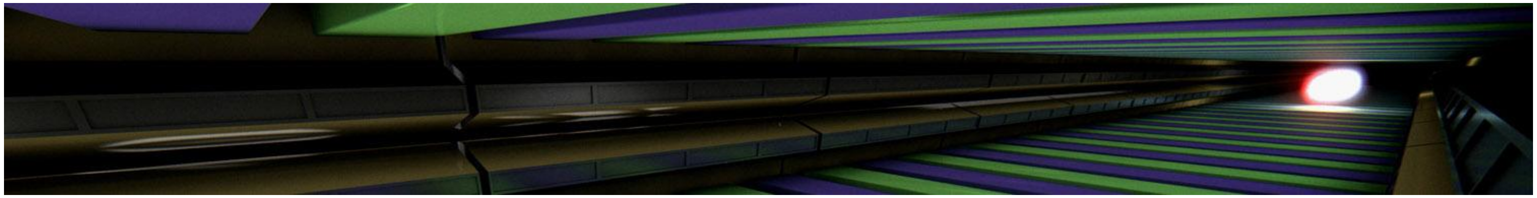


Using the longitudinal space charge instability for generation of VUV and X-ray radiation

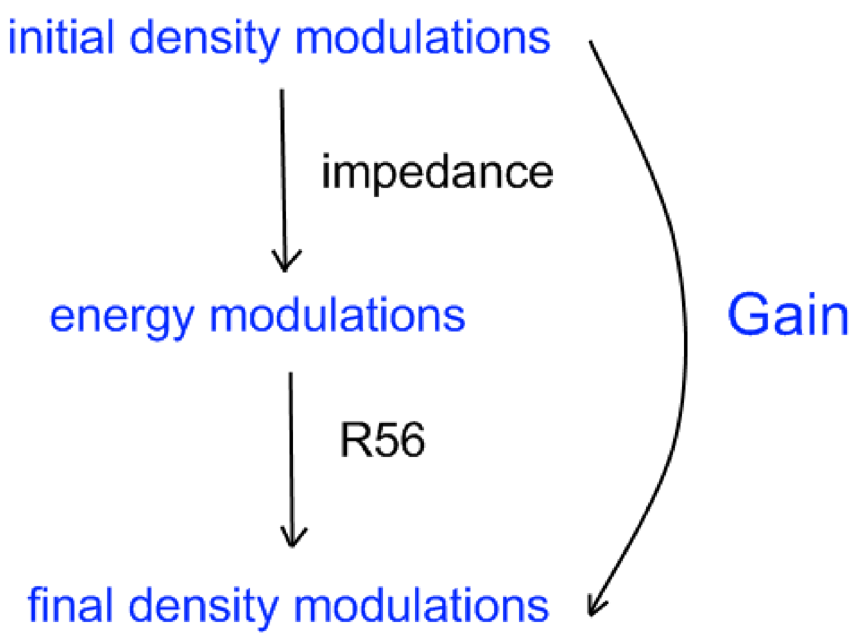
E. Schneidmiller and M. Yurkov

FEL Conference, Malmo, Sweden,

26 August 2010

Microbunching instabilities in linacs with bunch compressors

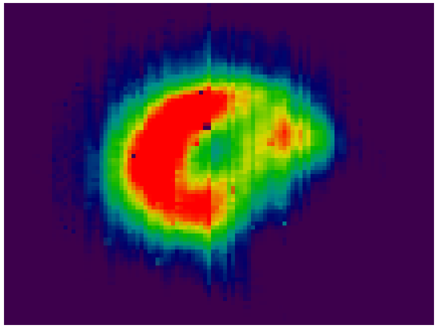
High-gain klystron-like amplifier



E. Saldin, E. Schneidmiller and M. Yurkov, NIM A483(2002)516

Longitudinal Space Charge (LSC) Instability

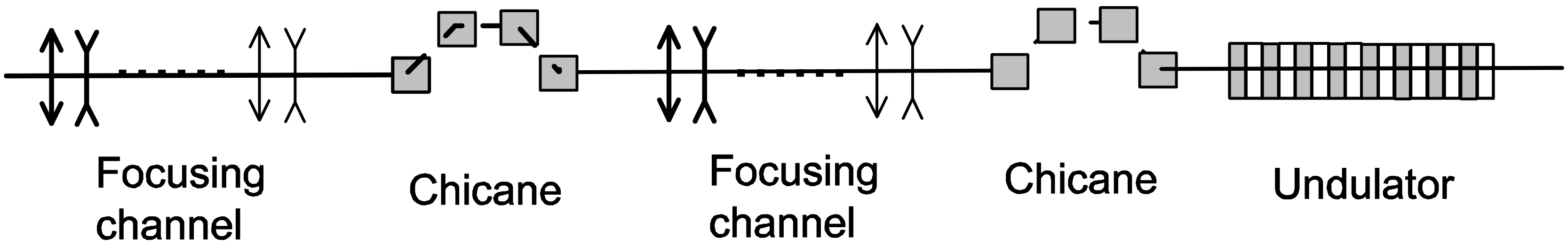
- New phenomenon in beam physics
- Harmful for beam instrumentation and FEL operation
- Strong and robust effect, difficult to suppress
- Develops parasitically in non-optimized systems
- Observed in infrared and visible wavelength ranges



S. Wesch et al., FEL'09

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 FELs? If not, are there useful applications?

Gain per cascade

Amplitude gain in n-th cascade:

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

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; CSR in chicanes is suppressed

Optimal wavelength

Impedance has maximum at

$$\lambdabar \simeq \lambdabar_{opt} \simeq \frac{\sigma_\perp}{\gamma_z} = \frac{\sqrt{\epsilon\beta}}{\gamma_z}$$

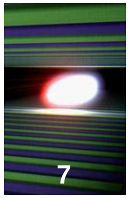
and can be approximated as

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

Optimal R_{56} for a given wavelength:

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

Gain at the optimal wavelength



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

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

How long can a drift be?

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

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

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

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 $L_d = L_2$:

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

and It quickly decreases as $\lambdabar^2$.

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):

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

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

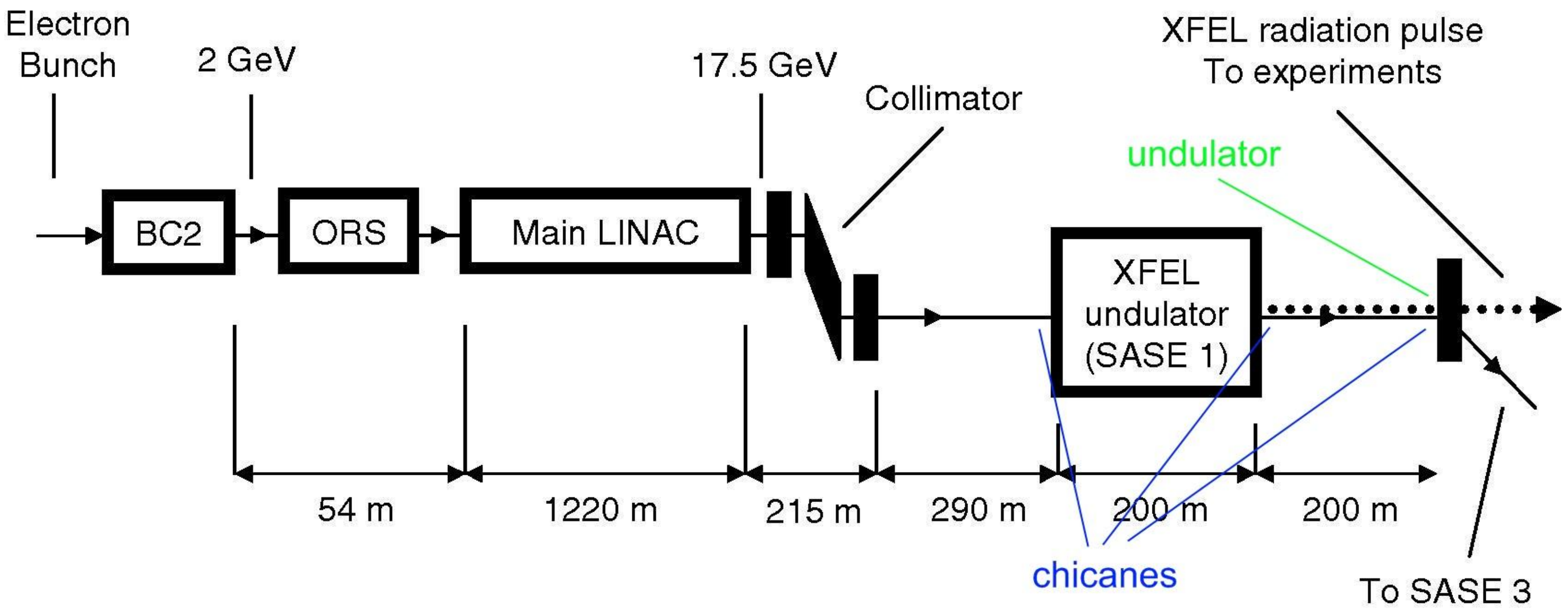
Big advantage of LSCA!

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.

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

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

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, PP experiments possible

Cheap addition to existing (planned) FELs: LCLS

- Longer wavelength limit is close to oxygen K-edge
- With present undulator it is difficult to operate in water window
- There is a long drift (about 200 m) in front of the undulator
- Optimizing optics, installing 3 small chicanes (R56 is a few microns) and a few meter long undulator for operation in water window
- Dedicated use of e-beam

Generation of attosecond pulses

Broadband nature of the amplifier supports generation of few-cycle pulses.

Different options:

1. Create current bump as in current-enhanced SASE scheme (Zholents); works in VUV and soft X-ray ranges
2. First cascades of LSCA work as usual, but then in front of the last chicane the beam is modulated by few-cycle laser (Ti:S) in two-period undulator. WL is compressed within very short part of the bunch. This compressed WL is in resonance with the radiator undulator.
3. Seeding in a few-period undulator by attosecond VUV pulses, obtained by HHG in gases. Short few-cycle density modulations can be amplified through LSCA without lengthening.
4. …

Attosecond pulses can be also produced in VUV (difficult with FELs)

Generation of attosecond 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, 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)

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:
  - Cheap extension towards longer wavelengths
  - Production of the second color for PP experiments
  - Broadband radiation (several %) is requested by some users
  - Few-cycle pulses are possible
- Due to robustness they can be used in light sources based on laser-plasma accelerators and other new technologies