X and gamma-ray due to inverse Compton scattering of CSR

CSR mini-workshop

Miho Shimada(KEK)

Inverse Compton scattering of CSR

Light source of Compact ERL (245MeV 2oop ERL)

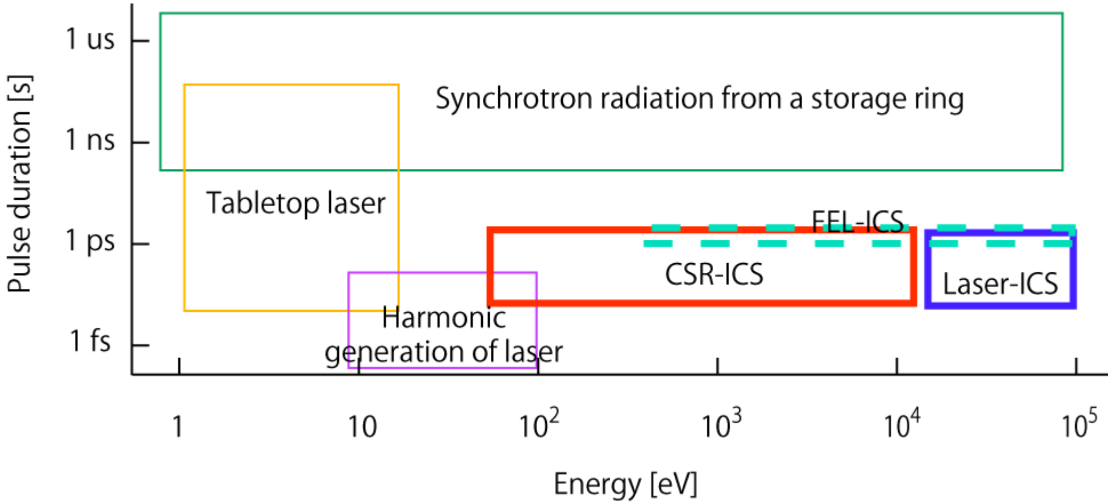
- Hard X-ray due to inverse Compton scattering of an external femto-second laser
- Intense CSR at terahertz region

We proposed **an inverse Compton scattering of CSR** as a light source of ERL.

M. Shimada and R. Hajima, PRSTAB **13,** 100701,(2010)

$$E_X = 4\gamma^2 E_L$$ Head-on collision

E_X : *Energy of scattered photon* E_L : *Energy of laser* γ : *Lorentz factor*



Soft X-ray can be expected at cERL.

Figure : Compared wavelength and pulse duration of scattered photons at Compact ERL with other light source.

Comparison CSR-ICS with conventional ICS

	Laser-ICS	FEL-ICS	CSR-ICS
Equipment	External laser	Undulator	Only mirror
Synchronization	Difficult	Easy	Easy
Spot size of laser (depends on wavelength)	Smaller	Smaller	Larger
Bandwidth	Narrow	Relatively narrow	Relatively narrow ~ white light
Electron energy	Lower	Lower	Higher
Bunch compression	Difficult	Difficult	Easy
Emittance	Larger	Larger	Smaller

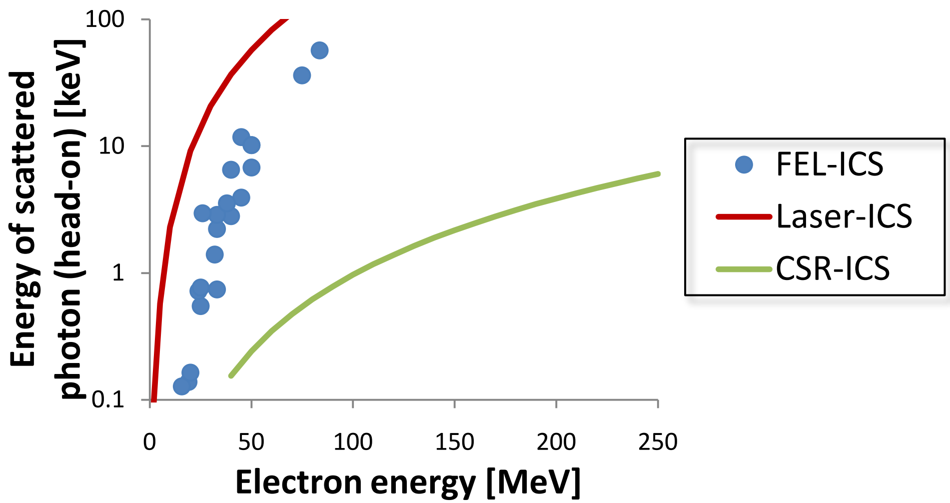


Figure :
Examples of scattered photon energy.

- Laser-ICS : Ti:Sa laser (800nm)
- FEL-ICS : Scattered photon energy estimated from the wavelength of FEL and the electron energy.
- CSR-ICS : Bunch length 100fs
  wavelength of CSR (30um x 2π)

Proposal of CSR-ICS by other institutes

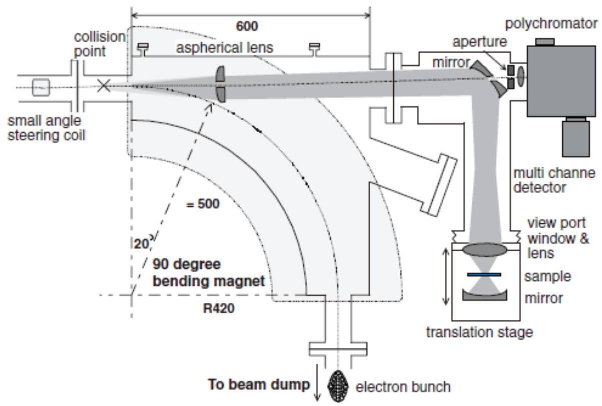


Fig. 1. A schematic view of the THz-wave spectrophotometry with the compact S-band linac at AIST.

N. Sei et al, APE **1,** 087003,(2008)

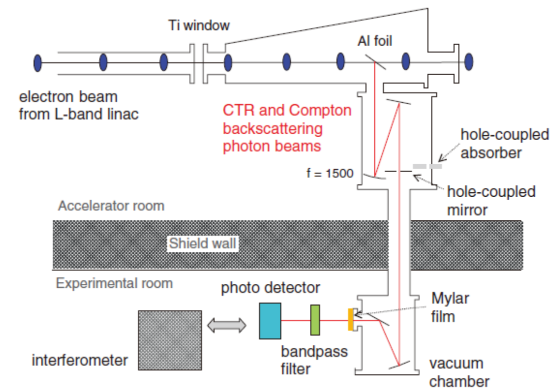
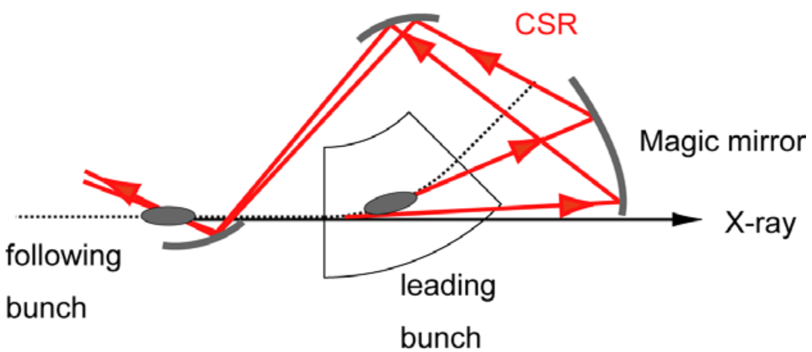


Fig. 1. Schematic layout of the experimental setup at KURRI-LINAC.

N. Sei and T. Takahashi, APE **3,** 052401,(2010)

- CSR-ICS is proposed as a spectroscopy of terahertz region at AIST and KURRI.
- Spectral information of terahertz is converted to the visible region. It enables us a real-time measurement.
- Intensity is very weak.

Optics : 1 Magic mirror scheme for white light source

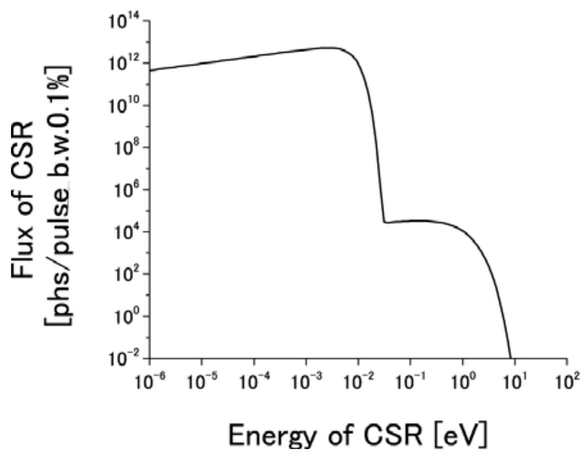


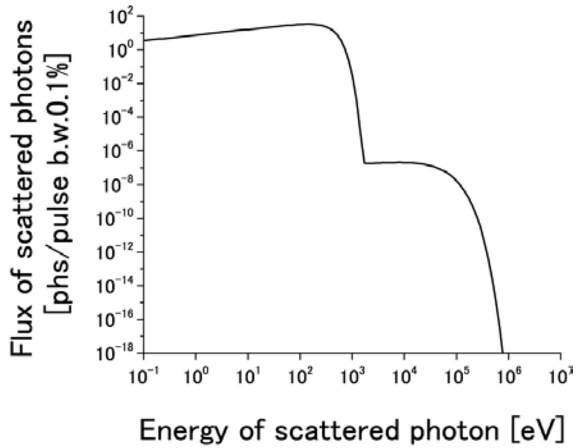
Acceptance angle of magic mirror
300 mrad [H] x 20 mrad [V]

Transverse electron beam size
100 um [H] x 50 um[V]

- including the energy spread at non-zero dispersion
- betatron function is limited due to the large acceptance angle in the longitudinal direction.
- spot size of CSR is assumed to be the same as that of electron beam (neglecting cut-off effect)

Example :
Electron charge 77pC/bunch,
Electron energy 60MeV,
Bunch length 100 fs

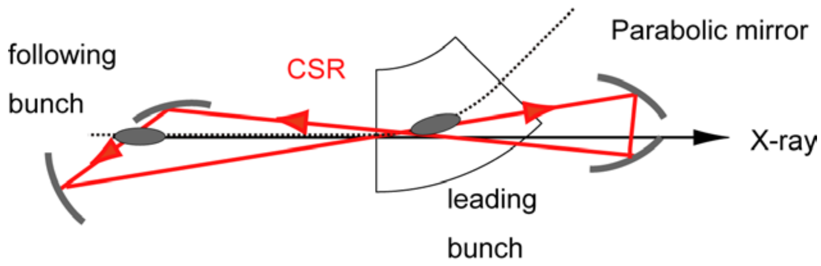




Number of scattered photon per pulse : 2×10^5 phs/pulse
Flux of scattered photon : 2×10^{14} phs/sec (1.3 GHz)
Pulse duration : 100 fs (it will be lengthened after narrowing the band width)

Optics 2 : Optical Cavity scheme for narrow bandwidth

CSR - ICS



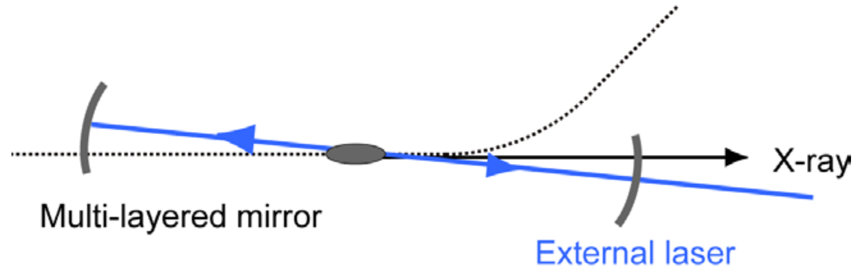
a. **Incoherent stacking** because the fluctuation of longitudinal position is larger than wavelength of CSR.

b. Electron bunch emits CSR **inside a cavity**.

c. **Four mirrors** is necessary for two focus points. One is for collection of CSR and another is collision point.

$$P_{CAV} = \frac{P_{in}}{1 - R^n}$$

ICS by an external laser



a. **Coherent stacking**

b. External laser is injected from **outside a cavity**. It passes though a multilayered mirror with low transmittance.

c. **Two mirrors** are enough for single focus point.

$$P_{CAV} = TF^2 P_{in} / \pi^2$$

E.R.Crosson et al, Rev. Sci. Instrum. **70,** p.4 (1999)

$$Finess: \quad F = \pi \sqrt{R^n} / 1 - R^n$$

P_{cav}:Power in a cavity, P_{in}:Input power, R: Reflectance, T:Transmittance, n:Number of mirrors

In both cases, pulse power is stacked by **1000 times** with reflectivity of mirror 99.97% .

Wavelength of CSR for pulse stacking in an optical cavity

Total radiation power : $P(k)$

$$P(k) = Np(k) + F(k)N(N-1)p(k)$$

Incoherent   Coherent

$$F(k) = \left| \int \rho(z) e^{ikz} dz \right|^2$$

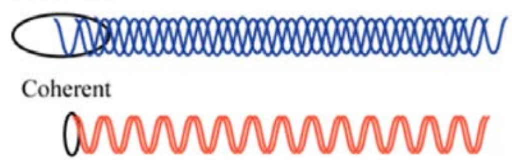
$P(k)$: Total radiation power

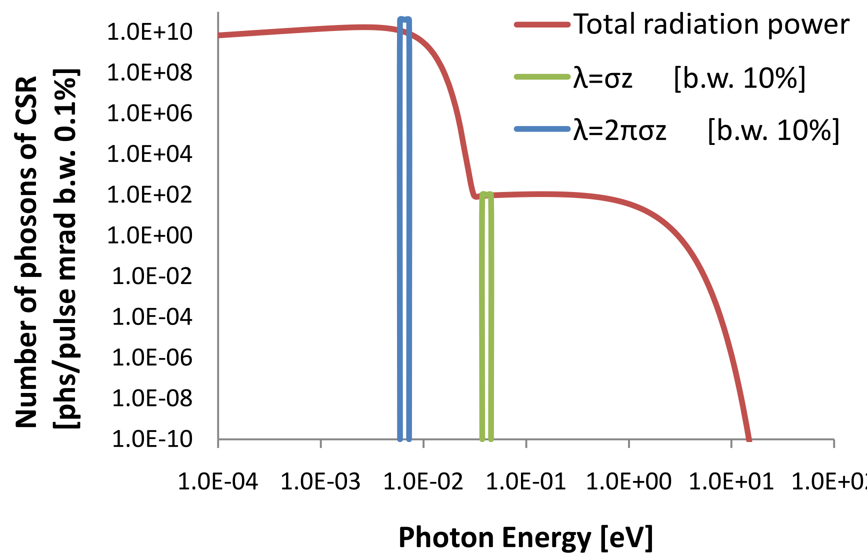
N : Number of electron

$p(k)$: Radiation power per an electron

$\rho(z)$: Longitudinal electron density distribution

$F(k)$: Form factor





Gaussian beam with bunch length σ_z

$$\rho(z) \approx \frac{1}{\sqrt{2\pi}\sigma_z} \exp\left[-\frac{z^2}{2\sigma_z^2} \right]$$

$$P(\lambda) \approx \exp\left[-\sigma_z^2 \left(\frac{2\pi}{\lambda} \right)^2 \right]$$

Wavelength of CSR stacked in an optical cavity is chose as follows,

$$\lambda \equiv 2\pi\sigma_z$$

Mode matching

Acceptance angle is limited for Mode matching

$$\sigma_x^{CSR}\sigma_{x'}^{CSR} \leq \frac{\lambda}{4\pi}$$

λ : *wavelength of CSR*

σ_x^{CSR} : *Horizontal spread of CSR source*

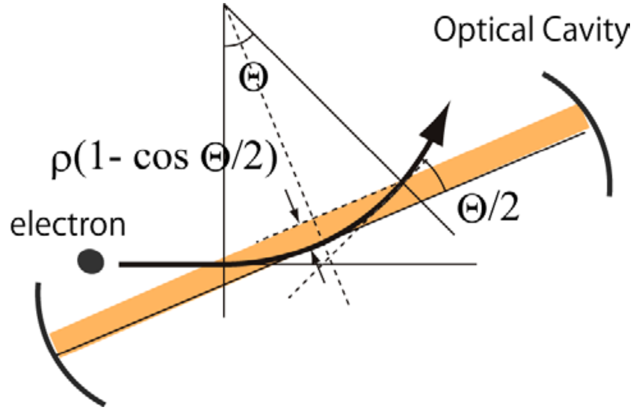
$\sigma_{x'}^{CSR}$: *Horizontal divergence of CSR source*

$$\Delta\theta_c = \left(\frac{3\lambda}{2\pi\rho}\right)^{1/3} = \frac{1}{\gamma}\left(\frac{2\lambda}{\lambda_c}\right)^{1/3}$$

$\Delta\theta_c$: *divergence of CSR*

$$\sigma_x^{CSR} = \sqrt{\sigma_x^2 + \left[\rho\left(1 - \cos\frac{\Theta}{2}\right)\right]^2}$$

$$\sigma_{x'}^{CSR} = \sqrt{\sigma_{x'}^2 + \Delta\theta_c^2 + \left(\frac{\Theta}{2}\right)^2}.$$



Acceptance angle Θ is determined to satisfy the mode matching.

High reflectivity mirror

In the wavelength range of a few 10 um ∼a few 100 um,

- Reflectivity of metal is lower than 98 %.
- It is difficult to fabricate multilayered mirror with larger than 99% reflectivity by conventional method.

Development of high reflectivity mirror for terahertz region

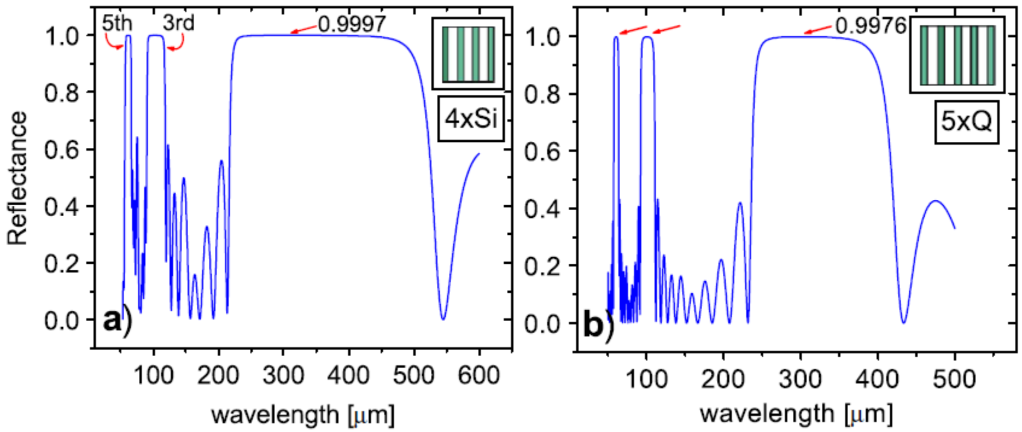


FIG. 2. (Color) In (a) four layers of 23 μm thick Si, and in (b) five layers of 36 μm thick z-cut quartz, each separated by 75 μm vacuum gap, create high reflectivity bands centered at $\lambda_C \sim 300$–320 μm. The harmonic band centers are located at ~100 and ~60 μm, respectively.

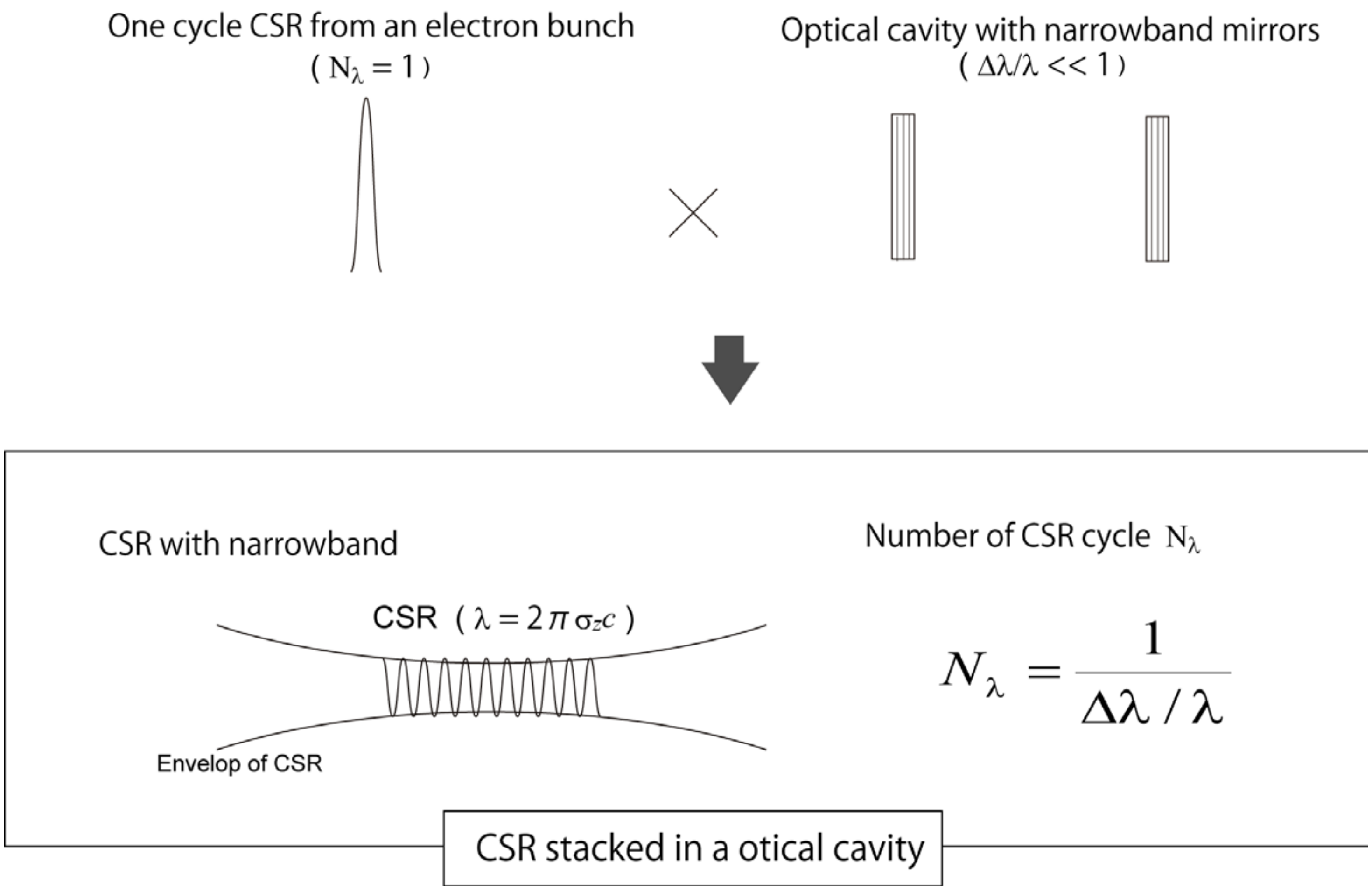
M.Tecimer et al, PRSTAB **13,** 030703,(2010)

- Stacking up photonic crystal separated by vacuum layer.
- Bandwidth is narrow at the higher order wavelength.
- Wavelength, which depends on thickness of the layers, is controllable without losing the high-reflectivity.

Optimization of collision area : 1

- **Half cycle of CSR is destroyed** by an narrow band mirror.

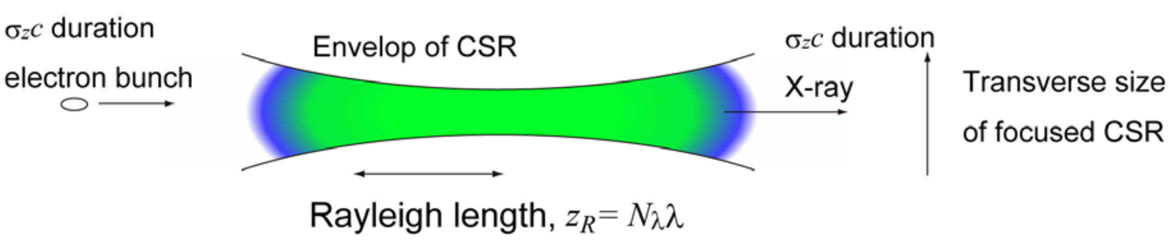
In the case of bandwidth Δλ/λ, pulse duration of CSR is lengthened by a factor 1/(Δλ/λ).

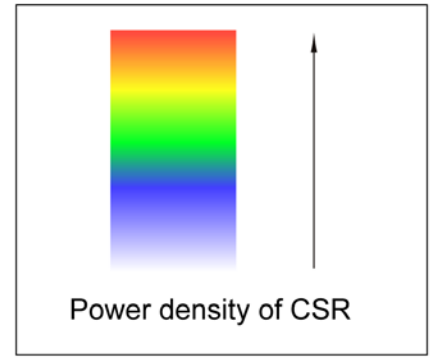


Optimization of collision area : 2

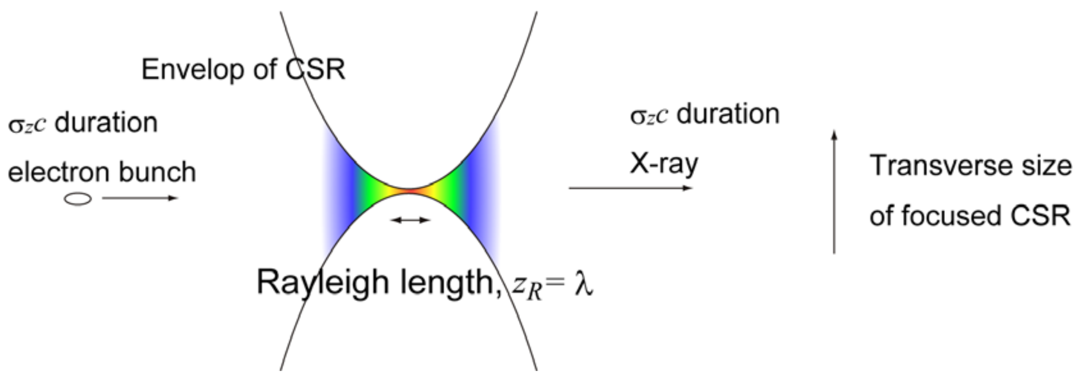
- CSR in optical cavity is assumed to be **Gaussian beam**.
- **Hour glass effect** is considered at the collision.

(i) Large Rayleigh length, Large spot size





(ii) Small Rayleigh length, small spot size



Minimum spot size w_0 of focused CSR

$$\pi w_0^2 = \lambda z_R$$

Number of CSR photons with small collision area

$$N_{CSR}^{collision} = \frac{z_R}{\lambda} N_{CSR}^{all}$$

Number of scattered photons Nx is independent in Rayleigh length z_R.

$$N_X \propto N_{CSR}^{collision} N_e / \pi w_0^2 = N_{CSR}^{all} N_e / \lambda^2$$

X-ray at 200 MeV-ERL

TABLE I: Optical cavity scheme in the Compact ERL : Horizontal acceptance angle are 50 mrad for λ = 190 μm and 110 mrad for λ = 1900 μm for mode matching. Bandwidth of the on-axis X-ray is considered to be $\Delta\lambda_X/\lambda_X \sim \Delta\lambda/\lambda \sim 0.1$ (10%). Pulse duration of the X-ray is same as σ_z/c.

Electron energy [MeV]	Charge [nC]	σ_z/c [ps]	Spot size [mm × mm]	CSR energy [mJ]	K	X-ray energy [keV]	N_X [phs./pulse]	N_X [phs./s]
60	0.077	0.1	0.3 × 0.3	0.14	0.013	0.4	1×10^4	2×10^{13}
60	0.5	1	3 × 3	0.6	0.009	0.04	4×10^4	0.7×10^{13}
200	0.2	0.1	0.3 × 0.3	1.0	0.034	4	2×10^5	1×10^{14}
200	1	1	3 × 3	2.5	0.017	0.4	3×10^5	3×10^{13}

- Number of photons of X-ray (b.w.10%)
  - Number of photons per pulse : ~ **10^{4-5} phs/pulse**.
  - Flux : ~ **10^{13-14} phs/s**.
- Energy range of X-ray
  - From **0.04 to 4 keV**.
  - 10 keV X-ray is possible at electron energy of 200 MeV and bunch length 50 fs, which is accomplished in tracking simulation.
- Pulse duration of X-ray is **100 fs – 1 ps**.
- Electron transverse beam size is much smaller than the focus size of focused CSR.

Gamma-ray at 5 GeV-ERL

TABLE II: Optical cavity scheme in 5-GeV ERL : Horizontal acceptance angle are 12 mrad for $\lambda = 60$ μm and 9 mrad for $\lambda = 20$ μm for mode matching. Bandwidth of the on-axis γ-ray is considered to be $\Delta\lambda_\gamma/\lambda_\gamma \sim \Delta\lambda/\lambda \sim 0.1$ (10%). Pulse duration of the γ-ray is same as σ_z/c.

Electron Charge [nC]	σ_z/c [fs]	Spot size [μm $\times$ μm]	CSR energy [mJ]	K	γ-ray energy [MeV]	N_γ [phs./pulse]	N_γ [phs./s]
1	30	100 $\times$ 100	80	0.56	8	3×10^8	3×10^{16}
0.5	10	30 $\times$ 30	65	0.87	25	4×10^8	0.7×10^{17}

- Number of photons of gamma-ray (b.w.10%)
  - Number of photons per pulse : ~ **10^8 phs/pulse**.
  - Flux : ~ **10^{17} phs/s**.

- Most powerful gamma-ray source is achieved at FEL-ICS in Duke univ. : ~ 10^{10}phs/s (10 MeV) [IPAC 2010].

- For what is the intense gamma-ray used?
  - For nuclear and neutron experiments ?
  - Generation of positron for ILC
  - 10^{12} phs/pulse gamma-ray with 10MeV can be achieved by electron charge of 10 nC and bunch length of 24 fs. (Rough estimation)

Summary

- We proposed the inverse Compton scattering of CSR.
  - ERL is a nice platform for both high-intensity CSR source and inverse Compton scattering.

- Two optical schemes
  - Magic mirror : **White light with pulse duration of 100 fs**.
  - Optical cavity : **Narrow bandwidth**. Power amplification by pulse stacking is estimated almost **1000 times**.

- Scattered photon expected in ERL（Optical cavity)
  - Generation of soft X-ray with energy range of **0.04-4keV** is expected at 200 MeV ERL. Pulse duration is from **100 fs to 1 ps**.
  - Number of photon per pulse is **$10^{4\text{-}5}$ phs/pulse**, Flux **$10^{13\text{-}14}$ phs/s**.

  - Intense gamma ray with 10 MeV can be obtained at 5 GeV ERL.
  - Number of photon per pulse is **10^{8} phs/pulse**, Flux **10^{17} phs/s**.