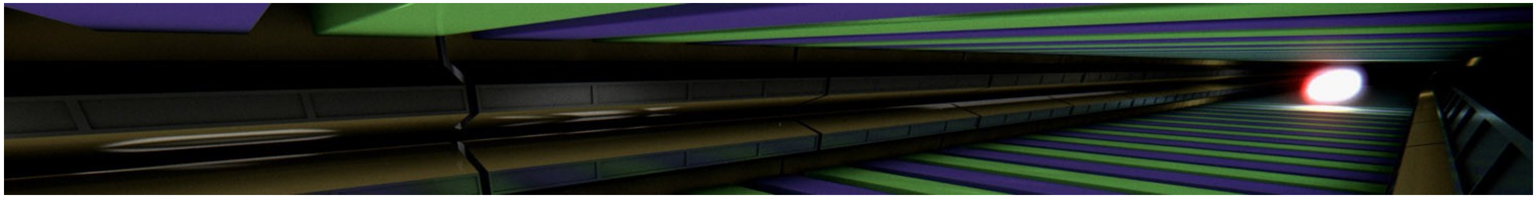

Using the longitudinal space charge instability for generation of short wavelength radiation

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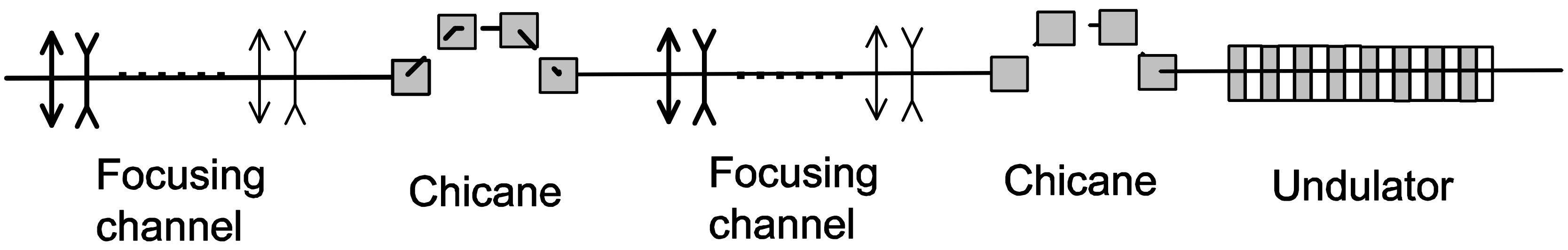
Longitudinal Space Charge (LSC) instability

- New phenomenon in beam physics
- Strong and robust effect, difficult to suppress
- Develops parasitically in non-optimized systems
- Observed in infrared and visible ranges

Why not try to consider using this effect for generation of VUV and X-rays?

Longitudinal Space Charge Amplifier (LSCA)



- Does it work in VUV and X-ray ranges?
- Can it compete with (or be complementary to) FELs?

Gain per cascade

Amplitude gain in n-th cascade:

$$G_n = Ck|R_{56}|\frac{I}{\gamma I_{\mathrm{A}}}\frac{4\pi|Z(k)|L_d}{Z_0}\exp\left(-\frac{1}{2}C^2k^2R_{56}^2\frac{\sigma_\gamma^2}{\gamma^2}\right)$$

Use γ_z for impedance calculations:

$$\frac{4\pi Z(k)}{Z_0} = \frac{2ik}{\gamma_z^2}\int d\vec{r'}_\perp \int d\vec{r''}_\perp \rho(\vec{r'}_\perp)\rho(\vec{r''}_\perp)K_0\left(\frac{k|\vec{r'}_\perp - \vec{r''}_\perp|}{\gamma_z}\right)$$

First assume no compression, C=1

Optimal wavelength

Impedance has maximum at

$$\lambda \simeq \lambda_{opt} \simeq \frac{\sigma_\perp}{\gamma_z} = \frac{\sqrt{\epsilon\beta}}{\gamma_z}$$

and can be approximated as

$$\frac{4\pi|Z|}{Z_0} \simeq \frac{1}{\lambda\gamma_z^2} \simeq \frac{1}{\sigma_\perp\gamma_z} \; .$$

Optimal R_{56} for a given wavelength:

$$R_{56} \simeq \lambda\frac{\gamma}{\sigma_\gamma}$$

Gain at the optimal wavelength

Gain is a product of the longitudinal brightness and a number of LSC formation lengths:

$$G_n \simeq \frac{I}{\sigma_\gamma I_A} \frac{L_d}{\lambdabar \gamma_z^2}$$

How long can a drift be?

$$L_d \leq min(L_1, L_2)$$

$$L_1 \simeq \lambdabar_p = \gamma_z \left(\frac{I}{\gamma I_A} \frac{4\pi |Z| k}{Z_0} \right)^{-1/2} \simeq \lambdabar \gamma_z^2 \sqrt{\frac{\gamma I_A}{I}}$$

$$L_2 \simeq \frac{\lambdabar}{\sigma_\theta^2} = \frac{\beta \lambdabar}{\epsilon}$$

Limit due to plasma oscillations

Gain is independent of wavelength if $L_d=L_1$:

$$G_n \simeq \frac{1}{\sigma_\gamma}\sqrt{\frac{\gamma I}{I_\mathrm{A}}}$$

If we decrease β (and adjust R_{56}), then wavelength and the drift get shorter, but the gain stays the same until

$$\beta \simeq \beta_{cr} \simeq \epsilon\gamma_z^2\sqrt{\frac{\gamma I_\mathrm{A}}{I}}$$

For smaller β the limit is given by emittance

Limit due to emittance

Gain is proportional to 6-D brightness if L_d=L_2:

$$G_n \simeq \frac{I}{\sigma_\gamma I_\mathrm{A}} \left(\frac{\lambda\!\!\!^{-}}{\epsilon}\right)^2$$

and It quickly decreases as $\lambda\!\!\!^{-2}$.

It might still be worth working in this limit if low beta-function is technically possible

Operation at $L_d = L_1 = L_2$

$$\lambdabar \simeq \epsilon \left(\frac{\gamma I_A}{I} \right)^{1/4}$$

$$G_n \simeq \frac{1}{\sigma_\gamma} \sqrt{\frac{\gamma I}{I_A}}$$

$$\beta \simeq \beta_{cr} \simeq \epsilon \gamma_z^2 \sqrt{\frac{\gamma I_A}{I}}$$

$$L_d \simeq \epsilon \gamma_z^2 \left(\frac{\gamma I_A}{I} \right)^{3/4}$$

$$R_{56} \simeq \lambdabar \frac{\gamma}{\sigma_\gamma}$$

Total gain at saturation

$$G_{tot} = G_1 G_2 ... G_n \simeq \sqrt{N_\lambda}$$

Power gain (increase over spontaneous emission):

$$G_{tot}^{(p)} \simeq N_\lambda$$

Numerical example

Energy 3 GeV, current 2 kA, normalized emittance 2 mm mrad, energy spread 0.3 MeV

$$\beta_{cr} \simeq 1.4 \text{ m} \quad \lambda = 2\pi\lambda\!\!\!^{-} = 15 \text{ nm} \quad R_{56} \simeq 25\mu\text{m}$$

$$L_d \simeq 20 \text{ m} \quad G_n \simeq 40 \quad N_\lambda \simeq 10^6 \quad G_{tot} \simeq 10^3$$

Instead of two long cascades it is better to take 3-5 shorter ones. For example, with 3 cascades:

$$L_d \simeq 5 \text{ m} \quad G_n \simeq 10$$

Total length about 20 m. Undulator with 50 periods and period length 5 cm: 2 % BW and GW level of power within central cone

Can be easily tunable within 7-30 nm

Wavelength compression

$$C = (1 - hR_{56})^{-1}$$

For large C: $$\frac{\Delta C}{C} \simeq C \ \frac{\Delta h}{h}$$

$$\frac{\Delta C}{C} < \frac{\Delta k_{max}}{k} \qquad \Delta k_{max} = max(\Delta k_{den}, \Delta k_{rad})$$

$$\frac{\Delta h}{h} < \frac{1}{C} \ \frac{\Delta k_{max}}{k}$$

For coherent modulations $\Delta k_{max}/k \ll 1$

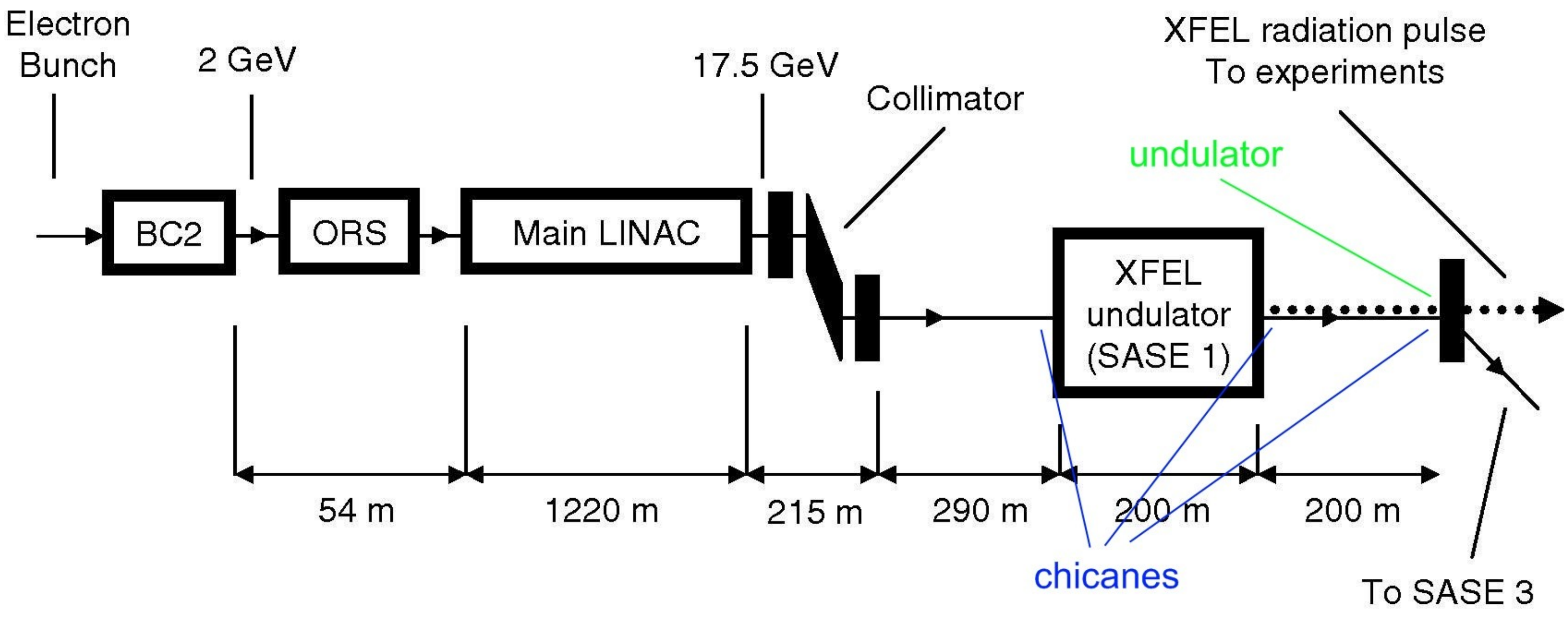
For LSCA $\Delta k_{max}/k = \Delta k_{den}/k \simeq 1$

Possible applications

- Cheap addition to existing (planned) FELs: extension towards longer WL and two-color operation for pump-probe experiments
- Generation of attosecond pulses
- Relatively broadband radiation is requested by some users
- Because of robustness it might be a good concept of a light source based on laser-plasma accelerators
- …

Cheap addition to existing (planned) FELs: European XFEL

Long drifts plus undulators themselves can be used parasitically as amplification cascades (add chicanes).



Cheap addition to existing (planned) FELs: European XFEL (cont'd)

High-current part of the bunch (3-5 kA) is spoiled by FEL saturation (too large energy spread). Use unsaturated low-current parts, about 1 kA. Beam energy 17.5 GeV, undulator tuned to 0.5 Angstroem, normalized emittance 0.4 mm mrad, energy spread 1.5 MeV. Beta in the undulator 15 m, in the drifts 30-40 m.

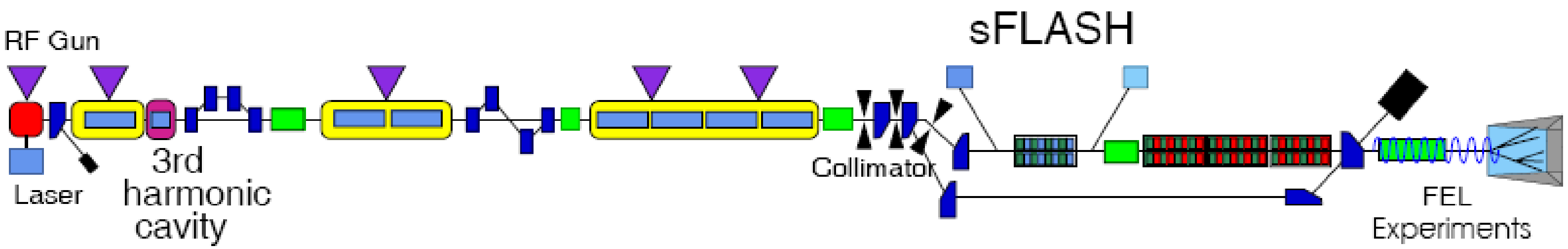
$\lambda_{opt} \simeq 4 \ \mathrm{nm}$ $\qquad$ $G_{tot} \simeq 8 \times 13 \times 5 \simeq 500$

$\sqrt{N_\lambda} \simeq 300$ $\qquad$ $R_{56} \simeq 8 \mu\mathrm{m}$

Undulator with 50 periods and period length 10 cm: 2 % BW and a few hundred MW within the central cone

Wavelength is tunable within 2-10 nm

Cheap addition to existing (planned) FELs: FLASH



1.25 GeV after shutdown

Long drift (between dogleg and undulator) plus undulator: two cascades are sufficient to saturate at 100 nm (within unspoiled parts of the bunch, at about 0.5 kA).

Production of short pulses: European XFEL

Special mode of operation: uncompressed beam (or a bit of velocity bunching, BCs off) with the current about 100 A.

Few-cycle laser (Ti:S), two-period undulator, chicane (R56=0.6 mm), energy modulation about 3 MeV.

Compression of a short slice by factor of 10, rms size of the spike about 10 nm, current 1 kA.

Amplification as described before; undulator with 5-10 periods

Wavelength is tunable within 2-5 nm, pulse duration ~100 as

LSCA and laser-plasma accelerators

The technology is progressing well:

1 GeV beams in Berkley (Leemans et al., Nature Phys., 2006)

Undulator radiation at 18 nm in Munich (Fuchs et al., Nature Phys., 2010)

FEL projects are in preparation.

Are they ready for FELs?

LSCA is much more robust than a high-gain FEL: it can survive very large energy chirps, it is less sensitive to orbit distortions. As an option one can consider WL compression (LSC induced energy chirp, dogleg instead of chicane)

LSC instability in FEL systems

- Can develop parasitically at wavelengths that are longer than a FEL wavelength
- Chicanes in FEL schemes, achromatic bends for separation of beamlines can have R_{56} that are in "optimal" range for LSC instability
- HGHG, "fresh bunch" chicanes, seeding, self-seeding schemes etc. have to be checked out
- If LSC instability develops to a significant level of density modulations, strong energy modulations (acting as local energy spread) can be induced in last parts of FELs thus hampering their operation

Conclusions

- LSC based amplifiers can operate in VUV and X-ray ranges
- They can not directly compete with FELs in terms of wavelength (but WL compression may help), power, brilliance …
- However, they can be complementary to FELs:
  - o Cheap extension towards longer wavelengths
  - o Production of the second color for PP experiments
  - o Broadband radiation (several %) is requested by some users
  - o Few-cycle pulses are possible in principle
- Due to robustness they can be used in light sources based on laser-plasma accelerators and other new technologies
- Harmful LSC instabilities at short wavelengths should be avoided in FEL systems with dispersive elements