Eduard Prat :: SwissFEL Beam Dynamics :: Paul Scherrer Institut

Review of schemes for improved peak power and coherence in X-ray FELs

Future Light Source 2018

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PAUL SCHERRER INSTITUT

Apologies in advance to not include all schemes and to be biased towards SwissFEL!

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- **Conclusion**

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
- State-of-the-art FEL facilities are based on the SASE process starting from the electrons' shot noise. The obtained radiation is not fully coherent over the longitudinal extent of the bunch, being the relative bandwidth in the order of the Pierce-parameter ρ ($10^{-3} - 10^{-4}$ for XFELs)
- In general, standard SASE-FEL is lacking *individual* control on several radiation properties, namely ***longitudinal* coherence**, bandwidth, pulse length and **power**. Moreover, SASE is not intrinsically locked to an external signal.
- Ideally we would like to:
  - Gain more control over the radiation properties: bandwidth, pulse length, power, multiple pulses, external synchronization.
  - Customize FEL radiation for specific user needs
- This talk will review schemes to improve the peak power and the (longitudinal) coherence of XFELs.

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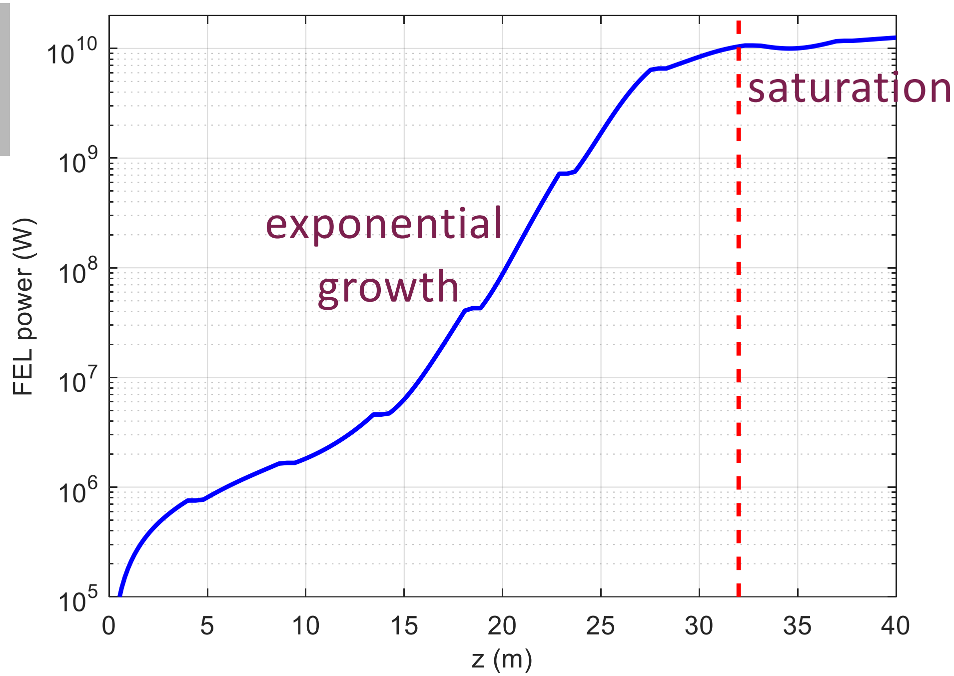
Schemes to improve peak power

Typical power growth along the undulator beamline



FEL power at saturation:

$$P_{FEL} \approx \rho P_{beam}$$

$$\rho = \frac{1}{\gamma_0}\left[\left(\frac{f_c K}{4 k_u \sigma_x}\right)^2 \frac{I}{2 I_A}\right]^{\frac{1}{3}}$$

f_c: coupling factor (~0.9 for planar undulator)

I: electron peak current

σ_x: transverse beam size

I_A: Alfven current (~17 kA)

Emittance and energy spread effectively decrease ρ

- Saturation power limited to 10-100 GW (ρ is 10^{-3} – 10^{-4} for XFELs).
- Saturation power can be increased by increasing ρ, i.e. by improving beam quality: increase current, reduce emittance, reduce energy spread…
- If energy spread is reduced, beam can be effectively more compressed
- Power after saturation can be increased with: tapering and methods based in superradiance

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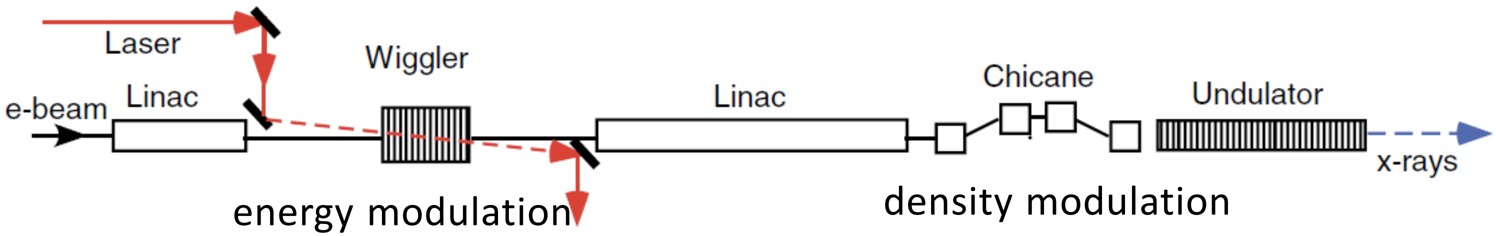
Increase the electron peak current

➢ Use a laser

ESASE and similar schemes: *[A. Zholents, PRSTAB 8, 040701, 2005]*

XLEAP: current project at LCLS to demonstrate attosecond generation with ESASE



➢ Higher compression

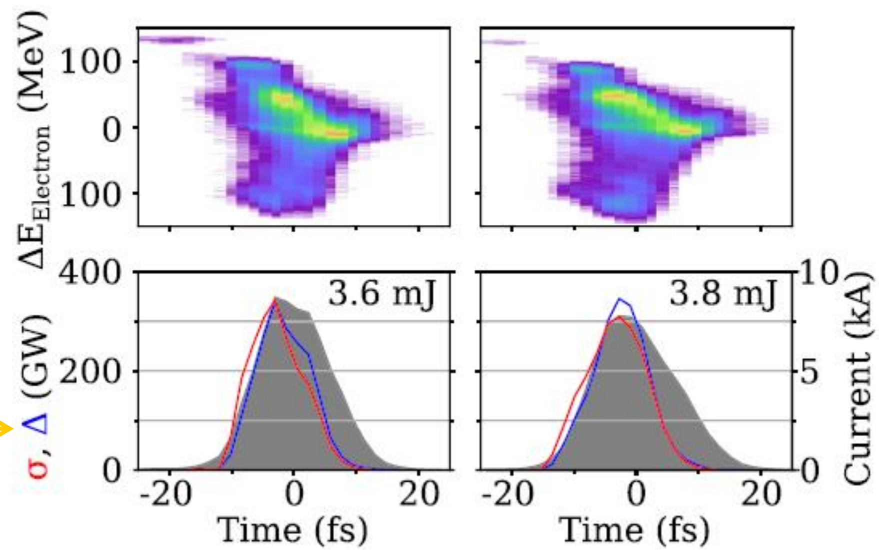
Low charge: attosecond generation demonstrated at LCLS for 20 pC

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

High charge: space charge and CSR limits the performance. Demonstrated solution (250 pC): CSR-beam tilt correction with dispersion

[M. Guetg et al, PRL 120, 014801, 2018]

A factor of 3 improvement in peak power (from ~100 GW to ~300 GW)



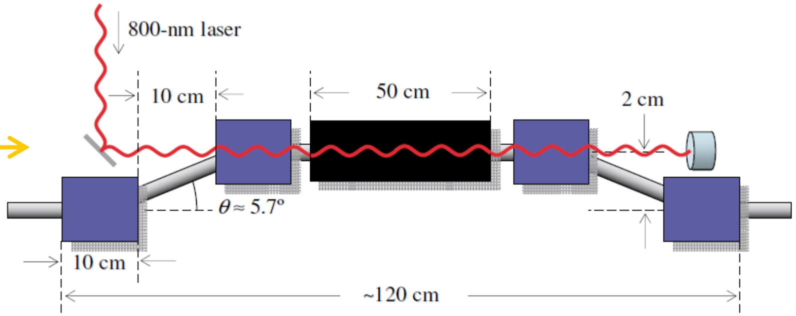
6.6 keV photons

Reduce the energy spread

- Microbunching instability is typically suppressed in XFEL facilities with a "laser heater" *[E. Saldin et al, NIMA 528, 355, 2004]*

LCLS laser heater design

[Z. Huang et al, PRSTAB 7, 074401, 2004]



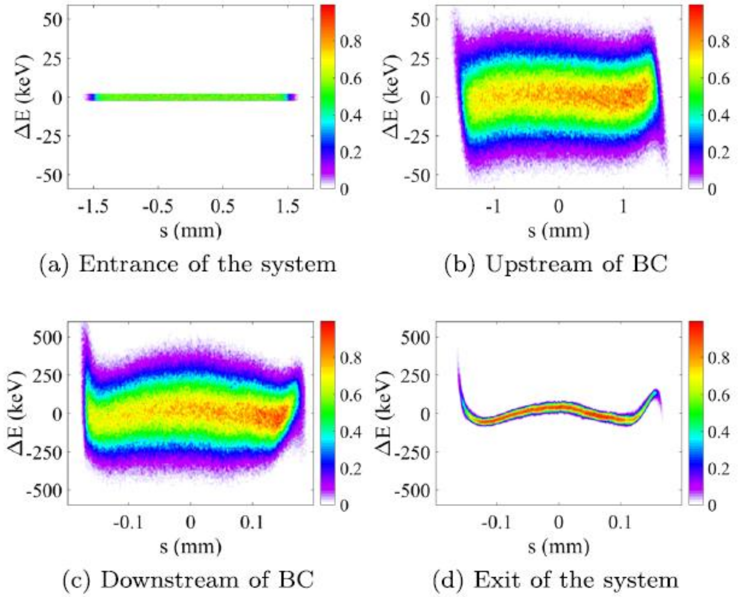
- A laser heater is not an optimum solution since it spoils the beam, decreasing the output FEL power.
- Ideally the heater effect should be reversible (heat before compression, reverse it afterwards)
- Some reversible methods have been proposed :

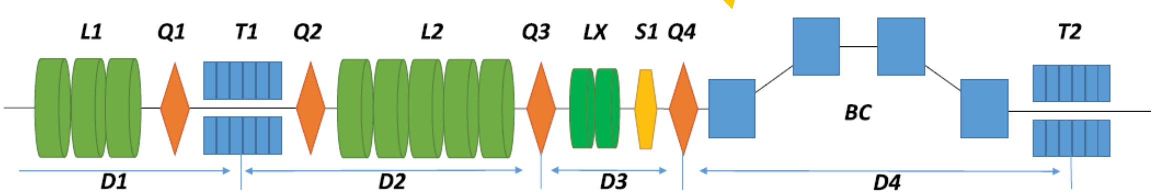
  With transverse-deflectors

  [C. Behrens et al, PRSTAB 15, 022802, 2012]

  With transverse-gradient undulators

  [T. Liu et al., PRAB 20, 082801, 2017]





- Reversible methods not experimentally verified yet

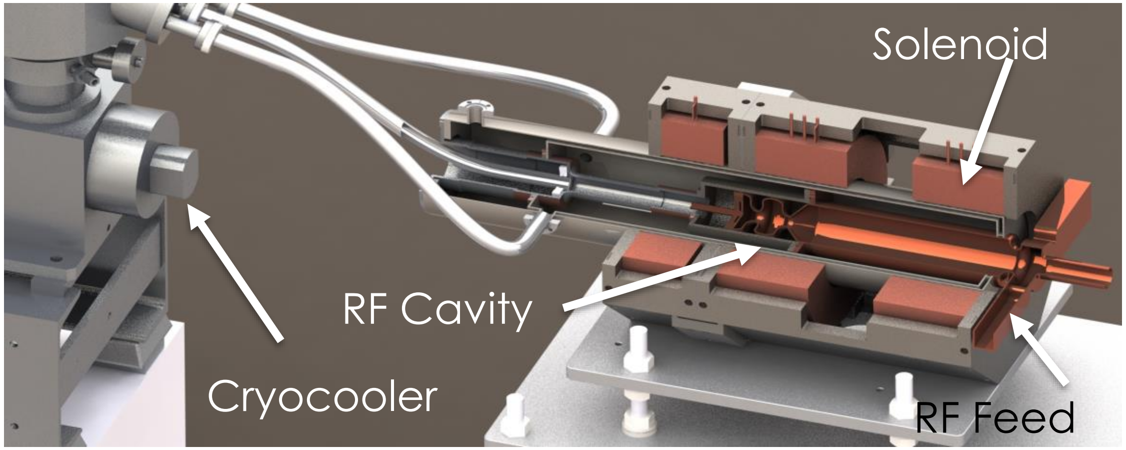
Reduce the emittance

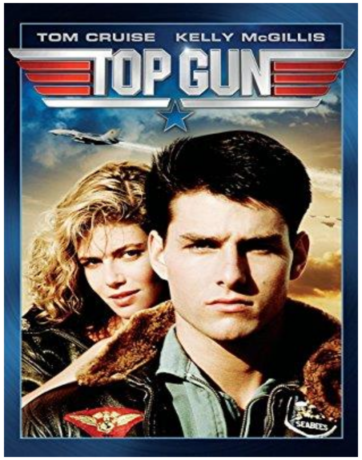
- ➢For a given energy, higher FEL powers can be obtained with smaller emittances
- ➢Moreover, for small emittances, further enhancement by stronger focusing is possible

Emittance is defined by the source, normally an RF photoinjector. How to improve it?

➢Increase RF field:

- Higher frequencies, e.g. X-band : *[C. Limborg-Deprey et al, PRAB 19, 053401, 2016]* – 200 MV/m, higher brightness but worse emittance
- Cryogenic : *[A. Cahill et al, NIMA 865, 105, 2017], [J. Rosenzweig et al, arXiv: 1603.01657, 2016].* Expected emittances ~40 nm for 100-200 pC, brightness increased by 25





➢Improve cathode (thermal) emittance with new materials:

- Standard materials (Cu and Cs_2Te) have shown an intrinsic emittance down to 500 nm/mm *[E. Prat et al, PRSTAB 18, 043401, 2015]*
- Other materials such as alkali antimonide showed ~200 nm/mm *[H. Lee et al. APL 108, 124105, 2016]*

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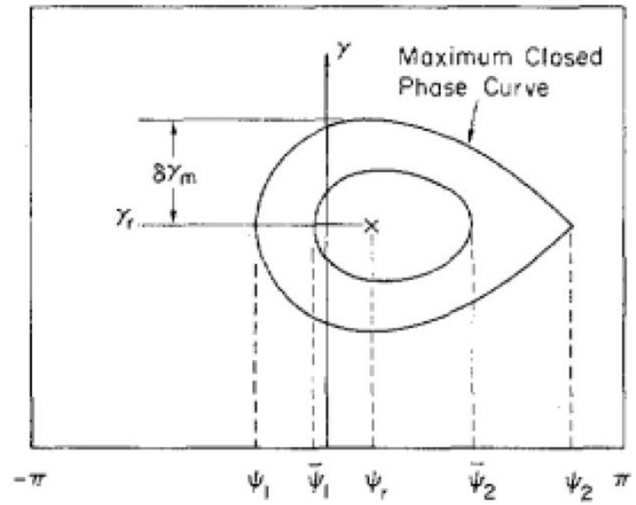
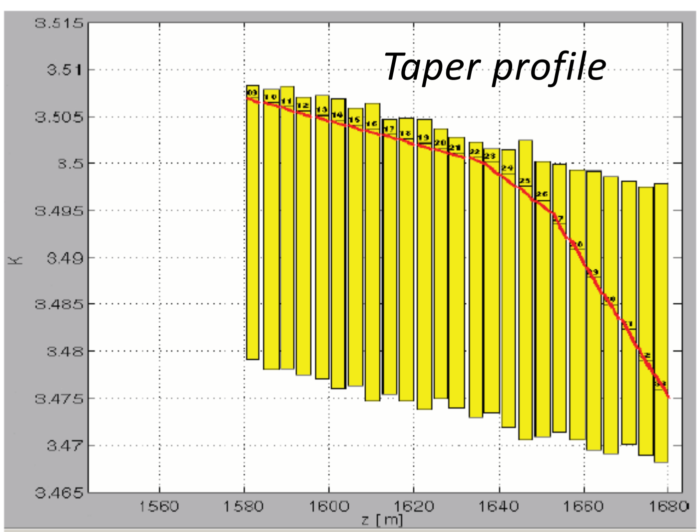
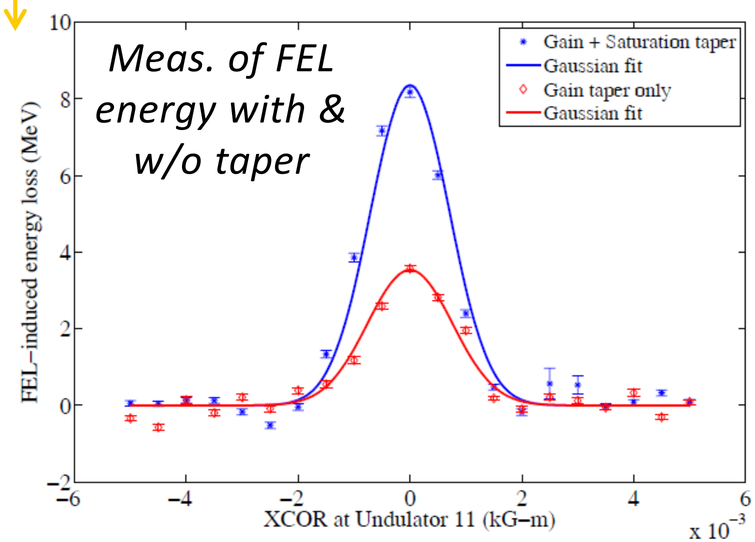
Tapering

- It consists in changing the undulator field to keep the resonance condition by compensating the energy loss of the electrons.
- The electrons are trapped in the FEL radiation bucket to maintain energy transfer from the electron beam to the radiation field.
- Proposed almost 40 years ago *[N. Kroll et al, IEEE JQE 17, 1436, 1981]*
- Experimentally demonstrated for SASE, e.g. at LCLS: *[D. Ratner et al, FEL09, 221, 2010]*



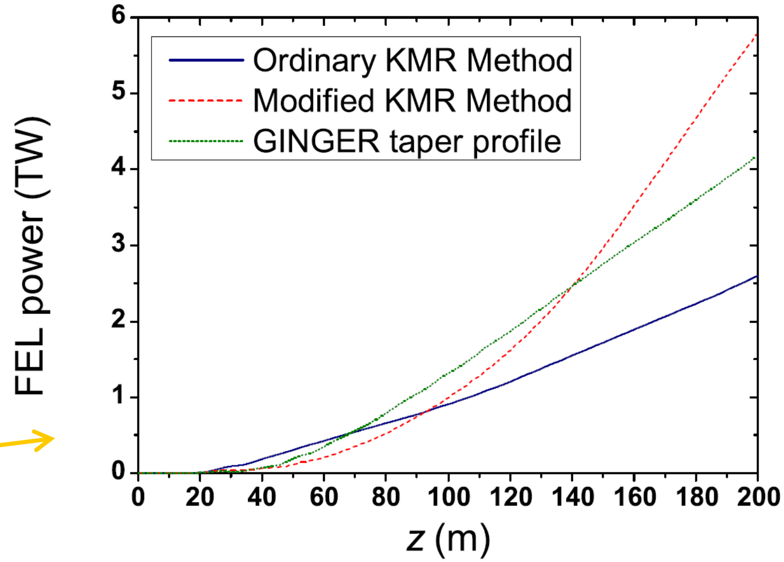




Increase of FEL pulse energy by more than a factor of 2

Tapering

- Tapering works better if coherence is higher than in SASE *[W. Fawley et al, NIMA 483, 537, 2002]*
- Extensive research on how to optimize taper profile (model and simulations), e.g. *[E. Schneidmiller and M. Yurkov, PRSTAB 18, 030705, 2015]* *[A. Mak et al, PRSTAB 18, 040702, 2015]*



- Optimization work also with other parameters, such as transverse beam distribution, phase shifters and focusing in the undulator line, e.g.

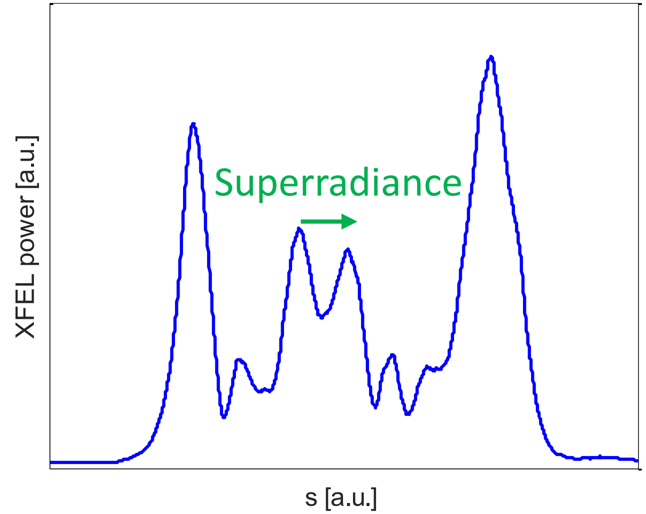
  [Y. Jiao et al, PRSTAB 15, 050704, 2012]

  [C. Emma et al, PRSTAB 17, 110701, 2014]
- Simulations show that several TW of power should be possible…
- … but high-efficient taper has not been yet empirically demonstrated (requires long undulators)

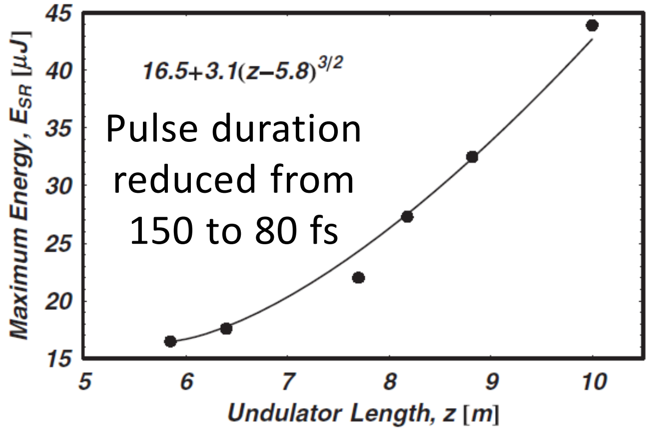
- Limit: Side-band instabilities (detrapping effect, bunching is destroyed)

Superradiance

- Regime after exponential growth where there is a quadratic increase of the FEL power and a shortening of the pulse length
- In SASE the growth stops 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



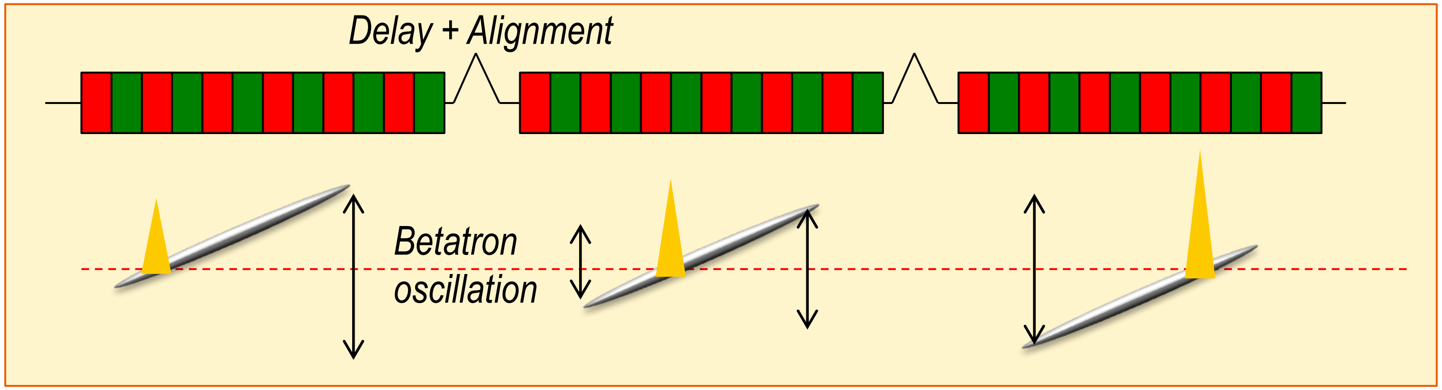
- It is an old concept… : *[R. Bonifacio et al, NIM A 296, 358, 1990], [R. Bonifacio et al, PRA 44, R3441, 1991]*
- … demonstrated for λ~800 nm ~10 years ago: *[T. Watanabe et al, PRL 98, 034802, 2007]*



- There are several proposals promising TW-as pulses for XFELs. These methods use inter-undulator chicanes to shift the photons to fresh parts of the electron bunch. The fresh regions are obtained tailoring some beam property:
  - Current: *[T. Tanaka, PRL 110, 084801], [T. Tanaka et al, JSR 23, 1273, 2016]*
  - Emittance: *[E. Prat and S. Reiche, PRL 114, 244801, 2015]*
  - Trajectory: *[E. Prat et al, PRSTAB 18, 100701, 2015]*
- None of these methods has been (fully) demonstrated yet.

Example: use a transverse beam tilt

- Shift the FEL pulse to fresh electrons for “superradiant” amplification (with chicanes)
- Thee fresh bunch slices are derived from a realignment of a tilted beam.



[E. Prat, F. Löhl and S. Reiche, PRSTAB 18, 100701 (2015)]

Simulation results for SwissFEL

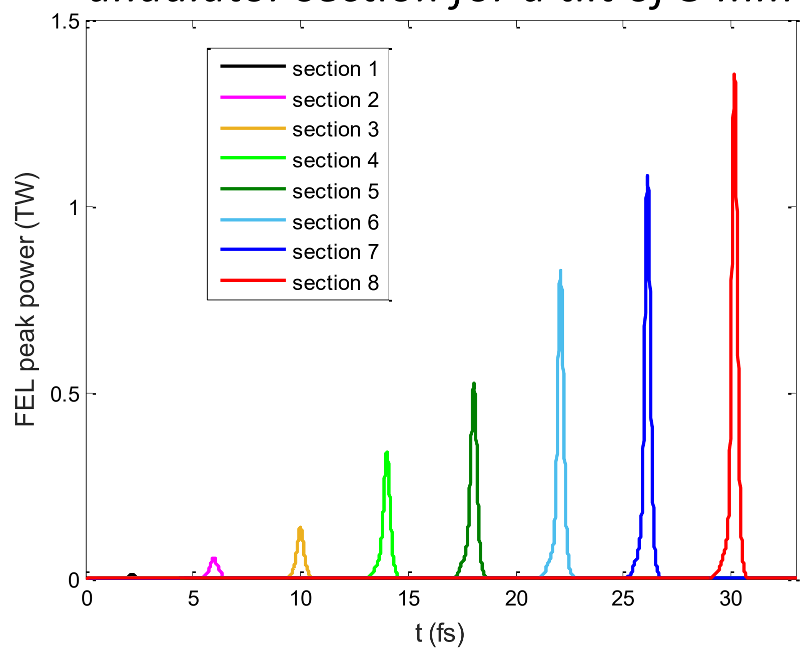
20 modules (x 2m), 2 nm, 6 kA, 8 sections

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-as pulses can be obtained (also for hard X-rays)

Partially demonstrated at LCLS with 3 sections *[unpublished]*

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



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External seeding

Key idea: properties of the laser (coherence) are transferred to the FEL radiation

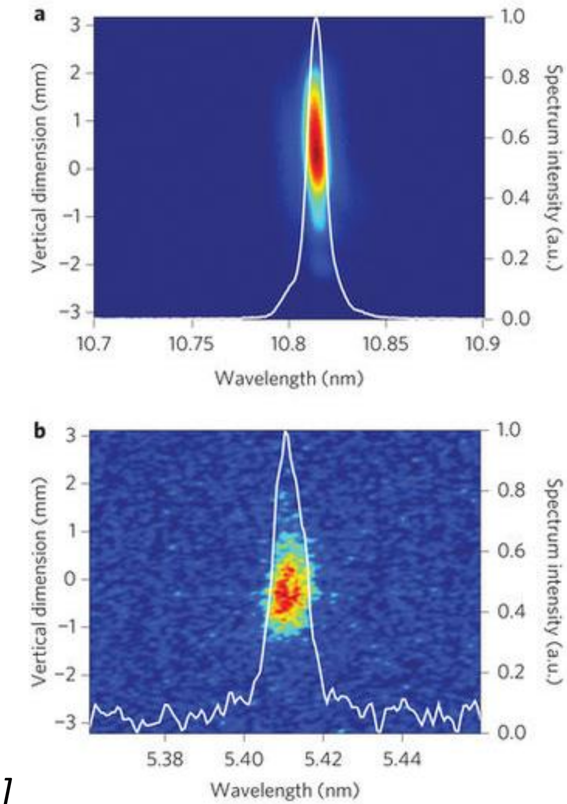
1. Direct seeding with high-harmonic generation source

[E. Ferray, J. Phys. B 21, L31, 1988]

- Demonstrated down o 40 nm

  SCSS at 60 nm: *[T. Togashi et al, Optics Express 19, 317, 2011]*

  FLASH at 40 nm: *[S. Ackermann et al, PRL 111, 114801, 2013]*



2. Using modulators and chicanes:

2.1. High-gain-harmonic generation (HGHG)

- Proposed long time ago: *[L. Yu, PRA 44, 5178, 1991]*
- Demonstrated at FERMI with single and double stage down to 4 nm: *[E. Allaria et al, Nat. Photonics 7, 913, 2013]*

2.2. Echo-enabled harmonic generation (EEHG)

- Proposed about 10 years ago: *[G. Stupakov, PRL 102, 074801, 2009]*
- First demonstration at 350 nm in 2012: *[Z. Zhao et al, Nat. Photonics 6, 360, 2012]*
- Recently demonstrated 75th harmonic at 32 nm: *[E. Hemsing et al, Nat. Photonics 10, 512, 2016]*
- Presently FERMI is running a project to achieve EEHG down to 5 nm (and to compare performance with HGHG)

Difficult to go < 4 nm due to due to wavelength limitations of lasers and noise degradation problems

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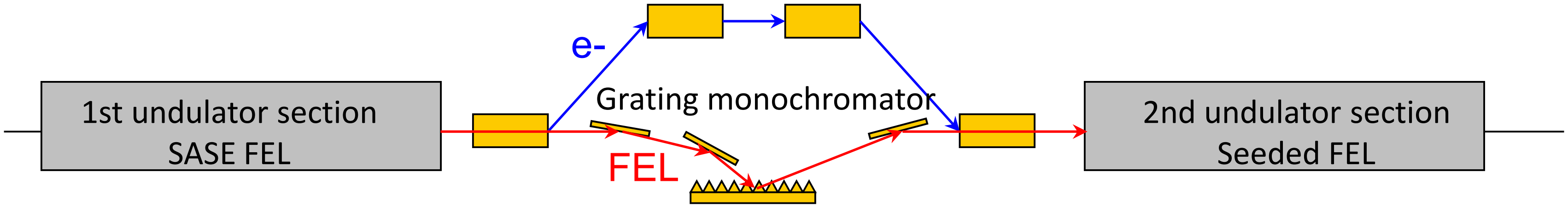
Self-seeding

- First concept developed more than 20 years ago for soft X-rays: SASE signal from 1st undulator section is monochromatized and seeded in a 2nd undulator section
  [J. Feldhaus et al, Optic Comm. 140, 341, 1997]



- For hard X-rays: use crystals as monochromator

[E. Saldin et al, NIMA 475, 357, 2001], [G. Geloni and E. Saldin, DESY 10-053, 2010]

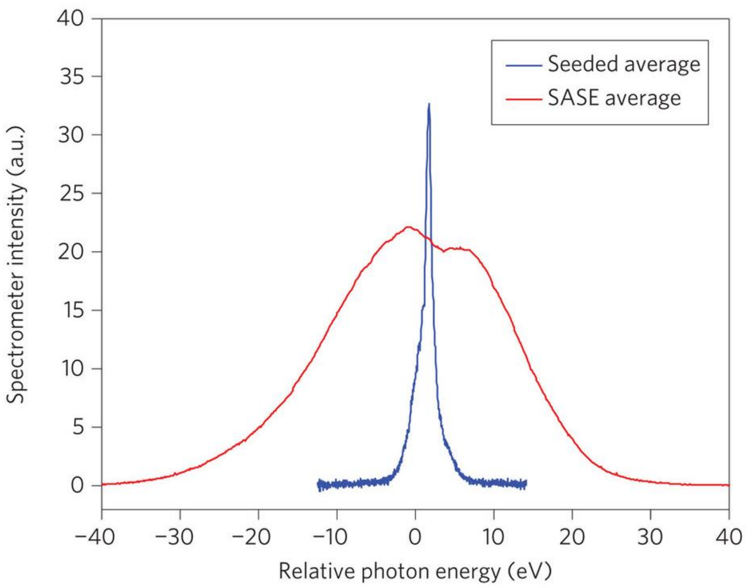
Demonstrated at LCLS:

Hard X-rays: *[J. Amann et al, Nat. Phot. 6, 693, 2012]*

Bandwidth reduction of 40-50

Soft X-rays: *[D. Ratner et al, PRL 114, 054801, 2015]*

Bandwidth reduction of 10-30



Improvement: fresh-slice self-seeding

[C. Emma et al, APL 110, 154101, 2017]: 2 times higher brightness

Limitations: SASE pedestal and coherence (specially for soft X-rays)

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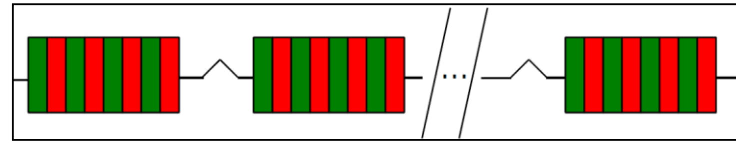
High-brightness SASE (HB-SASE)

The cooperation length is increased by delaying the electrons with respect to the photons between undulator modules

[N. Thompson et al, IPAC2010, 2257, 2010]

[B. McNeil et al, PRL 110, 134802, 2013]



- Pros:

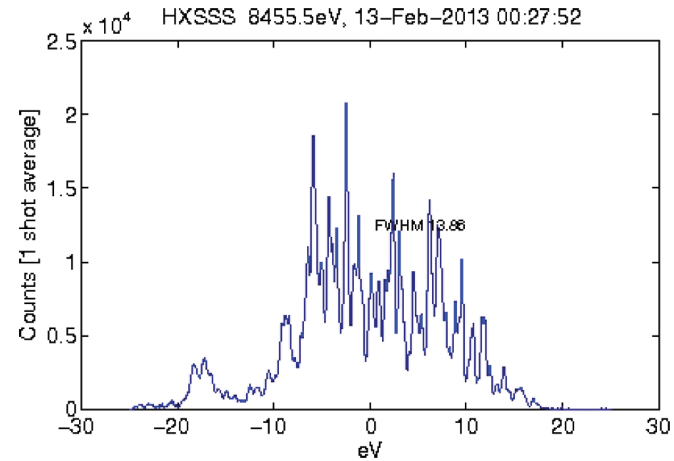
Potentially as good as self-seeding

It improves the problem of pedestal in self-seeding

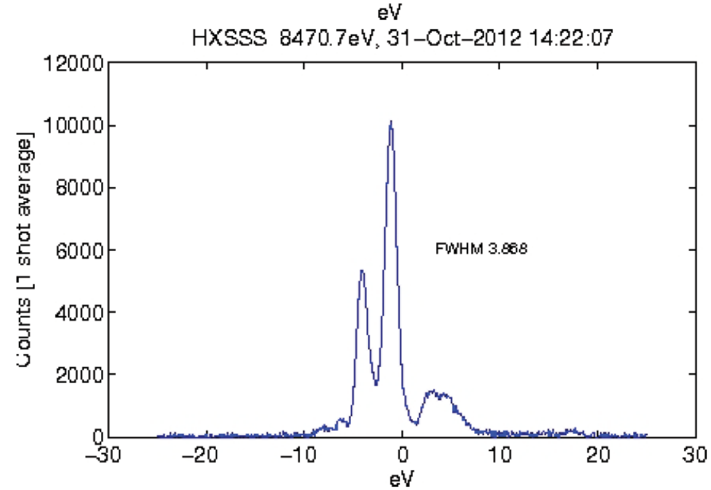
It does not require a monochromator

It works for any repetition rate

It is more compact than self-seeding



- It requires chicanes between undulator modules and *short* undulator modules
- Demonstrated an improvement in bandwidth of 3.5 at LCLS by detuning some undulator segments *[J. Wu et al, IPAC2013, 2068, 2013]*
- Planned to be fully exploited at other facilities (e.g. Clara and SwissFEL)
- It could be used in first stage of self-seeding

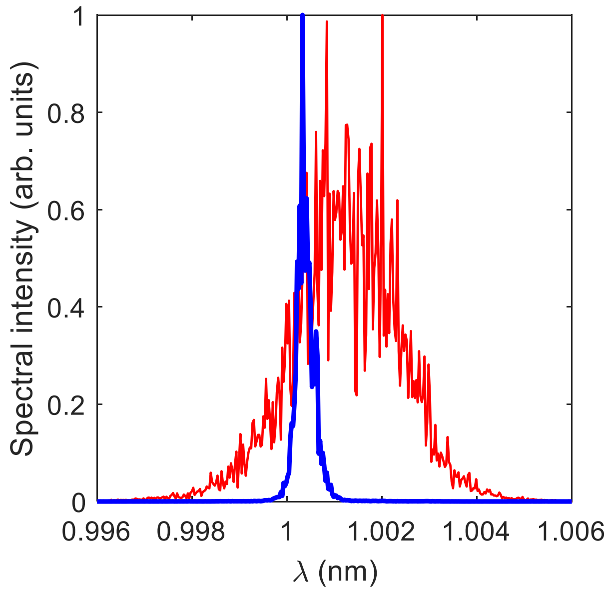


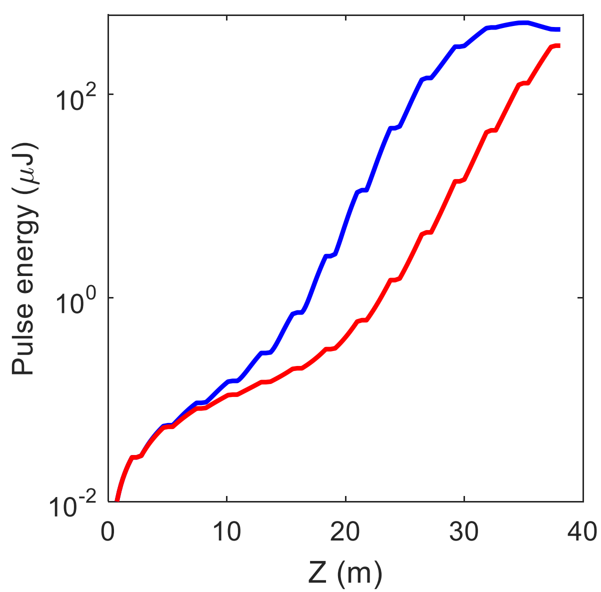
Compact and simple HB-SASE

- Original HB-SASE: isochronous chicanes + increased delay with each step.
- Isochronous chicanes need quadrupole magnets and are long.
- Dispersive chicanes (with only bending magnets) are simpler and shorter.
- HB-SASE does not work with dispersive chicanes and increased delay (overbunching)

- Proposal: **compact and simple HB-SASE**
  - With dispersive chicanes and decreased delays at each step
  - As a result: No overbunching + more compact (optical klystron effect)

Simulation results for SwissFEL (1 nm)





In comparison to SASE:

10 times brighter

30% shorter saturation length

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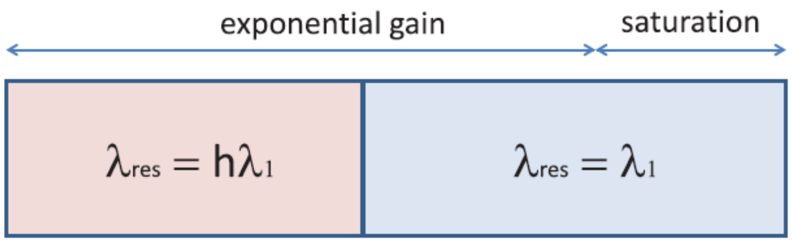
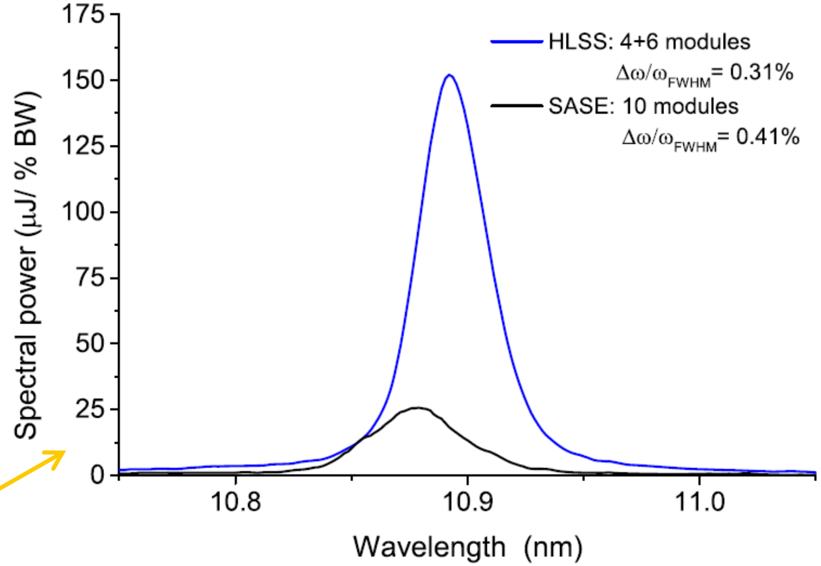
Harmonic lasing self-seeded

- First part tuned to a subharmonic of the wavelength of interest. FEL process stops well below saturation. Generation of light at the subharmonic (fundamental) and the wavelength of interest (harmonic)
- Second part tuned to the wavelength of interest. Power is enhanced up to saturation.
- Bandwidth is defined by harmonic lasing→ the brightness is increased
- Improvement is much less than in self-seeding or HB-SASE but it only requires variable-gap undulators
- Experimentally demonstrated at FLASH2 *[E. A. Schneidmiller et al PRAB 20, 020705, 2017]*

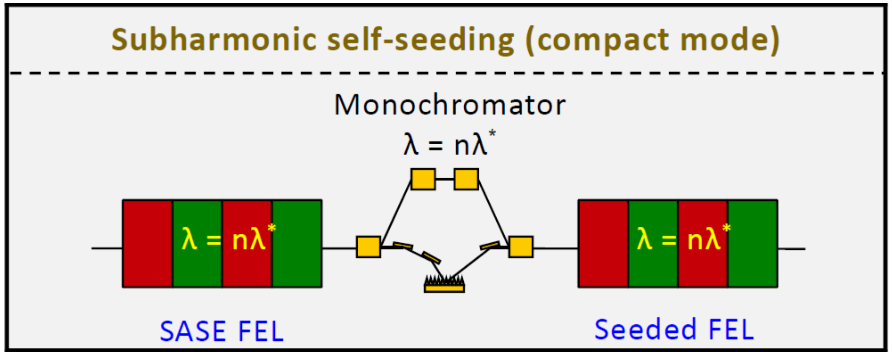
[E. A. Schneidmiller and M. V. Yurkov, PRSTAB 15, 080702, 2012]

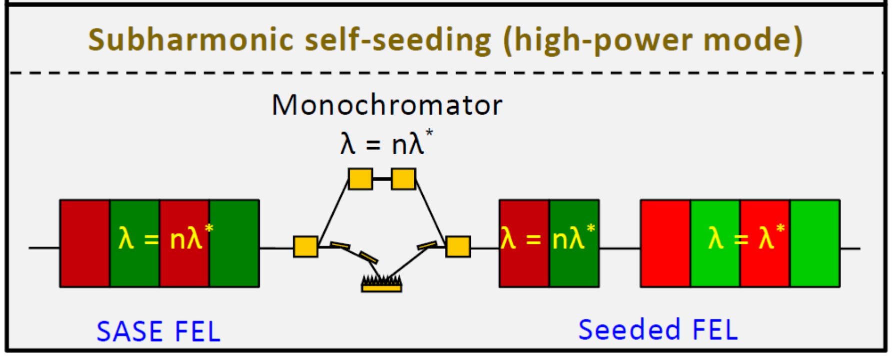




Bandwidth improved by 25%

Subharmonic self-seeding



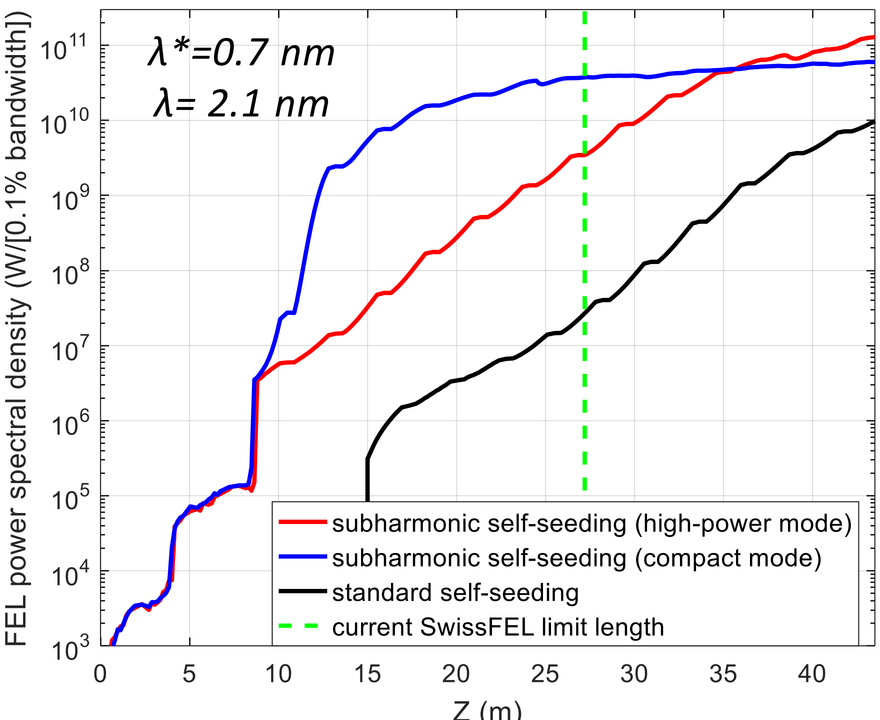


- It combines self-seeding and harmonic lasing
- 1st stage + monochrom. tuned to a subharmonic of the wavelength of interest λ^* ($\lambda = n\lambda^*$)
- Benefits wrt standard self-seeding: higher coherence, compactness, easier monochromator
- **Compact and high power modes.**

[E. Prat and S. Reiche, JSR 25, 329, 2018]

Simulations for SwissFEL with *n=3* show:

- Coherence improvement of a factor 2/3 for compact/high power modes
- For a given space brightness increases by more than one order of magnitude



Previous similar proposals:

[G. Geloni et al, DESY Report 11-224, 2011]. High-power mode using bunching at 2nd harmonic

Harmonic laser self-seeded: high-power mode for SASE

Summary

High power:

- Standard FELs can already provide up to ~100 GW
- Lasers can be used to increase peak current (e.g. ESASE, soon to be proven at LCLS)
- Recently 300 GW were obtained at LCLS by increasing peak current with compression
- Saturation power can be improved with better emittances (new sources required) and lower energy spreads (need to find a *reversible laser heater*)
- Tapering works for SASE, high-efficient taper promises TW but is not demonstrated yet
- Methods based on superradiance are promising but have not been experimentally proven yet for XFELs

Coherence:

- Laser-based seeding is great but limited to 3-4 nm
- Self-seeding works for soft and hard X-rays but it can be improved
- High-brightness SASE may be a good alternative for X-rays. It needs to be experimentally verified
- HLSS is a simple scheme to moderately improve the coherence of SASE pulses
- Subharmonic self-seeding can improve the efficiency of self-seeding

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Next generation of XFEL facilities

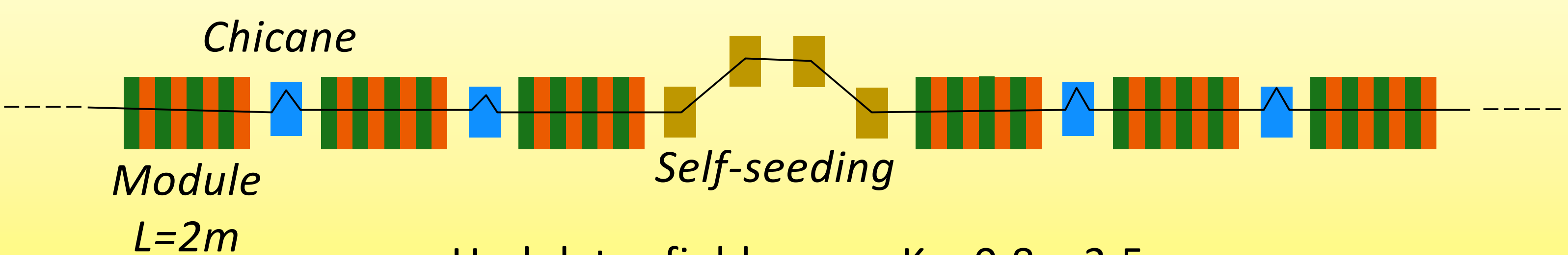
Challenges:

- Improve existing methods (i.e. self-seeding, tapering)
- Verify other methods (HB-SASE, superradiance)
- Develop new methods

How should be the new generation of FEL facilities?

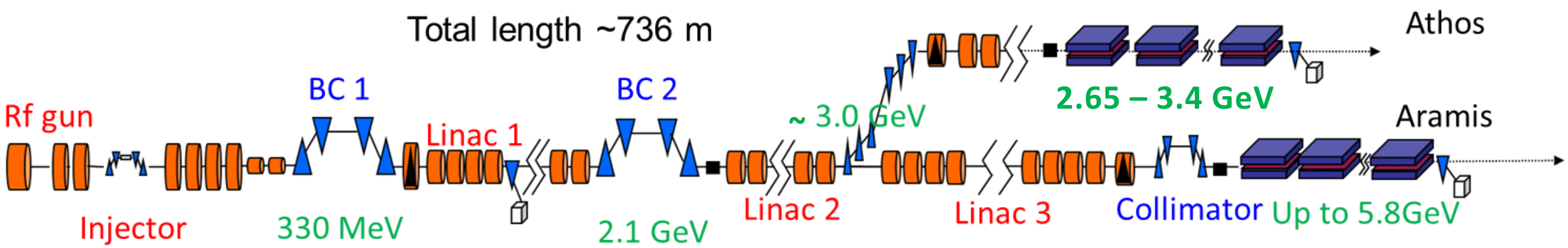
- Undulator beamline: flexible modules (large tunable range for field, polarization)
  with chicanes between modules
  with self-seeding option
  with optimum module length (shorter than standard)
  flexible in space for future updates
- Able to shape the electron beam (e.g. slotted foil, beam tilts)
- Bonus: have one or more lasers (to shape and synchronize the beam)

Example: Athos, the soft X-ray beamline of SwissFEL



Undulator field range: K = 0.8 – 3.5

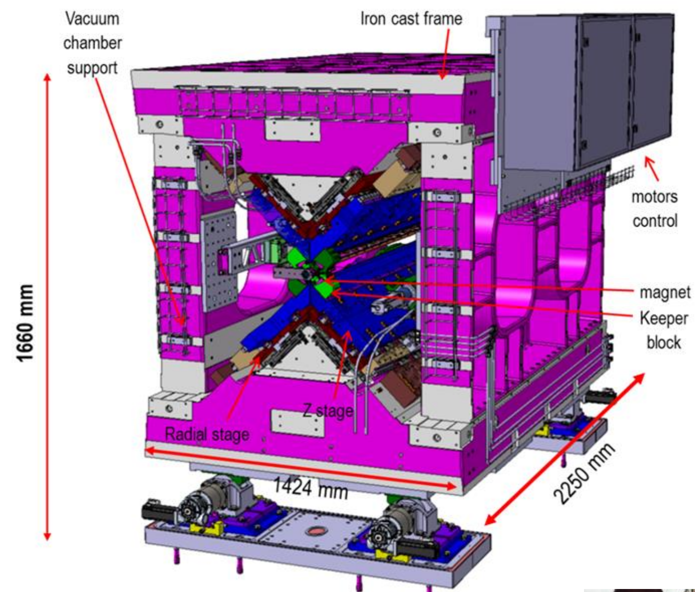
Athos: the soft X-ray beamline of SwissFEL



- SwissFEL will (initially) serve 2 beamlines:

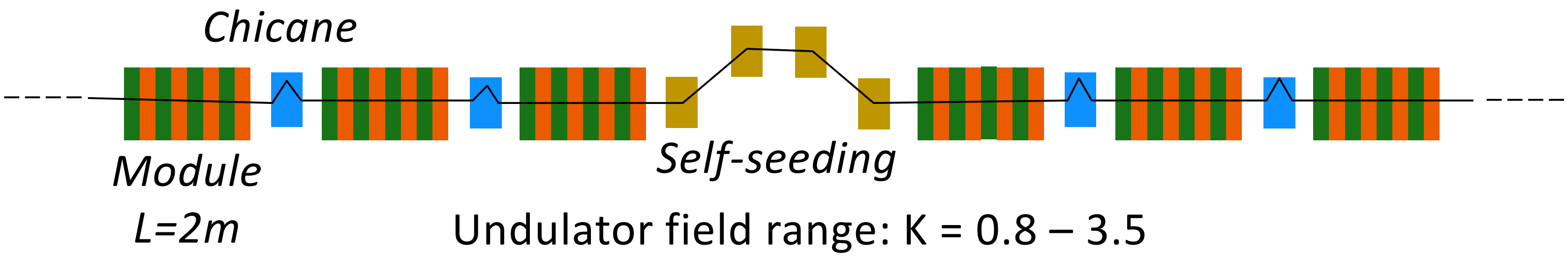
  Aramis: 0.1-0.7 nm.
  - Commissioning started in 2016
  - First lasing @24 nm Dec. 2016
  - First XFEL light in 2017

  Athos: 0.65-5 nm.
  - First lasing expected in 2019



- Athos undulators :
  - APPLE devices
  - Undulator field parameter: K = 0.8 – 3.5
  - Able to provide continuous taper and transverse gradient
  - Variable polarization
  - Initially 16 modules with a length of 2 m each

Overview of Athos Operation Modes



Undulator field range: K = 0.8 – 3.5

Basic Modes + Enhancement

- SASE
- Optical klystron
- Harmonic lasing

Spectral Control

- High-brightness SASE
- Large bandwidth mode*
- Self-seeding (standard and subharmonic)

High-power modes

- High current with compression
- Tapering
- High power and short pulses based on superradiance*

Other modes

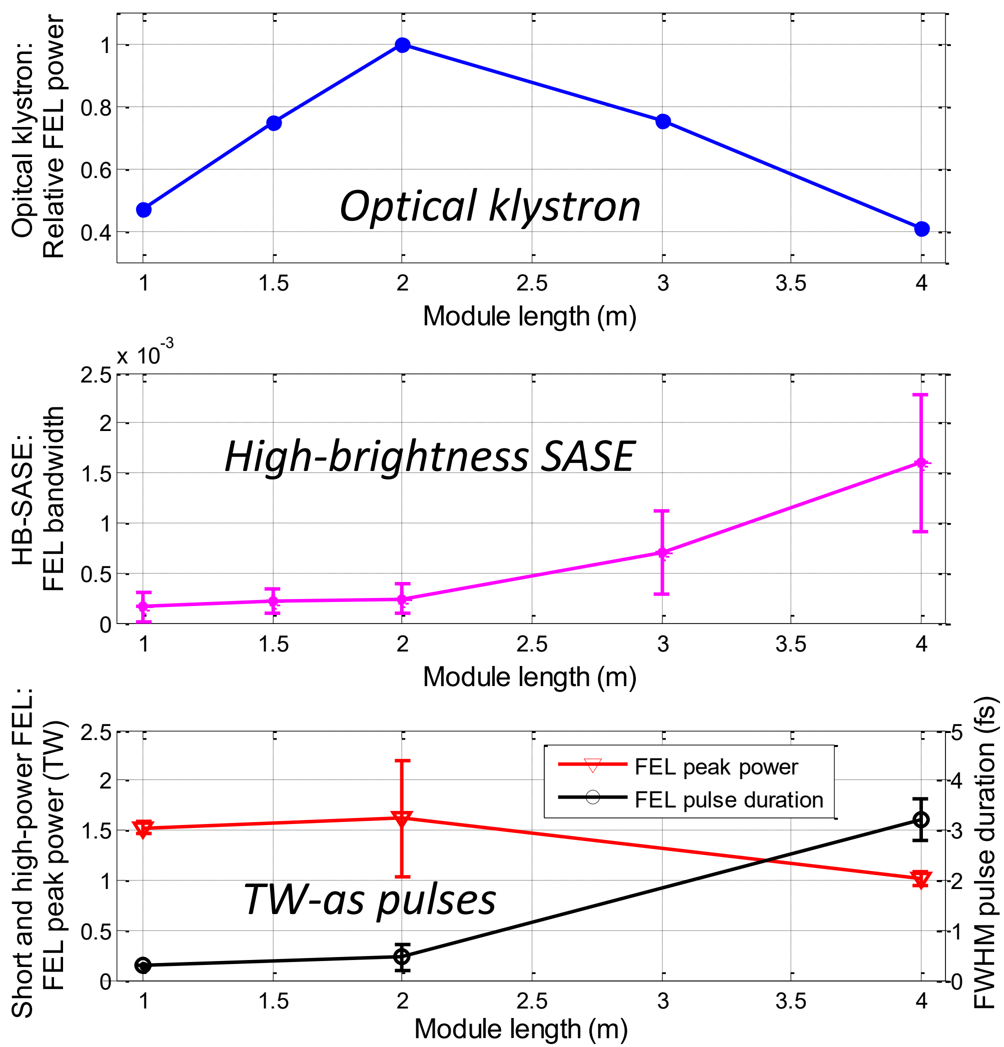
- Two colors*
- Mode-locked lasing
- Slicing

Legend:

APPLE-X Configuration | *Tilt** | *Chicanes* | *Self-seeding chicane* | *Baseline* | *Not Baseline*

Optimization of undulator module length

Summary of FEL performance as a function of the undulator module length (1 nm)



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

- In most of FEL facilities, the module length is not optimized based on FEL performance
- Typical undulator module length is about 3-5 m
- Most of the modes benefit from shorter modules

Based on physics and costs

Final module length is 2 m

(in original design was 4 m)

Contents

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Conclusion

- XFEL users would benefit from higher power and improved coherence than the one obtained at state-of-the-art facilities
- Several methods have been proposed:
  - Power: tapering, superradiance…
  - Coherence: self-seeding, high-brightness SASE…
- Some of them need to be improved, others verified.
- Future XFEL facilities should be able to accommodate most of these schemes and the new to come.
- Athos at SwissFEL → flexible and short undulator modules + intra-undulator chicanes + self-seeding + …

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- Thanks to all of you for your attention!