Sven Reiche :: SwissFEL Beam Dynamics Group :: Paul Scherrer Institute

Status and Future of XFEL Source Developments

FLS Workshop – Lucerne, September 2023

Outline

- SASE Process and FEL Pulse Properties
- Short Pulse Generation
- Spectral Control
- Summary

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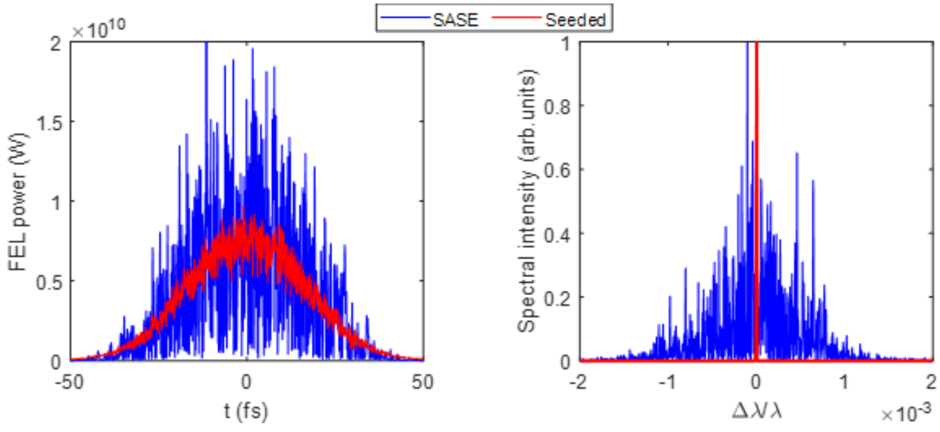
The SASE FEL

The SASE principle has been a stable foundation for almost all X-ray FEL facilities.

Most parameters, characterizing the performance, are coupled with each other by the FEL parameter:

- Saturation Power
- Saturation Length
- Coherence Length
- Spectral Bandwidth

Only the electron bunch length and thus the FEL pulse energy can be regarded as a second, independent “knob”



SASE vs Seeding at SwissFEL [Courtesy of E.Prat]

Many experiments have to deal with the intrinsic fluctuation of the SASE signal, in particular after filtering it with a monochromator

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FEL Pulse Properties

$$\vec{E} = \vec{P}(t) \cdot W(x,y) \cdot A(t) \cdot e^{i\phi(t)} \cdot e^{ikz - i\omega t}$$

Property	Polarization	Wavefront	Envelope	Phase	Central Frequency
Principle Mechanism	Undulator Technology	Diffraction	E-Beam Shaping	Slippage	E-Beam Energy
Research Activities	Fast Switching	Orbital Angular Momentum (OAM)	Slicing or Power	Filtering or Seeding	Compact Facilities

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Achieving Short Pulses

The characteristic length for a SASE spike is the cooperation length (slippage over one gain length)

$$L_c = \frac{\lambda}{4\pi\rho}$$

The cooperation length is minimum length needed to have undistorted FEL amplification

Bunch Length < Cooperation Length → Weak Superradiance

Bunch Length >> Cooperation Length → Non-Interacting Regions (SASE Spikes)

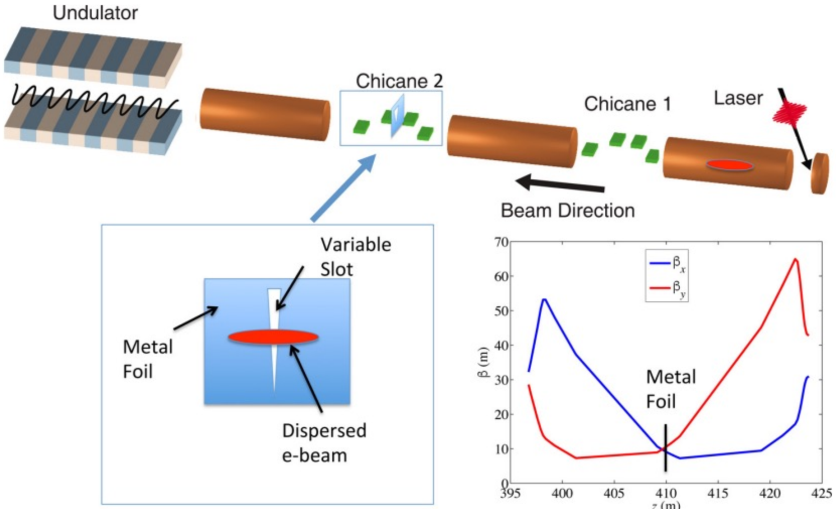
Restrict lasing to about one cooperation length

- *Spoiling beam quality of most of the bunch except for one slice*
- *Beam tilts or correlated beam mismatch*
- *Full (non-linear compression) for short current spike*
- *Local compression with periodic energy modulation (ESASE)*

Emittance and Laser Heater Spoiler

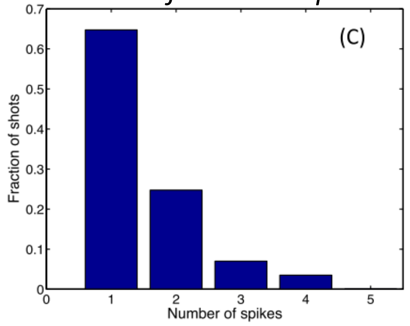
Tilted electron beam passes through thin foil. The scattering increases the slice emittance, reducing the ability to drive the FEL process. A slits let some electrons pass undisturbed.

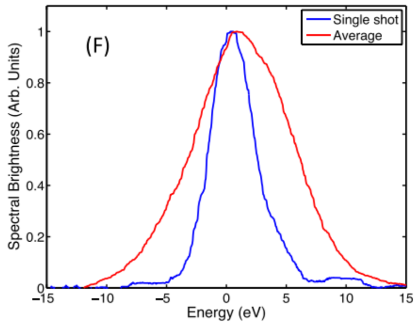
Idea: *P. Emma et al, PRL 92, 074801 (2004)*
Demonstration: *A. Marinelli et al, APL 111, 151101 (2017)*



Similar idea with notch in laser heater pulse:
A. Marinelli et al, PRL 116, 254801 (2016)

Statistic of measure spikes





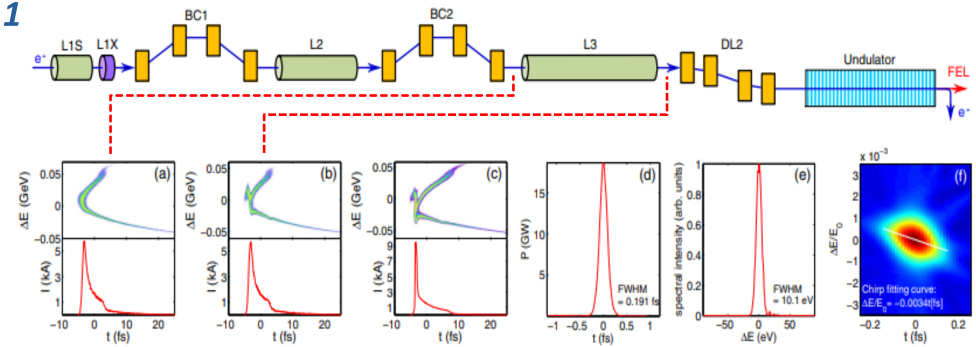
Primary diagnostic device is the single-shot spectra.

Short SASE pulse should have few observable spikes in spectra.

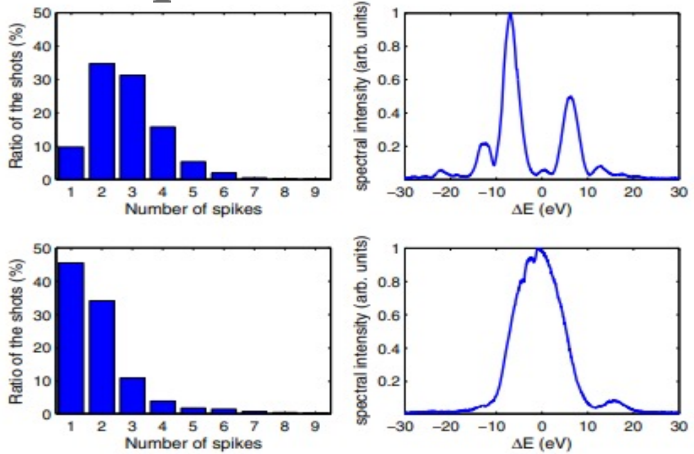
Ideally a single spike in spectrum corresponds to single spike in time domain

Short Pulses – Non-Linear Compression

1



1



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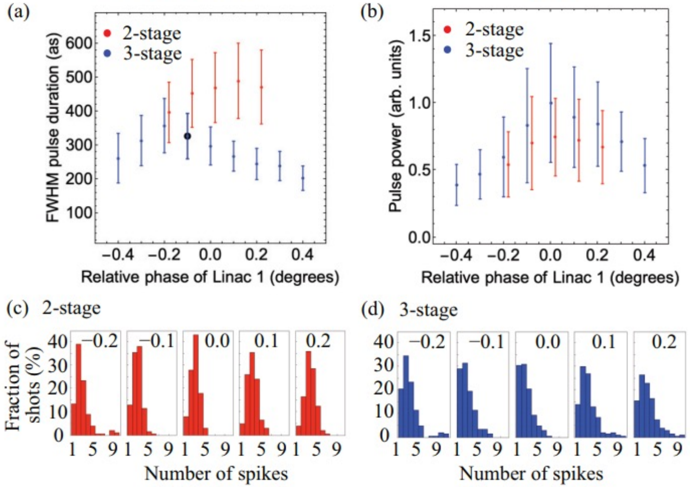


Electron beam is over-compressed with one leading current spike, driving the lasing. Performance is rather robust against RF jitter

The width of current spike can be controlled by:

- Linearizer (X-band) amplitude
- Large chirp in Linac and less R56 of last Chicane
- Laser heater induced energy spread

Strong space charge + CSR effects favors compression at the latest stage for shortest pulses.

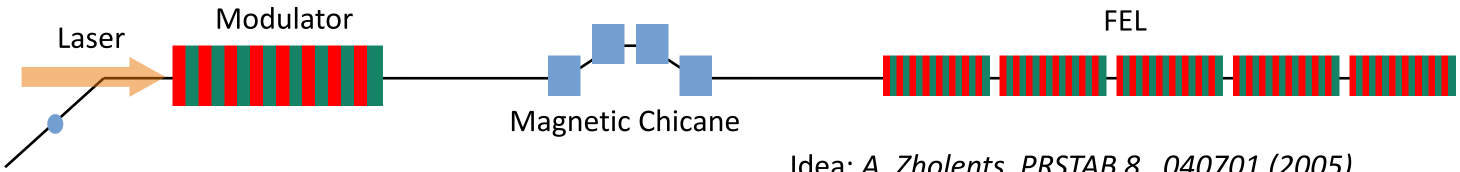
Slippage favors hard X-ray for a better matching of pulse length with cooperation length but works also in soft X-ray regime

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

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

Enhanced SASE

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



Idea: *A. Zholents, PRSTAB 8, 040701 (2005)*

Demonstration: *J. Duris et al, PRL 126, 104802 (2021)*

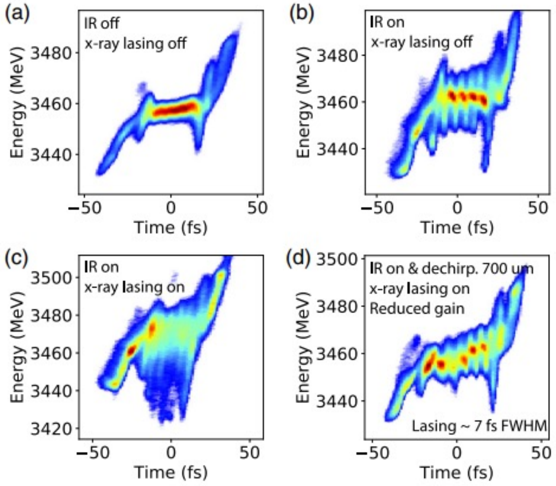
- Laser interacts with electron beam modulating it in energy
- Magnetic chicane converts energy modulation into current spikes
- Higher Current (despite higher energy spread) can drive FEL process faster, locking FEL pulse to current spike.

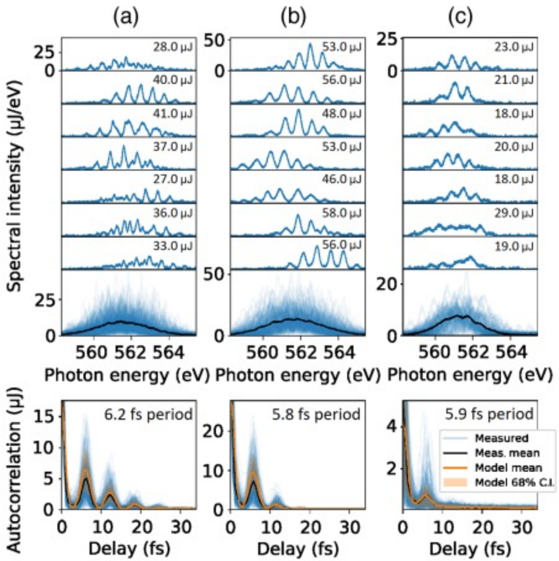
Pulse length is defined by laser pulse and modulator length.

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

This can be reduced by tilting the electron bunch ((a) – (c) in right figure)

Longitudinal Phase Space

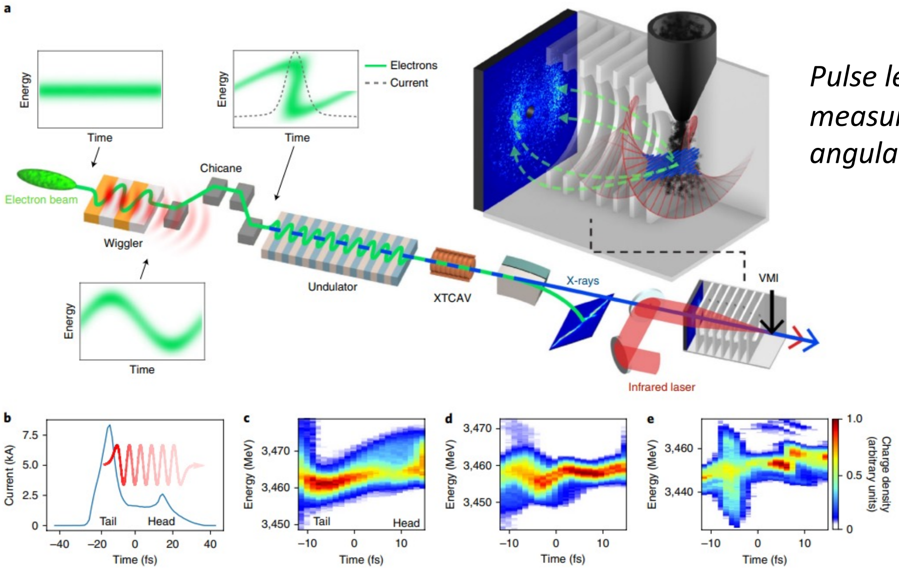




Self-Modulation Mechanism

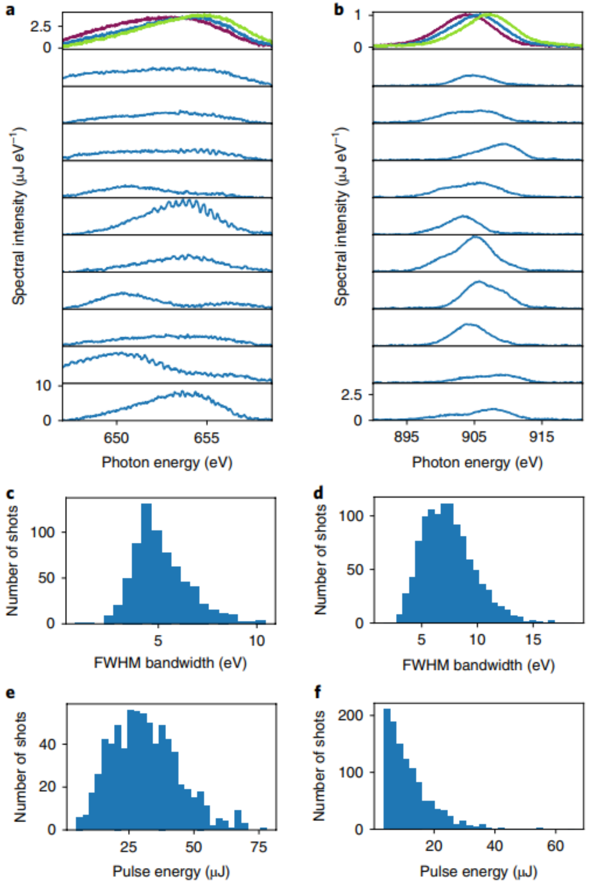
To achieve a single spike and avoid synchronization issues with external laser, self-modulation mechanism can be used.

Demonstration with the tail current spike, emitting coherently in modulator, modulating the beam ahead.



Pulse length measurement with angular streaking

Single Shot Spectra

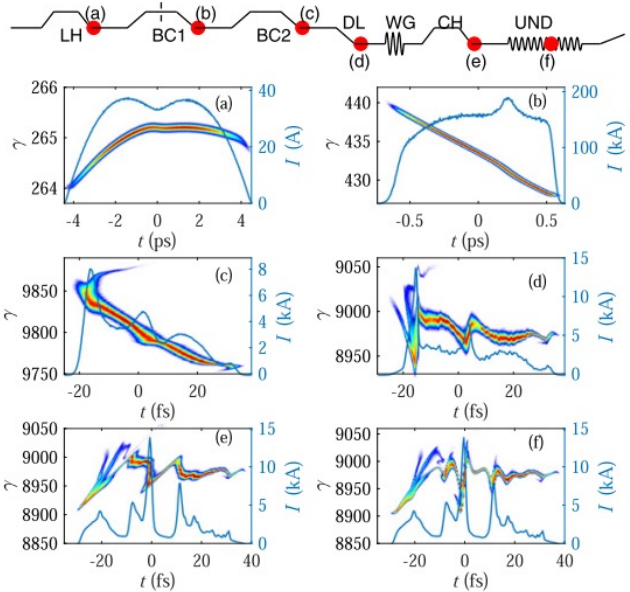


J. Duris et al, Nature Photonics 14, 30-36 (2020)

Controlled Self-Modulation Methods

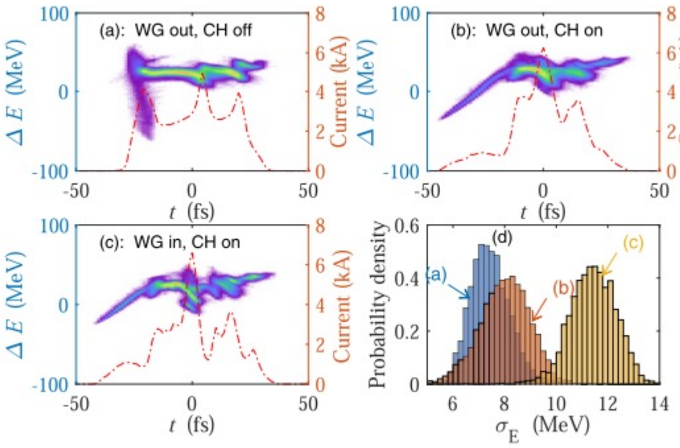
- Instead of relying on tail spike, a current spike can be induced by adding a small notch in current profile at gun.
- Lower current cause a reduced dechirping by space charge and thus a formation of a current spike.
- Effect is enhance by self-modulation and compression (see previous slide)
- Method can generate two spikes for possible two color operation.

Model

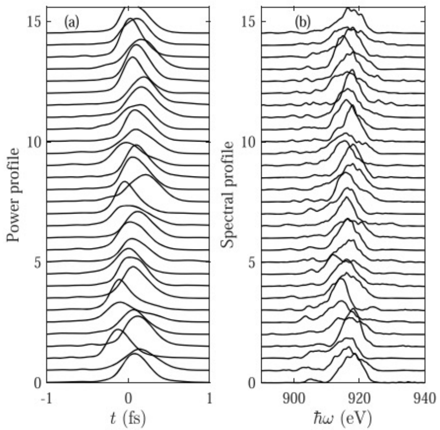


Demonstration: *Z. Zhang et al, New J. of Phys. 22, 083030 (2020)*
(similar idea based on laser heater: D. Cesar et al , PRAB 24, 110703 (2021))

Measurement



Profiles & Spectra

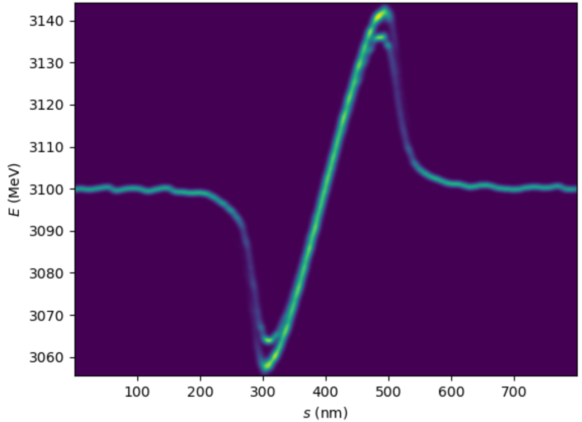


Issue 1: Space Charge

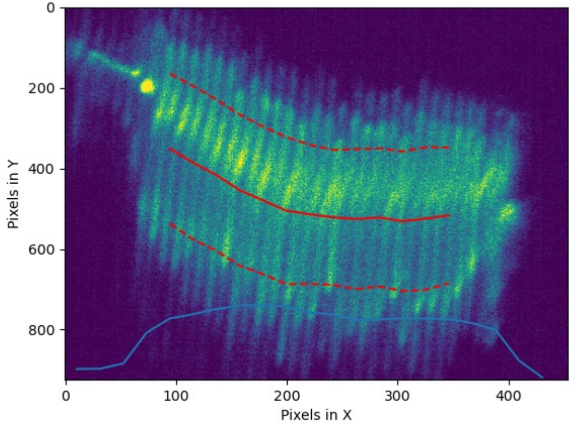
Most methods utilizing short current spikes (e.g. ESASE) exhibit strong space charge forces:

- Removes and reverts initial energy modulation
- Builds up a linear chirp over the current spike
- Elongates the current spike due to run-time differences in the undulator.

Fourier Series Space Charge Model

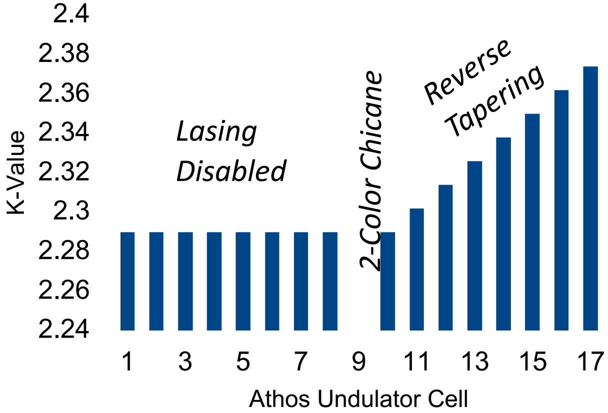


Measurement at SwissFEL (800 nm Mod.)

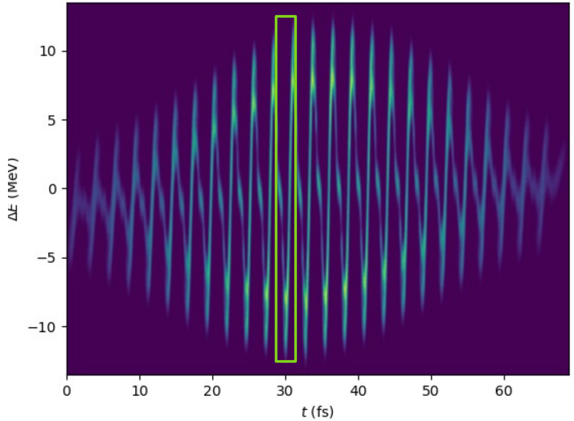


Needs Reverse Tapering

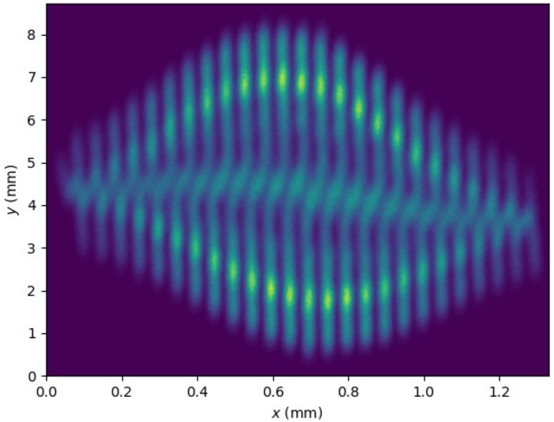
Taper Profile at SwissFEL



Elegant Tracking: Long. Phase Space



Elegant Tracking: Deflector Measurement

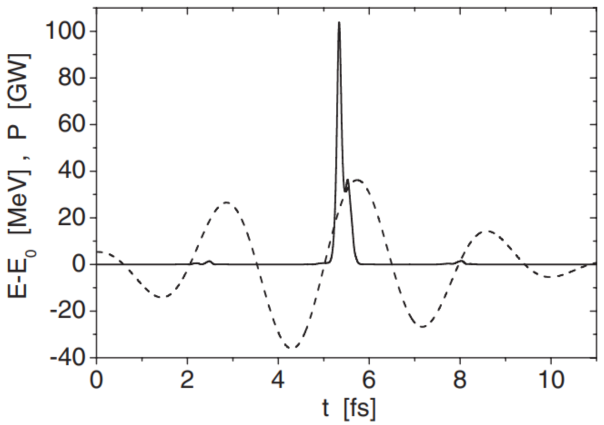


Issue 2: Strong Slippage Regime

At longer wavelength the cooperation length becomes longer than current spike length and FEL performance drops.

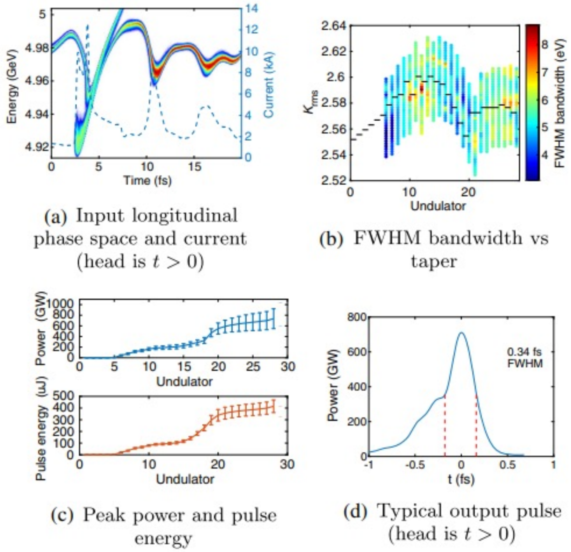
Short pulse duration can be maintained by adapting taper profile to “local” beam energy (Extension of reverse tapering for a linear chirp)

Only Energy Modulation



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

Current Spike + Self-Modulation



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

Pulses Below Cooperation Length

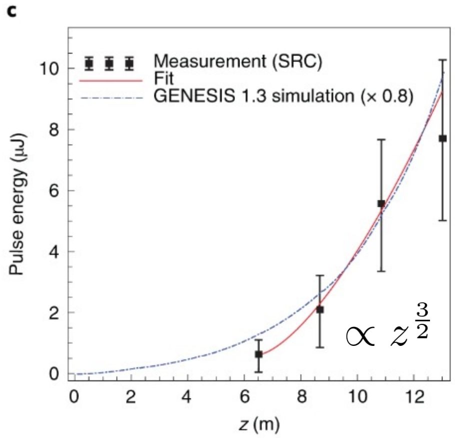
Superradiance

Superradiance is a mechanism beyond saturation where any pulse, entering an unspoiled part of the electron beam, grows quadratically in power while shortening the pulse duration.

Works best with seeded pulses but they are typically longer than the cooperation length. For SASE FELs superradiance effects the individual spike duration but not the much the rms pulse duration.

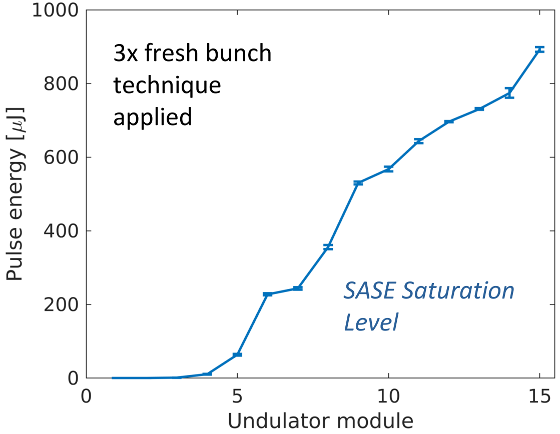
Superradiance has the additional benefit for peak power levels well above saturation (improving FEL power levels)

Seeded: FERMI @ 14.7 nm: 4.7 fs FWHM



N. Mirian et al , Nat Phot 15, 523 (2021)

SASE: Athos @ 2.4 nm: < 3 fs FWHM



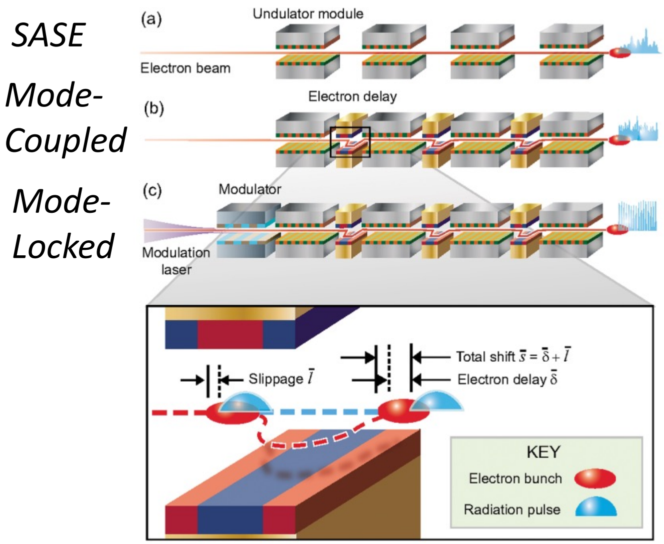
Talk by G. Wang on Thursday (TH2A3)

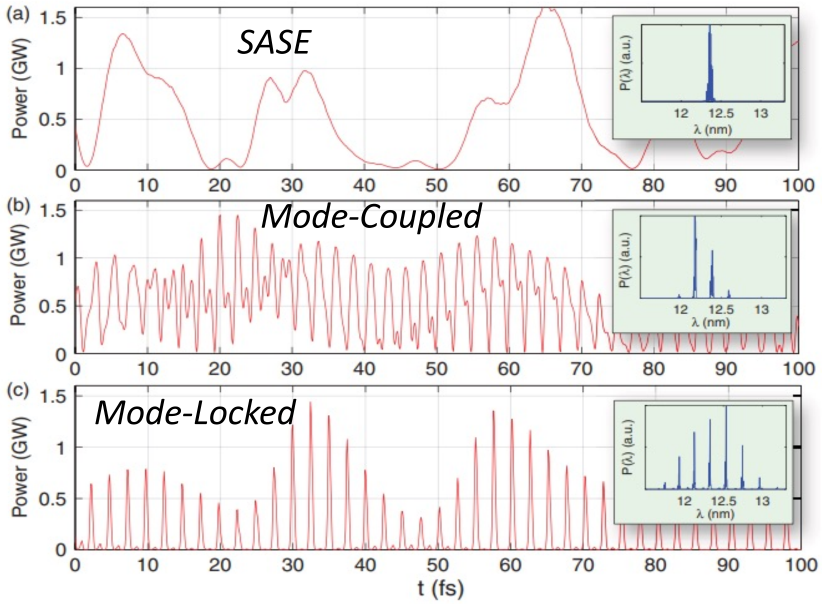
Pulses Below Cooperation Length

Mode-Locked/Coupled Lasing

With an array of undulator modules (***much shorter than a gain length***) and delaying chicane, the duration of the pulses scales with the number of undulator periods in the mode-coupled operation

If the slippage and delay matches an external modulation (e.g. in energy) it is mode-locked operation



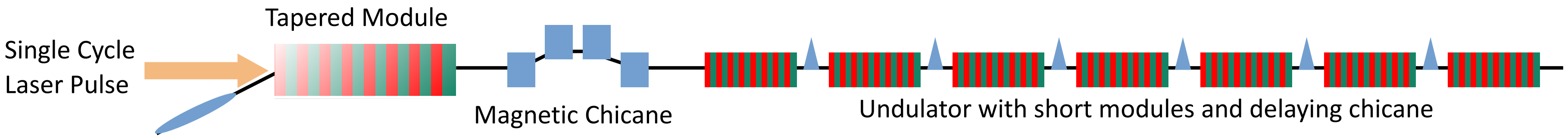


N.R. Thompson & B.J.W. McNeil, PRL 100, 203901 (2008)

Possible Future Research *(Personal Opinion)*

1) Synchronization

With sub-femtosecond pulses an active stabilization of the X-ray pulse to an external signal becomes important, excluding the impact of beam-arrival jitter.
The electron bunch is a "sand box" where an external laser pulse defines the lasing part (e.g. ESASE)
Principle Idea (following T. Tanaka et al., JSR 23, 1273 (2016)) to produce unevenly spaced current spikes, which then created a ***single spike*** with gets amplified by all current spikes with matching delays.



Alternatively a chirped laser pulse and a short modulator can be used.
With short modules the pulses can be shorter than the cooperation length.

2) Reliable single spike

Exploring short pulse seeding + superradiance ➡ (overcome SASE) → *see next topic*

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Some Limitations of SASE Pulses

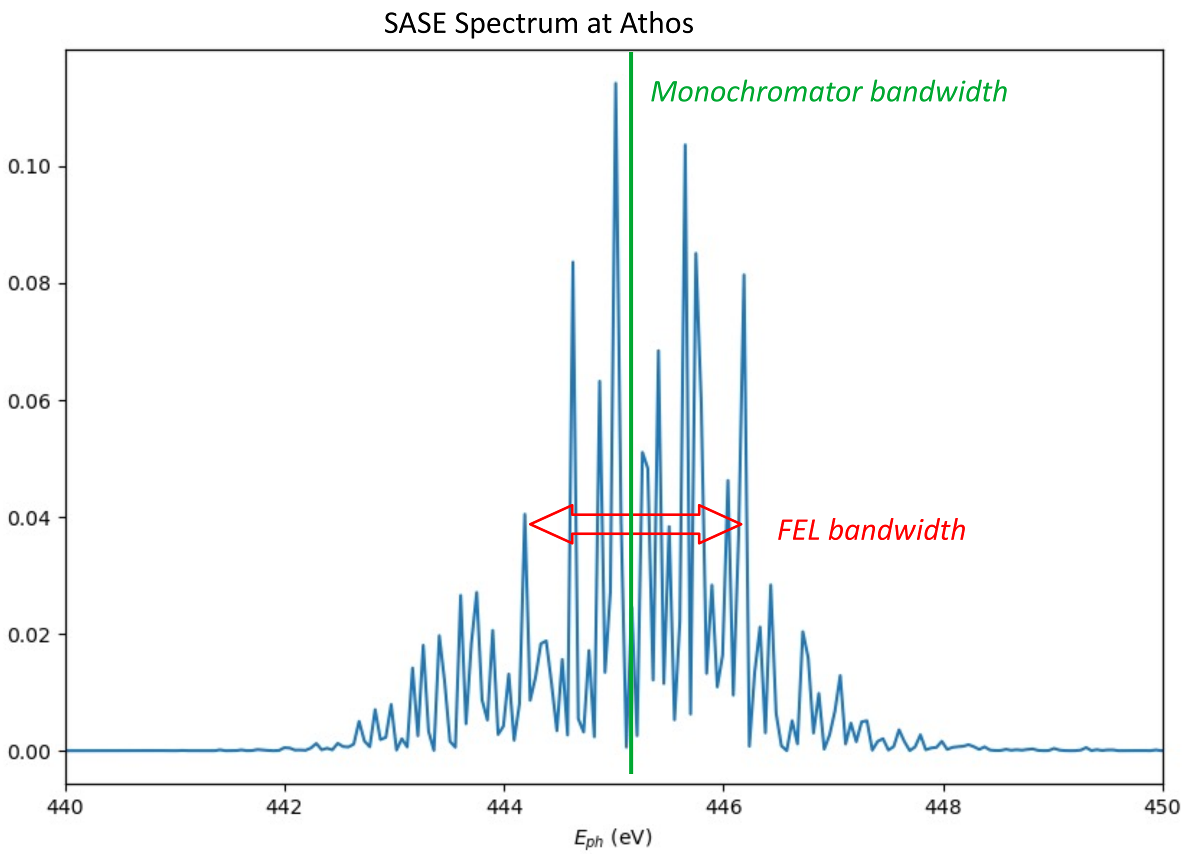
SASE bandwidth scales with FEL parameter.

Better performance makes spectrum wider but does not increase spectral brightness (Unless energy or current is increased).

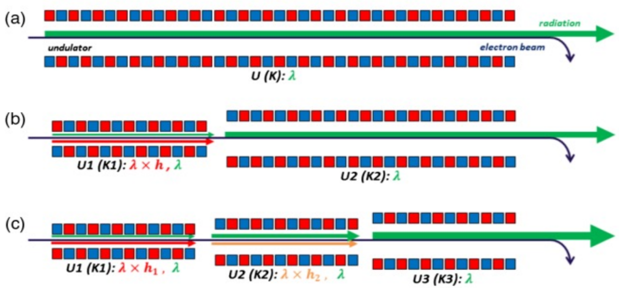
Central wavelength jitters with electron beam jitter.

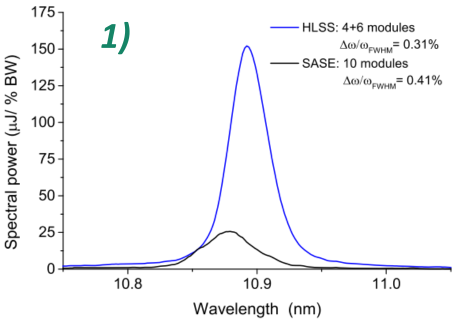
Stabilizing a frequency with a monochromator causes large fluctuation in output power. Events with low power have also poor transverse coherence.

Monochromator can elongate pulse duration



Enhancing Slippage with Harmonic Lasing





[1]E.A. Schneidmiller et al , PRAB 20, 020705 (2017)

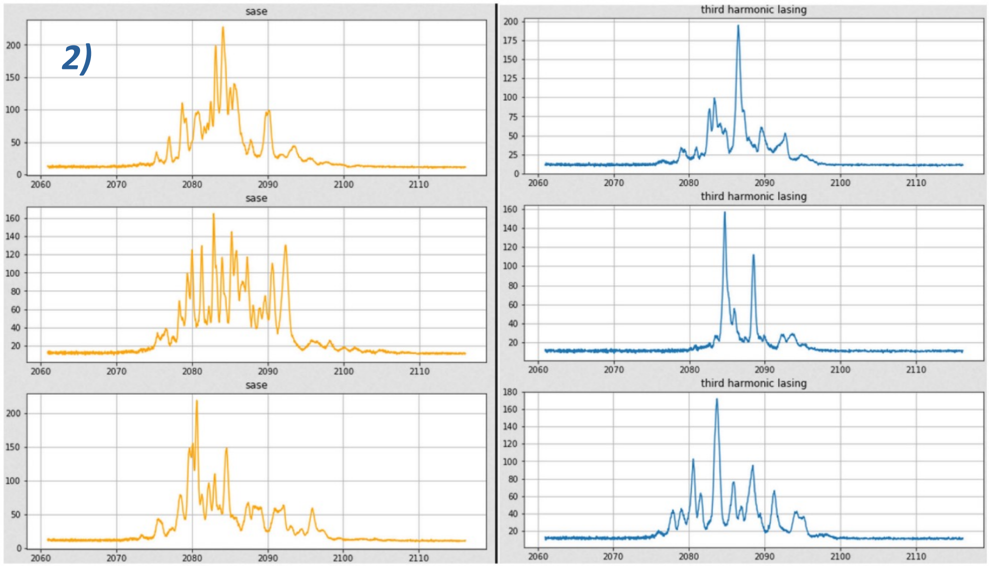
[2]E.A. Schneidmiller et al , PRAB 24, 030701 (2021)

Similar idea of purified SASE:
D. Xiang et al, PRAB 16, 010703 (2013)

In planar undulators odd harmonics can also drive the FEL process albeit on a lower growth rate.
However, the slippage is enhanced by the harmonic number, resulting in increased coherence length

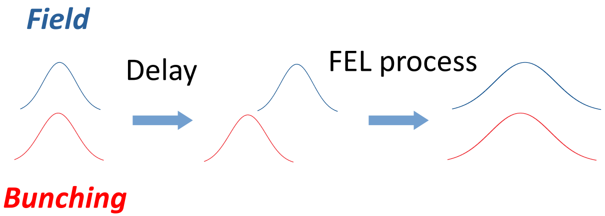
Harmonic Lasing Self-Seeding

- Requires high K-value for sufficient coupling, but can extend photon energy range if K-value is too small for driving fundamental
- Suppressing the sub-harmonics is a challenge. Best results with final stage at fundamental (aka “self-seeding”)
- If beam has residual chirp, spectra have less spikes then narrower bandwidth (see ***2)***)



Enhancing Slippage with Delays (HB-SASE)

Undulator with short modules and delaying chicane

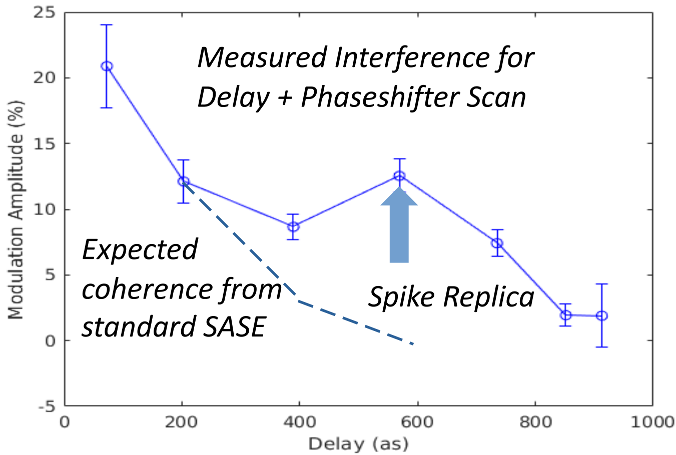


After each module the SASE spike is replicated by shifting field and bunching apart. Both can start the FEL process again, increasing the coherence length with each delay.

1) ***High Brightness SASE***

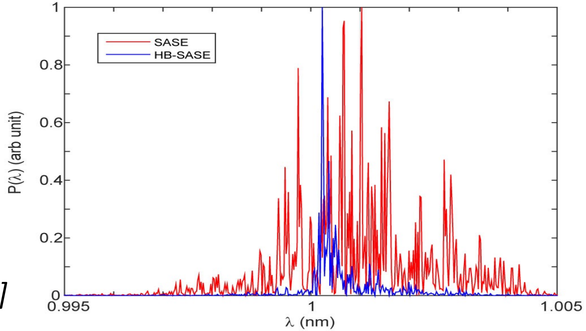
Challenges:

- Requires modules (much) shorter than a gain length and delaying chicanes → larger number of applied delays till saturation is reached
- Energy chirp results in less spike but no enhanced spectral brightness
- Competing with optical klystron effect, limiting the maximum usable delay, particular for:
  - Shorter Wavelength
  - Higher Energy Spread



$$R^*_{56} = \frac{\lambda}{2\pi\sigma_\delta}$$

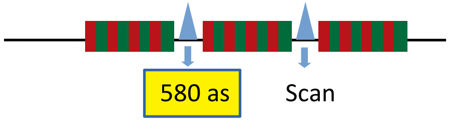
Athos simulation for ideal beam



$R_{56} > R^*_{56}$ → *Landau damping of bunching*

$R_{56} \approx R^*_{56}$ → *"Reducing" gain length*

$R_{56} < R^*_{56}$ → *Efficient operation of HB-SASE*

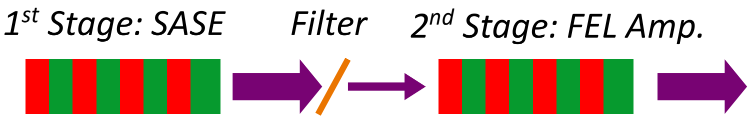


[B.W.J. McNeil et al, PRL 110, 134802 (2013)]

Self-Seeding

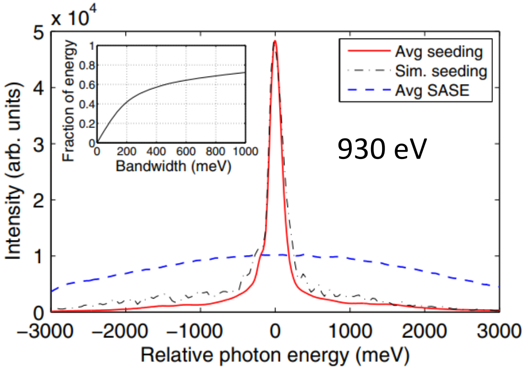
A filter (monochromator) selects a single mode out of white-noise drives it to saturation

Delaying chicane match electron beam and filtered X-ray radiation and wipes out any bunching from first stage



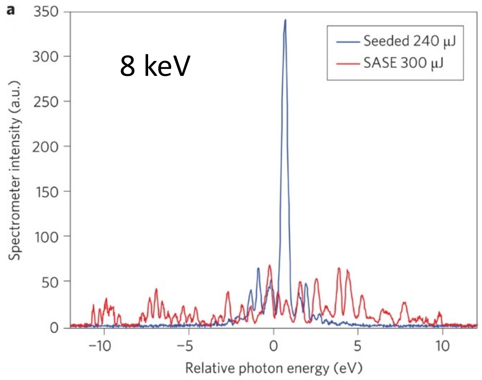
Soft X-rays

Idea: *J. Feldhaus et al., Optics Comm. 140, (1997), 341*
Demonstration: *D. Ratner et al, PRL 114, (2015), 054801*



Hard X-ray

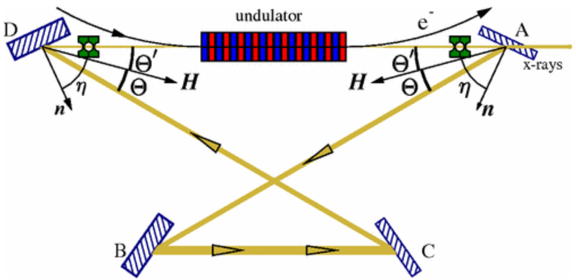
Idea: *G. Geloni et al, J. Mod. Optics 58, (2011), 1391*
Demonstration: *J. Amann, et al., Nature Photonics 6, (2012), 180*



In particular hard X-ray self-seeding has been adopted by most X-ray Facilities

X-ray FEL Oscillator

For high repetition rate machines (LCLS II, EU-XFEL, SHINE) the filtering with Bragg diffraction can be extended to a cavity set-up seeding the succeeding bunches to obtain the stability of a cavity based system.
The original proposal foresees a tunable cavity, initiatives at LCLS and European XFEL are working with fixed wavelength.

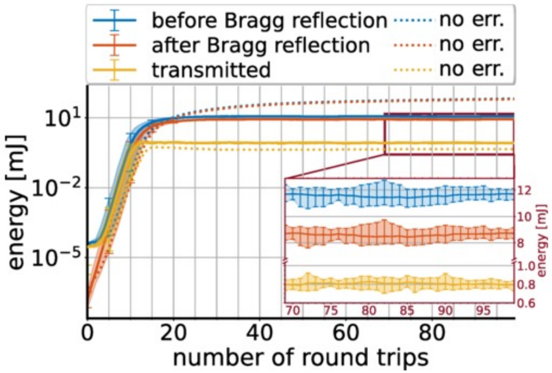


[KJ. Kim et al, PRL 100, 244802 (2008)]

Potential to exceed in:
- Peak Brightness (narrow bandwidth)
- Average Brightness (repetition rate)
- Stability (Bragg wavelength)

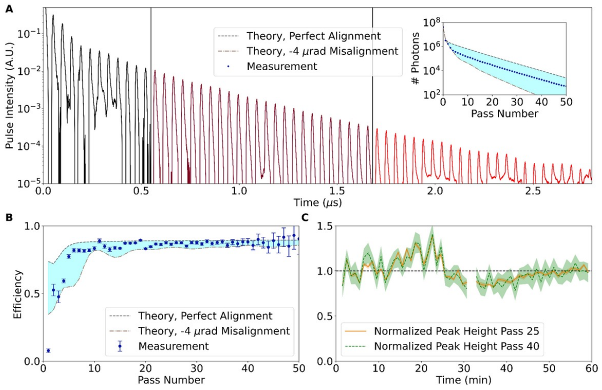
More info by Z. Huang in the next talk

Simulation with ideal condition



[P. Rauer et al, PRAB 26, 020701 (2023)]

Quality of X-ray Cavity



[R. Margraf et al, submitted to Nature Portfolio]

External Seeding

Filtering (self-seeding, XFELO) is very efficient to achieve a narrow bandwidth with stable central frequency, but it lacks the flexibility of quantum laser system:

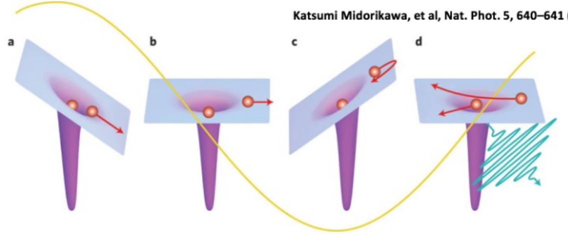
- Chirp Pulse amplification
- Pulse Shaping (e.g. pulse lengths control, beat wave of two frequencies)
- Pulse compression

With an external source the FEL can operate as a single pass amplifier preserving most of the characteristics of the seed pulse.

High Harmonic Generation (HHG)

Drive laser ionize electrons, accelerate them and then recombined them, locking photons with higher energies to laser phase

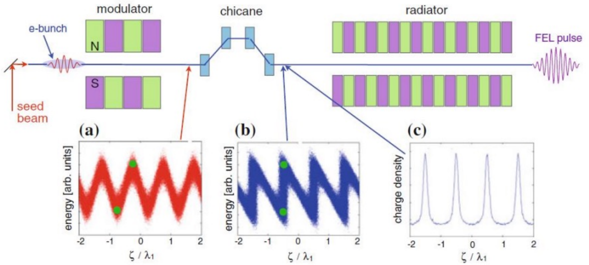
Katsumi Midorikawa, et al, Nat. Phot. 5, 640–641 (2011)



Focus at short pulses in soft X-ray regime

High Gain Harmonic Generation (HGHG)

Similar to ESASE but current spikes are shorter than final wavelength, emitting coherently.

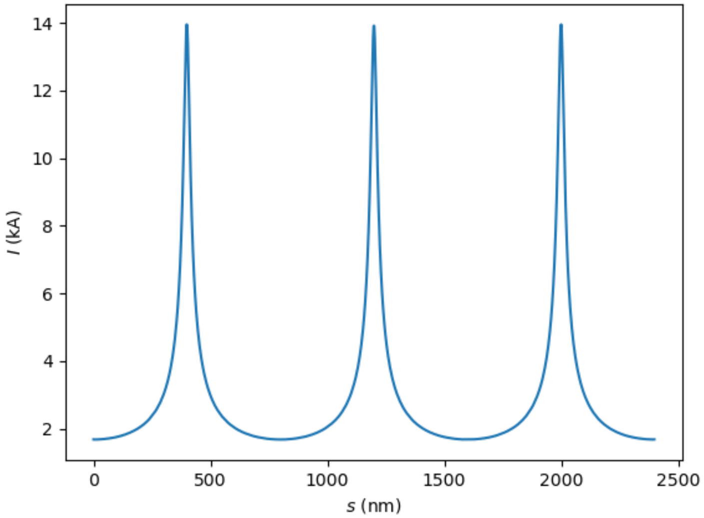


Basic principle even for advanced schemes (EEHG or Cascaded HGHG)

Harmonic Generation

Scaled ESASE principle to make current spike shorter than the final FEL radiation length.

- Beam is 'bunched' at final wavelength
- Emission phase is locked to bunching phase
- ***Principle of Harmonic Generation***



Requirement for Energy Modulation

$$\frac{\Delta E}{\sigma_E} > h$$

→ Increase of energy modulation ΔE

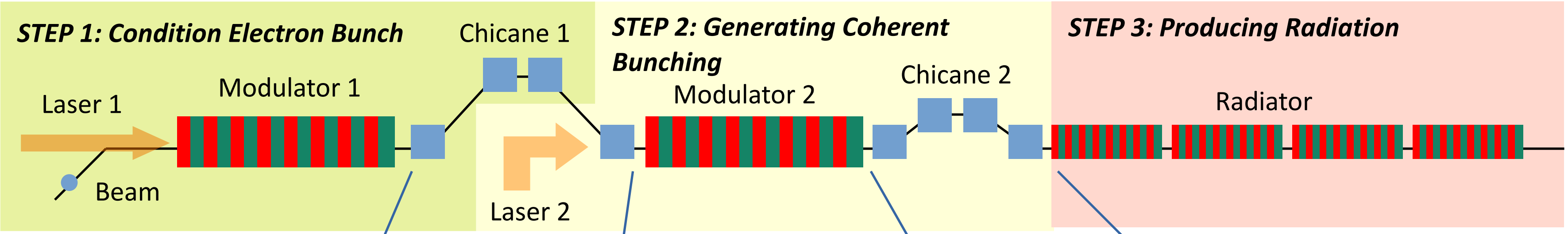
Number Example:

- External Laser: 264 nm
- Target Wavelength: 4 nm
- Energy spread 1 MeV at 3 GeV

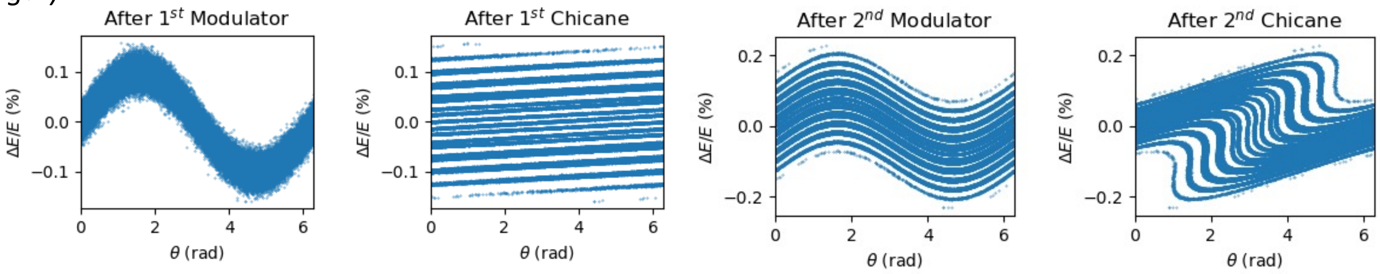
→ h = 66 → 1.5% Energy Spread induced → FEL lasing inhibited

To reach higher harmonics, the energy spread needs to be reduced (effectively) → ***Echo-enabled Harmonic Generation (EEHG)***

Echo-Enabled Harmonic Generation Principle



Longitudinal Phase Space (over 1 seeding wavelength)



The second pulse is the actually input signal and can have "customized" properties (short, long, chirped)

Coherent Current Spikes, starting the FEL (Radiator)

[G. Stupakov, PRL 102, (2009), 07480]

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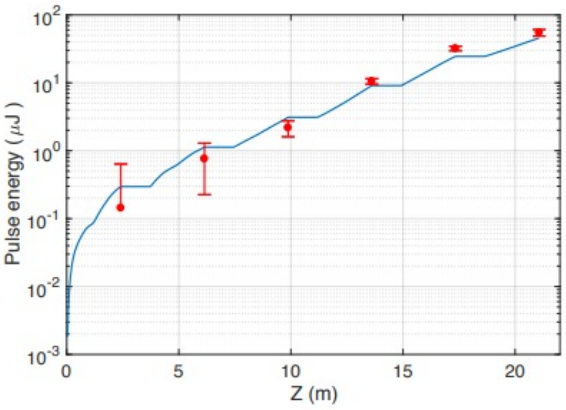
EEHG

[P. Rebernik Ribic, Nat. Phot. 13, 555 (2019)]

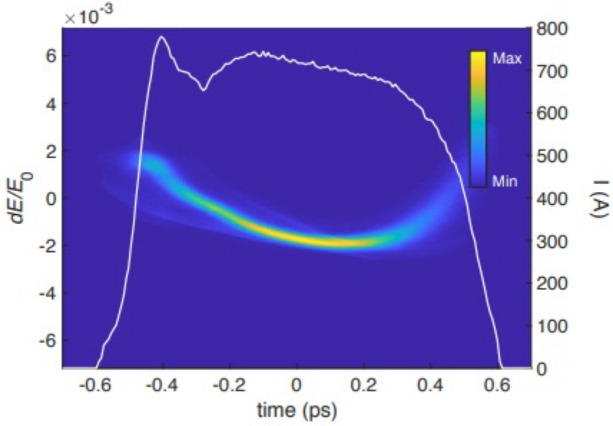
Shortest achieved wavelength with external seeding at FERMI down to 5.9 nm:

- Comparison of single Stage EEHG with cascaded HGHG-HGHG.
- Coherent bunching down to 2.6 nm
- Less sensitivity to residual chirp in electron beam (temporal overlap)

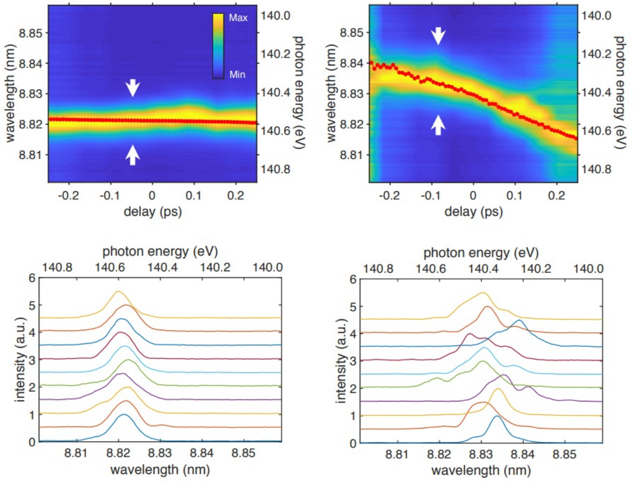
Gain Curve



Longitudinal Phase Space



Wavelength shift with delay between seed and beam



Reaching Shorter Wavelengths

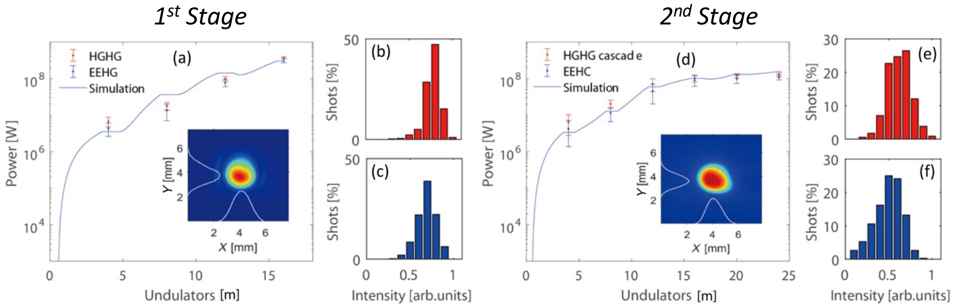
Scaling to 1 nm has many problems:

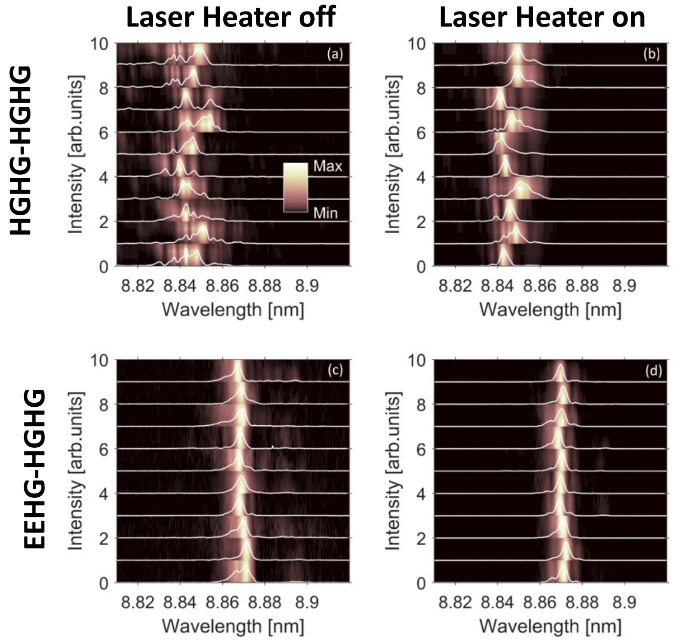
- limited strength of chicanes
- Degrading effect by CSR and IBS
- Sidebands become visible.

Apply HGHG-HGHG or EEHG-HGHG cascade with fresh bunch technique

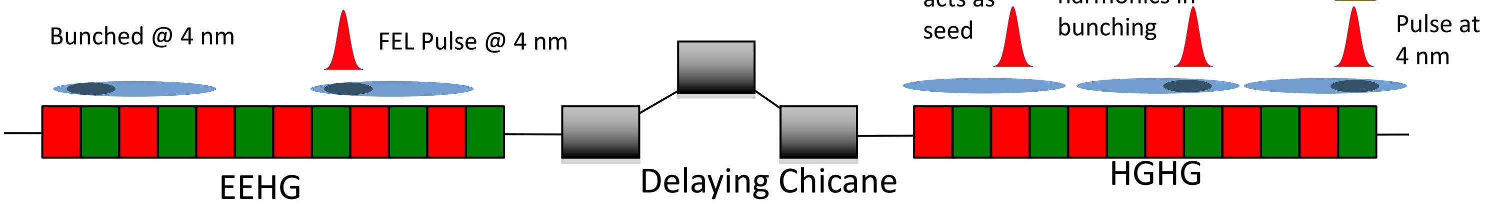
Cascade demonstrated with 44 nm/8.8 nm at SINAP

[C.Feng et al, Optica 7, (2022), 785]





Cascade EEHG-HGHG



Possible Future Research *(Personal Opinion)*

1) Post-saturation Tapering

With large temporal coherence raising the power level above saturation becomes more feasible.
[J. Duris et al, Tapering enhanced stimulated superradiant amplification, New J. of Phys., 17 (2015) 063036]
Similar to superradiance methods a longer undulator is needed.

2) Chirped Pulse Amplification

One of the break-through in quantum laser is the methods of chirped pulse amplification and its application of pulse compression. It might be doable even with a chirps SASE pulse. The key challenges are:

- Losses in the dispersive elements (in particular in the soft X-ray regime).
- Space requirement and tunability in wavelength
- Direction of frequency chirp

3) Direct Seeding in the hard X-ray

How far can we go in photon energies with direct seeding. Is a two-stage EEHG feasible with high repetition rate machine?

Summary

Active research and development to improve FELs beyond standard SASE Operation

Short pulse generation by advanced electron beam manipulation providing sub-fs pulses in the X-ray regime. Open questions/activities:

- **Reliable single spike generation**
- **Locking to external signal**

Self-seeding and/or external seeding to achieve near Fourier-limited FEL pulses. Open questions/activities :

- **With high repetition machines XFELO becomes feasible**
- **Development of external seeding towards shorter wavelength**