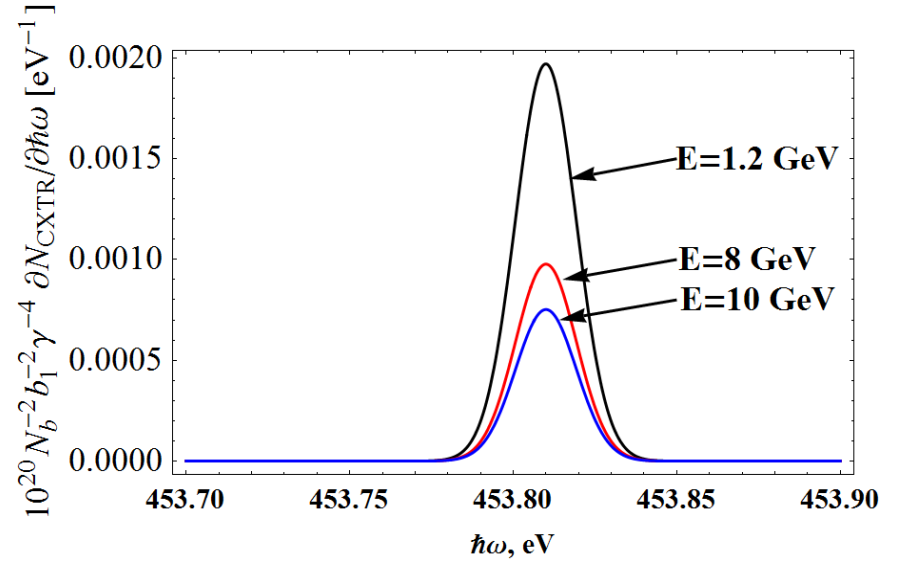
Fig.1 a) and b) for C and Ti, respectively.

It is seen that θ are less than $1/\gamma$.

3b. The Spectral Distributions of CXCR



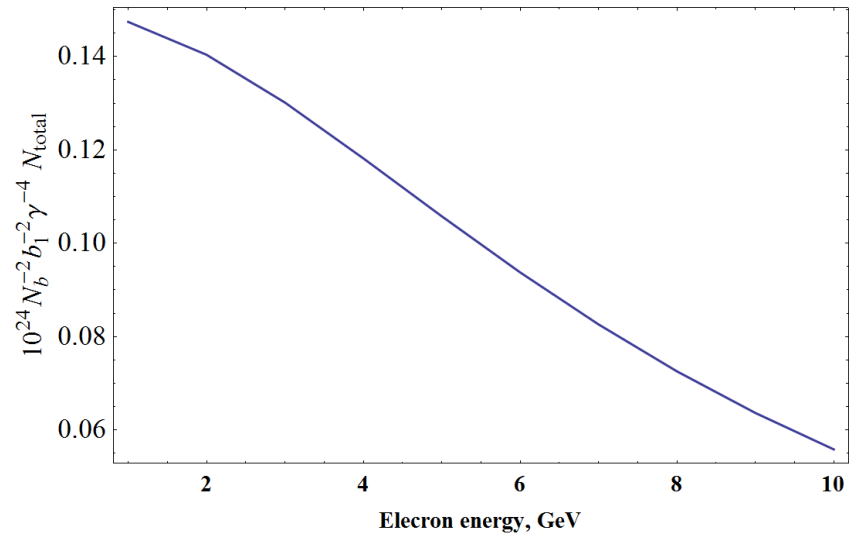
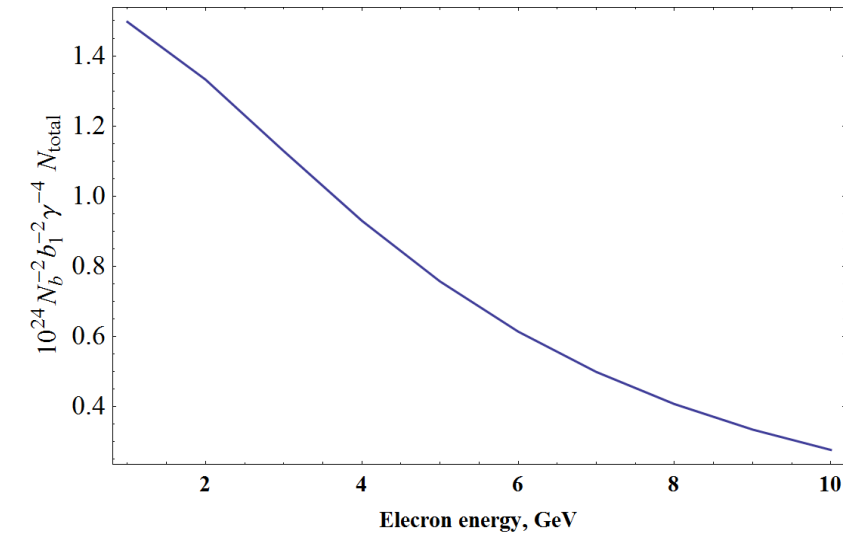
a)



b)

Fig.2 The Spectral Distributions of CXCR for C and Ti, a) and b), respectively

3c. The Energy Dependence of CXCR



a) Fig.2 a) and b) for C and Ti b)

It is seen that N increases slightly more weakly than $\sim \gamma^4$.

4. Discussion and Conclusions

For comparison Table gives the main parameters of SASE, XCR and CXCR radiation for C expected at FLASH at $E=1.2$ GeV.

	SASE	XCR	CXCR
N	10^{12}	3×10^6	1.8×10^9
$\Delta\omega/\omega$ (%)	1.0	0.35	0.0014
$\Delta\omega$ (eV)	2.8	1.0	0.027

The situation becomes much better for higher energy electrons and Ti radiator. However, it has been taken $b_1=1$, and any real $b_1 < 1$ reduces the CXCR intensity $\sim b_1^2$. In our knowledge, the values of b_1 have not been measured anywhere.

Let us note that as for the first real X-ray laser [17] the CXCR beam has more stable $\hbar\omega$ line since it is the characteristics of radiator atoms

17. N.Rohringer et al, Nature, 481 (2012) 488.

Summarizing one can make the following conclusions:

- 1) New type of radiation, CXCR, has been predicted and studied.**
- 2) The use of microbunched beams, which are now sent to dumps, can provide CXCR beams very monochromatic and stable. As the beams of [17] they can find application in atomic physics and for the measurement of b_1 . Indeed, if by another simple method, say, measuring the current, one knows the value of N_b , then the measured intensity can serve for determination of b_1 .**

Thank you