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

Full Coherence Control for Porthos

Porthos Brainstorming Meeting – May 2023

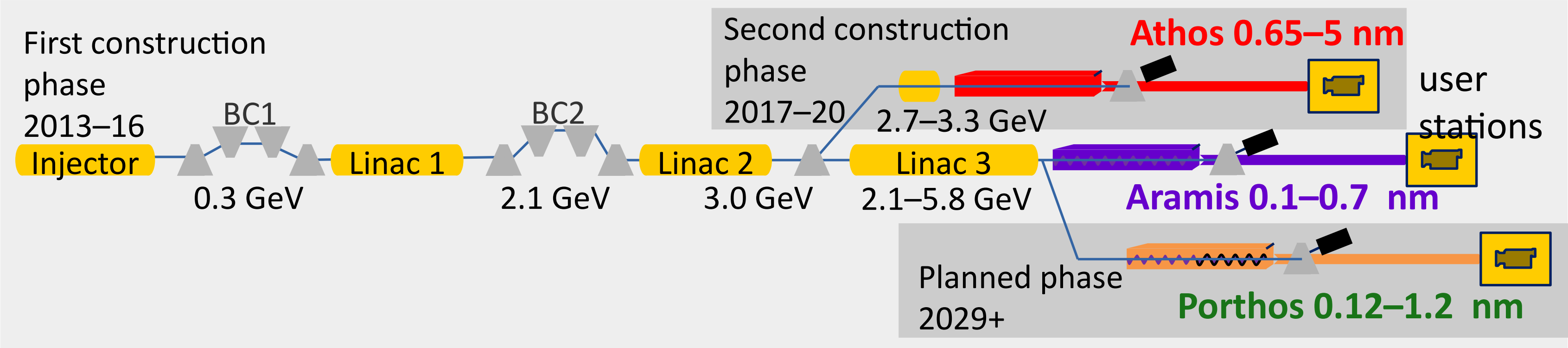
Porthos Project

Athos:

Soft X-ray FEL, λ=0.65–5.0 nm

Variable polarization, Apple-X undulators

First users 2021



Porthos (current planning):

Linac energy upgrade (< 7 GeV)
λ=0.12–1.2 nm
Variable polarization
Cryo-Apple or SCU
25 mm undulator period

self-seeding
two-color operation
high power, short pulses
beam manipulation with external laser

Aramis:

Hard X-ray FEL, λ=0.1–0.7 nm

Linear polarization, variable gap, in-vacuum undulators

First users 2018

Glossary of FEL and Beam Dynamics Concepts

SASE FEL
FEL starts from the incoherent undulator radiation. The FEL process builds up coherence but longitudinally it still limited

Self-Seeding
A two stage process with the first stage as a SASE FEL filtered by a monochromator. The second stage amplifies this signal till saturation

Intra-Undulator Chicanes
Magnetic field which delays the electron beam with respect to the radiation field. It shifts electrons in their longitudinal position depending on their energy. The strength of this shift is expressed by the R56 value

Energy Chirp
A correlation between the longitudinal position of the electrons and their energy. In SASE operation – since it is a self-tuning process – the chirp is transferred to the photon beam

Beam Tilt
A transverse misalignment of the electrons, depending on its longitudinal position. Only a fraction of the electron beam stays on axis and can amplify the radiation

Fresh-Bunch Technique
If not the full bunch is lasing, e.g. by a beam tilt,the FEL amplification can be continue by overlapping the FEL radiation with a part of the bunch, which has been aligned to the undulator axis.

Outline

Self-Seeding

- Basic Configuration
- Fresh Bunch Technique
- Advanced Methods

Short Pulses

- Standard Methods
- Multi-stage Fresh Bunch Technique
- Self-Modulation
- Externally Synchronized Short Bunches

External Seeding

- Seeding with Athos Beam
- External Radiation Source at 13.5 nm
- Short Pulses

Conclusion

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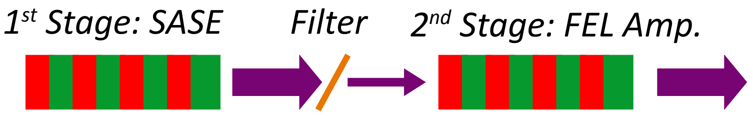
Self-Seeding

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

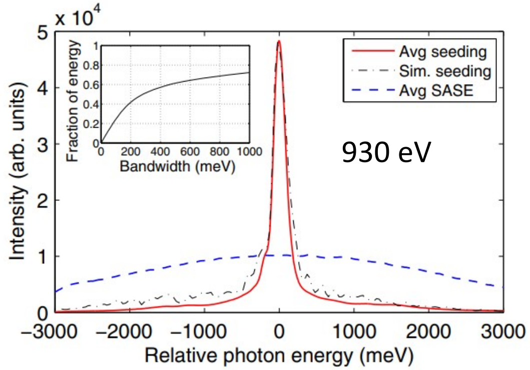
Delaying chicane match electron beam and filtered X-ray radiation and wipes out any bunching from first stage



Soft X-rays

Idea: *J. Feldhaus et al., Optics Comm. 140, (1997), 341*

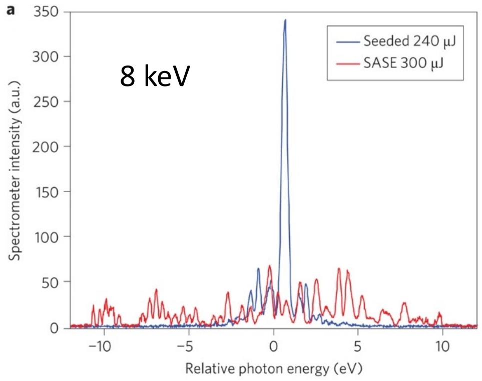
Demonstration: *D. Ratner et al, PRL 114, (2015), 054801*



Hard X-ray

Idea: *G. Geloni et al, J. Mod. Optics 58, (2011), 1391*

Demonstration: *J. Amann, et al., Nature Photonics 6, (2012), 180*



Implementing Self-seeding at SwissFEL will complement the existing portfolio of FEL Modes

Self-Seeding

Self-Seeding requires much longer undulators than basic SASE operation, since the FEL process is restarted by the filtering process.

Self-seeding has to avoid that the first stage drives the beam into saturation. The beam would not able to amplify the filtered radiation in the second stage otherwise.

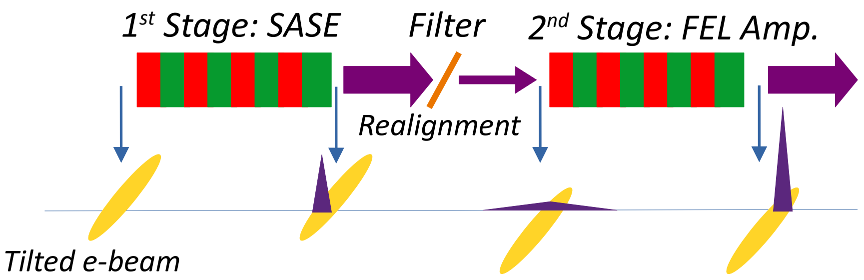
More stable operation can be used with fresh-bunch technique with a tilted beam. The second half will provide the SASE amplification till saturation and then the filtered signal is than overlapped with the first half, which has been realigned to the undulator axis.

Pro:

- Fresh-bunch techniques for better stability and cleaner signal (*See next slide*)
- Two-color operation mode comes for free
- Space for post-saturation taper
- Same-bunch technique is still usable

Cons:

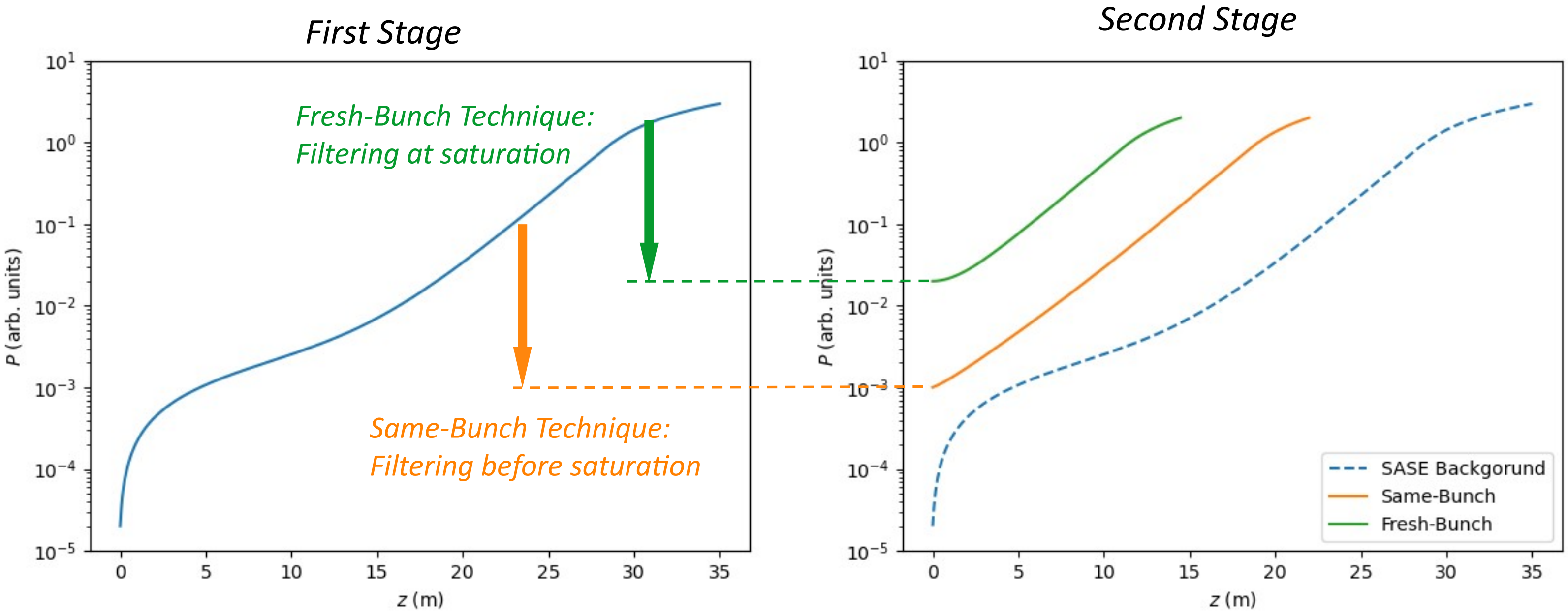
- Longer Undulator



Self-Seeding (same bunch vs fresh bunch)

Same-bunch technique needs to extract signal way before saturation to prevent degradation of beam quality, needed to lase in second stage.

Fresh-bunch technique has same power, better signal-noise contrast, but less pulse energy



Bandwidth of Self-Seeding

Same-Bunch self-seeding covers the full bunch. Thus the bunch length defines the coherence length and thus the spectral bandwidth.
Fresh-bunch technique has overall a shorter coherence length since half of the bunch is used for generating the seed signal and only the second half will amplify it.

PAL: [*I. Nam et al, Nat. Phot. 15, 435 (2021)*]

Photon Energy (keV)	Bandwidth (eV)	Pulse Energy (mJ)
3.5	0.95	0.93
9.7	0.19	0.85
14.6	0.32	0.26

SACLA: [I. Inoue et al, FEL Conference 2019]

Photon Energy (keV)	Bandwidth (eV)	Pulse Energy (mJ)
10.0	0.5 (FWHM)	0.15

LCLS: [[1]J. Amann *et al, Nat. Phot. 6, 693 (2012)*]
[[2]https://lcls.slac.stanford.edu/machine-faq (2021)]

Photon Energy (keV)	Bandwidth (eV)	Pulse Energy (mJ)
8.3[1]	0.4 (FWHM)	0.05
> 4.5[2]	0.35 – 1.5	0.25-0.5

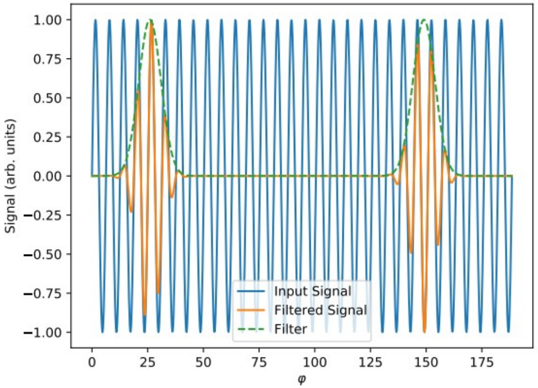
European XFEL: [S. *Liu et al, Nat. Phot. 17, 984 (2023)*]

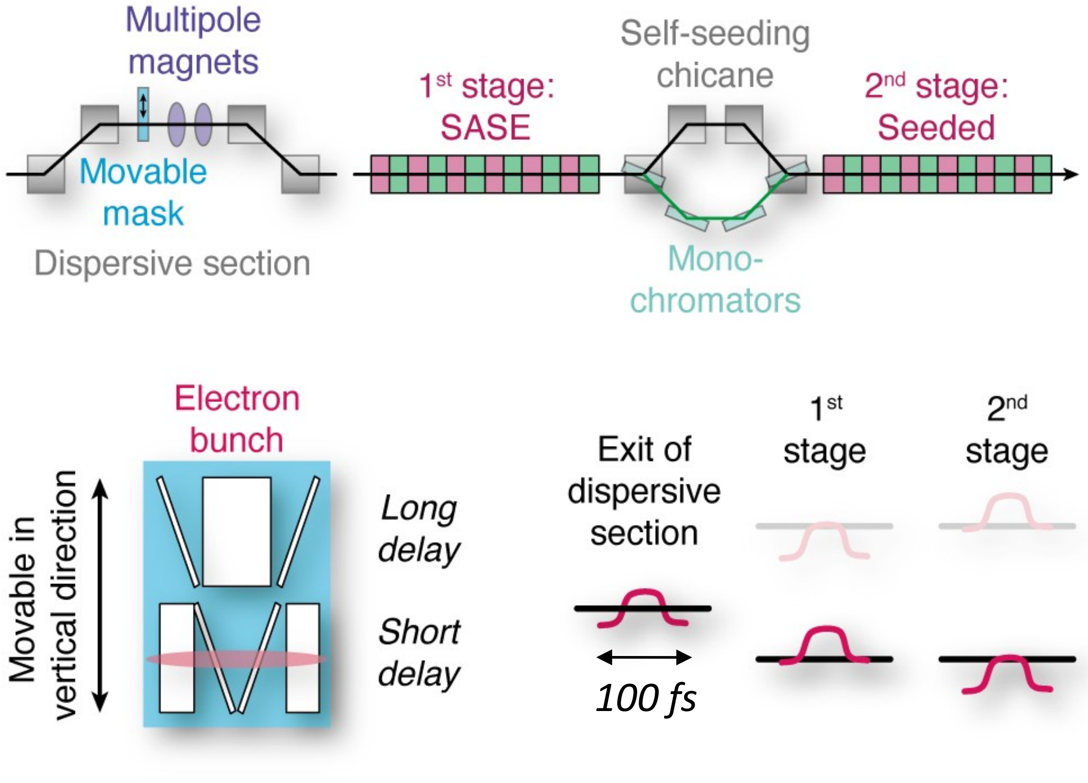
Photon Energy (keV)	Bandwidth (eV)	Pulse Energy (mJ)
9	0.8 (FWHM)	1.2

Phaselock Pulses with Self-Seeding

Build upon fresh-bunch self-seeding, where the lasing part in the second stage is masked with emittance spoiler foil (or laser heater notches)

Basic Principle is that this approach slices only in the envelope, while the phase is fully defined by the output of the filter (monochromator). Any split and delay optics are avoided



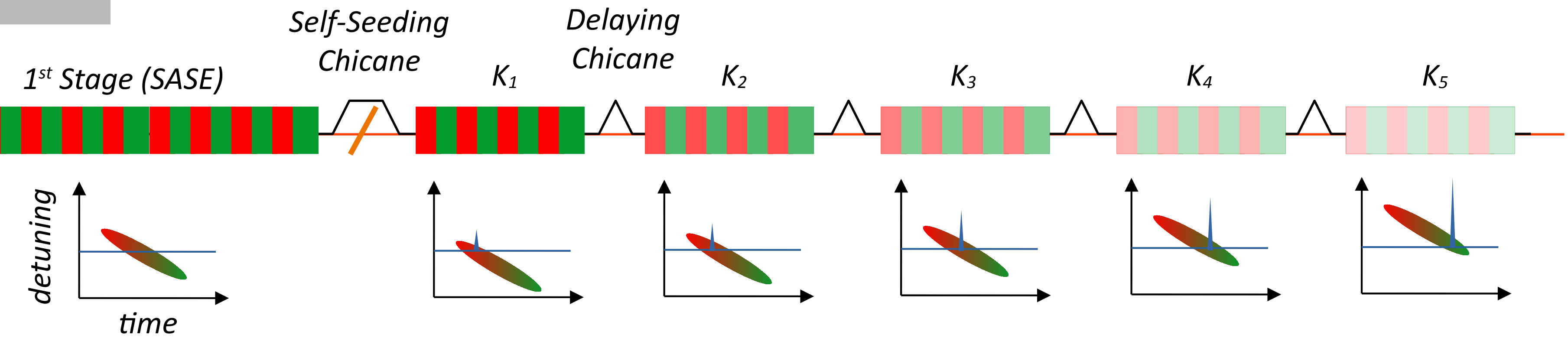


Reiche, Knopp, Pedrini, Prat, Aeppli & Gerber
PNAS **119,** e2117906119 (2022)

Proof-of-principle experiment planned at PAL-FEL next year

Multi-Stage Fresh Bunch with Self-Seeding

Operation with a chirped bunch will act as slicing when used in conjunction with self-seeding. This can be combined to a multi-stage fresh bunch amplifications



The changing K-values matches the resonance condition for slice mean energy when radiation pulse is pushed through the bunch

Delays above 400 nm will destroy the micro bunching so that the SASE background is suppressed

Avoids problems of multi-stage fresh-bunch amplification with a tilt and its frequent realignment

(Method needs to be studied in detail)

Short Pulses

Self-Seeding

- Basic Configuration
- Fresh Bunch Technique
- Advanced Methods

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- Multi-stage Fresh Bunch Technique
- Self-Modulation
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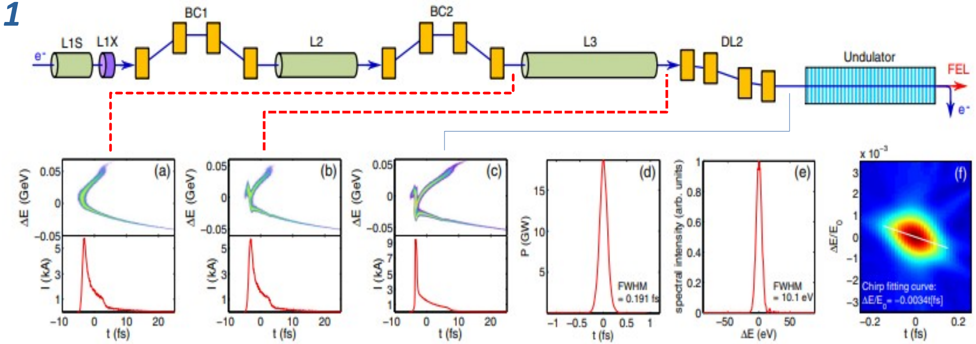
External Seeding

- Seeding with Athos Beam
- External Radiation Source at 13.5 nm
- Short Pulses

Conclusion

Short Pulses – Non-Linear Compression

1



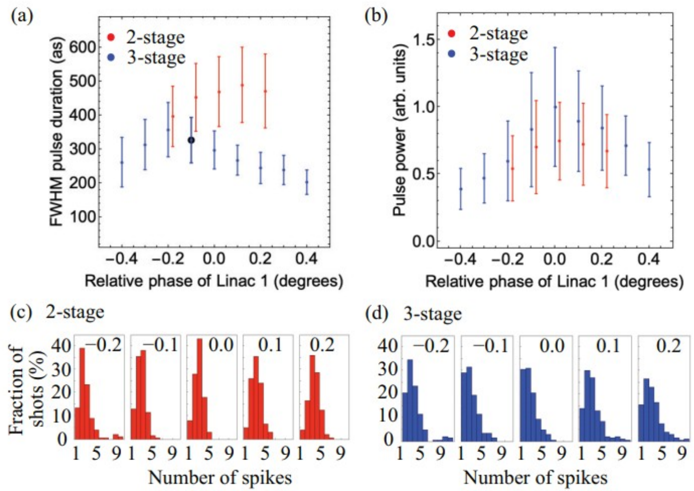
Electron beam is over-compressed with one leading current spike, driving the lasing. Performance is rather robust against RF jitter

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

Demonstrated at SwissFEL for 2 and 3 stage compression at hard (Aramis) and soft (Athos) X-rays.

2



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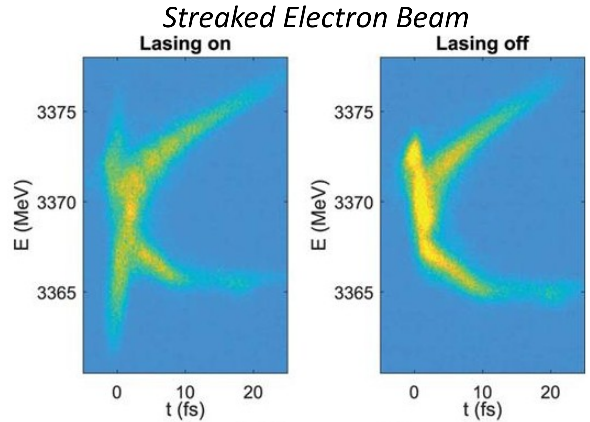


LCLS: *[1]S. Huang et al, PRL 119, 154801 [2017]*

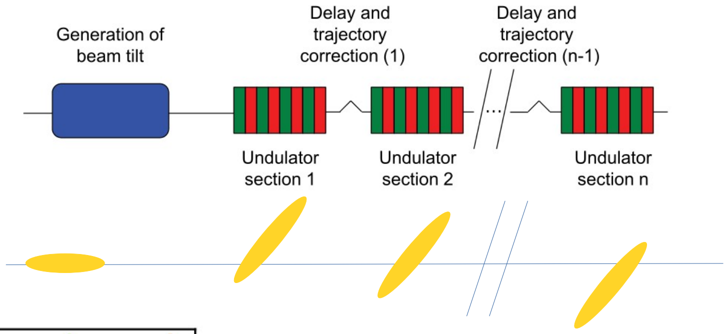
SwissFEL – Aramis: *[2]A.Malyzhenkov et al, PRR 2, 042018 (2020)*

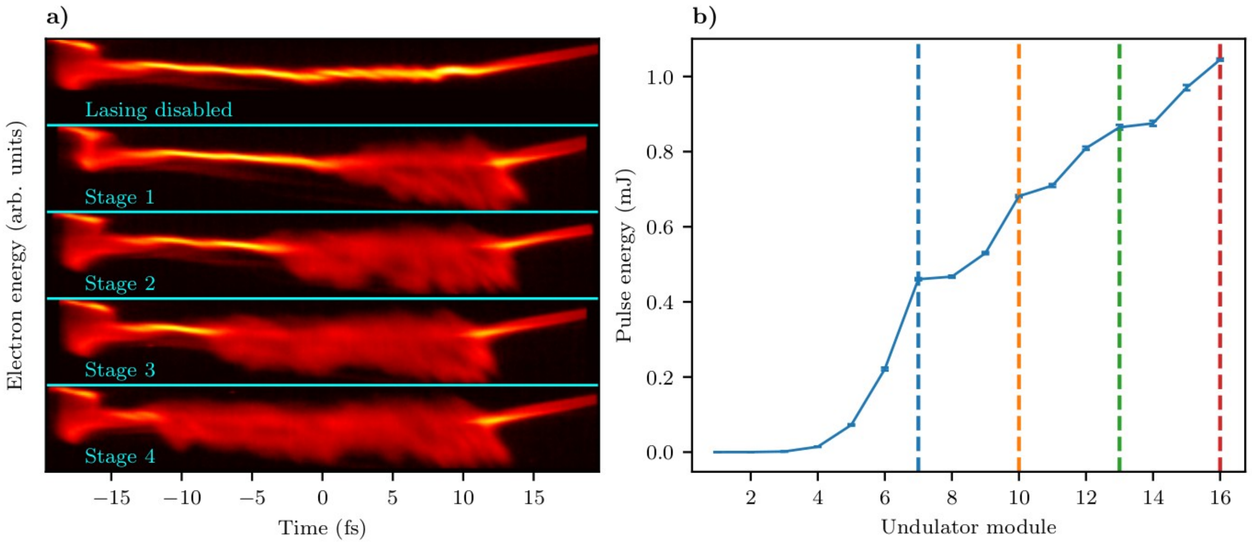
SwissFEL – Athos: *[3]E. Prat et al, APL Photonics 8, 111302 (2023)*

Multistage Fresh Bunch Technique

Multistage Fresh Bunch technique pushes the radiation to a new part of the bunch, which hasn't been spoiled yet by any FEL amplification.

This allows for further amplification even beyond the saturation power level.





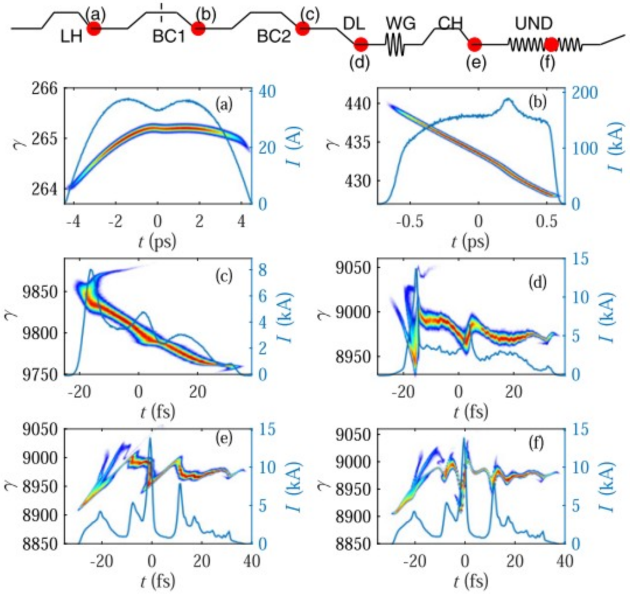
Pulse duration of few femtoseconds (below 3 fs rms)

[G. Wang et al, submitted to PRL]

Controlled Self-Modulation Methods

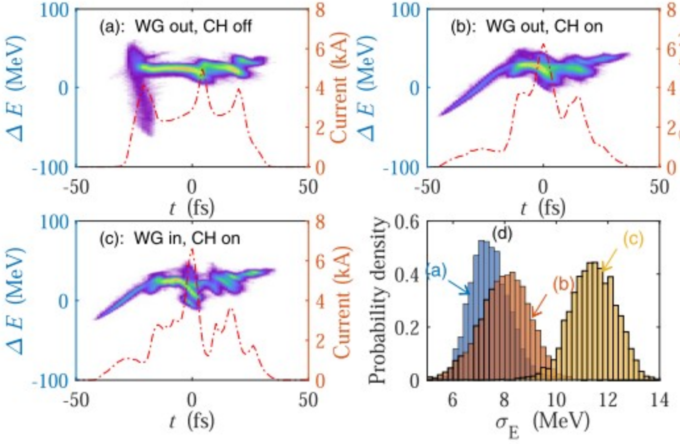
- Pulse shaping at the cathode in conjunction with space charge fields during acceleration and compression causes a short current spike
- This works as Enhanced SASE (ESASE) where the FEL process is strongly driven (and localized) by the current spike. This can be make more robust by applying a positive taper in the undulator field
- ***Currently explored at SwissFEL with initial promising results.***

Model

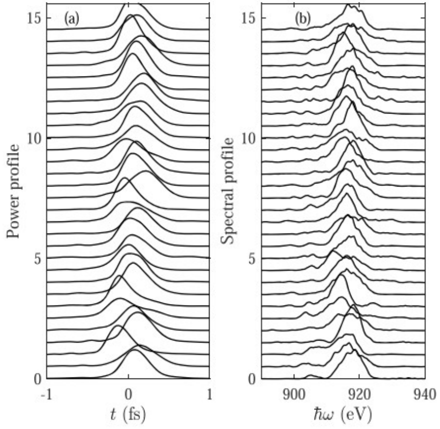


Demonstration: *Z. Zhang et al, New J. of Phys. 22, 083030 (2020)*
(similar idea based on laser heater: D. Cesar et al , PRAB 24, 110703 (2021))

Measurement

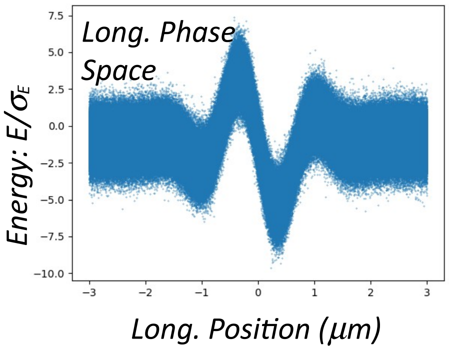


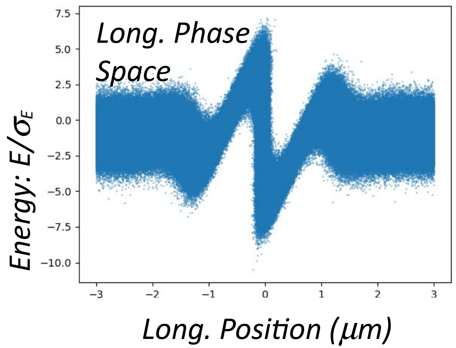
Profiles & Spectra

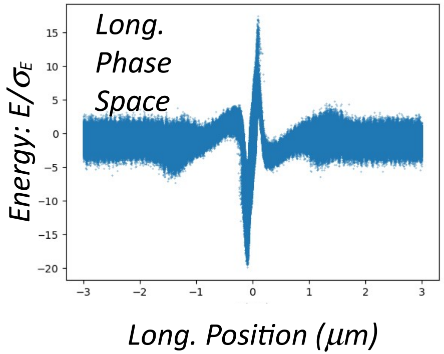


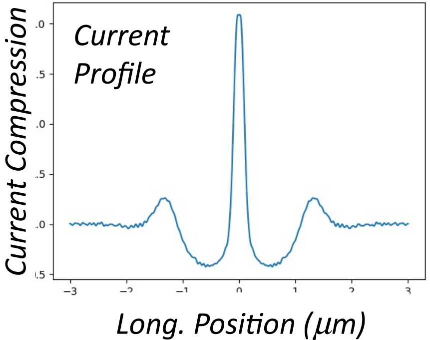
Synchronized Self-Modulation (ESASE)

Self-modulation works reliable but is locked to the beam arrival jitter of the electron bunch.
Synchronization can be improved by imprinting a single cycle energy modulation on the beam.



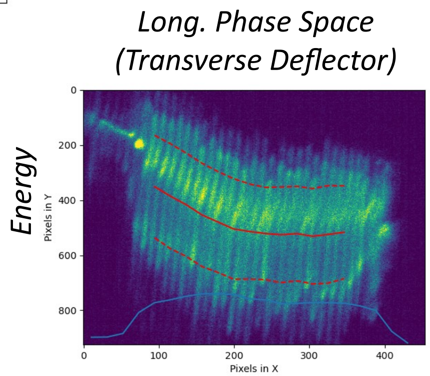






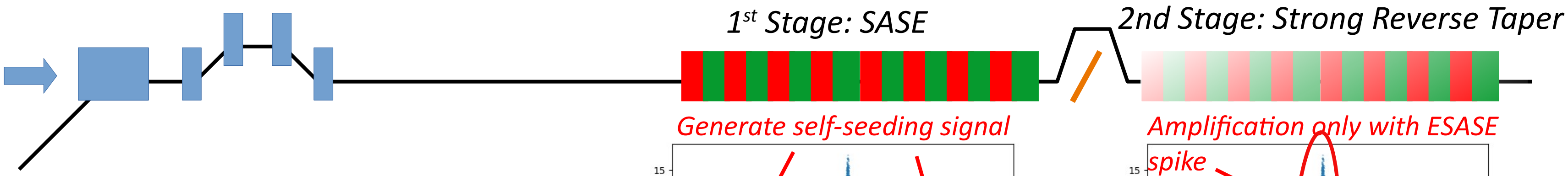
Laser:
Wavelength: 1.6 µm
Quasi Single Cycle
CEP Stabilization
Pulse Energy: > 1 J

ESASE Demonstration at Athos (multi-cycle pulse)



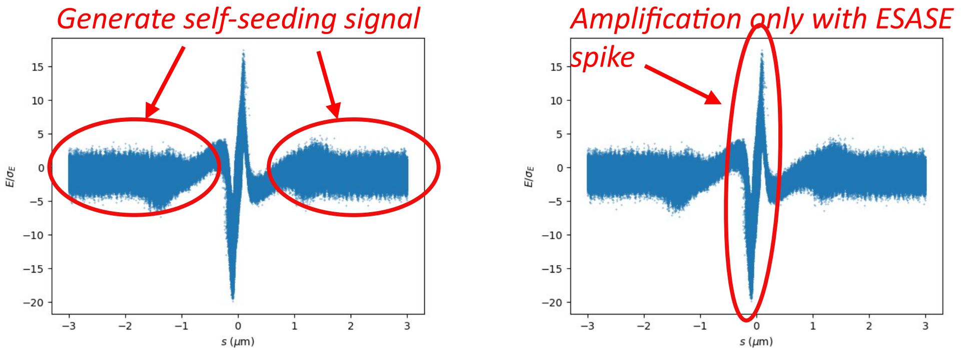
ESASE with Self-Seeding

Generate a seeded signal and slice it with ESASE spike and strong reverse taper



Benefit of combining both methods:

- ***Stabilized central wavelength***
- ***Longitudinal coherence (single spike)***
- ***Synchronized to external signal***



Generating a split and delay of ESASE laser pulse allows for phase locked pulses without the need for beam tilts and emittance spoiler foil

Reverting order should give a more stable output of self-seeding [*Hemsing et al, PRL 125 (2020), 044801*]

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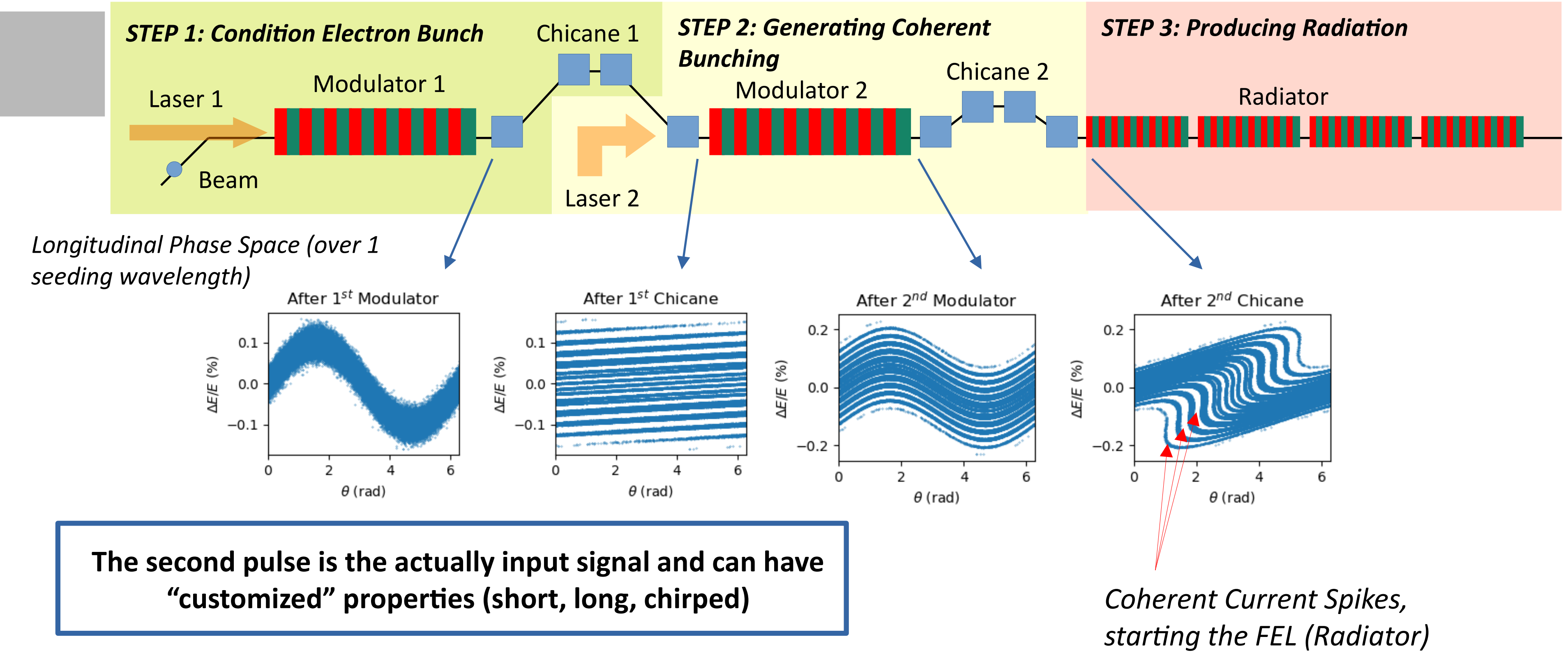
Echo-Enabled Harmonic Generation Principle

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



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

Currently Commissioned at Athos Beamline

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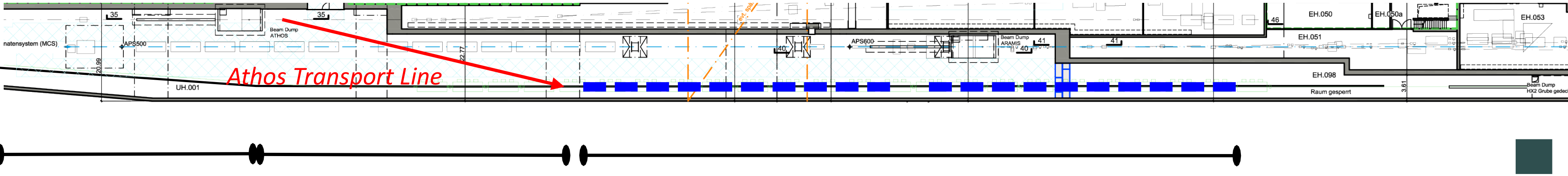
Seeding with Athos

Athos with a seeded signal up to 1.2 keV (EEHG) could be used for seeding Porthos

A harmonic conversion of up 5 allows for the simpler scheme of High-Gain Harmonic Generation (HGHG), using only one laser signal, modulator and chicane.

Athos beam is outcoupled after the Athos dump. Shown transport line (including going upwards to the ceiling for crossing Aramis line) has a distance of about 55 m over a longitudinal distance of 50 m

Time-of-Flight Difference is 16 ns or longer, suitable for the proposed time separation of Athos and Porthos bunch of 21 ns



Switch yard

Space for beam stopper, RF and beam manipulation devices
≈55 m

20 × 4 m undulator modules (80% filling ratio)
≈100 m undulator line
(total,with chicane for two color/self-seeding)

Beam dump
(certified to
7 GeV)

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External Seeding

Any external seeding needs to overcome the shot noise power of the electron beam. In the hard X-ray regime the shot noise power level is a few kW.

The ideal seed pulse would be about 1 MW for 100 fs (E > 100 nJ)

No such direct seeding source exists.

Applying EEHG to Porthos with 266 nm seed laser signals requires harmonic conversion of up to 1000:

- Band structures in longitudinal phase space cannot be preserved
- Excessively large chicanes and strong modulator needed

Need to reduced wavelength of external seed laser

13.5 nm might be a viable option since there are a lot of research for lithography applications

Crude estimate requires pulse energies of about 100-200 uJ per pulse.

Sources at 13.5 nm

	Performance	Hardware	Comments
HHG	10^{10} photons/s/1% band @ 13nm @ 1 kHz	KMLabs Commercial Product XUUS5	This corresponds to about 1 nJ per pulse. Pulse length about 50 fs *[Talk by H. Kapteyn, EUV Litho Workshop 2016]*
Tin Laser	$2 \cdot 10^{11}$ W/cm^2 for 5 ns pulse duration. >1% bandwidth	Liquid tin jet and 2 um laser	Emission is in all direction. For seeding an electron beam the effective power would be about 200 kW. *[L. Behnke et at, Opt.Express 29 (2021) 4475]*
EEHG	100 uJ per pulse. 0.05% bandwidth, ~50 fs pulse duration	FEL facility!	*[E. Allaria et at, Nat Photonics 6 (2012) 699]*
Storage Ring	120 nJ per pulse, 16 fs FWHM, Fourier Limited, about 5 MW peak power	Compact Storage ring with dogleg and modulator at 266 nm	Angular Dispersion HG, similar to Phase Emerging HG induces coherent bunching on beam. *[C. Feng and Z. Zhao, Sci. Reports 7 (2017) 4724]*

Possible Source (→ EEHG)

A 13.5 nm FEL Facility

Layout similar to FERMI but scaled down in energy.

Crude Design Parameters:

- Beam Energy 700 MeV
- Beam Current 700 A (Single Stage Compression)
- Beam Charge: 200 – 500 pC
- 100 Hz rep rate

30 m Injector + 30 m Linac + 10 m Transport + 30 m EEHG & Undulator

(scaled from SwissFEL layout)

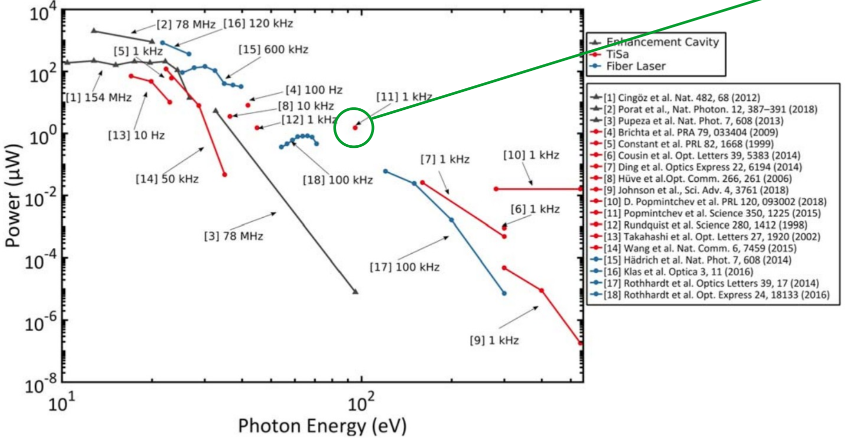
More compact layout could be an ERL for 13.5 nm, which can drive a lithography end station for most of the time.

Ultra-short Seeded Pulses

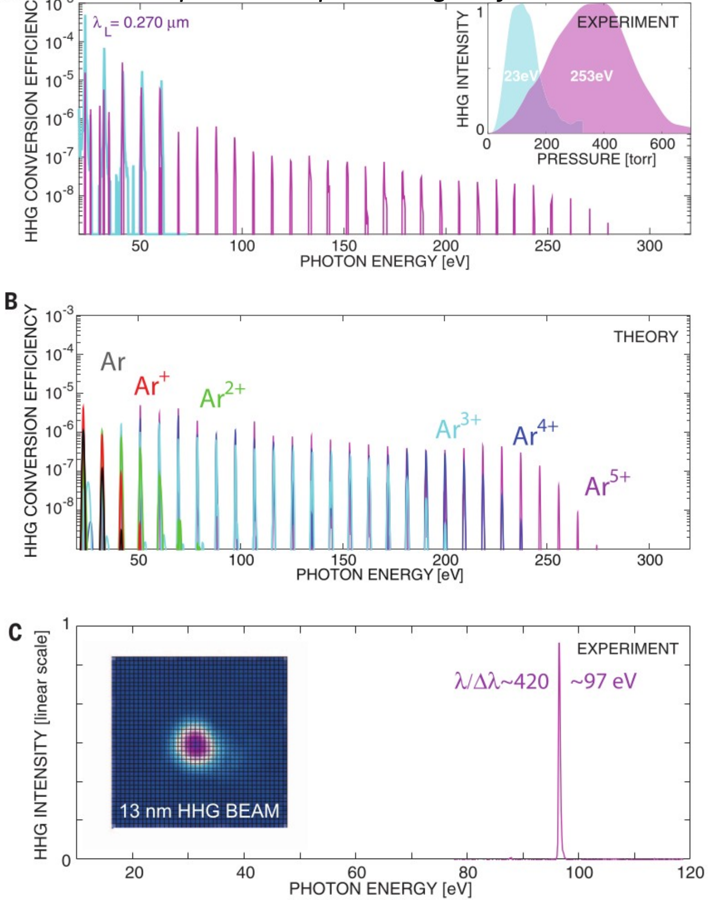
[D. Popmintchev et al, Science 350, 1225 (2015)]

Paper claims pulse length of 100 as

HHG might be coming in reach as a possible attosecond seed for the second EEHG stage



Survey of HHG Sources [*J. Rothhardt et al, Science (2018) 113001*]



Putting the numbers together, that means 10 MW peak power!!!!

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Outline

Self-Seeding:

- Not currently provided at SwissFEL
- Stability in central frequency
- Advanced Modes needs to be explored to shape X-ray pulse

Short Pulse Modes:

- Several methods established based on SASE. No reliable delivery of single spike
- Advanced methods can provide longitudinal coherence and/or locking to external signal (ESASE laser)

External Seeding:

- Ultimate goal for full control of FEL pulse. Needs a lot of R&D.
- EEHG at 13.5 nm the most likely candidate, calling for independent FEL beamline at lower energy
- Possible synergy with ERL-based lithography station at 13.5 nm
- Second stage of EEHG could be seeded with HHG source for attosecond pulses.