Fresh slice self-seeding and fresh slice harmonic lasing at LCLS

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Los Alamos
NATIONAL LABORATORY
EST. 1943

UCLA

SLAC
NATIONAL ACCELERATOR LABORATORY

Presentation Outline

(1) Motivation

- Science applications for TW X-ray FELs
- Tapering for high power XFELs: promises and limitations

(3) Fresh-slice self-seeding: experimental demonstration

- Description of proof of principle at LCLS
- Performance comparison with SASE, self-seeding and simulation

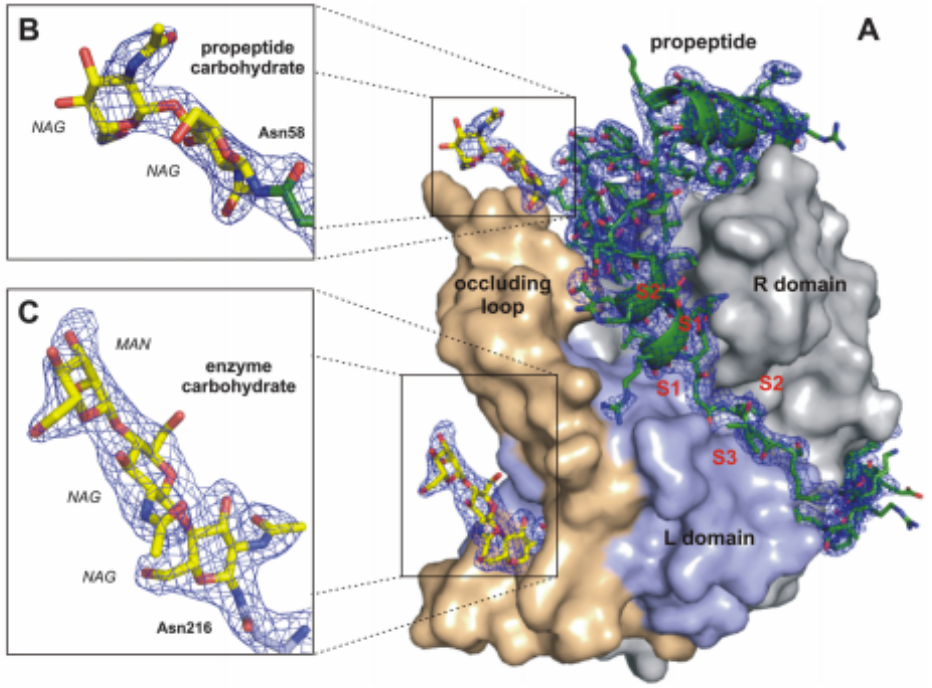
(4) Fresh-bunch harmonic lasing: theoretical work and experimental proposal

(5) Conclusion and future work

Motivation for High efficiency TW-level X-ray FEL

Imaging single molecules via "Diffraction before destruction" method

Redecke et al., Science 339, 6116, (2012)



2.1 A resolution

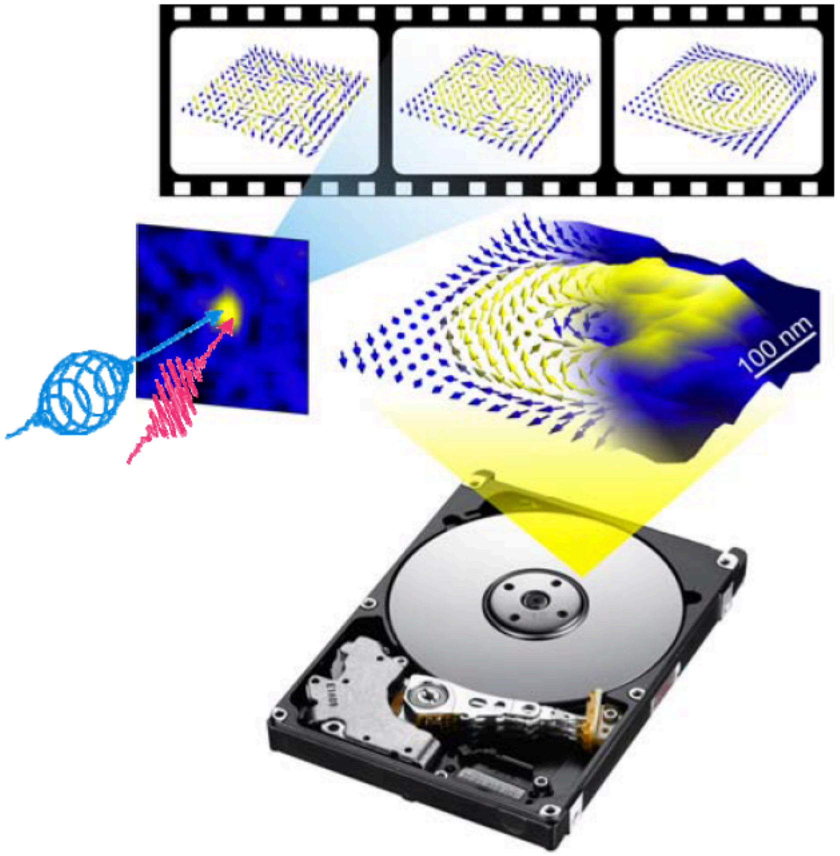
Trypanosoma brucei cysteine protease cathepsine B

Single Molecule Imaging Goal
10 fs - 10 mJ - 2020

Aquila et al., "The LCLS single particle imaging roadmap" Stuct. Dynam. **2**, 041701

Understanding Quantum Materials

LCLS-II New Instruments Workshop Report (2012)

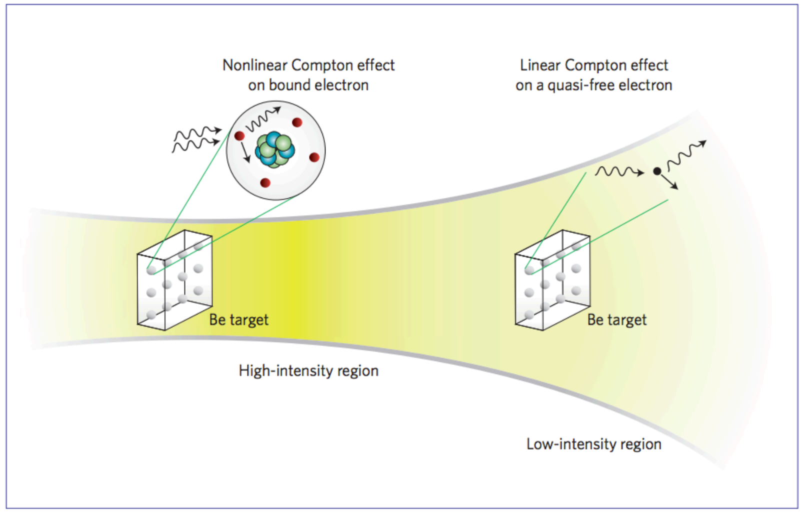


Topological magnetic structures representing magnetic bits on future disk drives

TW power increases resolution of Resonant X-ray scattering

Probing nonlinear X-ray physics

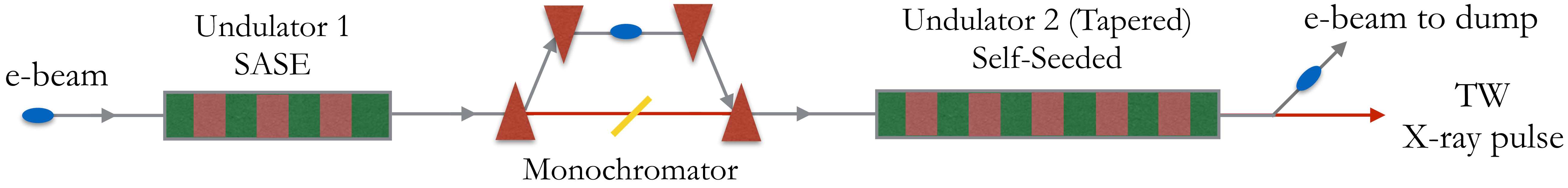
Fuchs et. al., Nature Physics 11, 964–970 (2015)
Shwartz et. al., PRL 112, 163901 (2014)
A. Palffy, Nature Physics 11, 893–894 (2015)



Nonlinear ("two-photon") compton scattering from bound electrons. Anomalous frequency shift suggests new physics to be understood.

High intensity X-rays necessary to probe nonlinear physics close to the Schwinger field

How do we reach high efficiency (TW) FEL?
Why fresh bunch self-seeding for optimal tapering?



- FEL resonant interaction can continue *past saturation* by tapering the undulator magnetic field to match the e-beam energy loss. When optimized, tapered FEL can reach high efficiency ~ 10 % and P ~ 1 TW.
- In a long tapered undulator section time dependent effects (sideband instability) limit maximum efficiency.
- Time dependent losses can be overcome using a large seed ($P/P_{noise} \sim 1000$) and a small energy spread ($\sigma_\gamma \sim 0.01$ %)
- Escaping the trade-off between seed power and energy spread requires **fresh bunch self-seeding**

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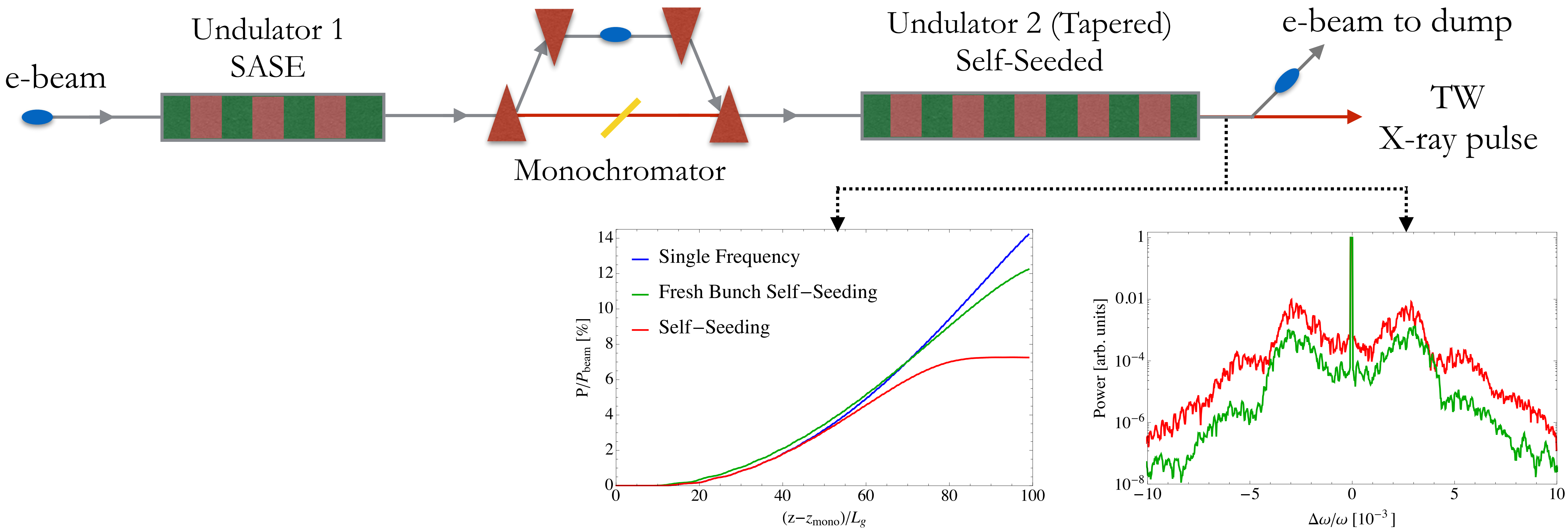

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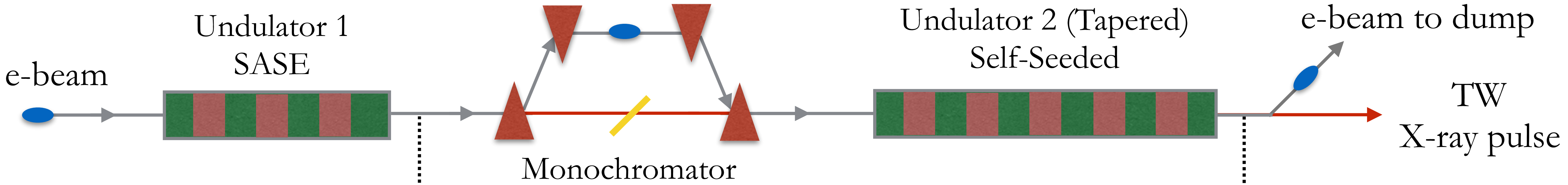


e-beam

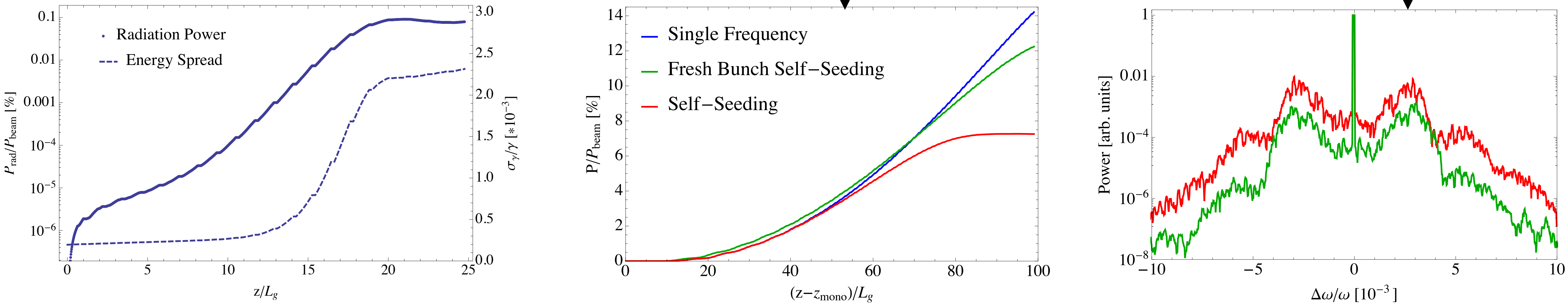
Undulator 1
SASE

Monochromator

Undulator 2 (Tapered)
Self-Seeded

e-beam to dump

TW
X-ray pulse



C. Emma et al., PRAB **19**, 020705 (2016)

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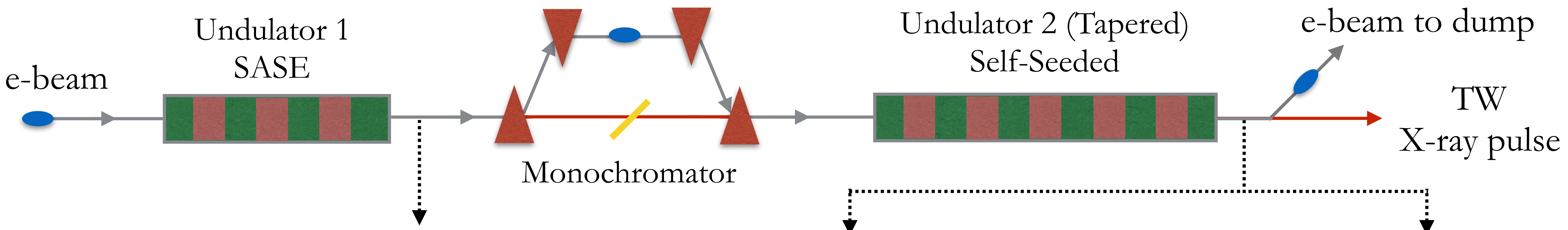

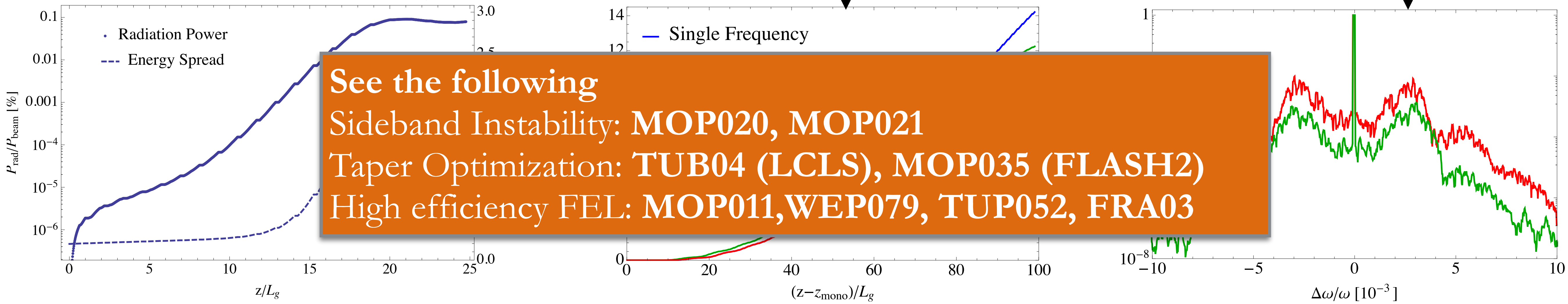

See the following
Sideband Instability: **MOP020, MOP021**
Taper Optimization: **TUB04 (LCLS), MOP035 (FLASH2)**
High efficiency FEL: **MOP011,WEP079, TUP052, FRA03**

C. Emma et al., PRAB **19**, 020705 (2016)

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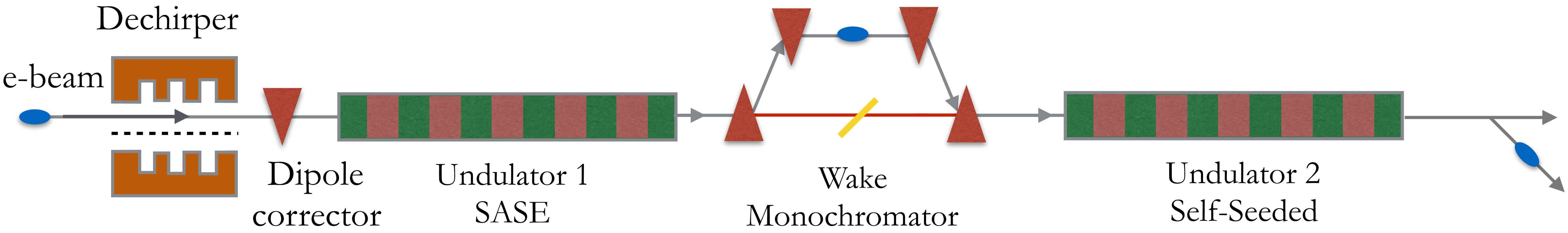
The “fresh-slice” lasing method



Method

- FEL can be suppressed by inducing transverse oscillation on parts of the bunch
- Can be controlled in real time by moving the dechirper jaws (changing the offset)
- Dipole correctors with an appropriate delay can steer seed pulse onto “fresh” electrons

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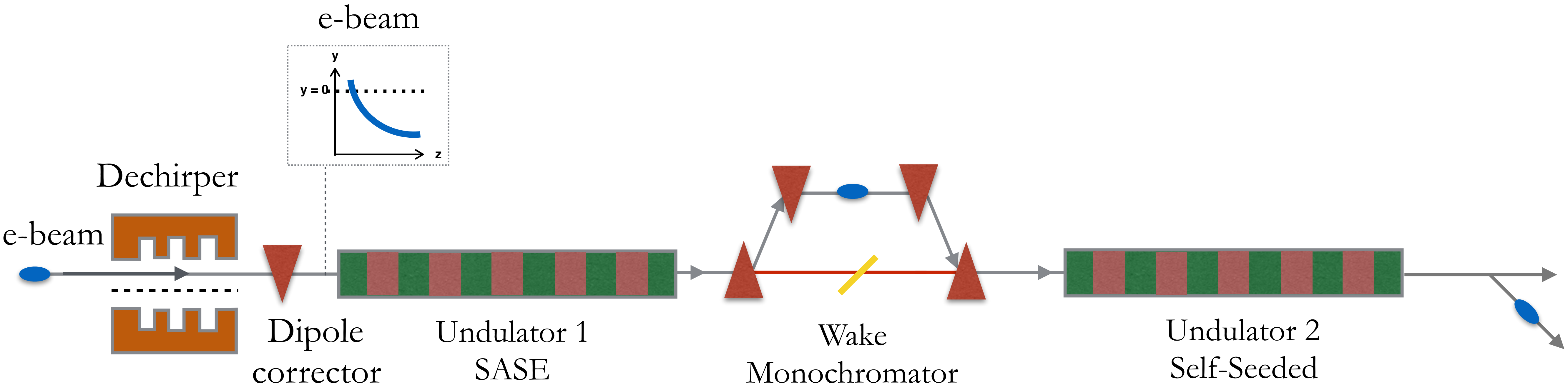

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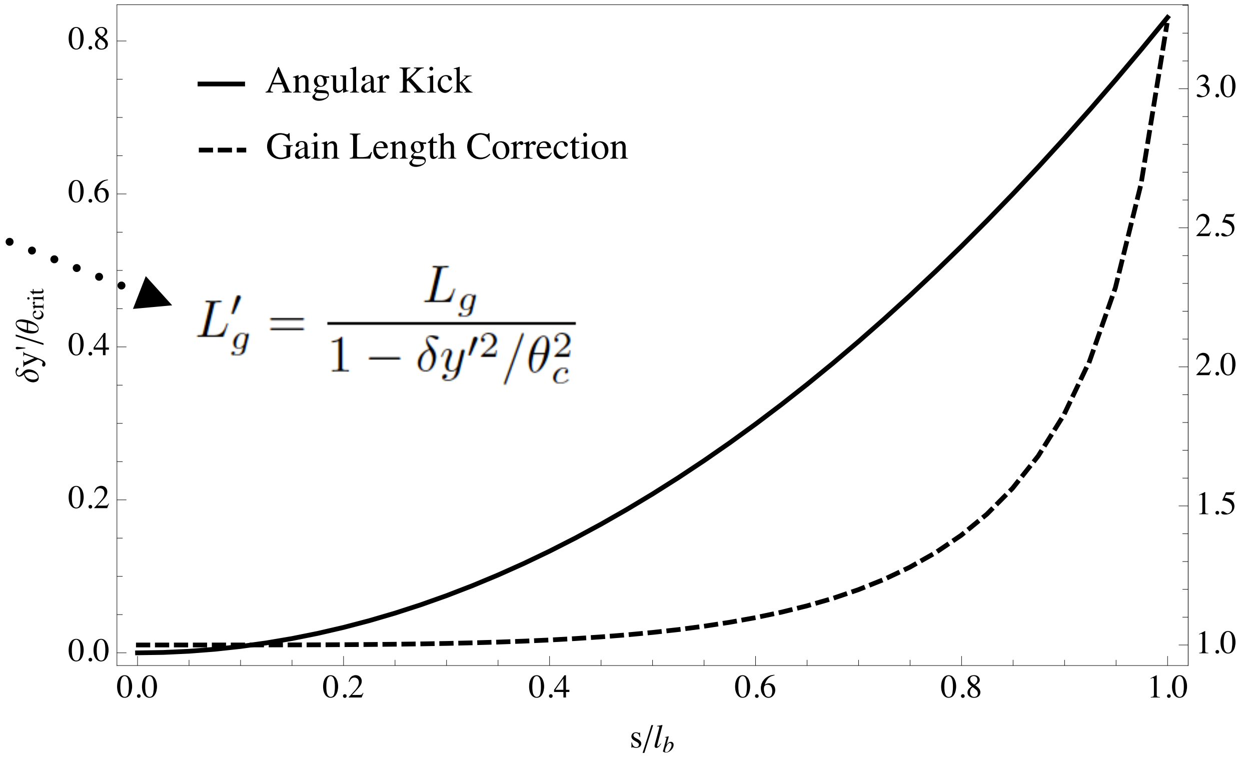

K. Bane, G. Stupakov, I. Zagorodnov SLAC PUB 16497 (2016)

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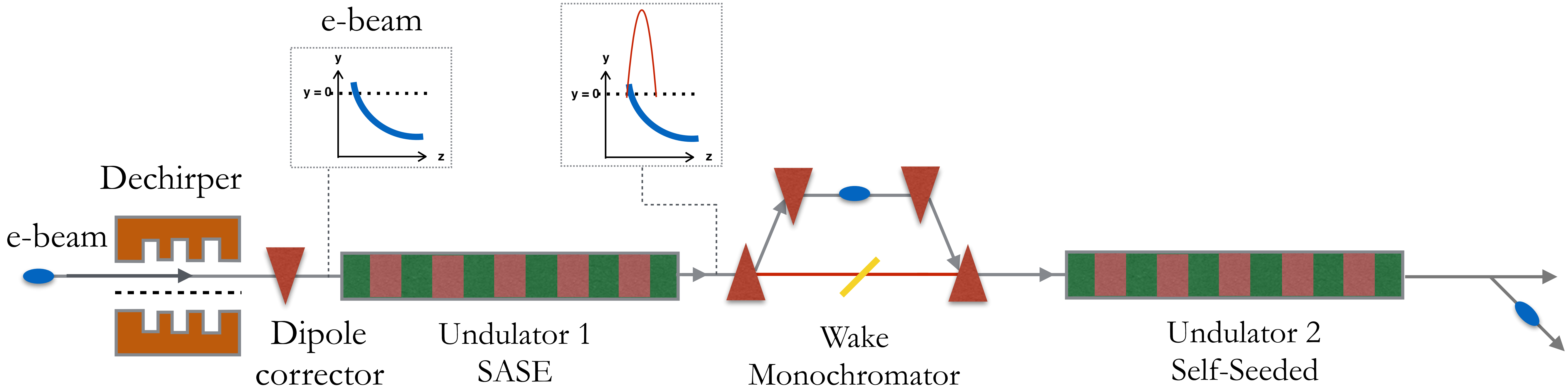

e-beam

Dechirper

e-beam

Dipole corrector

Undulator 1 SASE

Wake Monochromator

Undulator 2 Self-Seeded

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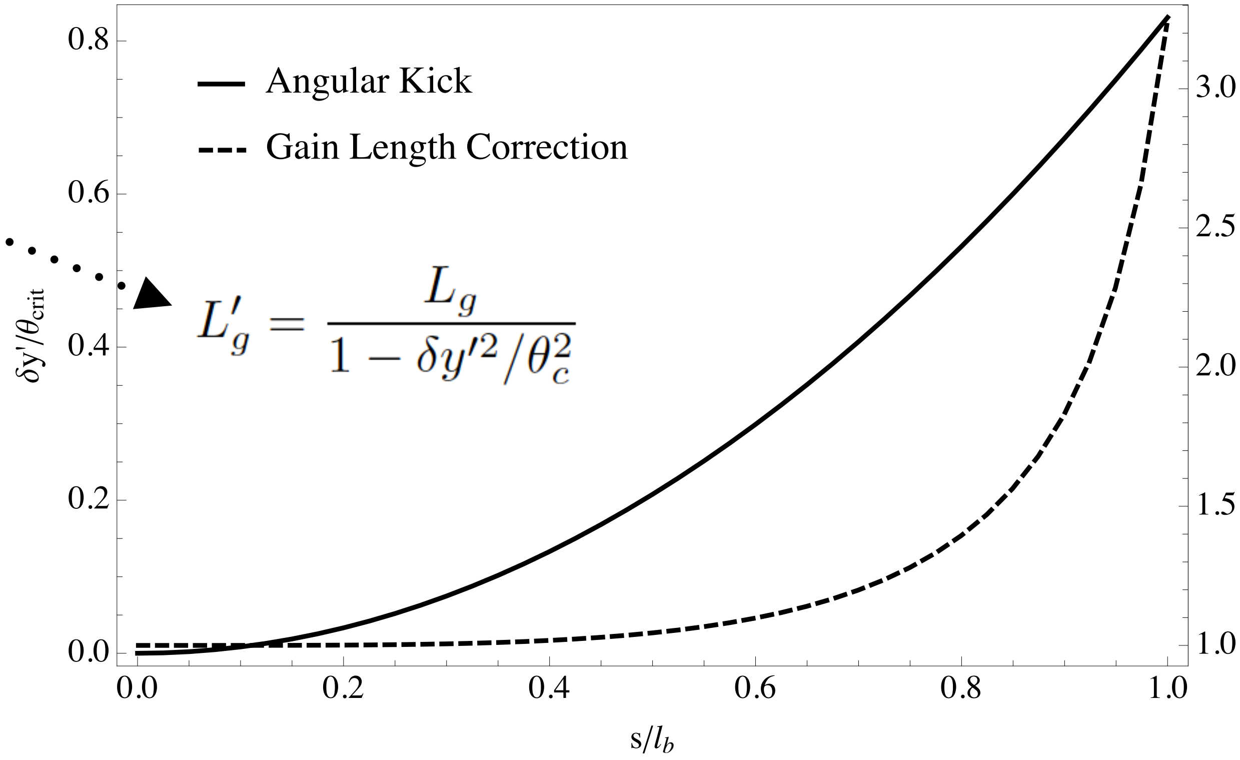

$$L'_g = \frac{L_g}{1 - \delta y'^2/\theta_c^2}$$

K. Bane, G. Stupakov, I. Zagorodnov SLAC PUB 16497 (2016)

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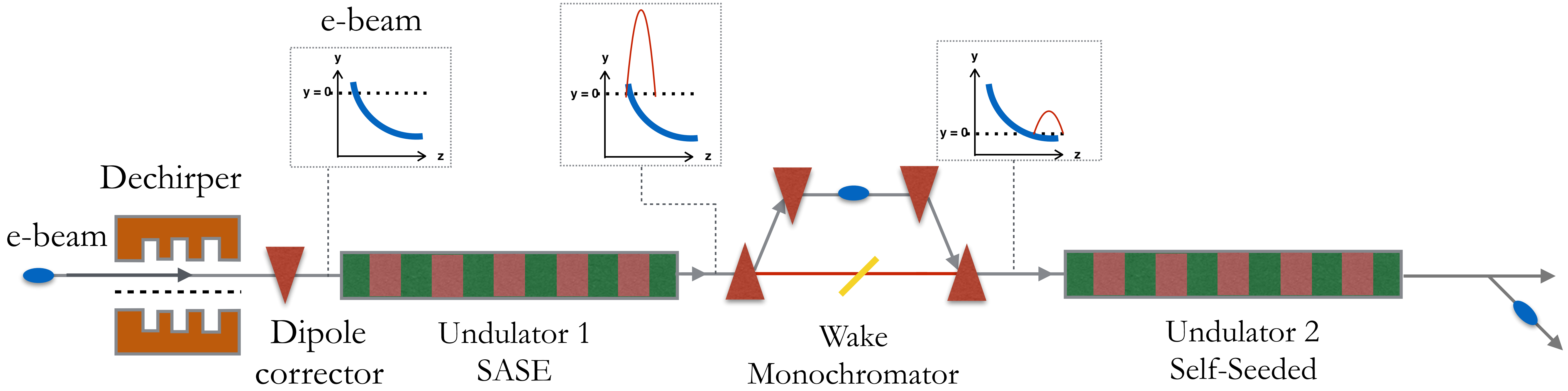

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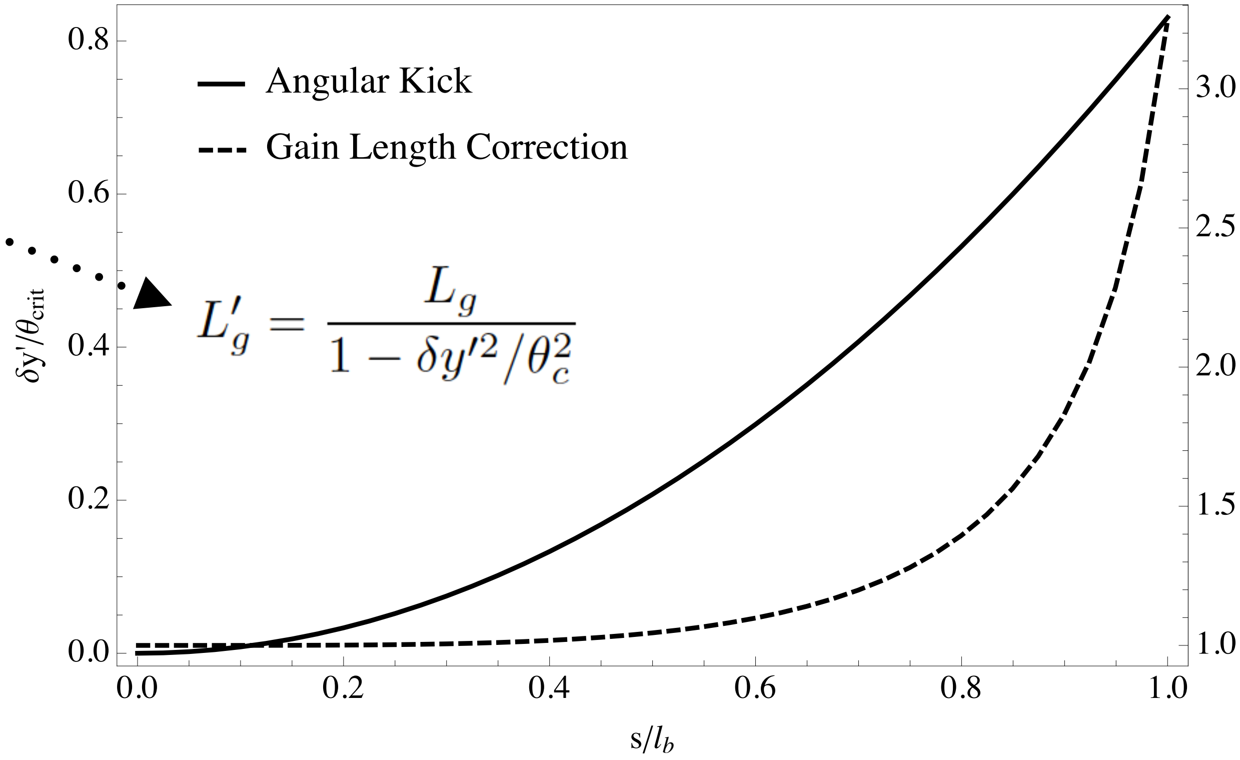

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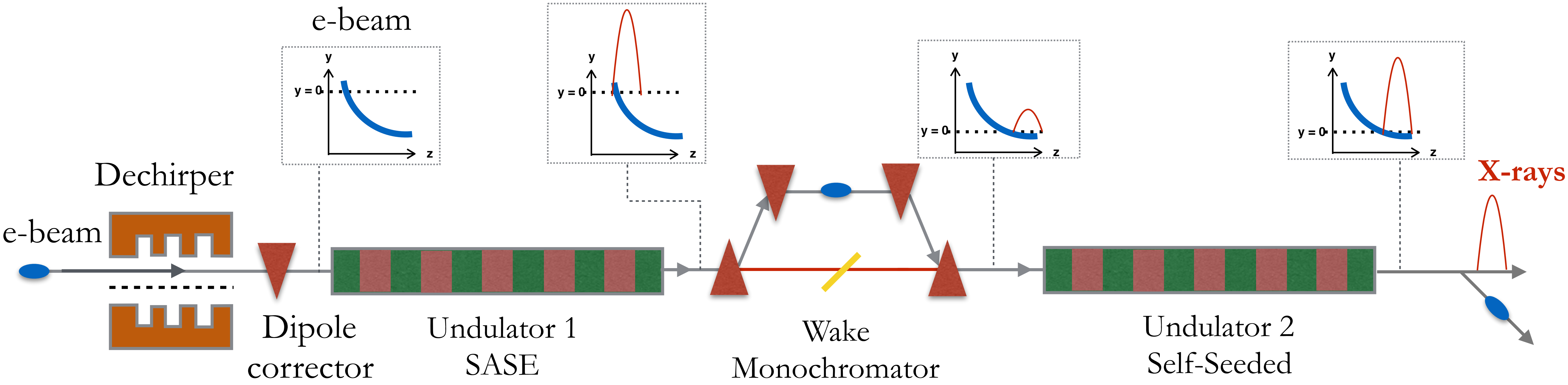

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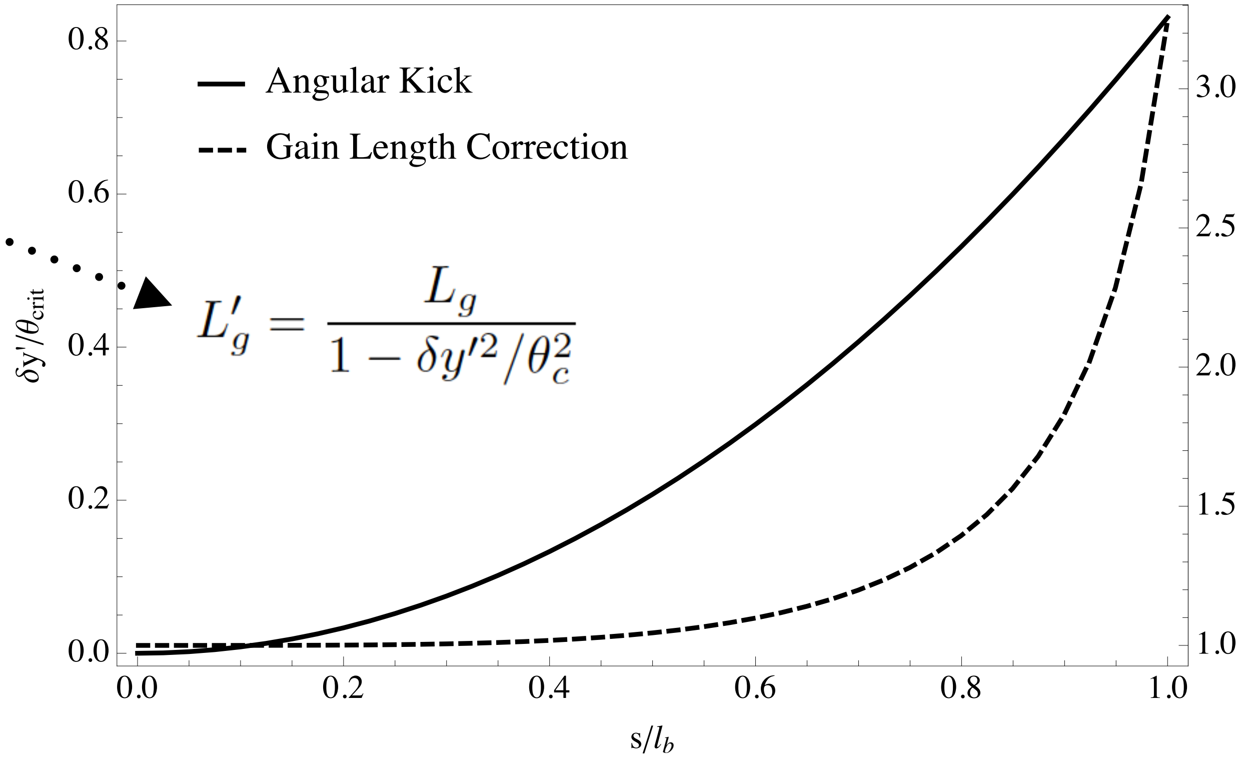

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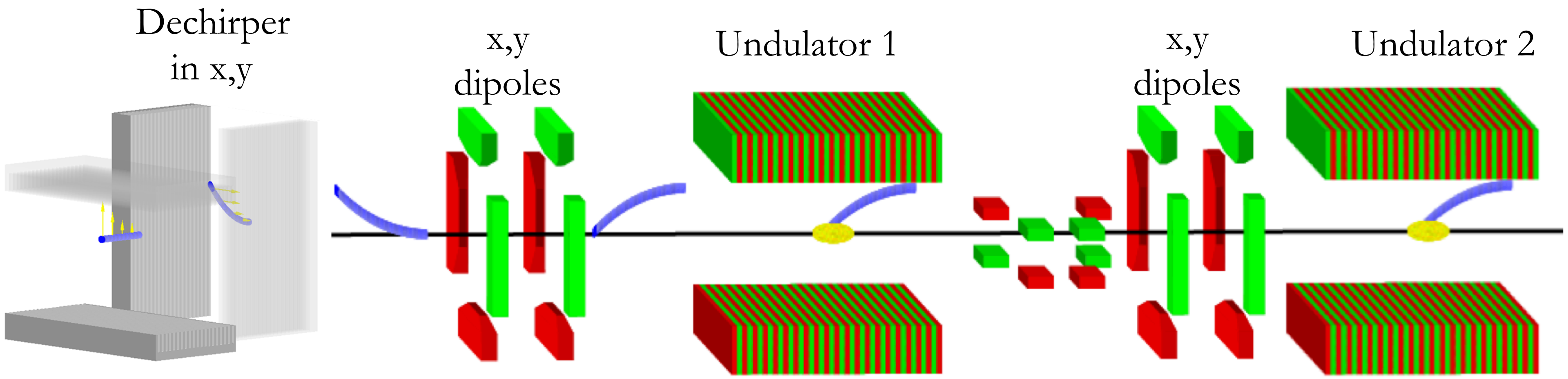
The "fresh-slice" method at LCLS: modes of operation

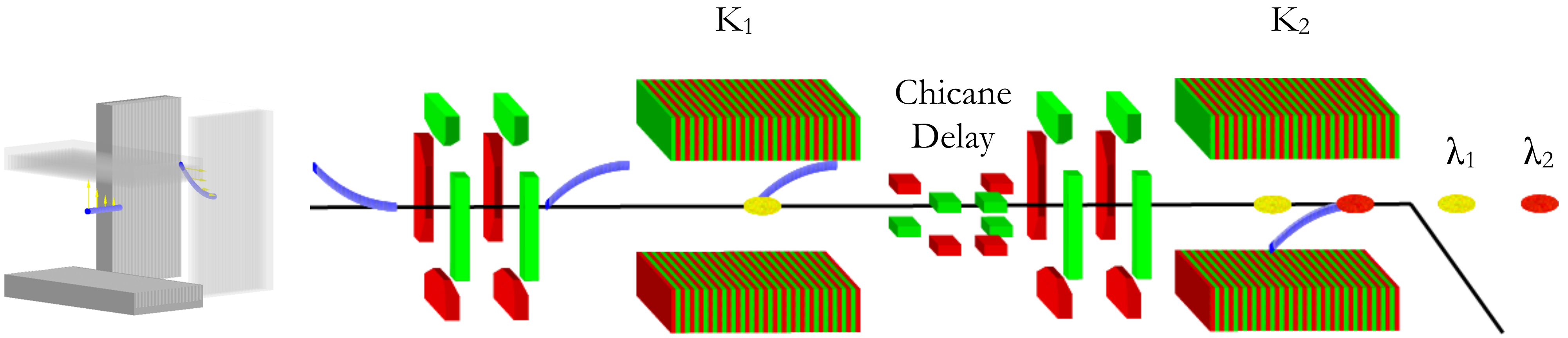
See FRA01

1) Fresh slice SASE for control of pulse duration



A. Lutman *et. al.* Nature Photonics **10**, 745–750 (2016)

2) Two-color fresh slice SASE with polarization control



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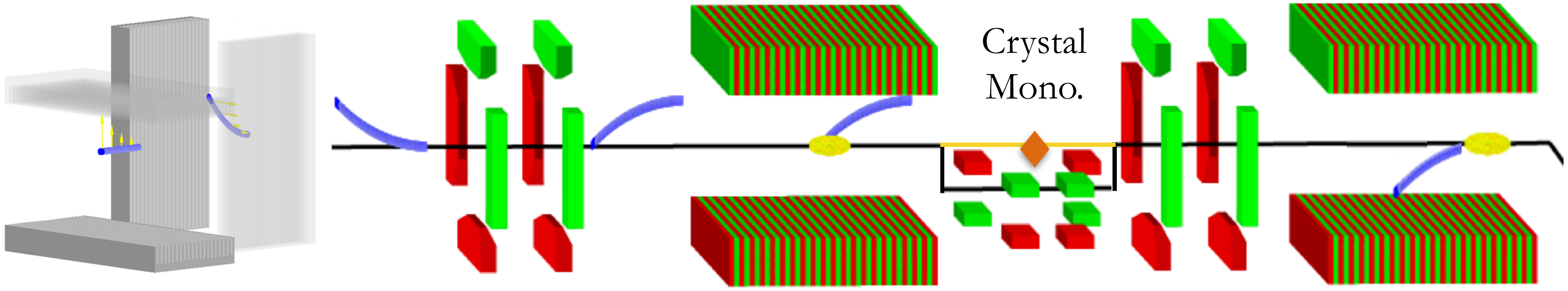
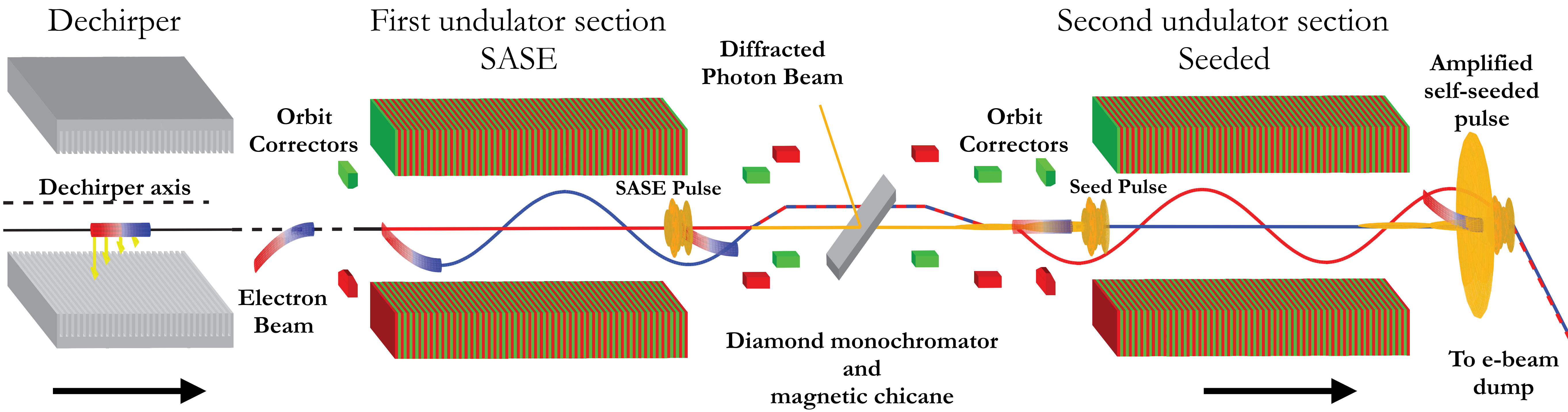
3) Fresh Bunch Self-Seeding for high intensity short seeded pulses



C. Emma *et. al.* App Phys. Lett. **110**, 154101 (2017)

For additional fresh-slice schemes see TUP026 TUP055 TUP056

FBSS proof of principle experiment



Dechirper

First undulator section
SASE

Diffracted
Photon Beam

Second undulator section
Seeded

Orbit
Correctors

Orbit
Correctors

Amplified
self-seeded
pulse

Dechirper axis

SASE Pulse

Seed Pulse

Electron
Beam

Diamond monochromator
and
magnetic chicane

To e-beam
dump

$E_{\text{X-Ray}} = 5.5\ \text{keV}$

E-beam

I_{pk}= 4 kA
E= 11 GeV
Q= 180 pC

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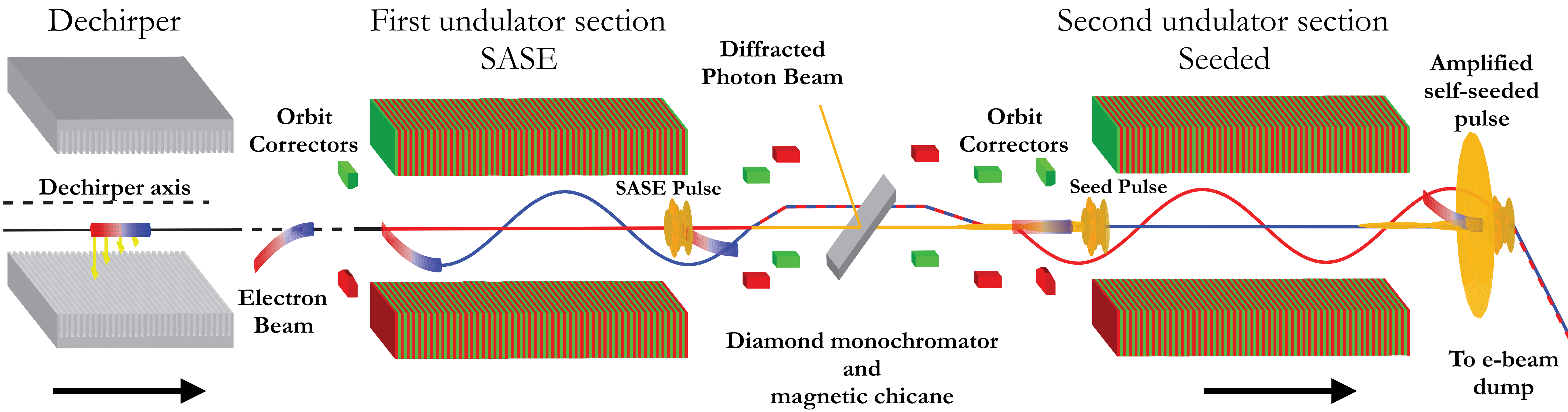

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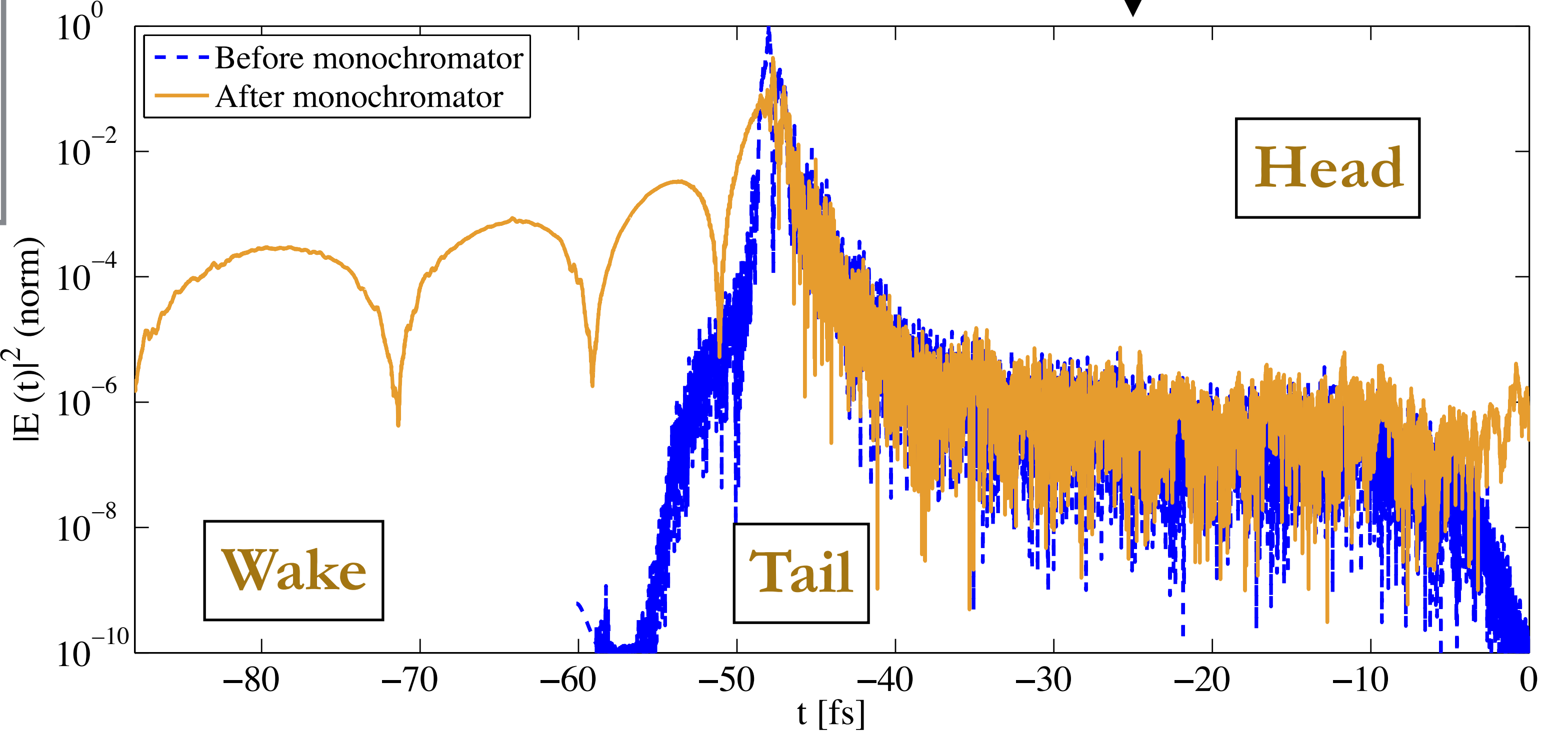

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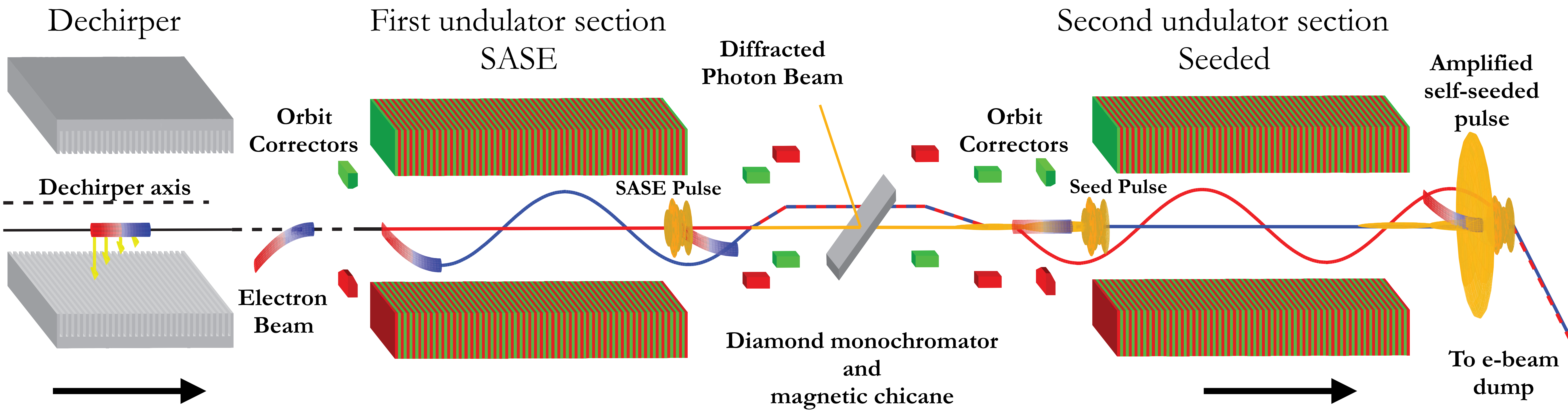

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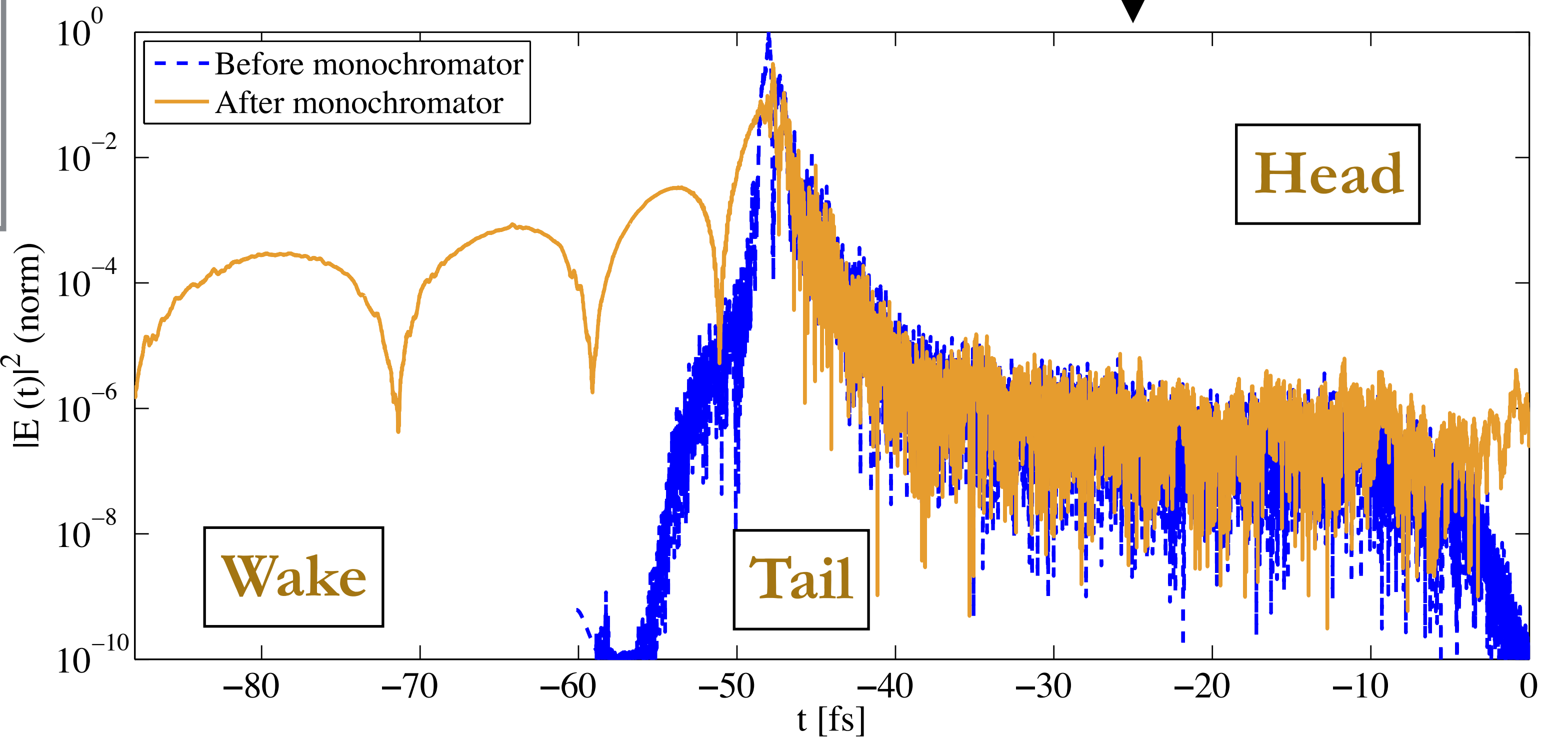


Diagnostics

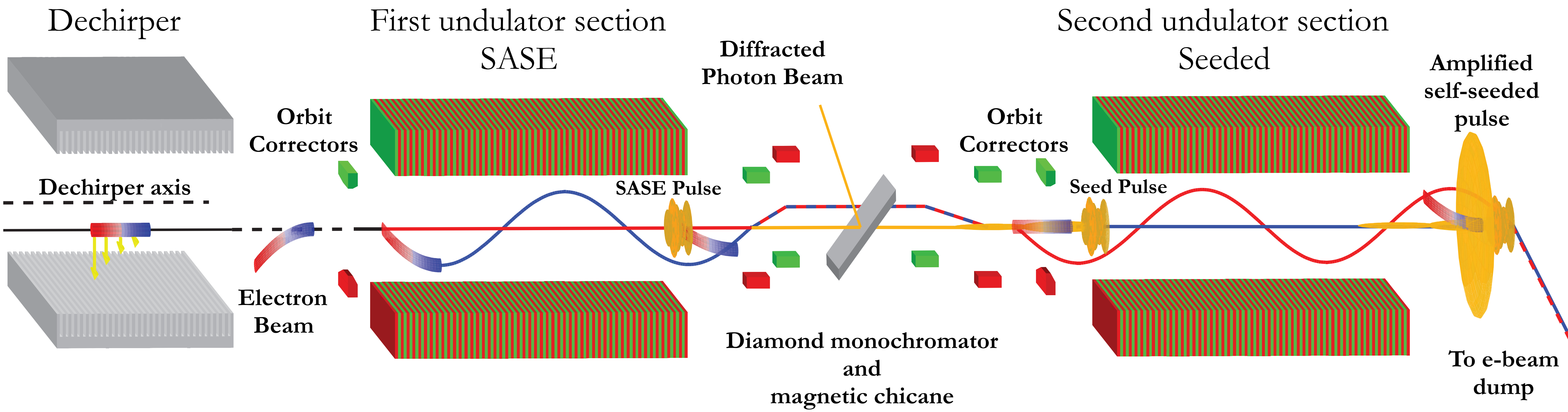
1) **Transverse deflecting cavity**
Electron beam energy loss
(time resolved)

2) **Gas detector**
X-ray intensity

3) **X-ray spectrometer**

C. Emma *et. al.* App Phys. Lett. **110**, 154101 (2017)

FBSS proof of principle experiment



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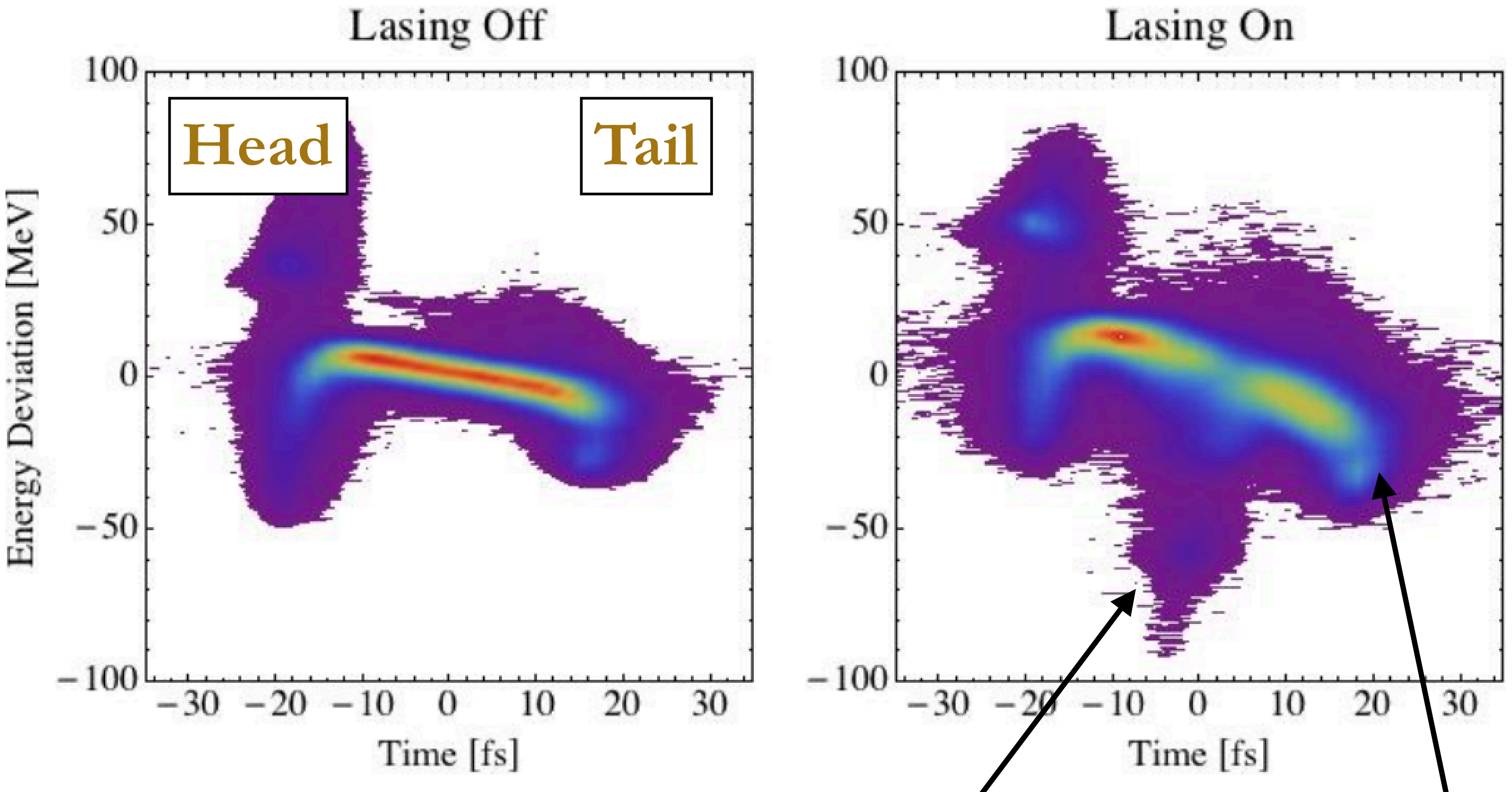

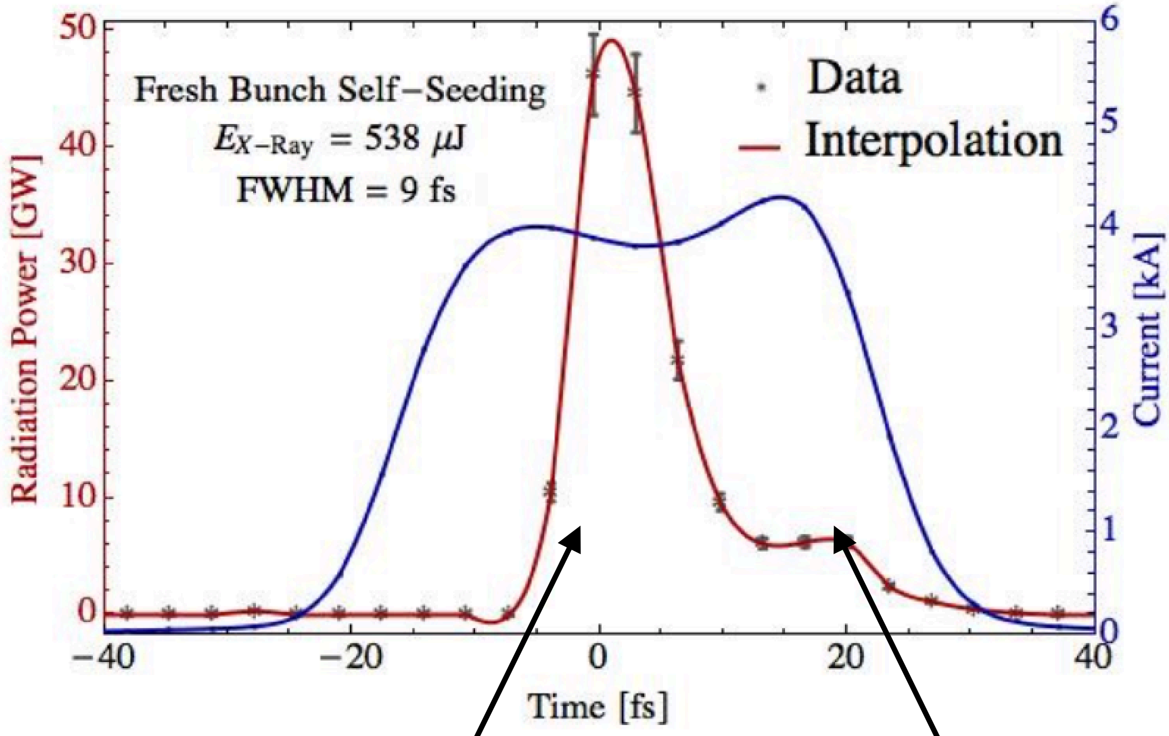

Seeded core

SASE lasing slice

Seeded core

SASE lasing slice

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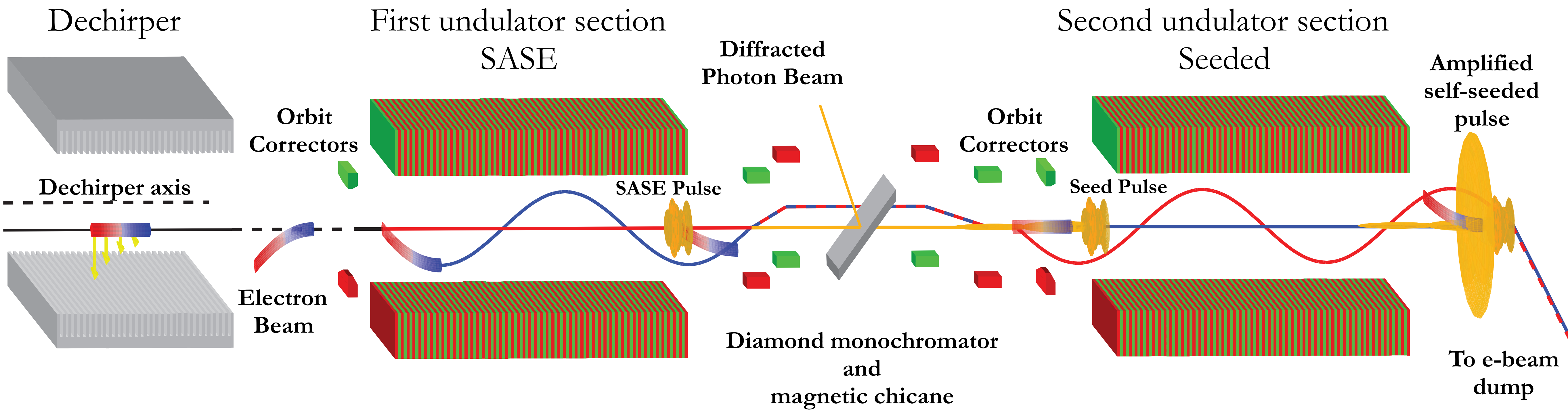
FBSS proof of principle: statistical properties



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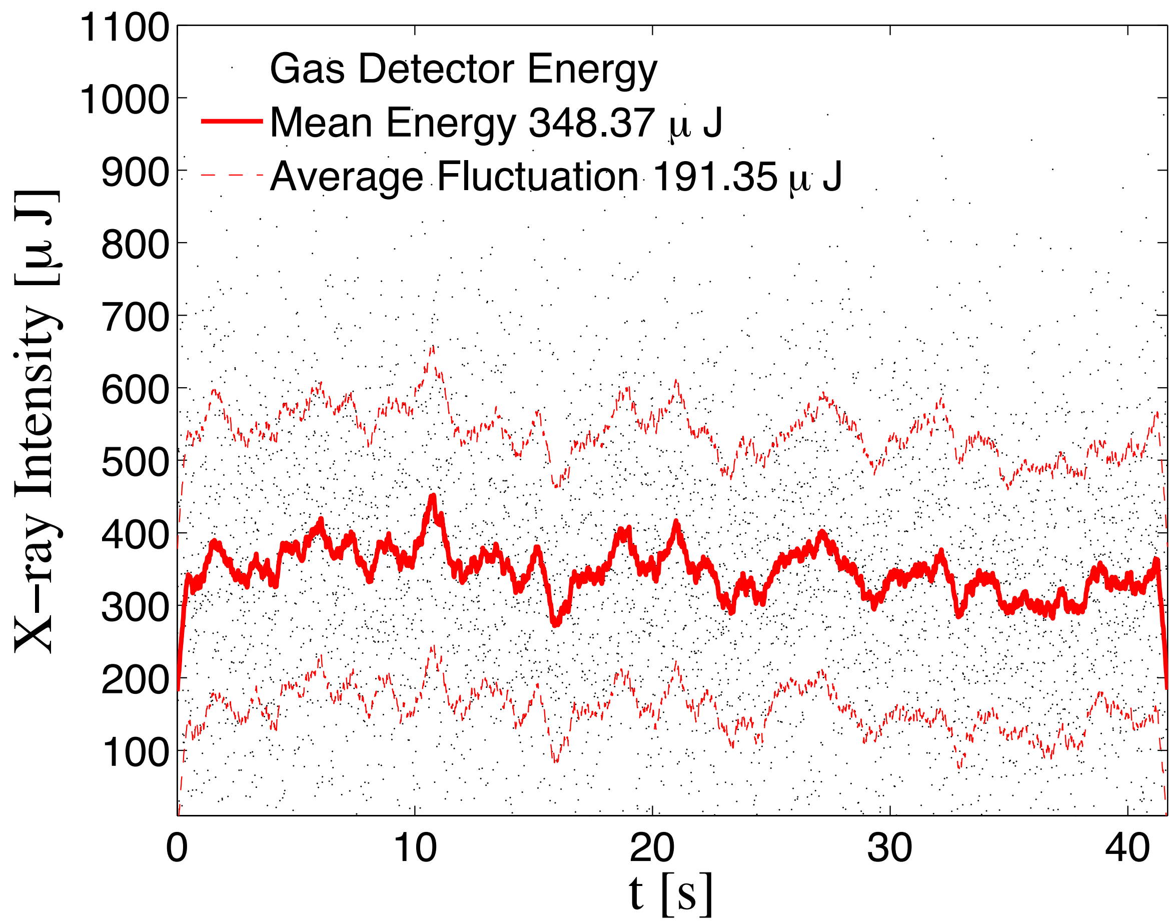
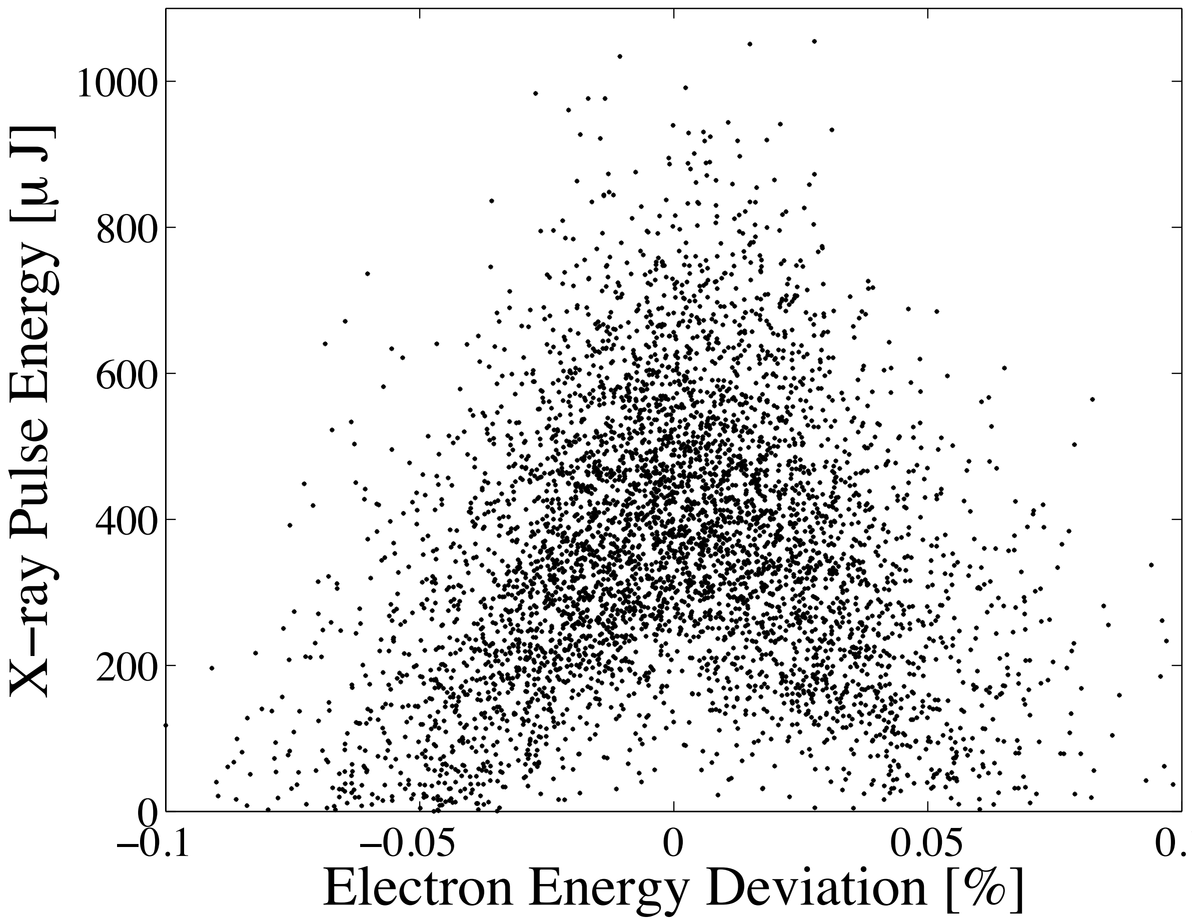
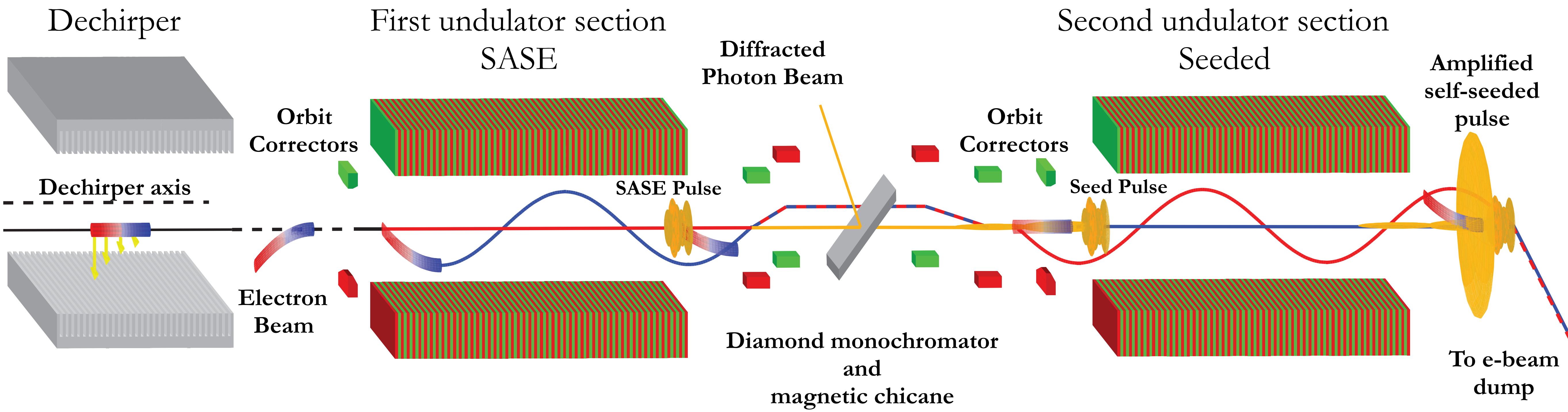
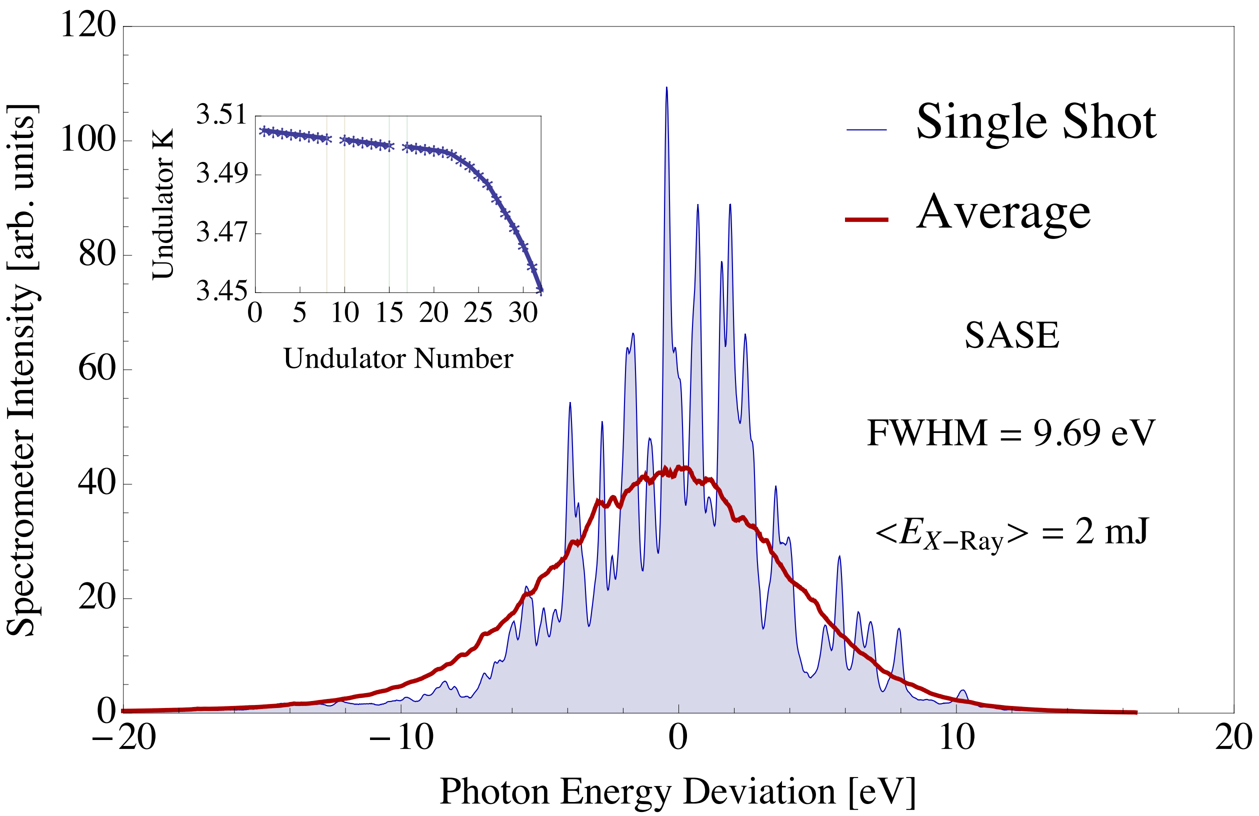


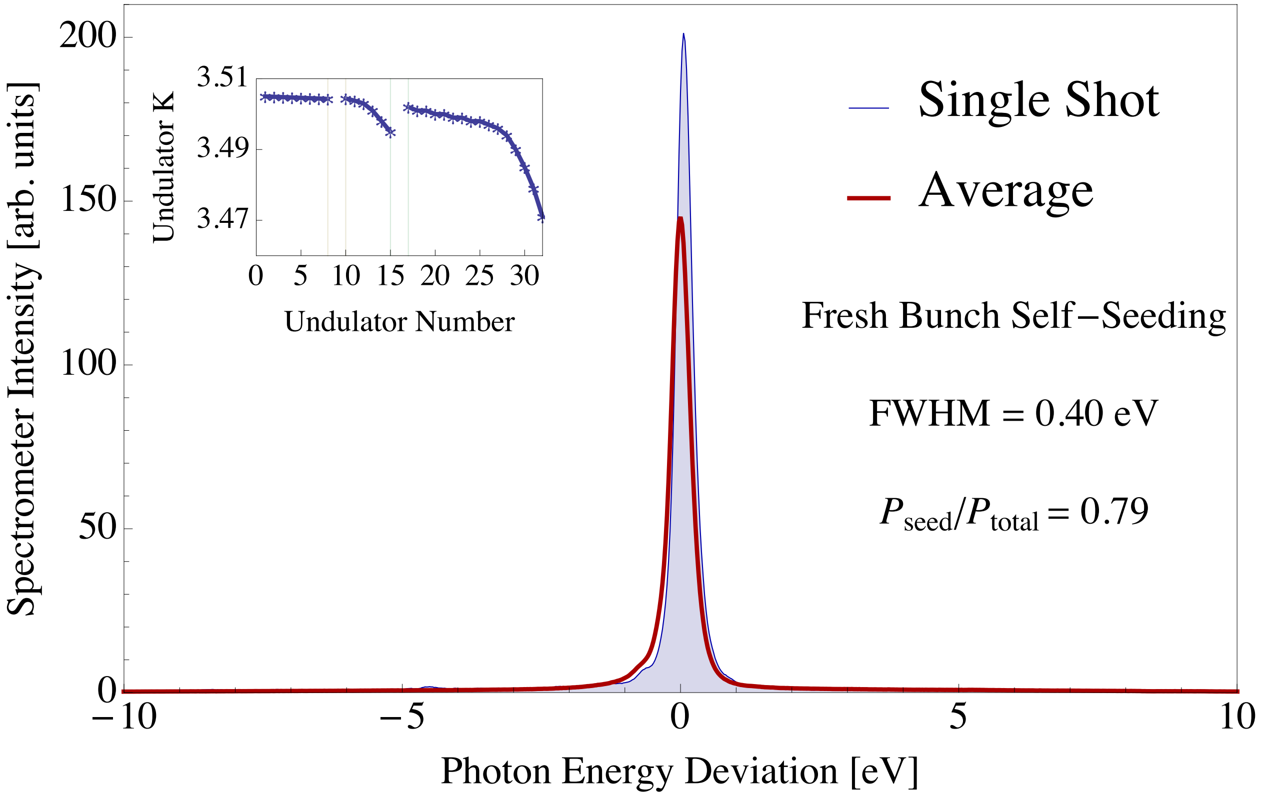


C. Emma *et. al.* App Phys. Lett. **110**, 154101 (2017)

FBSS proof of principle: comparison with SASE







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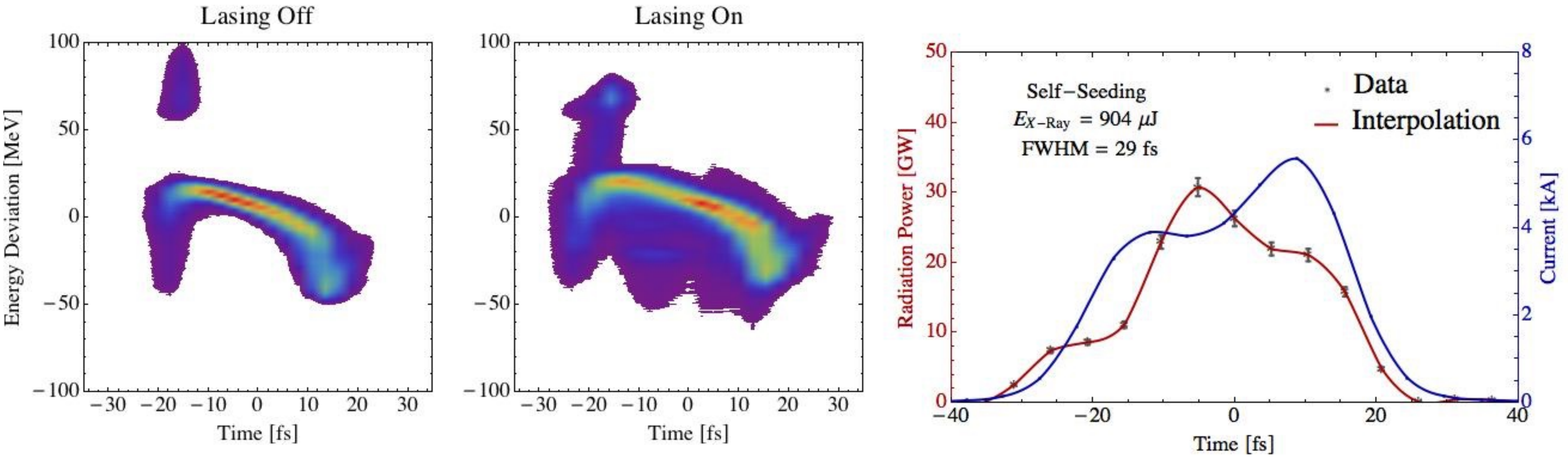
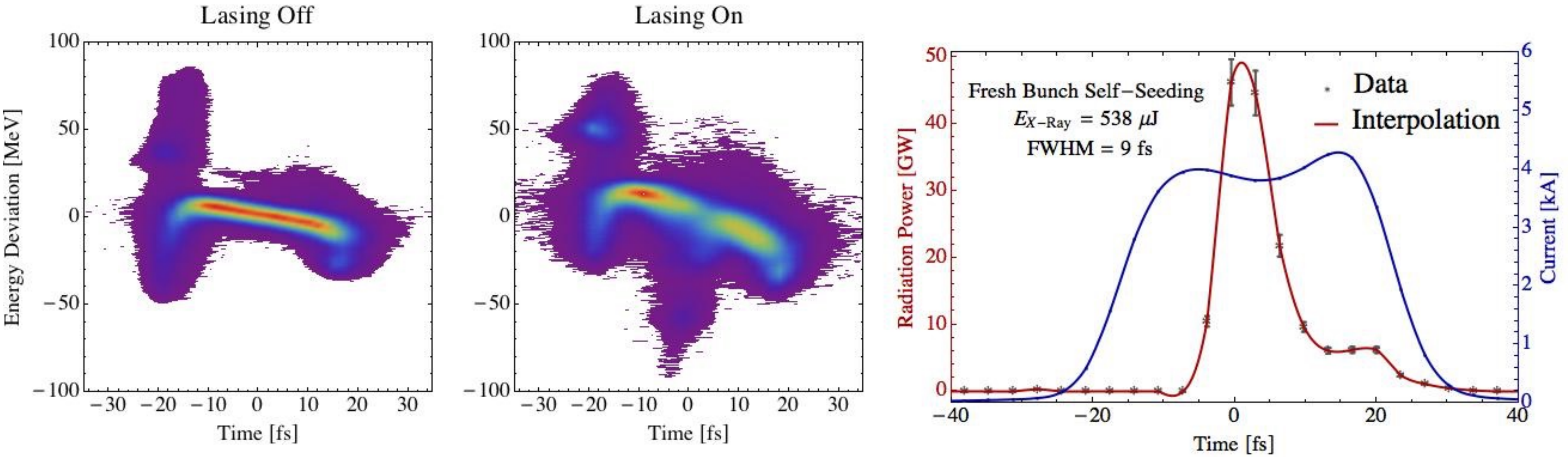
~12* increase in X-ray beam brightness compared to SASE

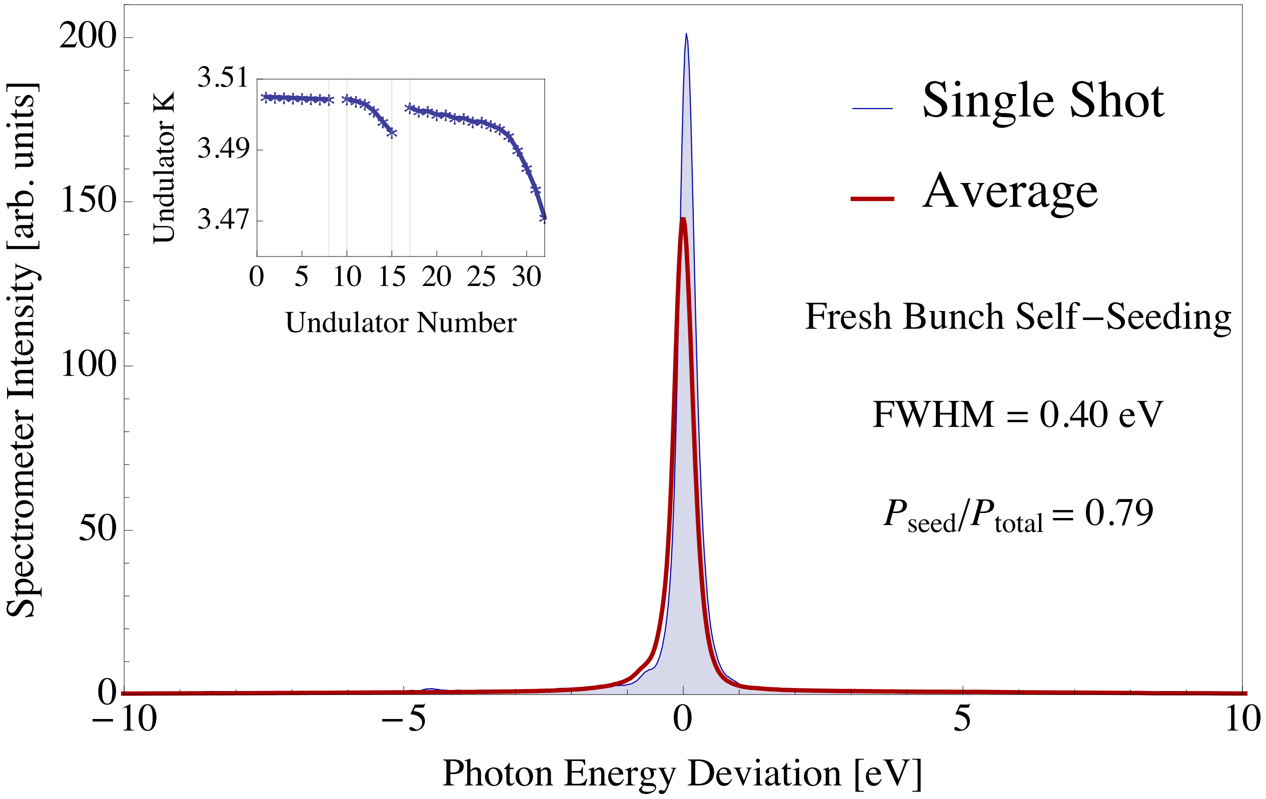
FBSS proof of principle: comparison with self-seeding

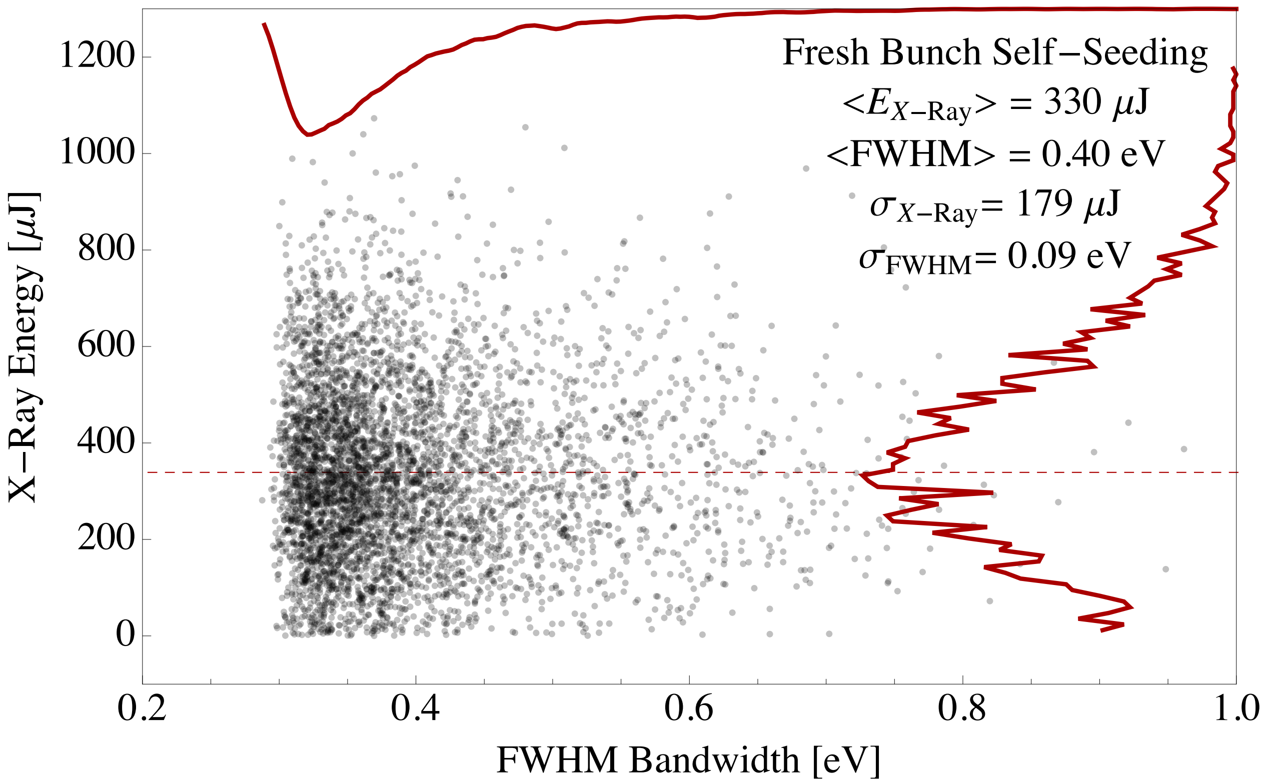


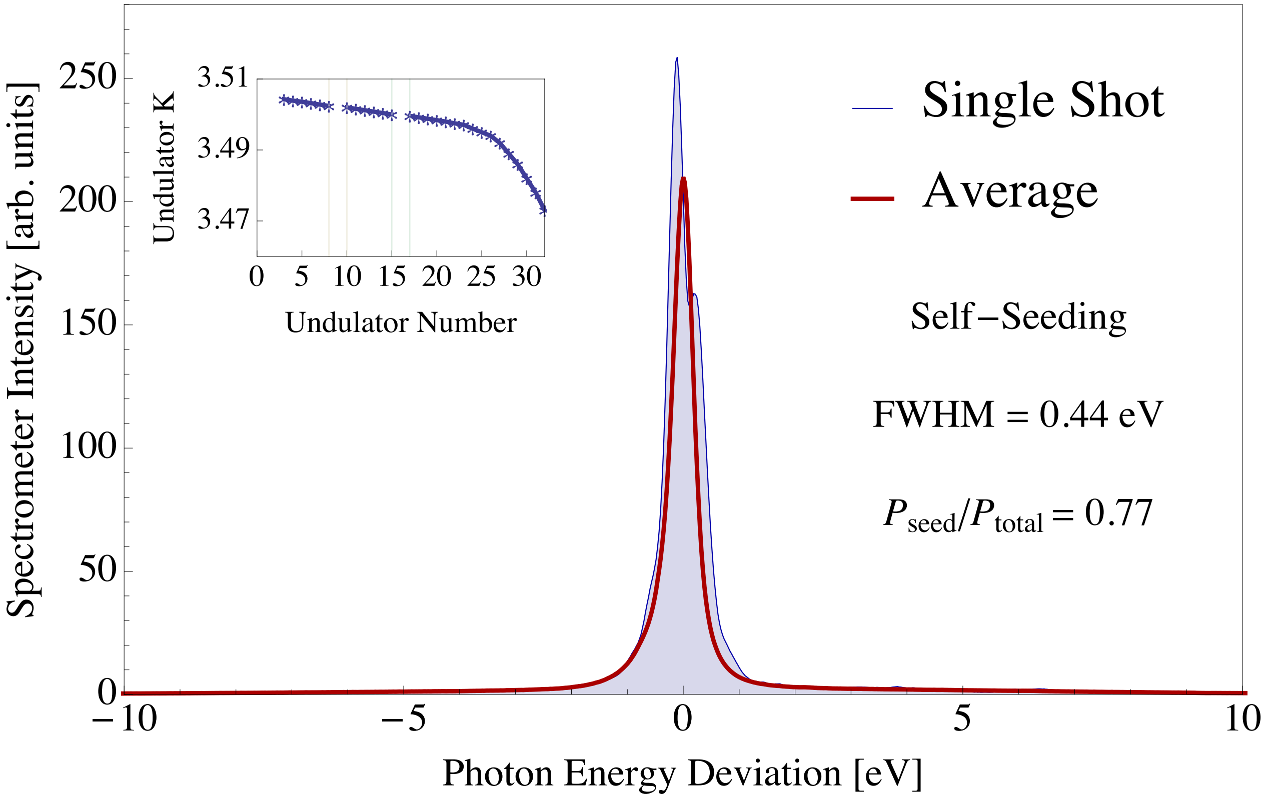


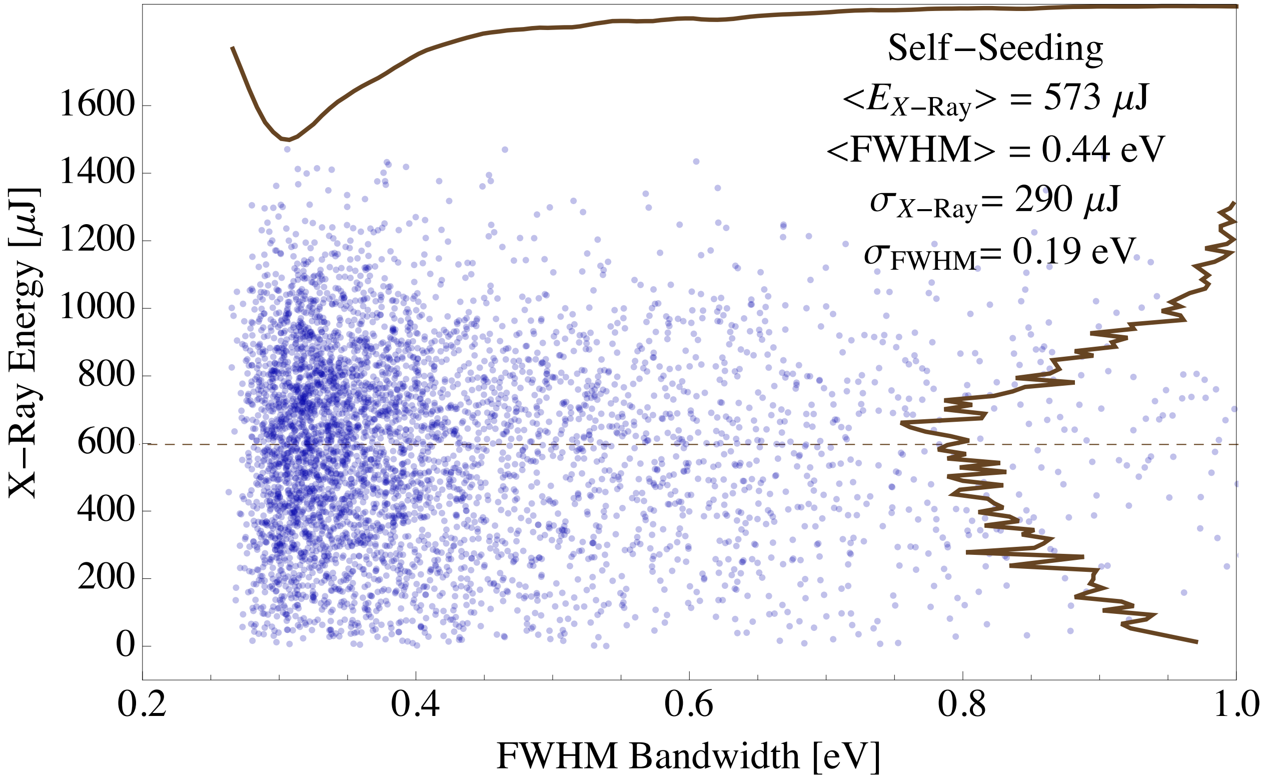
FBSS generates ~3* shorter pulses with higher peak power than self-seeding

FBSS proof of principle: comparison with self-seeding



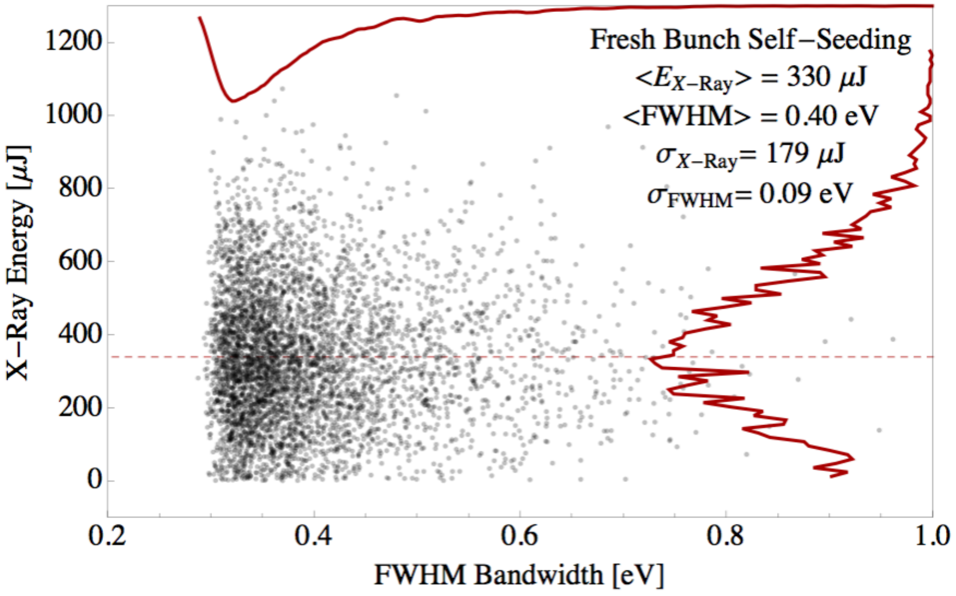


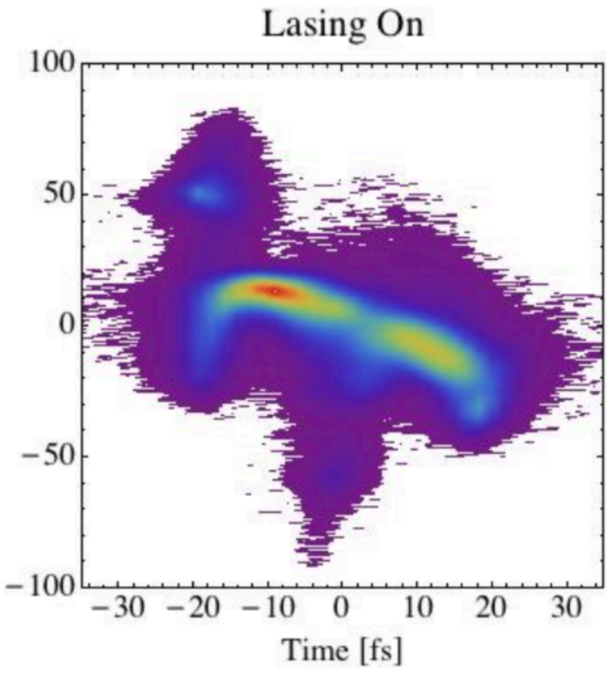


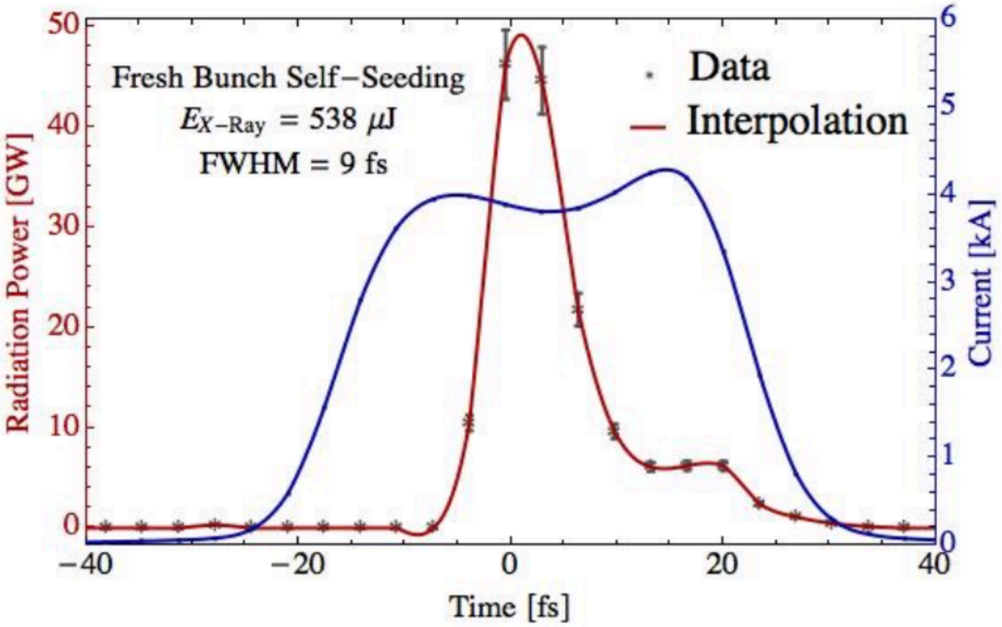


~ 2* increase in X-ray beam brightness compared to self-seeding

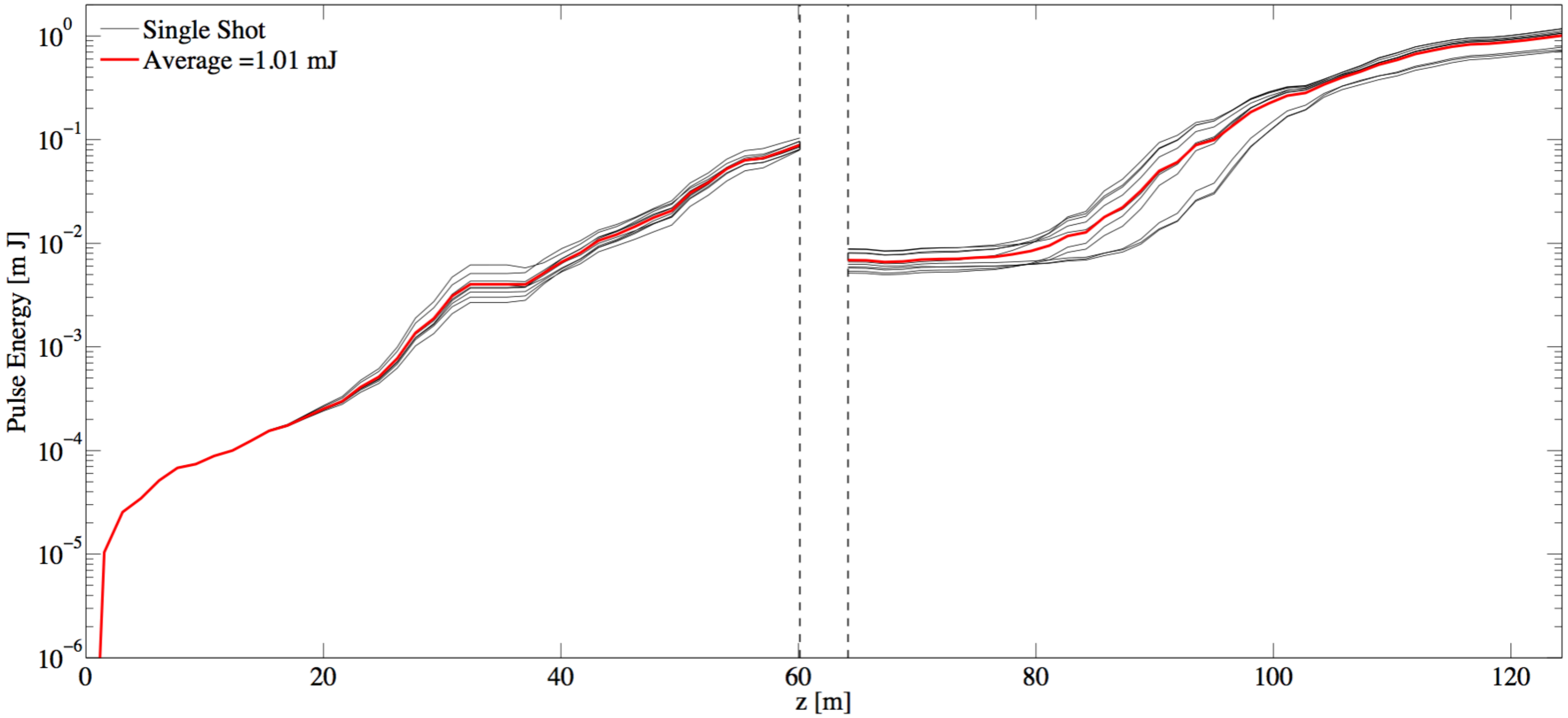
FBSS proof of principle: comparison with simulations







GENESIS Simulation



Simulation intensity matches the best shots ~ 1 mJ. Pulse duration ~10 fs matches dechirper kick

Average intensity higher than experiment.

Simulation does not include energy jitter, quadrupole wakefield from dechirper, self-consistent orbit correction.

Presentation Outline

(1) Motivation

Science applications for TW X-ray FELs

Tapering for high power XFELs: promises and limitations

(3) Fresh-slice self-seeding: experimental demonstration

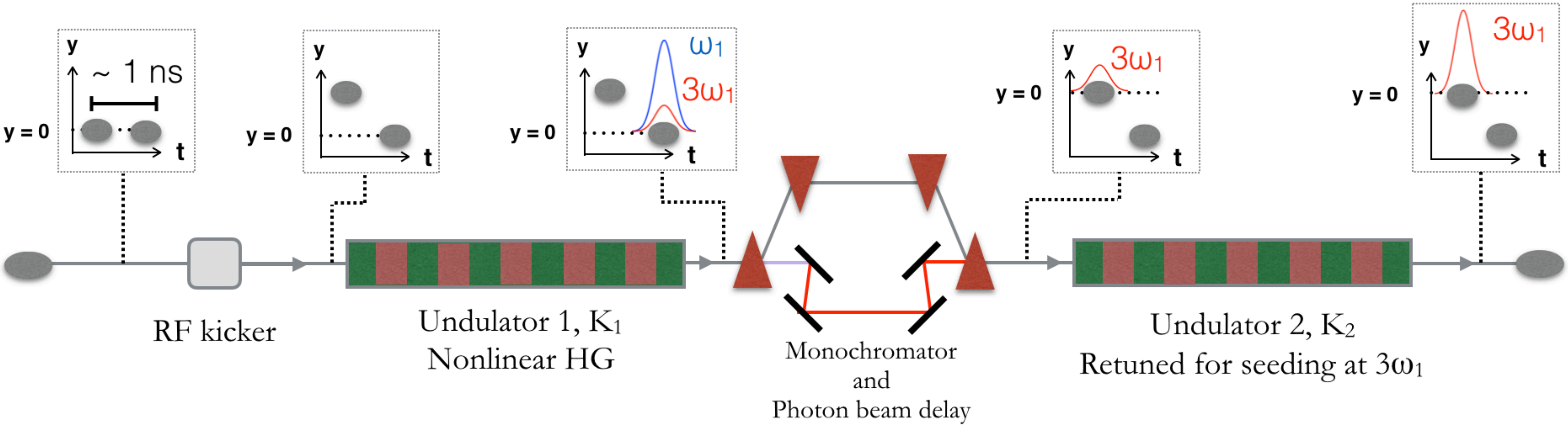
Description of proof of principle at LCLS

Performance comparison with SASE, self-seeding and simulation

(4) Fresh-bunch harmonic lasing: theoretical work and experimental proposal

(5) Conclusion and future work

Fresh Bunch Harmonic Seeding in an X-ray FEL



Why fresh bunch harmonic lasing?

1) Cheap and efficient way to extend the photon energy reach of FELs.
2) Welcome features of the scheme (compared to nonlinear HG, coherent HG, HLSS, HGHG, EEHG…)
    1) Strong seed allows **compact**, **efficient** amplification to high power.
    2) Small energy spread allows **higher peak efficiency** compared to harmonic self-seeding.
    3) **Small hardware requirement** (1 rf kicker and photon beam delay line). No phase shifters needed.
    4) Double-bunch avoids beam degradation issues with dechirper based fresh-slice scheme.
    5) Possibility of cascading with 3 or more bunches can amplify even higher harmonics

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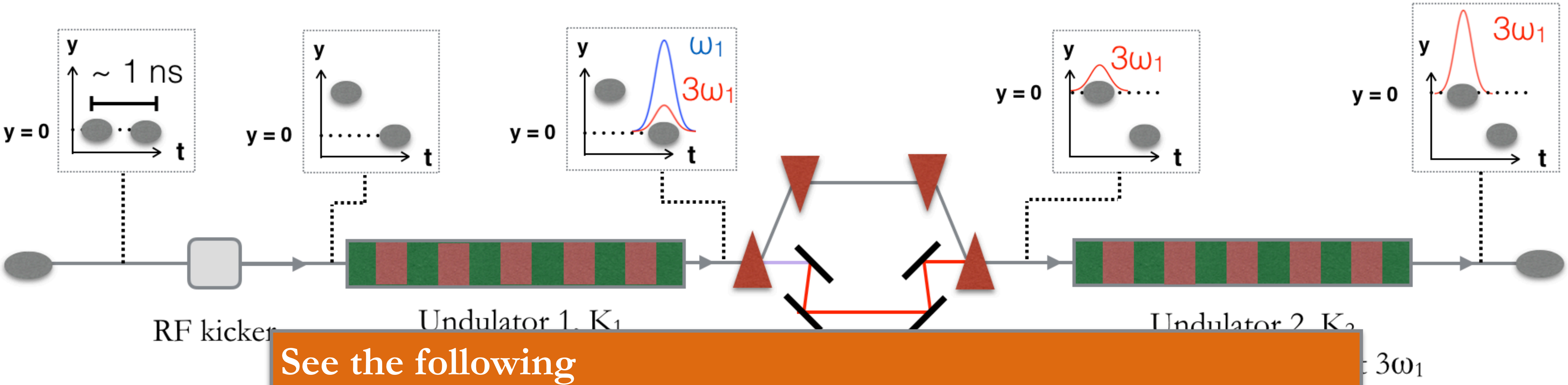
Fresh Bunch Harmonic Seeding in an X-ray FEL



See the following
MOP014, MOP015, MOBB01, MOP016, MOP031, MOP062…

Why fresh bunch harmonic lasing?

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2) Possible advantages over other methods (nonlinear HG, coherent HG, HLSS, HGHG, EEHG…)
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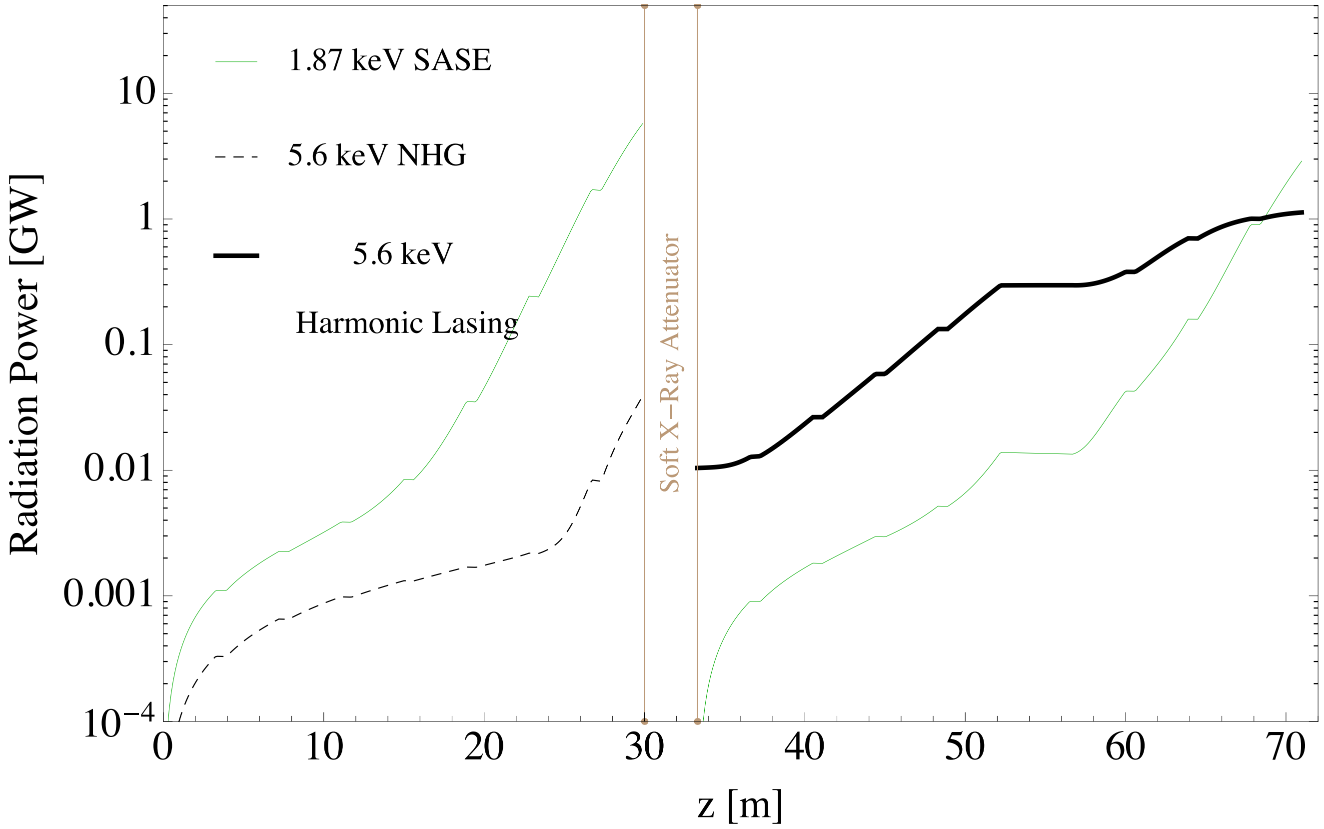
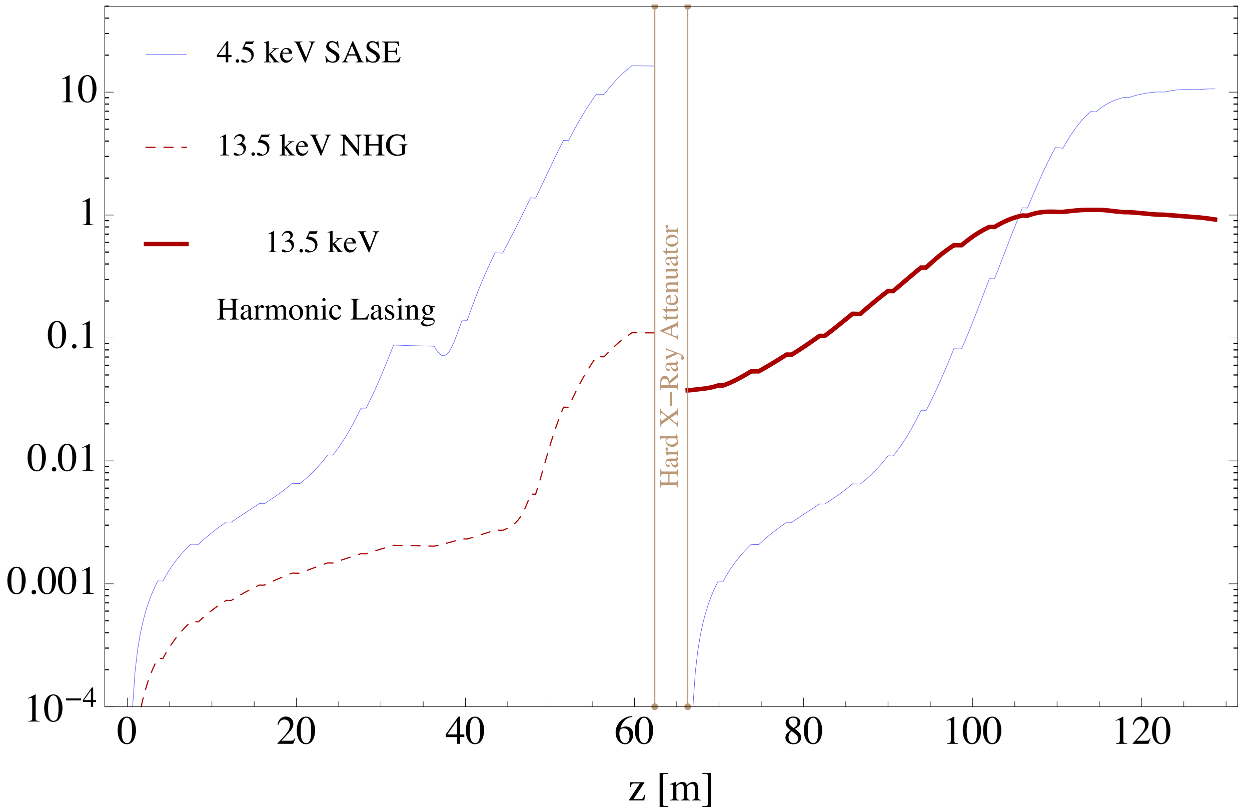
Fresh bunch harmonic lasing demonstration at LCLS

Phase 1: Soft X-rays



Phase 2: Hard X-rays



Goals

2) Demonstrate fresh slice method with HL ✔

3) Measure exponential gain of third harmonic in section 2 ✔

4) Measure harmonic spectrum from HL to compare with NHG✔

Goals

1) Increase spectral brightness in energy range 12-16 keV✔

2) Increase power in energy range 12-16 keV compared to Nonlinear Harmonic Generation✔

Conclusion

(1) We studied **undulator tapering strategies** to increase the efficiency of XFELs and reach TW peak power levels. Scientific applications are in single molecule imaging, AMO science, nonlinear physics, quantum materials etc.

(2) The **sideband instability** was identified as a fundamental process which limits the peak power of high efficiency tapered XFELs.

(3) We have presented a solution to the sideband problem, the **fresh bunch self-seeding method**, and demonstrated it experimentally at the LCLS.

(4) Our demonstration of FBSS shows a **brightness increase** of 12/2 times compared to SASE/self-seeding.

(5) We studied **fresh bunch harmonic lasing** by proposing a double-bunch FEL system for high power, high photon energies (> 12 keV).

What Next?

(1) Plan to demonstrate fresh slice harmonic lasing at LCLS in the near future.

(2) Can we ever reach 1 PW?

Acknowledgments

This work would not have been possible without the support of many people. I would like to acknowledge in particular:

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Thank you