Two-stream Instability at Soft X-ray Wavelengths for Increasing Brightness of Compton Sources

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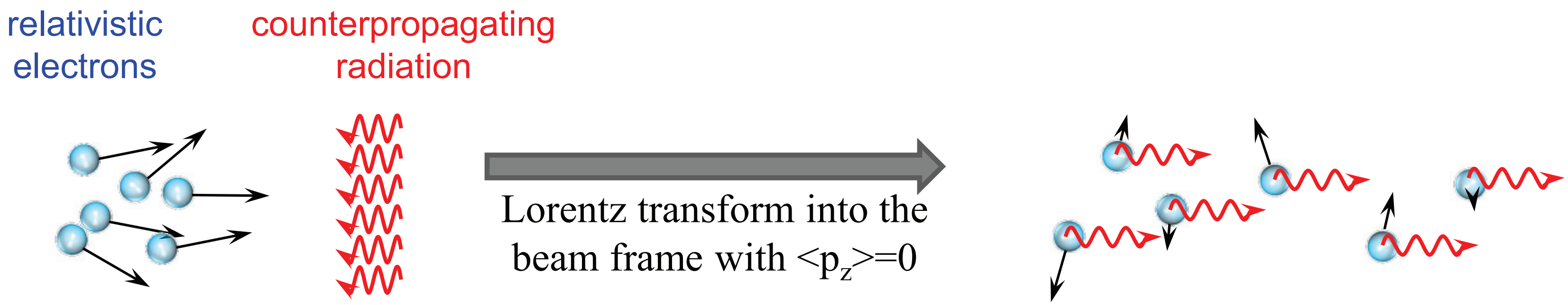
Incoherent Compton source

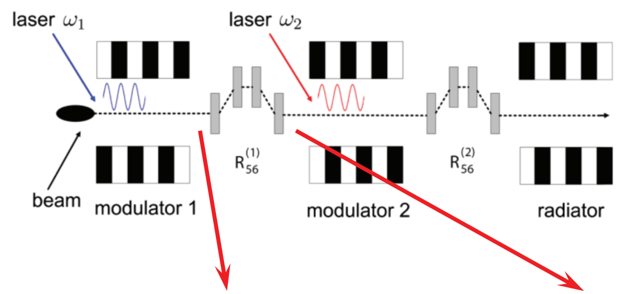


$$\lambda_{Compton} = \frac{\lambda_{laser}\left(1 + a_0^2/2\right)}{4\gamma^2}$$

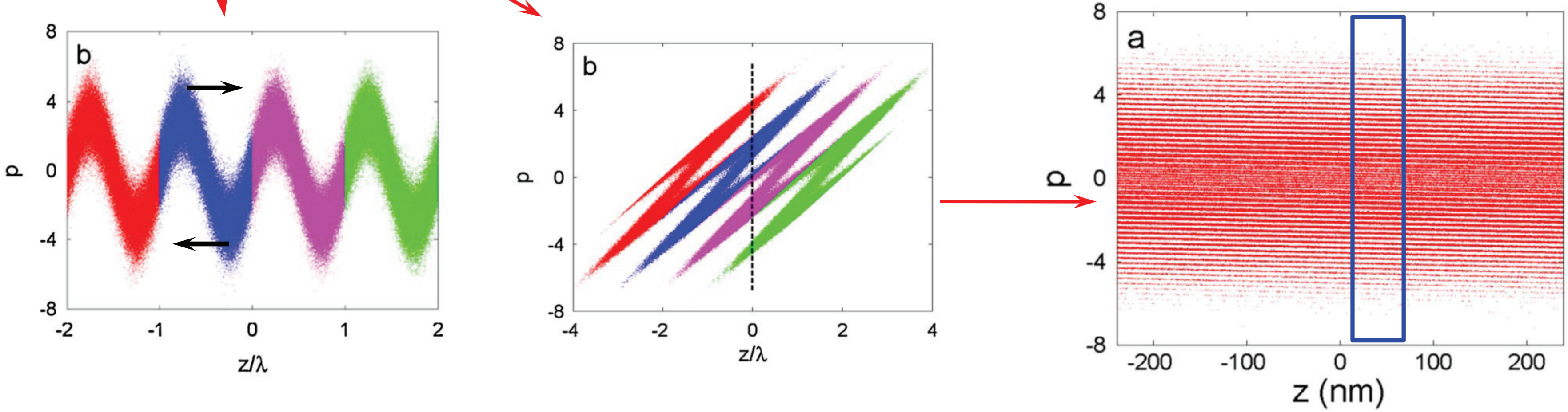
Very short wavelength radiation with relatively low energy electrons

- Coherency of Compton source can be dramatically increased if electrons are bunched at the wavelength of radiation
- Modern lasers are not powerful enough to cause self-bunching similar to FELs
- Electrons can be pre-bunched at short wavelengths using advanced FEL seeding concepts

The danger of using advanced seeding concepts



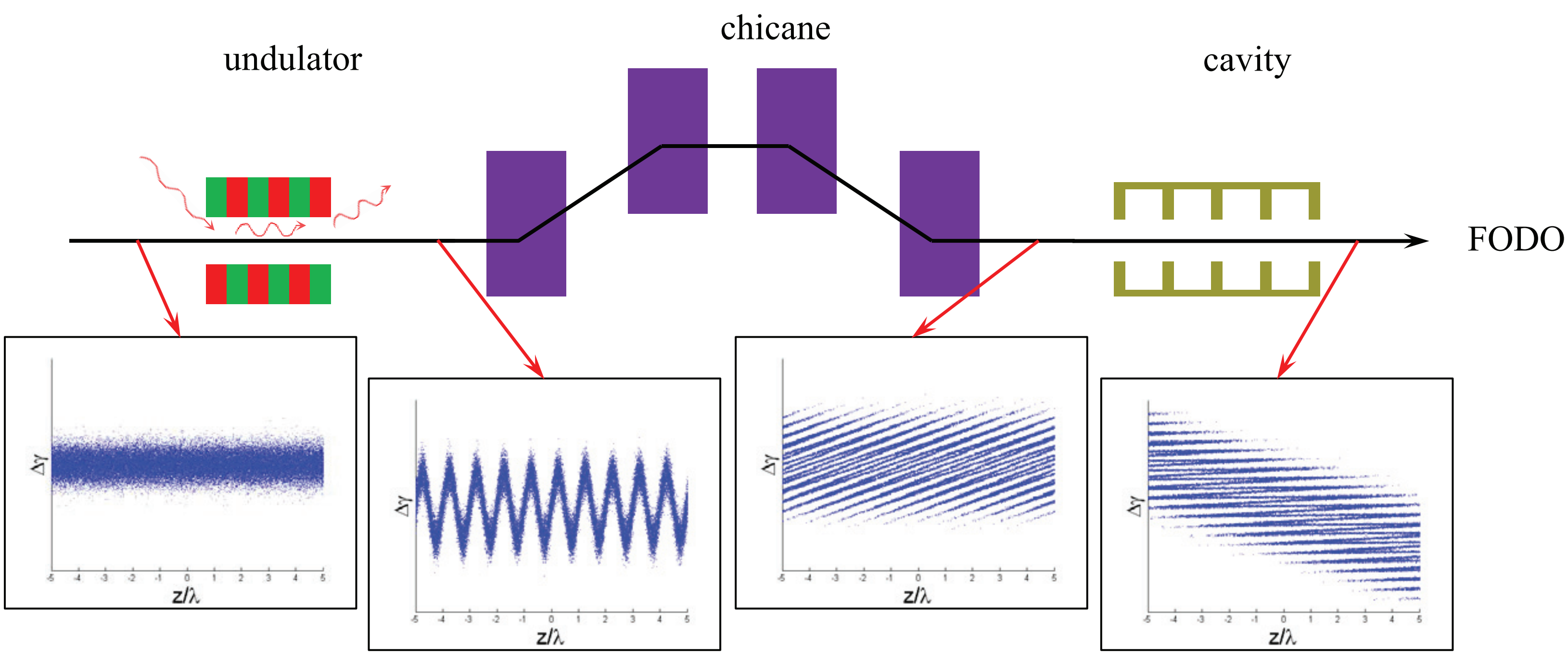
EEHG scheme is a promising candidate for producing bunching at high harmonics. This scheme, in principle, can be adopted for Compton source when the final radiator is replaced with the counterpropagating laser.



All figures from
D. Xiang and G. Stupakov,
"*Echo-enabled harmonic generation free electron laser*",
Phys. Rev. ST-AB **12**, 030702 (2009).

At any longitudinal beam slice multiple streams of electrons with different energies are present. This distribution may drive *the two-stream instability*

Using two-stream instability for beam bunching

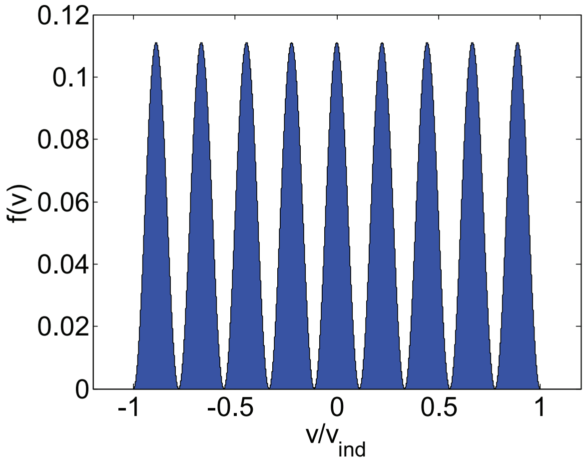


Final cavity is required to impose overall energy chirp to eliminate the residual chirp of each electron stream

Instability growth rate (beam frame)

Distribution function used for finding plasma dispersion relation

$$f(V)=\frac{1+\cos(\pi N_{bands}V/\Delta V_{ind})}{2\Delta V_{ind}},\quad V\in[-V_{ind},V_{ind}]$$

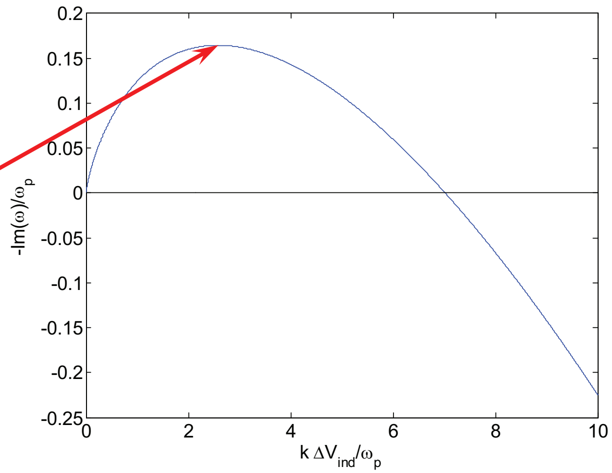


$$D(\omega,k)=1+\frac{\omega_p^2}{k}\int\frac{\partial_V f(V)}{\omega-kV}dV=0$$

$$-i\omega=\frac{k\Delta V_{ind}}{\pi N_{bands}}\ln\left(\frac{2k^2(\Delta V_{ind})^2}{\pi^2 N_{bands}\omega_p^2}\right)$$

$$-\mathrm{Im}(\omega)_{\max}\sim\omega_p/\sqrt{N_{bands}}$$

$$k_{\max}\sim\sqrt{N_{bands}}\,\omega_p/\Delta V_{ind}$$



Instability growth rate for $N_{bands}=10$

Instability growth rate (lab frame)

plasma density in the lab frame,
i.e. plasma frequency

$$\lambda_{\max} = \frac{0.12}{\gamma^{3/2}} \sqrt{\frac{r_\perp^2[100\mu m]\tau[ps]}{Q[nC]} \frac{\Delta E_{ind}[keV]}{N_{bands}}}[mm], L_g = \frac{c}{-\operatorname{Im}(\omega)} = 0.24\gamma^{3/2}\sqrt{N_{bands}\frac{r_\perp^2[100\mu m]\tau[ps]}{Q[nC]}}[mm],$$

Lorentz transform of time and space between the lab and beam frames;
(longitudinal mass in the lab frame scales as γ^3)

<u>NLCTA parameters:</u>

γ=240, Q=0.3nC, $r_\perp$=100μm, τ=0.5ps, ΔE_{ind}=10keV, N_{bands}=10

the fastest growing mode has 60nm wavelength and 3.6m growth length

Saturation of instability

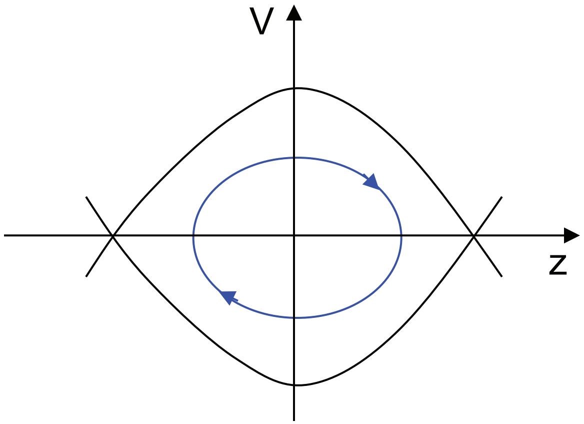
$$\omega_B = \sqrt{\frac{eEk}{m}} \sim |\mathrm{Im}(\omega)|$$

$$\nabla E = 4\pi en\frac{\delta n}{n} \quad \Rightarrow \quad E \sim \frac{4\pi en}{k}\frac{\delta n}{n}$$

$$|\mathrm{Im}(\omega)| \sim 0.1\omega_p = 0.1\frac{4\pi e^2 n}{m}$$

$$\frac{\delta n}{n} \sim 10\%$$

Strong bunching may be generated

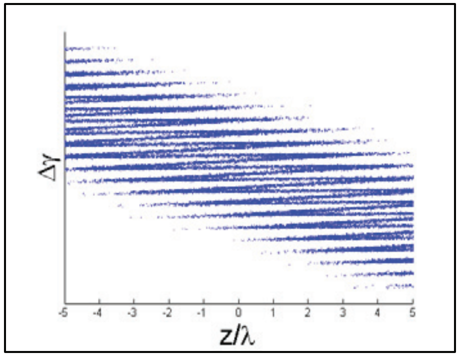


Kinetic instabilities saturate when the bounce frequency of electrons in the wave potential reaches the instability growth rate (particles mix up in the phase space faster than the change of the potential)

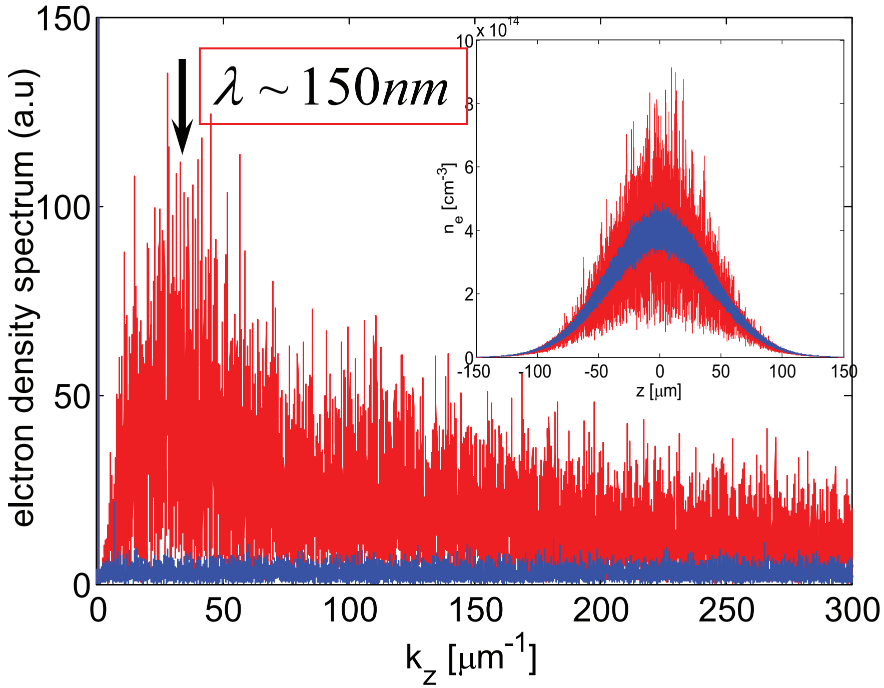
Numerical simulations

Electrostatic CPIC code was used to simulate N-stream instability in 1D.

Positrons with the same macroscopic distribution but different shot noise were added to suppress artificially large longitudinal space charge in 1D geometry



Initial electron distribution

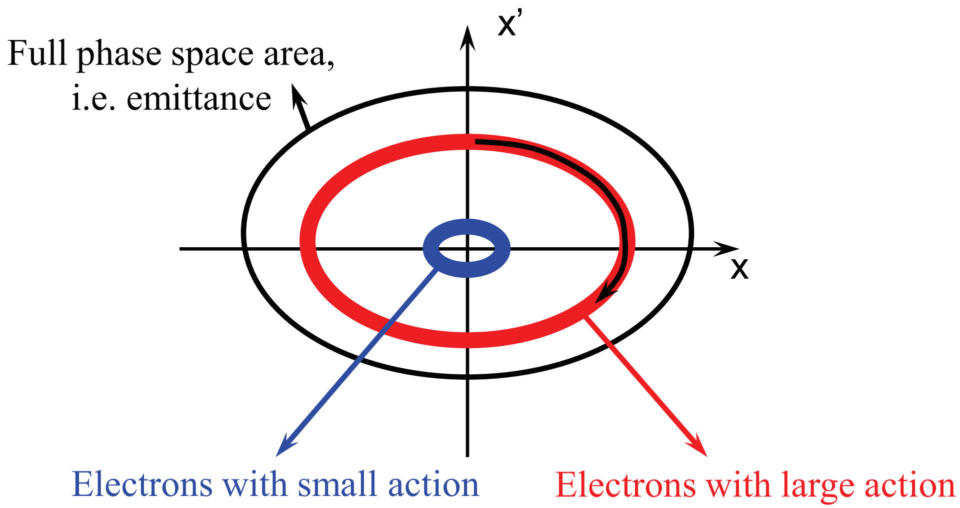


Parameters of the scheme were chosen to generate microbunching at 100nm.

Large density modulation is observed after 50m of vacuum drift

What can go wrong? *Emittance effect*

Transverse electron phase space



Electrons have different average longitudinal velocities

$$V_z = \beta c \sqrt{1-(x')^2}$$

$$\delta z \sim \delta V_z \frac{L}{c} \sim \frac{<(x')^2>}{2} L \sim \frac{\varepsilon_n^2 L}{4\gamma^2 <x^2>}$$

$\varepsilon_n \sim 1\ \mu m$
$\sigma_x \sim 100\ \mu m$
$\gamma \sim 200$
$L \sim 50m$

$\delta z \sim 30nm$

Emittance effects cause significant longitudinal slippage along the entire beamline but are small within one growth length.

What can go wrong? *Intra-beam scattering*

$$\partial_z f = D\partial^2_{VV} f$$

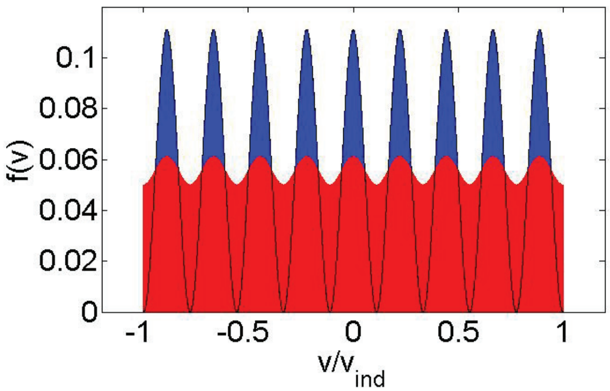
$$D = 3.1\frac{I[kA]}{\varepsilon_n[\mu m]\sigma_x[100\mu m]}\frac{keV^2}{m}$$

G. Stupakov,
"*Effect of Coulomb Collisions on Each-Enabled Harmonic Generation (EEHG)*",
Proceedings of FEL2011 Conf., 49 (2011).

$$\Delta E_{ind}[keV] >> \left(\frac{90\Lambda_{sat}N^2_{bands}r_\perp[100\mu m]}{\varepsilon_n[\mu m]\lambda[nm]}\right)^{2/3}$$

For NLCTA parameters intra-beam scattering will smear out distribution within one growth lengths of the instability

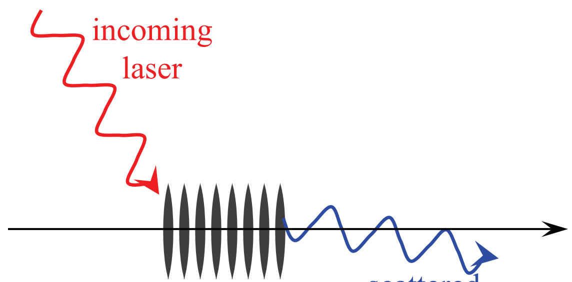
The intra-beam scattering will smear out the distribution and eliminate the source of the instability



Possible solution:

- Large emittance
- Overfocusing in strong FODO lattice

Application to Compton source



Microbunched beam can be considered as the density wave with dispersion relation

$$\omega = \beta c \cdot k$$

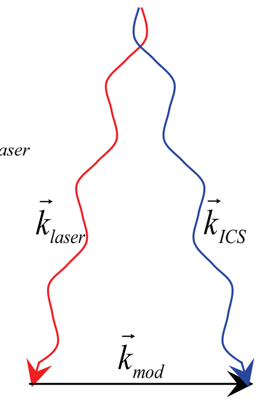
Compton scattering cane be considered then as conventional 3-wave interaction

Conventional resonant conditions between coupled waves should be satisfied which makes ICS similar to Raman scattering

<u>Beam frame resonance condition</u>

$$\omega_{ICS} = \omega_{\mathrm{mod}} + \omega_{laser} \approx \omega_{laser}$$

$$\vec{k}_{ICS} = \vec{k}_{\mathrm{mod}} + \vec{k}_{laser}$$



Scattered light will be coherent not because of the **longitudinal** coherence of bunching but because of its **transverse** coherence.

<u>Lab frame resonance condition</u>

$$\frac{1}{\lambda_{ICS}} = \frac{1}{\lambda_{laser}} + \frac{1}{\lambda_{mod}} \approx \frac{1}{\lambda_{mod}}$$

Improvement over incoherent Compton source

Peak brightness of radiation can be represented with its spectral intensity, i.e. depends on the beam bunching

$$B \propto |b_k|^2$$

$$|b_k|_{incoh} \sim \frac{1}{\sqrt{N_e}}$$

$$|b_k|_{2-stream} \sim \sqrt{\frac{\lambda}{\sigma_z}}$$

Bunching in both cases depend on the number of density spikes inside the bunch envelope

Number of photons is proportional to the beam brightness and the solid angle of radiation

$$\frac{B_{2-stream}}{B_{incoh}} \sim \frac{3.3\cdot 10^9}{\gamma^{3/2}} \sqrt{\frac{Q[nC] r_\perp^2[\mu m]}{\tau[ps]} \frac{\Delta E_{ind}[keV]}{N_{bands}}} \sim 10^5 - 10^6$$

$$\frac{(\#\hbar\omega)_{2-stream}}{(\#\hbar\omega)_{incoh}} = \frac{0.34\cdot 10^9}{\gamma^{5/2}} \sqrt{\frac{r_\perp^2[\mu m]\tau[ps]}{Q[nC]} \left(\frac{\Delta E_{ind}[keV]}{N_{bands}}\right)^3} \sim 10^2 - 10^3$$

Advantages of proposed scheme

- Inexpensive wave to generate relatively bright radiation in soft X-rays using low energy electron beams

- Potentially transverse coherence and improved longitudinal coherence compared to convention Compton source. No collimation is required

- Wide tunability through the parameters of the electron bunch and/or the angle of the incident laser

- Easy polarization control

- Multi-stream distribution of electrons is generated inside a single electron bunch. No need to merge two beams with close energies

- Energy difference between the bands can be controlled and made smaller than the energy spread of a single bunch