Demonstration of fresh slice self-seeding in a hard X-ray free electron laser

C. Emma, A. Lutman, M. Guetg, A. Marinelli, T. Maxwell, J. Wu, C. Pellegrini

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THE UNIVERSITY OF CALIFORNIA · UCLA

SLAC NATIONAL ACCELERATOR LABORATORY

Presentation Outline

Introduction

Motivation for Enhanced Self-Seeding (ESS) using the fresh slice technique

Fresh slice technique at LCLS: modes of operation

- Two stage two color fresh slice lasing
- Pulse duration control

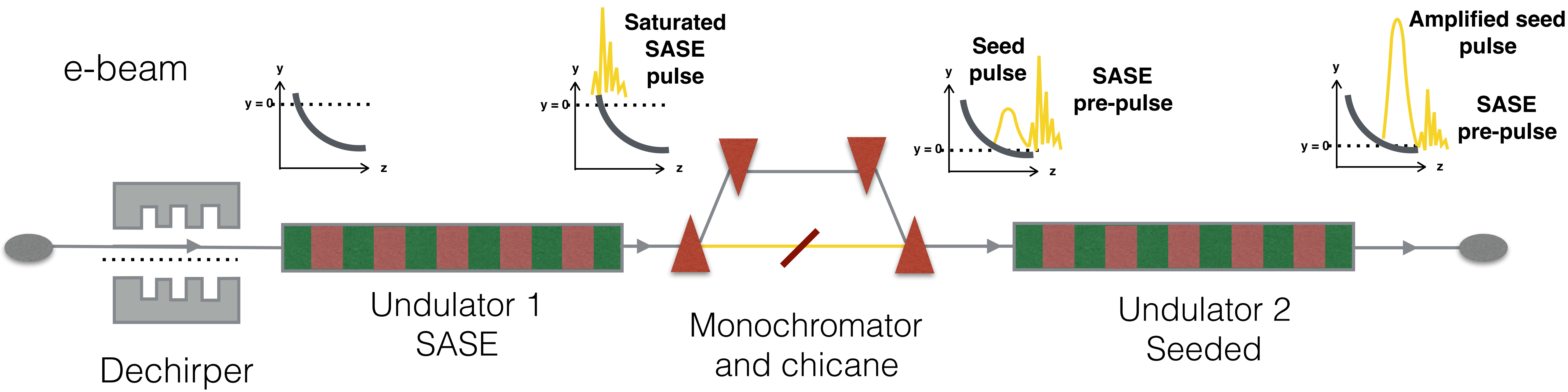
Enhanced self-seeding demonstration: experimental results

- Proof of principle experiment
- Comparison with SASE and regular self-seeding

Harmonic lasing via ESS: simulation study

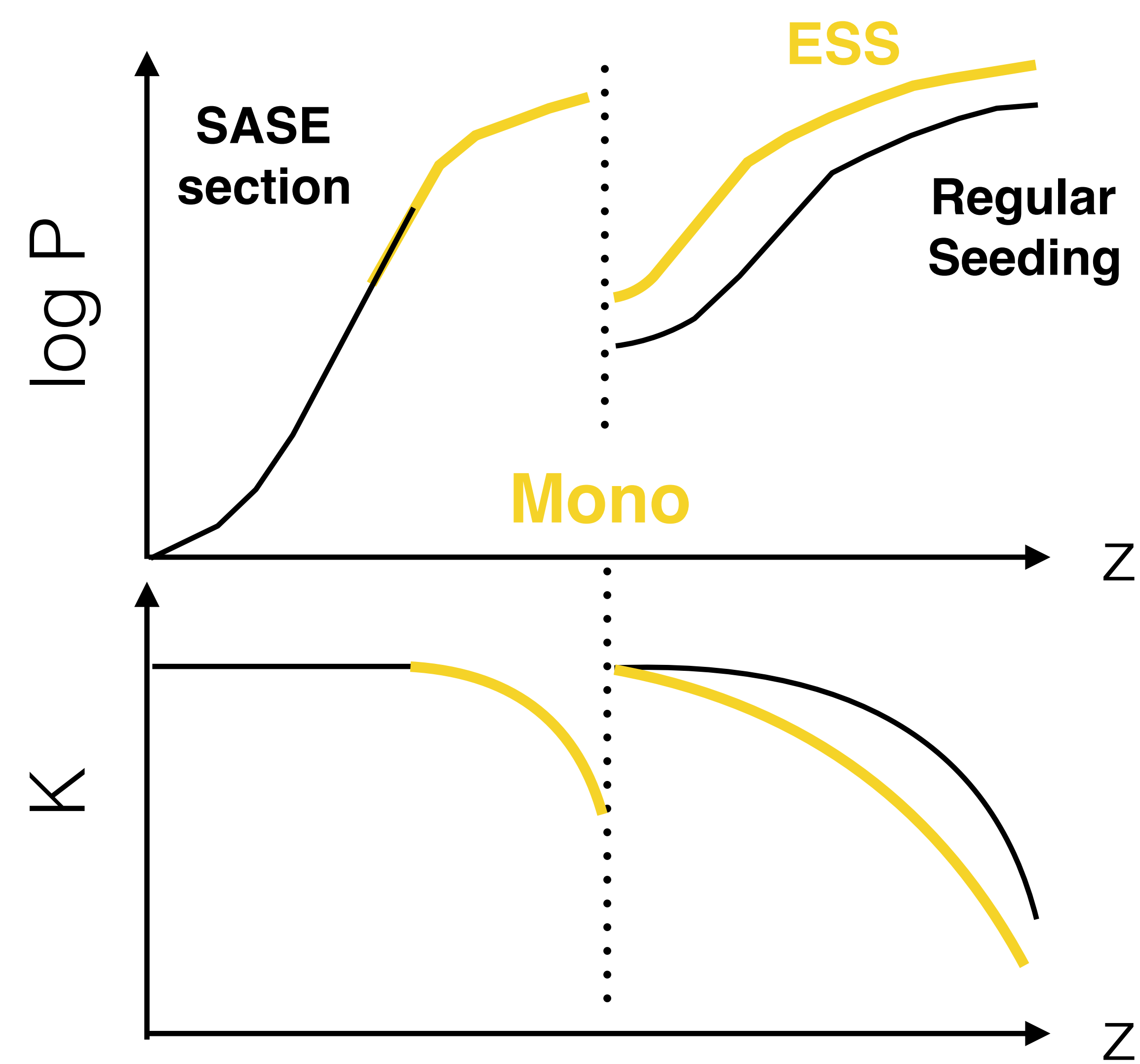
Conclusions and future outlook

Enhanced Self-Seeding (ESS)

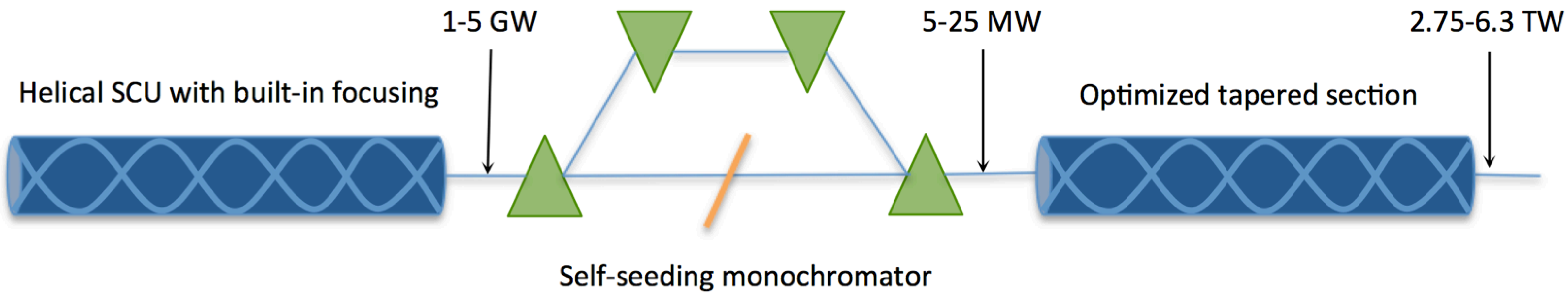


Motivation

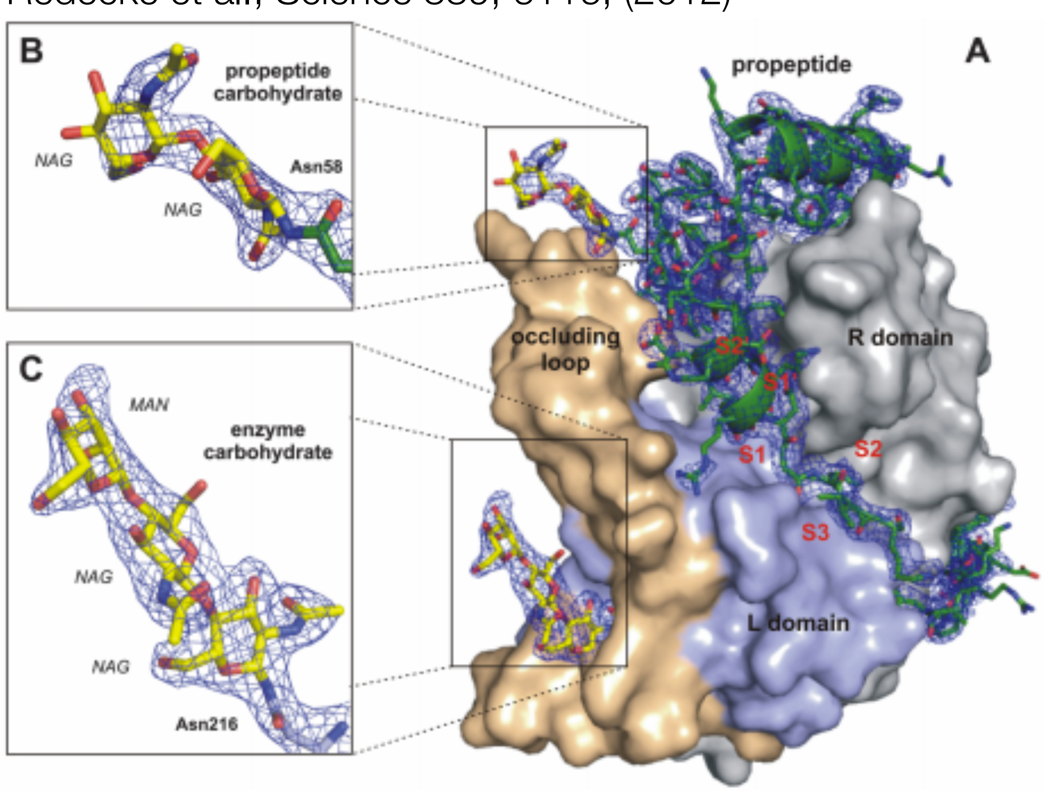
- ESS is a method to increase the brightness and efficiency of XFELs
- Performance of self seeded XFELs is limited by the trade off between seed power and electron slice energy spread. Seeding with fresh electrons eliminates trade-off
- Large seed power increases taper efficiency downstream of the monochromator
- ESS generates short (sub 10 fs) high intensity, high brightness X-ray pulses
- Useful for experiments needing short seeded pulses with high peak intensity



Pushing the imaging frontier:
ESS for TW-XFEL with a superconducting undulator

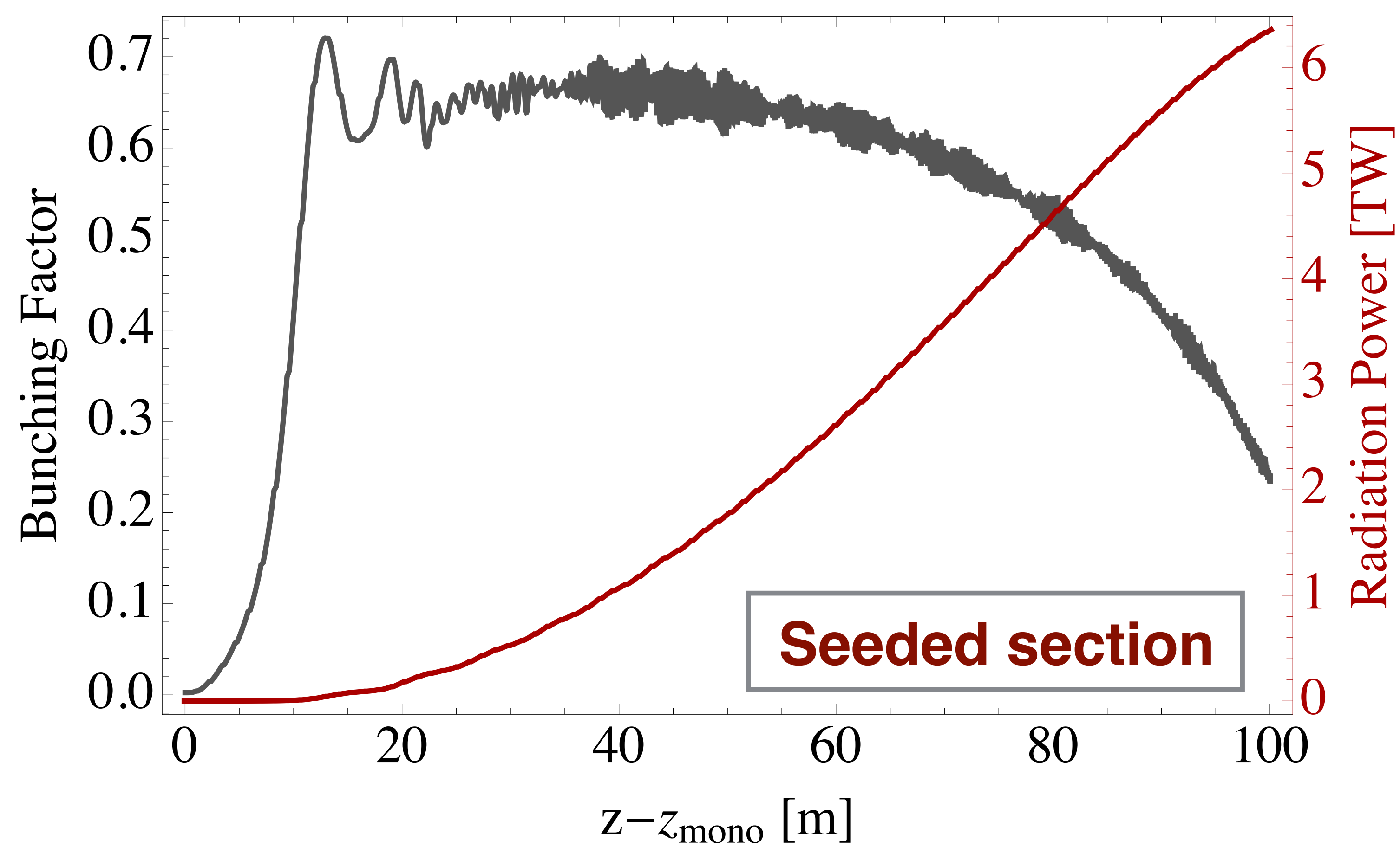


Redecke et al., Science 339, 6116, (2012)



2.1 A resolution

Trypanosoma brucei cysteine protease cathepsine B



Single Molecule Imaging Goal
10 fs - 10 mJ - 2020

C. Emma *et. al.*, "High efficiency, multiterawatt X-ray free electron lasers", PRAB **19**, 2016

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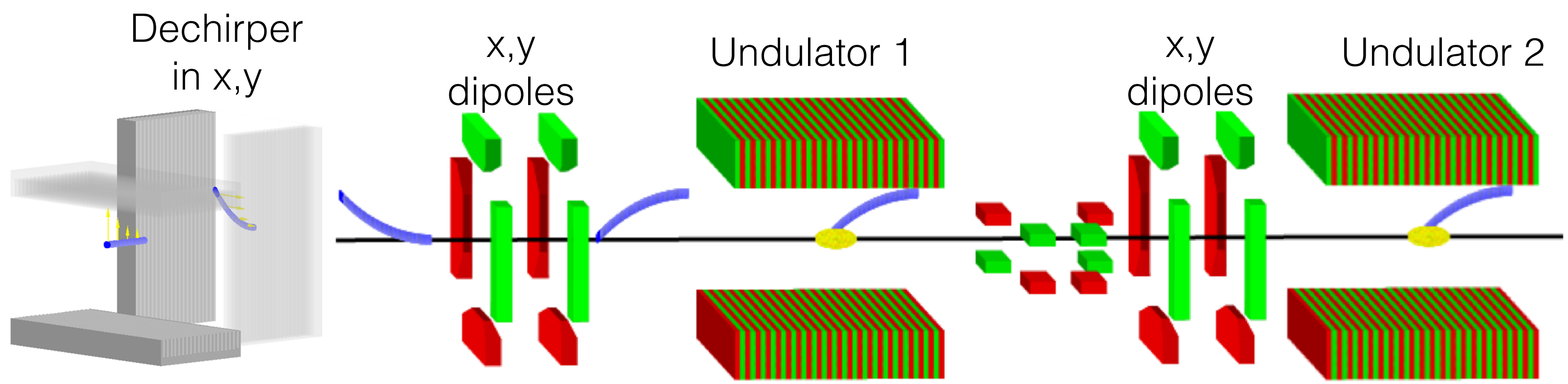
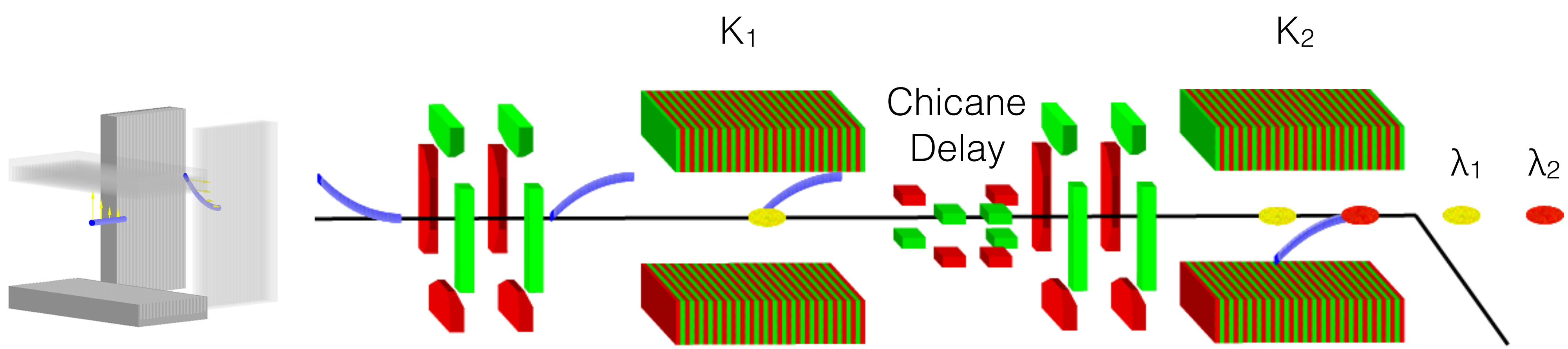
Fresh slice lasing at LCLS: modes of operation

1) Fresh slice SASE for control of pulse duration



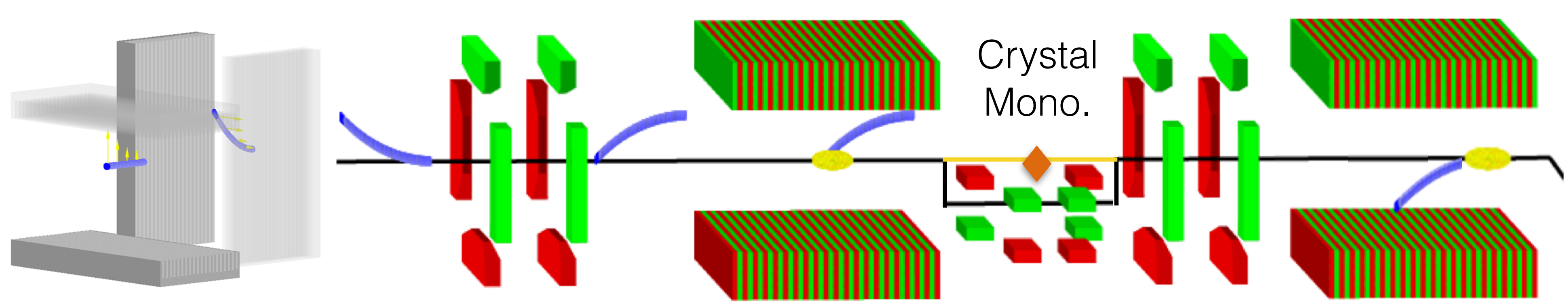
A. Lutman *et. al.* accepted in Nature Photonics, DOI: 10.1038/NPHOTON.2016.201

2) Two-color fresh slice SASE with polarization control



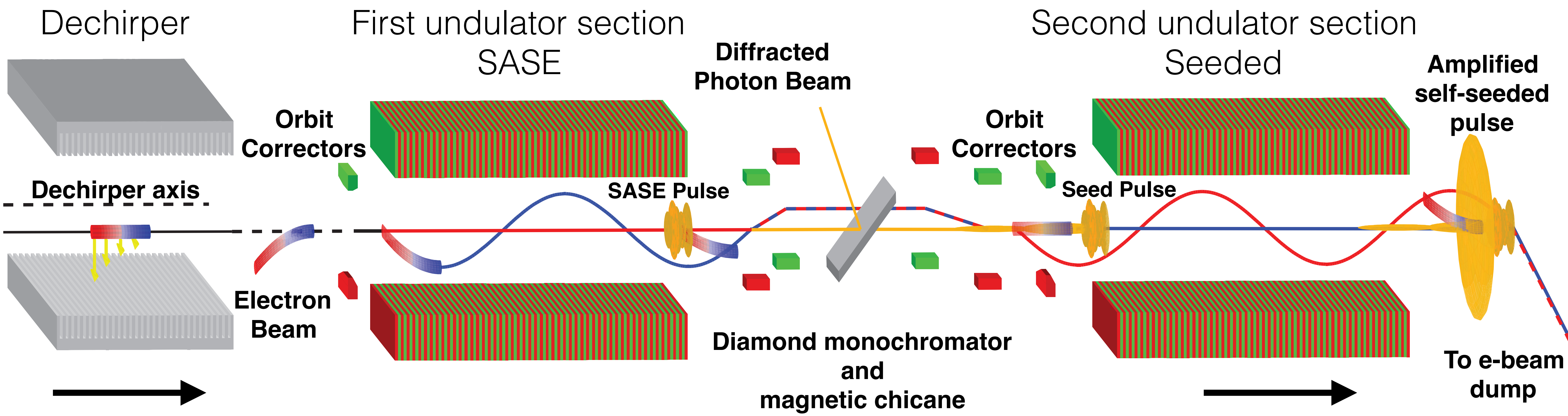
A. Lutman *et. al.* accepted in Nature Photonics, DOI: 10.1038/NPHOTON.2016.201

3) Enhanced self-seeding for high intensity short seeded pulses



C. Emma *et. al.* submitted for publication

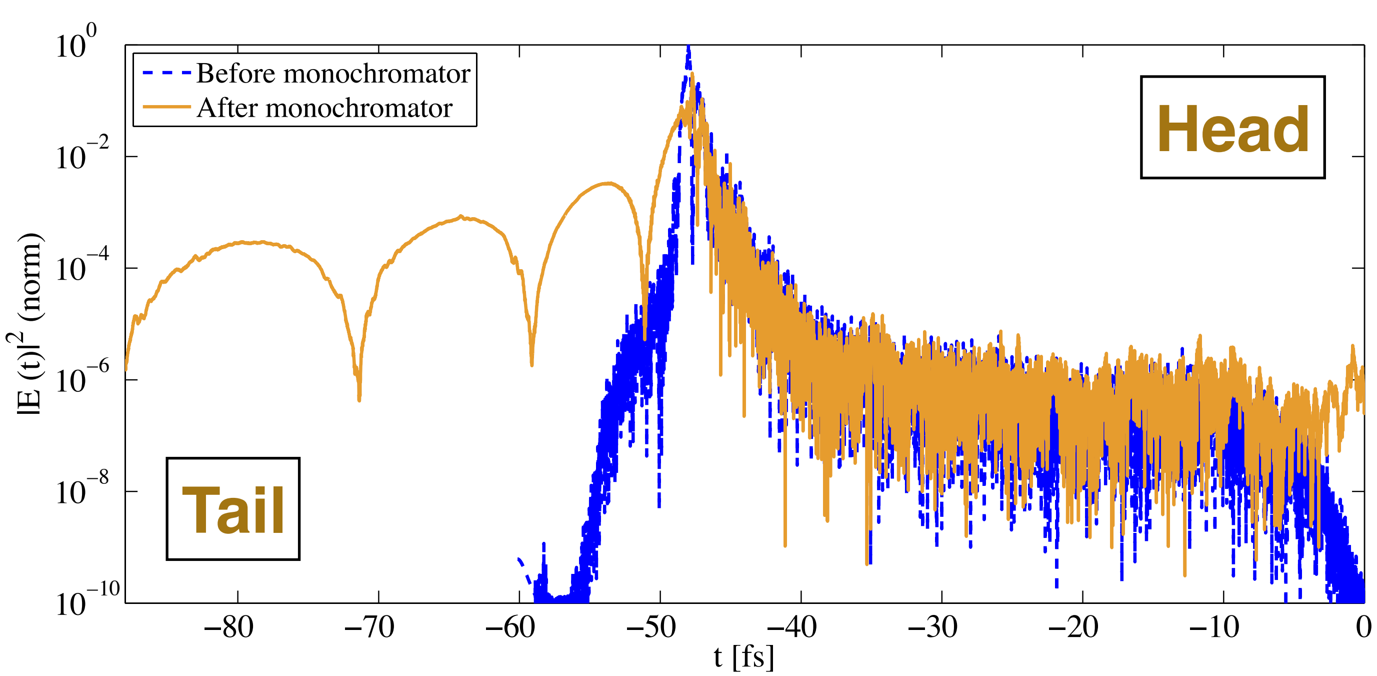
ESS proof of principle experiment



$E_{photon} = 5.5$ keV

E-beam

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



Diagnostics

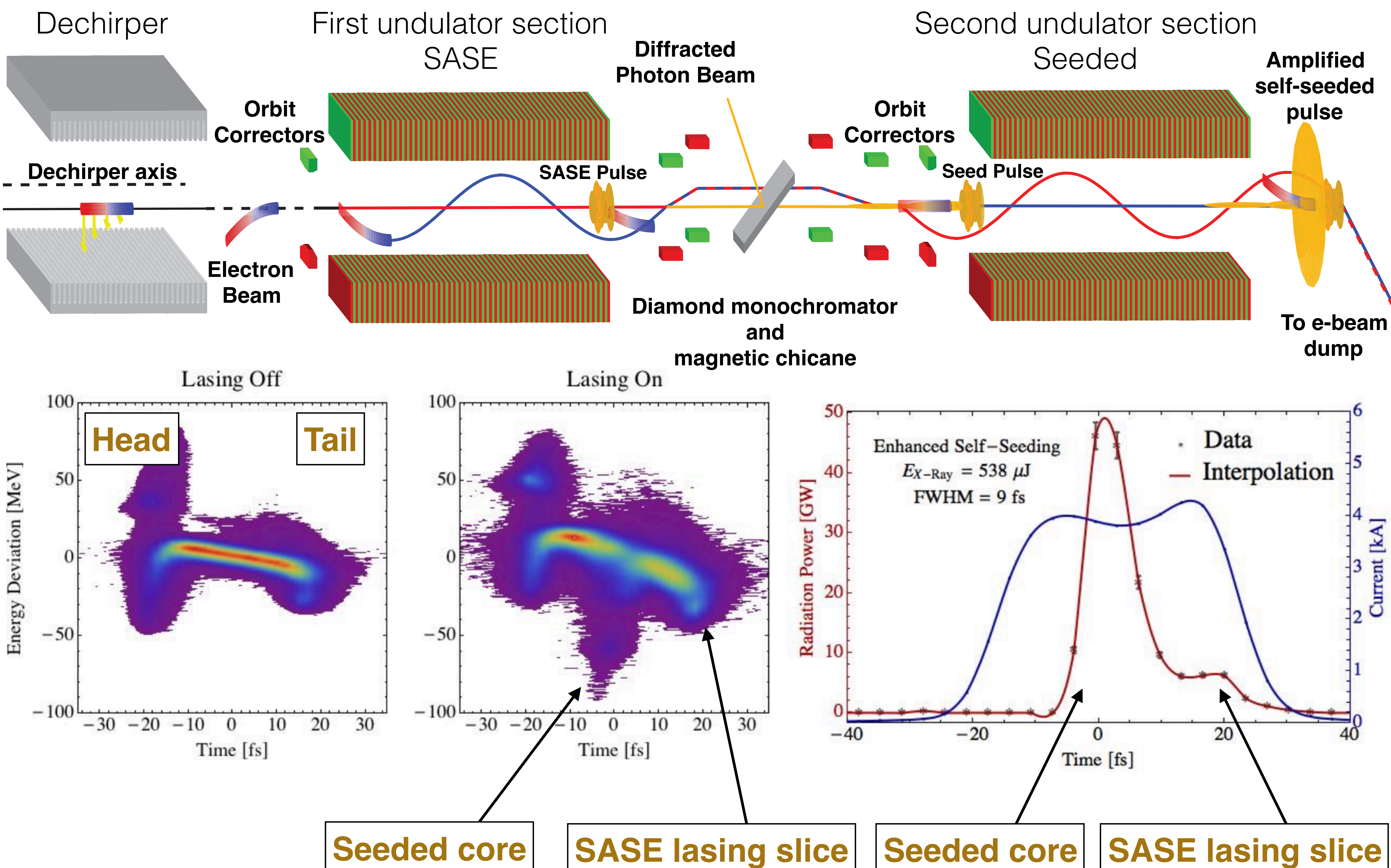
1) **Transverse deflecting cavity**
Electron beam energy loss
(time resolved)

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

3) **X-ray spectrometer**

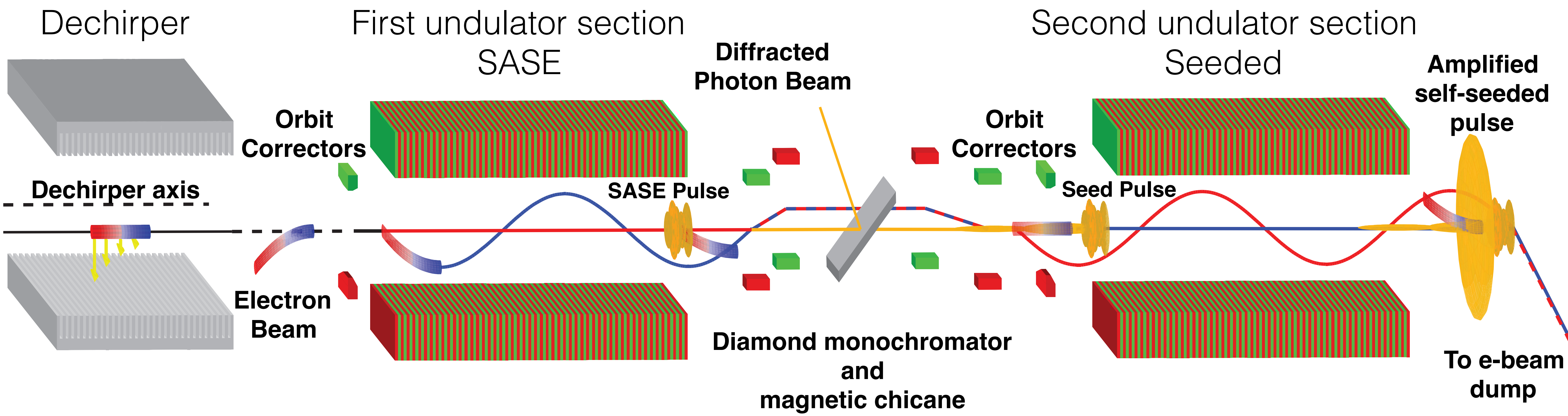
C. Emma *et. al.* submitted for publication

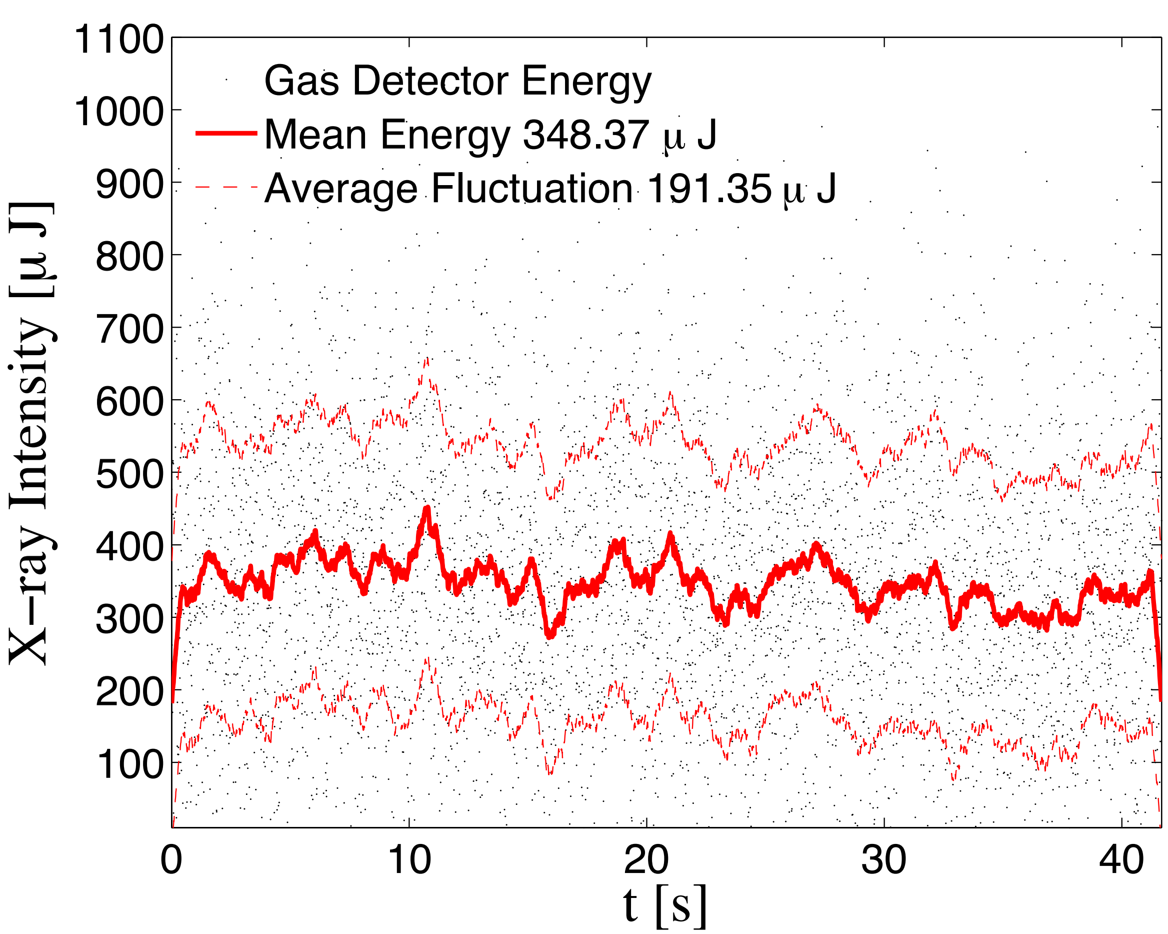
ESS proof of principle experiment

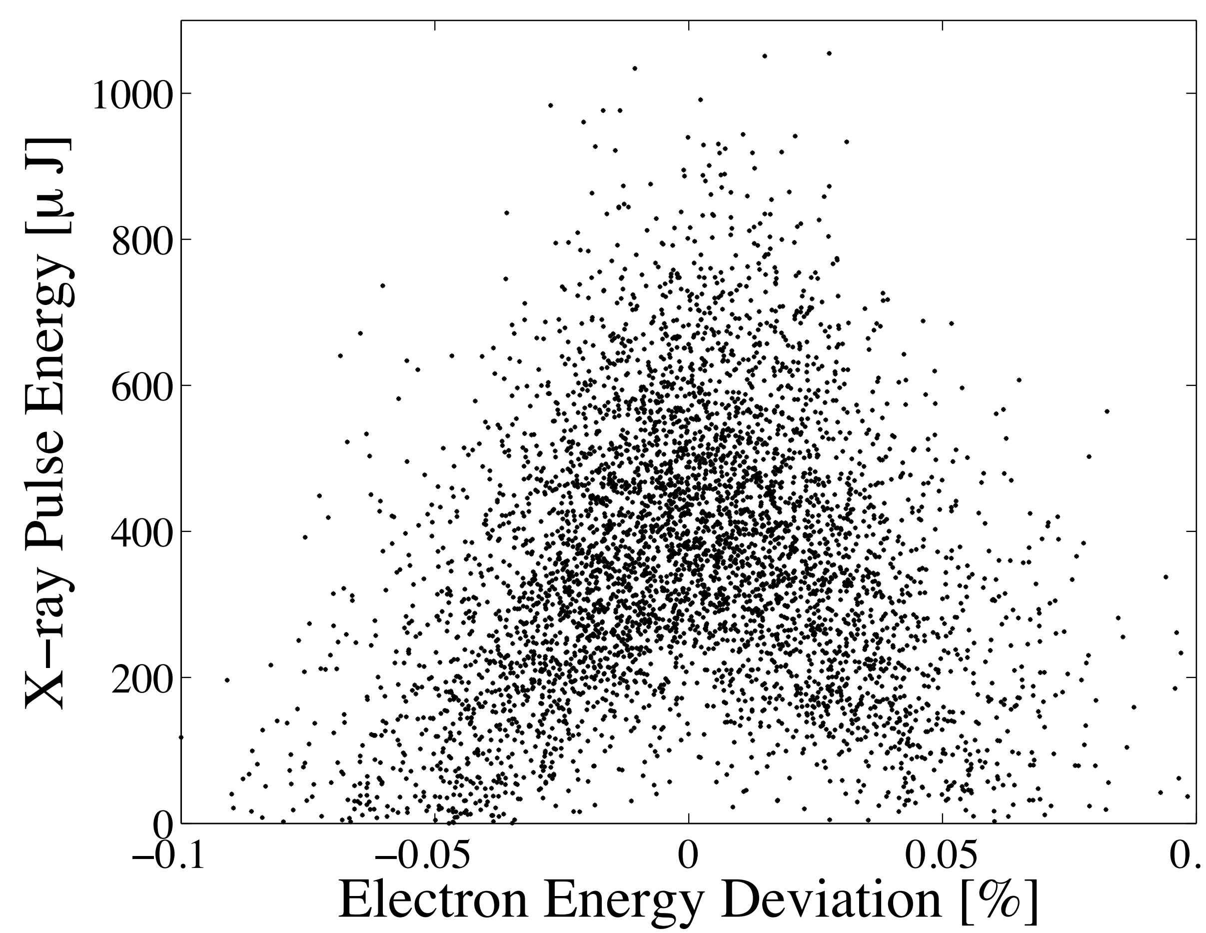


C. Emma *et. al.* submitted for publication

ESS proof of principle: statistical properties

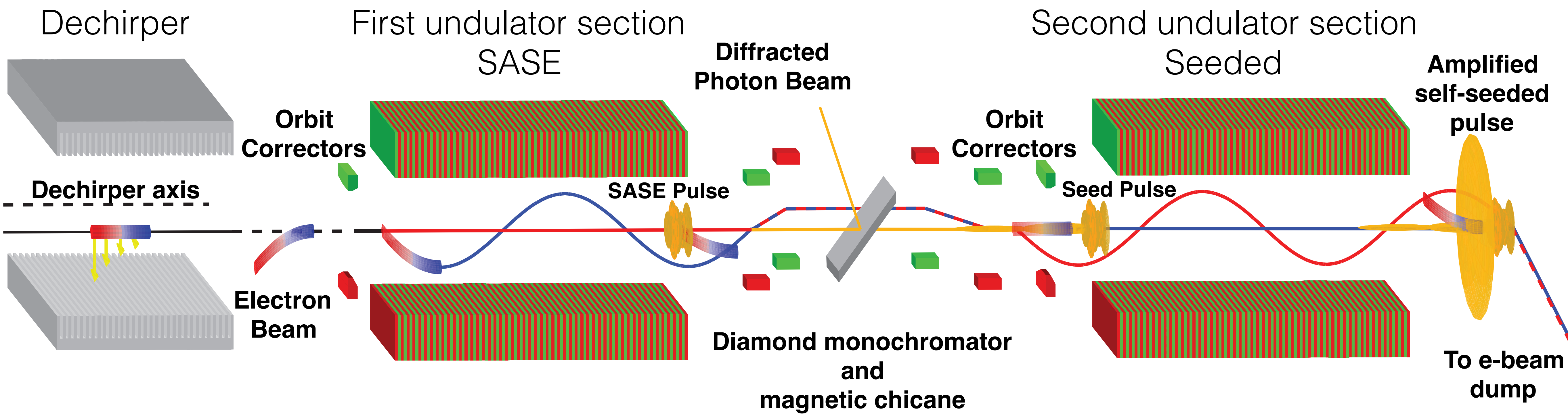


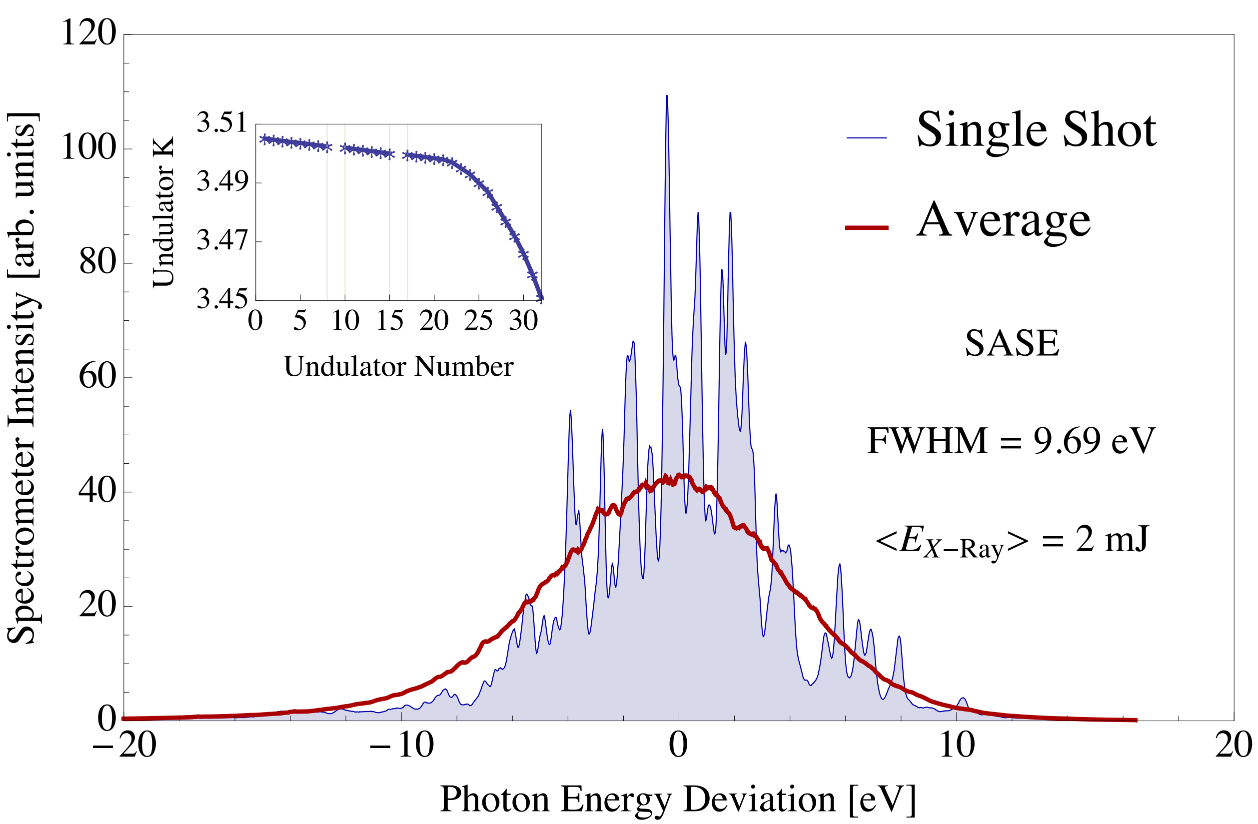


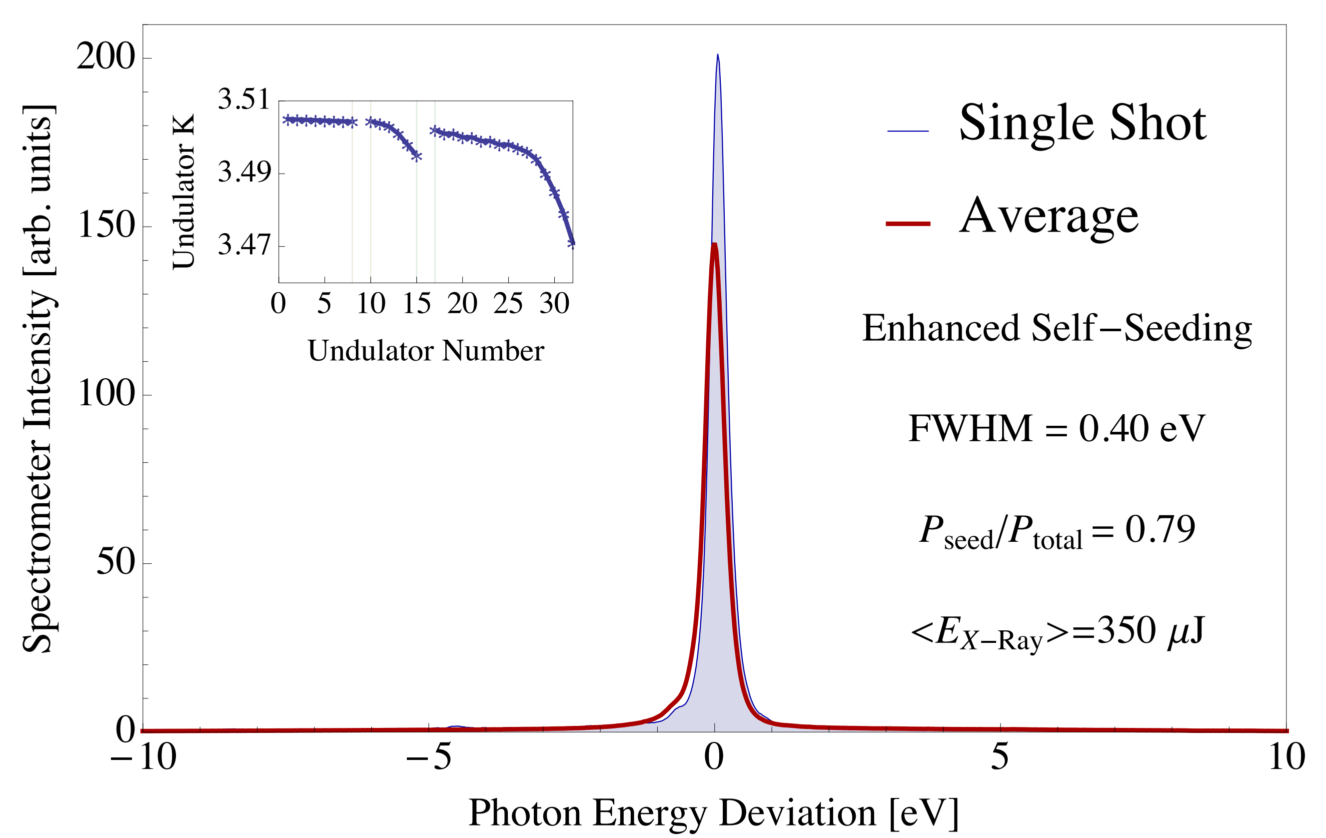


C. Emma *et al.*, submitted for publication

ESS proof of principle: comparison with SASE



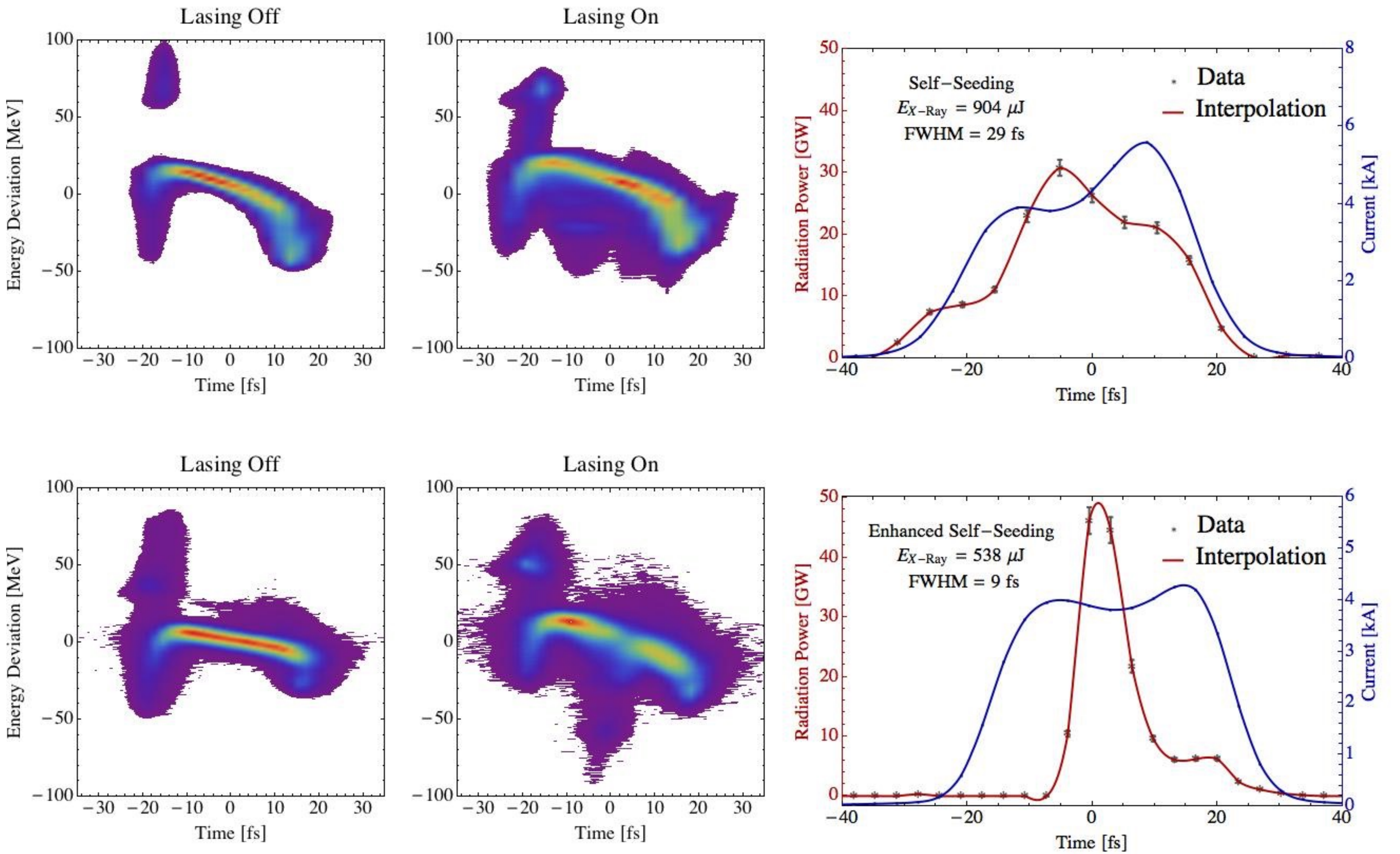




C. Emma *et. al.* submitted for publication

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

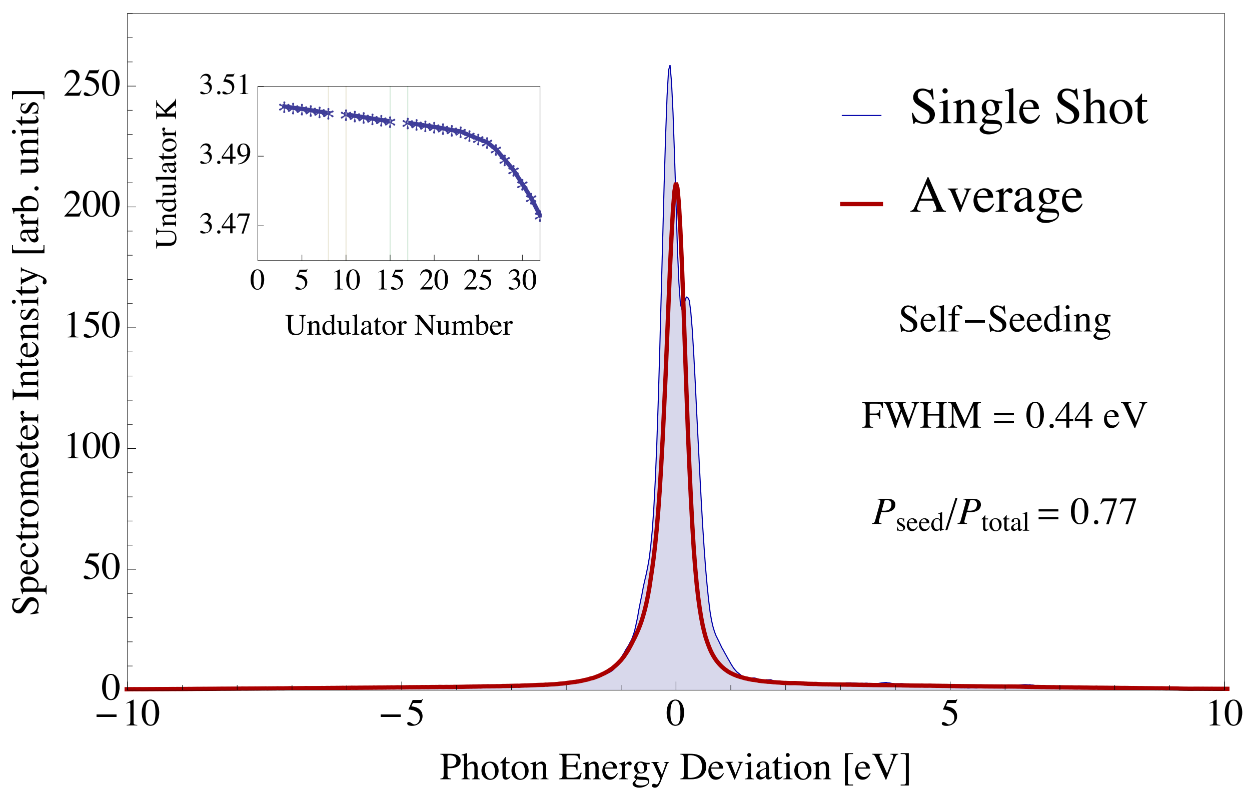
ESS proof of principle: comparison with self-seeding

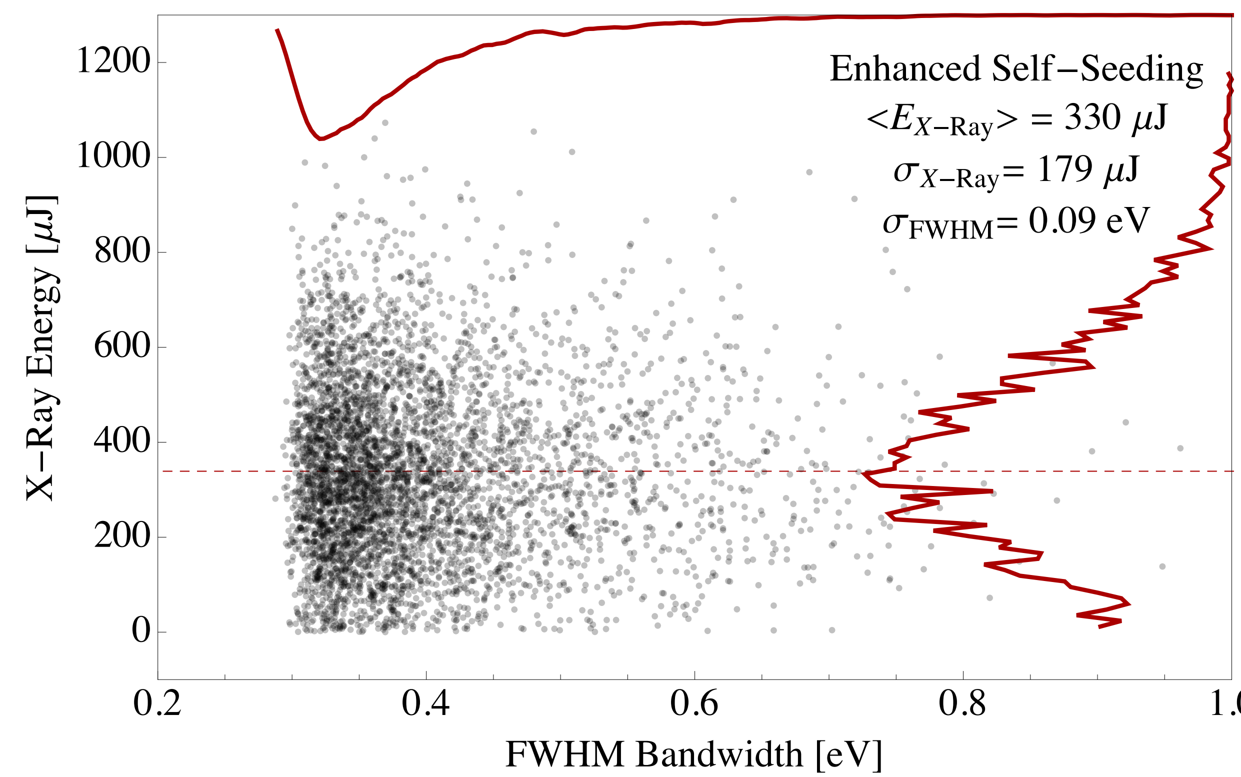


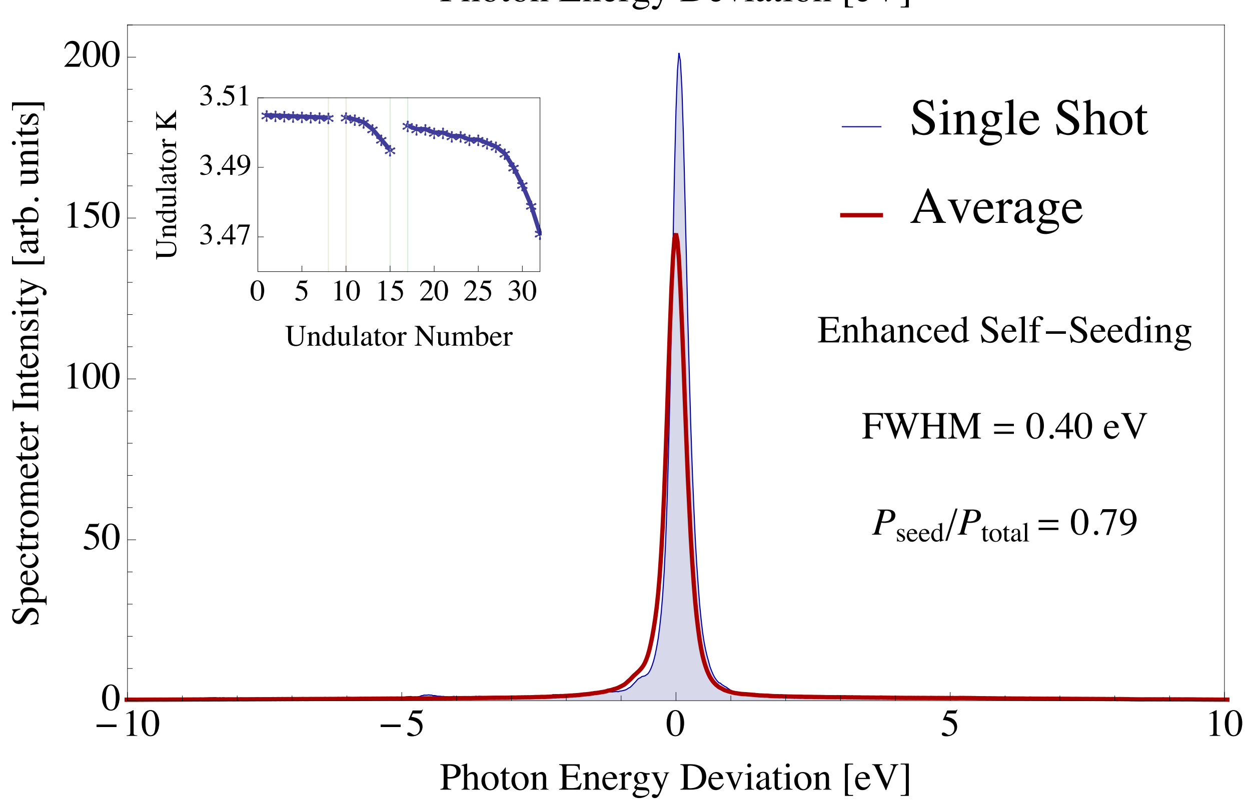
C. Emma *et. al.* submitted for publication

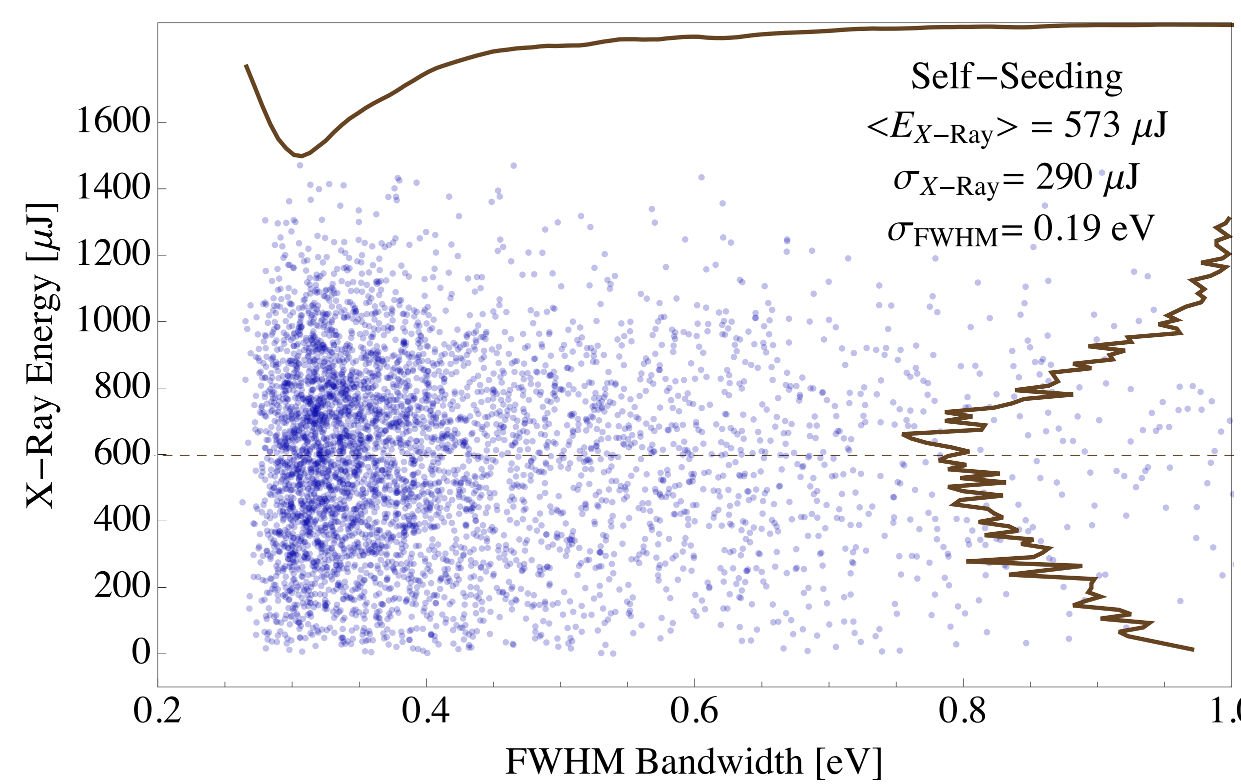
ESS generates ~4* shorter pulses with higher peak power

ESS proof of principle: comparison with self-seeding









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

C. Emma *et. al.* submitted for publication

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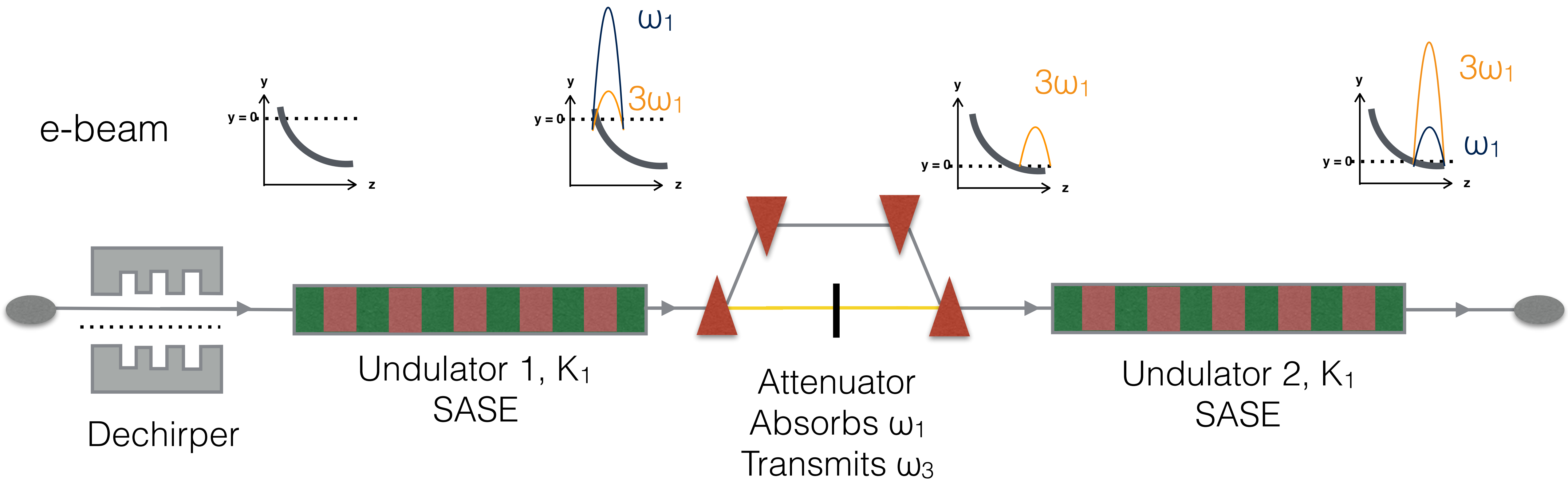
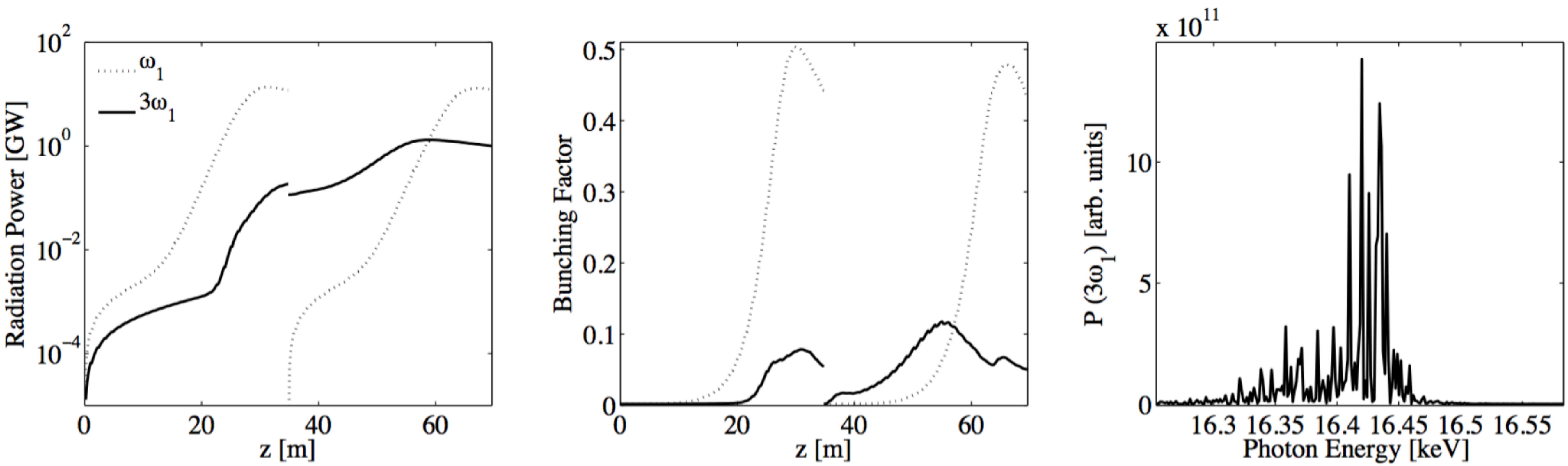
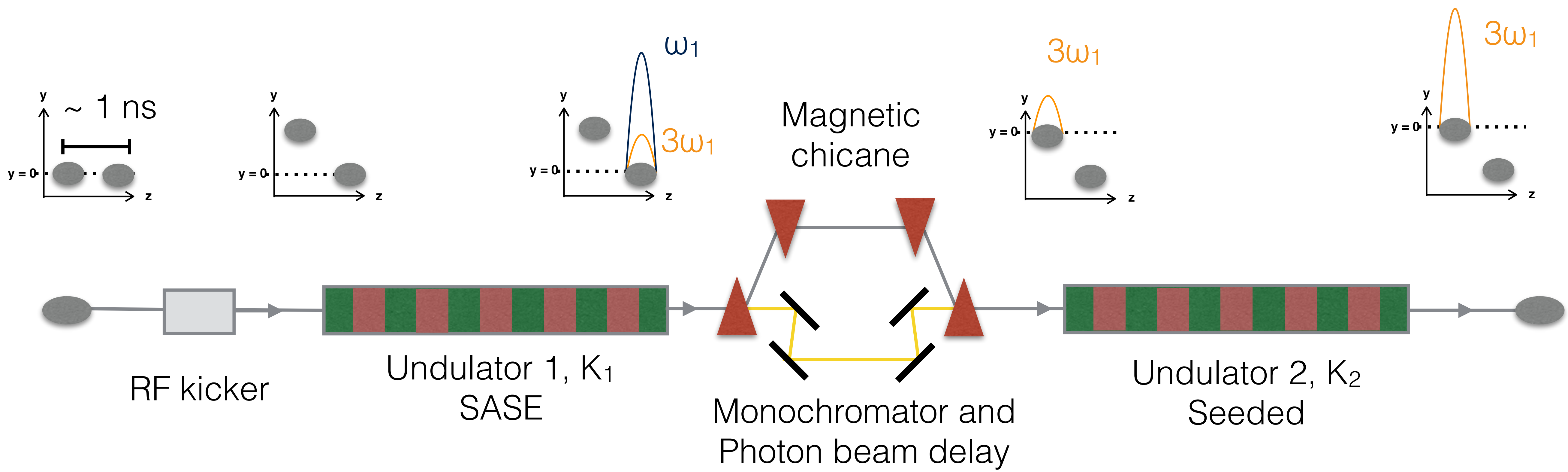
Single bunch harmonic ESS: simulation study

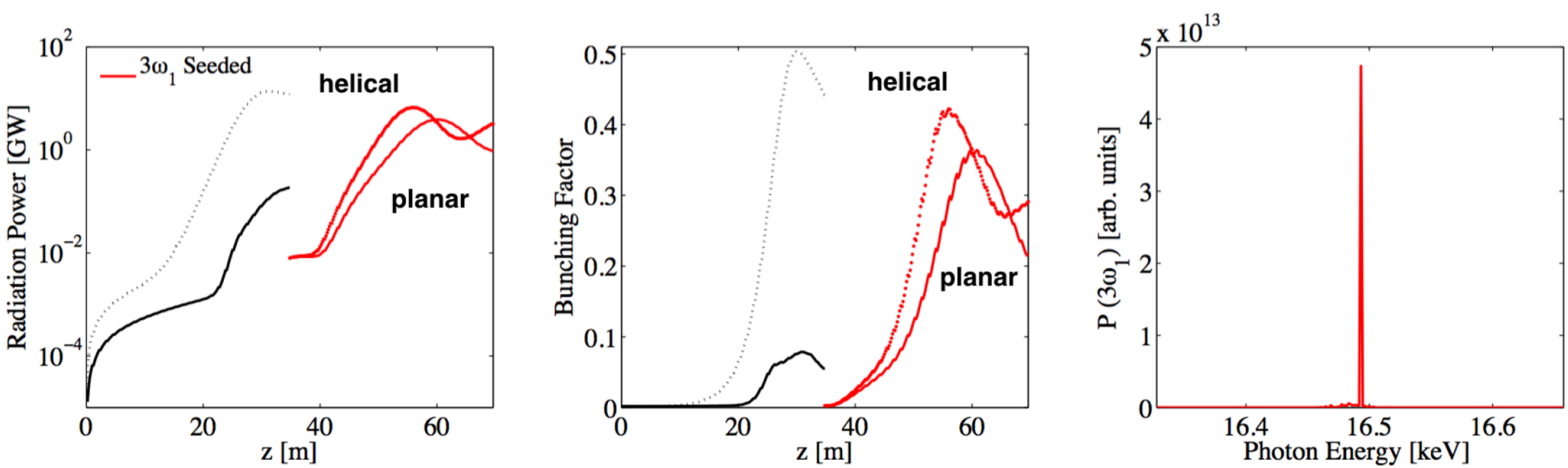




C. Emma *et. al.*, in preparation

Double bunch harmonic ESS: simulation study





C. Emma *et. al.*, in preparation

Conclusion

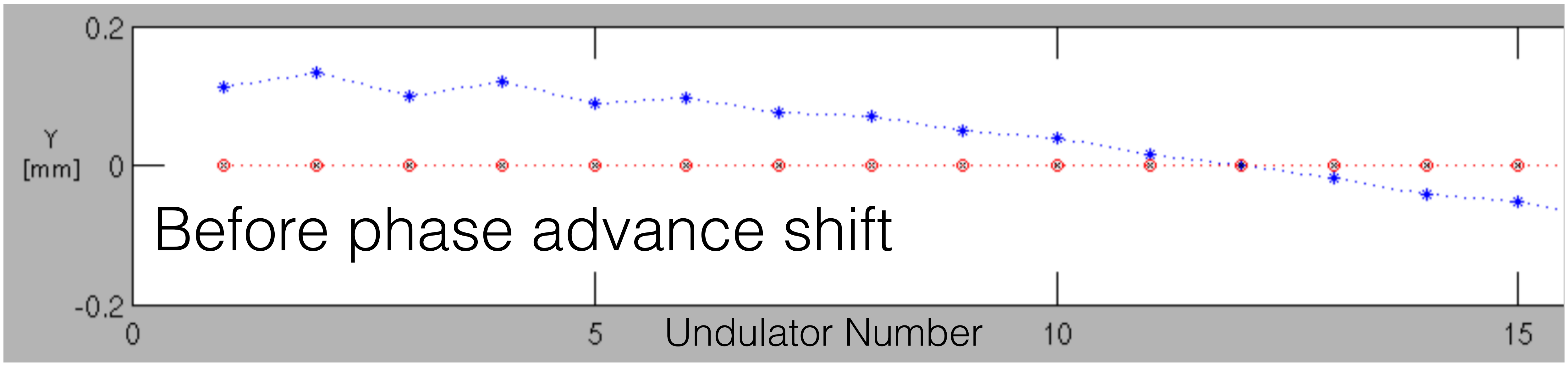
- We discuss Enhanced Self-Seeding (ESS) as a method to increase the brightness and enhance the capability of X-ray FELs.
- We report the results of the first experimental demonstration of ESS at LCLS.
- We measure ESS pulses with high peak power (~ 50 GW) short pulse duration (sub 10 fs) and narrow bandwidth (~ $8*10^{-5}$).
- We perform a comparison of ESS performance with SASE and self-seeding at the same photon energy and estimate an increase in brightness of a factor of 12 and 2 respectively.
- Application of this method to optimized undulator designs promises peak powers in the TW range sufficient for X-ray imaging and nonlinear science applications.
- Further exploration of this method including its application to harmonic lasing is currently under study.

Acknowledgments

Thanks to D. Ratner for discussions about fresh bunch and harmonic lasing and the LCLS operations group for their experimental support.

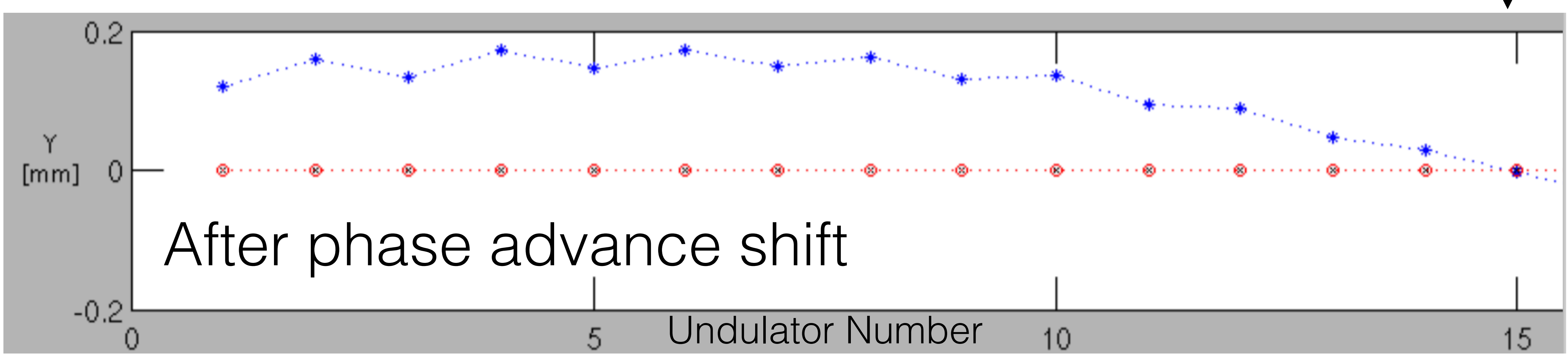
Additional Slides

Orbit correction: setting waist position at HXRSS

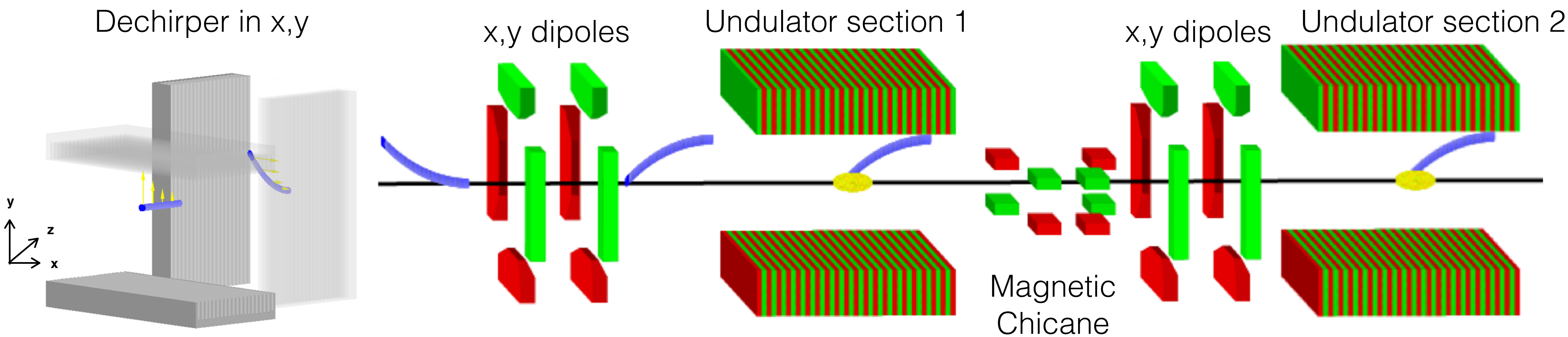


Orbit correction is critical! Orbit control within 5 micron after HXRSS necessary for good overlap of beam with seed

HXRSS



Fresh slice SASE: pulse duration control

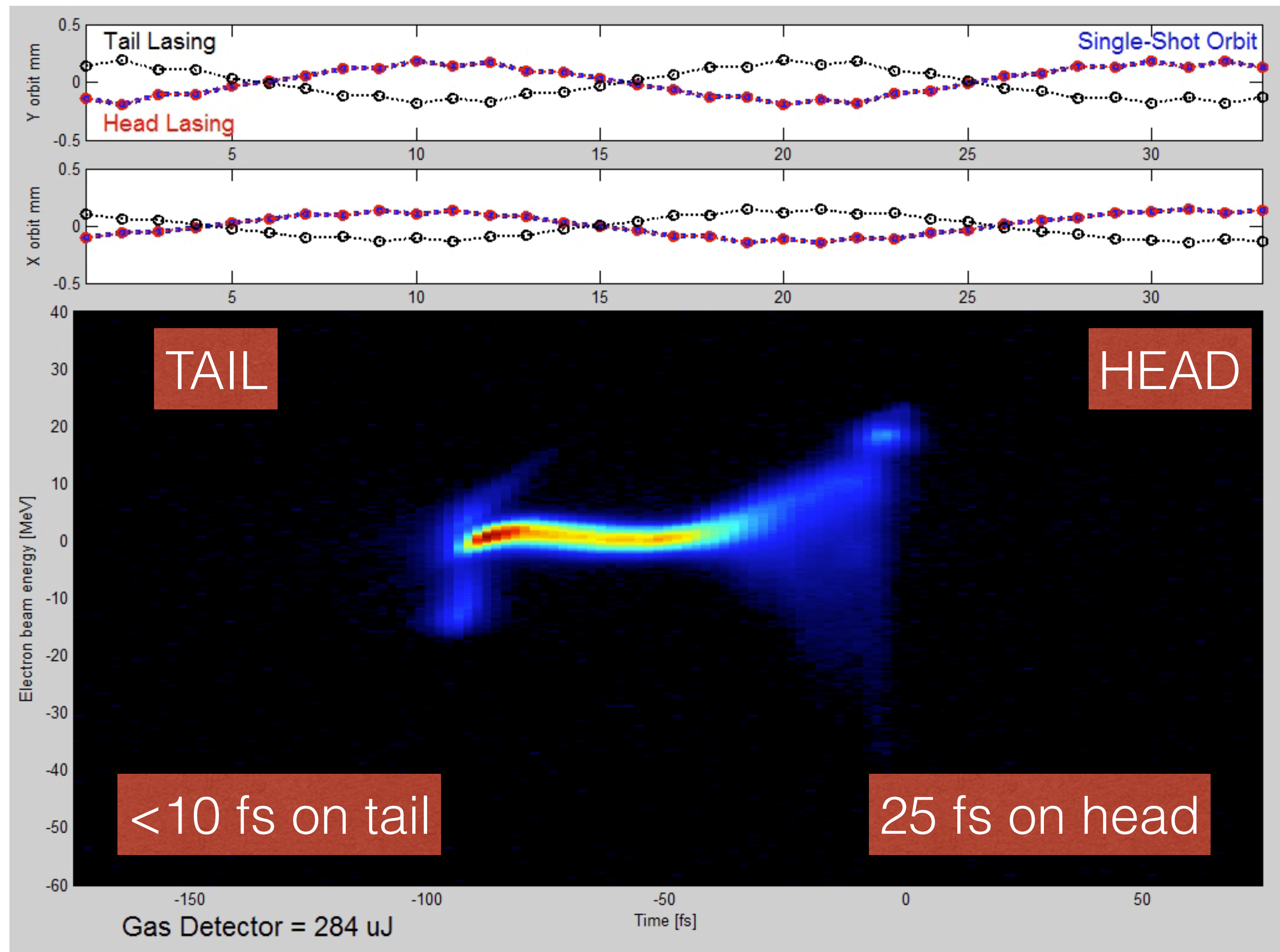


Upstream of the undulator section:

- The dechirper is set to an offset off machine axis
- The electron beam gets a correlated kick toward the closest jaw
- The tail performs betatron oscillations in y and x
- The head is on the nominal zero-orbit (With feedbacks turned off)

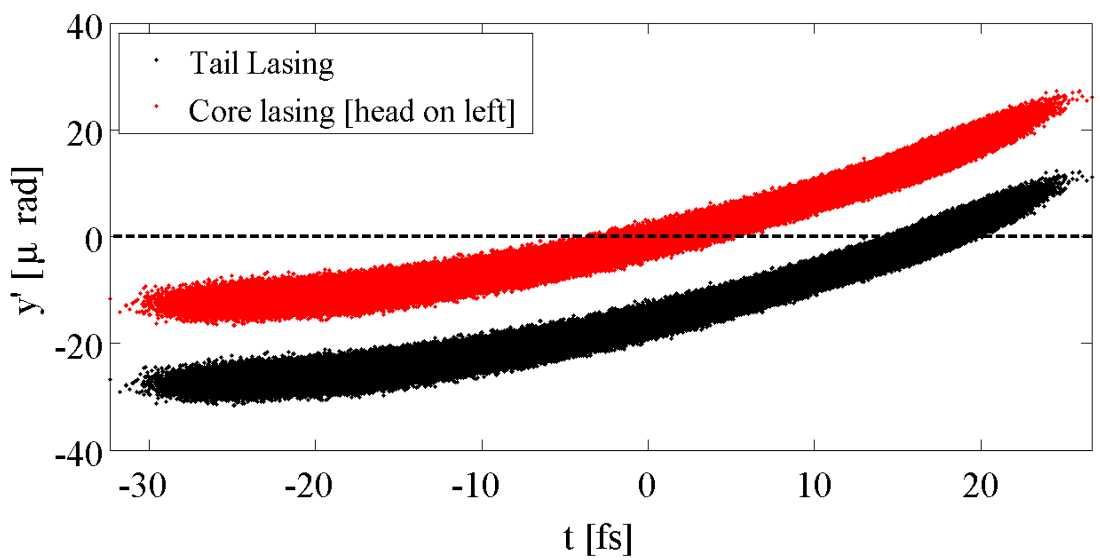
In the undulator section:

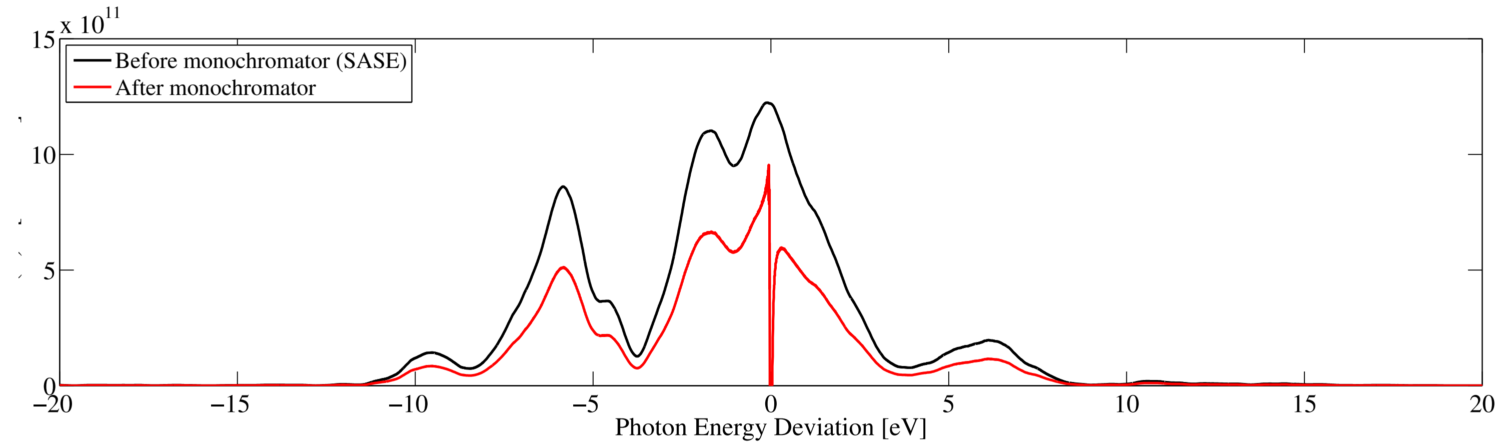
- All undulators used to lase on a single slice
- Easy way to control the pulse duration by selecting which slice of beam lases

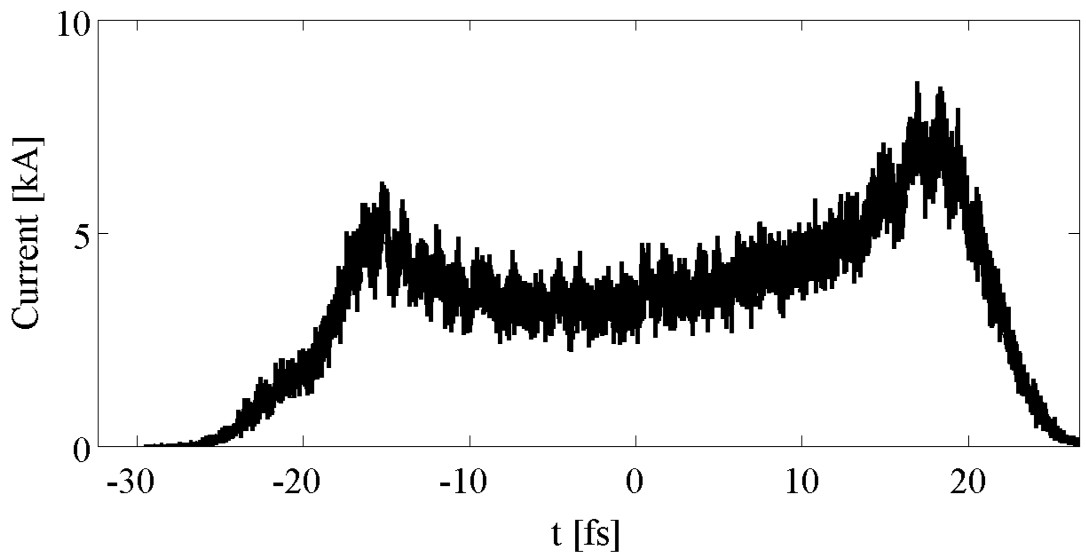


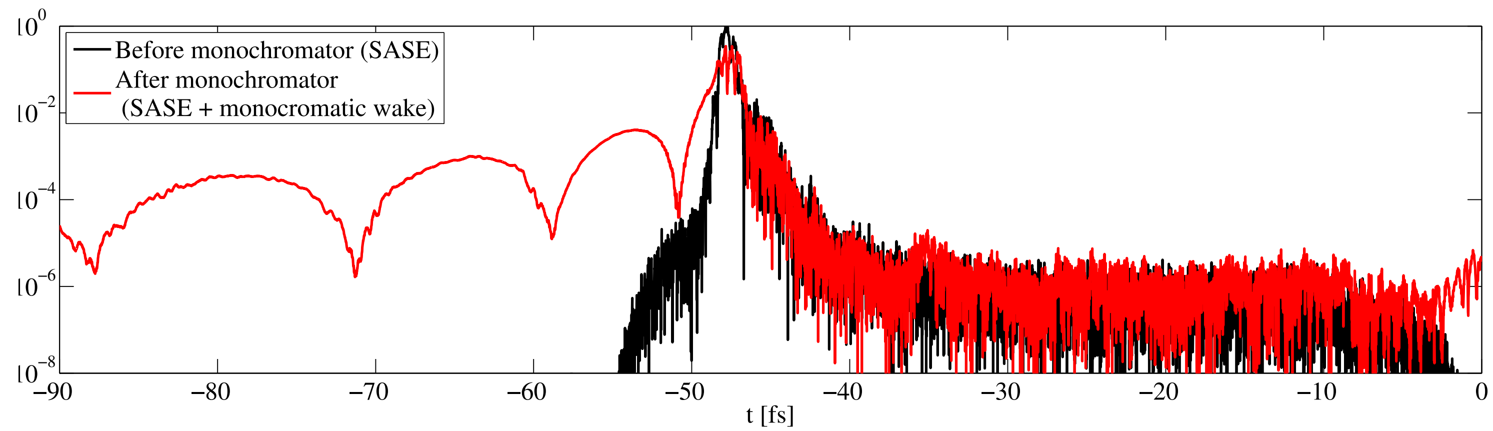
A. Lutman *et. al.*,, accepted in Nature Photonics

Start-to-end simulations-1





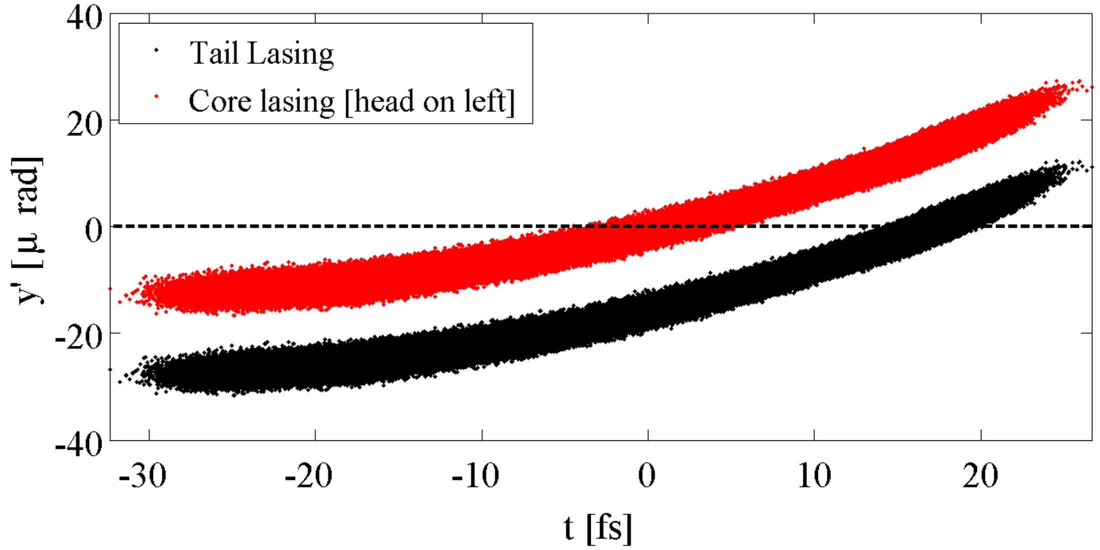


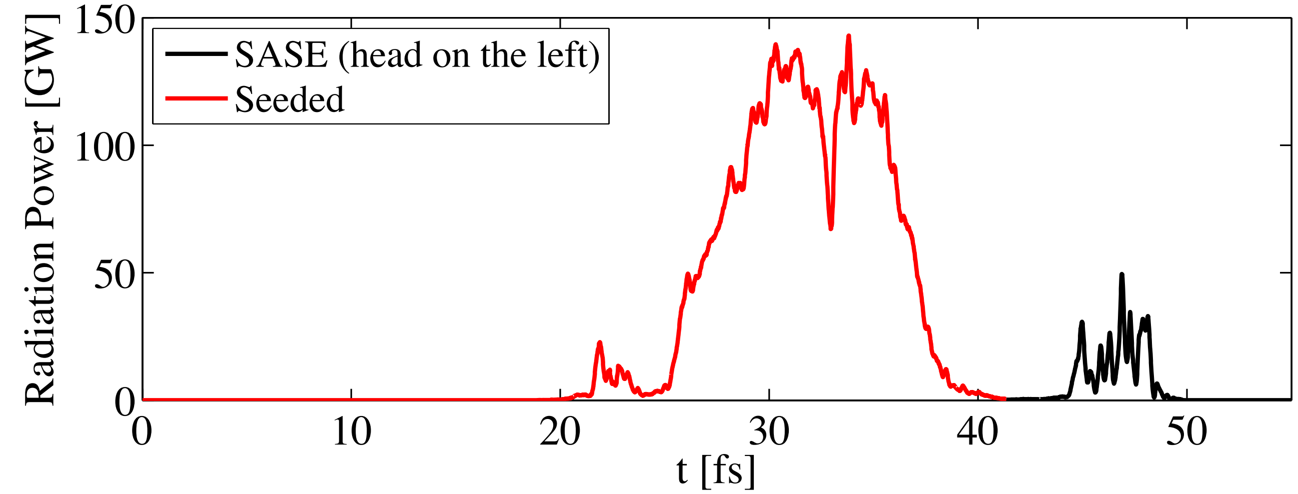


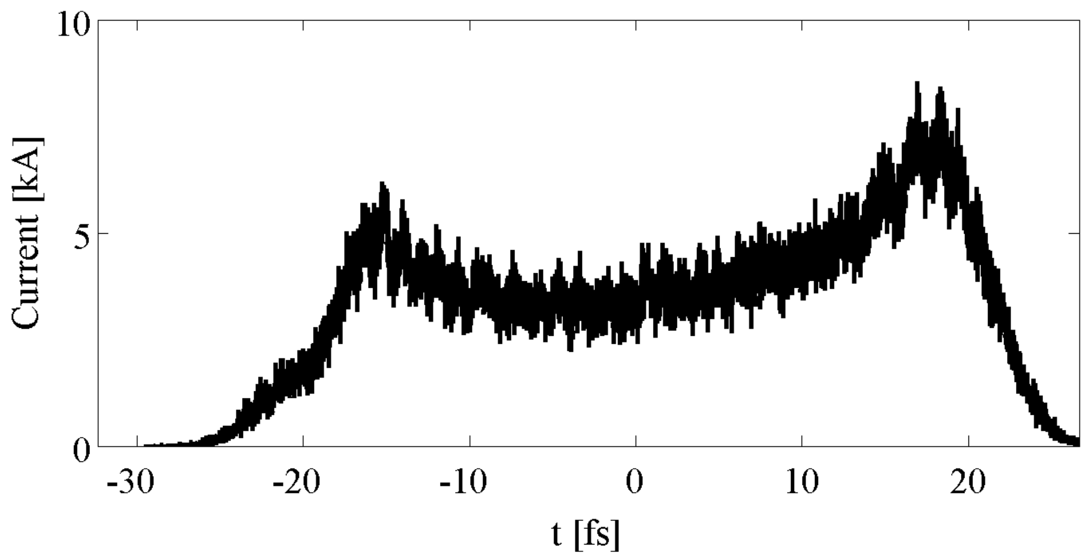
Monochromatization of SASE

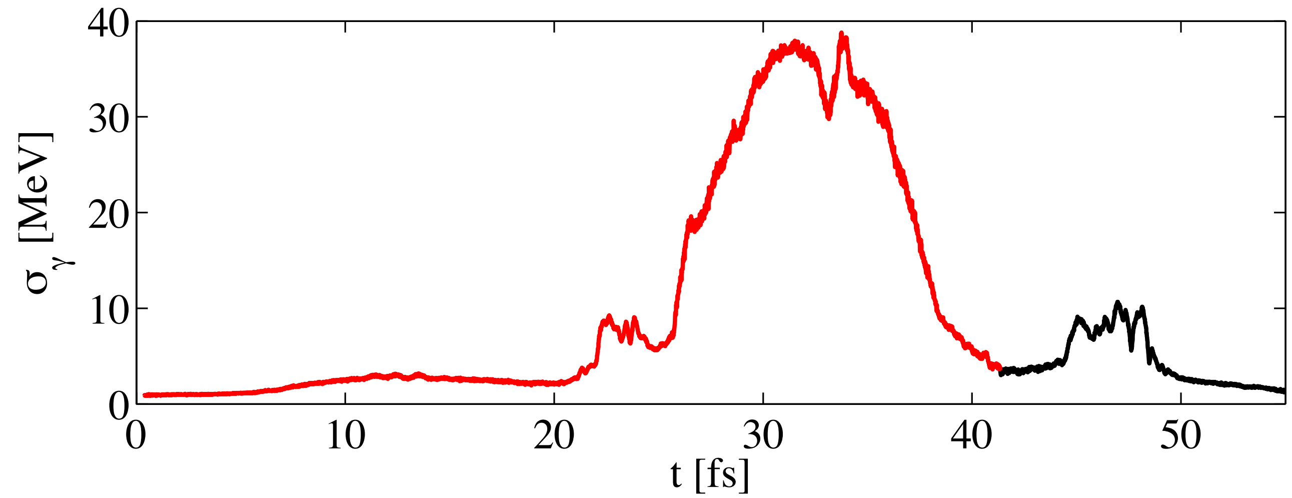
- Width of first maximum is 8 fs similar to seeded pulse width measured in ESS experiment

Start-to-end simulations-2





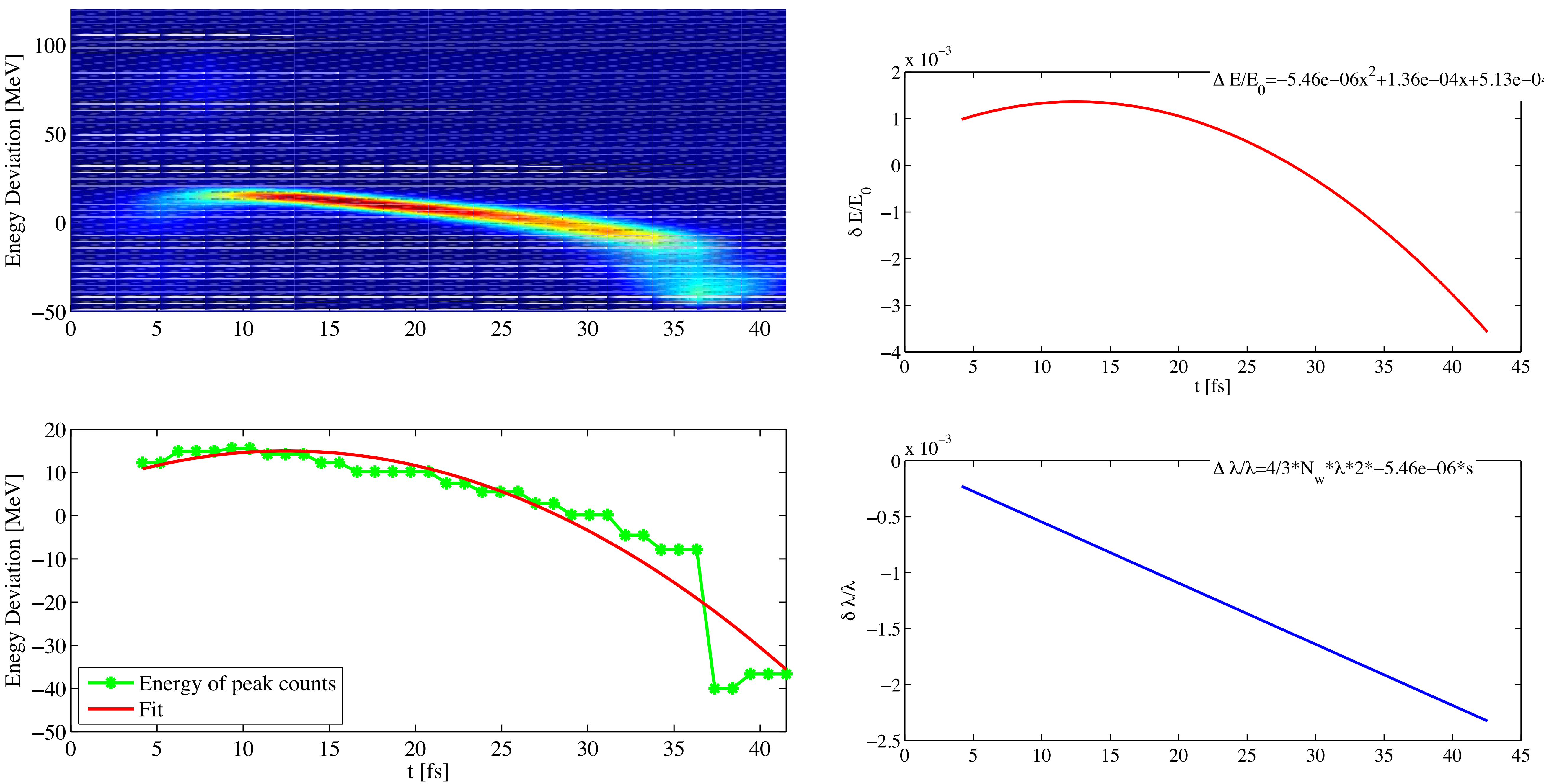




Two-stage GENESIS simulation

- Intensity is ~1 mJ matches the peak intensity measured in best shots
- Simulation includes dipole kick from dechirper but excludes quad. wake and slice energy spread increase on tail
- Including these effects and self-consistent steering in simulation is part of ongoing work

Possible bandwidth broadening from nonlinear chirp



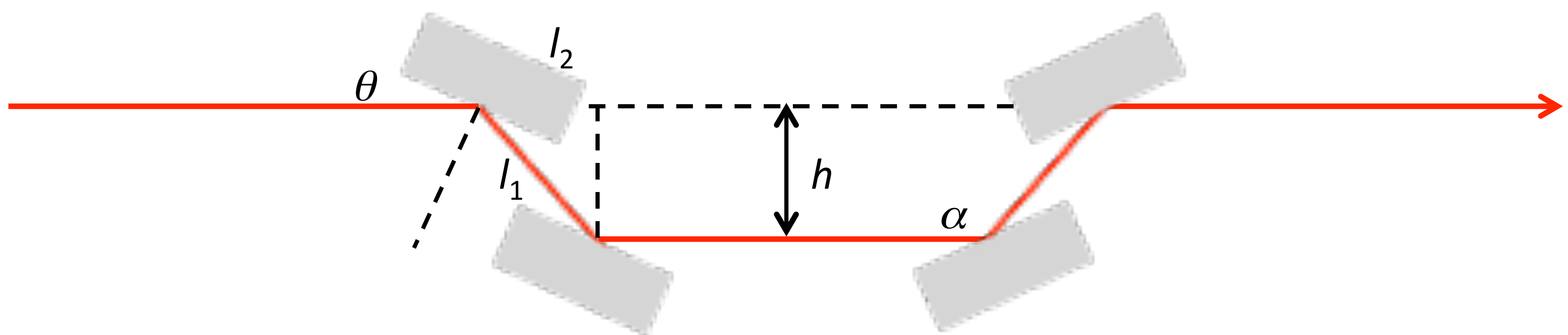
See A. Marinelli et. al., Comparative study of nonideal beam effects in high gain harmonic generation and self-seeded free electron lasers

Double-bunch monochromator design

C* (220) at 12 keV

$\theta = 24.18°$

- Schematics



- Time delay ~ 1 to 10 ns feasible w/ h > 330 mm

$$\Delta t = 2h(1+\cos\alpha)/\sin\alpha$$

$$\alpha = 2(\pi/2-\theta)$$

Courtesy Y. Feng