PSI Center for Accelerator Science and Engineering

Attosecond Pulses from X-ray Free-electron Lasers: Status and Outlook

SPS-Meeting

Sven Reiche
Zurich, September 2024

Outline

- FEL Principle
- Slippage (Information Propagation) in Free-Electron Lasers
- Demonstrated Methods
  - Short Electron Bunches
  - Slicing
- Proposed Advanced Methods
  - Strong Superradiance
  - Multi-Stage Synthesis
- Conclusion

FEL Principle

Free-Electron Lasers: Undulator – the Coupling Element

Injection of a relativist electron bunch (**2**) into the periodic magnetic field of an undulator (**1**), defined by its period λ_u and strength *K*, to emit radiation (**3**).

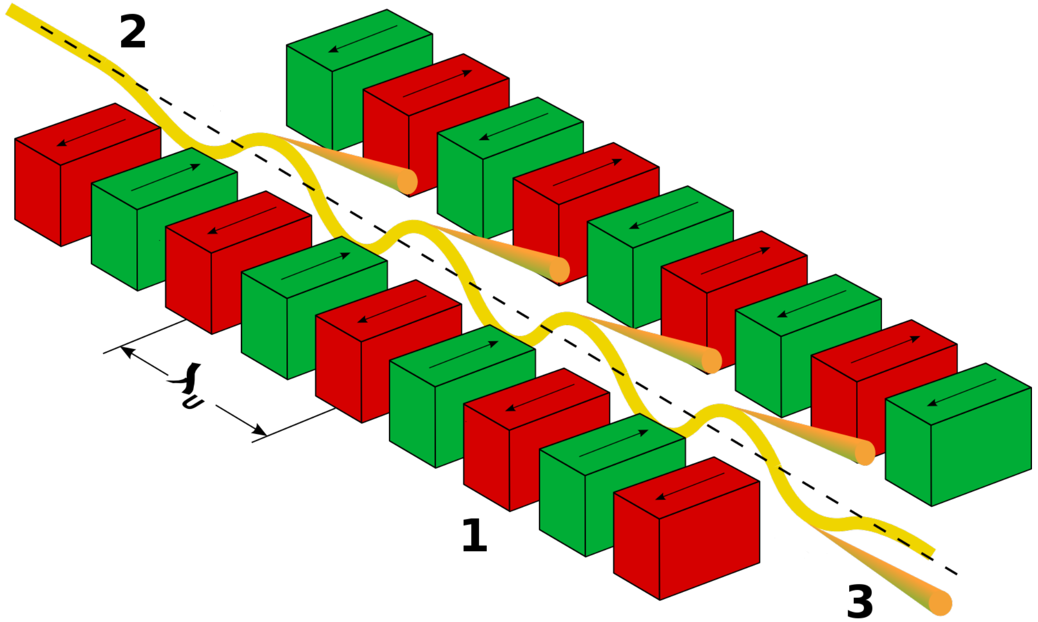
The resulting transverse wiggle of the electron causes:

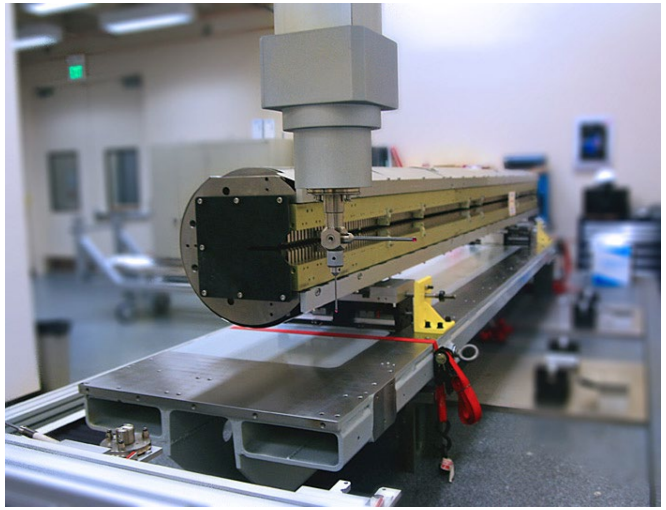
1) The emission of radiation (strongly blue shifted in the forward direction):

→ ***Electrons emit radiation***

2) The coupling to a co-propagating radiation field due to the transverse velocity components of the electron motion:

→ ***Radiation alters energy distribution of electron beam***





Undulator module from LCLS (SLAC, USA) – the first hard X-ray FEL

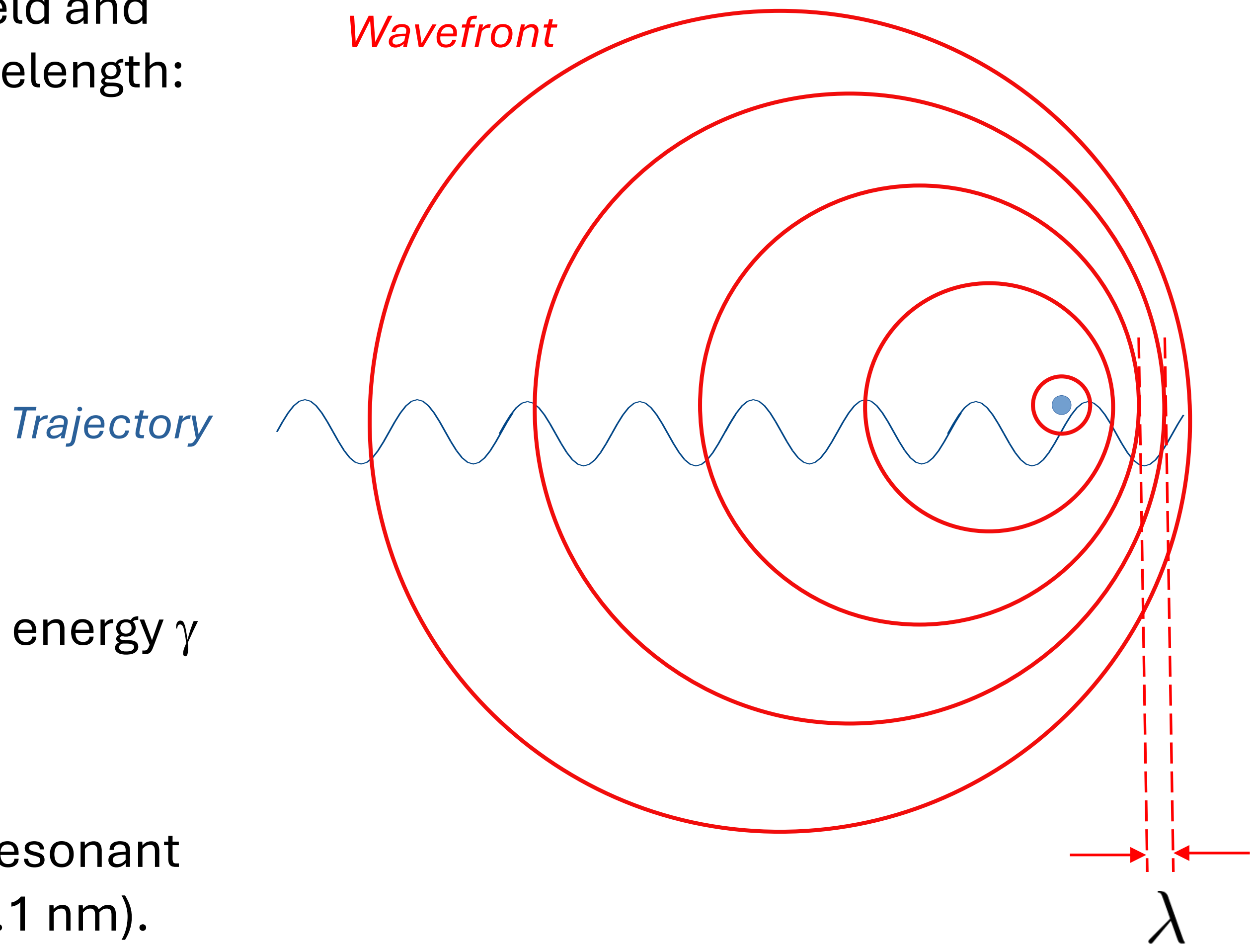
Free-Electron Lasers: Controlling the Wavelength

The run-time difference between radiation field and the electron bunch defines the resonant wavelength:

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

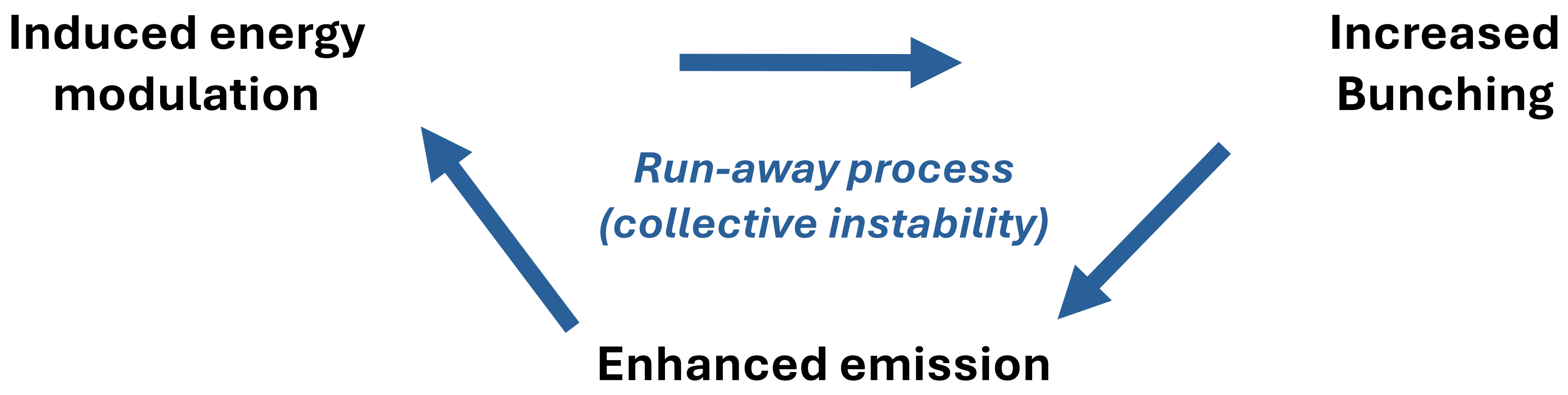
The wavelength can be tuned by the electron energy γ and the undulator field strength *K*.

For beam energies of 5 GeV and above, the resonant wavelength is of the order of 1 Angstrom (= 0.1 nm).



Free-Electron Lasers: The Collective Instability

- If enough electrons can stay in resonance (high current, little energy spread), the emitted radiation accumulates to a level it induces a noticeable energy modulation in the electron beam.
- With a periodic energy modulation electrons with higher energies become faster, those with lower energies fall back, and they tend to bunch together (micro-bunching)
- The bunches exhibit a growing coherent emission, strengthening the radiation field further.

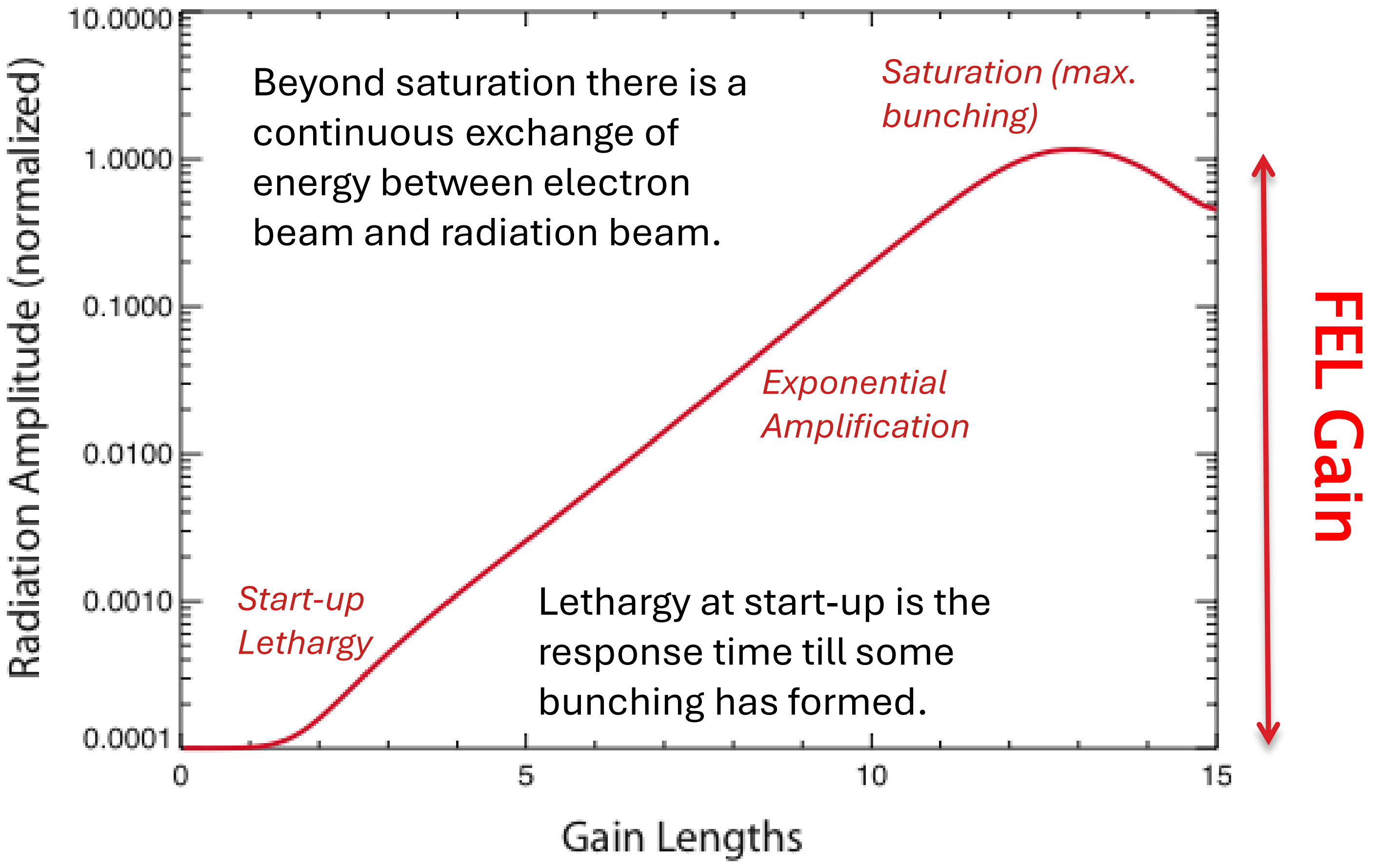


Bunching, energy modulation, and radiation field grow exponentially

The Generic FEL Process

The characteristic length scale of the exponential growth is the **gain length**. It requires an undulator with a length longer than 15 gain length to reach saturation.

The process ends (saturation) when the maximum number of electrons are pushed together



Electron Motion (Energy Modulation and Bunching)

Animation shows the longitudinal phase space as well as view of the electron bunch from the top over a slice of 4 wavelengths using SwissFEL Aramis parameters (radiation at 0.1 nm for a 52 m long undulator and a 6 GeV beam)

Self-Amplified Spontaneous Emission FEL

At short wavelength there is no powerful seeding source to start the FEL. Instead the FEL starts from the spontaneous undulator radiation.

It arises from fluctuation in the current distribution due to the finite number of electrons, forming some localized ‘hot spots’ of bunching with a small amplitude.

There exist many ‚hot spots‘ in an electron beam, which are not correlated to each other in amplitude or phase (nature of incoherent emission).

However the bunching information is **spread out**:

- Longitudinally by slippage (one radiation wavelength per undulator period)
- Transversely by diffraction

For typically 2000 undulator periods the longitudinal slippage is limited in its effects of spreading the bunching information (e.g. 200 nm for 1 Angstrom radiation) when compared to an electron bunch length of 20 micron.

SASE FEL pulse exhibits many independent modes (spikes) and is prone to fluctuations from shot to shot.

Evolution of SASE Profile

- Simulation for soft X-ray beamline Athos at SwissFEL at 250 eV
- Temporal profile is almost preserved in its shape while growing exponentially and slipping forward.
- Slippage of radiation spikes is slower than one wavelength per period (*group velocity of a signal in a dispersive medium!*)
- Note that the average spike durations is less than 1 fs at 250 eV and they are even shorter for higher photon energies (even less slippage)

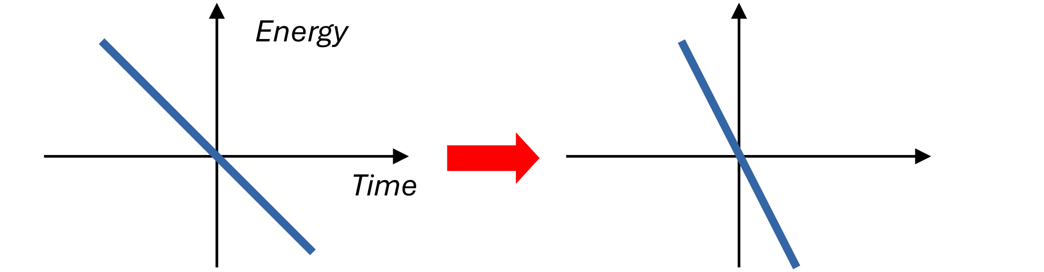
Can we pick a single spike for attosecond pulses?

Demonstraded Methods of Attosecond Pulse Generation

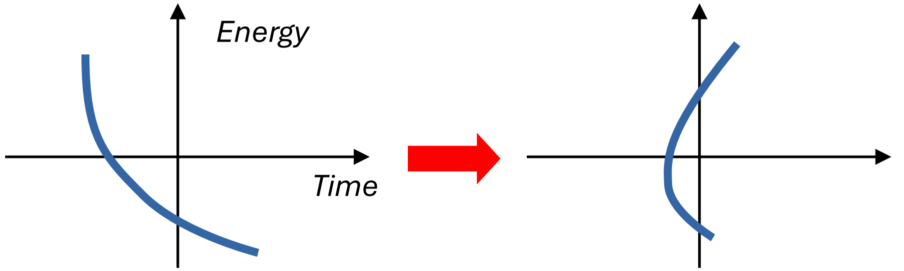
Short Electron Bunches by Non-Linear Compression

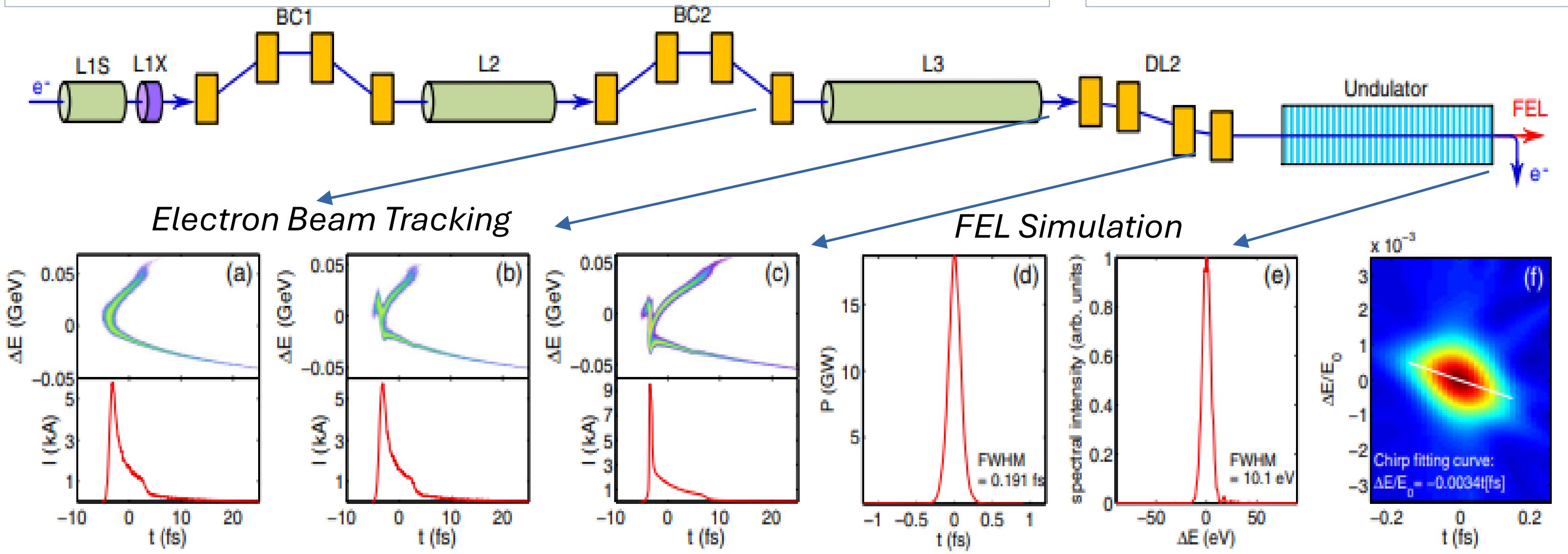
In FELs the electron bunch is compressed in bunch compressors (BCs) to increase beam current by time-of-flight difference in magnetic chicanes due to different beam energies (electrons with higher energies can catch up)

Linear Chirp in Energy



Linear + Quadratic Chirp in Energy





Non-linear compression causes a leading current spike with a length below 1 fs, which then defines the lasing part

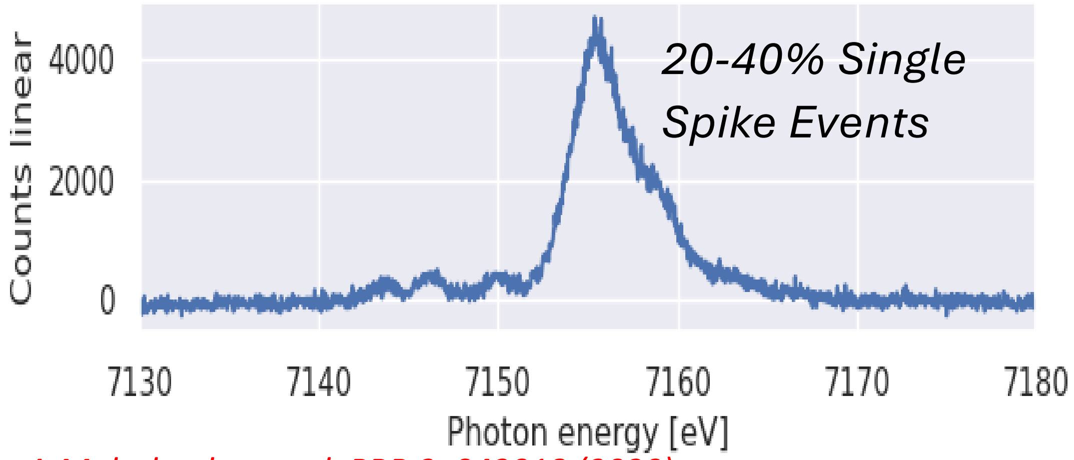
First demonstration at LCLS.

Key observable: single spike in photon spectrum

S. Huang et al, PRL 119, 154801 [2017]

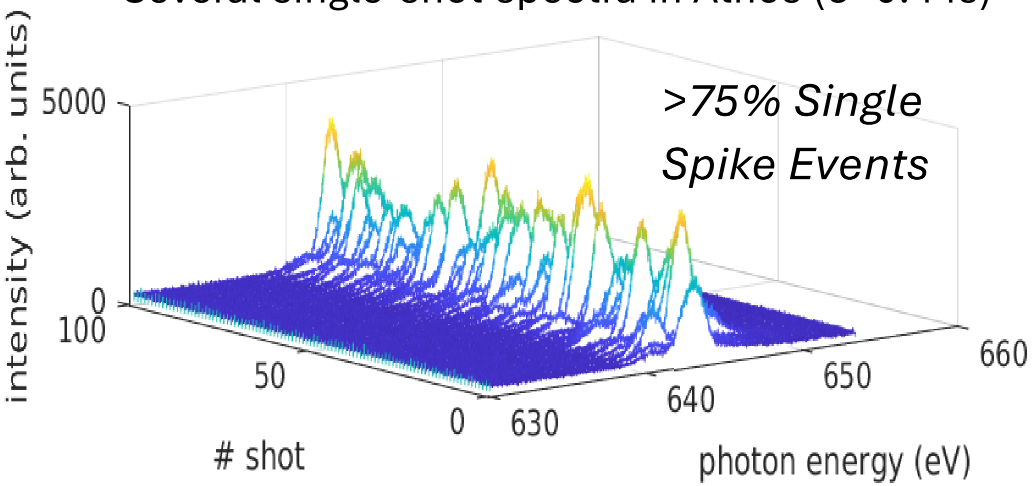
Demonstration at SwissFEL

Single shot spectrum in Aramis (σ<0.2 fs)



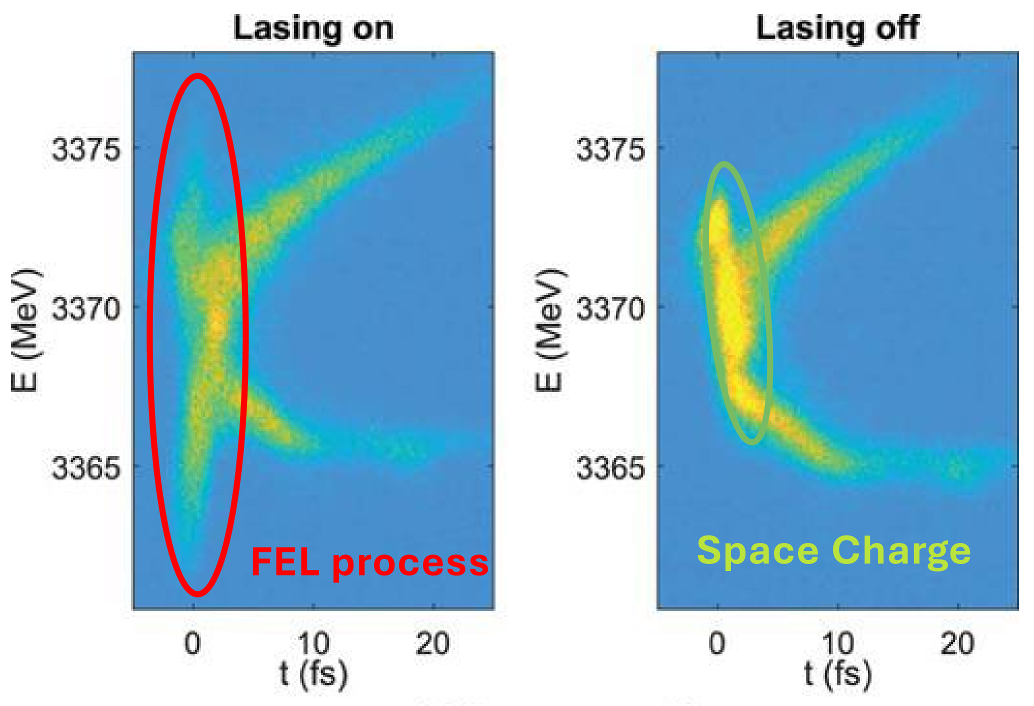
A.Malyzhenkov et al, PRR 2, 042018 (2020)

Several single-shot spectra in Athos (σ<0.4 fs)



E. Prat et al, APL Photonics 8, 111302 (2023)

Time-resolved **measurements** of imprint of FEL process on electron bunch with X-band in Athos (limited by resolution)



Current spike is prone to strong space charge forces, building up a strong energy chirp over the current spike.

In hard X-ray bunch is still too long: Events with more than one spike occurs more frequent.

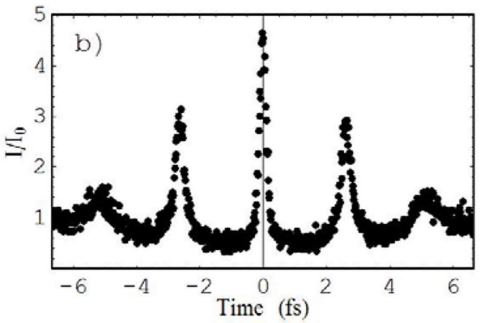
Slicing the Electron Beam

Slicing selects a subsection of the electron beam to provide FEL lasing while suppressing lasing in the other parts.

Current Spike

A local ripple in energy is used to locally compressed the beam to a high current spike.

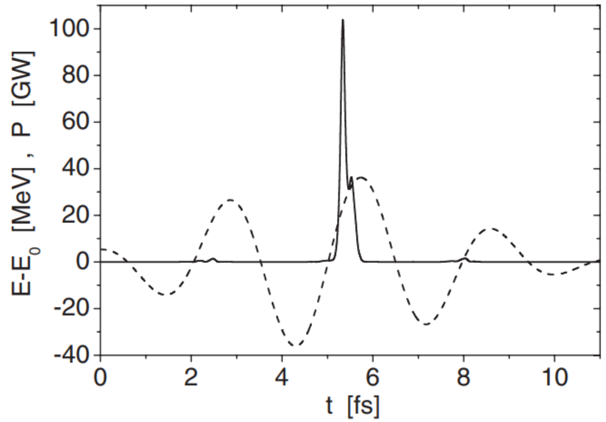
Works similar to principle of non-linear compression



A. Zholents, PRSTAB 8, 040701 (2005)

Energy Modulation

FEL Slippage over a strong energy modulation disrupts FEL performance, unless undulator field *K* follows to reson

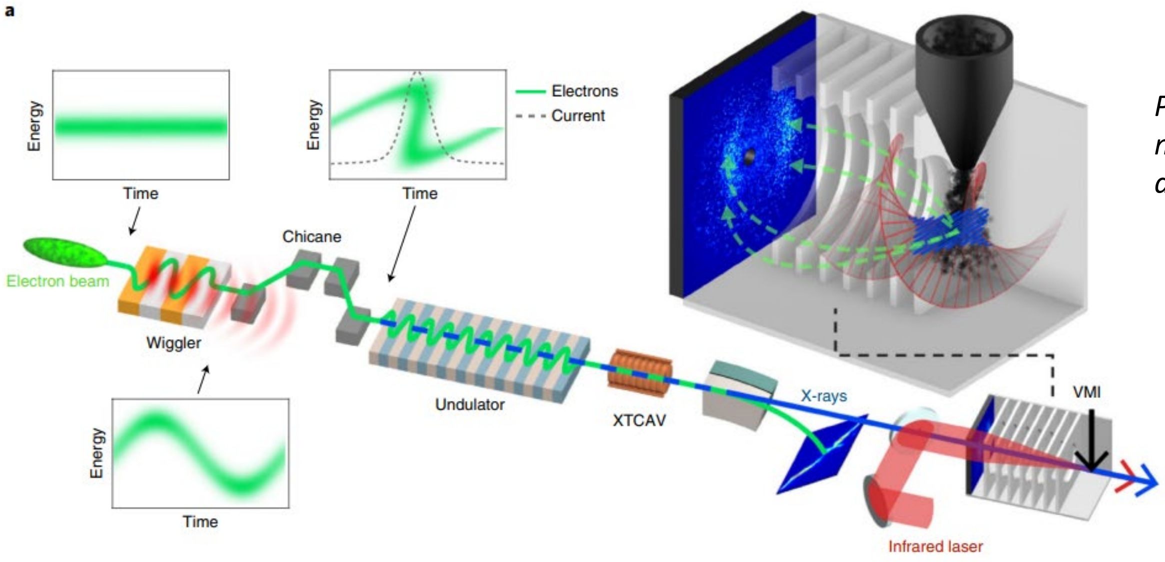


E.L. Saldin et al, PRSTAB 9, 050702 (2006)

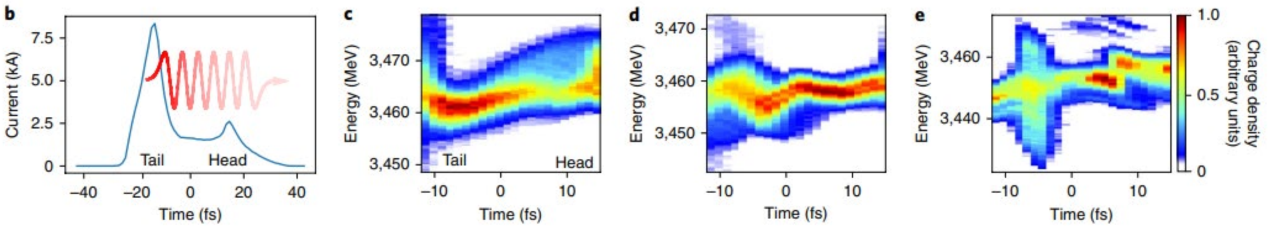
In reality, it is a mixture of both methods

Self-Modulation with Coherent Undulator Radiation

Demonstration with a current spike in the tail, emitting coherently in long period undulator, modulating the beam ahead. Then it is compressed to a local current spike.

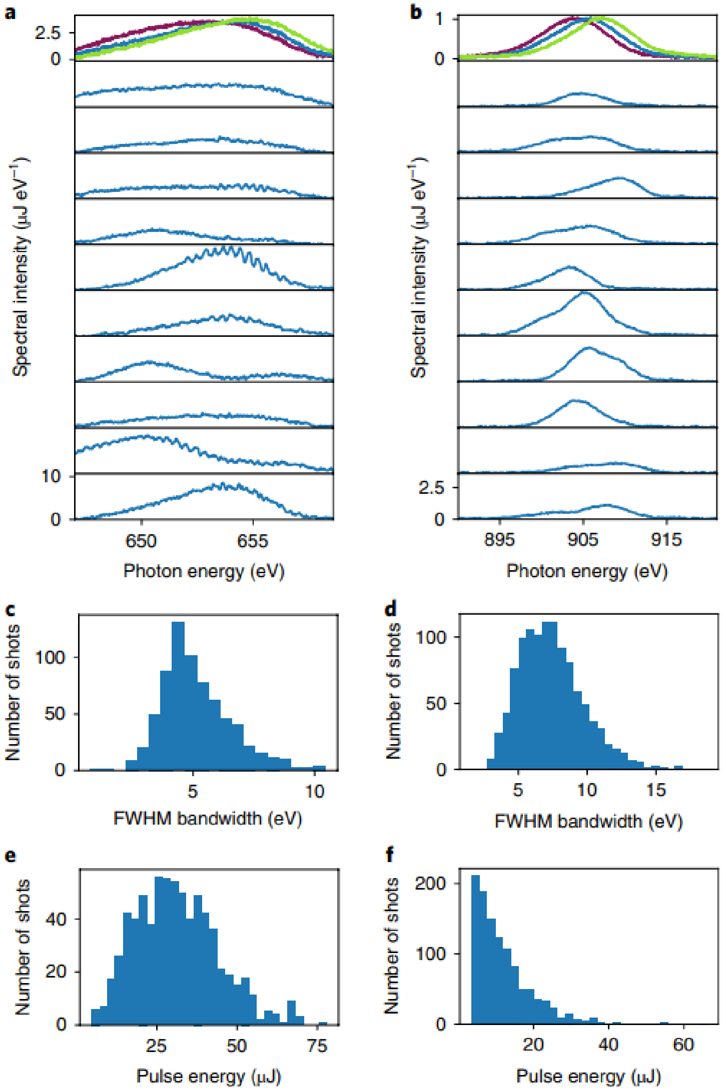


Pulse length measurement with angular streaking



J. Duris et al, Nature Photonics 14, 30-36 (2020)

Single Shot Spectra

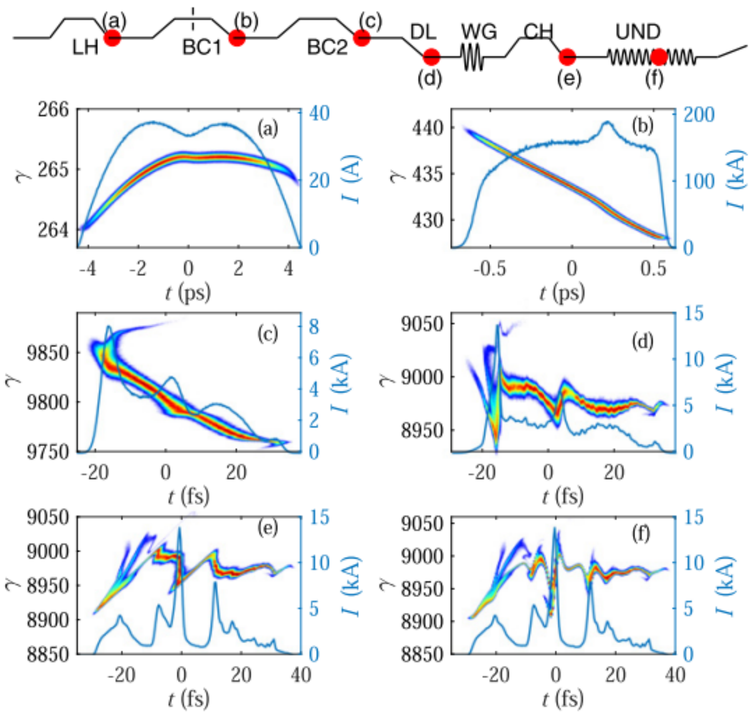


Self-Modulation with Photo-Cathode Pulse Shaping

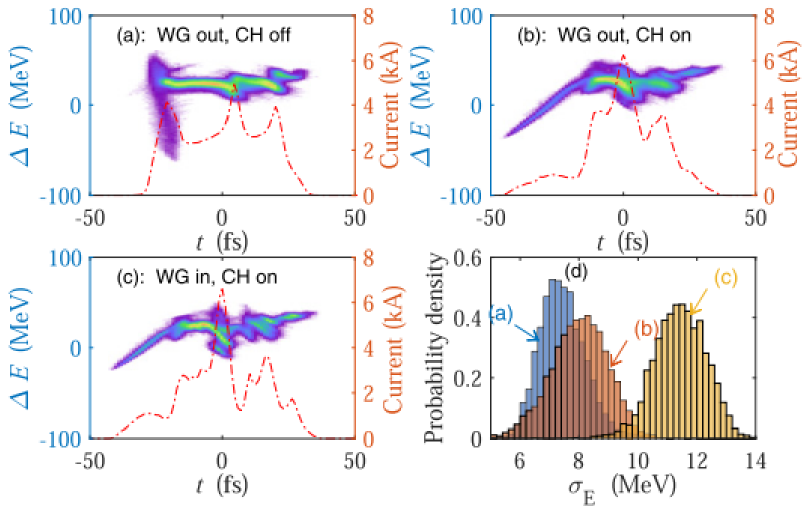
PSI

Self-modulation is improved when the energy modulation is generated already at the electron bunch source (photo-cathode) generating a current spike in the middle of the bunch and not at its end.

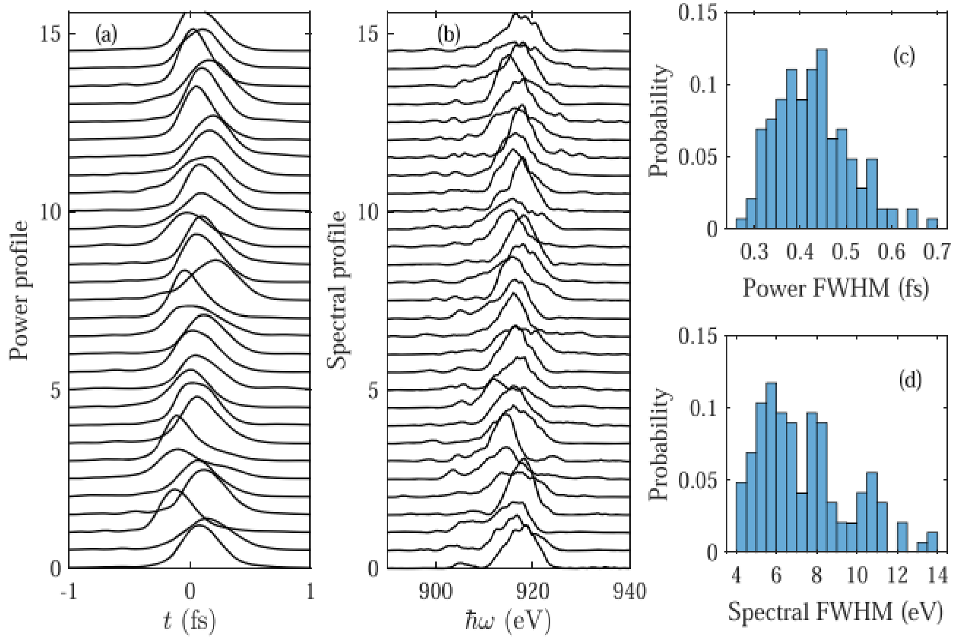
Tracking Simulation



Beam Measurement



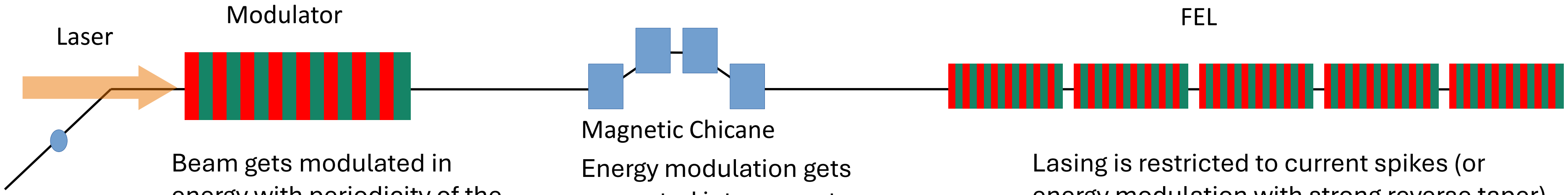
Profiles (angular streaking) and Spectra



Z. Zhang et al, New J. of Phys. 22, 083030 (2020)

External Modulation: Enhance SASE

Step 1 : Energy Modulation	Step 2 : Current Modulation	Step 3 : Lasing of FEL



Beam gets modulated in energy with periodicity of the laser wavelength

Energy modulation gets converted into current modulation (optional)

Lasing is restricted to current spikes (or energy modulation with strong reverse taper)

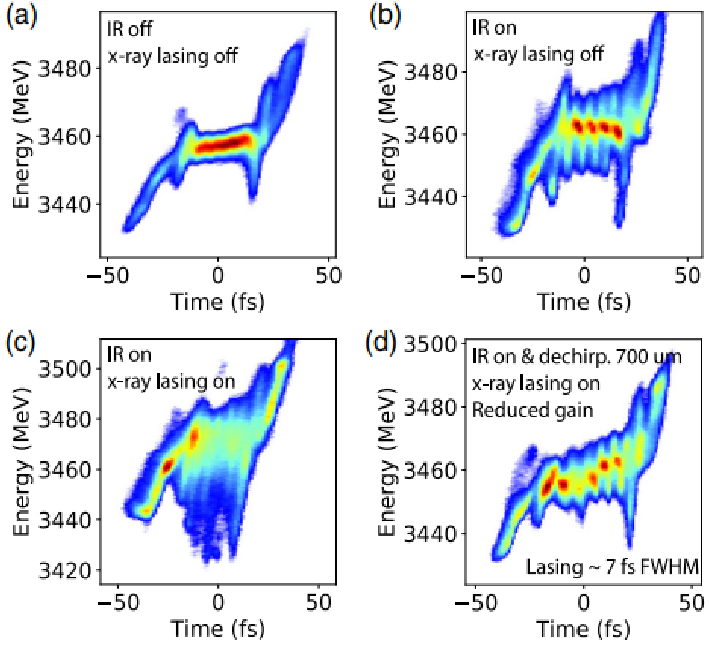
Similar effect to self-modulation but modulation is done by an external laser. ***Signal is locked to an external "clock"***

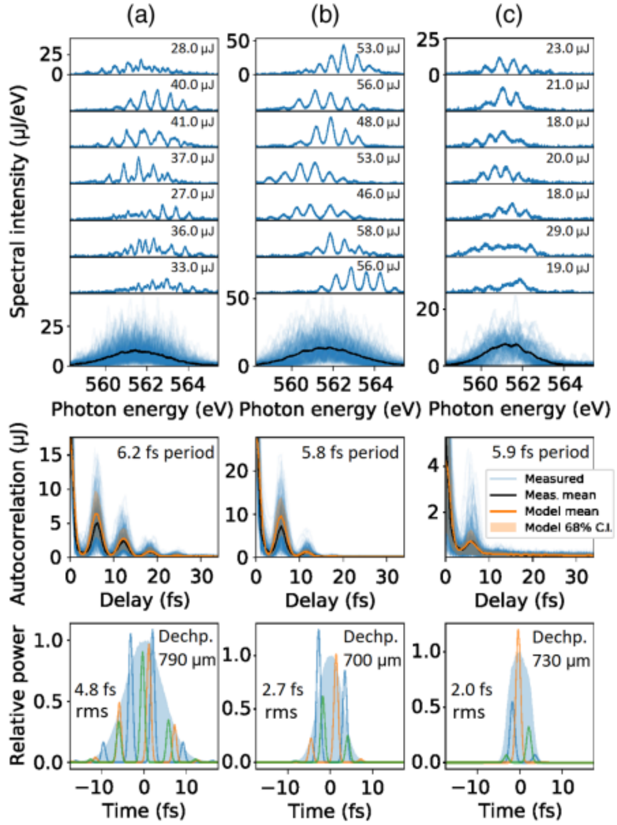
Produces rather pulse trains than single pulses, defined by the periods in laser signal and modulator.

$$N_{spikes} \approx \sqrt{N_u^2 + N_{laser}^2}$$

Challenge is to get only a single spike (e.g. by tilting the electron beam → see plot (d) in right figure)

Longitudinal Phase Space



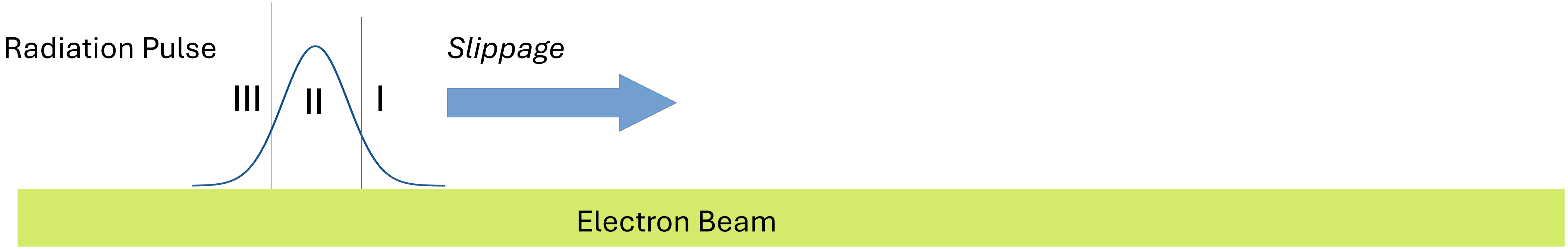


[J. Duris et al, PRL 126, 104802 (2021)]

Proposed Advanced Methods for Shorter Pulses

Strong Superradiance

When a short but strong radiation spike is slipping over a fresh electron bunch, the interaction bunches and extracts energy from the electron beam.

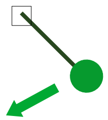


There is a strong analogy of the electron motion in longitudinal phase space to a pendulum (with a rubber band proportional to square root of radiation field)

Phase I:
Formation of bunching

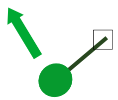
Pendulum is streched

Phase II:
Energy loss
(Fields gets stronger)



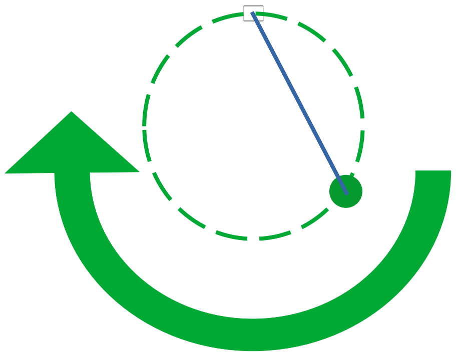
Pendulum swings through

Phase III:
Energy gain
(Field gets weaker)



Pendulum slows down

Full Picture:



Strong Superradiance (Simulations)

Strong superradiance shines in particular for radiation power above the FEL saturation power

In 1D theory the process causes a quadratic growth in the peak radiation power and a narrowing of the pulse durations the inverse square root of the distance

Superradiance stops at extreme high power level orders of magnitude above saturation power with a pulse length of a few wavelengths. Though it requires excessively long undulators to reach it (1 or more km)

However it can be used to reduce any pulse duration while adding more pulse energies.

Radiation Power

Electron Energy

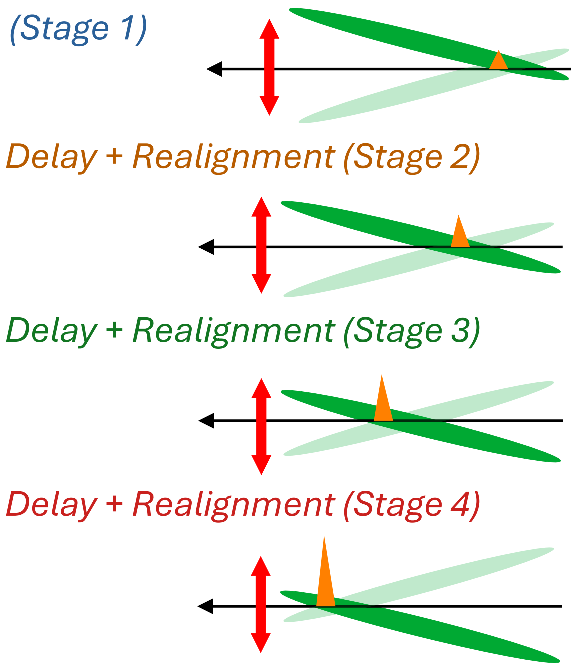
Electron Energy (Zoom)

Strong Superradiance - Limitation

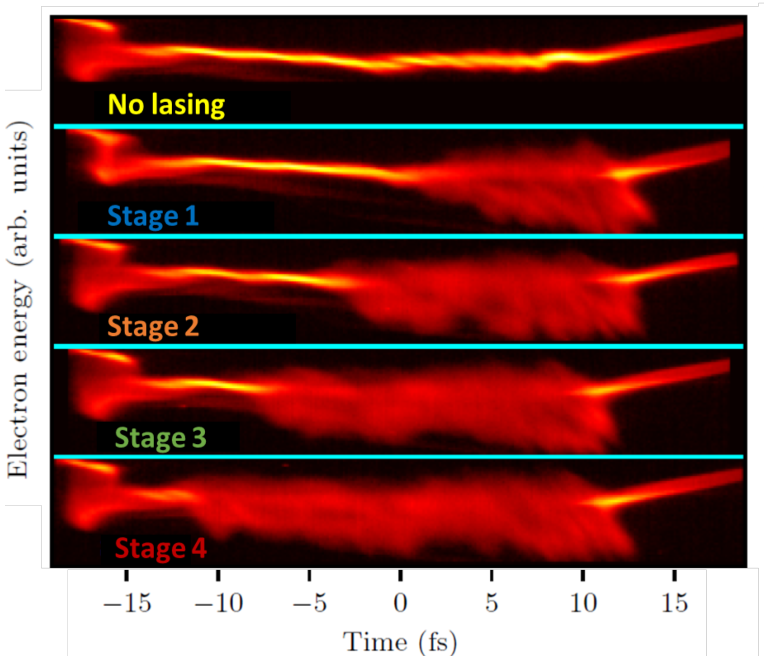
- Required undulator length is excessively long
- 3D effects lowers the saturation level
- Supplying always fresh electron bunch sections over the entire undulator
- Generating a single short spike at saturation power level

Demonstration of fresh-bunch technique to overcome (at least) third point [*Wang et al PRL132 (2024) 035002*]

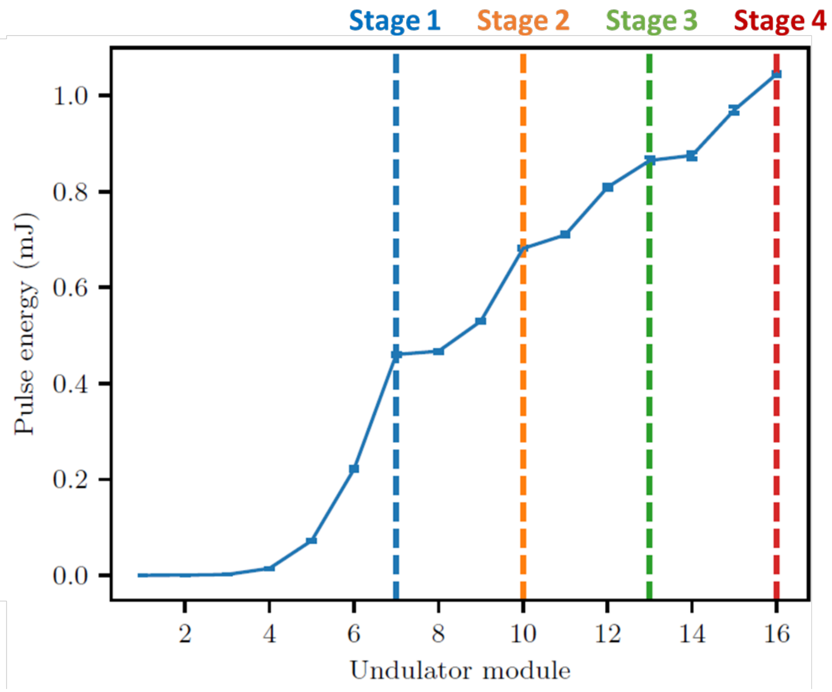
Wiggling beam tilt along undulator



Streaked Electron Beam on Dump Screen



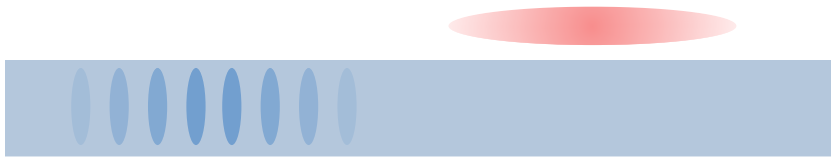
FEL Pulse Energy along Undulator



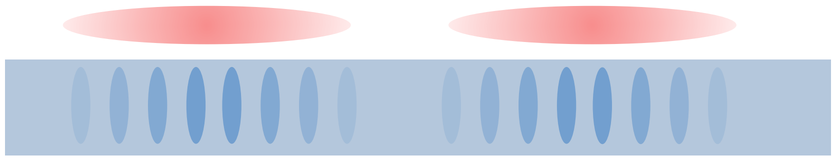
Making Replicas of Short Pulses

The FEL pulse is encoded in the radiation field but also in the induced bunching which emits coherently

A magnetic chicane delays the electron bunch with respect to radiation field. The micro-bunching structure can be preserved.



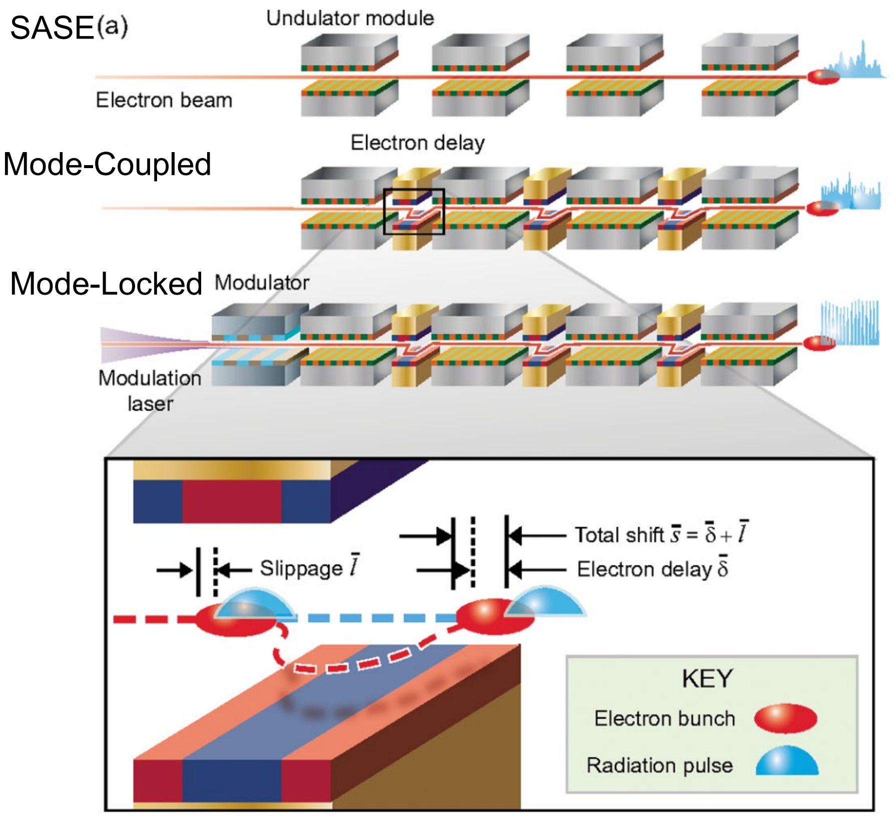
The bunching emits coherently, generating a replica of the pulse, while the original pulse induces the micro-bunching structure.



This can be repeated multiple times, generating a train of attosecond pulses.

Mode-Coupled Lasing

Idea: N.R. Thompson et al, PRL 100, 203901 (2008)



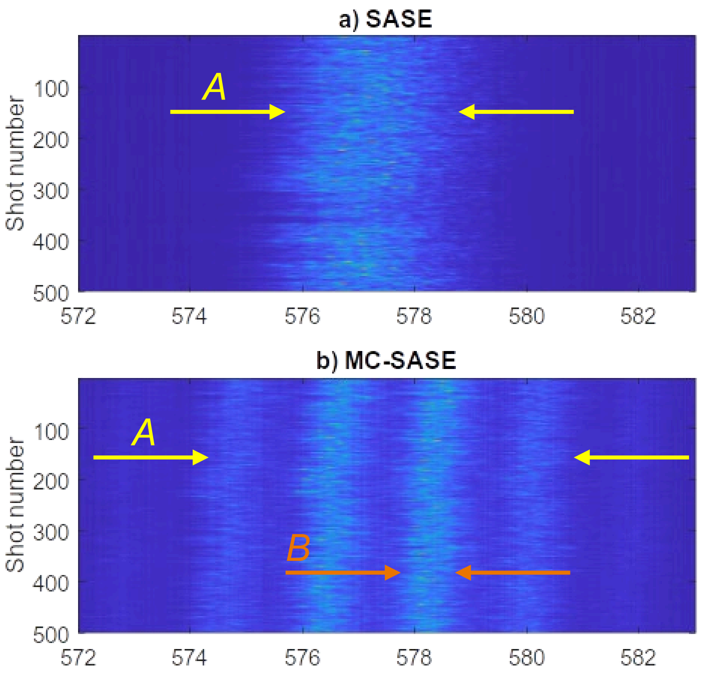
Mode-Locked Lasing uses an external signal: see next slide

The generation of pulse trains with delaying chicanes is called:

Mode-Coupled Lasing

The pulse duration is defined by the slippage in one undulator module, namely by the number of periods: $l = N_u \cdot \lambda$

Measurement at SwissFEL (E. Prat et al, submitted to PRL)



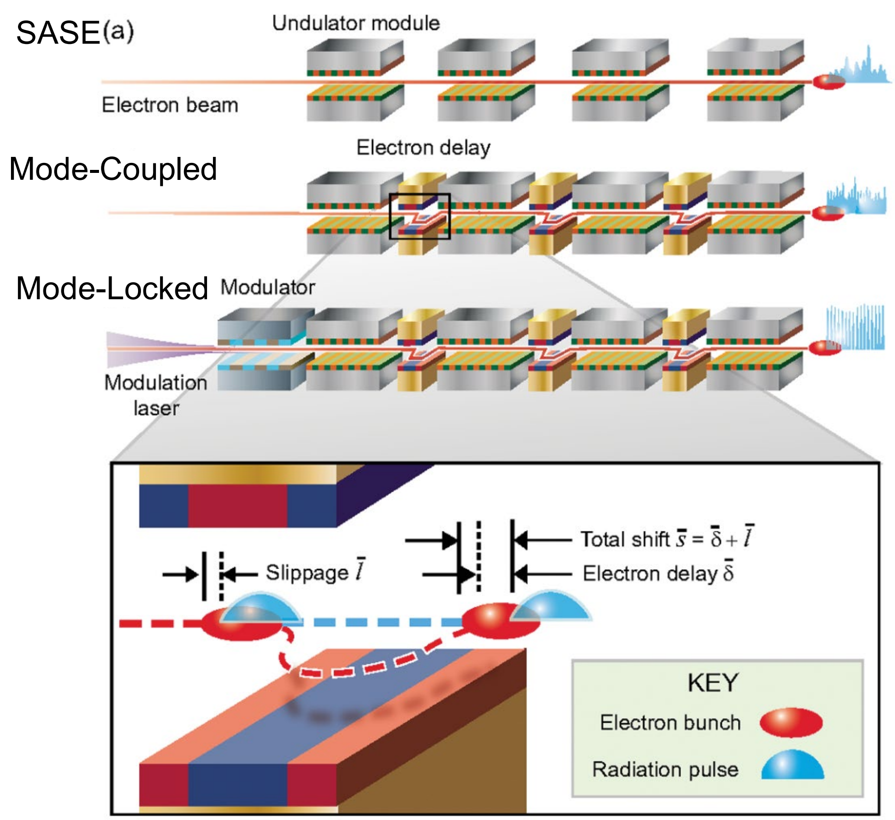
A) The width of the envelope in the spectra is a measure for the shortest feature in time-domain: pulse duration

B) The width of the bands in mode-coupled lasing is a measure of the coherence time (aka the pulses in the pulse train are locked in phase!)

Measurements indicate that pulses in MC-Lasing have roughly half the duration than in SASE

Mode-Locked Lasing

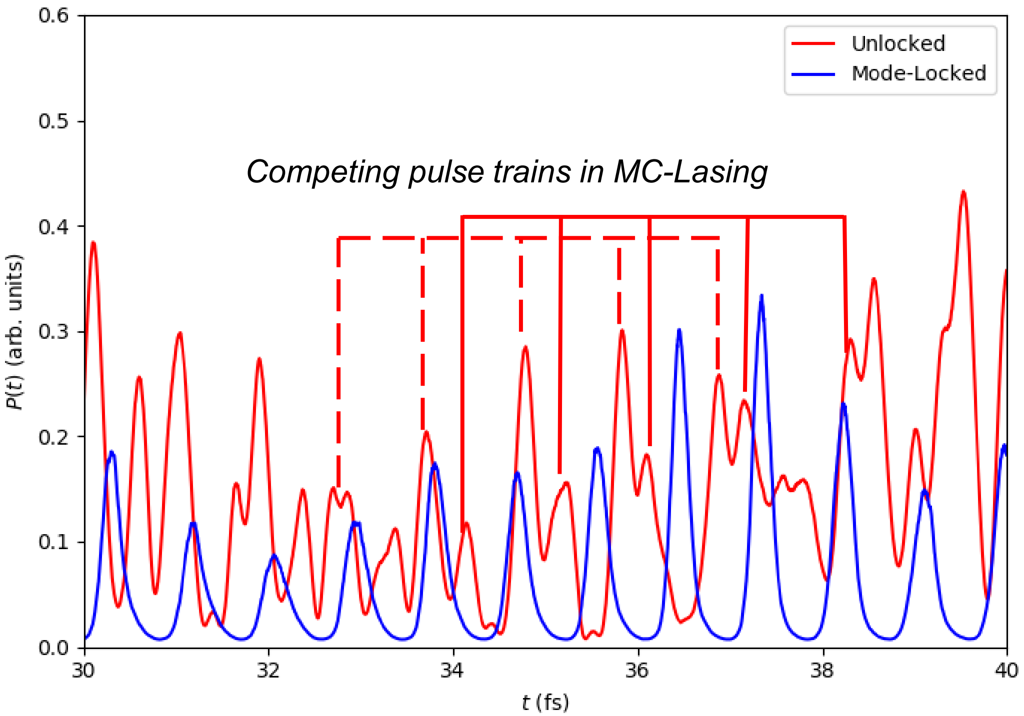
Idea: N.R. Thompson et al, PRL 100, 203901 (2008)



With an external modulation of the beam (current or energy modulation) the location of the pulses is restricted to certain location in the time-frame of the electron bunch:

Mode-Locked Lasing

Simulation of ML for Athos-SwissFEL @ 1 nm

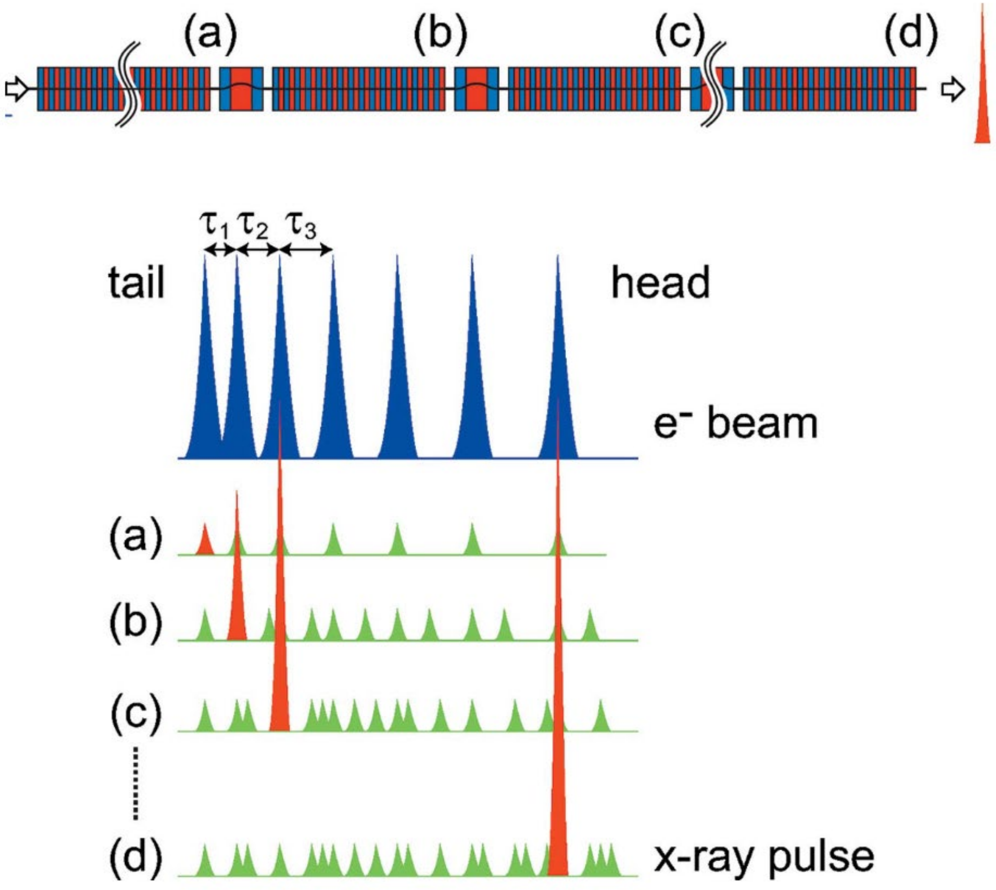


Pulse Durations of about 300 as FWHM for 52 period in each undulator module of SwissFEL

With effective shortening of the modules even shorter pulses can be achieved (e.g. 150 as at 4 nm)

From Pulse Trains to Single Pulse

Idea: T. Tanaka et al, JSR 23, 1273 (2016)



Similar to Mode-lock lasing but with irregular spacing between the ESASE spikes/energy modulation

Following the radiation pulse from the last current spike with matching delays the field will add up coherently. Radiation from other current spikes will not overlap with the preceding current spike, since the delay of the chicane is global.

There are various ways to achieve irregular-spaced ESASE spikes:

- Single-cycle laser field with a strongly tapered modulator
- A strongly chirped laser with a short modulator
- Normal laser pulse and modulator but with residual quadratic energy chirp resulting in a non-linear compression of the ESASE spikes

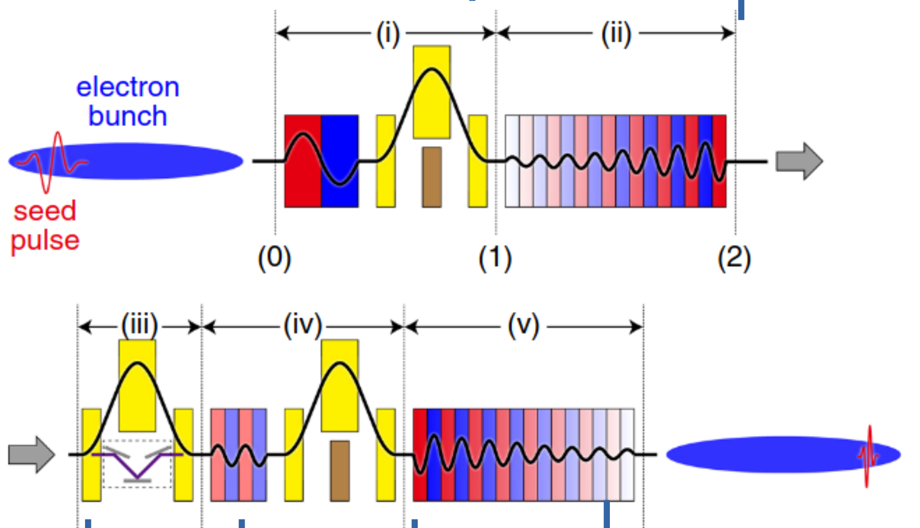
Single-Cycle: The Ultimate Short Pulse

If the ESASE current spike is shorter than the radiation wavelength, it will immediately emit coherently at shorter wavelength (Coherent Harmonic Generation) and does not relay on FEL amplification.

Idea: T. Tanaka, PRL 114, 044801 (2015)

Generation of single current spike

Chirped laser pulse

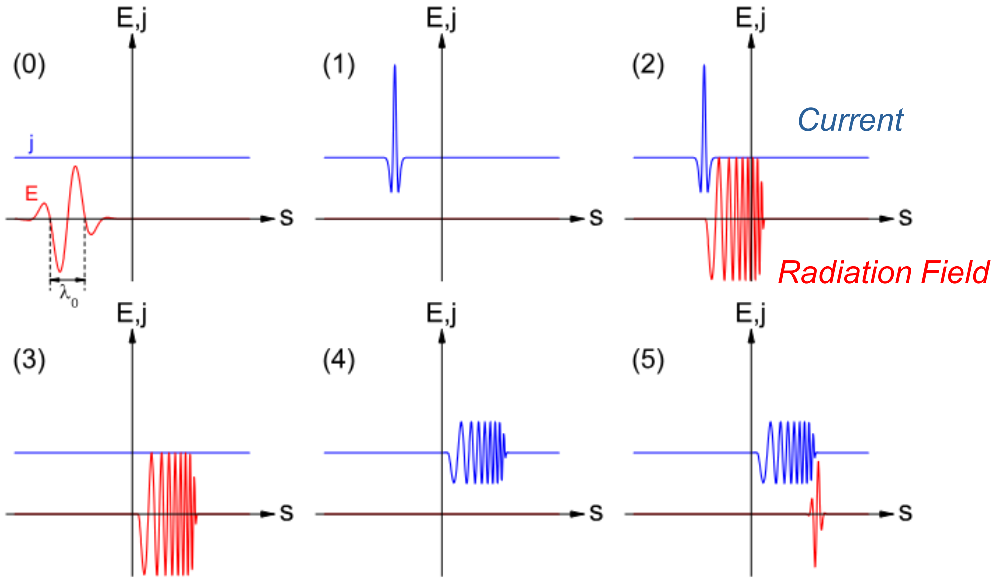


Fresh bunch

Chirped energy modulation

Coherent addition of single cycle radiation (effectively 1 period undulators with varying delay in between)

Coherent Harmonic Generation



Conclusion

Conclusion

PSI

- In the soft and hard X-ray the slippage during FEL amplification is limited, resulting naturally in sub-femtosecond pulses.
- Restricting lasing (Short electron bunch duration, slicing, ESASE current spike) can select a single spike and thus producing attoseconds pulses.
- LCLS pioneered at demonstrating attosecond pulses. Recent results shows durations of 100 as.
- Methods have been proposed to go shorter than the single SASE spike duration. Most prominent are:
  - Superradiance
  - Mode-locked lasing and variations of it
- Special undulator hardware is needed, often not compatible with standard SASE FEL operation
- FEL R&D is also user driven. So far there are no real requests for very short pulses below 100 as