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

CSR mini-workshop

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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

\( E_X : \text{Energy of scattered photon} \quad E_L : \text{Energy of laser} \quad \gamma : \text{Lorentz factor} \)

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

<table>
<thead>
<tr>
<th></th>
<th>Laser-ICS</th>
<th>FEL-ICS</th>
<th>CSR-ICS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Equipment</strong></td>
<td>External laser</td>
<td>Undulator</td>
<td>Only mirror</td>
</tr>
<tr>
<td><strong>Synchronization</strong></td>
<td>Difficult</td>
<td>Easy</td>
<td>Easy</td>
</tr>
<tr>
<td><strong>Spot size of laser</strong></td>
<td>Smaller</td>
<td>Smaller</td>
<td>Larger</td>
</tr>
<tr>
<td>(depends on wavelength)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Bandwidth</strong></td>
<td>Narrow</td>
<td>Relatively narrow</td>
<td>Relatively narrow</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>~ white light</td>
</tr>
<tr>
<td><strong>Electron energy</strong></td>
<td>Lower</td>
<td>Lower</td>
<td>Higher</td>
</tr>
<tr>
<td><strong>Bunch compression</strong></td>
<td>Difficult</td>
<td>Difficult</td>
<td>Easy</td>
</tr>
<tr>
<td><strong>Emittance</strong></td>
<td>Larger</td>
<td>Larger</td>
<td>Smaller</td>
</tr>
</tbody>
</table>

*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 (30μm x 2π)
Proposal of CSR-ICS by other institutes

• 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.

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

N. Sei and T. Takahashi, APE 3, 052401,(2010)
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 : $2 \times 10^5$ phs/pulse
Flux of scattered photon : $2 \times 10^{14}$ 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**

- **Incoherent stacking** because the fluctuation of longitudinal position is larger than wavelength of CSR.
- Electron bunch emits CSR **inside a cavity**.
- **Four mirrors** is necessary for two focus points. One is for collection of CSR and another is collision point.

**ICS by an external laser**

- **Coherent stacking**
- External laser is injected from **outside a cavity**. It passes through a multilayered mirror with low transmittance.
- **Two mirrors** are enough for single focus point.

\[
P_{CAV} = \frac{TF^2P_{in}}{\pi^2}
\]


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

\[
Finess = \frac{\pi\sqrt{R^n}}{1 - R^n}
\]
Wavelength of CSR for pulse stacking in an optical cavity

Total radiation power: \( P(k) \)

\[
P(k) = N p(k) + F(k) N (N - 1) p(k)
\]

\( P(k) \): Total radiation power
\( N \): Number of electrons
\( p(k) \): Radiation power per an electron
\( \rho(z) \): Longitudinal electron density distribution
\( F(k) \): Form factor

Incoherent Coherent

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

Gaussian beam with bunch length \( \sigma_z \)

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

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

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

\[
\lambda = 2\pi \sigma_z
\]
Mode matching

Acceptance angle is limited for Mode matching

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

\( \lambda : \) wavelength of CSR

\( \sigma_x^{CSR} : \) 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 \( \Theta \) is determined to satisfy the mode matching.
High reflectivity mirror

In the wavelength range of a few 10 µm ~ a few 100 µm,

- 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

- 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.

M.Tecimer et al, PRSTAB 13, 030703,(2010)
Optimization of collision area : 1

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

In the case of bandwidth $\Delta \lambda / \lambda$, pulse duration of CSR is lengthened by a factor $1/(\Delta \lambda / \lambda)$.

\[
N_\lambda = \frac{1}{\Delta \lambda / \lambda}
\]
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

\[
\sigma_z \text{ duration} \quad \text{electron bunch} \quad \text{Envelop of CSR} \quad \sigma_z \text{ duration} \quad \text{Transverse size of focused CSR} \quad \text{X-ray}
\]

Rayleigh length, \( z_R = \frac{N_e \lambda}{\lambda} \)

(ii) Small Rayleigh length, small spot size

\[
\sigma_z \text{ duration} \quad \text{electron bunch} \quad \text{Envelop of CSR} \quad \sigma_z \text{ duration} \quad \text{Transverse size of focused CSR} \quad \text{X-ray}
\]

Rayleigh length, \( z_R = \lambda \)

Number of scattered photons \( N_X \) is independent in Rayleigh length \( z_R \).

\[
N_X \propto N_{CSR}^{\text{collision}} N_e / \pi w_0^2 = N_{CSR}^{\text{all}} N_e / \lambda^2
\]
X-ray at 200 MeV-ERL

TABLE I: Optical cavity scheme in the Compact ERL: Horizontal acceptance angle are 50 mrad for $\lambda = 190 \, \mu m$ and 110 mrad for $\lambda = 1900 \, \mu m$ 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 $\sigma_z / c$.

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</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>0.077</td>
<td>0.1</td>
<td>0.3 x 0.3</td>
<td>0.14</td>
<td>0.013</td>
<td>0.4</td>
<td>$1 \times 10^4$</td>
<td>$2 \times 10^{13}$</td>
</tr>
<tr>
<td>60</td>
<td>0.5</td>
<td>1</td>
<td>3 x 3</td>
<td>0.6</td>
<td>0.009</td>
<td>0.04</td>
<td>$4 \times 10^4$</td>
<td>$0.7 \times 10^{13}$</td>
</tr>
<tr>
<td>200</td>
<td>0.2</td>
<td>0.1</td>
<td>0.3 x 0.3</td>
<td>1.0</td>
<td>0.034</td>
<td>4</td>
<td>$2 \times 10^5$</td>
<td>$1 \times 10^{14}$</td>
</tr>
<tr>
<td>200</td>
<td>1</td>
<td>1</td>
<td>3 x 3</td>
<td>2.5</td>
<td>0.017</td>
<td>0.4</td>
<td>$3 \times 10^5$</td>
<td>$3 \times 10^{13}$</td>
</tr>
</tbody>
</table>

- Number of photons of X-ray (b.w.10%)
  - Number of photons per pulse: $\sim 10^{4-5}$ phs/pulse.
  - Flux: $\sim 10^{13-14}$ 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

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

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

- For what is the intense gamma-ray used?
  - For nuclear and neutron experiments?
  - Generation of positron for ILC
  - \( 10^{12} \text{ phs/pulse} \) gamma-ray with 10 MeV 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 $10^{4-5}$ phs/pulse, Flux $10^{13-14}$ 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.