High efficiency, terawatt X-ray free electron lasers via fresh bunch self-seeding

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

Physics and Applications of High Brightness Beams

Havana, Cuba

March 28, 2016

SLAC NATIONAL ACCELERATOR LABORATORY

THE UNIVERSITY OF CALIFORNIA UCLA LET THERE BE LIGHT

Presentation Outline

Introduction

Motivation for Fresh Bunch Self Seeding (FBSS) via fresh slice lasing

1. Previous Experiments (SASE)

Two stage two color fresh slice lasing

Pulse duration, bandwidth separation and polarization control

2. Fresh Bunch Self Seeding at LCLS

Start-to end simulations

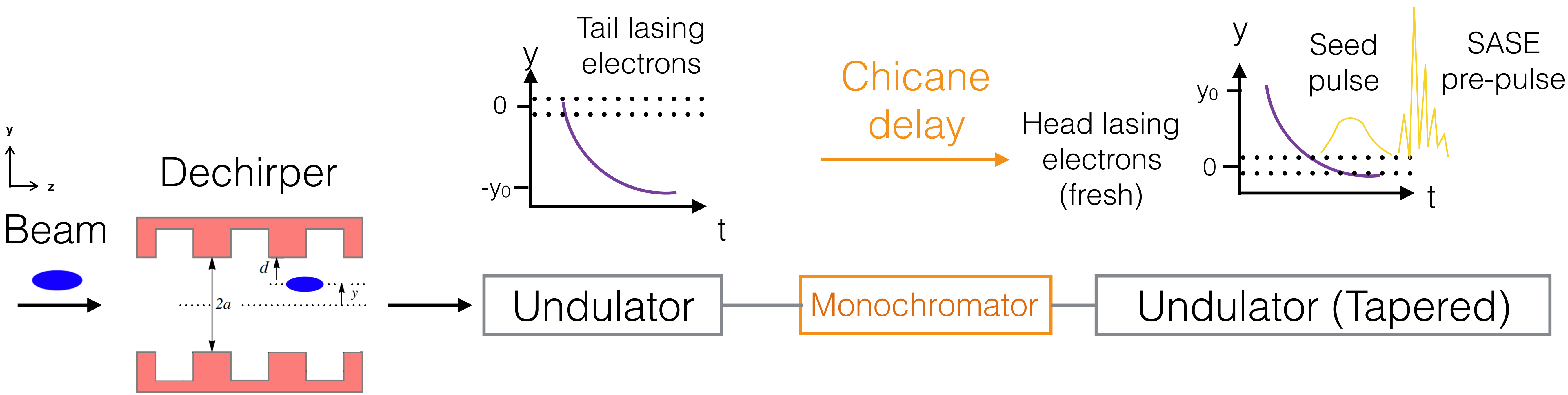
Proof of principle experimental results

Comparison with SASE and regular self-seeding

3. TeraWatt XFEL via fresh bunch self seeding: simulation study

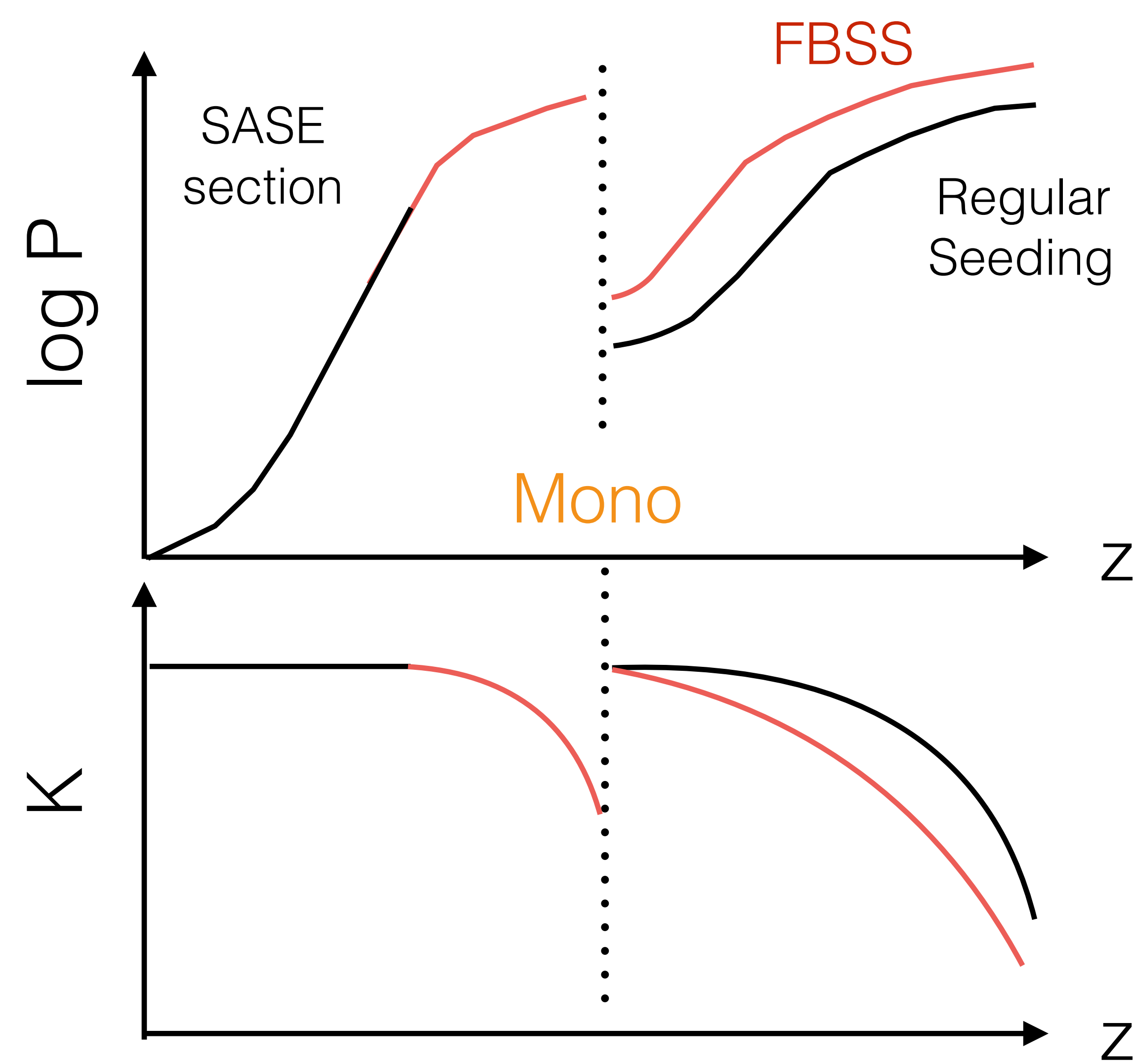
Conclusions and future outlook

Fresh Bunch Self-Seeding (FBSS)

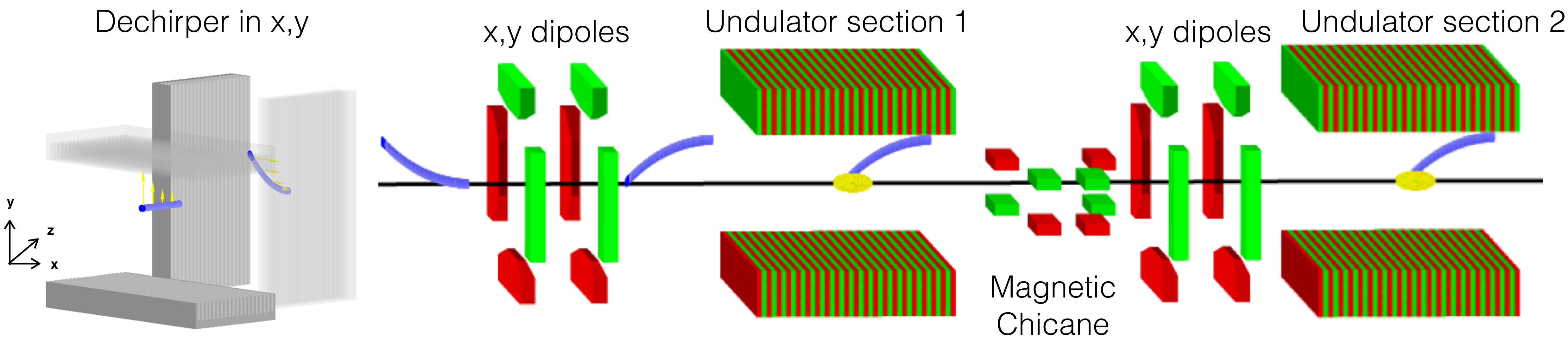


Motivation

- Performance of self seeded XFELs is limited by the trade off between seed power and electron beam energy spread
- Seeding with fresh electrons eliminates trade-off
- Large seed power increases taper efficiency downstream of the monochromator
- Fresh bunch seeding generates short (sub 10 fs) high intensity (>10 GW) high brightness seeded X-ray pulses
- Useful for pump/probe or experiments needing short seeded pulses with high peak intensity



Fresh slice SASE: pulse duration control

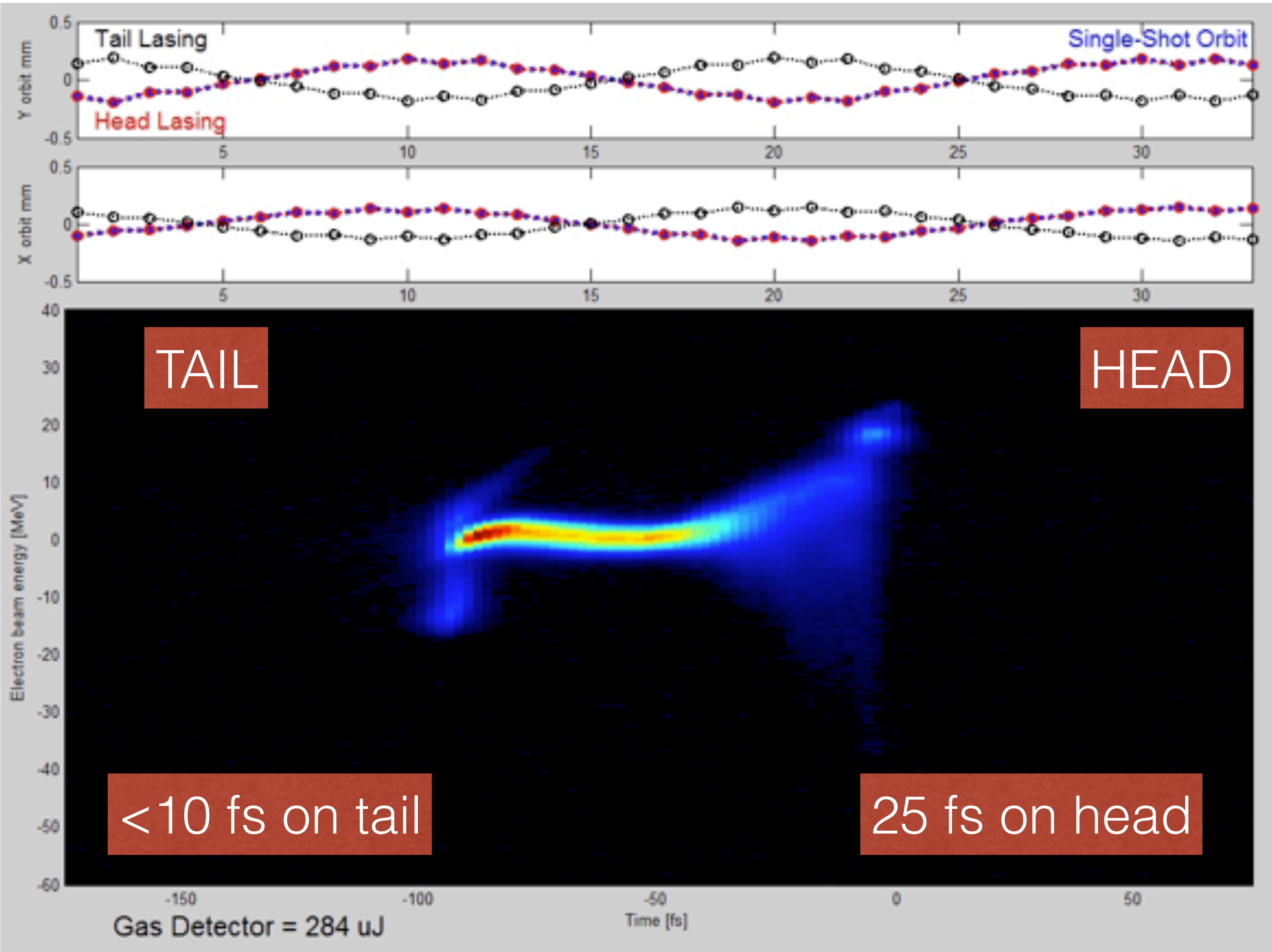


Upstream of the undulator section:

- 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)

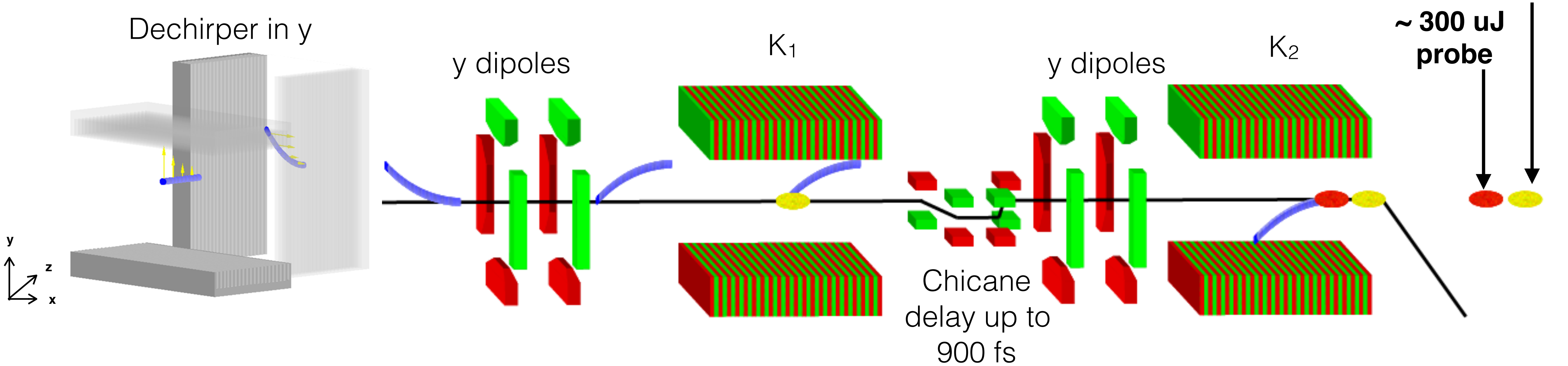
In the undulator section:

- 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, unpublished

Fresh slice SASE: two color scheme

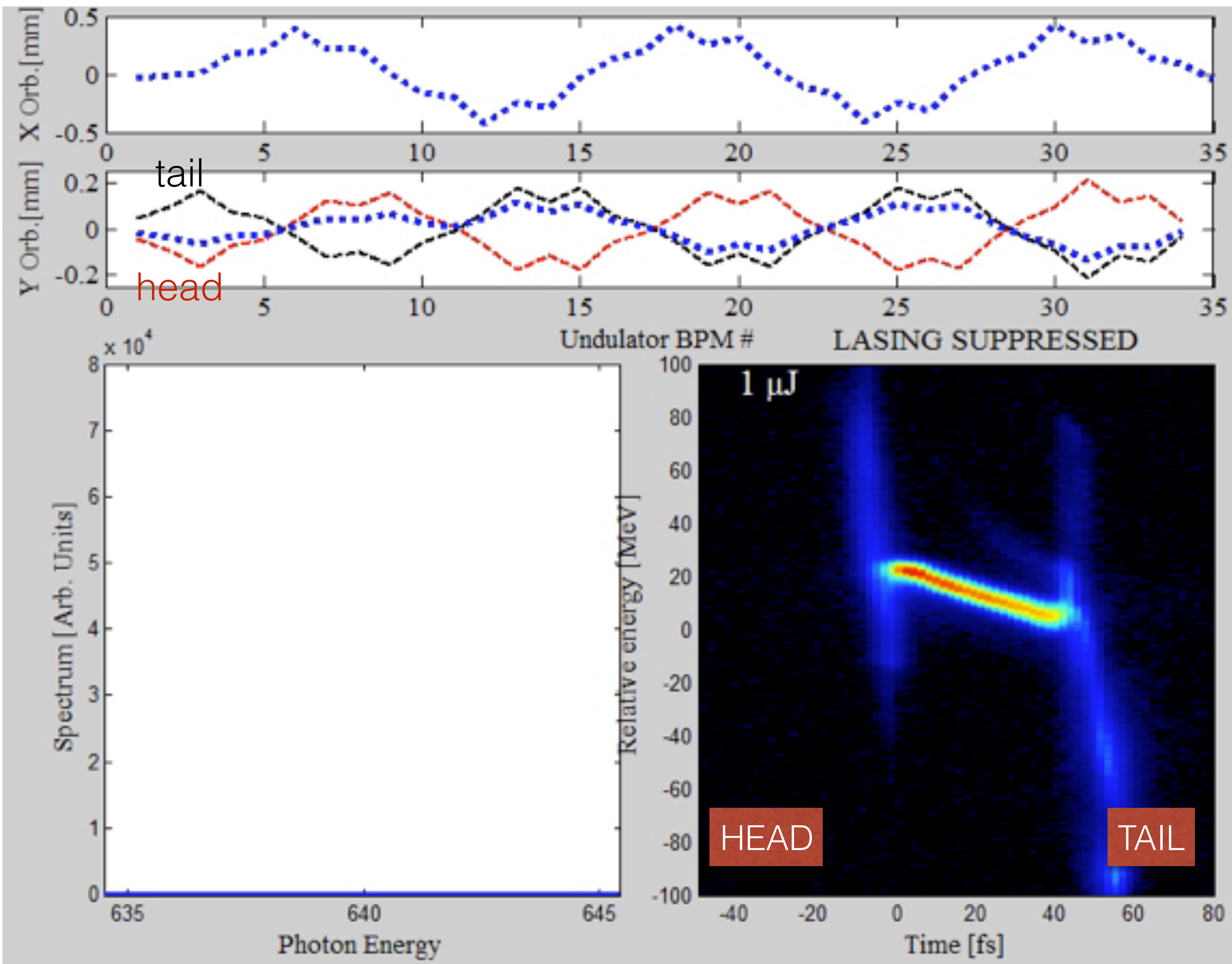


Advantages over previous two-color scheme

- ✓ Allows true zero delay
- ✓ Both colors can saturate
- ✓ Allows polarization control of the probe
- ✓ Simple delay scans (chicane only)
- ✓ Simple color scans (undulator K)
- ✓ Independent pointing

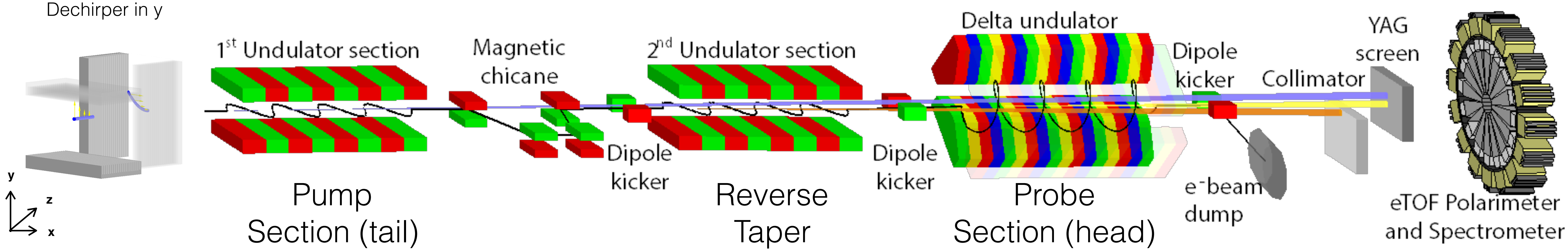
In the undulator section:

- ❖ Dipoles correct the orbit for tail-lasing before 1st undulator
- ❖ 1st undulator section tuned at K_1 makes FEL on the tail of the beam
- ❖ Chicane can delay the electrons with respect to the first X-ray pulse (up to 900 fs)
- ❖ Dipoles after 1st undulator section correct the orbit for the head
- ❖ 2nd undulator section tuned at K_2 makes FEL on the fresh head of the beam



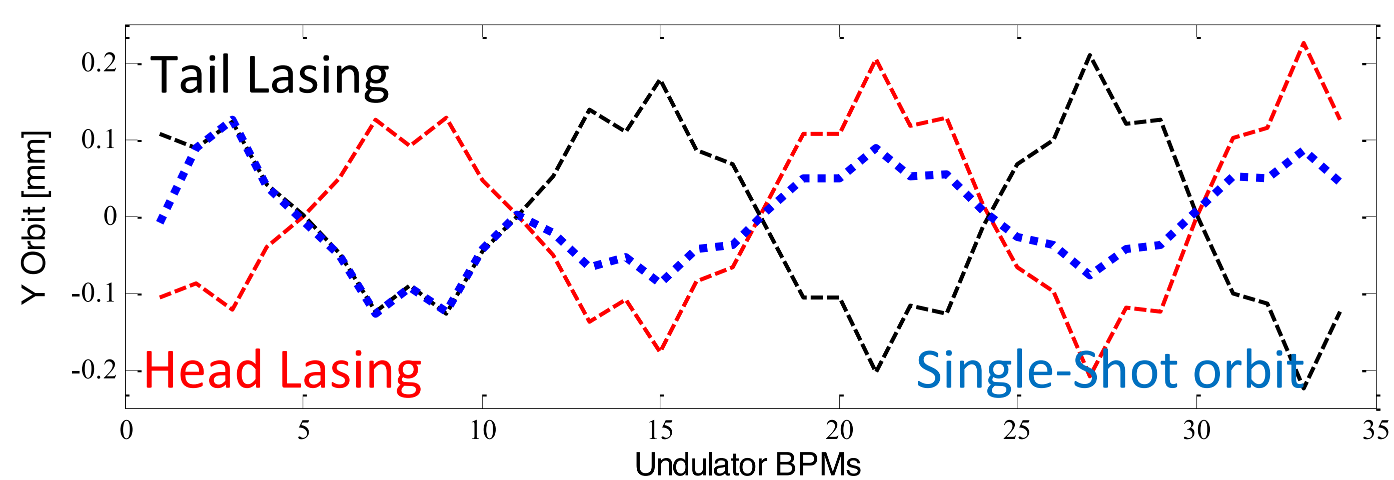
A. Lutman, unpublished

Fresh Slice SASE: Polarization control



Advantages over normal Delta operation

- ✓ Allows polarization switching so circular polarization can come first at the sample



In the undulator section:

Pump pulse generated on the bunch tail ~8 fs long

Probe pulse generated on the bunch head with reverse taper and beam diverting ~ 15 fs long

The collimator obstructs the unwanted linear polarization from the 2nd undulator section.

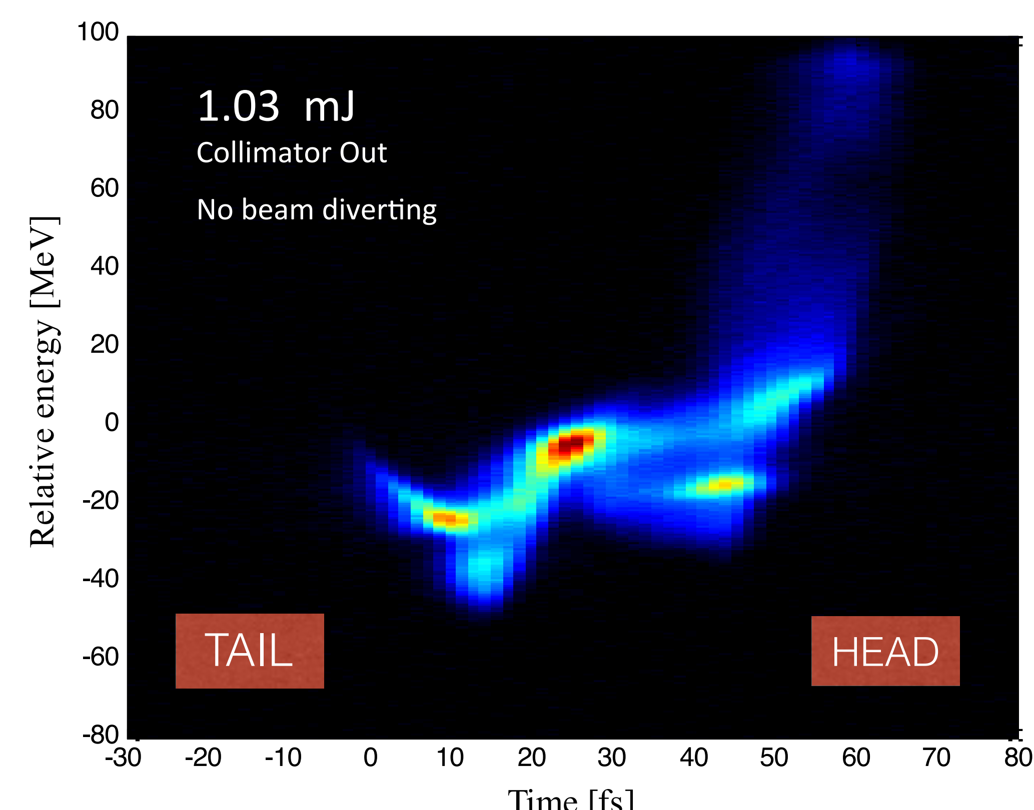
Collimator in

~ 200 uJ in the pump pulse
~ 200 uJ in the probe pulse

Collimator out

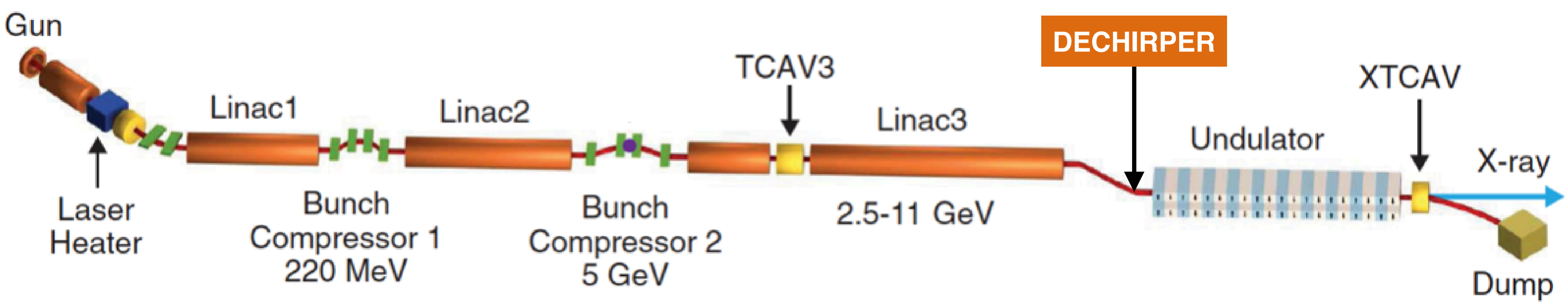
~ 250 uJ in the pump pulse
~ 500 uJ in the probe pulse

Und.	Status	K value
1-8	IN	K~3.455, Strong Saturation taper from Und #6
10-25	OUT	/
26-33	IN	K~3.505 Variable Taper (Regular/ Reverse)



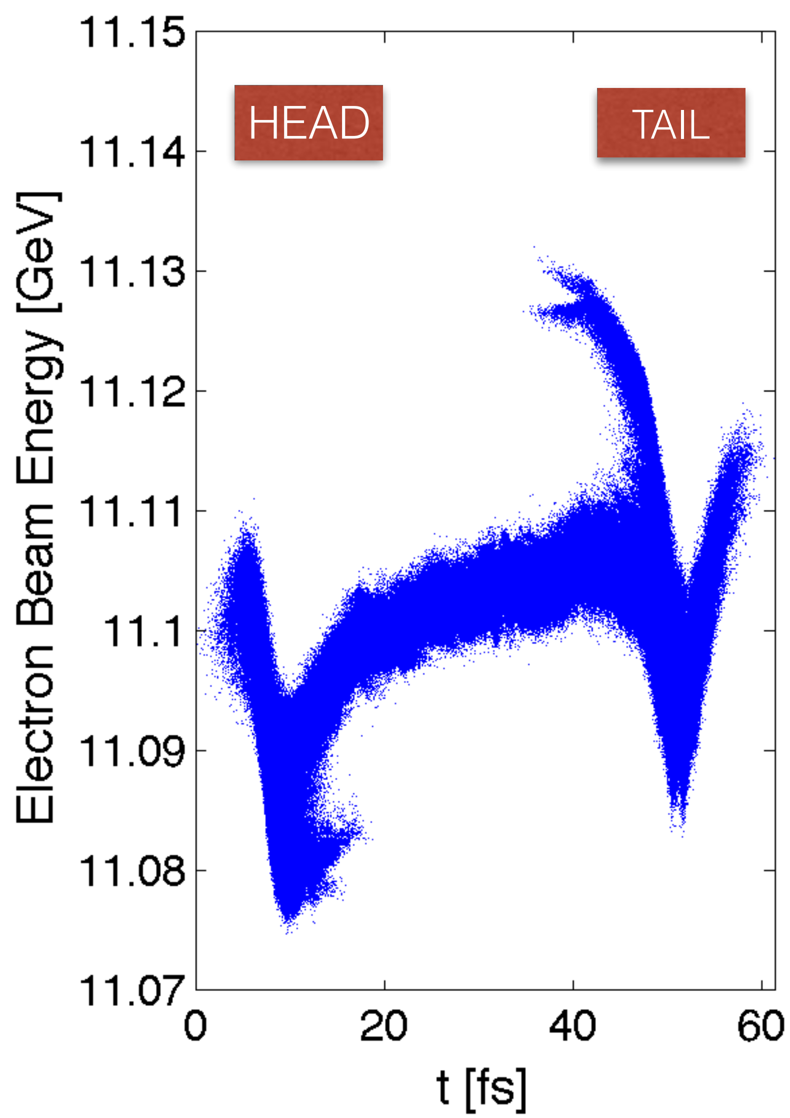
A. Lutman, unpublished

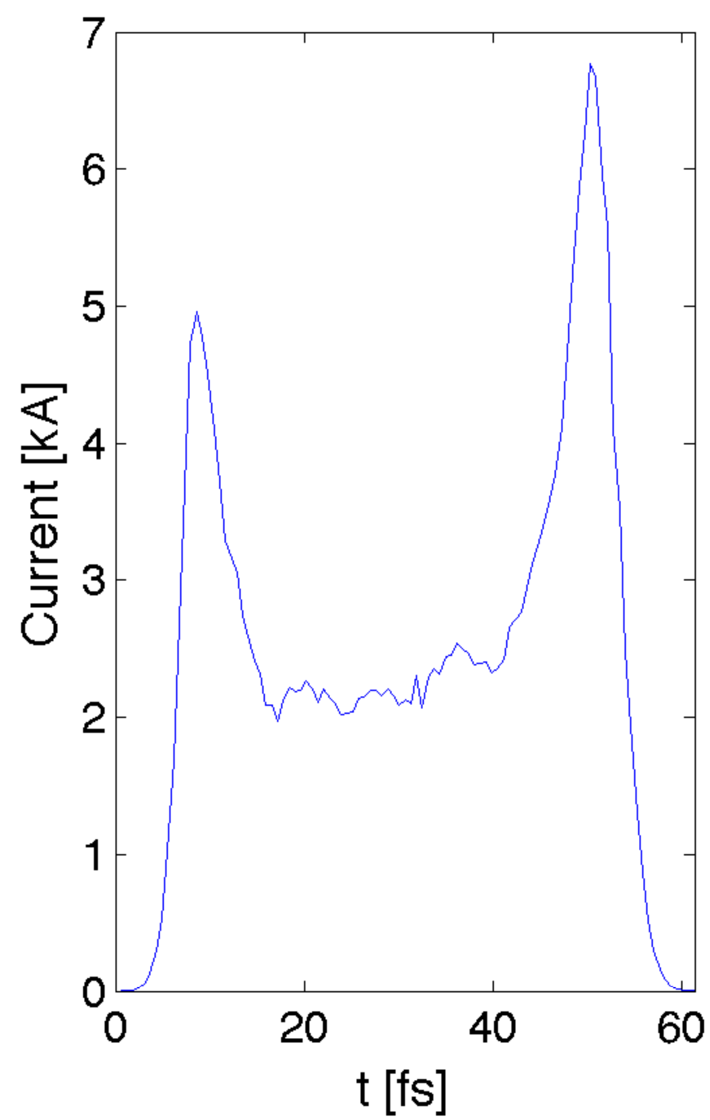
FBSS: Start-to-end simulation study at LCLS



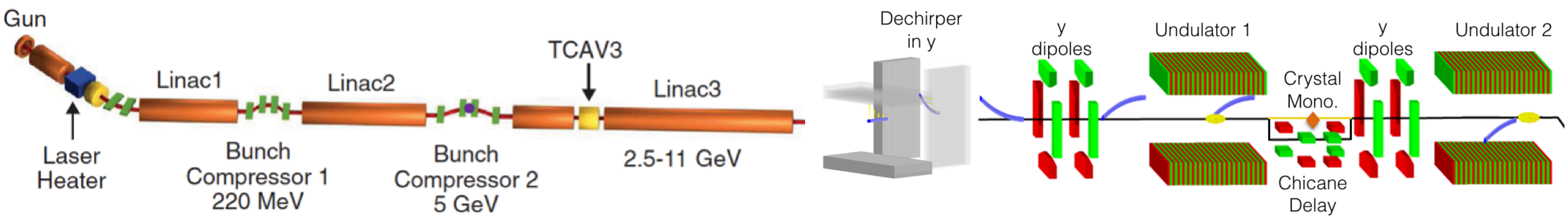
LCLS accelerator layout from electron gun to beam dump

Adapted from *Linac Coherent Light Source: The first five years,* Rev. Mod. Phys. Vol. 88, Jan-Mar 2016



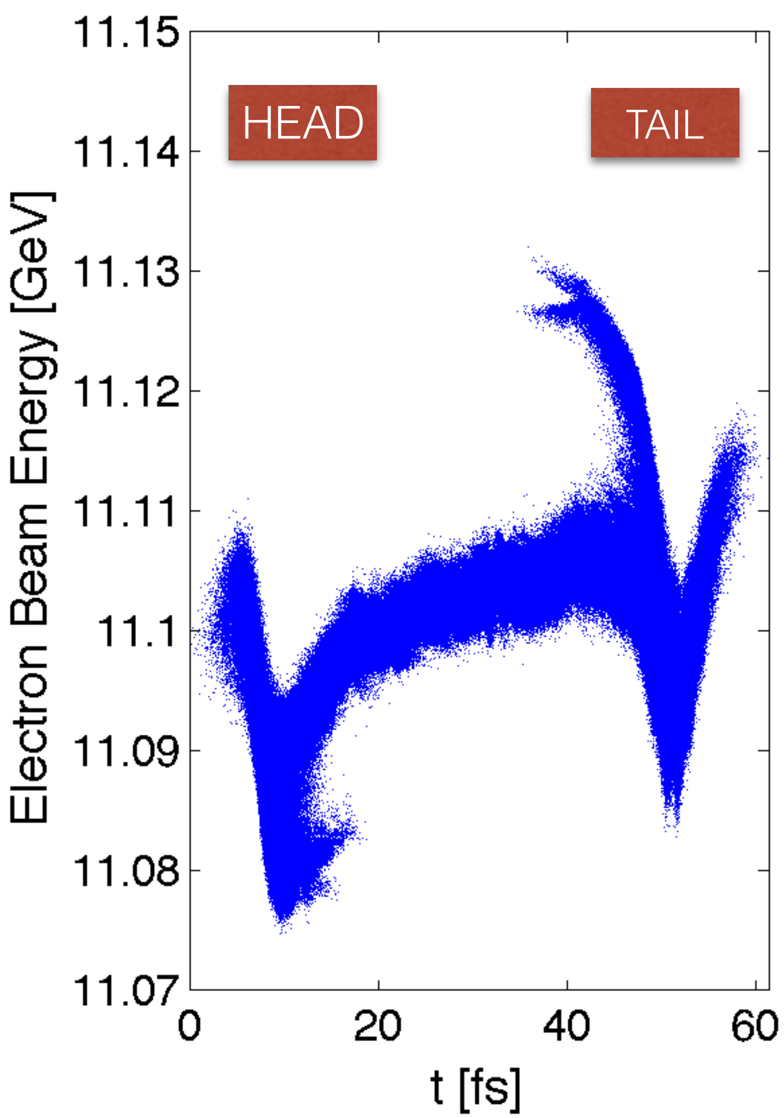


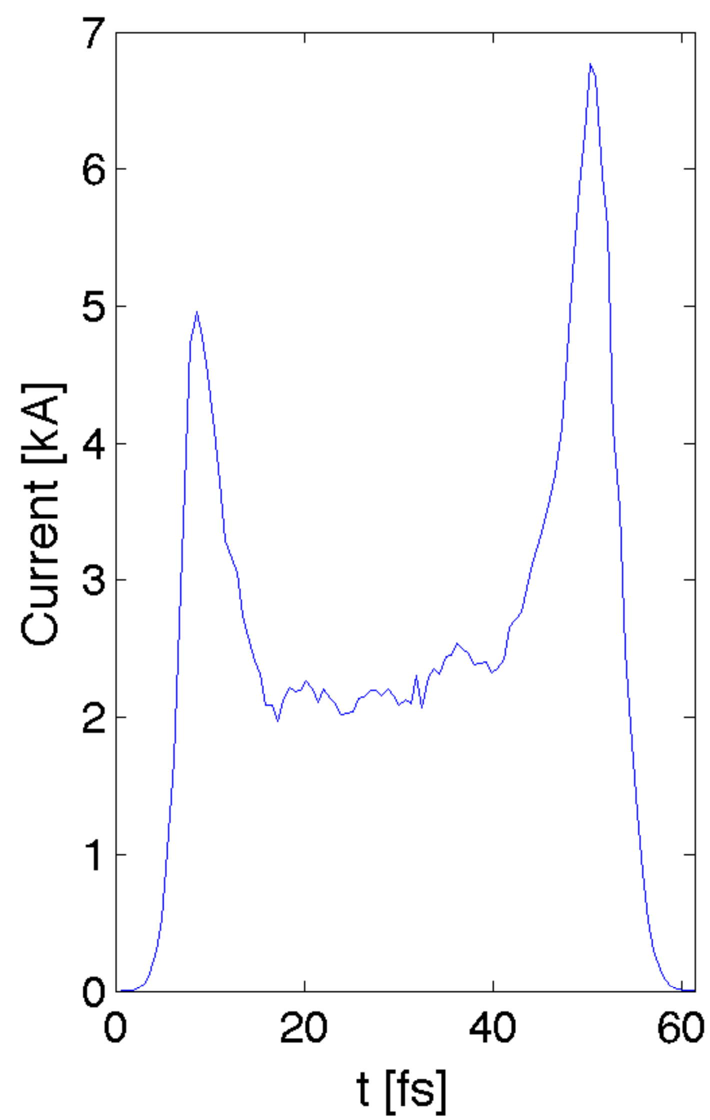
FBSS: Start-to-end simulation study at LCLS



LCLS accelerator layout from electron gun to beam dump

Adapted from *Linac Coherent Light Source: The first five years,* Rev. Mod. Phys. Vol. 88, Jan-Mar 2016

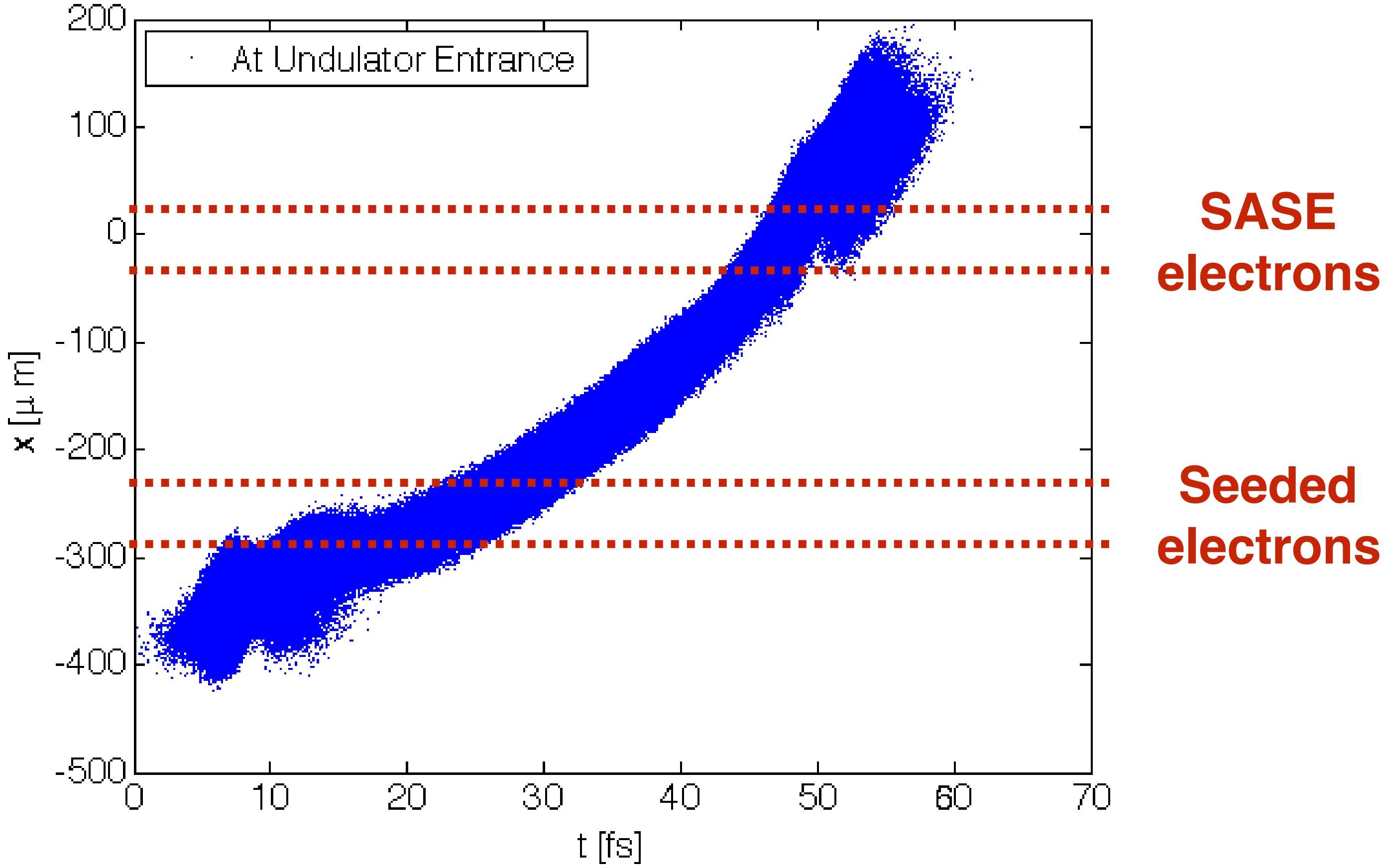


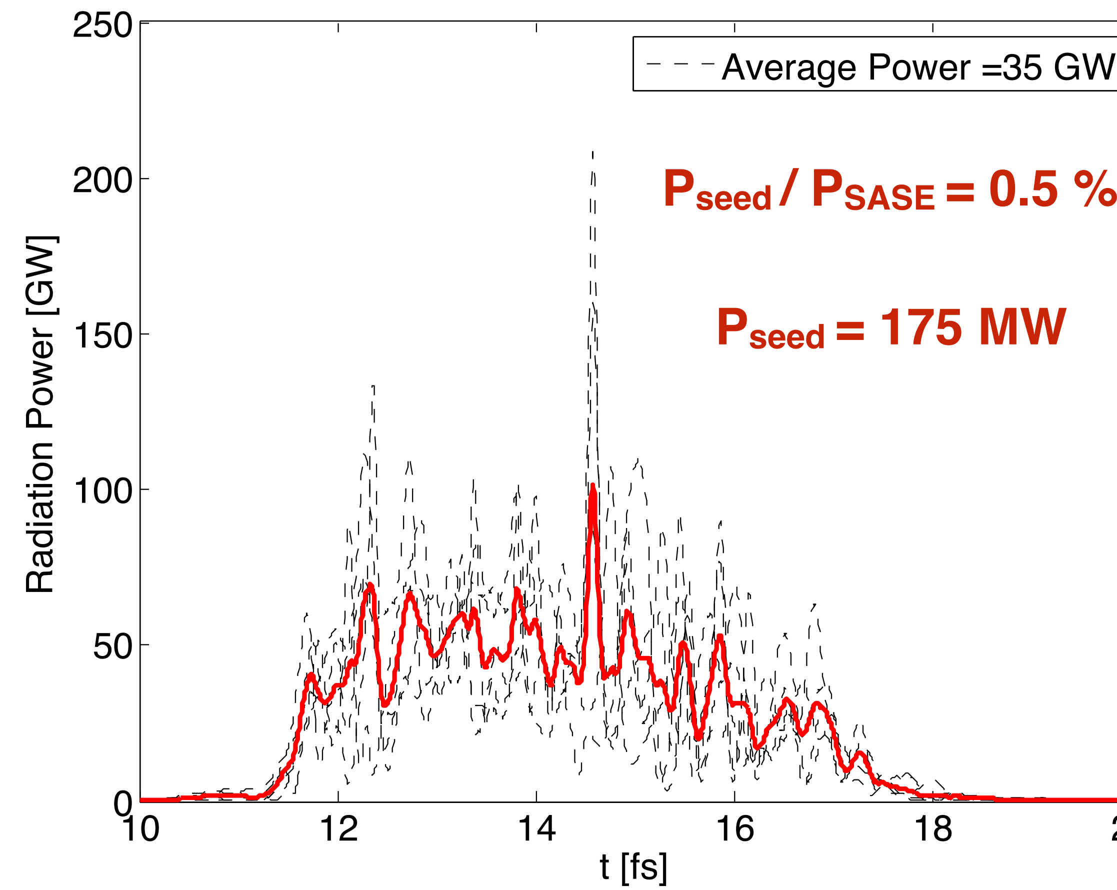


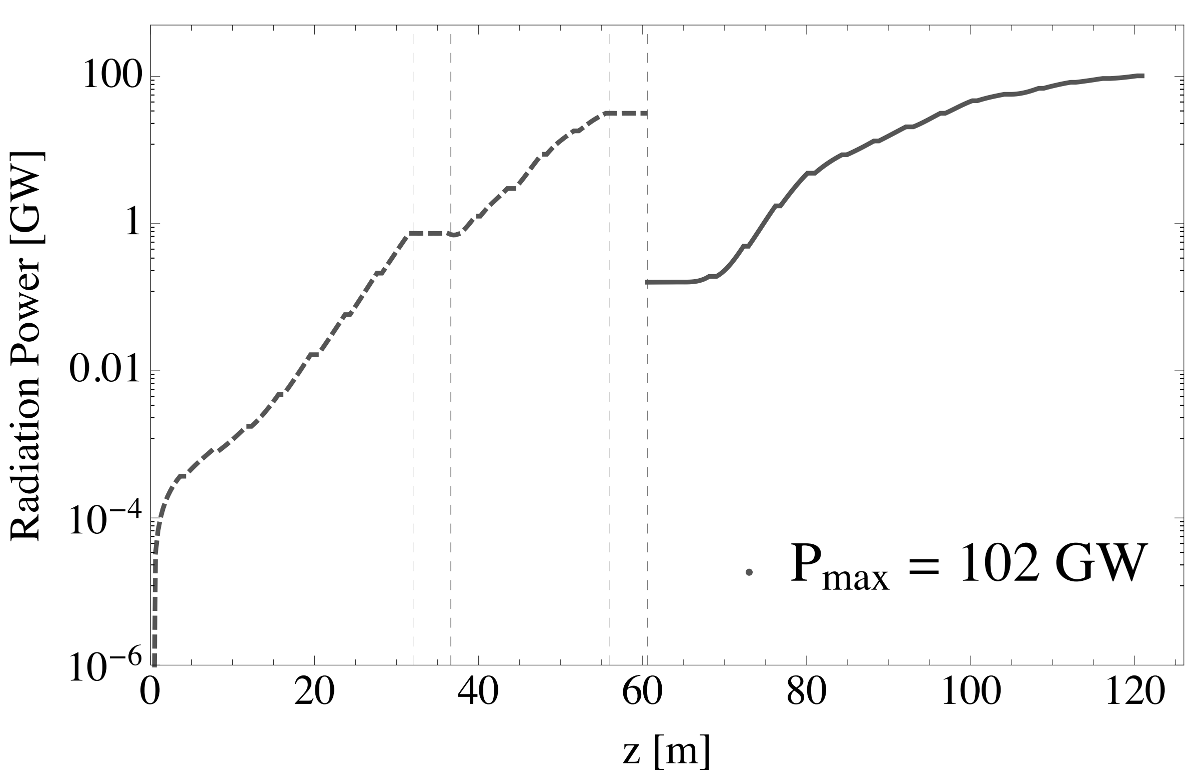
GENESIS Simulation Parameters

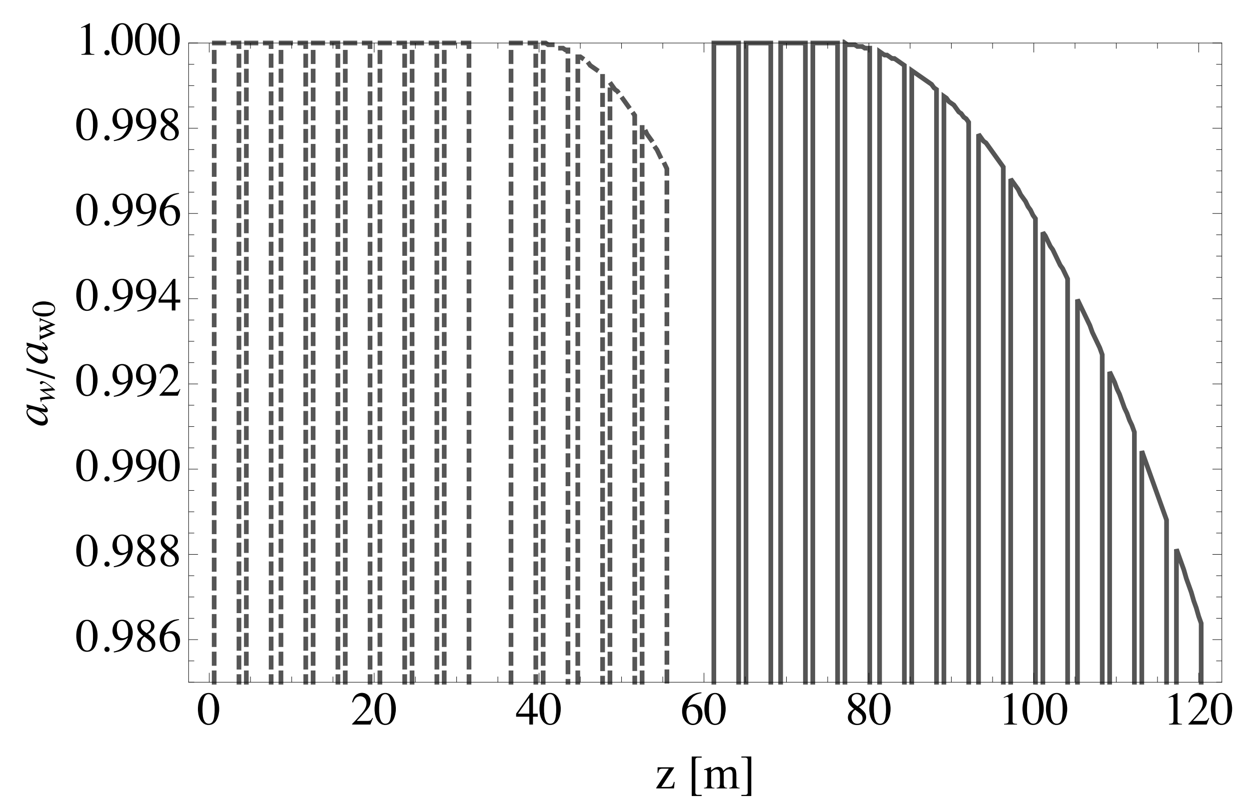
Parameter Name	LCLS
Beam Energy [GeV]	11
Slice Energy Spread [MeV]	2 (core)
Peak Current [kA]	2.2 (core)
Emittance $\epsilon_{x,n}/\epsilon_{y,n}$ [μ m]	0.4/0.4
Average β function [m]	18
Bunch length [fs]	60
Undulator Period [cm]	3
Undulator Parameter (RMS)	2.47
Photon Energy [keV]	5.5
FEL parameter ρ	7.7×10^{-4}

FBSS: Start-to-end simulation study at LCLS

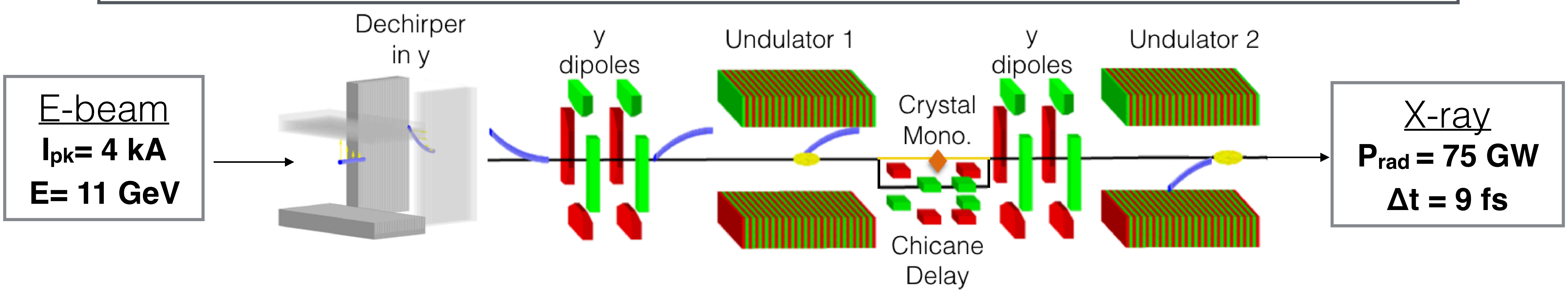


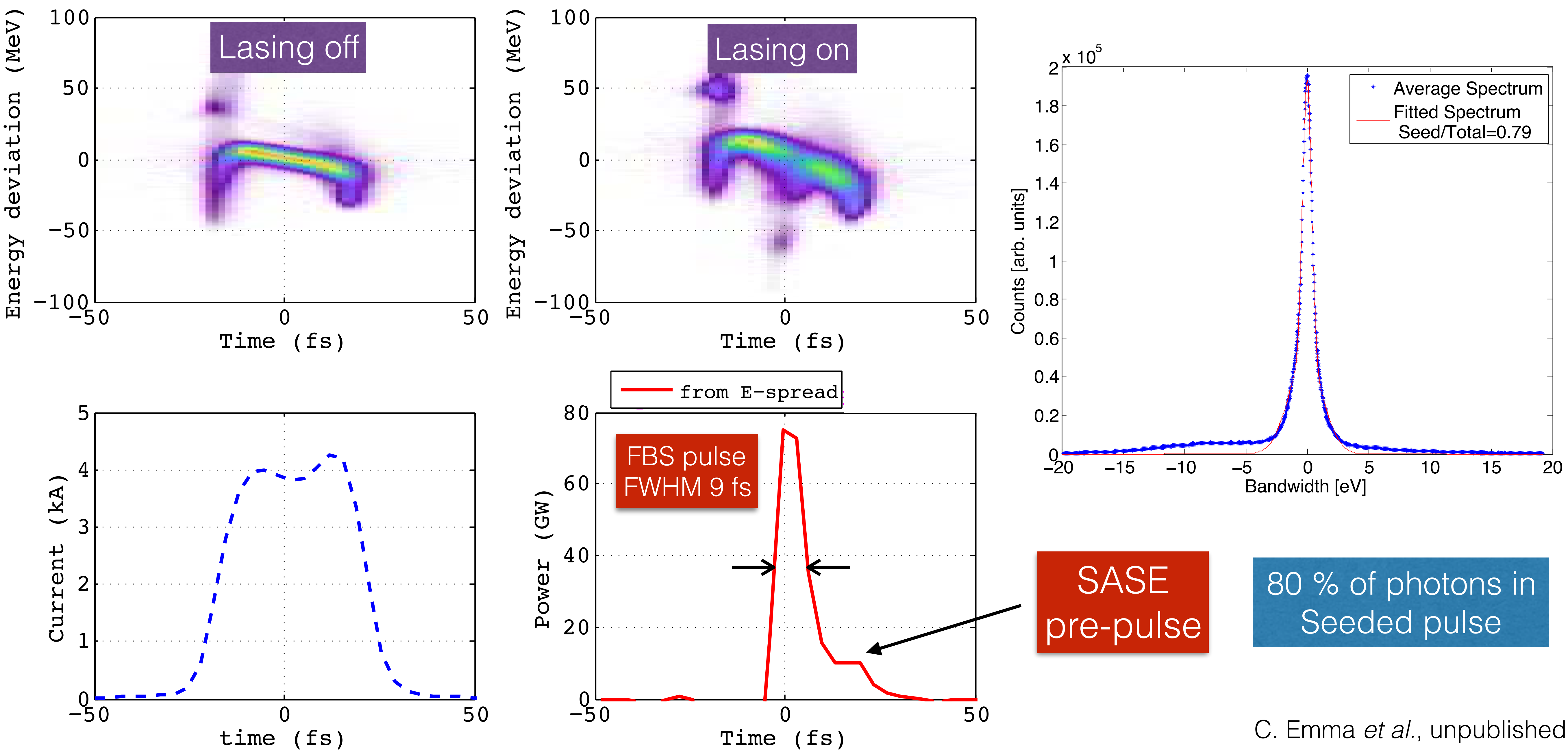






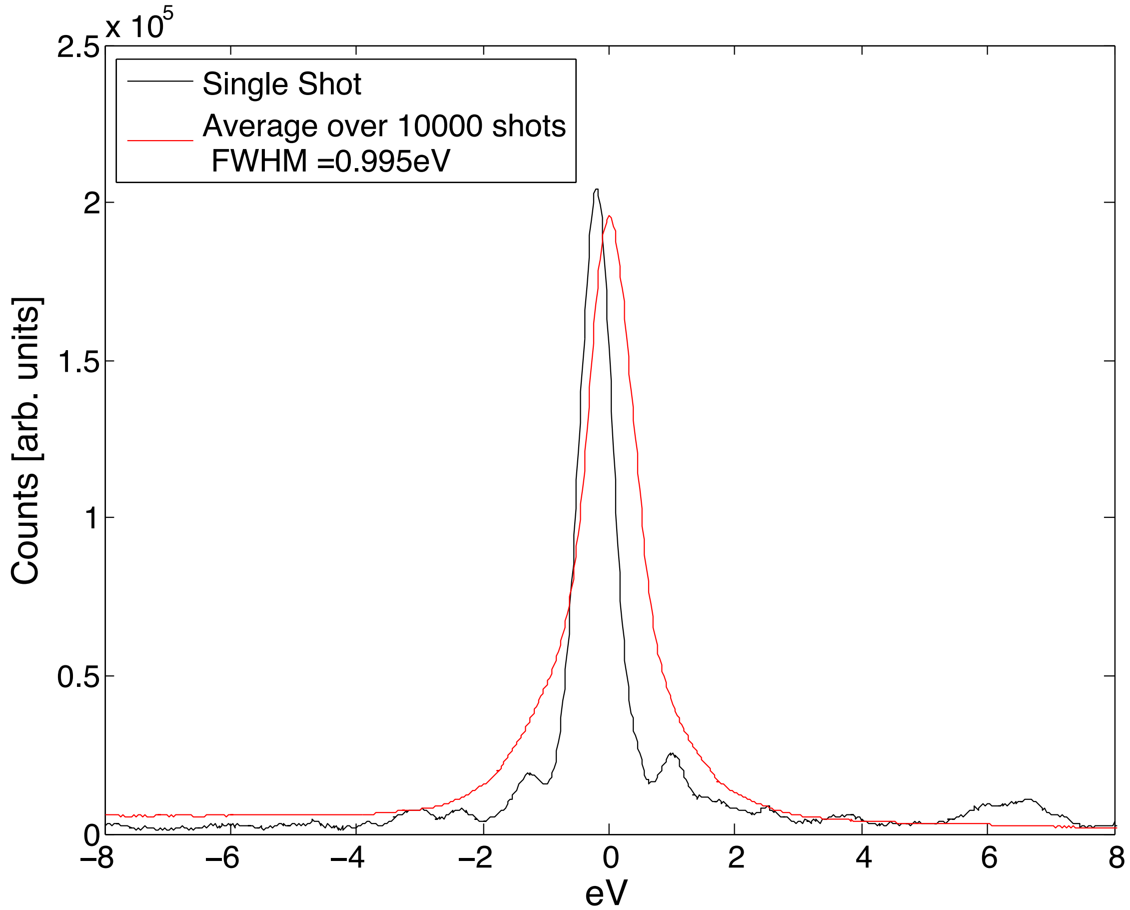
FBSS Proof of principle experimental results



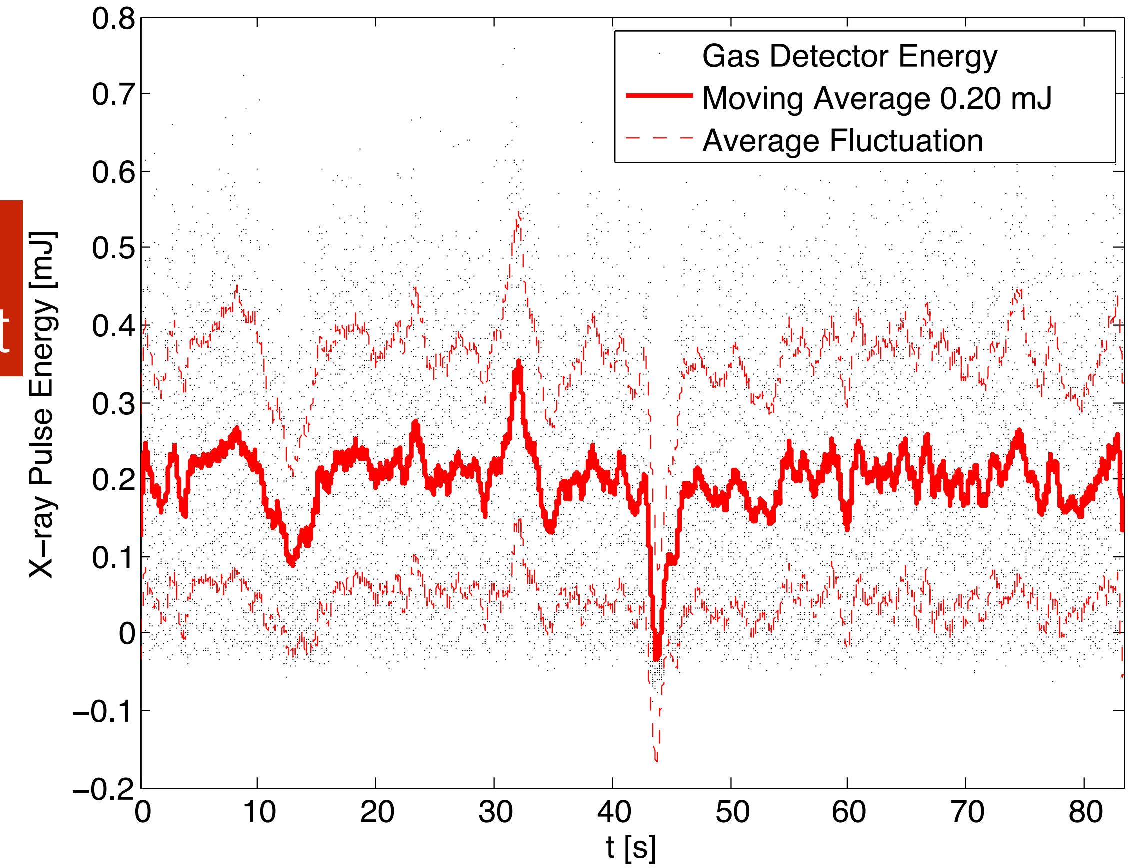


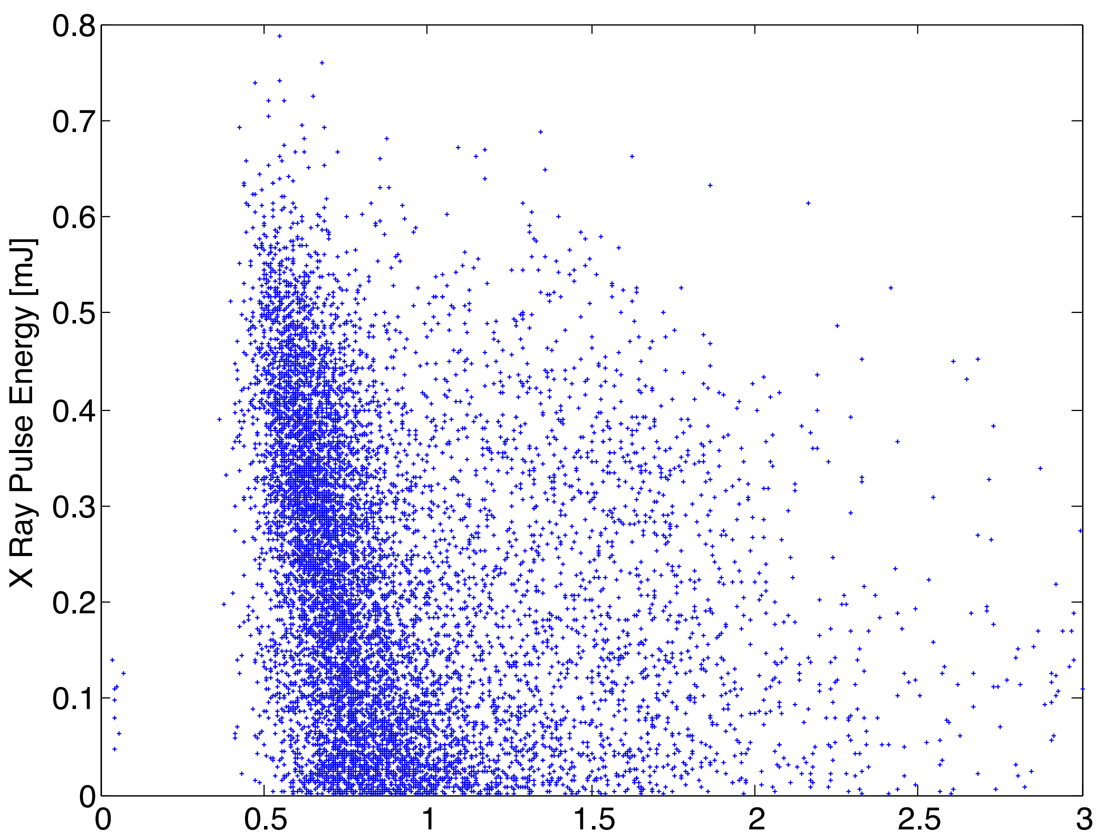
C. Emma *et al.*, unpublished

FBSS Experimental Results: spectral analysis

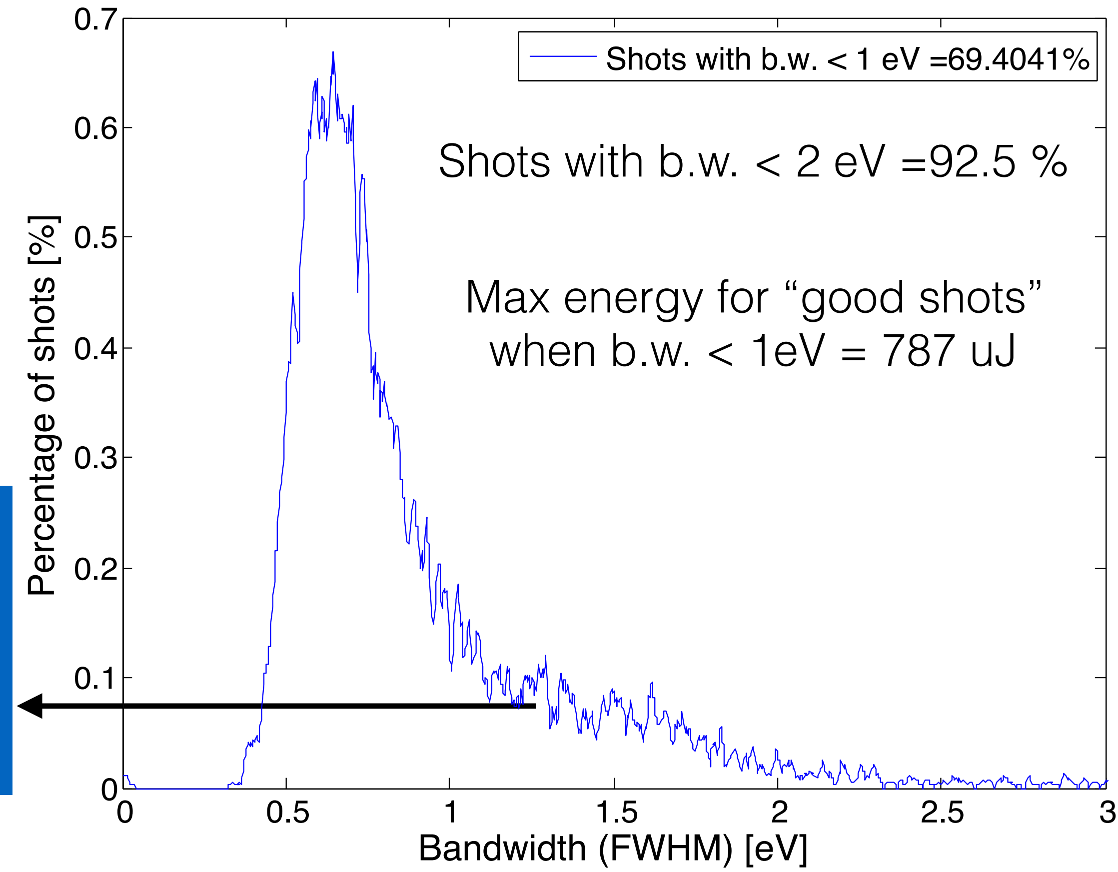


Average over whole data set



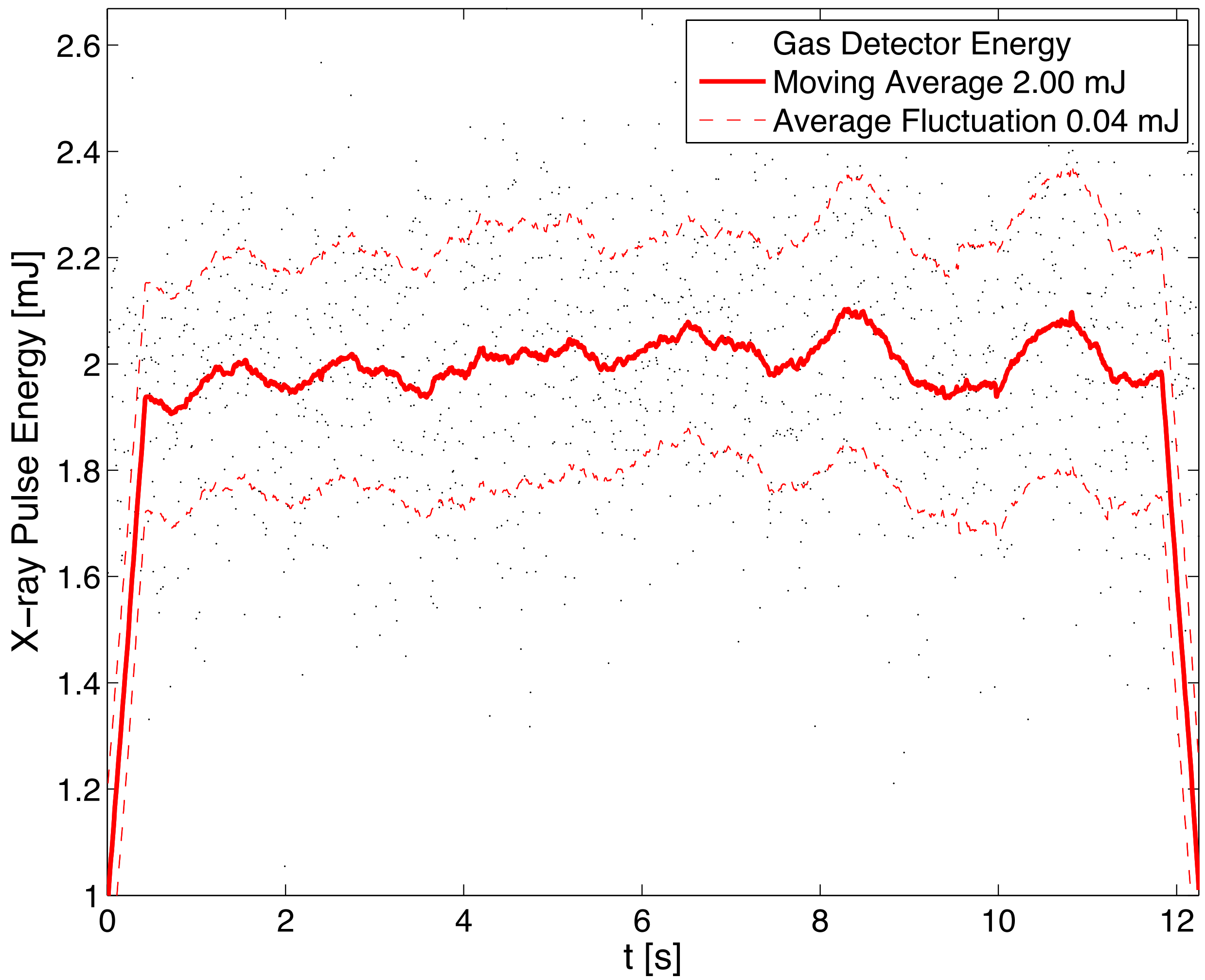


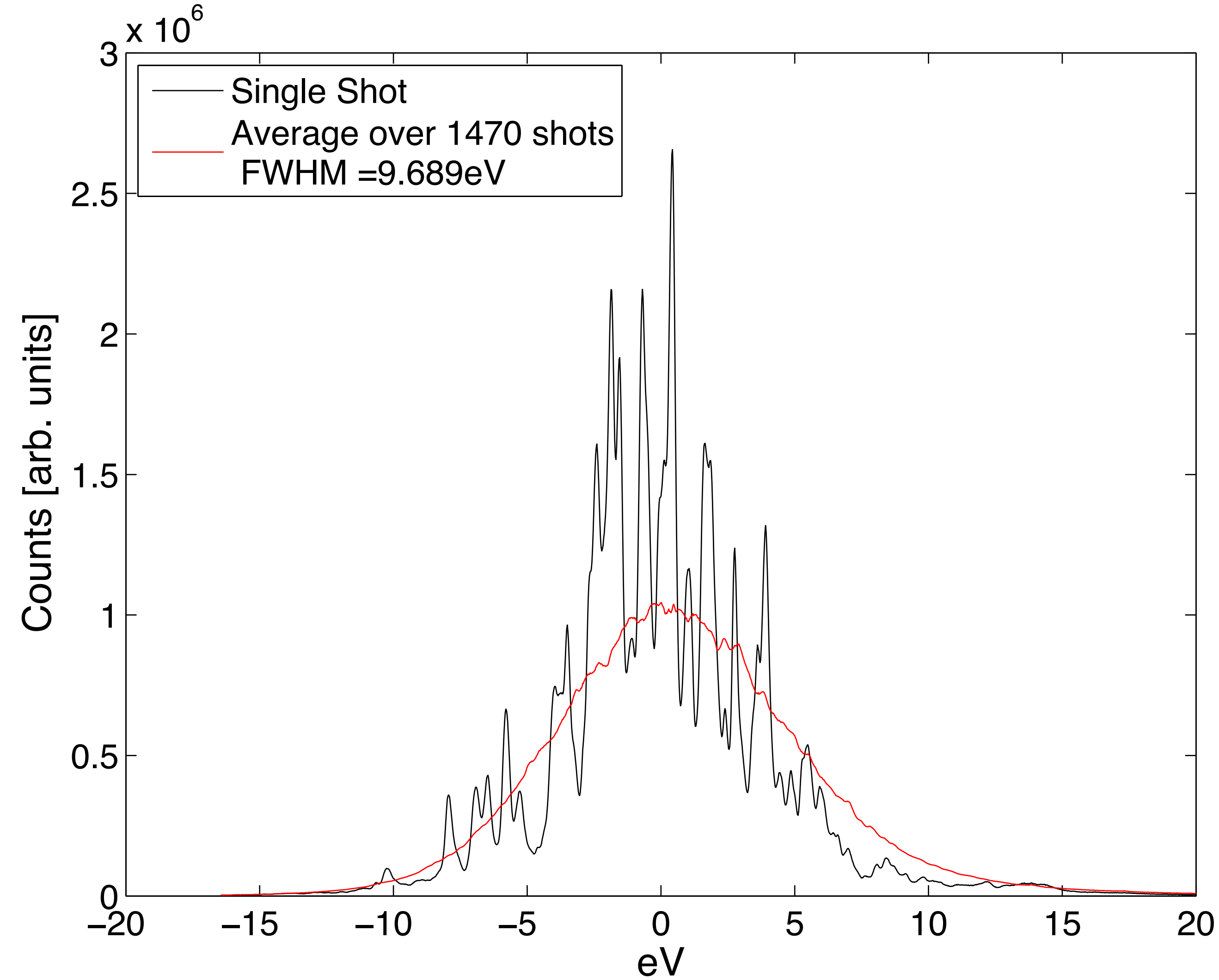
Shoulder may be due to shots w/ bad spatial overlap between beam and seed, e-beam phase space nonlinearity etc.



C. Emma *et al.*, unpublished

Comparison with SASE from the same shift





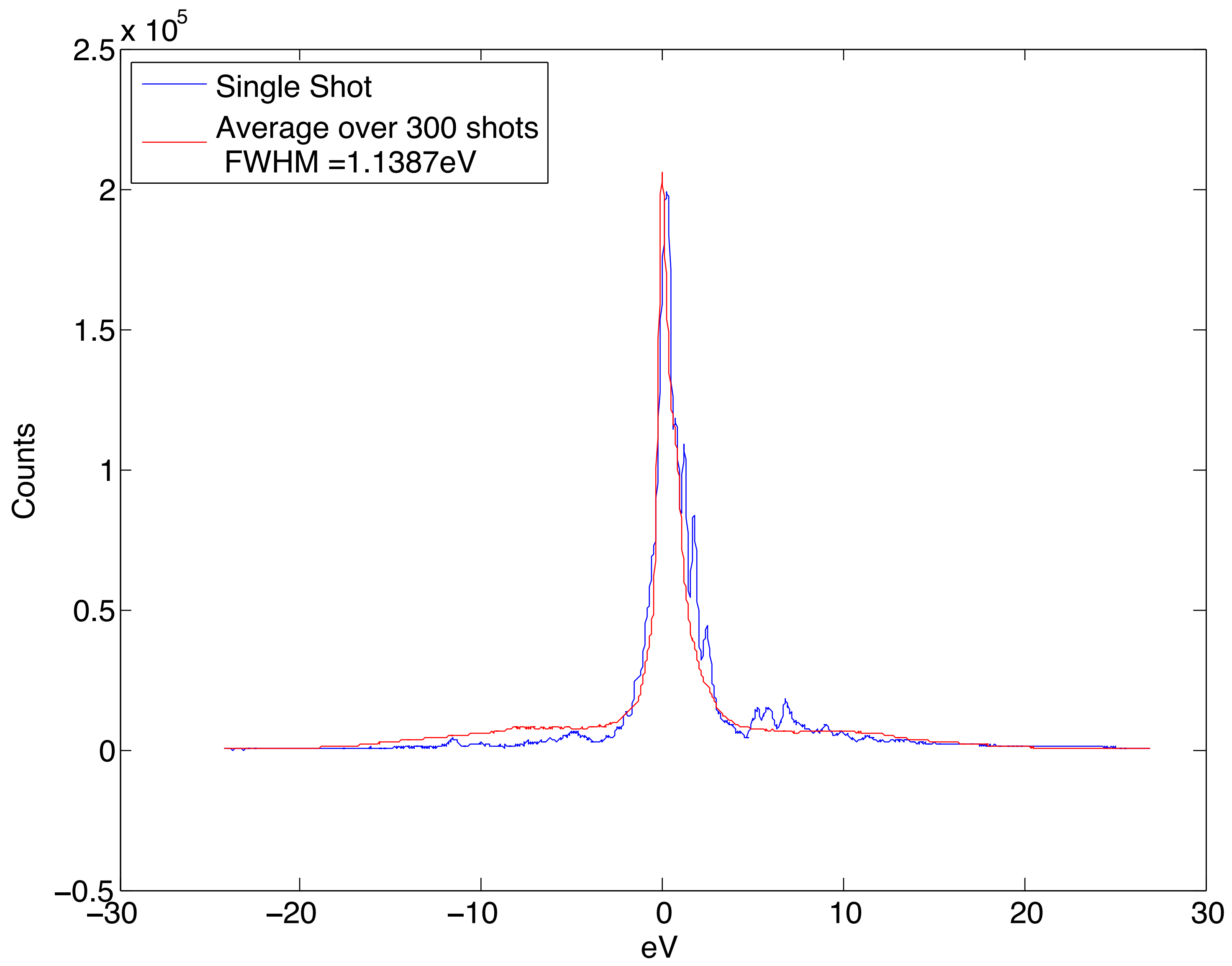
With 40 fs SASE pulse and 2 mJ

$$B_{\mathrm{ph}} = \frac{N_{\mathrm{ph}}}{4\pi^2 \Sigma 2\pi \sigma_t \sigma_\omega \omega}$$

$$\frac{B_{FreshBunch}}{B_{SASE}} \sim 5.7$$

C. Emma *et al.*, unpublished

Comparison with regular seeding from previous shift



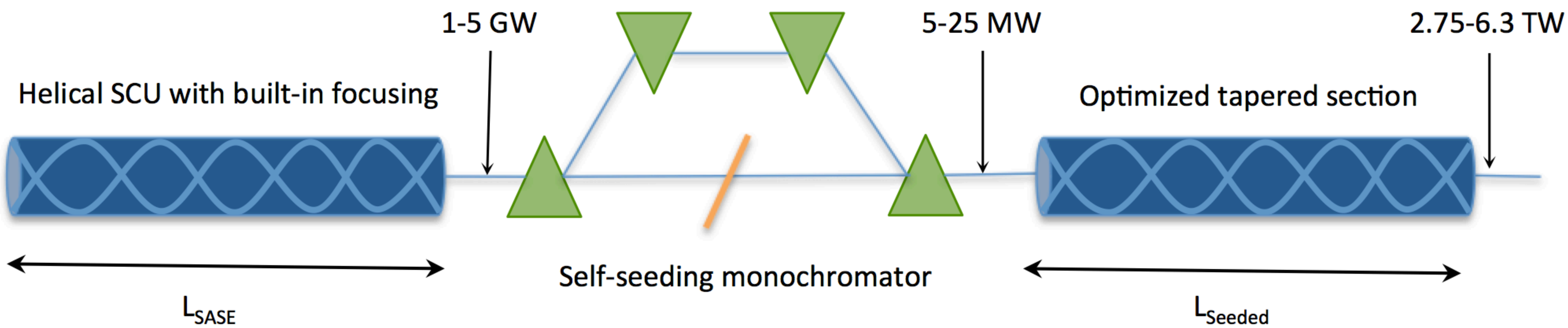
Assuming 20 fs seeded pulse (no XTCAV data)

Pulse Energy ~ 400 uJ

X-ray Power ~ 20 GW

$$\frac{B_{FreshBunch}}{B_{Seeded}} \sim 1.79$$

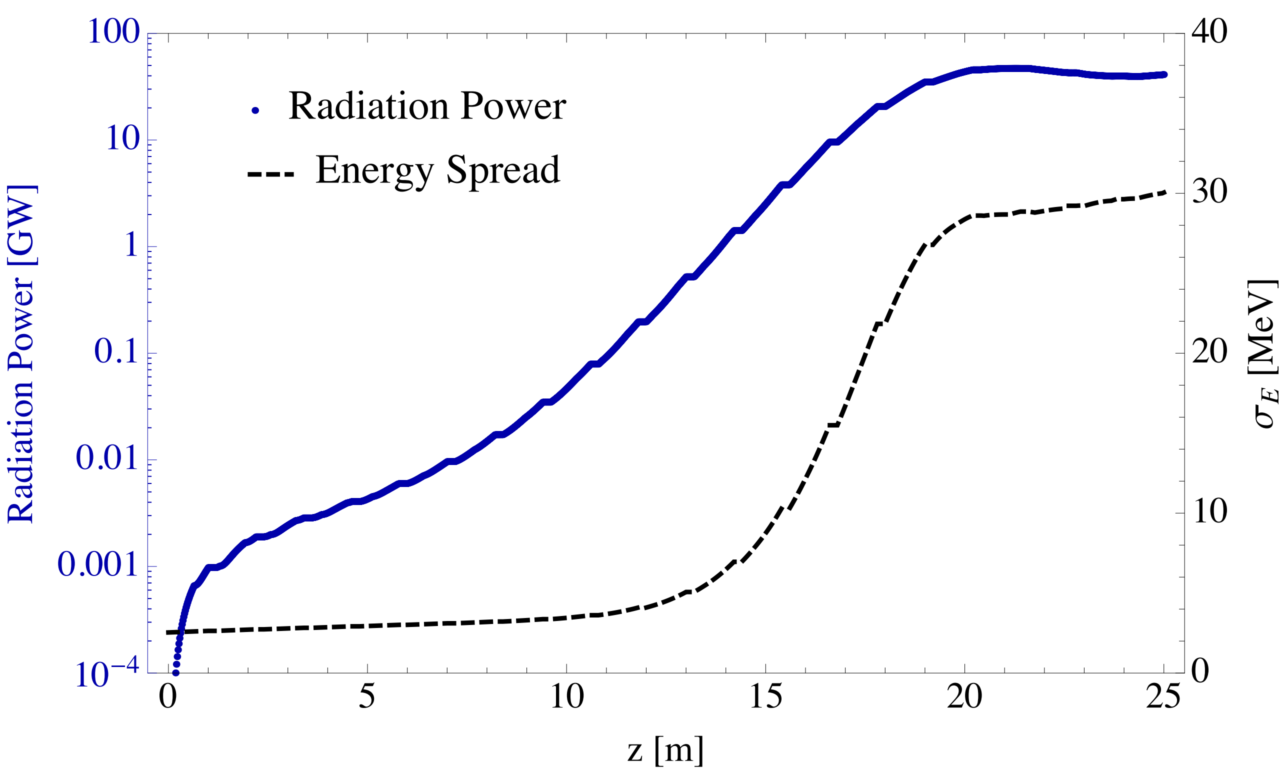
FBSS for TW-XFEL in a superconducting undulator



Design Feature	Performance Advantage
Superconducting Undulator	❖ High peak field K=3 ❖ Short period λ= 2cm ❖ Improved resistance to wakefields/ radiation damage
Short Break Sections	❖ Maximizes undulator fill factor ❖ Reduces diffraction ❖ Reduces electron phase mixing
Distributed Focusing	❖ Reduces FODO length and supports small β functions ❖ Reduces transverse beam envelope oscillations

I_{pk}= 4 kA σ_γ=1.5 MeV
E=13 GeV $\varepsilon_{x,y}$=0.3μm

SASE section



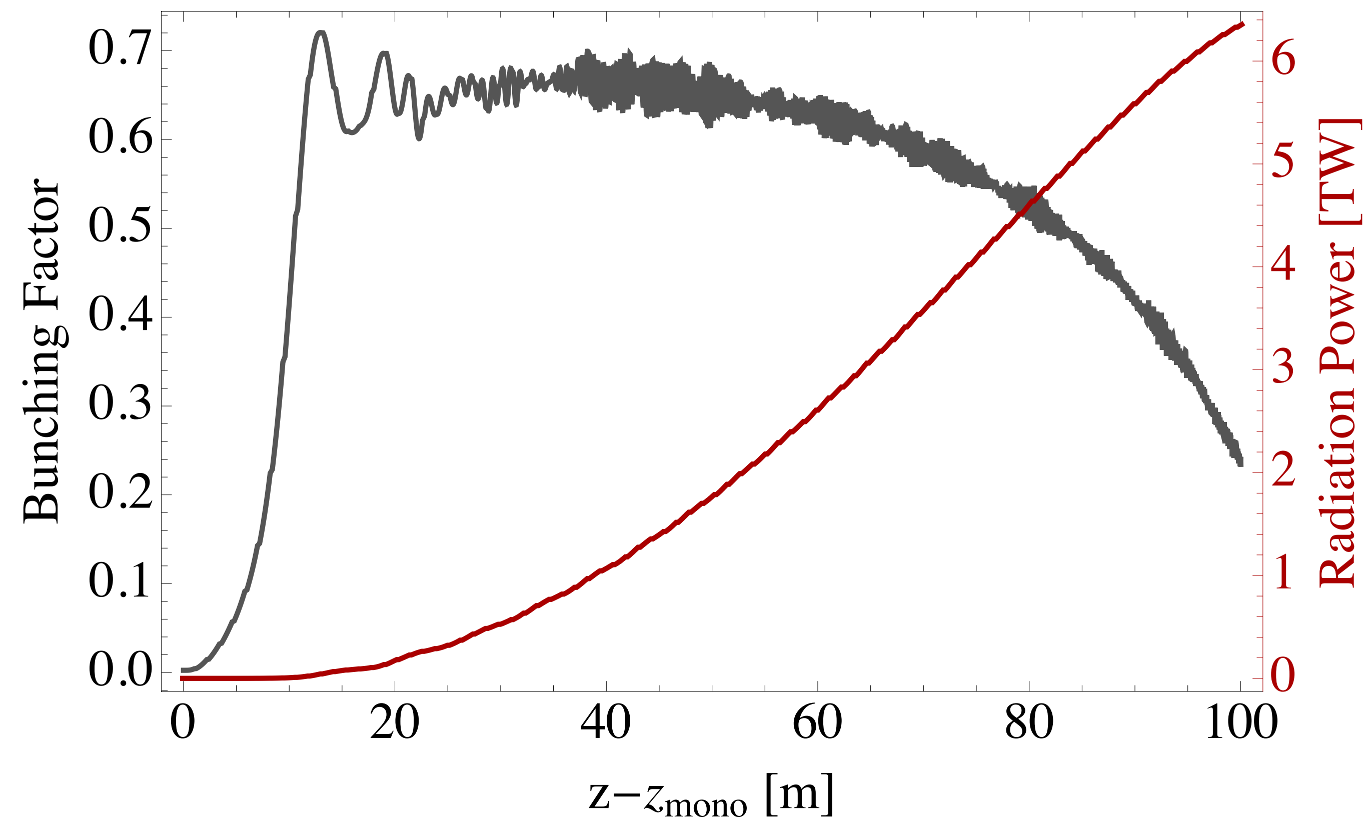
C. Emma *et. al.*, "High efficiency, multiterawatt X-ray free electron lasers", PRAB **19**, 2016

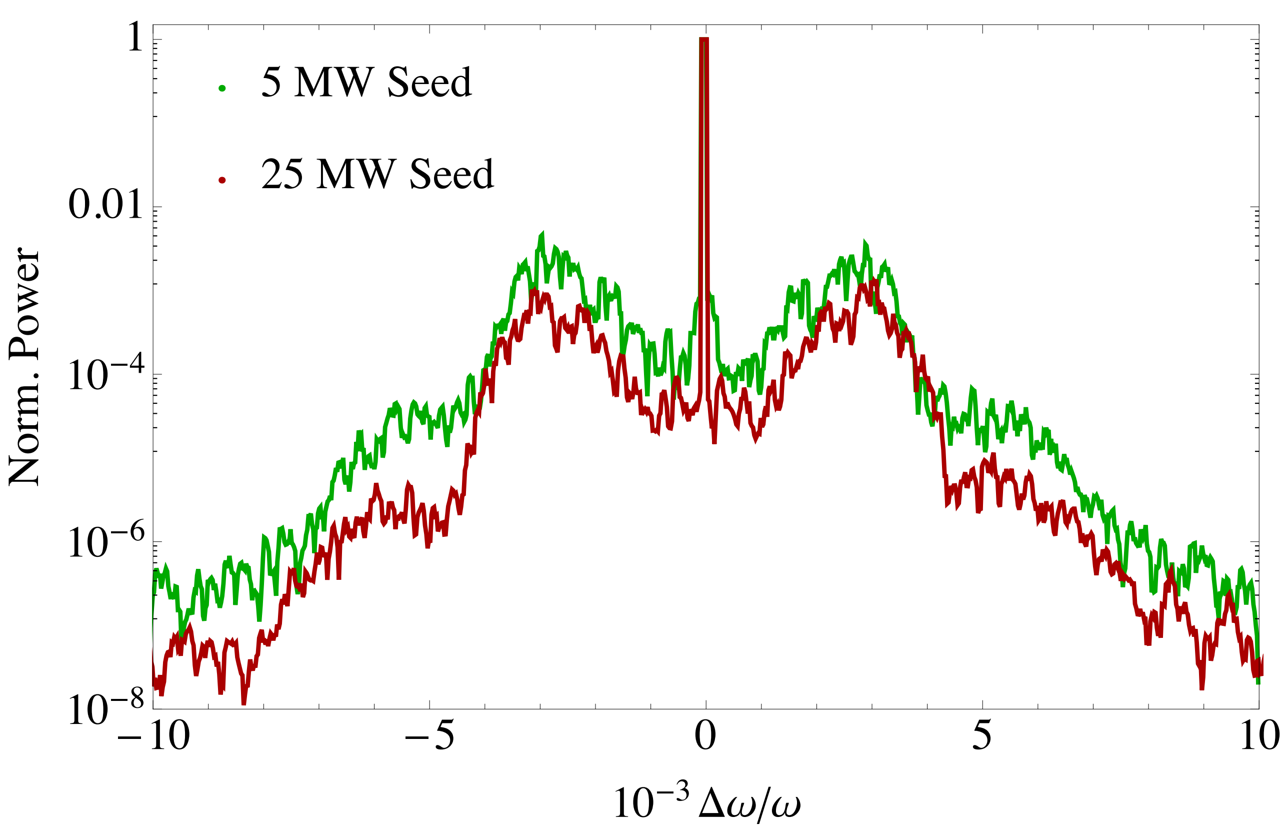
FBSS time dependent tapering optimization

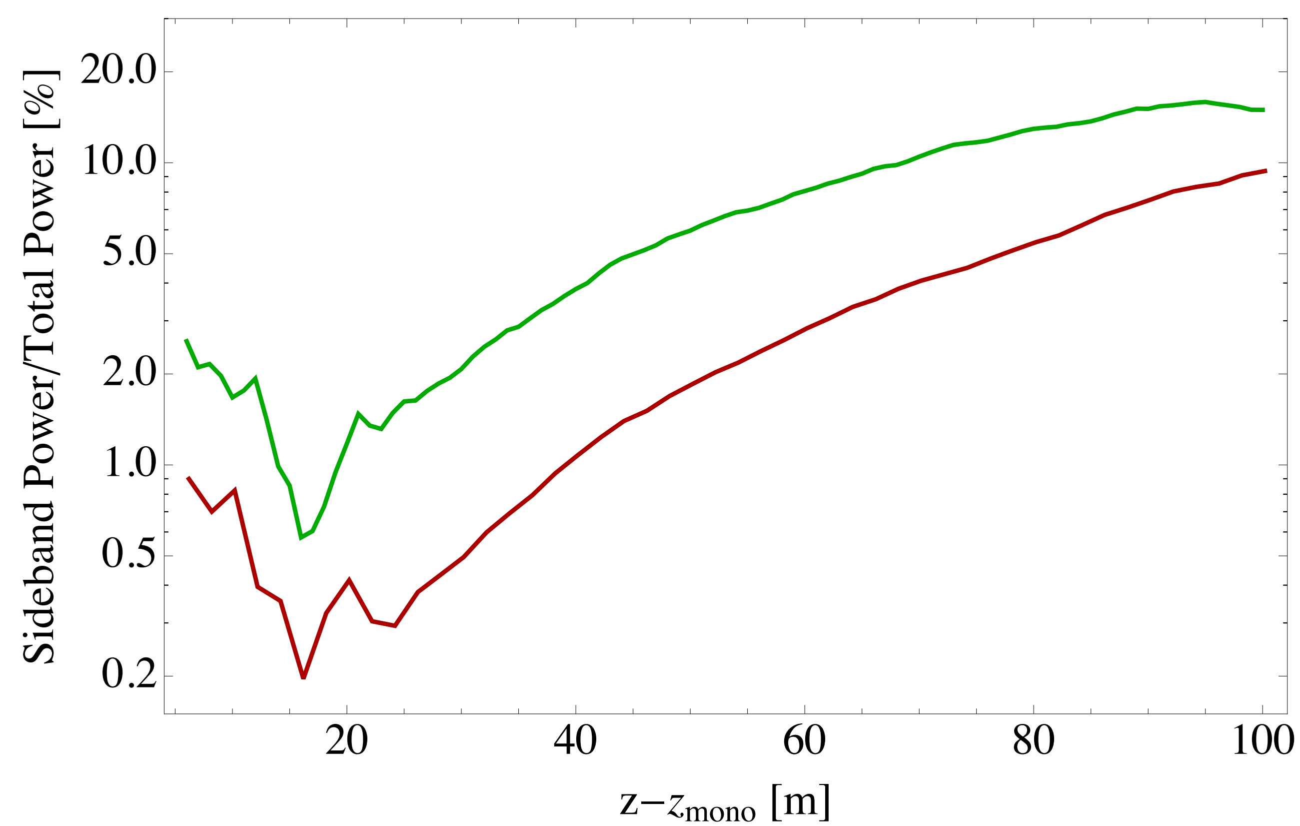
Simulation Cases:

5/25 MW seed with 1.5 MeV energy spread from linac

Efficiency=12%
Close to single-bucket value







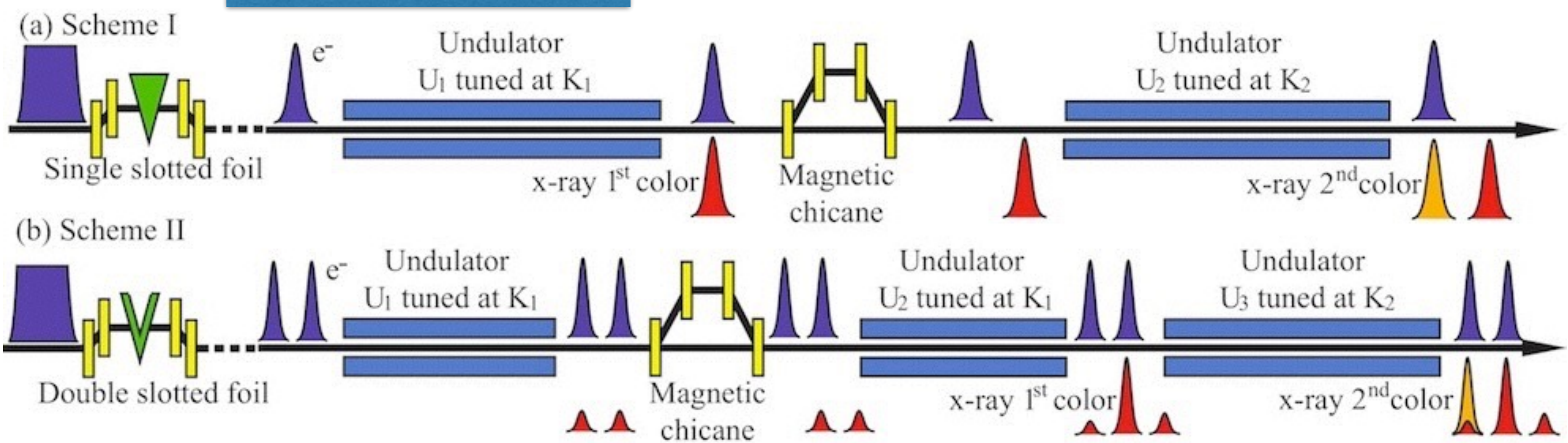
C. Emma *et. al.*, "High efficiency, multiterawatt X-ray free electron lasers", PRAB **19**, 2016

Conclusion and future goals

- Selective lasing suppression is a promising and versatile scheme for increasing the capabilities of current FELs.
- Control of SASE pulse duration, polarization and bandwidth separation has been recently demonstrated at LCLS.
- We used the technique to perform the first fresh bunch self seeding experiment at hard X-rays.
- We demonstrated the ability to increase the peak power to > 50 GW compared to regular seeding (~ 20 GW) and achieve short sub 10-fs pulses with narrow bandwidth increasing the brightness of the XFEL.
- 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 will include three stage selective lasing, three color SASE, superradiant pulse amplification etc…

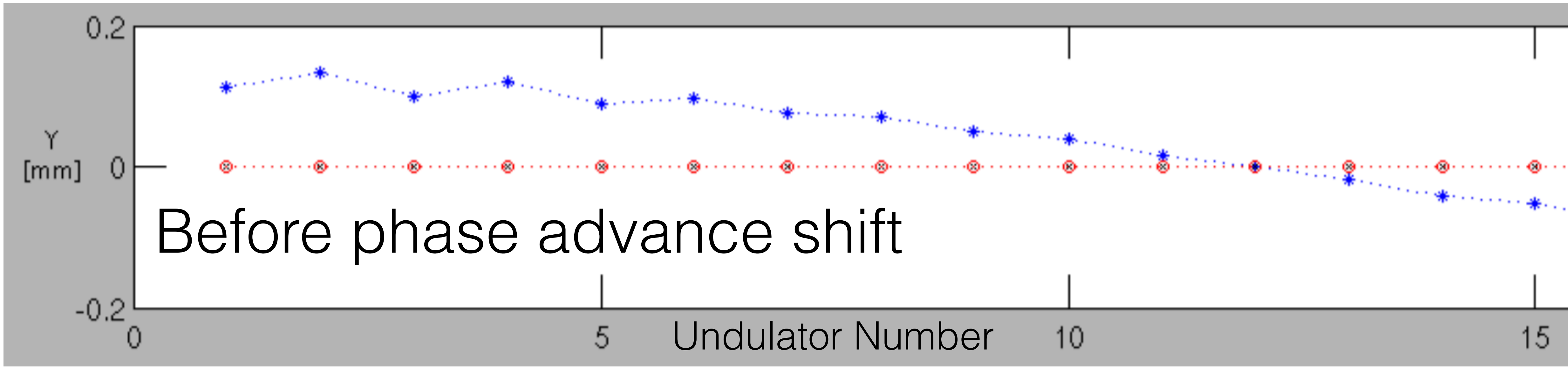
Original two-color scheme with/without delta

Variable pulse duration



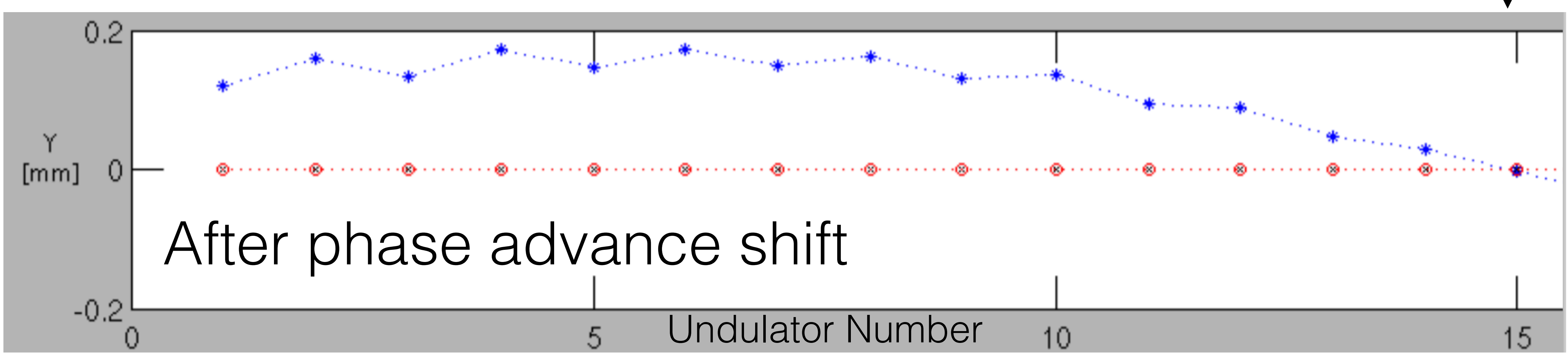
Variable delay

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

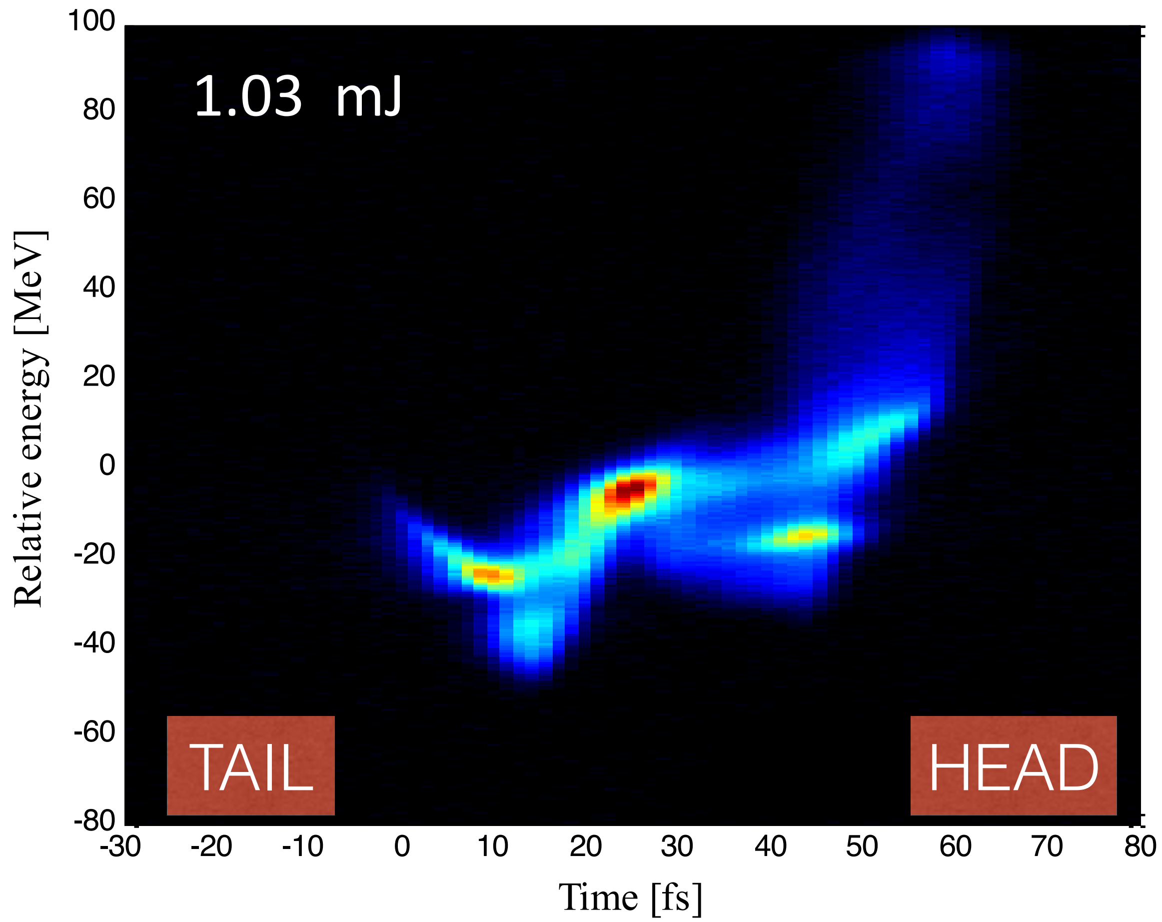
HXRSS



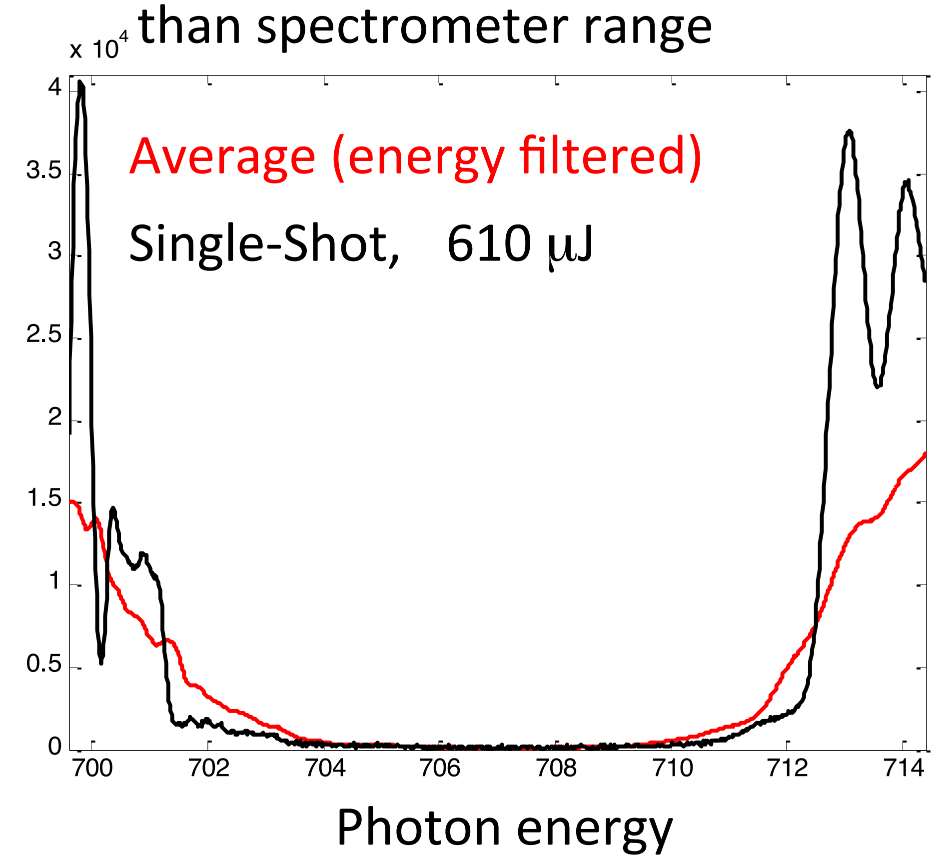
Fresh-Slice Two-Color experiment at 710 eV

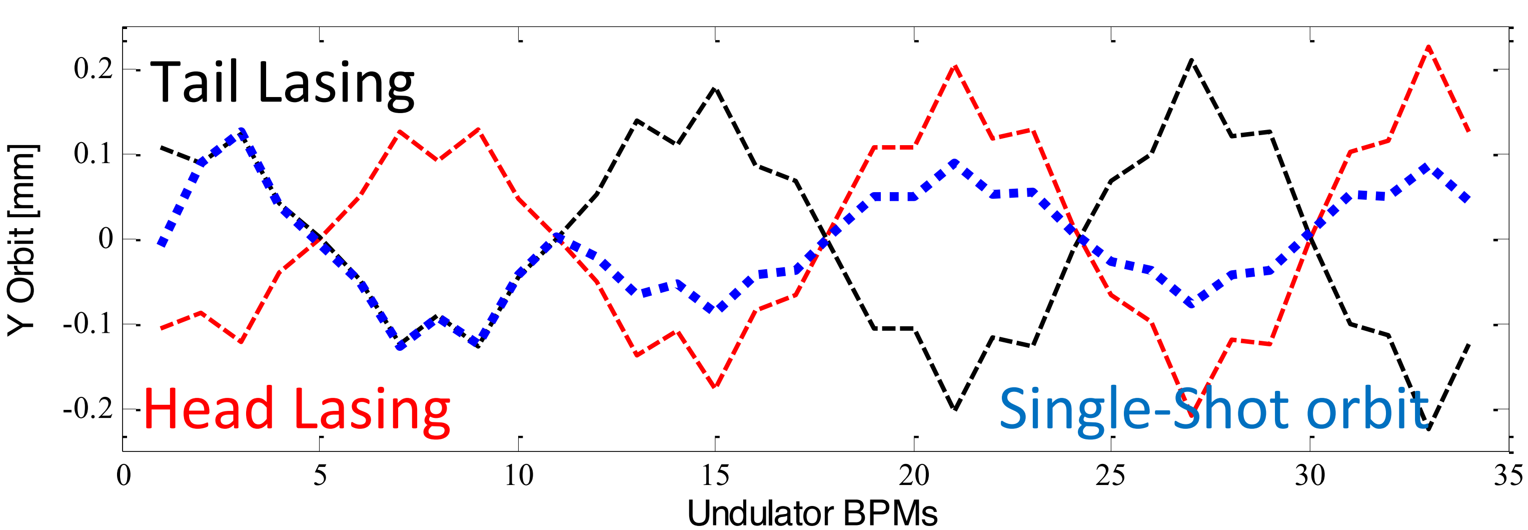
Dechirper	Gap	Offset
Vertical	3.5 mm	0.8 mm
Horizontal	OUT	/

Und.	Status	K value
1-8	IN	K~3.455, Strong Saturation taper from Und #6
10-25	OUT	/
26-33	IN	K~3.505 Variable Taper (Regular/Reverse)



Spectrum, color separation larger than spectrometer range



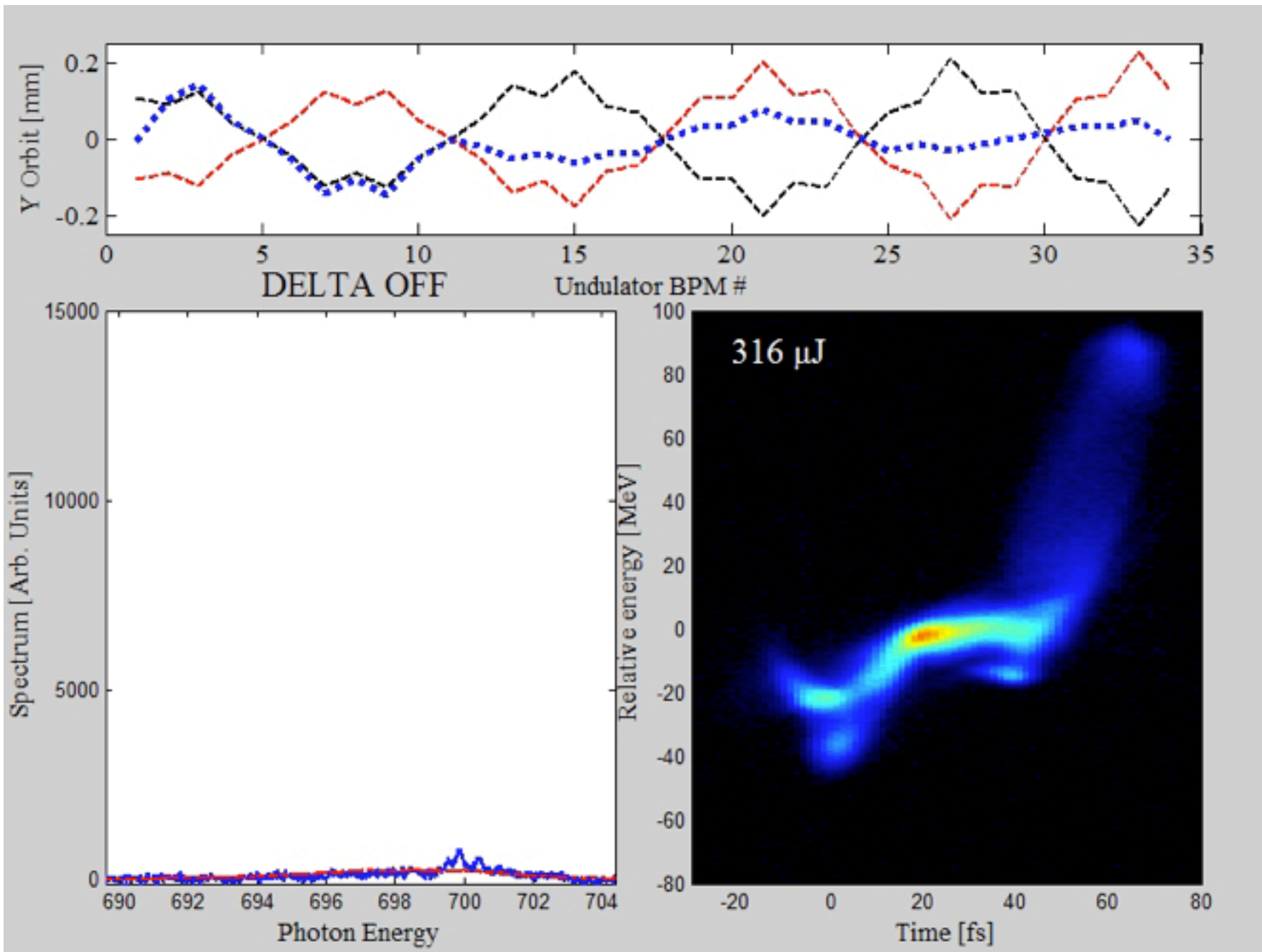


~ 250 uJ in the pump pulse

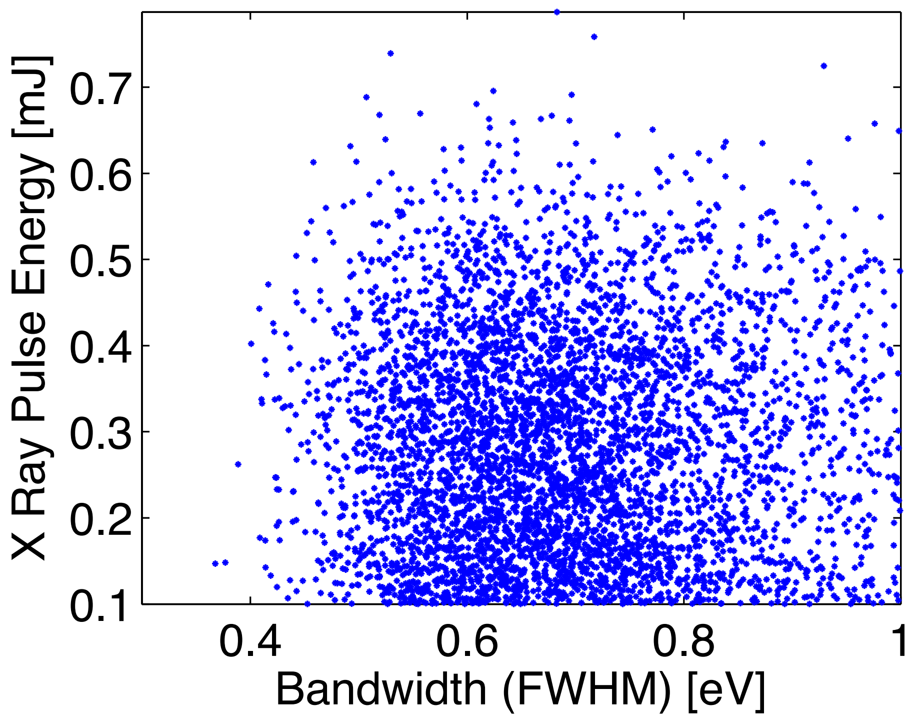
~ 500 uJ in the probe pulse

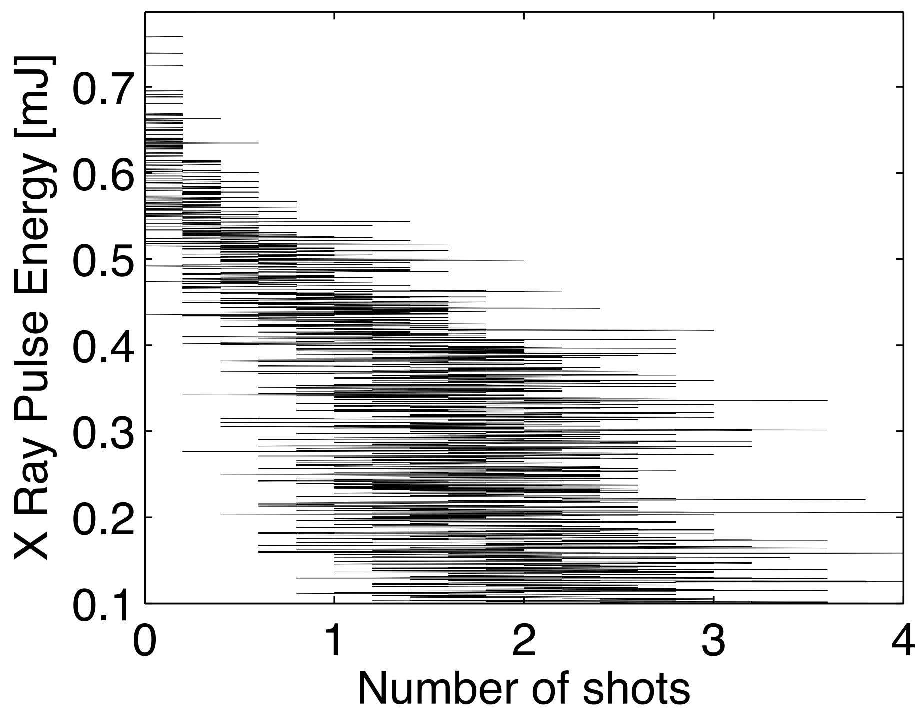
A. Lutman

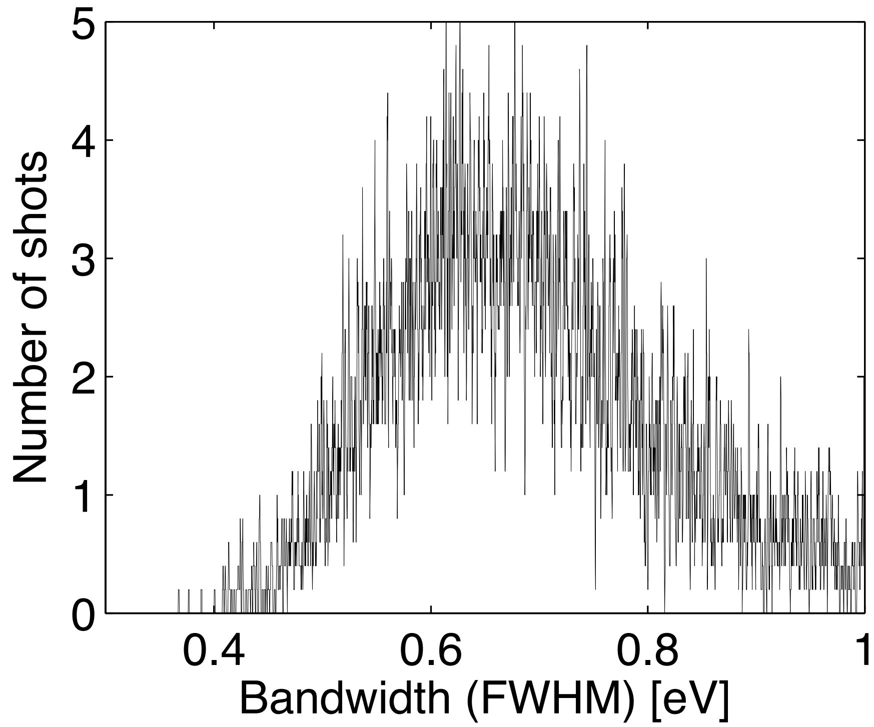
Polarization control experiment with delta



X-Ray Pulse Energy and b.w. filtering







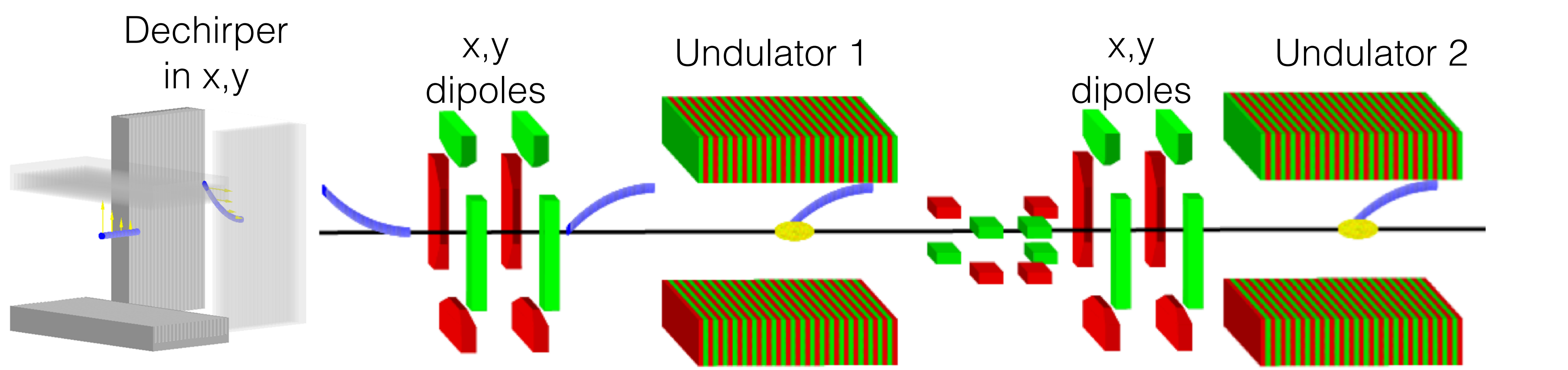
Filtered for good shots with energy >100uJ and for b.w. < 1 eV

Mean b.w. for "good shots" = 0.687 eV

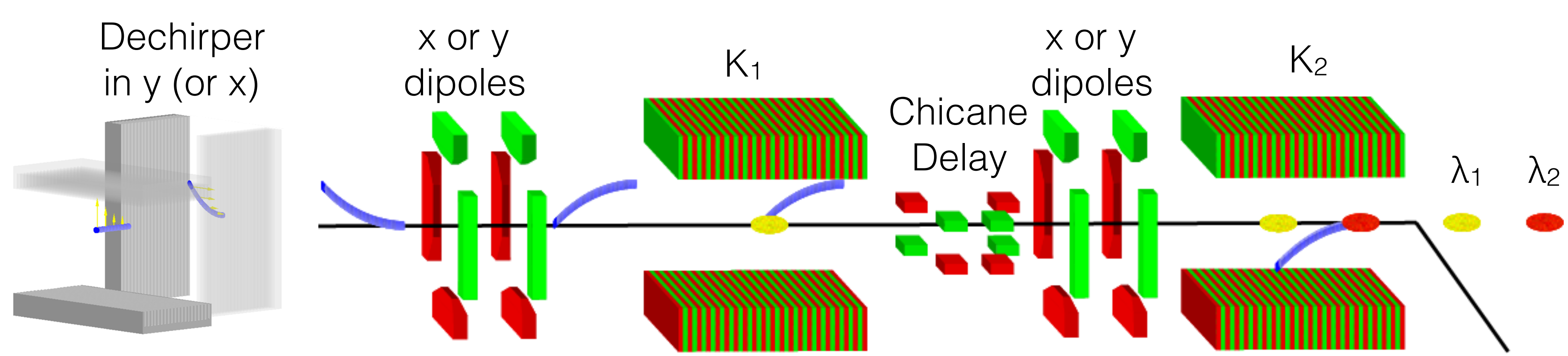
Mean energy for "good shots" = 290 uJ

Dechirper as a fast passive kicker: experimental uses

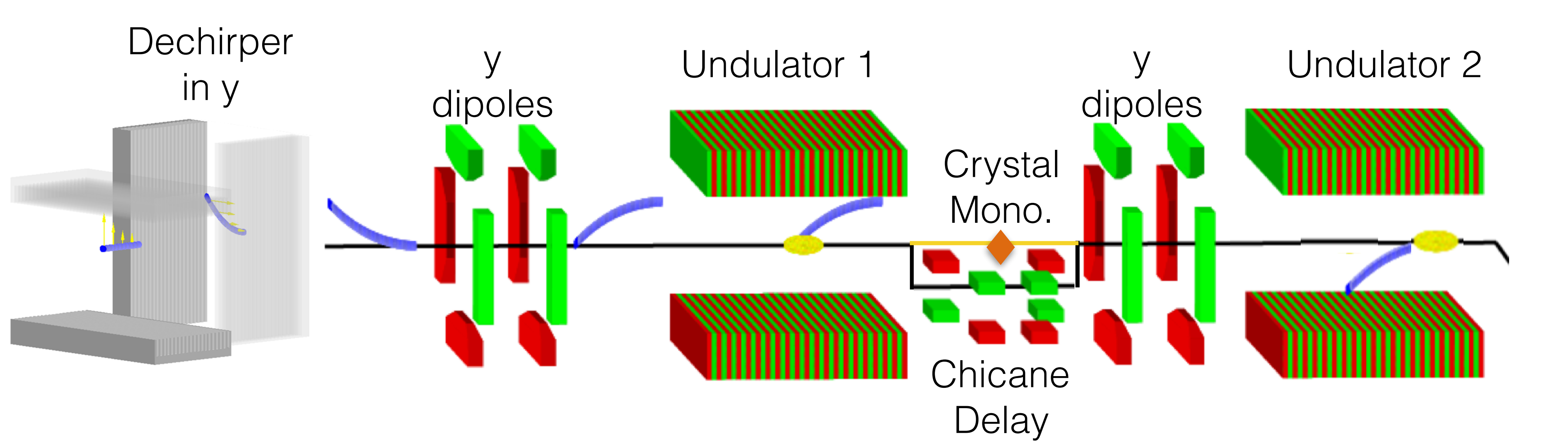
1) Fresh slice SASE for control of pulse duration



2) Two-color fresh slice SASE with polarization control

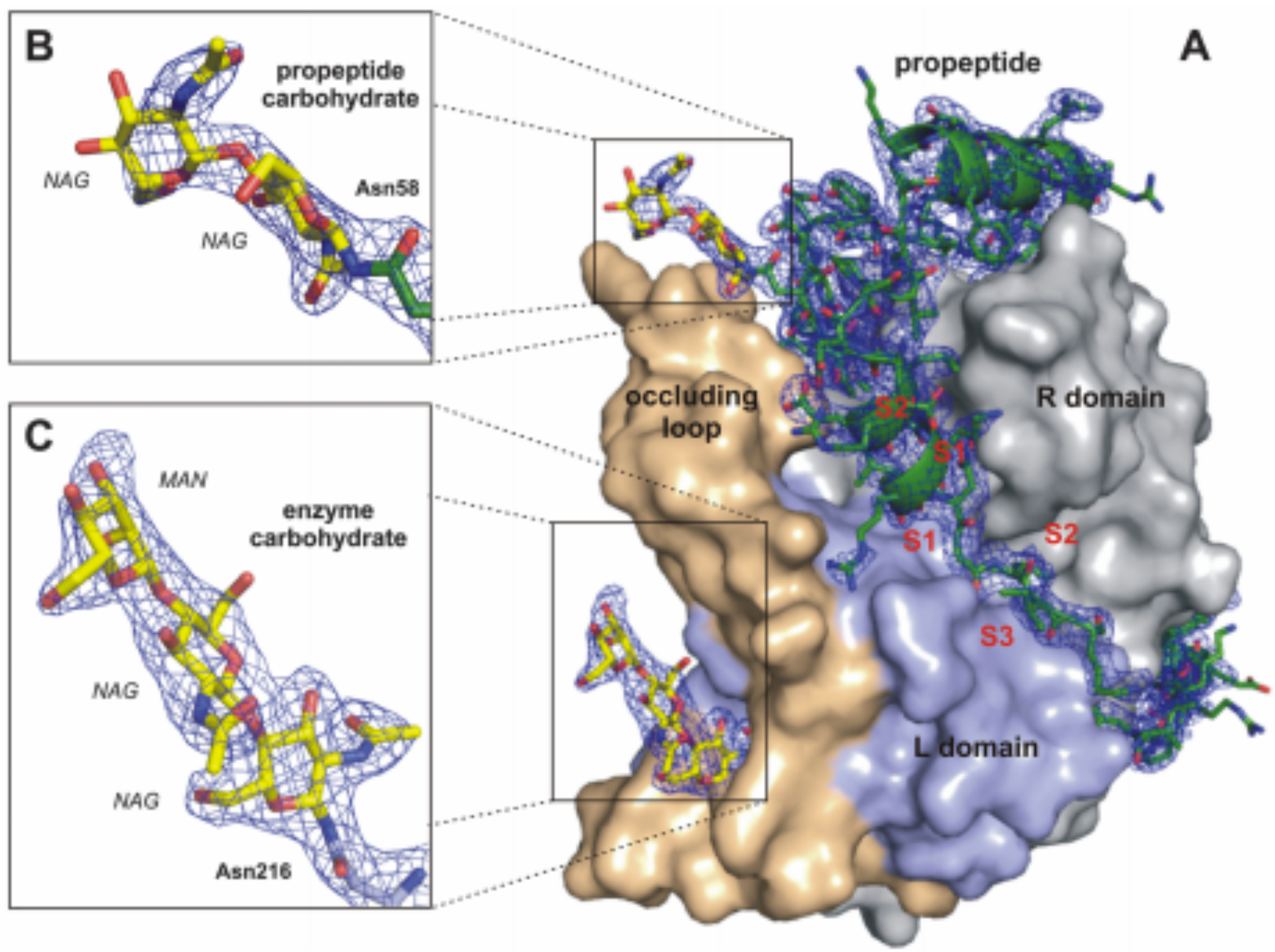


3) Fresh bunch self-seeding with high intensity short seeded pulses



Pushing the imaging frontier

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



2.1 A resolution
Trypanosoma brucei cysteine protease cathepsine B

Single Molecule Imaging Goal
20 fs - 20 mJ - 2020

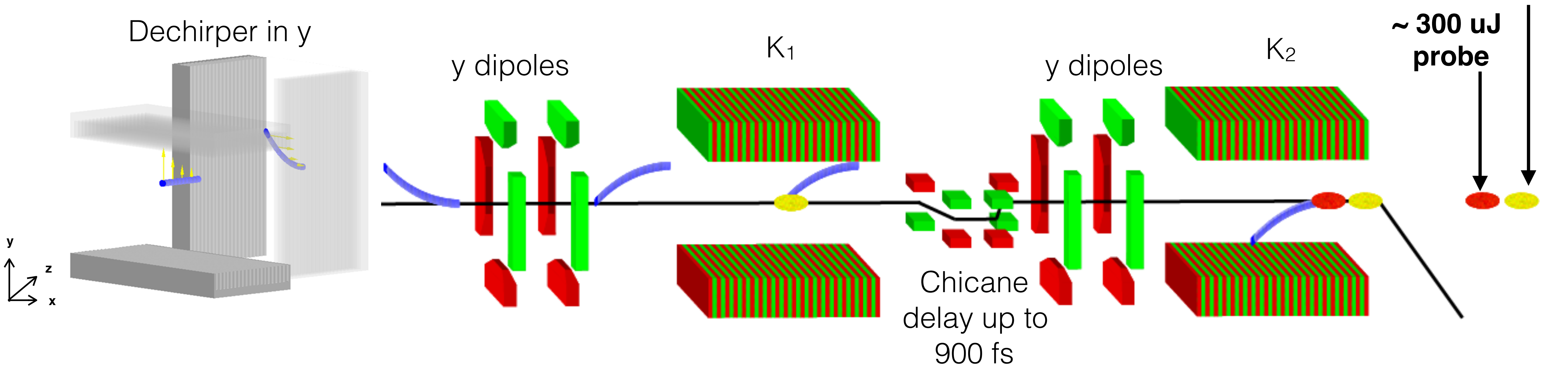
Angstrom scale X-ray diffraction experiments have been performed successfully at LCLS

Resolution improves with higher photon energy & shorter pulse duration reduces radiation damage

Achieving ~ 20 fs pulses with 2 x 10^{13} photons/pulse allows single molecule imaging

Need TW X-FELs

Fresh slice SASE: two color scheme

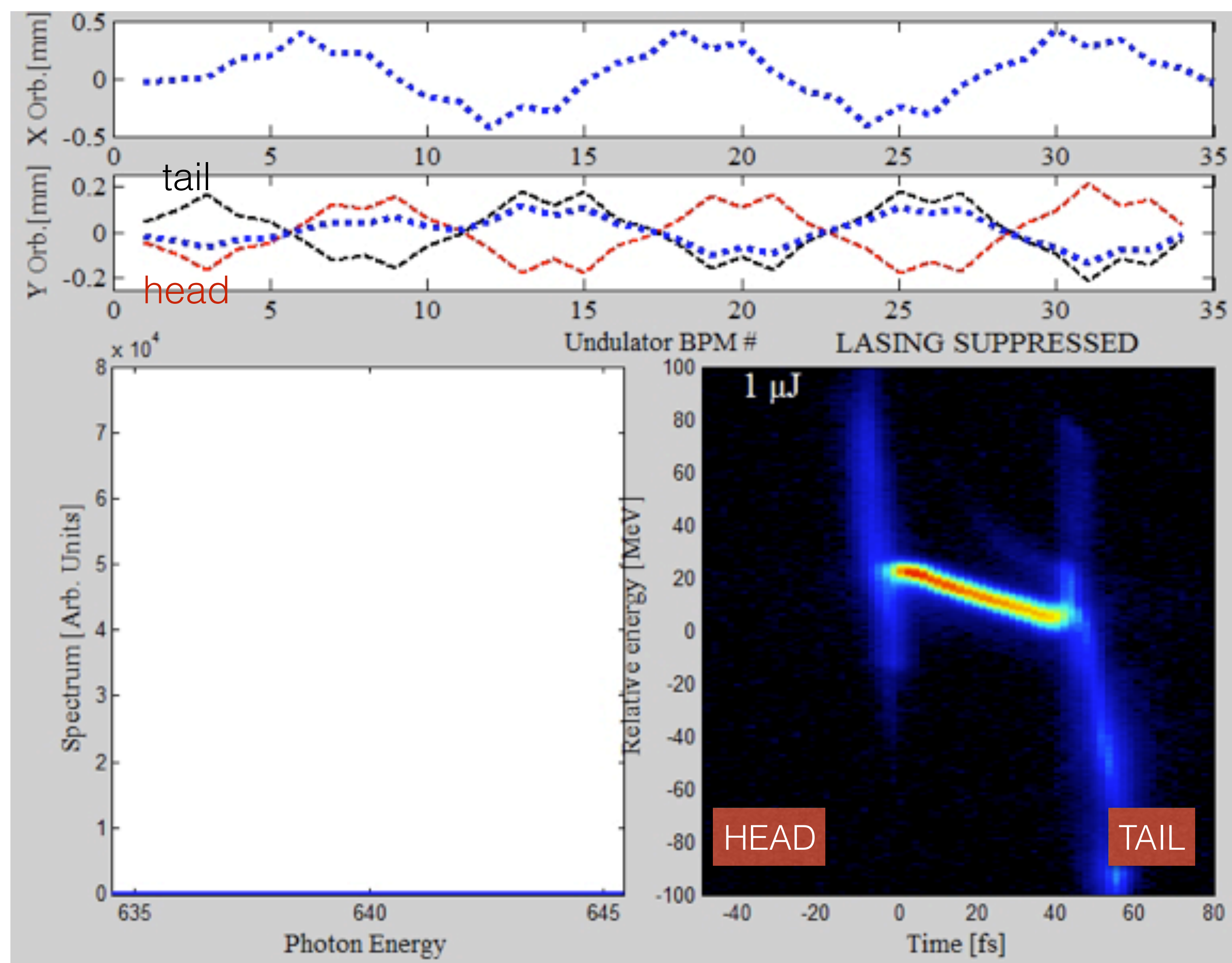


Advantages over previous two-color scheme

- ✓ Allows true zero delay
- ✓ Both colors can saturate
- ✓ Allows polarization control of the probe
- ✓ Simple delay scans (chicane only)
- ✓ Simple color scans (undulator K)
- ✓ Independent pointing

In the undulator section:

- ❖ Dipoles correct the orbit for tail-lasing before 1st undulator
- ❖ 1st undulator section tuned at K_1 makes FEL on the tail of the beam
- ❖ Chicane can delay the electrons with respect to the first X-ray pulse (up to 900 fs)
- ❖ Dipoles after 1st undulator section correct the orbit for the head
- ❖ 2nd undulator section tuned at K_2 makes FEL on the fresh head of the beam



A. Lutman, unpublished