Path to High Repetition Rate Seeding: Combination of High Gain Harmonic Generation with an Optical Klystron

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Outline

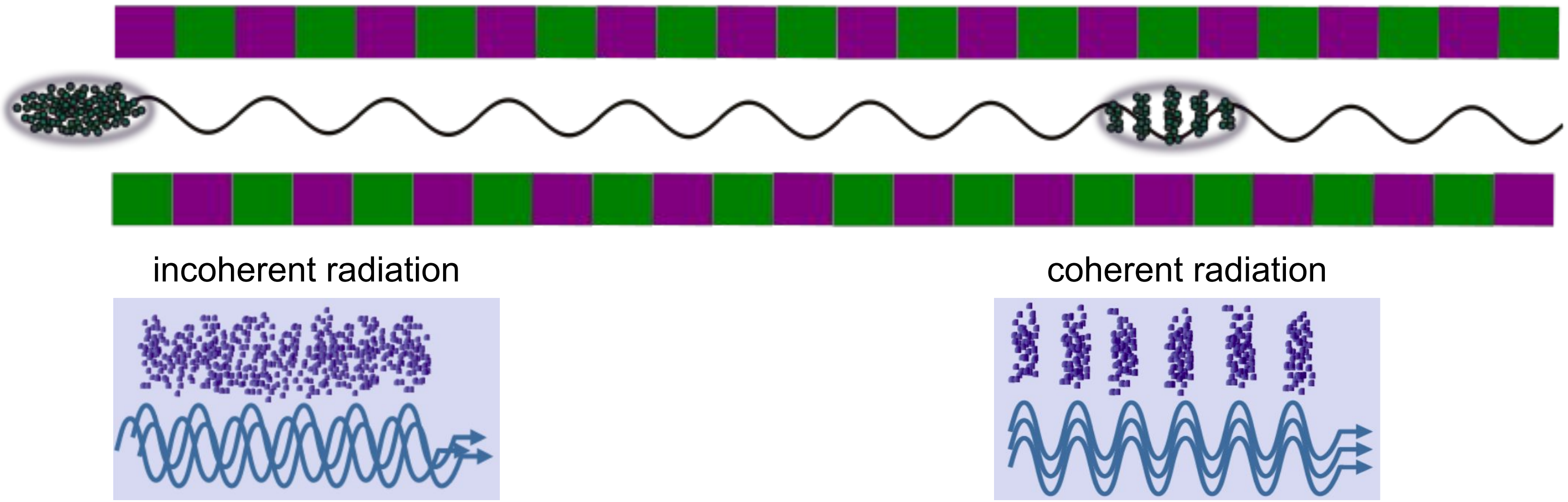
- ❖ **Introduction to seeded FELs and the need for high repetition rate seeding**

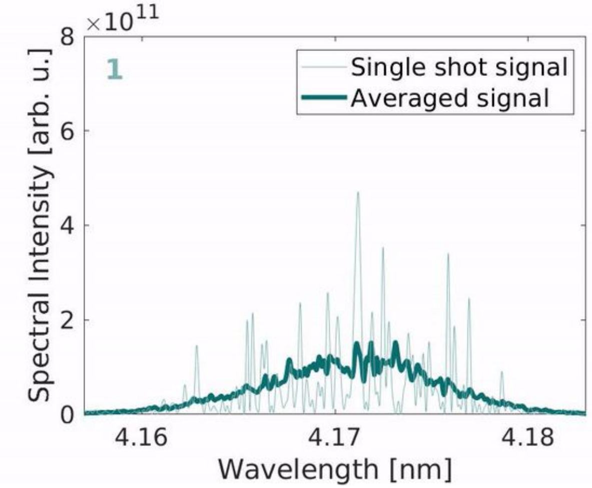
- ❖ **The optical-klystron high-gain harmonic generation (HGHG) FEL**
  - ➢ **The layout**
  - ➢ **Simulation results of OK HGHG**
    - ■ **Without e-beam energy chirp**
    - ■ **With e-beam energy chirp**

- ❖ **Summary**

The high-gain FEL

Self-amplified spontaneous emission



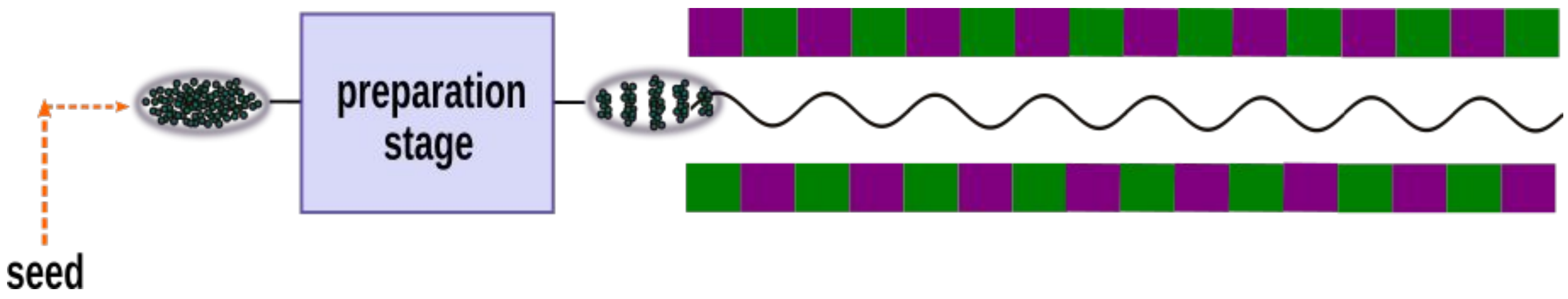


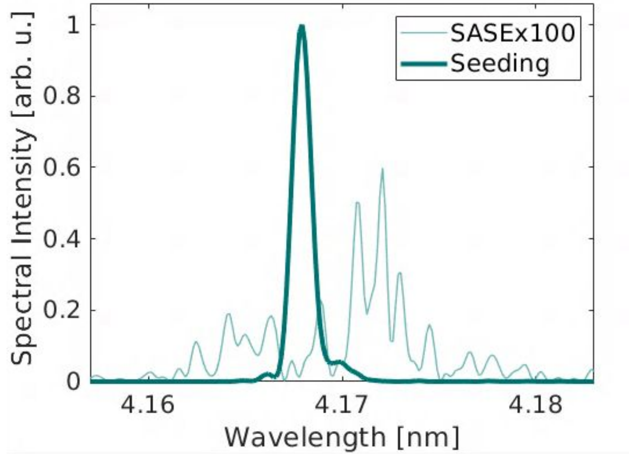
Simulated with Genesis 1.3 v4

- ✔ Wavelength tunability
- ✔ **Hard x-rays** possible
- ✔ MHz **repetition rate** possible
- ❌ Poor longitudinal coherence
- ❌ Shot-to-shot fluctuations

The high-gain FEL

External seeding and harmonic generation





Simulated with Genesis 1.3 v4

- ✔ Longitudinal coherence
- ✔ Shot-to-shot stability
- ✔ Shorter saturation length
- ✔ Control over the FEL radiation properties
- ✔ Synchronization of FEL pulse to seed laser

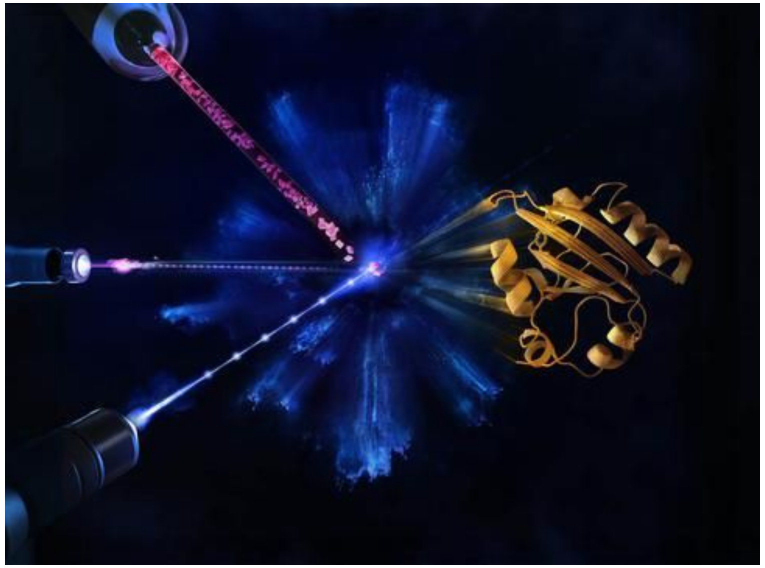
- ❌ Highest repetition rate
- ❌ Shortest possible wavelength
- ❌ Wavelength tunability

Requirements on seed lasers:

- Hundreds MW of peak power
- Shortest possible wavelength
- fs duration
- Pulse energy stability
- Wavelength stability
- Wavelength tunability

Why high repetition rate?

Science shapes the future of FELs



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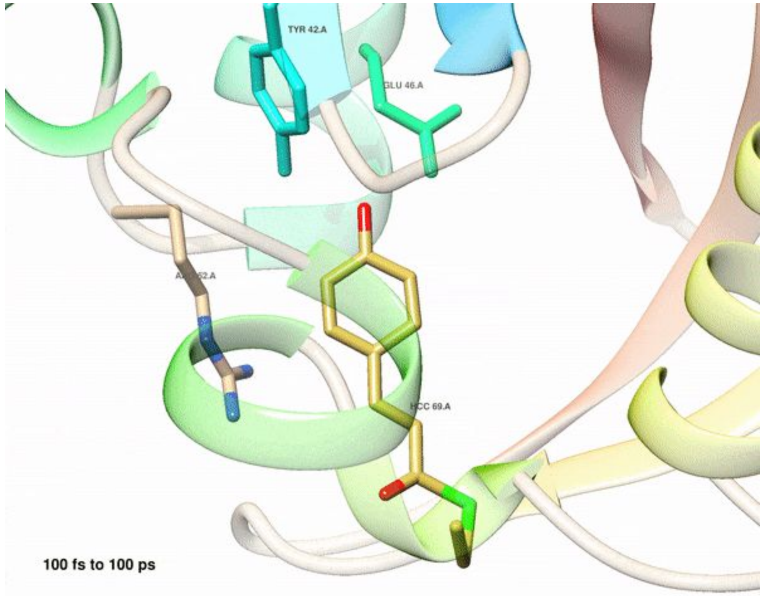

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Full coherence & high rep. rate:

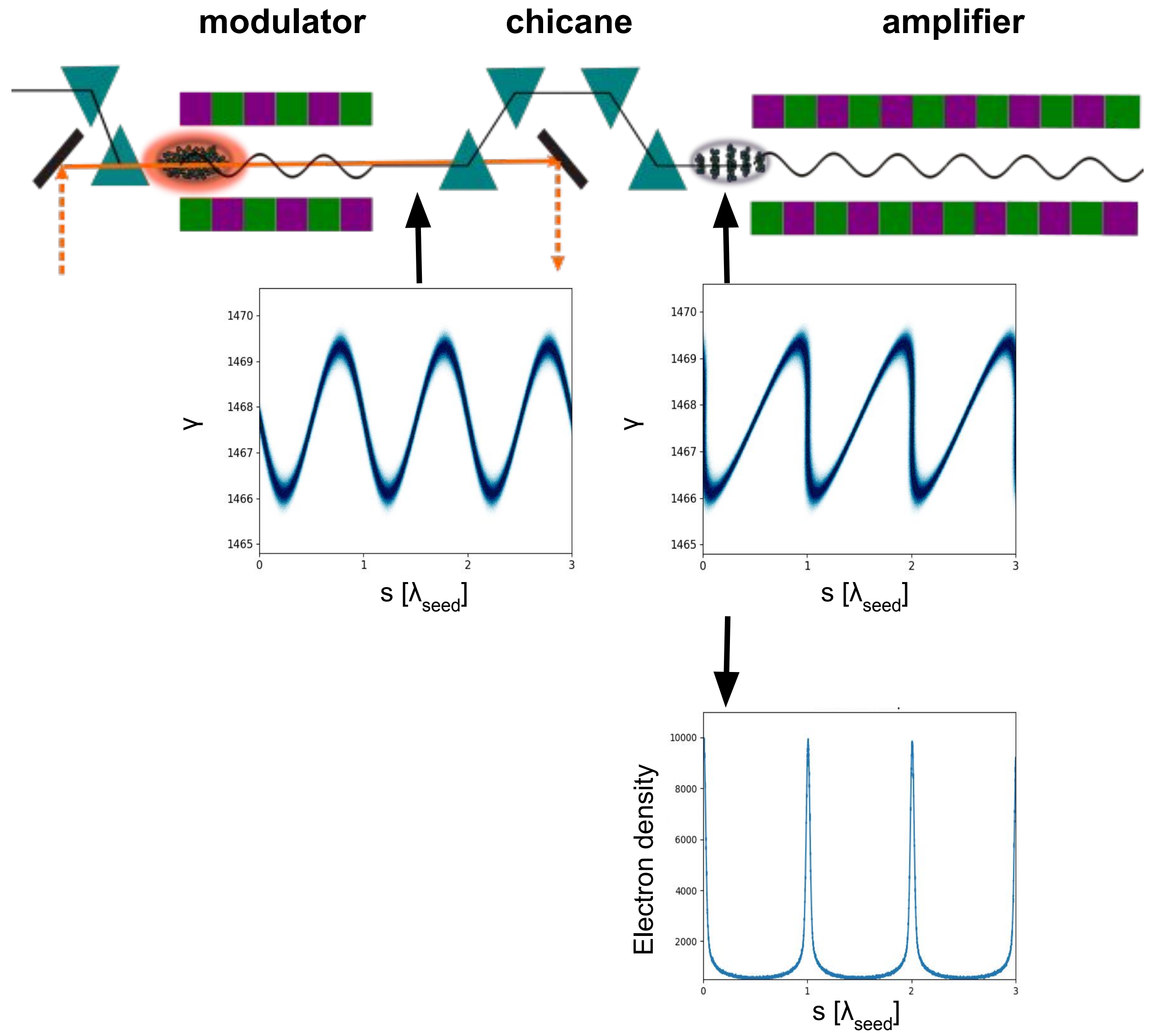
- **will tremendously increase the average flux**
- **will improve statistics**
- **will maintain stability and coherence**

Combining the standard high gain harmonic generation with an optical klystron scheme to achieve high repetition rate seeding

The working principle

Standard high gain harmonic generation

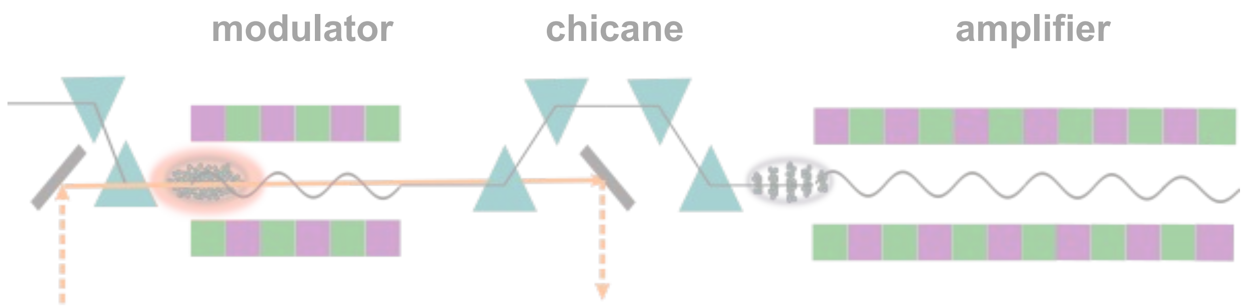
Standard HGHG



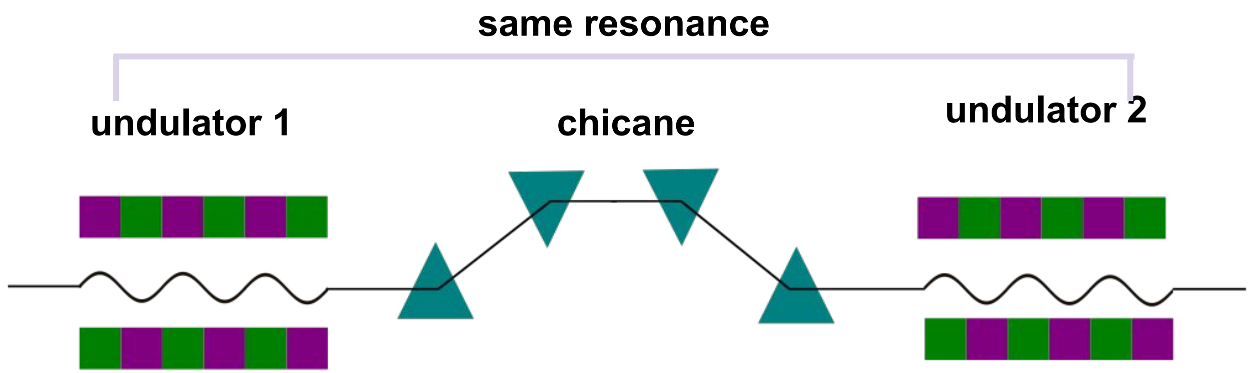
The working principle

The optical klystron

Standard HGHG



Optical klystron



weak energy modulation → **longitudinal density modulation** → **self-modulation & coherent emission**

The working principle

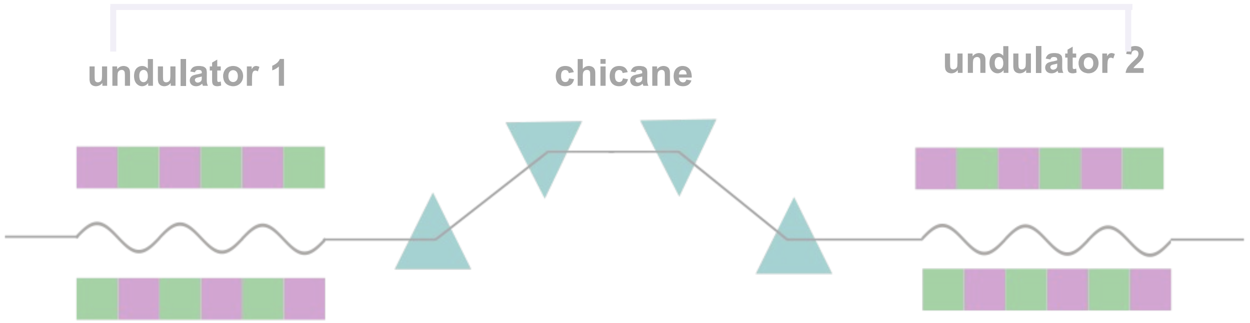
The optical klystron

Standard HGHG

+

Optical klystron

=

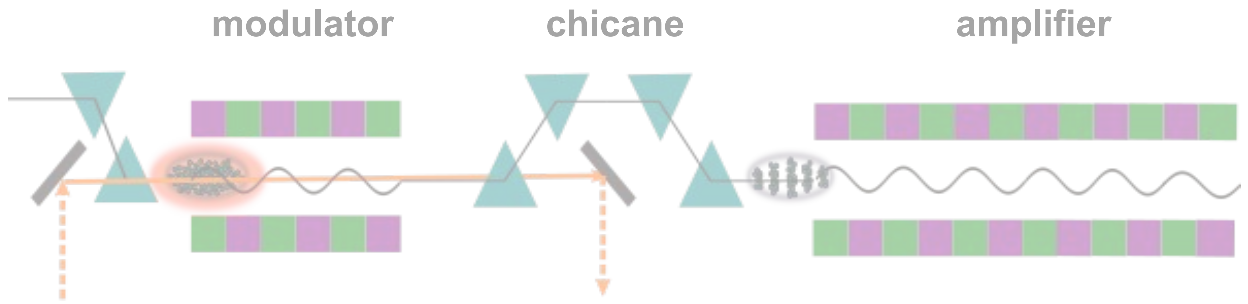


weak energy modulation → longitudinal density modulation → self-modulation & coherent emission

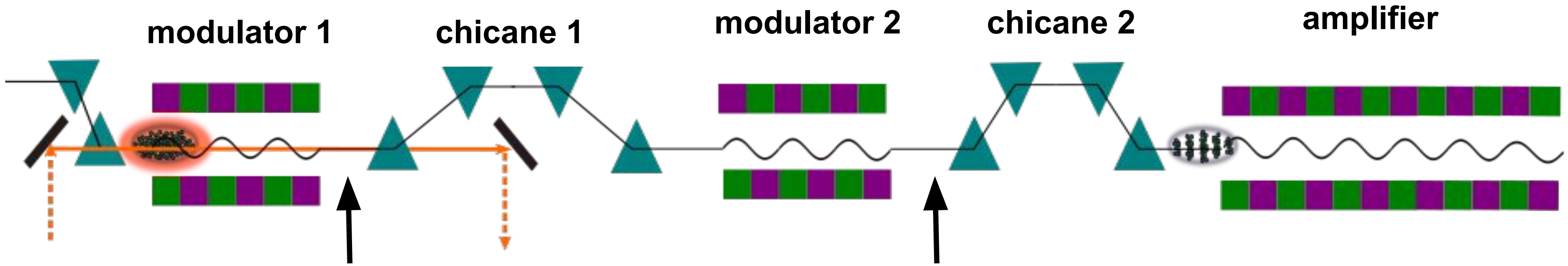
The working principle

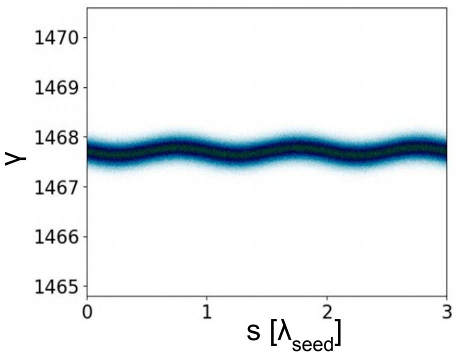
The optical klystron (OK) high gain harmonic generation

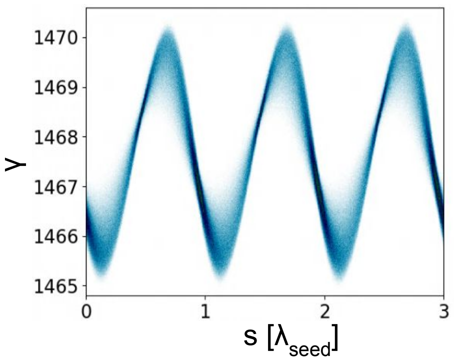
Standard HGHG



Optical klystron HGHG







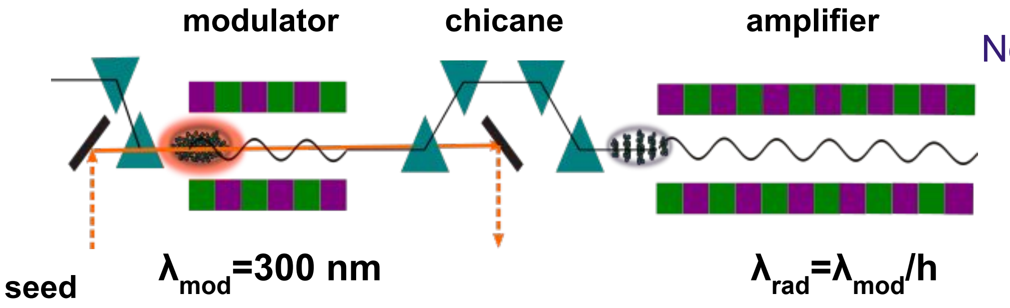
Simulation results

Comparison of an OK-HGHG to a standard HGHG scheme

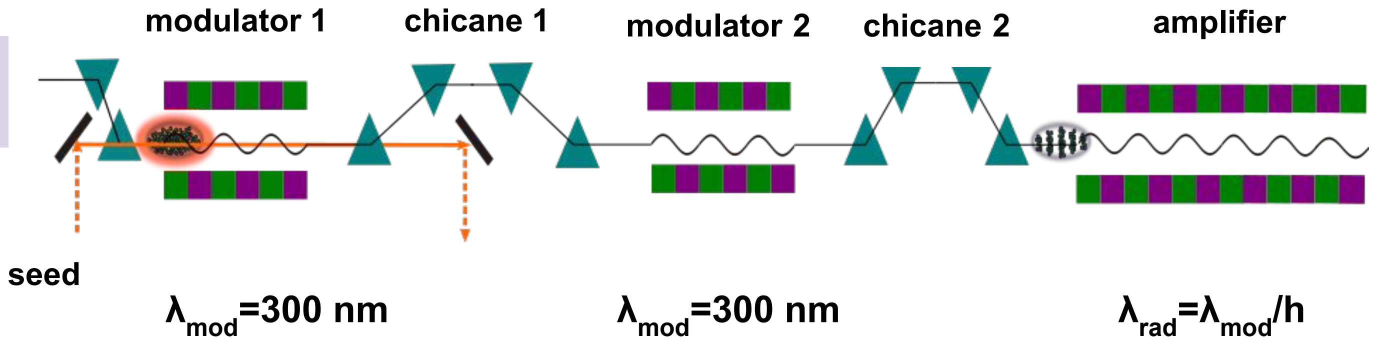
Can we reduce the seed laser power and still achieve the same output FEL pulse properties?

Simulation parameters

Standard HGHG



Optical klystron HGHG



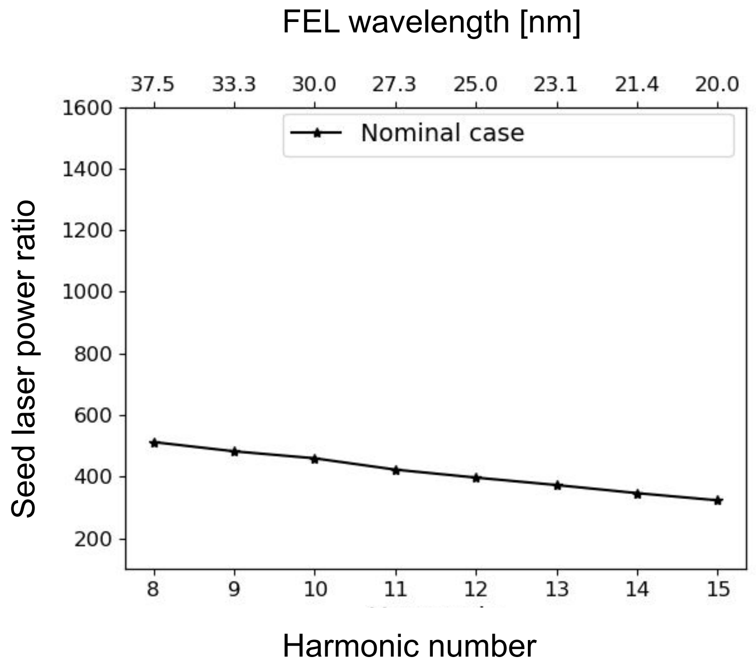
Nominal case

Simulated with Genesis 1.3 v4

FLASH2020+ parameters	
Electron beam parameters	
Peak current	500 A
Energy	750 MeV
Bunch duration	110 fs FWHM (flat-top)
Emittance	0.6 mm·mrad
Unc. energy spread	75 keV
Seed laser parameters	
Pulse duration	33 fs rms (Gaussian)
Lattice parameters	
Modulator periods	30
K_{rms} modulator	3.83
Modulator/ Radiator period	82.6 mm/33 mm
Modulator length Power gain length	2.5 m 0.94 m

Optimizing for 8% bunching at minimum seed power

Significantly lower seed power and slightly higher energy spread are required with the optical klystron

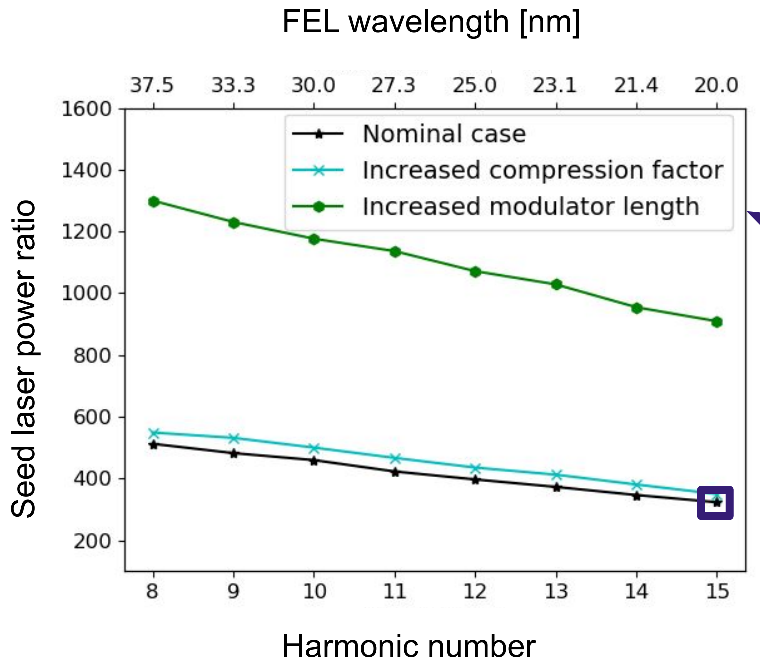


$P_{seed,\ HGHG} / P_{seed,\ OK\text{-}HGHG}$

		n=8 → n=15
Seed power	**OK HGHG**	0.041 MW → 0.26 MW
Seed power	**Standard HGHG**	21 MW → 83 MW

Optimizing for 8% bunching at minimum energy spread

Lower seed power and higher energy spread are required with the optical klystron



from 500 A and 75 keV to 750 A and 112.5 keV

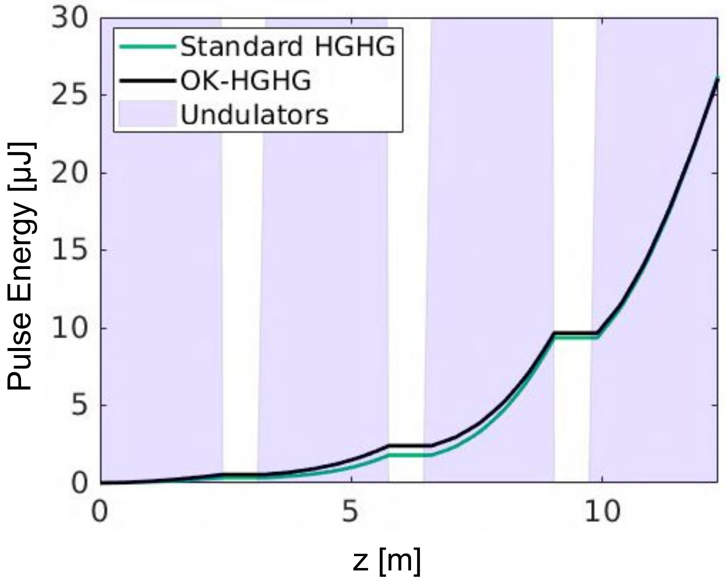
from 2.5 m to 3 m

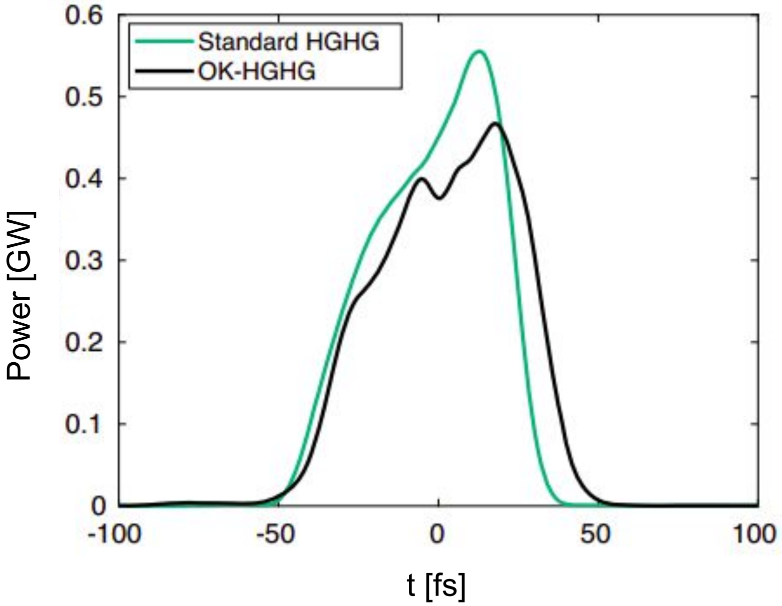
		n=8 →	n=15
Seed power	**OK HGHG**	0.041 MW →	0.26 MW
Seed power	**Standard HGHG**	21 MW →	83 MW

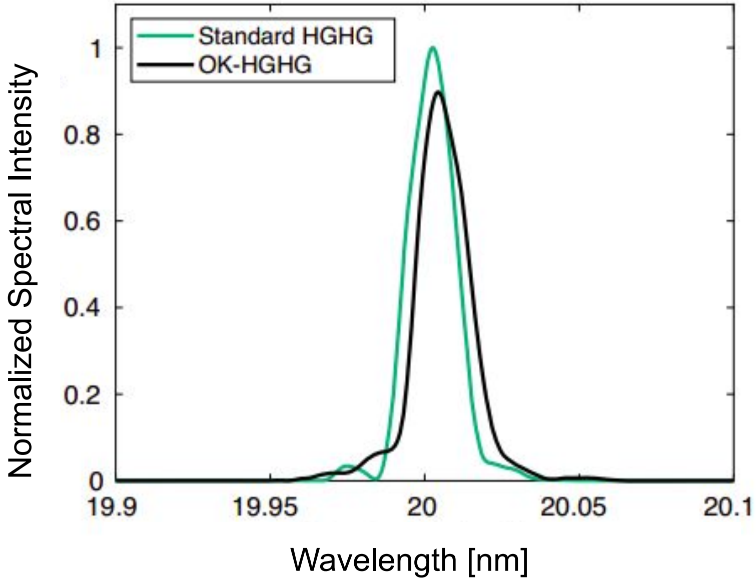
Output FEL radiation

15th harmonic of a 300 nm seed laser wavelength

after 4th undulator segment







	Bunching	Energy spread @ end of modulator	FWHM relative BW	Pulse duration rms	Pulse energy	Seed laser peak power
Standard HGHG	7%	580.9 keV	$9 \cdot 10^{-4}$	18.9 fs	26.3 μJ	61 MW
OK HGHG	7%	766.4 keV	$9.3 \cdot 10^{-4}$	21.5 fs	26 μJ	0.17 MW

reduction factor of 360

Longitudinal coherence ✔
High repetition rate ✔

Damage threshold ✔
Shorter wavelengths ✔

Immediate implementation ✔

Simulation results

OK-HGHG and standard HGHG

with a linear e-beam energy chirp

Is the linear chirp detrimental to the output FEL pulses, or can we recover their properties by appropriately optimizing ?

Effect of a linear energy chirp

HGHG

Bunch compression ⟷ **Wavelength compression in HGHG**

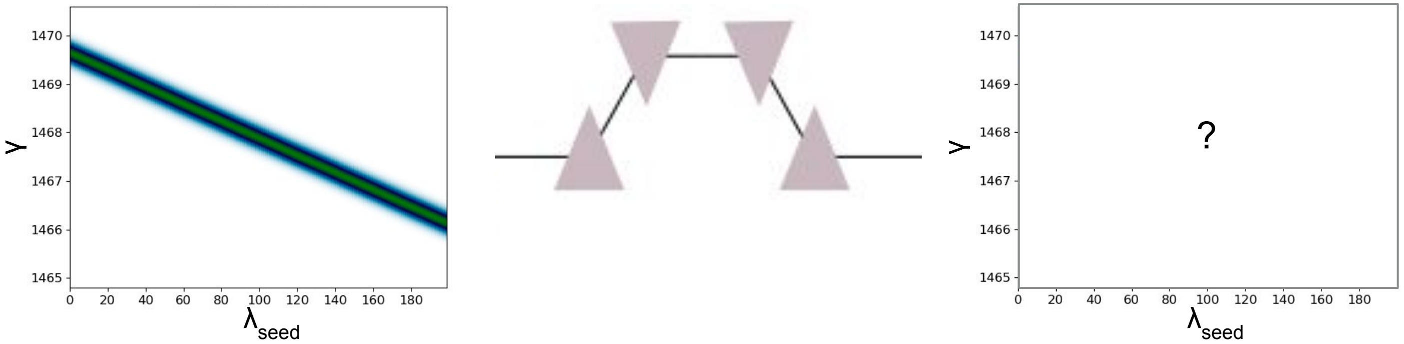
$s_f = s_i + R_{56}\delta$

$\delta = \delta_0 + hs_i$

→ $C_{BC}^{-1} = ds_f/ds_i = 1 + hR_{56}$

- $H \propto h$
- $B \propto R_{56}$

→ $C_{HGHG}^{-1} = \lambda'_{HGHG}/\lambda_{HGHG} = 1 + HB$

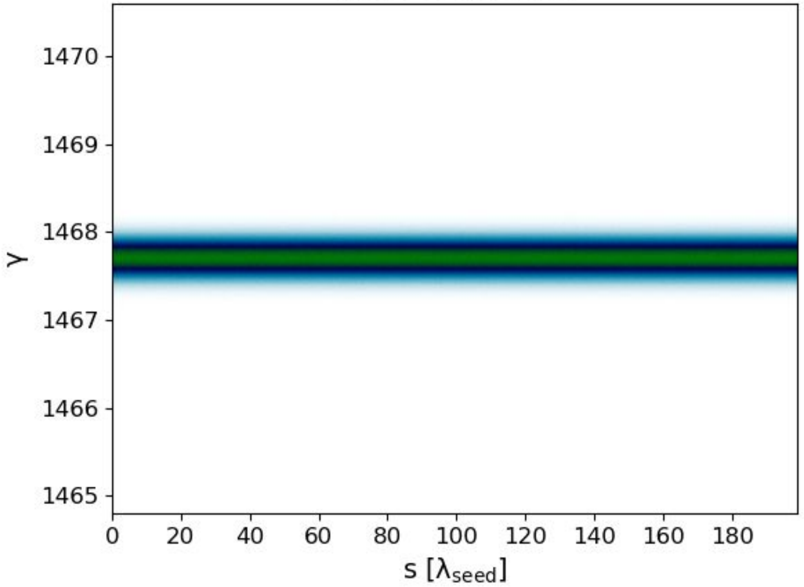


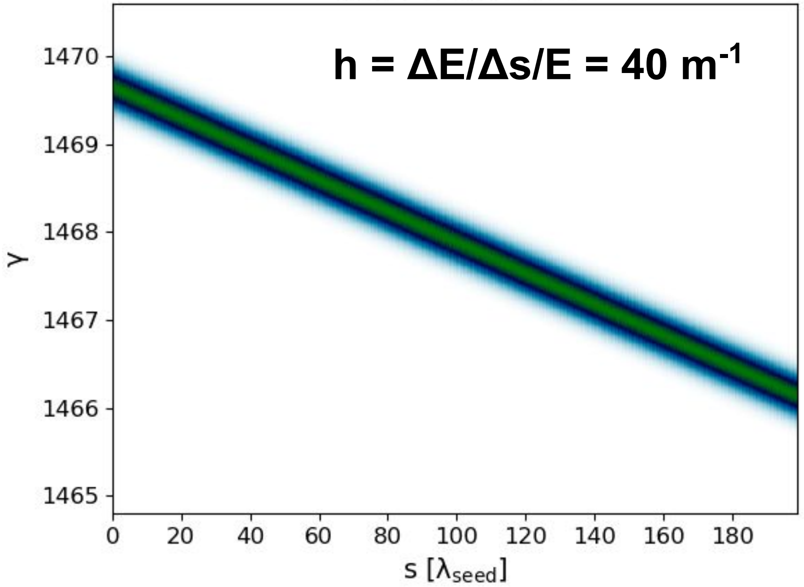
Effect of a linear energy chirp

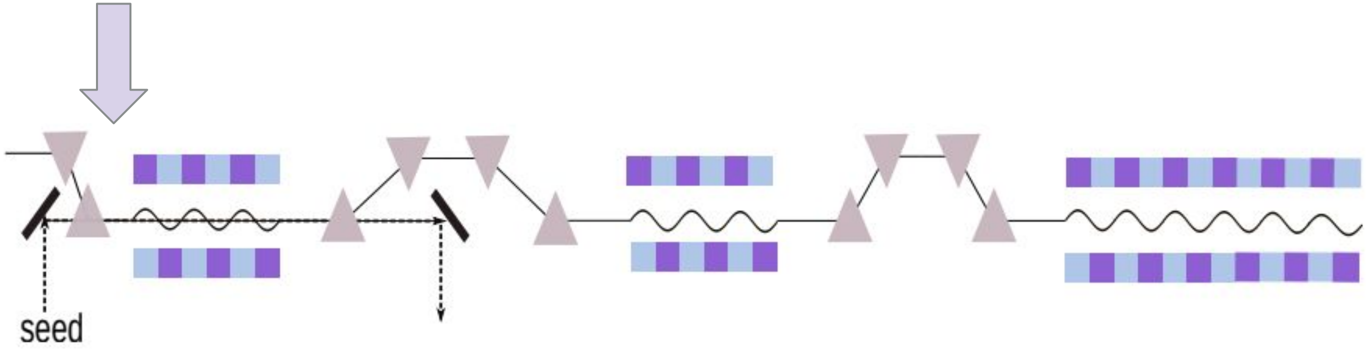
OK HGHG - Initial distribution

Initial distribution

Without chirp **With chirp**

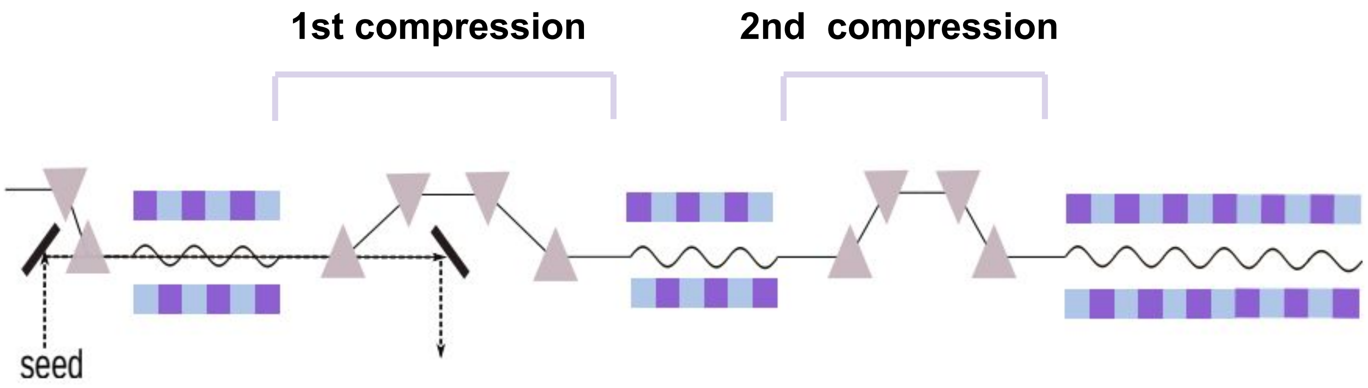






Effect of a linear energy chirp

OK HGHG - Compression

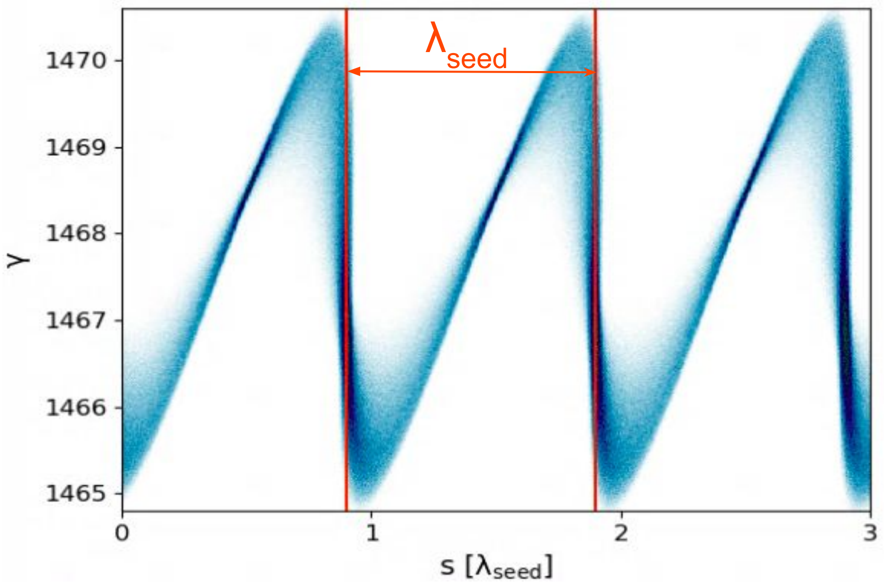


Effect of a linear energy chirp

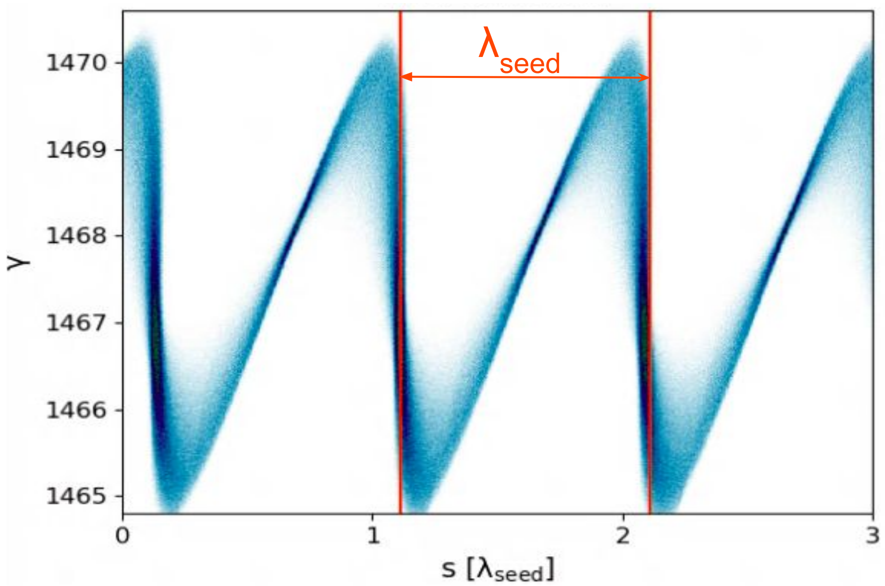
OK HGHG - After chicanes

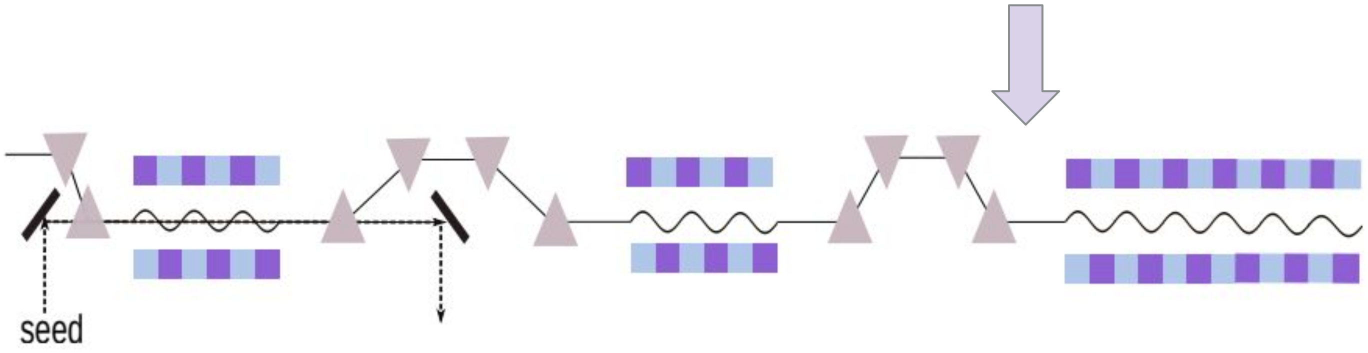
After chicanes

Without chirp



With chirp



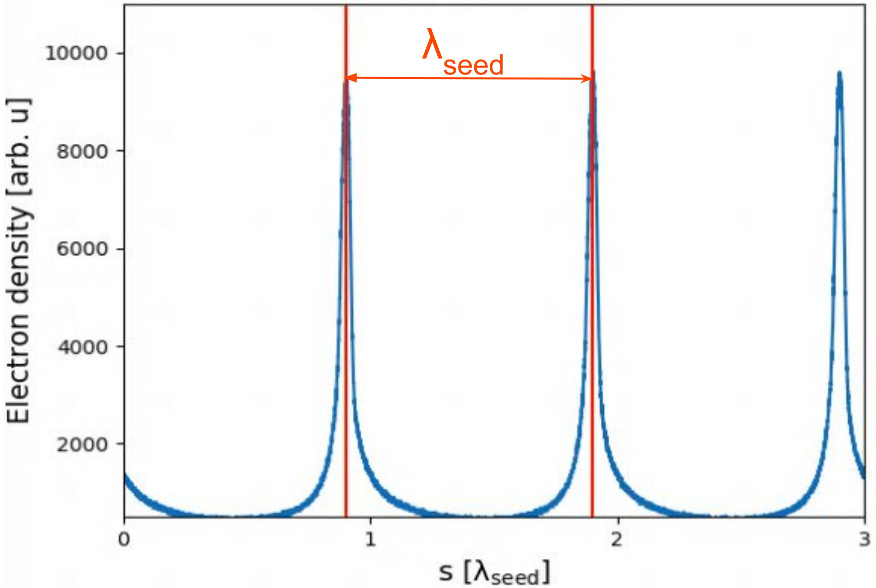


Effect of a linear energy chirp

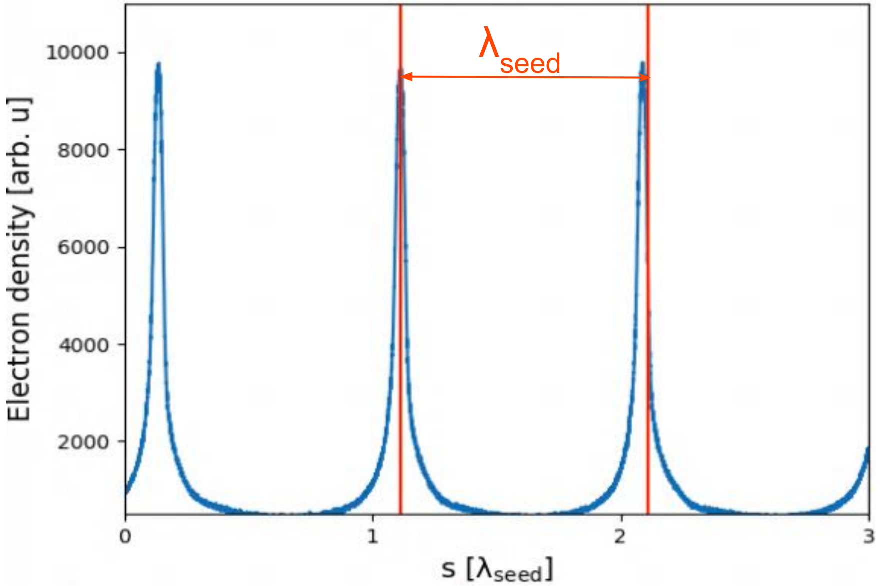
OK HGHG - After compression

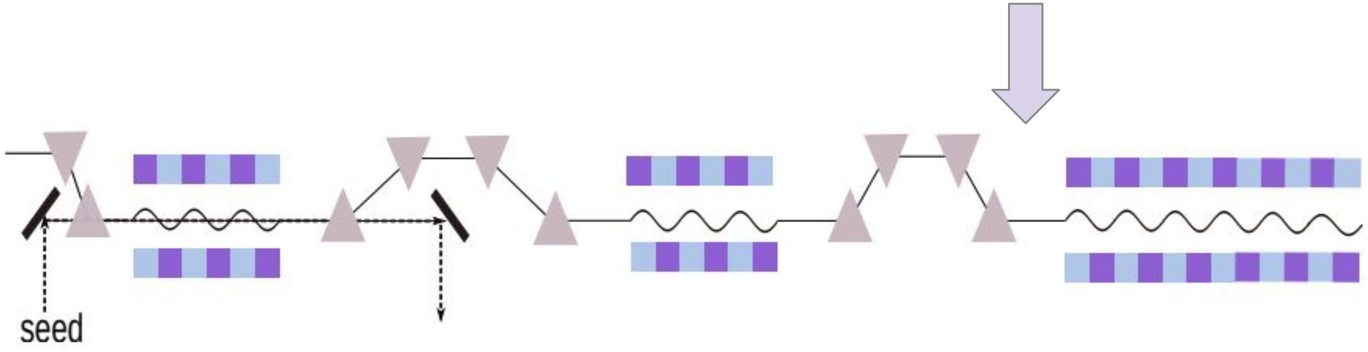
After compression

Without chirp



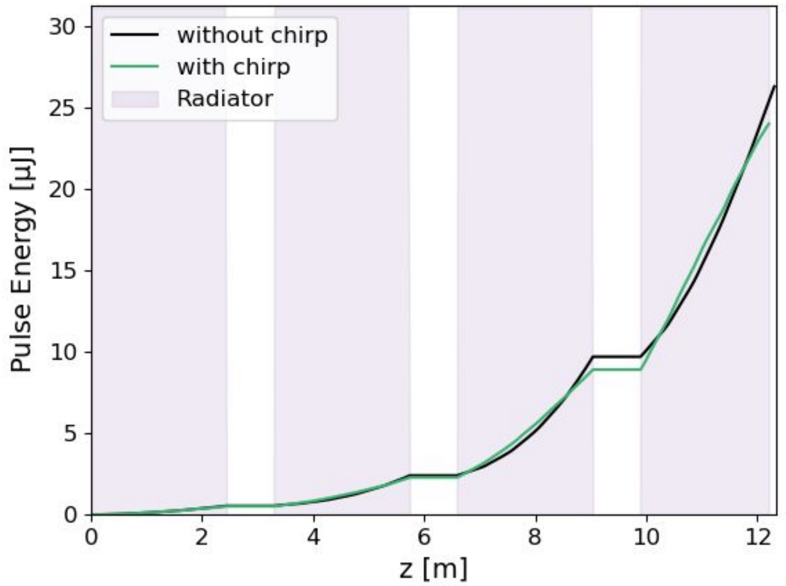
With chirp

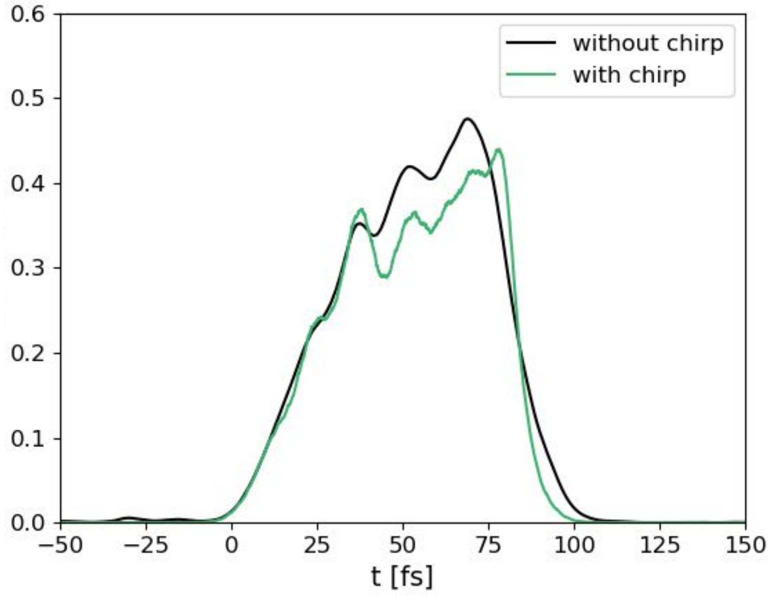


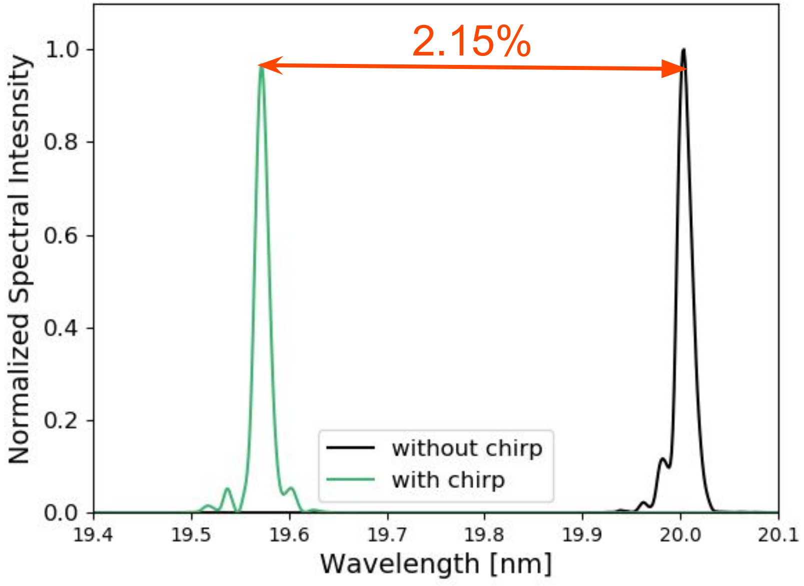


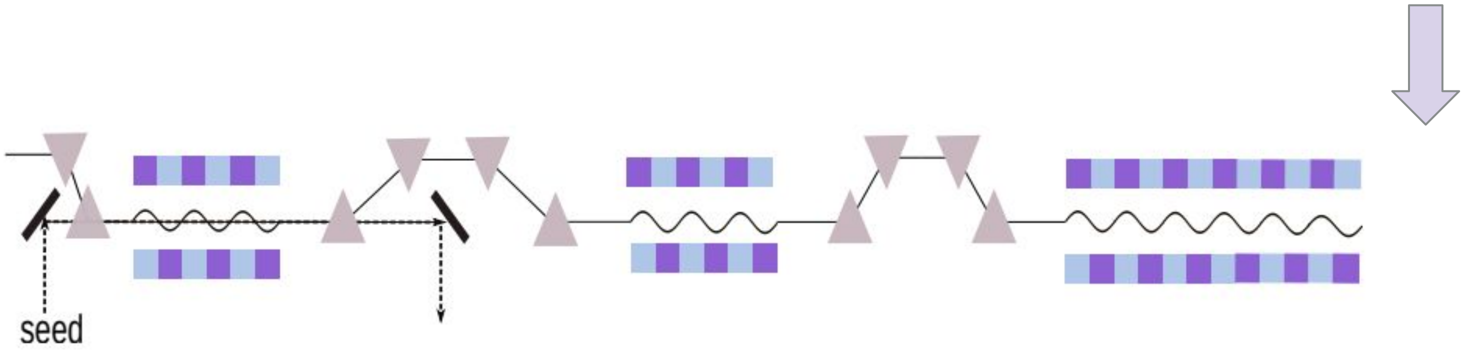
Optical klystron HGHG with a linear energy chirp

15th harmonic of 300 nm seed laser wavelength



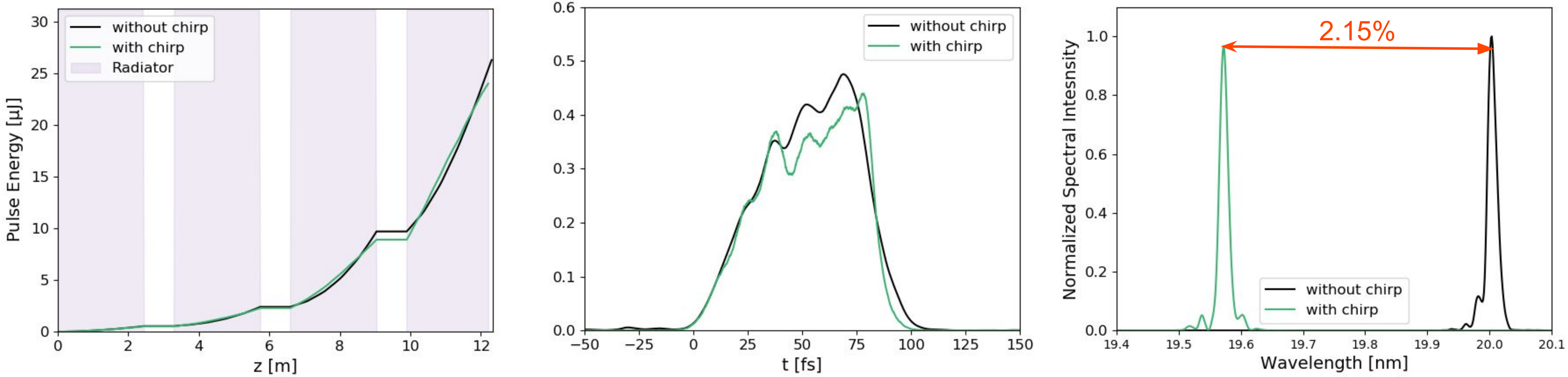






Optical klystron HGHG with a linear energy chirp

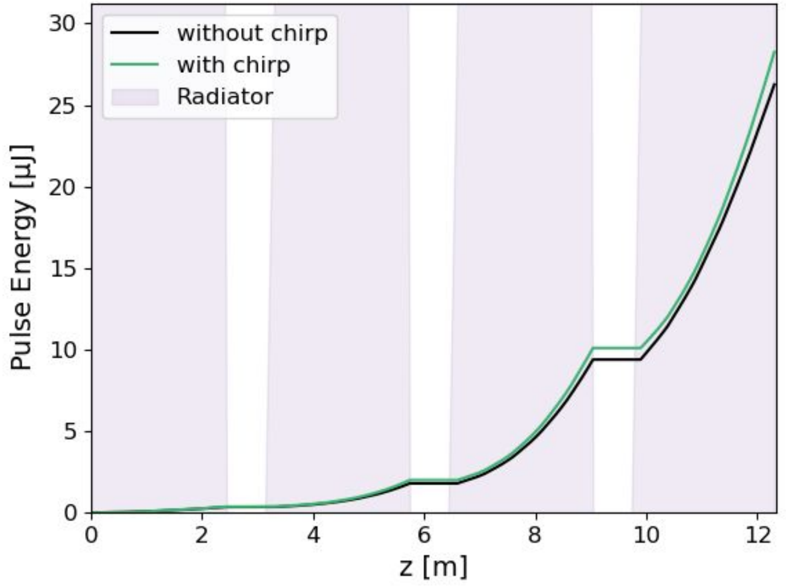
15th harmonic of 300 nm seed laser wavelength

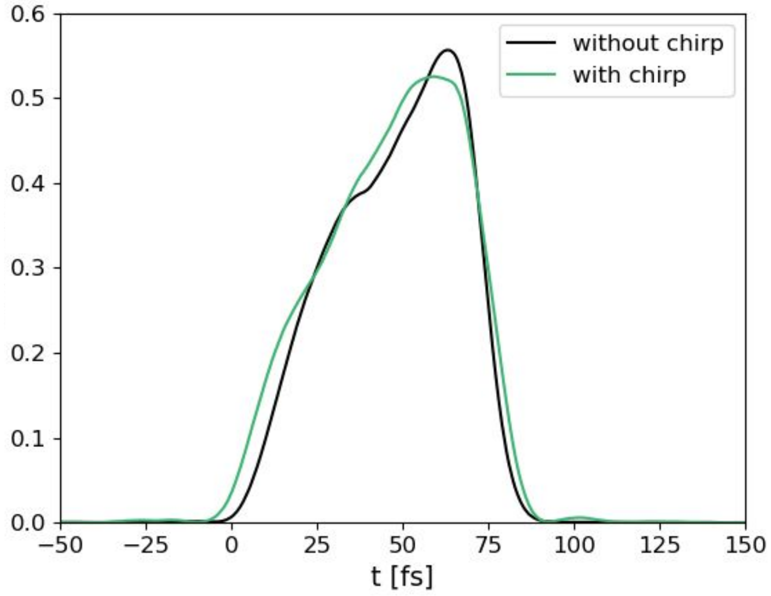


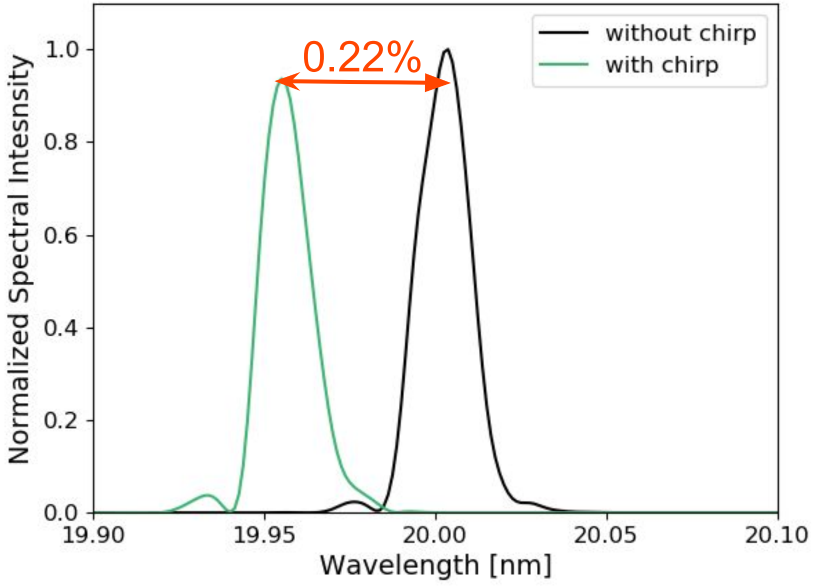
	FWHM relative BW	Pulse duration rms	Pulse energy
Without chirp	8.1 10^{-4}	22.2 fs	26.6 μJ
With chirp	7.9 10^{-4}	21.5 fs	24.2 μJ

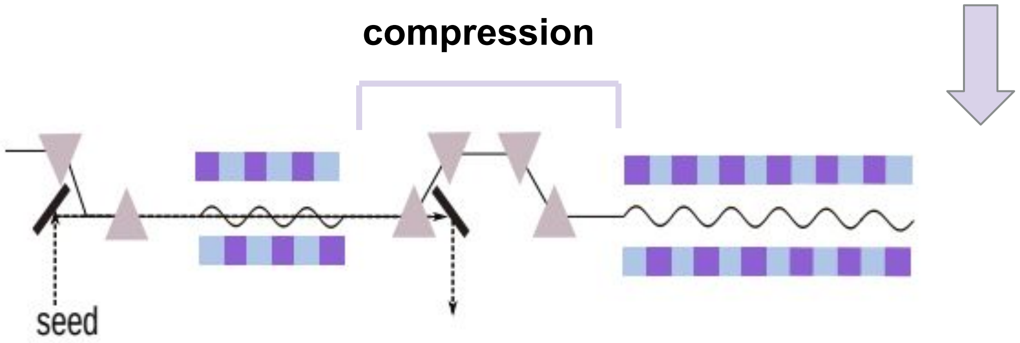
Standard HGHG with a linear energy chirp

15th harmonic of 300 nm seed laser wavelength



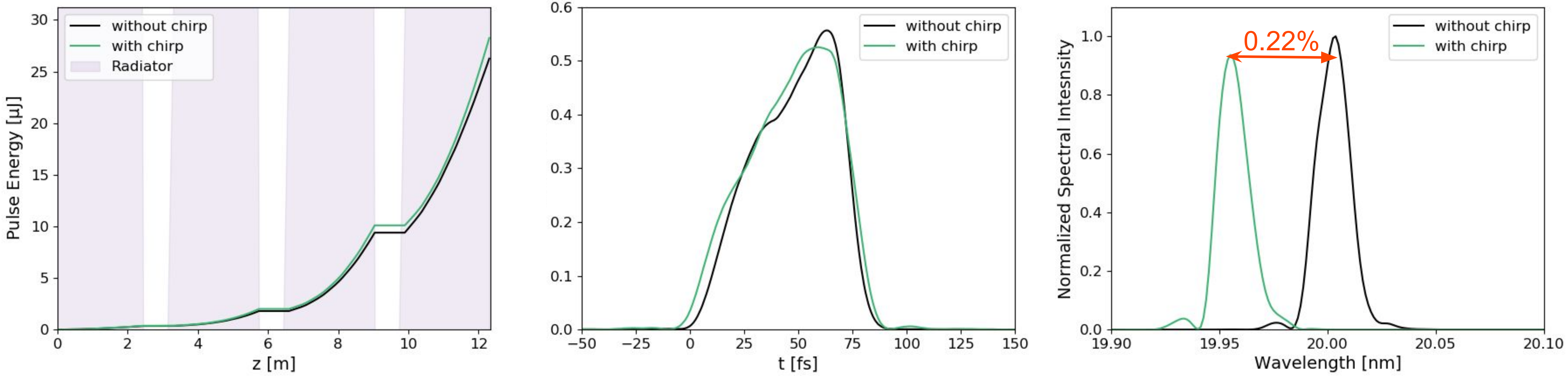






Standard HGHG with a linear energy chirp

15th harmonic of 300 nm seed laser wavelength



	FWHM relative BW	Pulse duration rms	Pulse energy
Without chirp	$8.7\ 10^{-4}$	18.9 fs	26.6 µJ
With chirp	$7.5\ 10^{-4}$	20.7 fs	28.6 µJ

Summary

Optical-klystron based HGHG → 2 to 3 orders of magnitude lower peak power

- relaxes **damage threshold** ✔
- increases **repetition rate** of seeded radiation ✔
- decreases the **wavelength** of seeded radiation ✔
- can be **immediately tested** in existing FEL beamlines ✔
- Electron bunches with **linear energy chirp** can be used ✔

Shot to shot stability ✔

Response to fluctuations ✔

Positive first experimental outcomes ✔

High repetition rate seeded free electron laser with an optical klystron in high-gain harmonic generation:
Georgia Paraskaki, Enrico Allaria, Evgeny Schneidmiller, and Wolfgang Hillert Phys. Rev. Accel. Beams 24, 120701

Proof of principle experiment at SXFEL:
J. Yan, Z. Gao, Z. Qi, K. Zhang, K. Zhou et al. Self-amplification of coherent energy modulation in seeded free-electron lasers. Phys. Rev. Lett., 126:084801, Feb 2021.

IPAC22 talk & poster by H. Deng: TUISP2

Thank you
for your attention!

Questions before the coffee break?