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Superradiance for X-ray Production

Worskhop “Shaping the Future of the EXFEL: Options for the SASE4/5 Tunnels”
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Contents

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Introduction

- XFELs are cutting-edge research tools that produce transversely coherent radiation with peak powers of 10-100 GW and pulse durations of the order of 10 fs or shorter

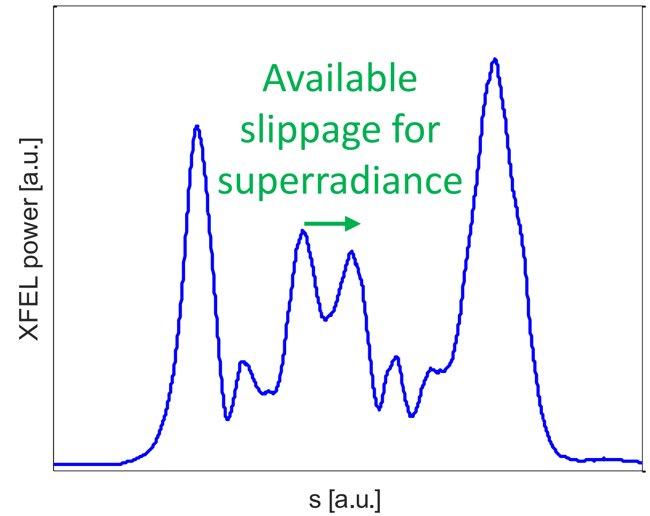
- There is strong demand to achieve higher pulse powers and/or shorter pulses (for e.g. bioimaging and non-linear optics).

- There are already some good ideas to achieve short electron pulses, e.g. ESASE, slotted foil, tilted beam, etc.

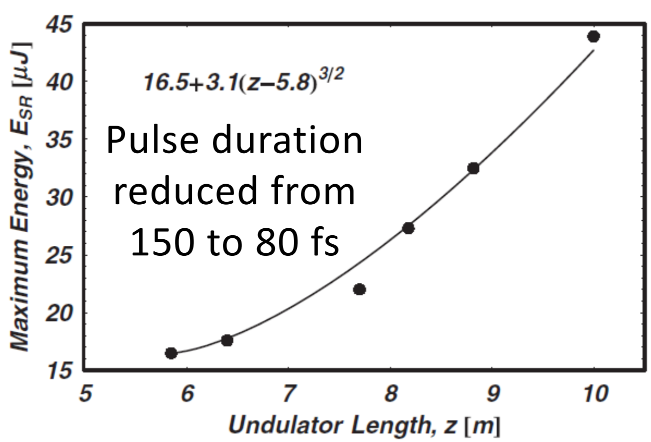
- Superradiance is a regime in which the pulse energy is increased (*beyond FEL saturation*) and the pulse duration is shortened at the same time. Schemes based on superradiance can potentially achieve TW sub-fs FEL pulses.

Superradiance

- Regime after exponential growth where there is a quadratic increase of the FEL power and a shortening of the pulse length
- Scaling: $E \propto Z^{\frac{3}{2}}, \sigma \propto Z^{-\frac{1}{2}}, P \propto Z^{2}$
- In SASE the growth severely reduces when the slippage equals the separation between 2 spikes, i.e. when the radiation spike interacts with degraded electrons
- To keep the superradiance one can shift the radiation pulse to a bunch region with fresh electrons before the slippage is too long



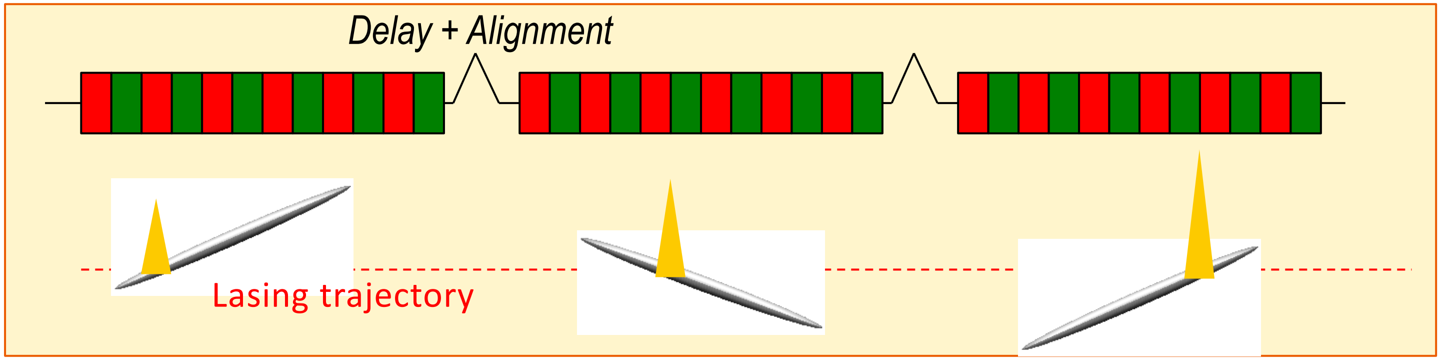
- It is an old concept *[R. Bonifacio et al, NIM A 296, 358, 1990], [R. Bonifacio et al, PRA 44, R3441, 1991]…*
- … demonstrated for λ~800 nm ~10 years ago: *[T. Watanabe et al, PRL 98, 034802, 2007]*



Superradiance amplification in XFELs

- How it works:
  1. The tail of the electron bunch generates a short FEL pulse
  2. This short pulse is later amplified with the rest of the bunch in several stages
- Key components:
  - Magnetic **chicanes** between the undulator modules to shift the FEL pulse to fresh parts of the electron bunch
  - "**Fresher**" to provide fresh electrons. This is done by tailoring some beam property (current, emittance, orbit)

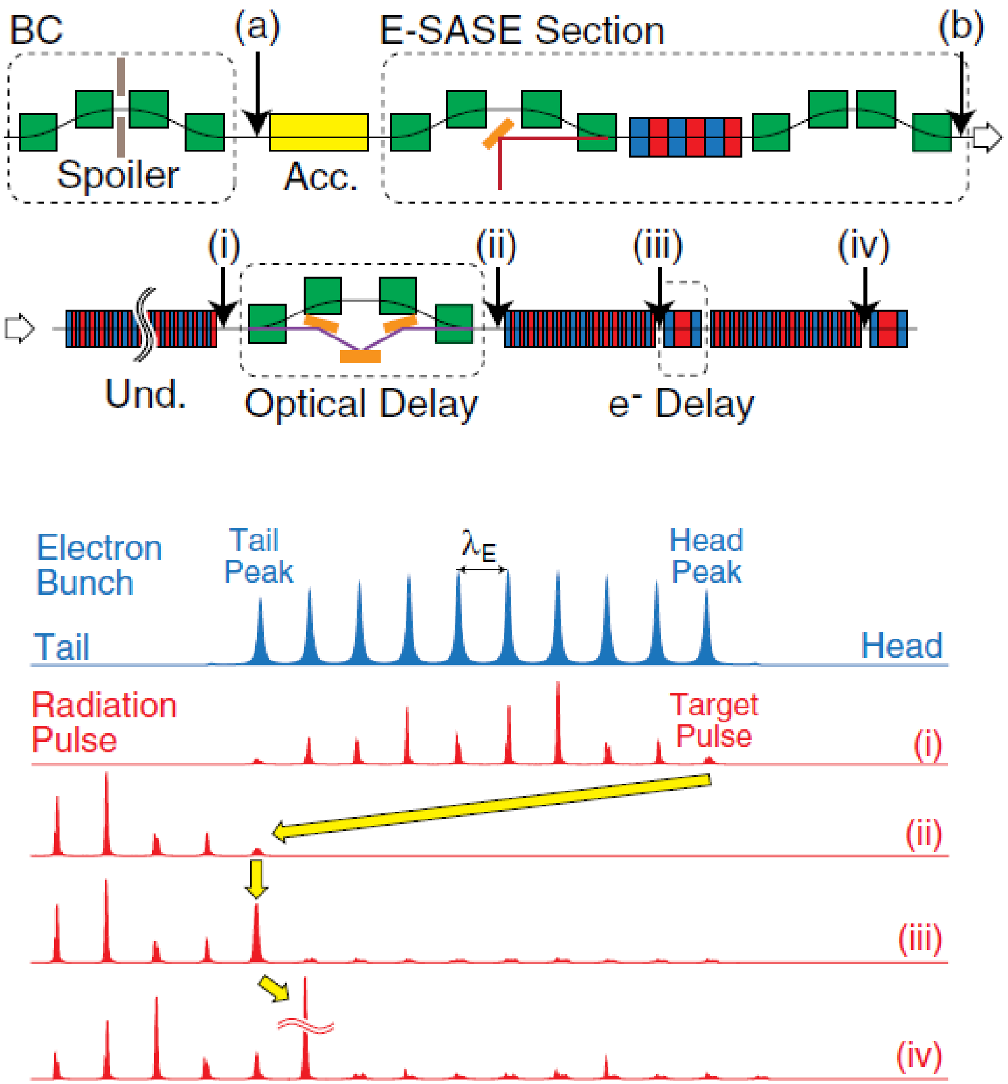
Example with orbit (transverse tilt)



- Bonus: more relaxed parameters since lasing occurs locally (e.g. energy chirp is ok, wakefields are less a problem so higher currents are possible)
- The practical limit for amplification is the length of the electron bunch or the length of the undulator beamline.

First idea: regularly-spaced current peaks

[T. Tanaka, PRL 110, 084801, 2013]

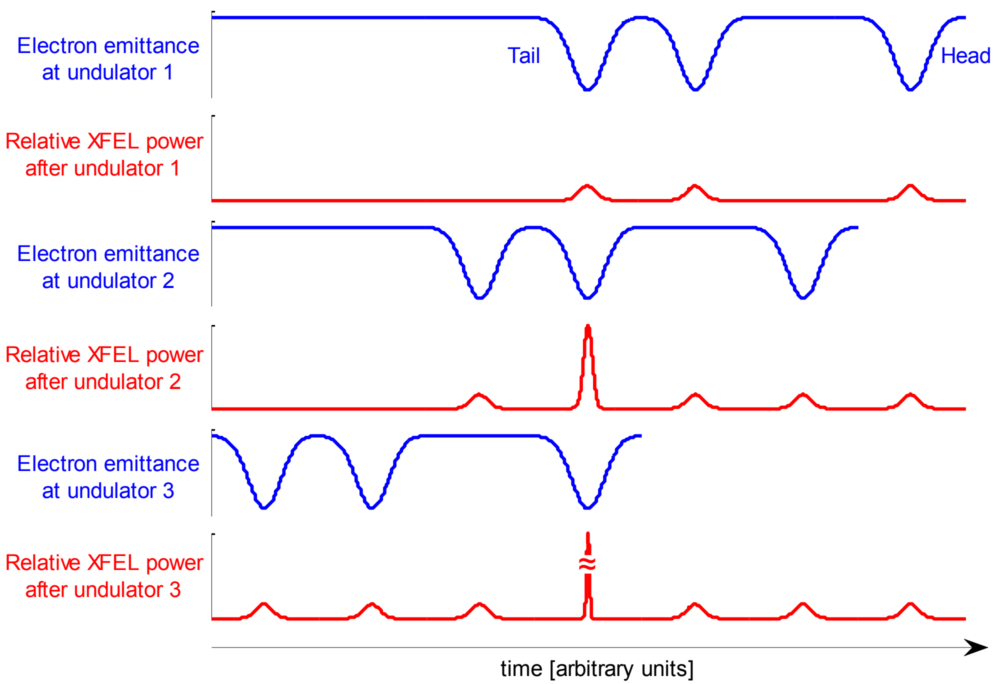


- Based on E-SASE *[A. Zholents, PRSTAB 8, 040701,* 2005]: a laser induces energy modulation that is converted to density modulation in the chicane
- What happens in the undulator:
  I. A pulse train is generated by normal SASE process
  II. Delay the FEL such that the target pulse matches the tail peak
  III. Enhance the target pulse
  IV. Delay the electrons to position the target pulse at a next fresh current peak
  V. Repeat (iv) until the target pulse arrives at the leading current peak

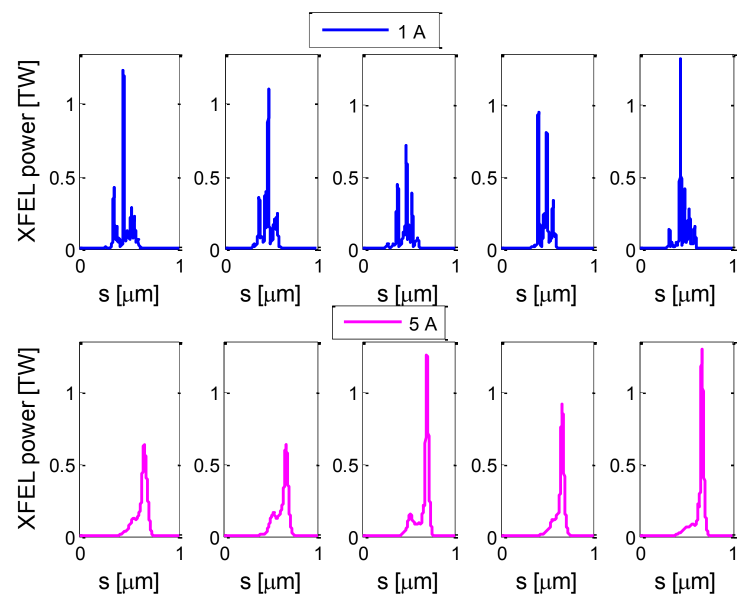
- Simulations show that TW sub-fs pulses can be achieved for hard X-rays
- Time-locking is possible (laser)
- Very complicated: E-SASE, optical delay, etc.
- Satellite pulses are not insignificant

Make it simpler with a multiple-slotted foil

[E. Prat and S. Reiche, PRL 114, 244801, 2015]



- Based on slotted foil idea to spoil the emittance of part of the bunch ([*Emma et al, PRL 92, 074801, 2004*]) demonstrated at LCLS.
- Position of the slots defines which slices of the bunch lase
- Multiple-slotted foil with **uneven separation** between slots allows superradiance amplification (no need for photon delay)

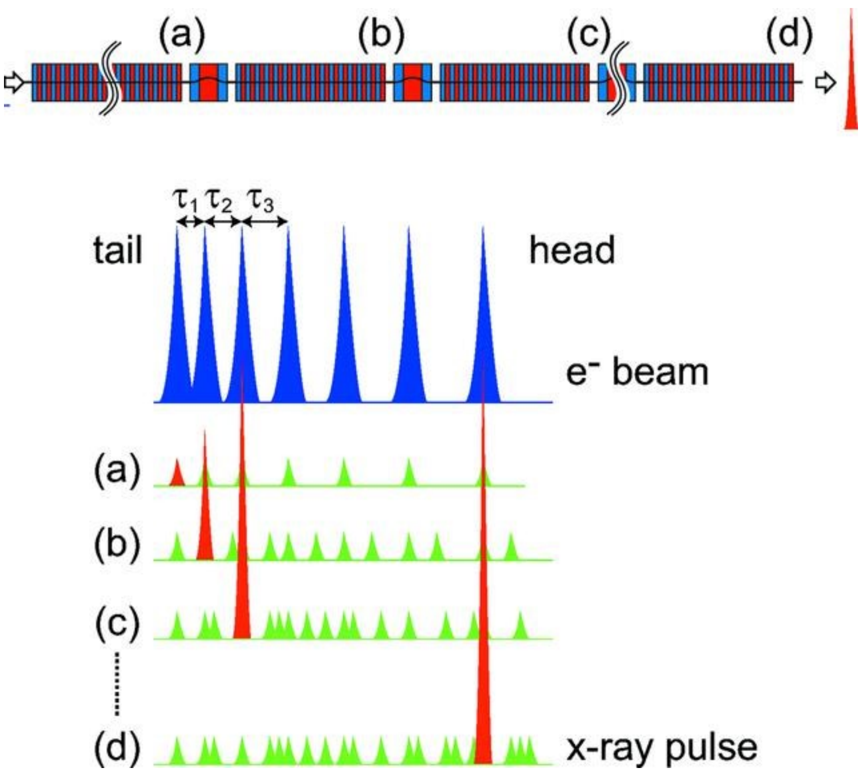


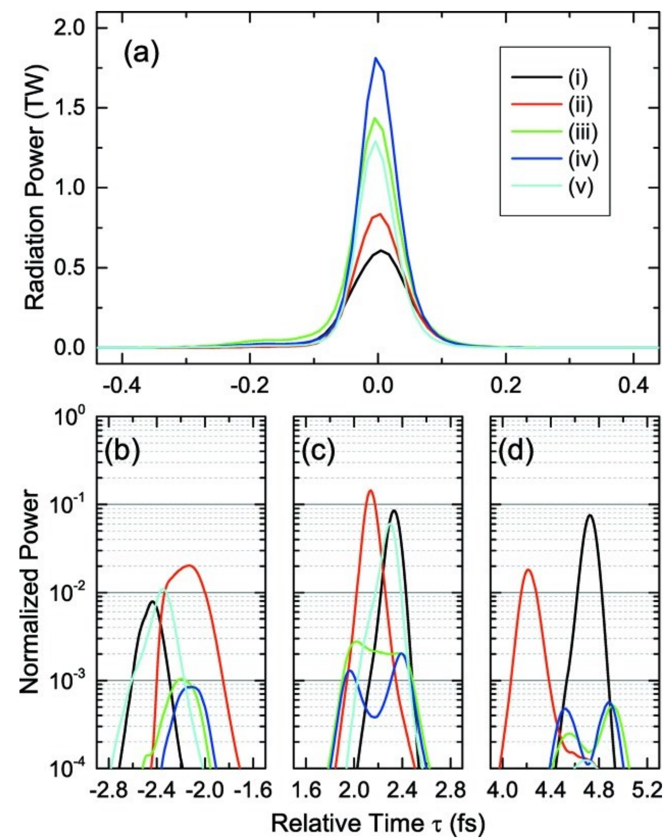
- Simulations for SwissFEL: TW-sub fs FEL pulses can be achieved for 0.1 nm (in 80 m of undulator) and 0.5 nm (in 40 m)
- Simple method, no major hardware
- No time-locking

Improved scheme using current peaks

- Use **irregular spacing** of the current peaks! This avoids the photon delay and reduces the intensity of the satellite pulses
- The irregular spacing is obtained with a chirped laser or pulse stacking
- Much simpler than original idea but still not simple
- Laser allows time-locking
- Simulations for SACLA: TW sub-fs pulses can be achieved for hard X-rays in 120 m

[T. Tanaka et al, JSR 23, 1273, 2016]





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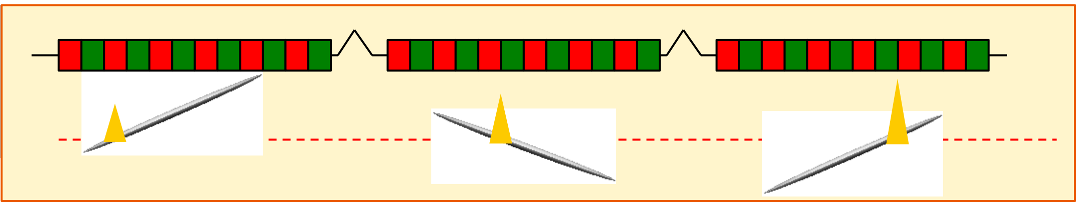
Make it more efficient with a beam tilt

[E. Prat et al, PRSTAB 18, 100701 (2015)]



Simulation results for SwissFEL

20 modules (x 2m), 2 nm, 6 kA, 8 sections

(error bar show deviation over different shots)

Tilt in offset (mm)	Peak power (TW)	Pulse energy (mJ)	FWHM pulse duration (as)
1.5	1.62±0.58	1.01±0.24	460±260
3	1.48±0.20	0.52±0.05	300±10

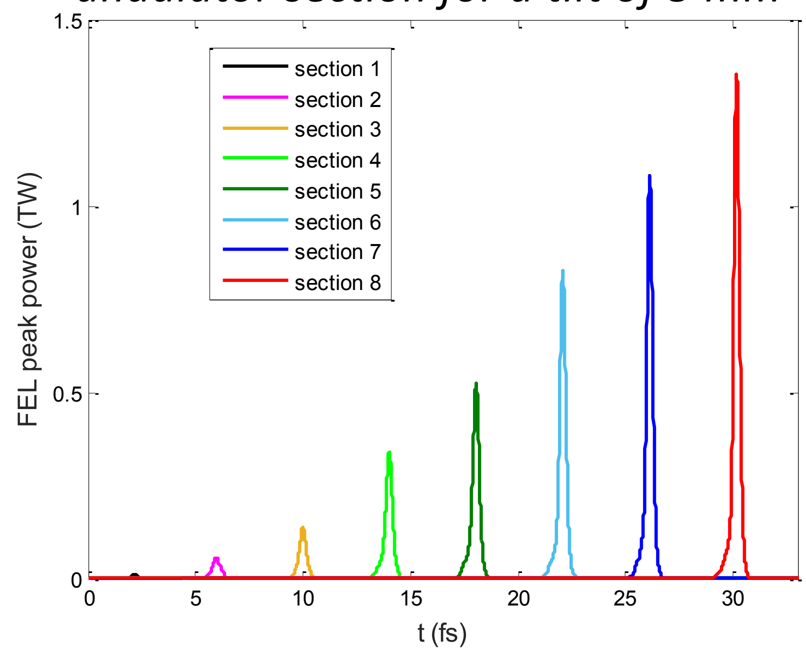
TW sub-fs pulses for soft and hard X-rays

By tuning the tilt amplitude one can choose shorter pulses with less energy or longer but more energetic

Alternative: induce mismatch along the beam *[Y. Chao et al, PRL 121, 064802, 2018]*. But difficult to make more than 2 stages and it requires matching sections.

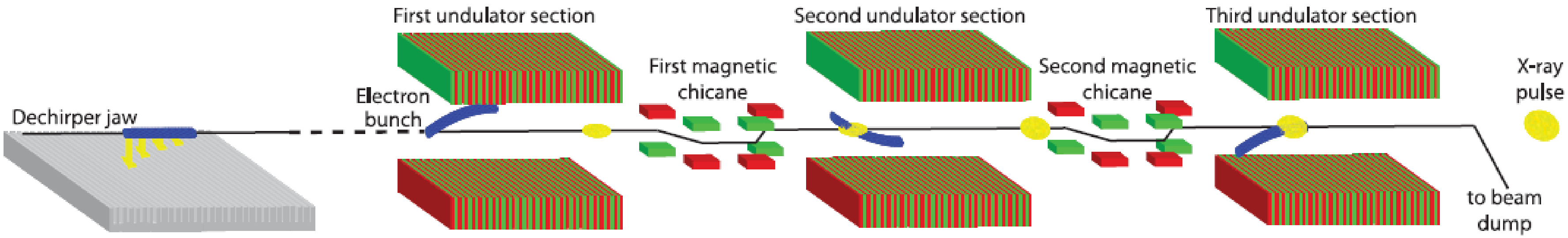
- The whole bunch can be used if the fresh slices are defined with the orbit (beam tilt)
- Very efficient, no satellite pulses
- No time-locking
- Large beam in the undulator can generate losses and is sensitive to wakefields

FEL radiation profile after each undulator section for a tilt of 3 mm

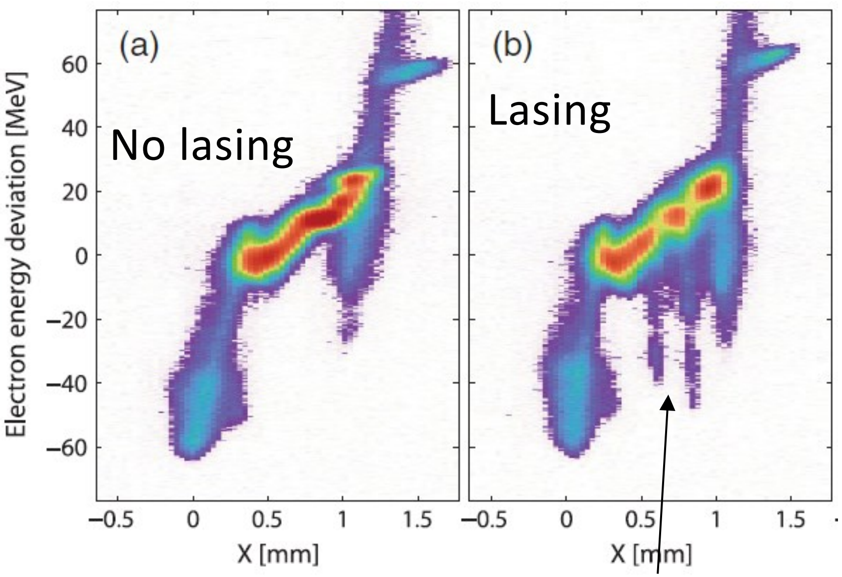


Experimental demonstration at LCLS

[A. Lutman et al, PRL 120, 264801, 2018]



XCAV diagnostics



Lasing of 2nd and 3rd stages

time

- 670 eV
- Only with 3 stages (2 chicanes)
- Tilt generated with wakefields
- FEL pulses with few hundreds of μJ and few fs were produced
- 85 % of the shots had 1 (13%), 2 (36%) or 3 (36%) spikes.

“For single-spike spectra x-ray pulses the pulse power is increased more than an order of magnitude compared to other techniques in the same wavelength range”

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Summary of the different methods

- All methods require chicanes between modules
- The difference is in the "fresher" (how to provide the fresh electrons):
  - Uneven separation of peak current or emittance
  - Continuous separation of orbit

Tailored property	Difficulty to implement	Efficiency	Time-locking	Contrast with noise
Current	Hard (ESASE section)	< 50%	Yes	Good
Emittance	Easy (slotted foil)	< 50%	No	Good
Orbit	Moderate (tilt)	100 %	No	Best

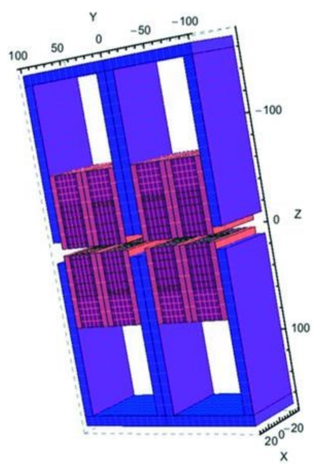
- The most promising method is the one based on the orbit:
  - It is efficient and offers the best contrast with noise
  - It is not difficult to implement
  - It has already been partially demonstrated
  - The tilt can be used for other modes
  - It is the easiest for high-repetition machines

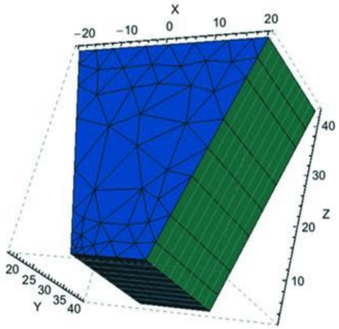
Inter-undulator chicanes

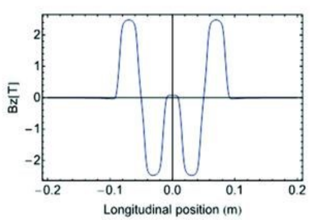
Chicanes between the undulator modules are required in all methods

As compact as possible → permanent magnets

For SwissFEL, 20 cm long chicanes can delay a 3 GeV beam by 5 femtoseconds



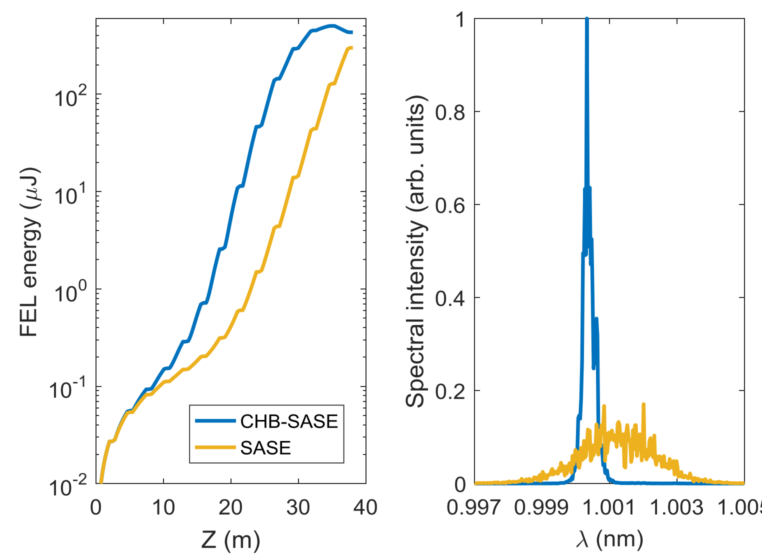




Chicanes can be used for other purposes:

1. Reduce saturation length with R_{56} (optical klystron effect, *[P. Elleaume, JPC 44, C1-333, 1983]*)
2. Increase brightness with delay (High-Brightness SASE scheme, *[B. McNeil et al, PRL 110, 134802, 2013])*

Simulations for SwissFEL for 1 nm. With respect to SASE, brightness is improved by ~10, saturation length is reduced by ~30%.



Beam tilt generation

The transverse tilt can be generated with:

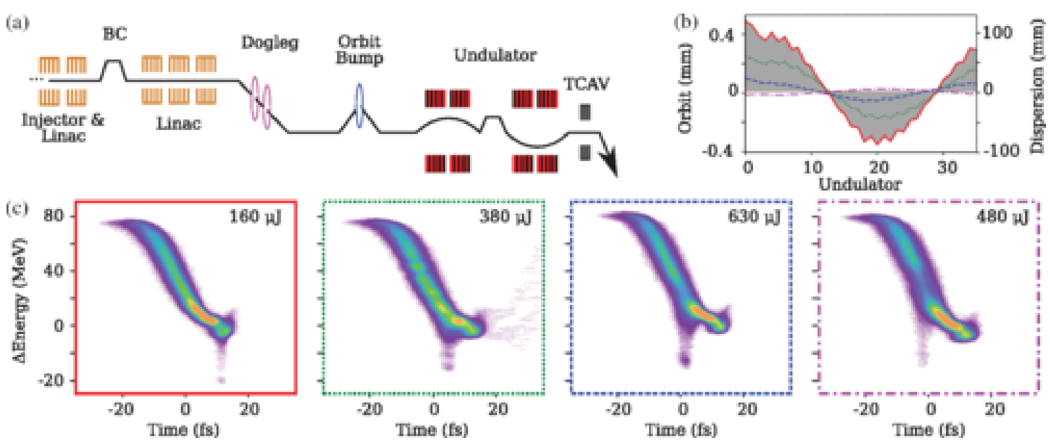
- Transverse deflecting structures
- Transverse wakefields
- Introducing dispersion to an energy chirped beam

Each method has its pros and cons (see *[E. Prat et al, NIMA 865, 1, 2017]*)

The beam tilt can also be used for other special modes:

- Fresh-bunch self-seeding *[C. Emma et al, Appl. Phys. Lett. 110, 154101, 2017]*
- Fresh-bunch two colors *[A. Lutman et al, Nat. Phot. 10, 745, 2016]*
- Large-bandwidth with a transverse-gradient undulator *[E. Prat et al, JSR 23, 874, 2016]*

At LCLS, tilt is normally generated with wakefields (of the “dechirper”).
LCLS also demonstrated the dispersion method (best for high-rep machines): *[M. Guetg et al, PRL 120, 264802, 2018]*

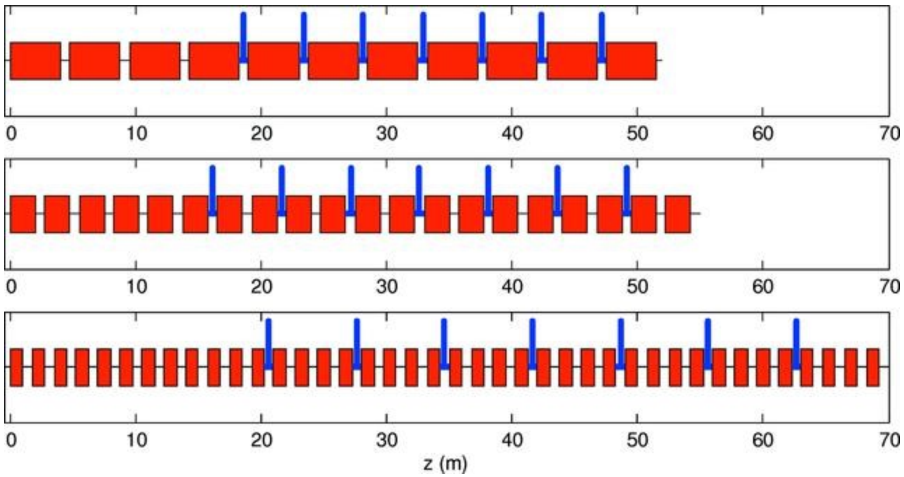


Optimization of undulator module length

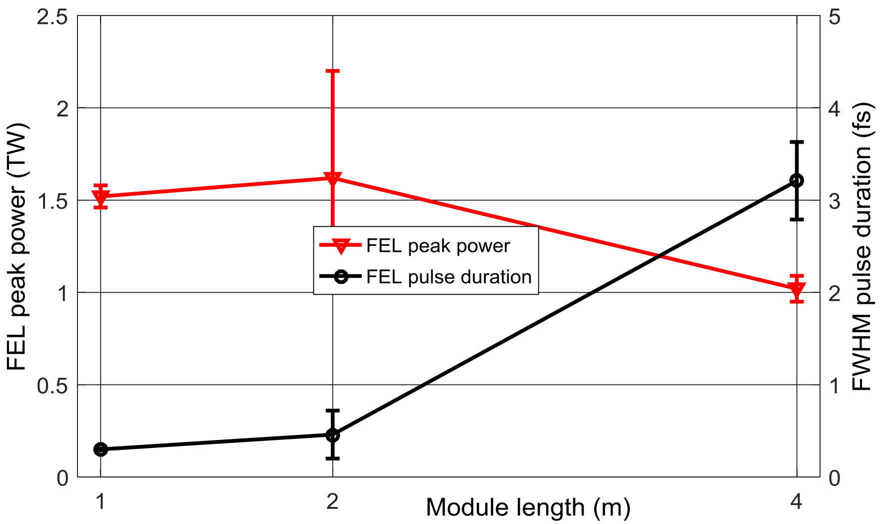
- The length of the undulator modules should be optimized for best performance
- Superradiance schemes may benefit of shorter modules than standard ones
  - delays can be applied more often
  - beta-function can be smaller (same tilt has higher effect)

- Simulations for SwissFEL for 2 nm, module lengths of 4, 2 and 1 m (1.5 mm tilt): modules of 2 m or shorter are required to reach sub-fs pulses.

Layouts



Results



Shorter modules are also beneficial for other modes such as HB-SASE and optical klystron

[E. Prat et al, JSR 23, 861, 2016]

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Conclusion

- XFEL users would benefit from higher FEL power and shorter pulses than the ones obtained at state-of-the-art facilities → superradiance can give that!
- Superradiance consists in amplifying a short FEL pulse with different fresh parts of the electron beam. This requires:
  - Chicanes between modules (useful for other purposes!)
  - "Fresher" (uneven separation of current peaks or emittance, or beam tilt).
- Simulations show that TW sub-fs can be achieved
- The method based on beam tilt seems the most promising and it has been partially demonstrated at LCLS
- Beam tilt can be achieved with different methods, it's useful for other purposes!
- Optimum performance may require shorter undulator modules

- Thanks to all of you for your attention!