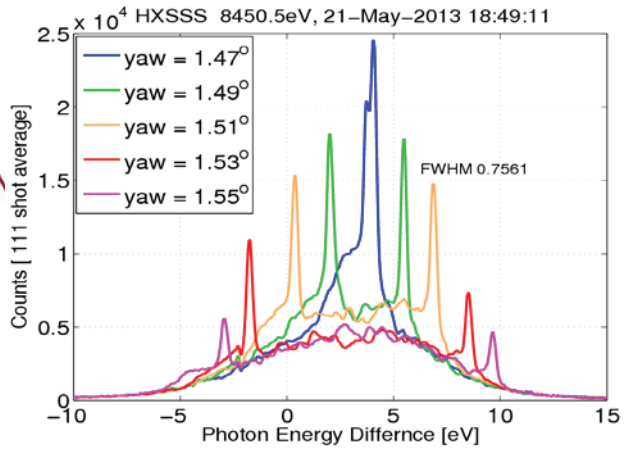
Two-Color Lasing with LCLS



Franz-Josef Decker 29-Aug-2013

Thanks to:

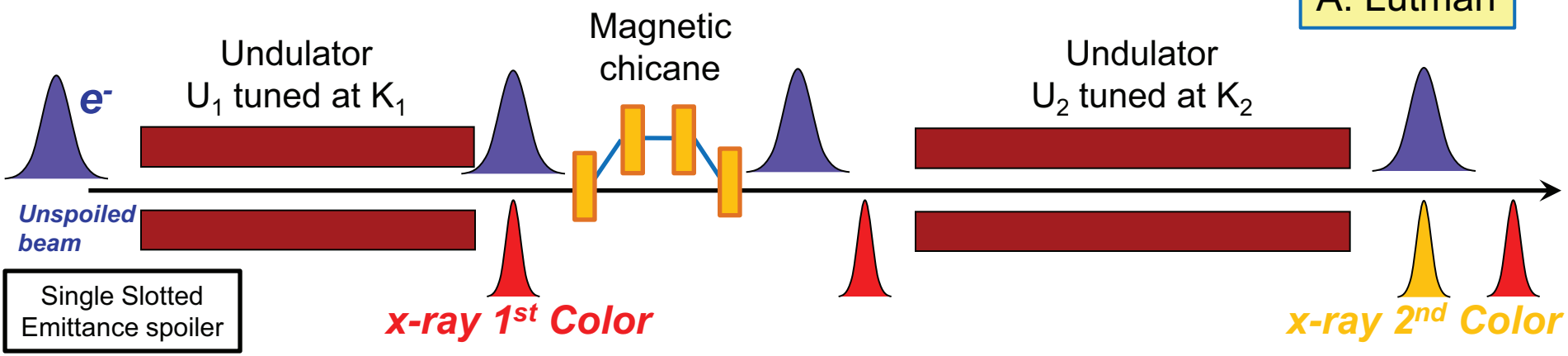
A. Lutman, A. Marinelli, Y. Ding, J. Welch, J. Turner, Z. Huang, J. Hastings, R. Coffee, S. Wakatsuki

Talk Overview Two-Color

- How to get two colors: $\lambda_L = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$
- **Four different generation schemes** (plus combinations):
- SASE two undulators K_1 and then K_2
  - Tunable: color, delay, pulse duration
- ISASE interleaving K_1 and K_2 (zero delay)
- Two-Color Self Seeding $\Delta\lambda_{Laser}$
- Energy distribution with two peaks $\Delta\gamma$ (or two electron beams +delay)
  - Slotted foil
  - Low L1X amplitude (found accidentally)
  - Double pulse ("bunchlets") with staggered Laser
- [$\Delta\lambda_u$?]

Two-Color X-ray SASE FEL

A. Lutman



- Single slotted foil controls the pulse duration
- K_1 and K_2 control the output wavelengths
- Magnetic chicane controls the delay between the pulses

+ Easy to set up

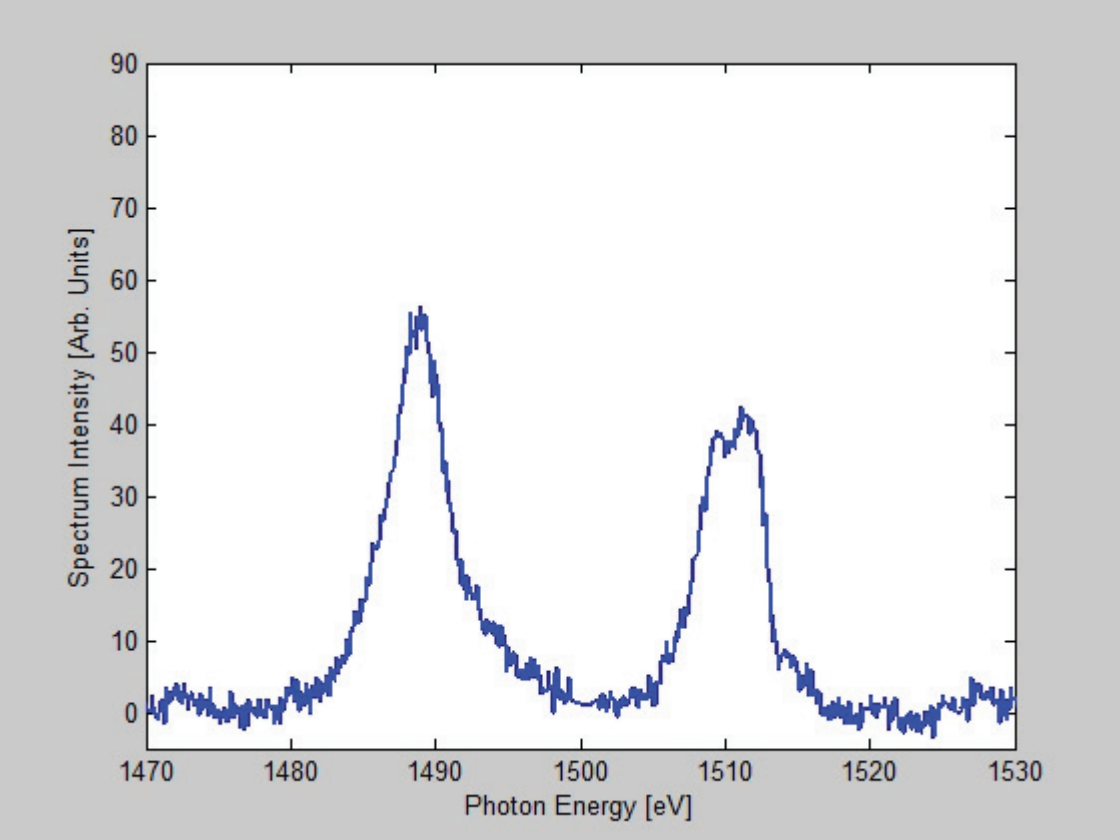
+ Pulse duration, output wavelength and delay between pulses are independently controlled

- Color 1 cannot achieve saturation

A. Lutman, Y. Ding, R. Coffee, Z.Huang, J.Krzywinski, T. Maxwell, M. Messerschmidt, H.-D. Nuhn,
Phys. Rev. Lett. 110, 134801 (2013).

Experimental Results (i)

Two-Color Beam on SXR Spectrometer



Chicane delay 0 fs

Pulse Duration ~ 18 fs FWHM

1st sec. length: 9 Undulators
2nd sec. length: 10 Undulators

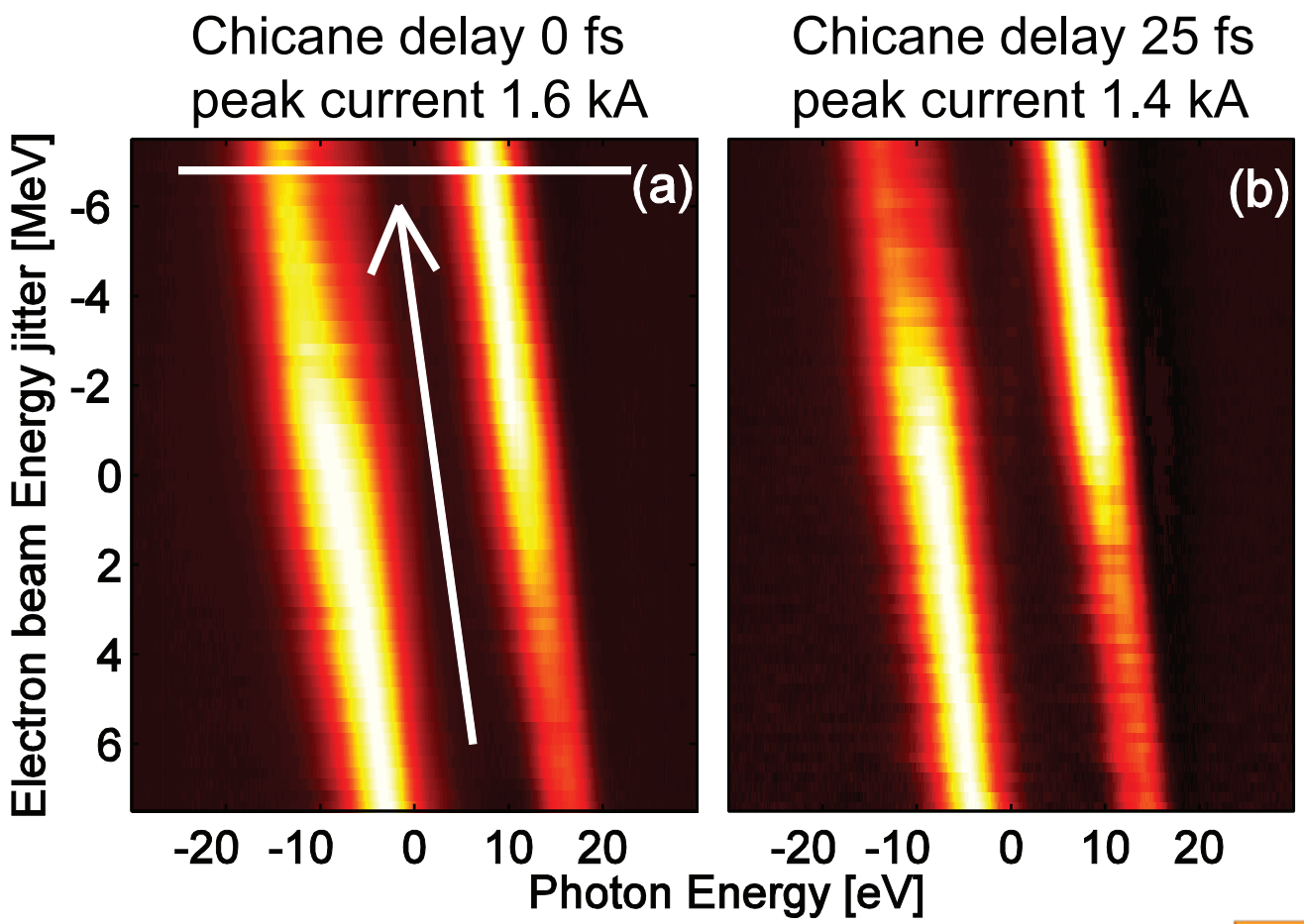
Photon Energy 1.5 keV

Beam Charge: 150 pC

Colors distance 19 eV

Data from the SXR spectrometer using the 100 lines/mm grating

Experimental Results (ii)



Color 1	Color 2
K_1 low	K_2 high
Higher energy	Lower energy

Central electron beam energy: 5800 MeV

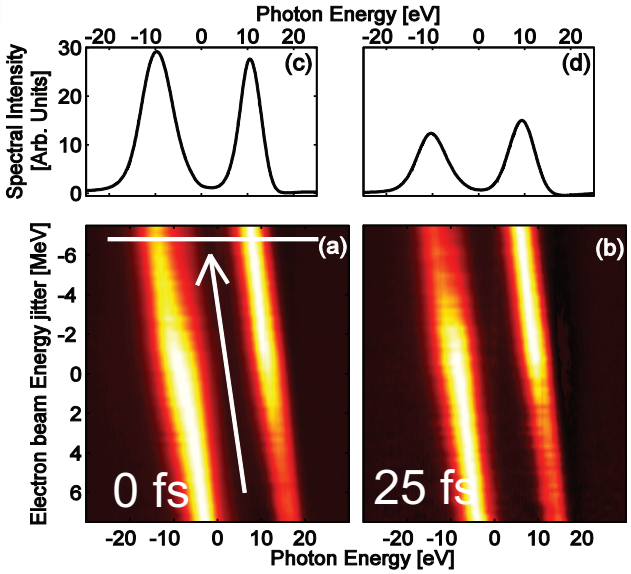
Central photon beam energy 1.5 keV

Pulse Duration ~ 18 fs FWHM

Photon energy is linearly correlated with the electron beam energy; the distance between the two colors is fixed

Color Separation ~19 eV

Experimental Results (iii)

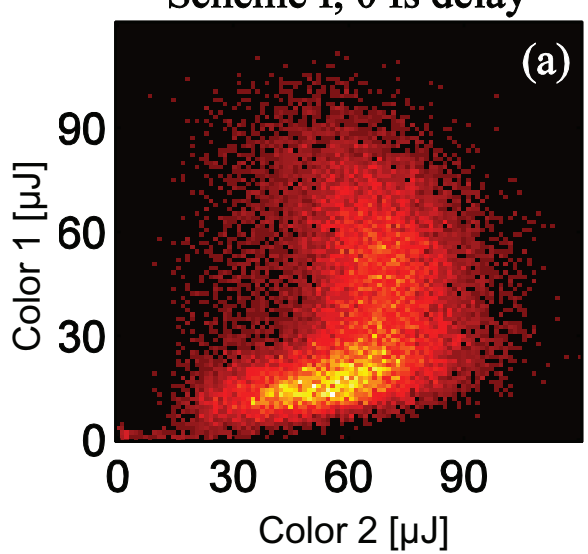


delay	color	avg	fluct	BW fwhm
0 fs	Color I	40 uJ	60%	5.5 eV
	Color II	60 uJ	30%	8.2 eV
25fs	Color I	20 uJ	58%	6.5 eV
	Color II	25 uJ	36%	7.7 eV

Correlation between the two different Colors

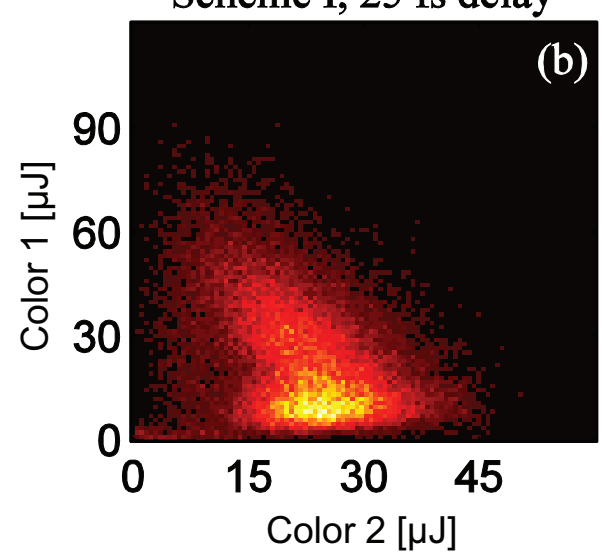
Peak current: 1.4 kA

Scheme I, 0 fs delay

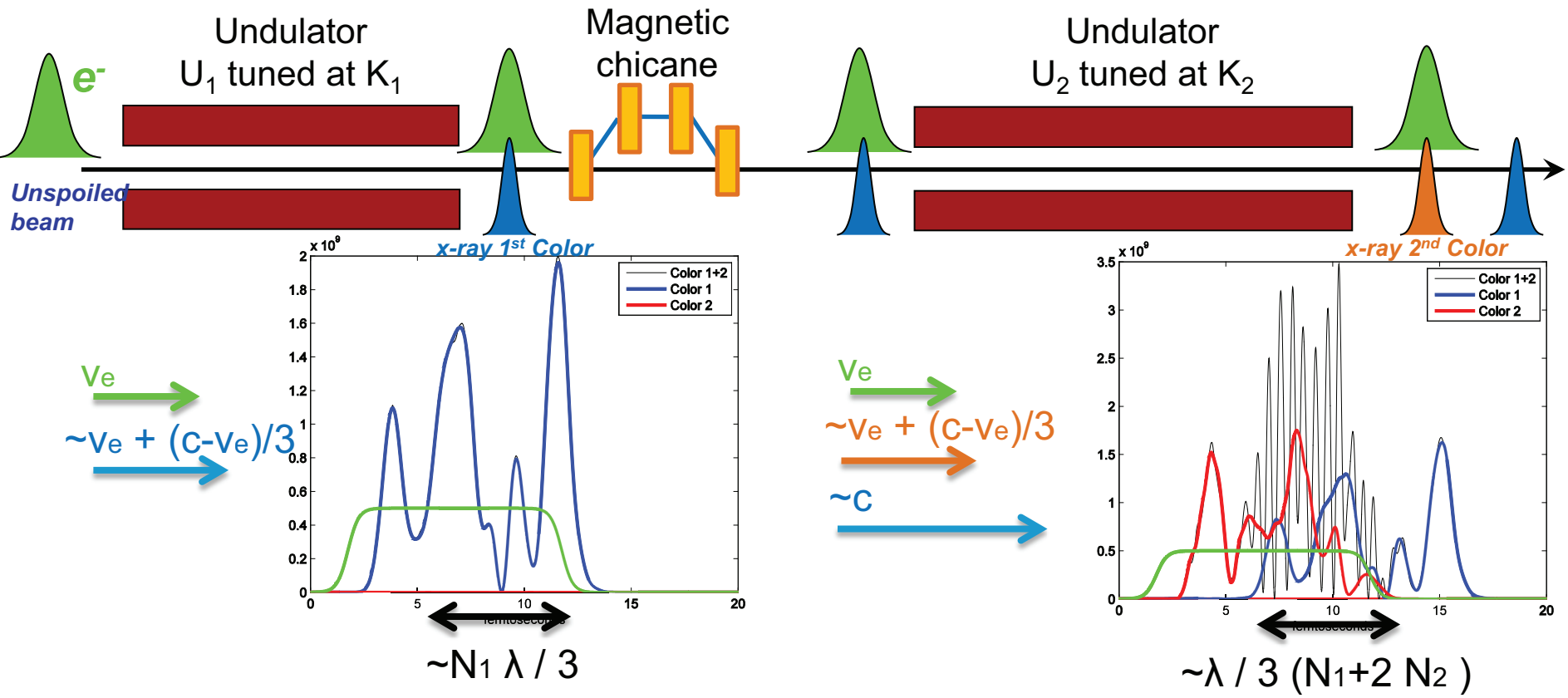


Peak current: 1.6 kA

Scheme I, 25 fs delay



Minimum Delay between Pulses (Chicane off)



Two-Colors delay ~ N λ , N undulator periods in a single section ($N_1 = N_2$)

@ 532 eV	**~ 850 as / undulator**	**(9 undulators) ~7.6 fs**
@ 8.3 keV	**~ 54 as / undulator**	**(15 undulators) ~800 as**

Two-Colors FEL – Beyond Scheme I

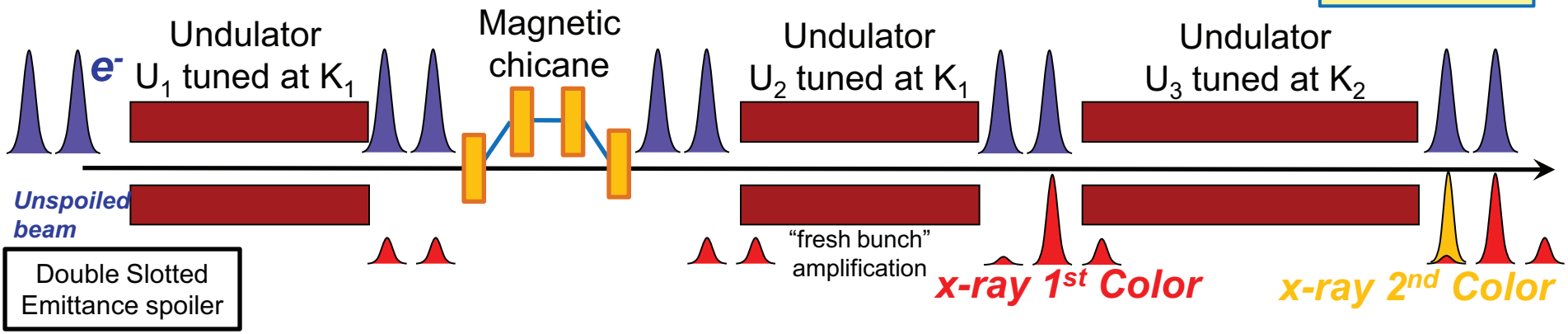
SLAC

What we want to improve:

- Saturating both colors
- Allowing for true zero delay between the pulses also for longer wavelength SXR.
- Closer source points
- Much narrower bandwidth

Two-Color X-ray FEL – Scheme II

A. Lutman



- Distance between slots controls delay between pulses
- K_1 and K_2 control the output wavelengths
- Magnetic chicane must delay the head unspoiled electrons on the trailing photons

+ Color 1 can reach saturation

- More difficult to set up

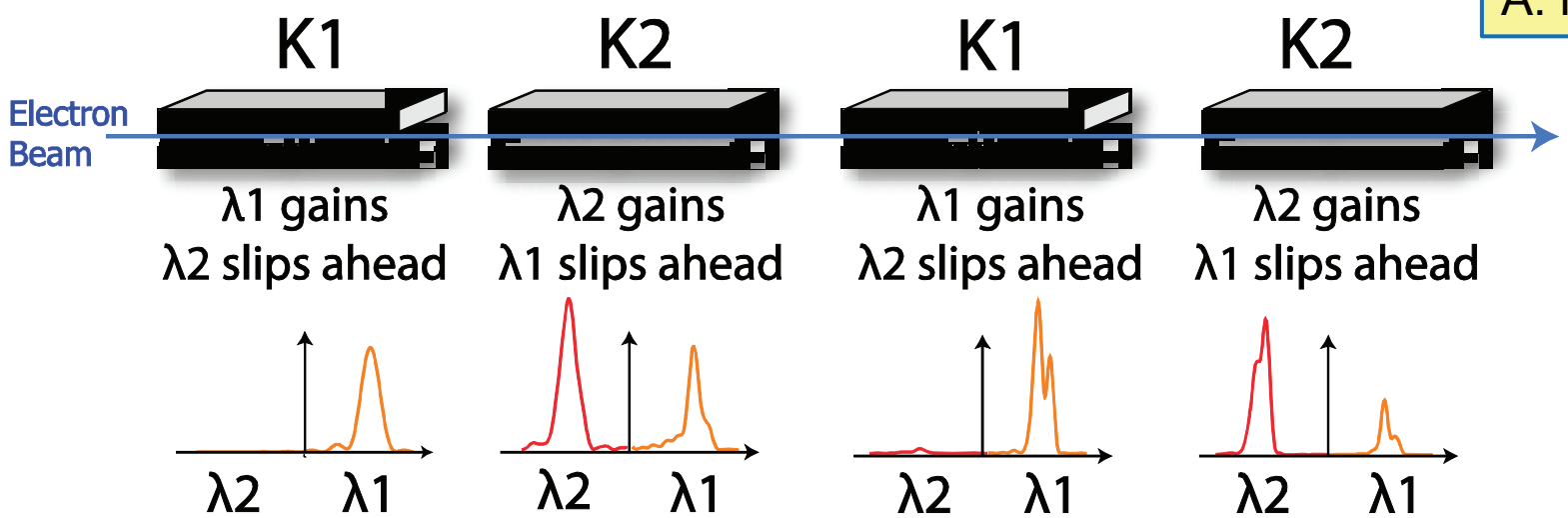
- Minimum delay imposed by the distance between the slots

- Maximum delay imposed by the electron bunch length

A. Lutman, Y. Ding, R. Coffee, Z.Huang, J.Krzywinski, T. Maxwell, M. Messerschmidt, H.-D. Nuhn,
Phys. Rev. Lett. 110, 134801 (2013).

Two-Color iSASE

A. Marinelli



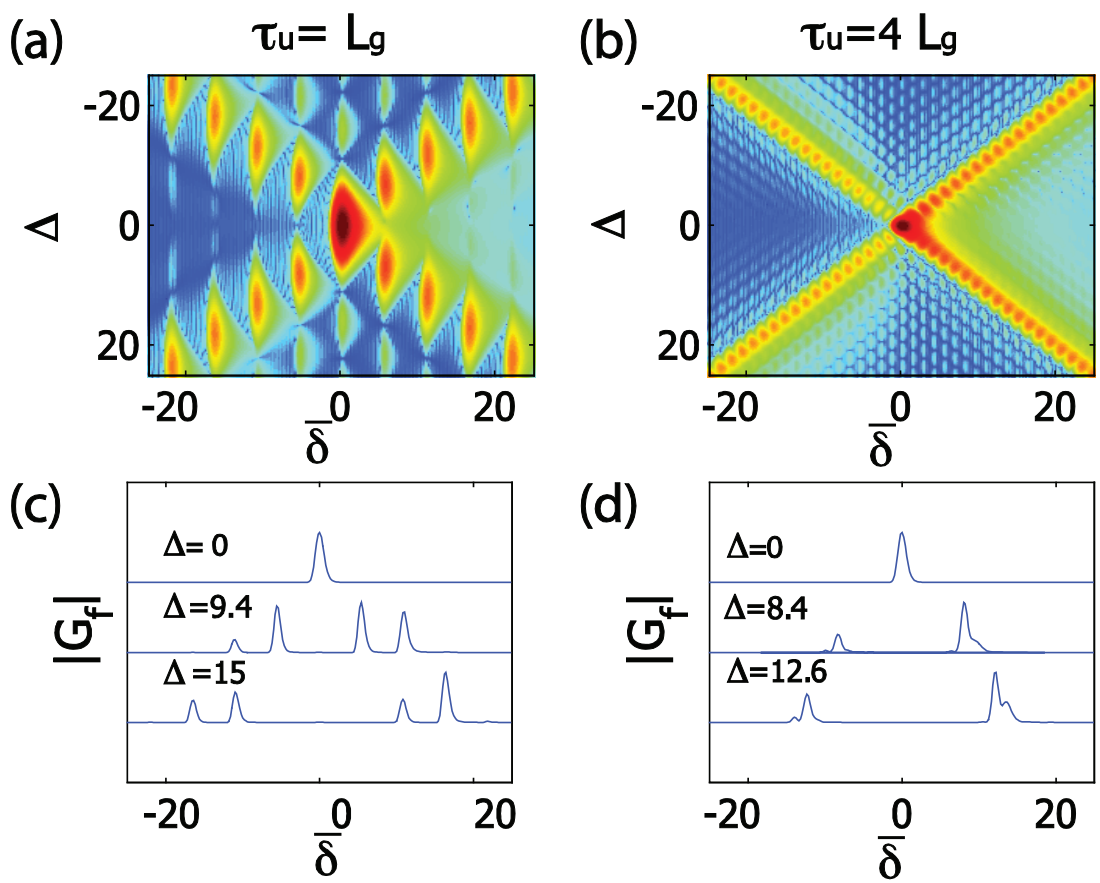
Alternating K1 and K2, instead of simply detuning gives a Two-Color scheme instead of simple bandwidth reduction

For K1 = K2 it is the regular SASE

K1 ≠ K2 gives 2,3,4 colors configurations, depending on the phase advance.

A. Marinelli, A. Lutman, J. Wu, Y. Ding, J. Krzywinski, H. D. Nuhn, Y. Feng, R. Coffee, C. Pellegrini, Phys. Rev Lett, 2013 (In production).

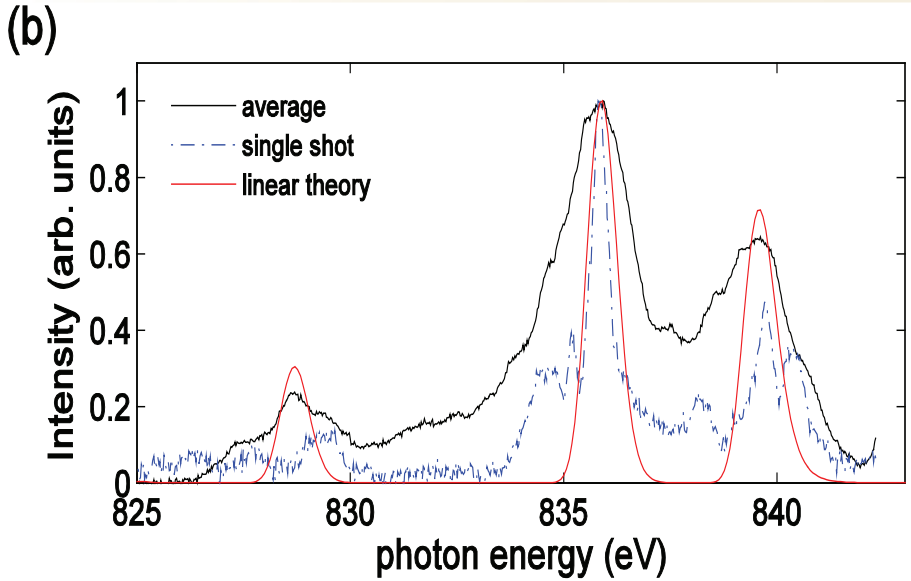
iSASE Simulations

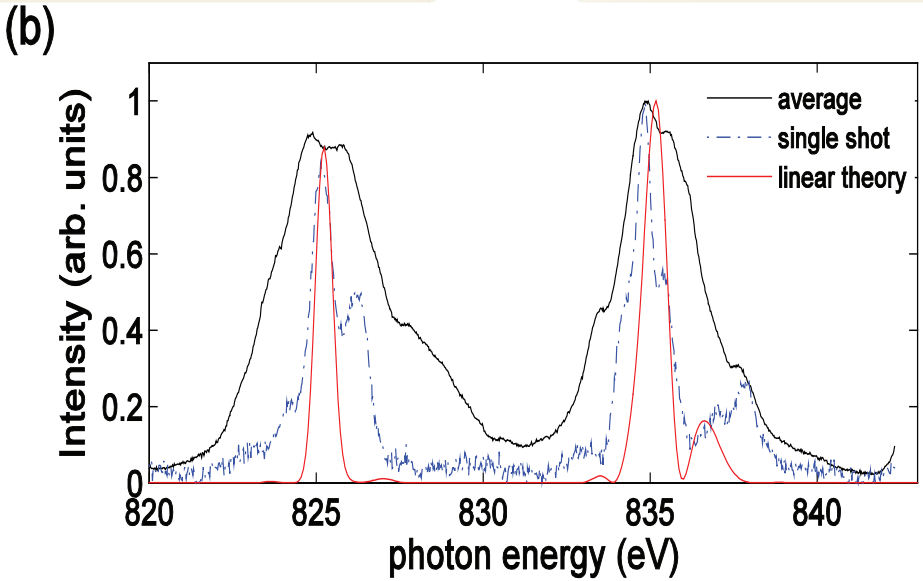


Gain vs Detuning for different color separation… (normalized to rho)

Spectral peaks around multiples of modulation periodicity…

Experimental Data





Alternating **every other** undulator:
3 spectral lines
Sidebands are clearly seen

Alternating **every other 3** undulators:
2 spectral lines

+ Can generate true <u>overlapped</u> Two-Color pulses also in the long wavelength SXR
+ Source points for the two different colors are closer

- Harder to tune up compared to scheme I
- Time delay is not controllable

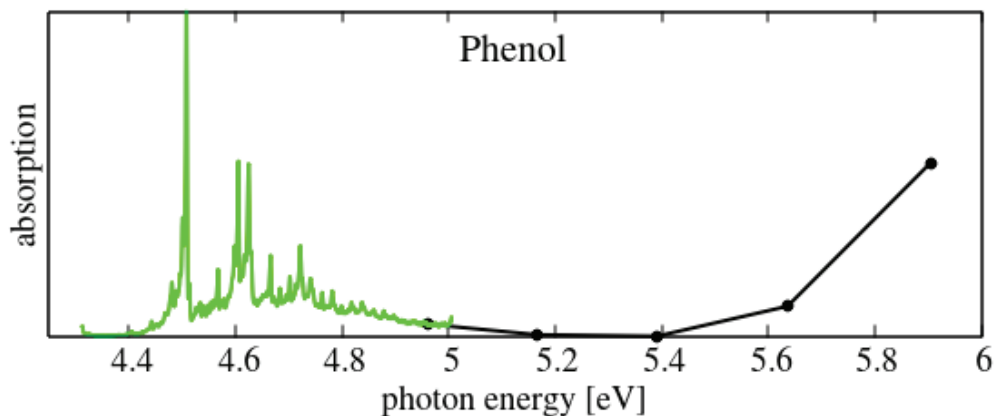
Molecular Science

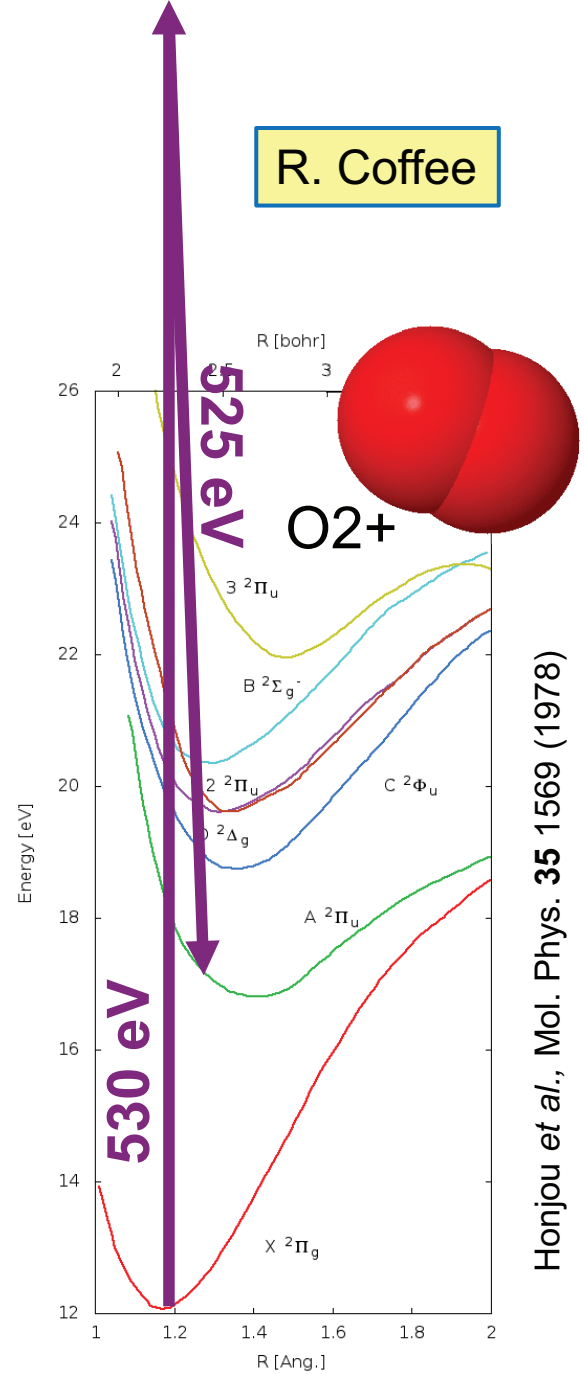
R. Coffee

Stimulated RIXS gives correlated electron motion in femtosecond timescale C, N, O

- *K*-shell resonances in 250 – 540 eV range
- Electronic excitations ~ 5 – 10 eV

We want 5 – 10 eV color separations in the vicinity of C, N and O resonances



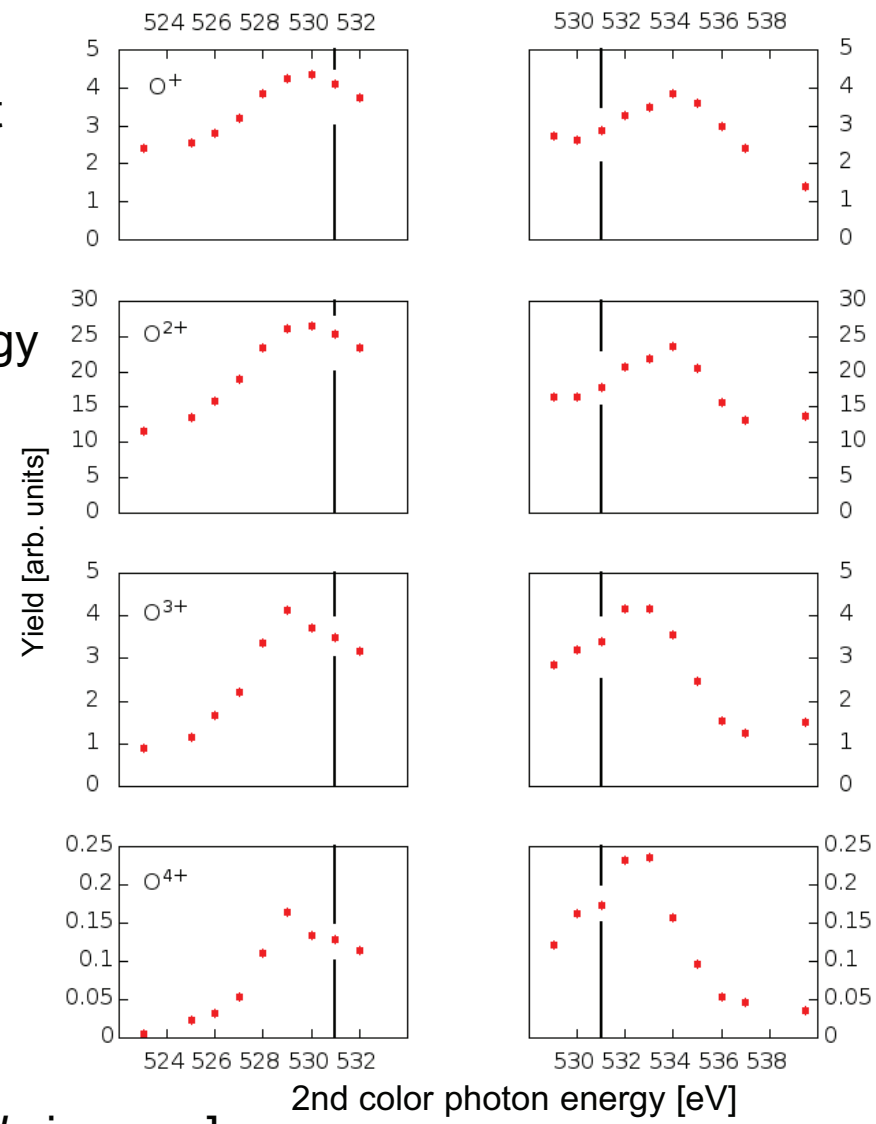


Honjou *et al.*, Mol. Phys. **35** 1569 (1978)

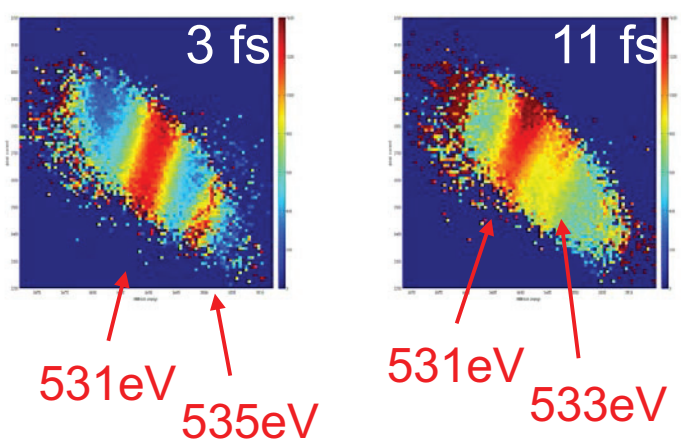
2-color operation
531 eV + 534 eV

Preliminary O2 results

Expect a ~535 eV resonance for very short delays
Resonance should change as molecule dissociates on 10 fs time-scale
FEL fluctuations sample the time and energy phase space

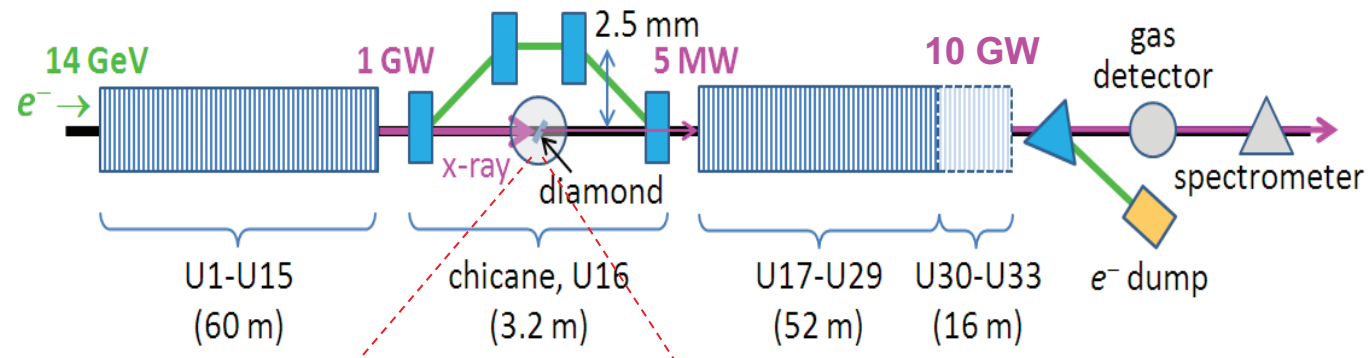


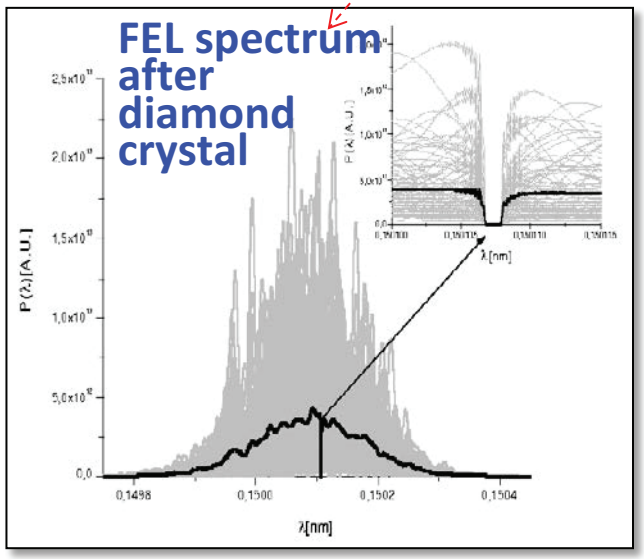
O++ counts
fluctuating FEL phase space

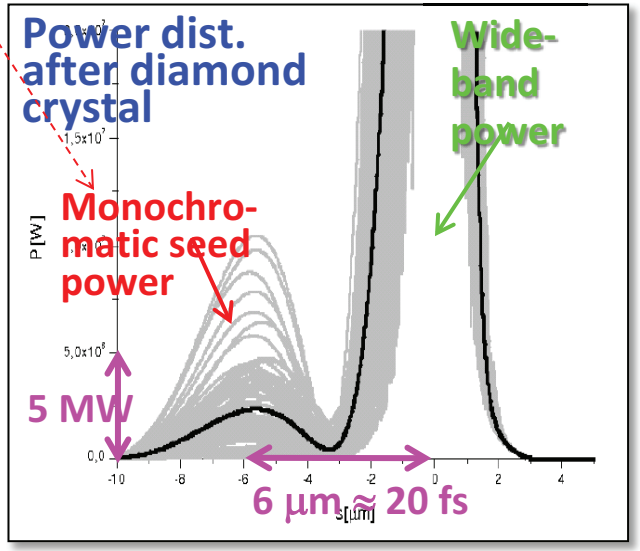


[Coffee *et al.*, in prep.]

HXR-Self Seeding







HXR Self Seeding demonstrated in 2012

J. Amman et al., Nat. Photon. 6, 693

Geloni, Kocharyan, Saldin, *DESY 10-133*

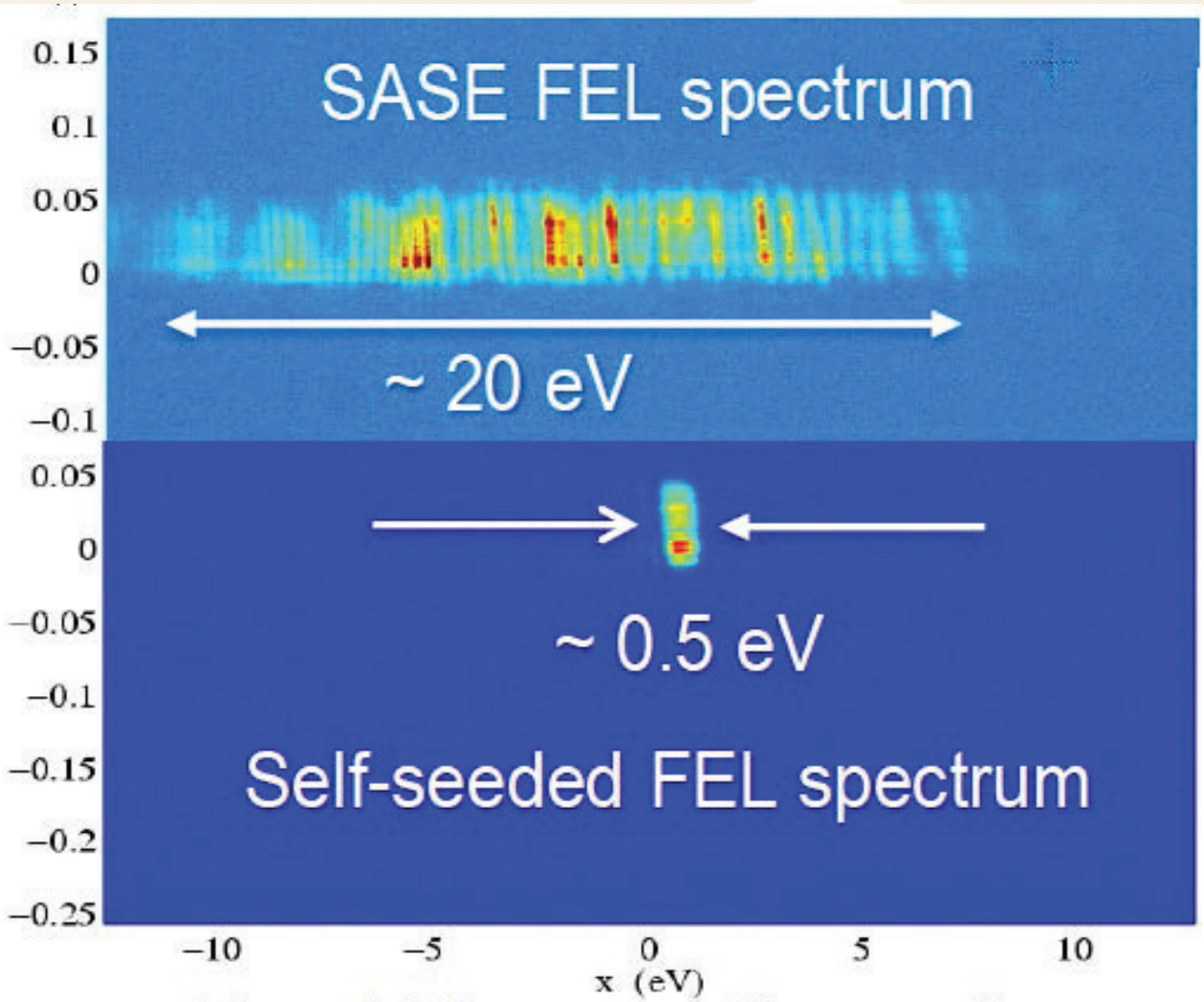
The wavelength of the crystal notch filter depends on the crystal reflection used and on the crystal angle.

Comparison of Seeded and SASE FEL Spectra

SLAC

How to get two energies (colors) ?

Add a second crystal, but there is an easier way …



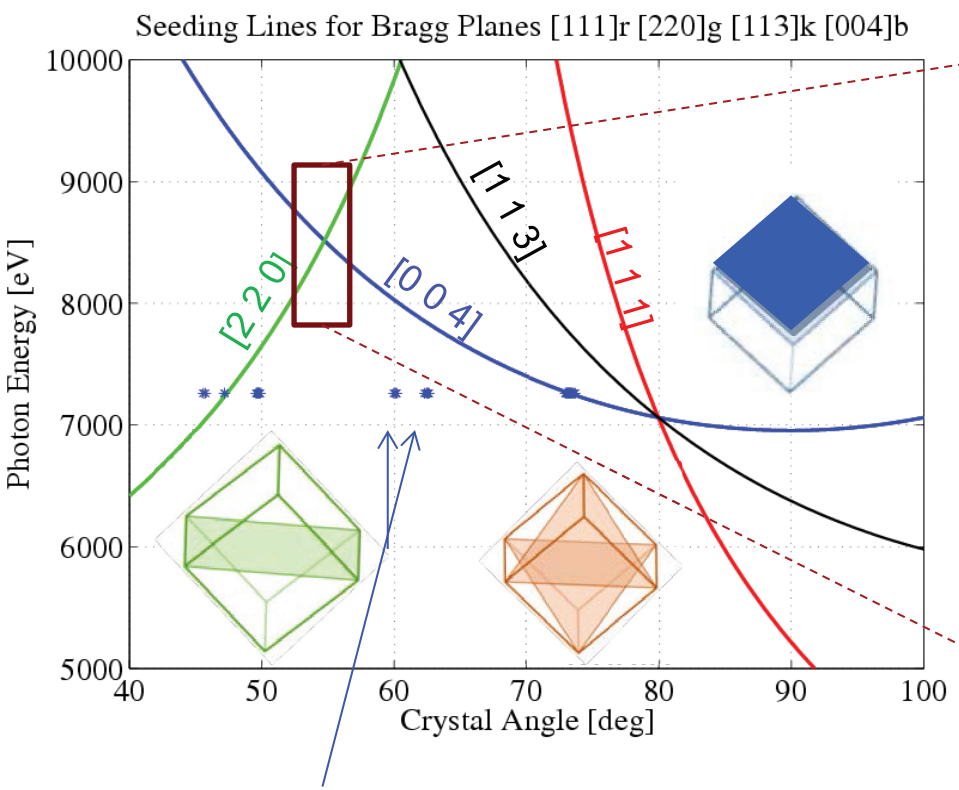
Hard X-ray self-seeding

Two-Color HXR-Self Seeding at Bragg Line Crossing

SLAC

Theory

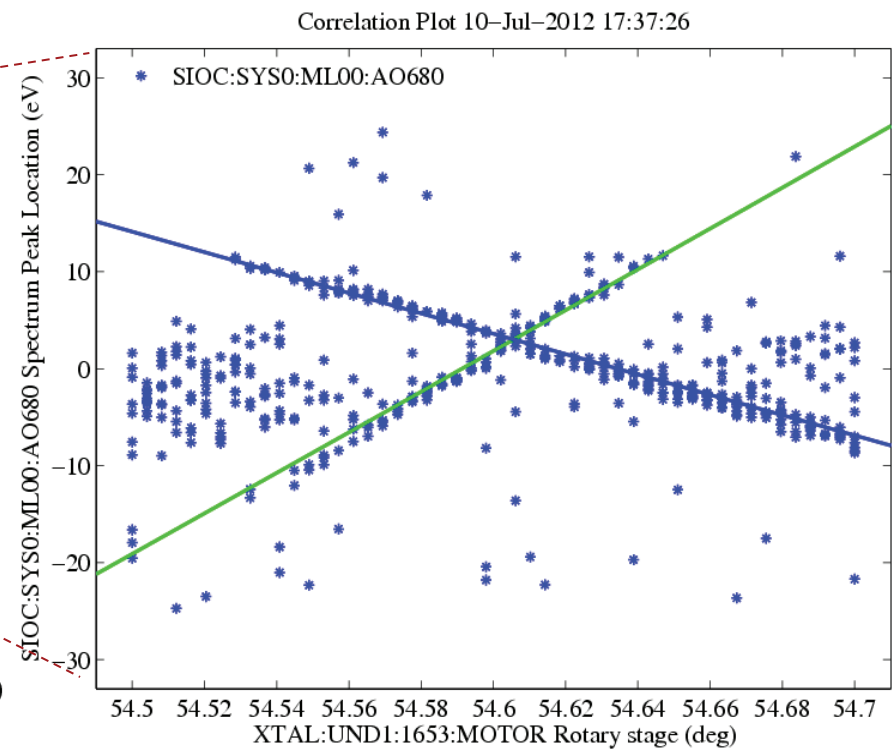
Bragg 004 and Laue 220, Energy vs Crystal angle



Experimental lines

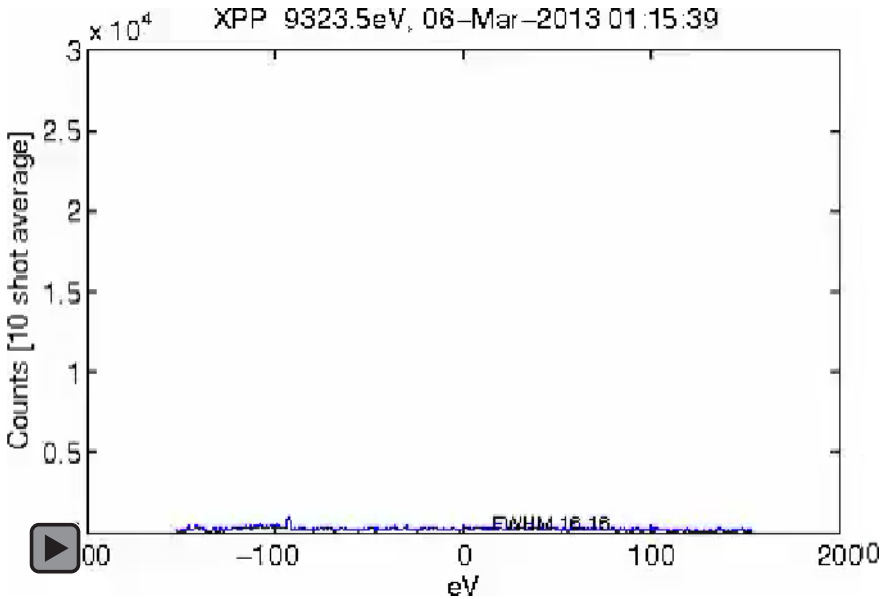
Experiment

Self-seeded peak location



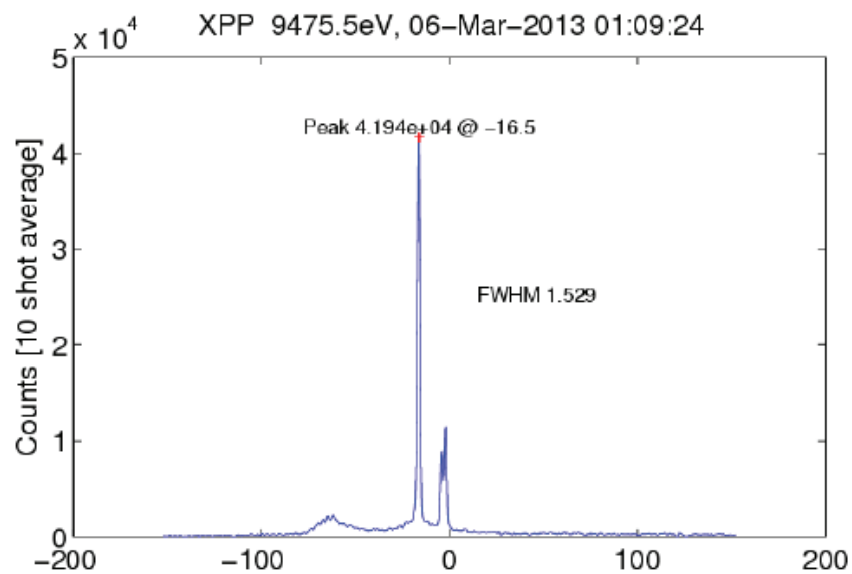
F.-J. Decker et al., “Two-Color Self-seeding and Scanning the Energy of Seeded Beams at LCLS”, FEL2013, WEPSO09

Two-Color HXR-Self Seeding (Tracking Movie)



photon energy [eV]

Ten shots average



photon energy [eV]

+ Colors bandwidth much narrower than SASE-based Two-Color schemes
+ Pulses are overlapped in time

[- Distance (in photon energy) must be within amplification bandwidth]
[- Needs to sit on a crossing between two different reflections]
[- No tunable time delay between pulses]

OLD (not really negative any more)

F.-J. Decker, J. Welch, J. Turner, Z. Huang, J. Hastings, D. Zhu, M. Gibbs, H. Smith

More Crystal Lines: 3-11 keV
Yaw Angle Control Allows Two-Color Seeding at ANY Energy

SLAC

Rules:

All odd or even

If even, sum = n*4

Colors:

indices family

Line styles:

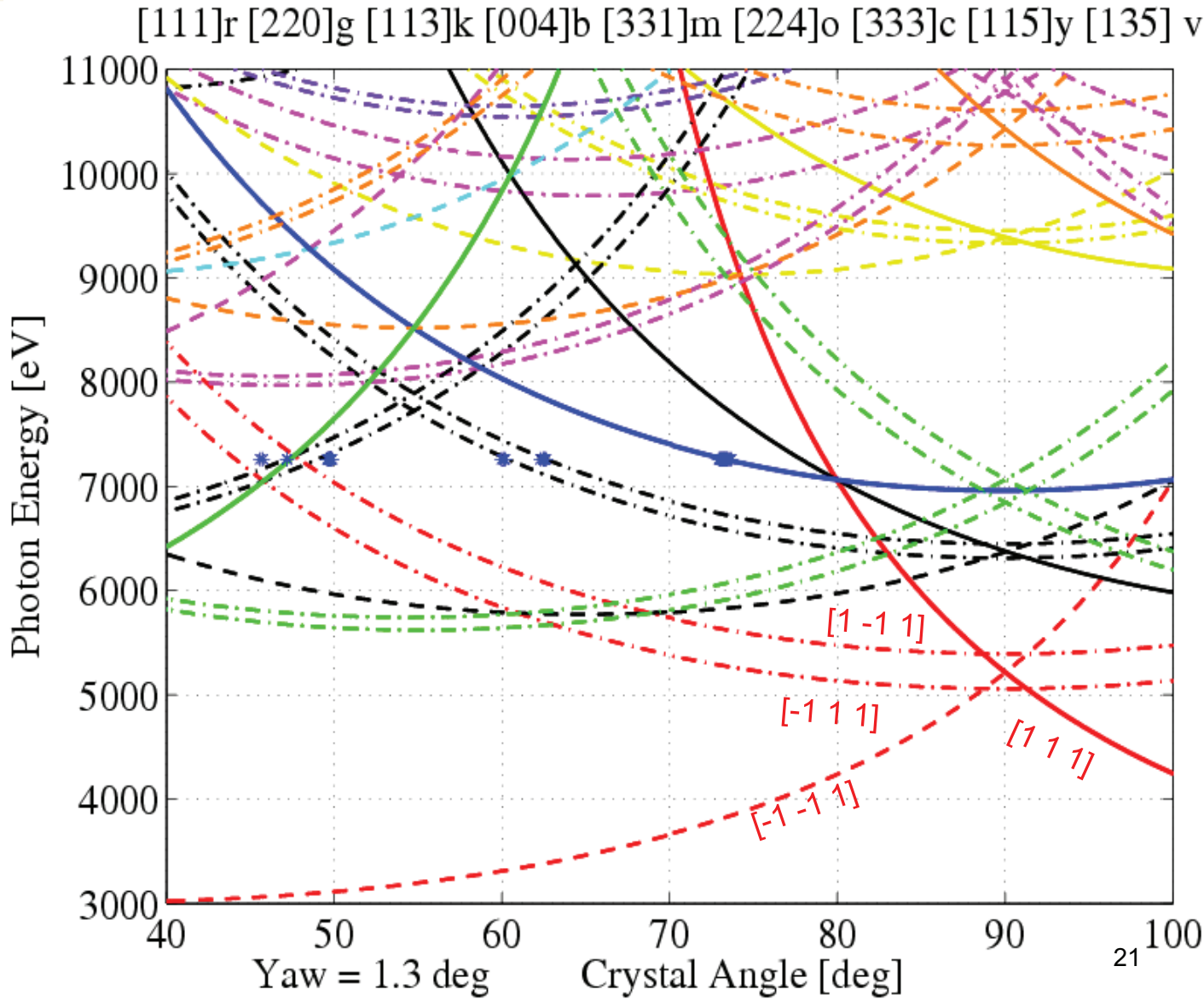
In-plane:

__ positive: [a a b]

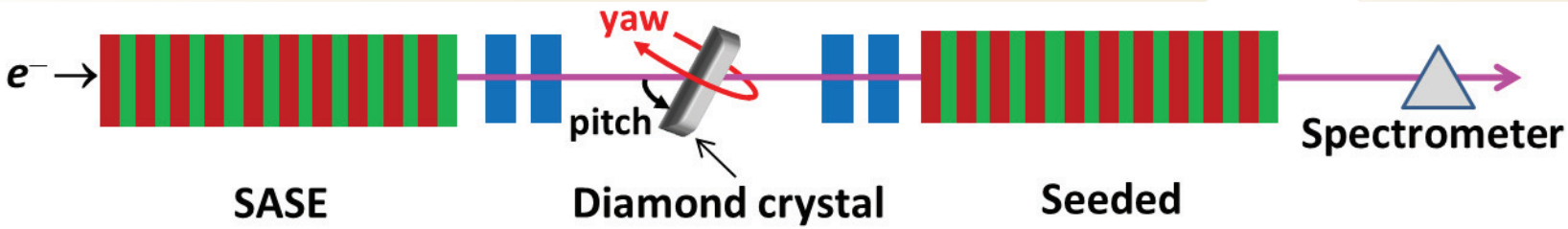
--- negative: [-a -a b]

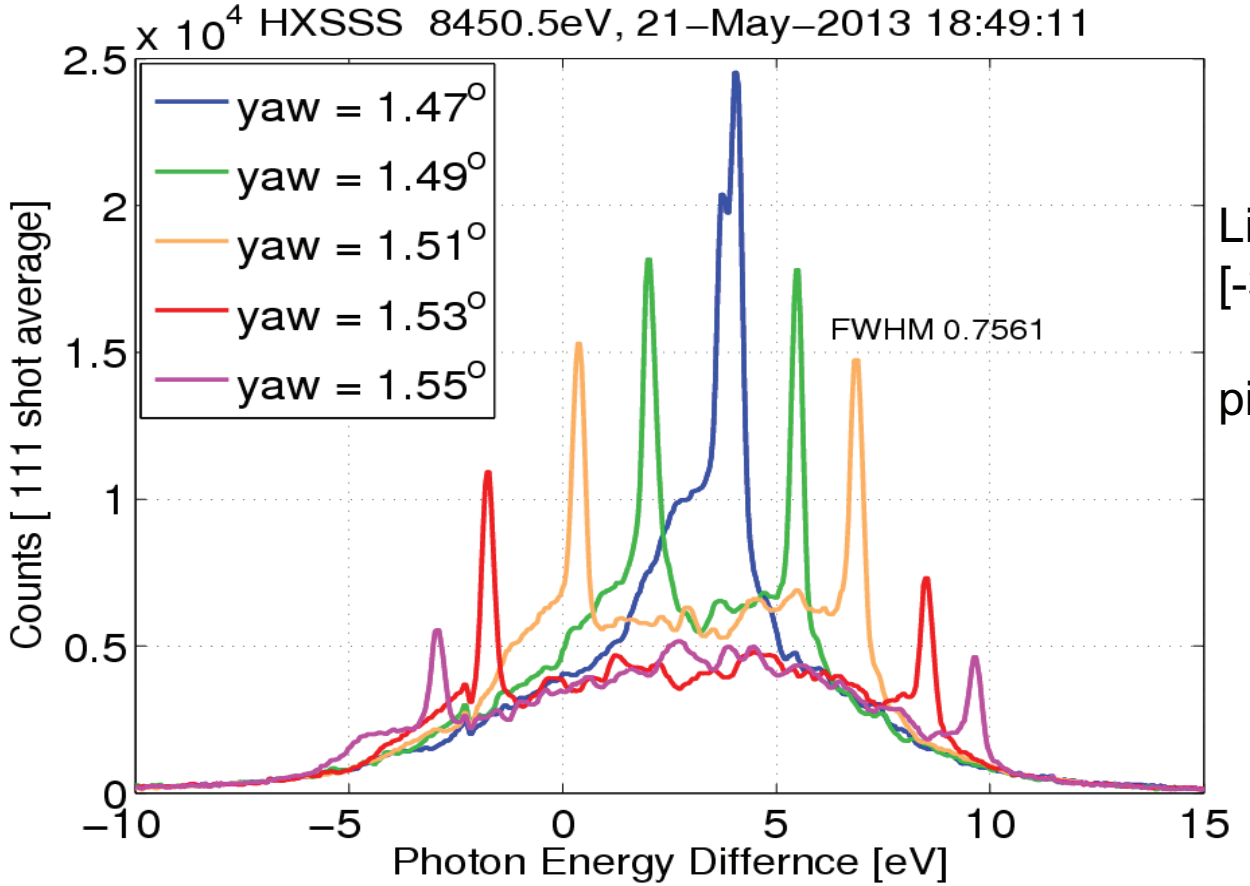
-.- Out-of-plane:

[a b c] with a ≠ b



Seeding Chicane Side View





Line pair:
[-3 -1 1], [-1 -3 1]

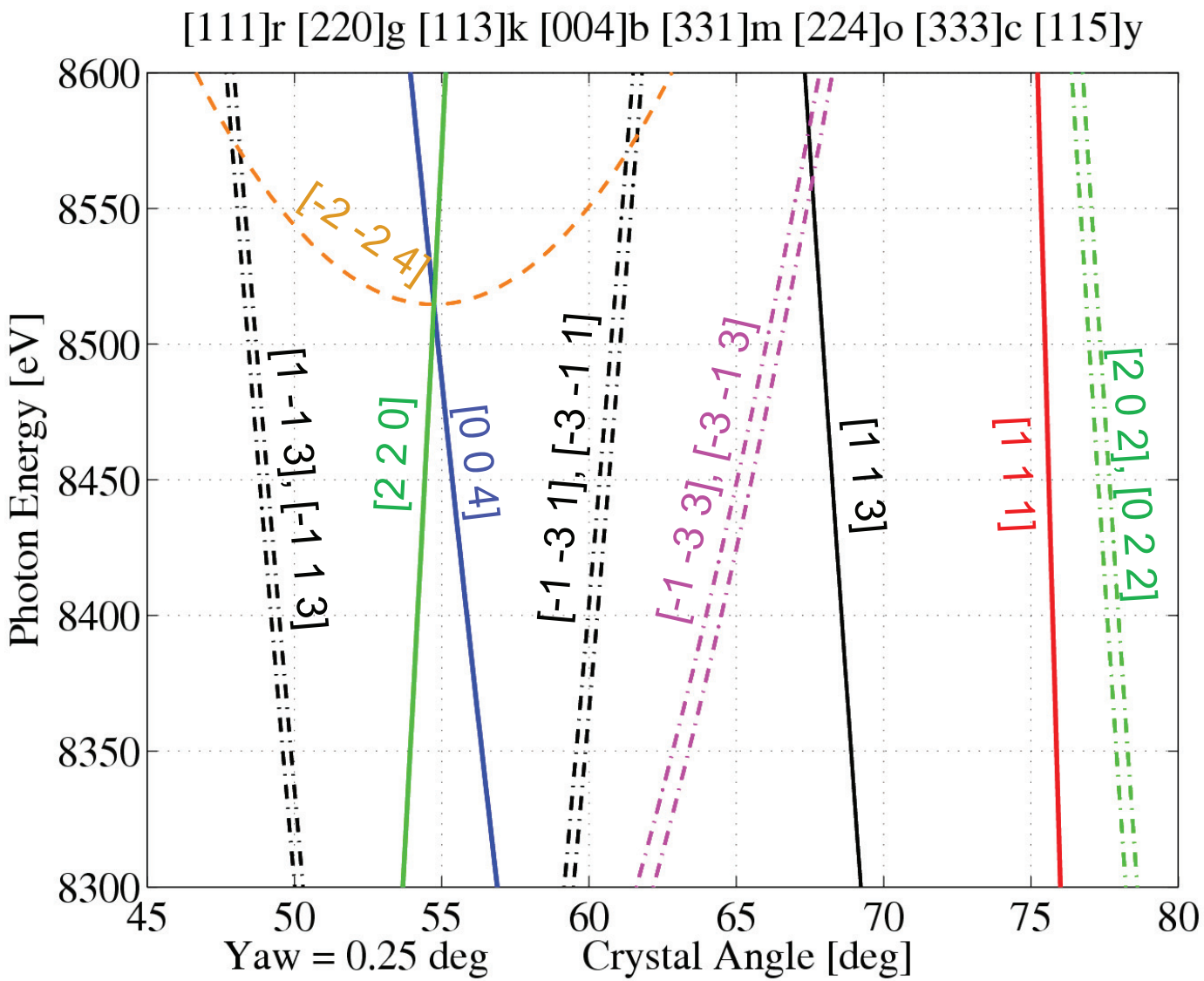
pitch angle: 60.5º

Seeding 12 Bragg Crystal Lines at FEE Spectrometer Energy of 8.45 keV

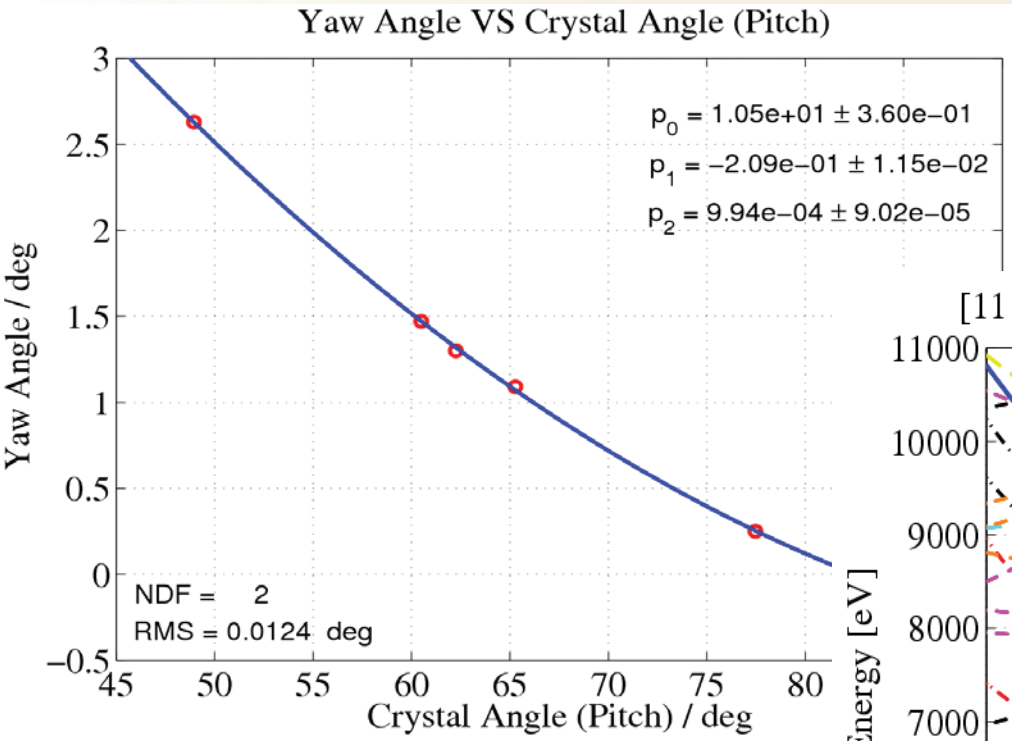
Solid: in-plane

Dash: first two minus

Dash-dotted: out-of-plane (will split with yaw (or roll) angle)

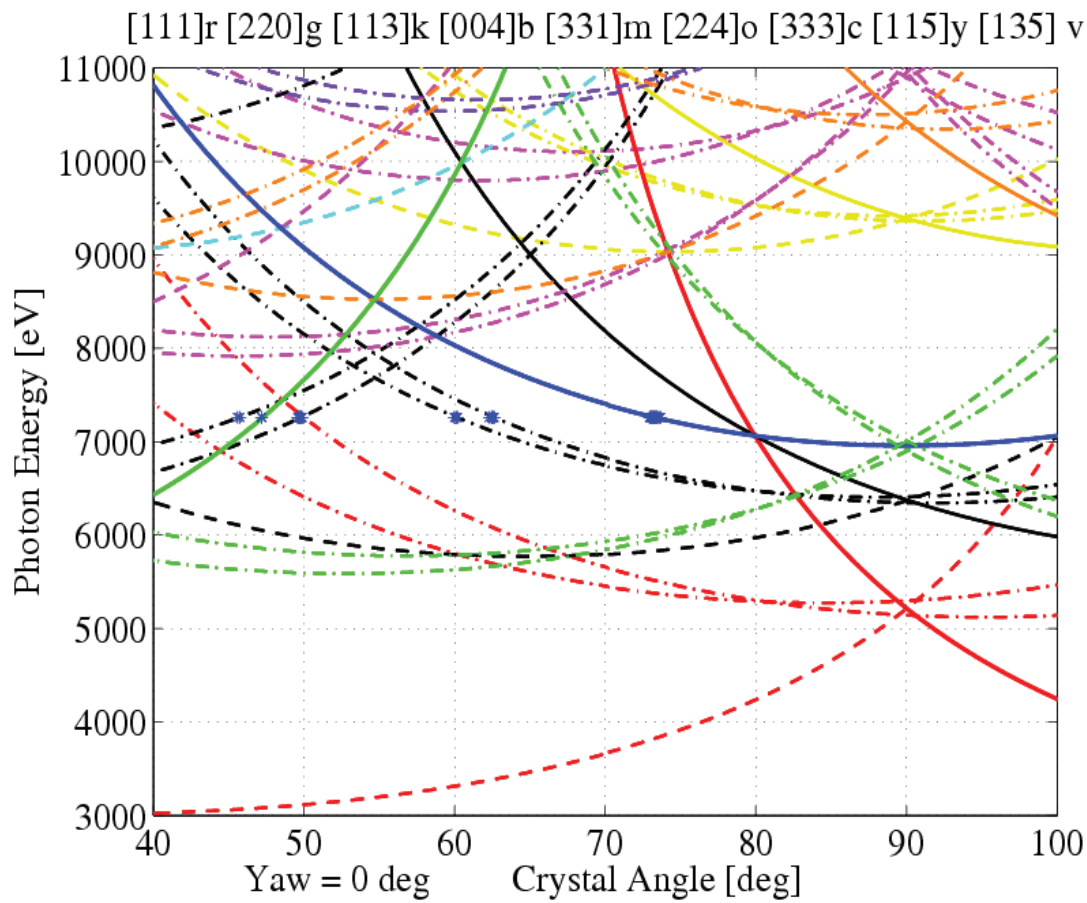


Yaw Angle to Put Off-Planes on Top Helped Define Angle Offsets



roll offset: -3.73º

yaw offset: -0.61º



Best understanding of actual crystal angle response →

L1X at Low Amplitude Gives Two SASE Peaks 40-50 MeV Apart

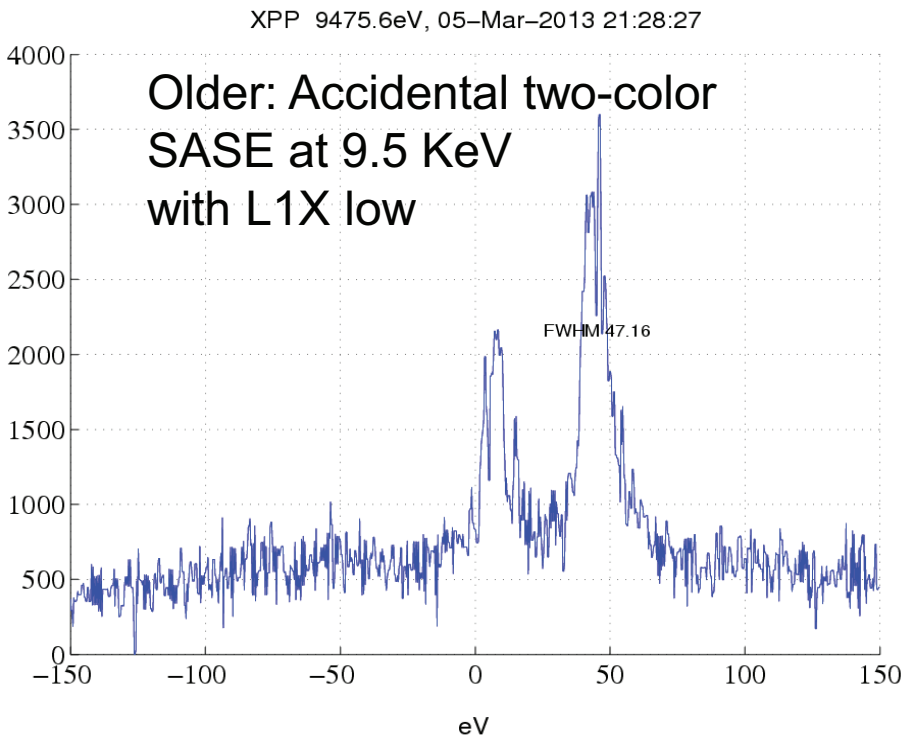
SLAC

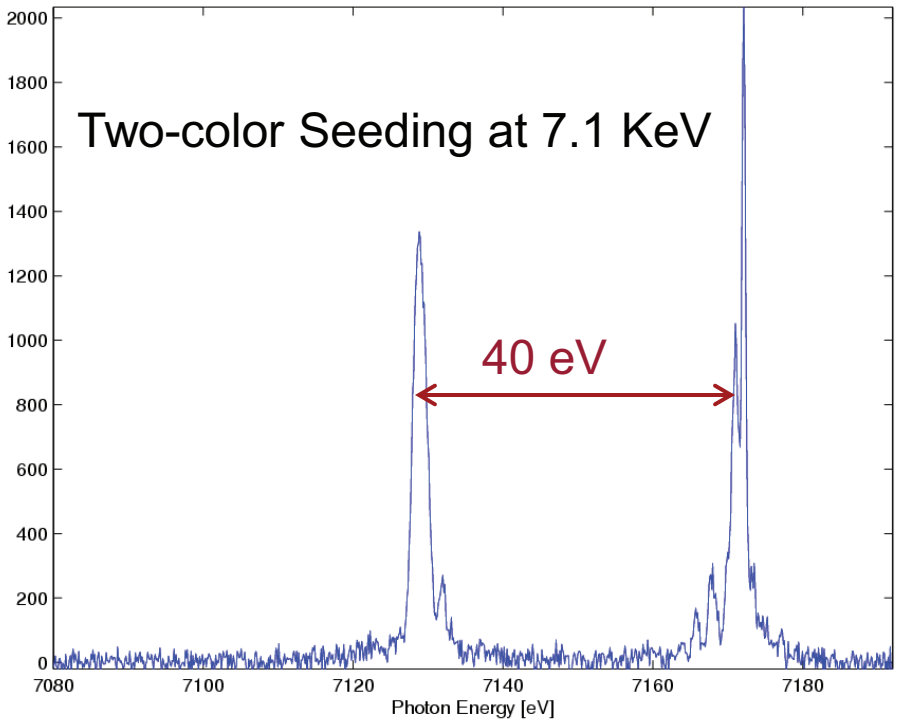
Two-color bio-imaging experiment at 7.1 keV around the iron K-edge [MAD: Multi-wavelength Anomalous Dispersion]

[-1 1 3] and [1 -1 3] line pair

L1X amplitude lowered from 21 to 14 MeV

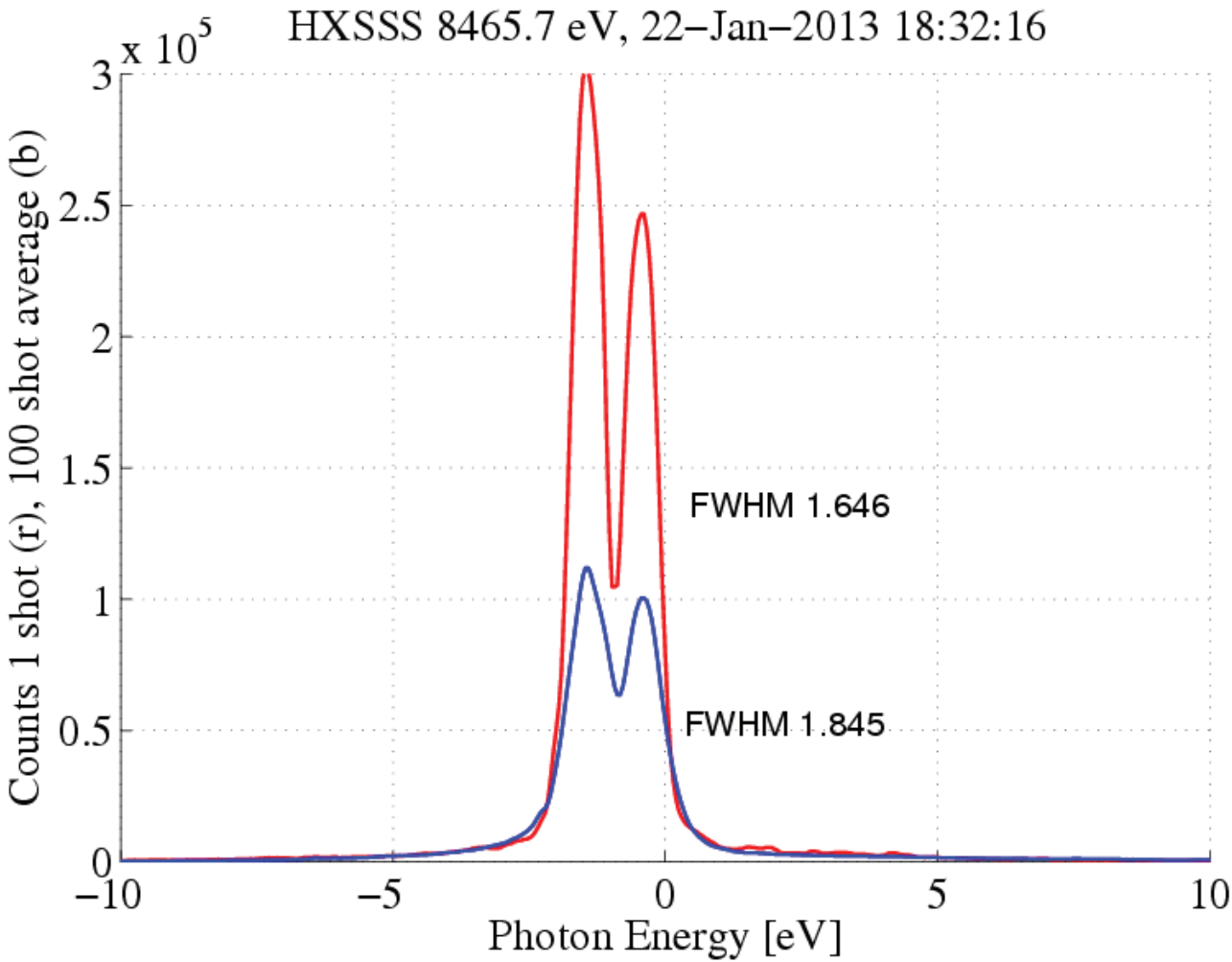
S. Wakatsuki





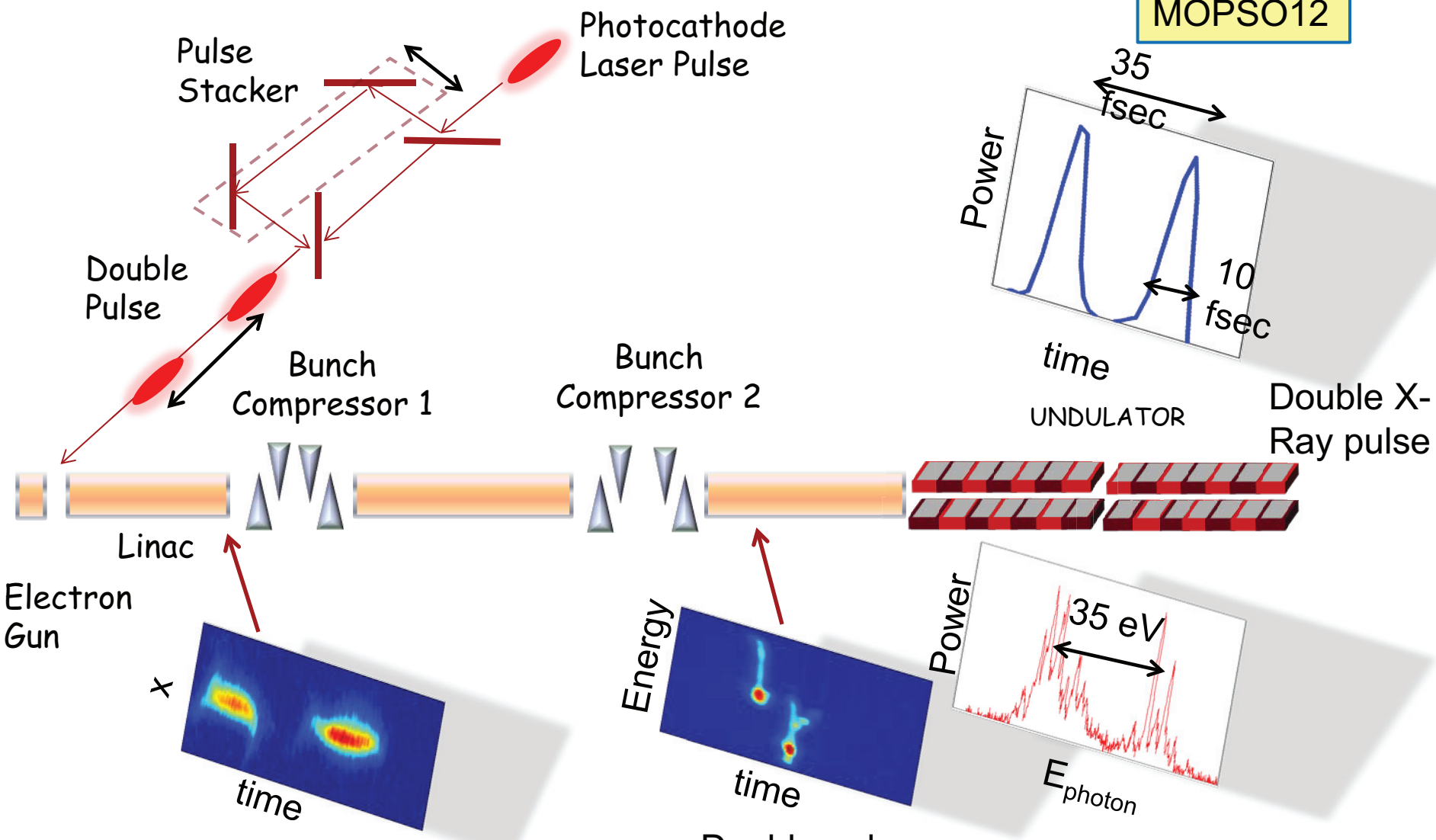
Single Bragg Line after Tuning for Maximum Intensity

Second peak disappears with slotted foil in (horns get cut)



Double Pulse Setup and Measurements

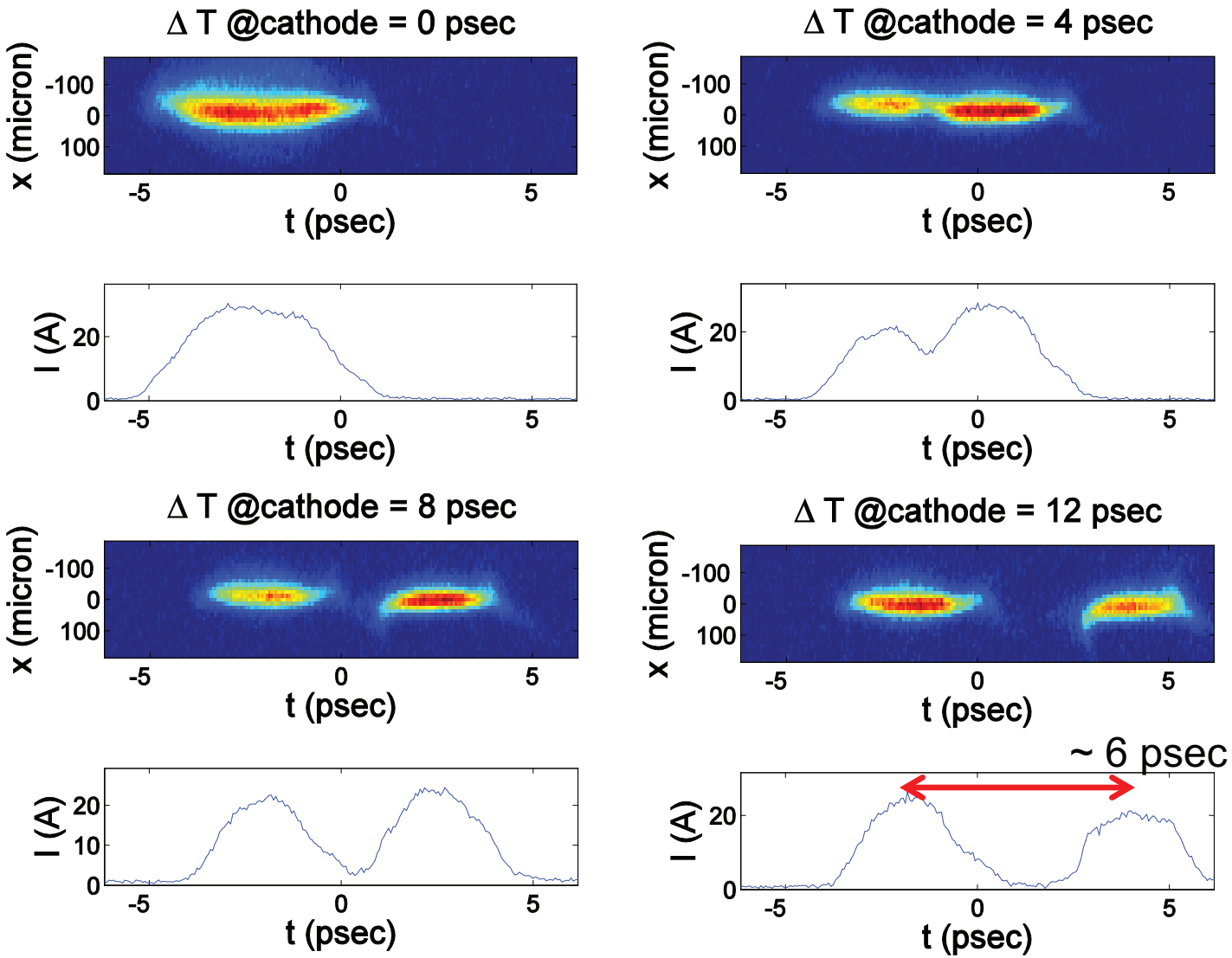
A. Marinelli
MOPSO12



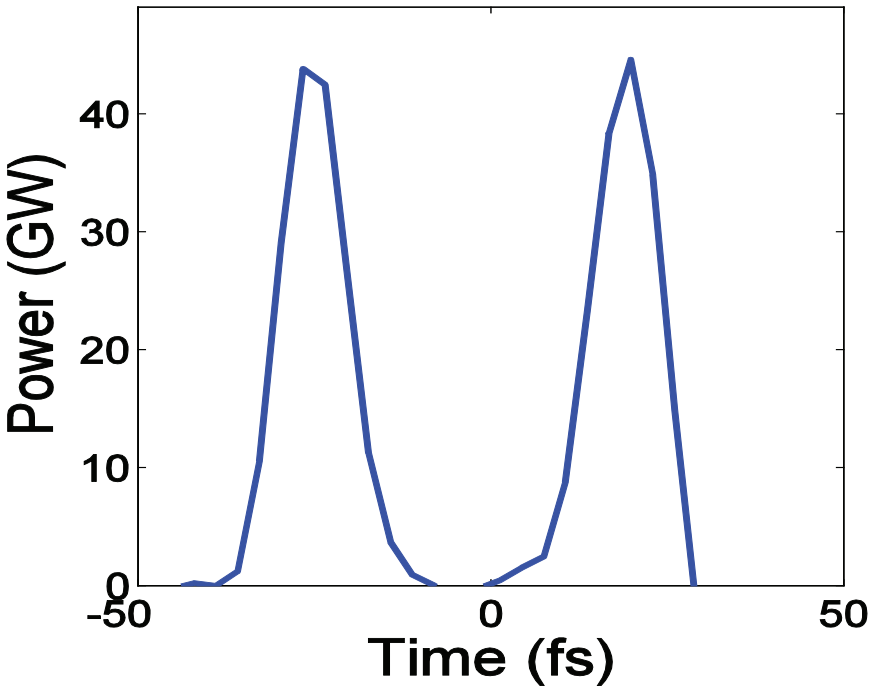
Double pulse
psec delay

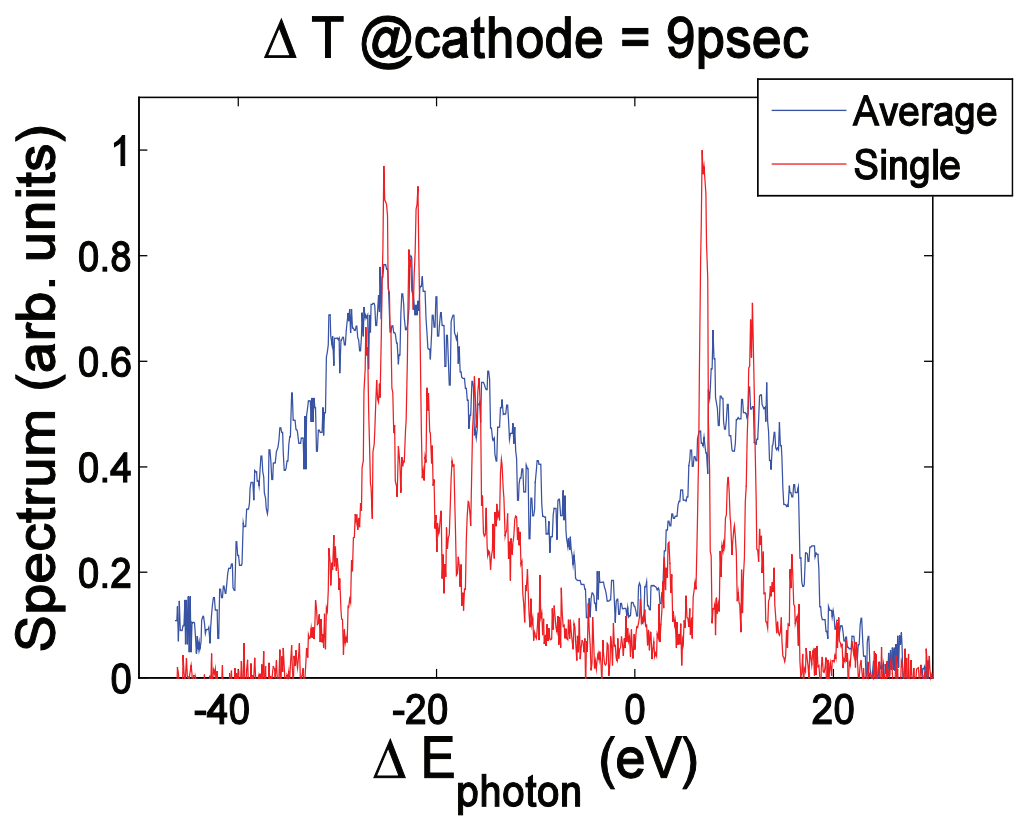
Double pulse
femtosec delay
~1% energy
separation

TCAV0 Images for Different Delays



Double Pulses at 9.1 keV and 12 psec Delay
Time Profile from X-TCAV Spectrum



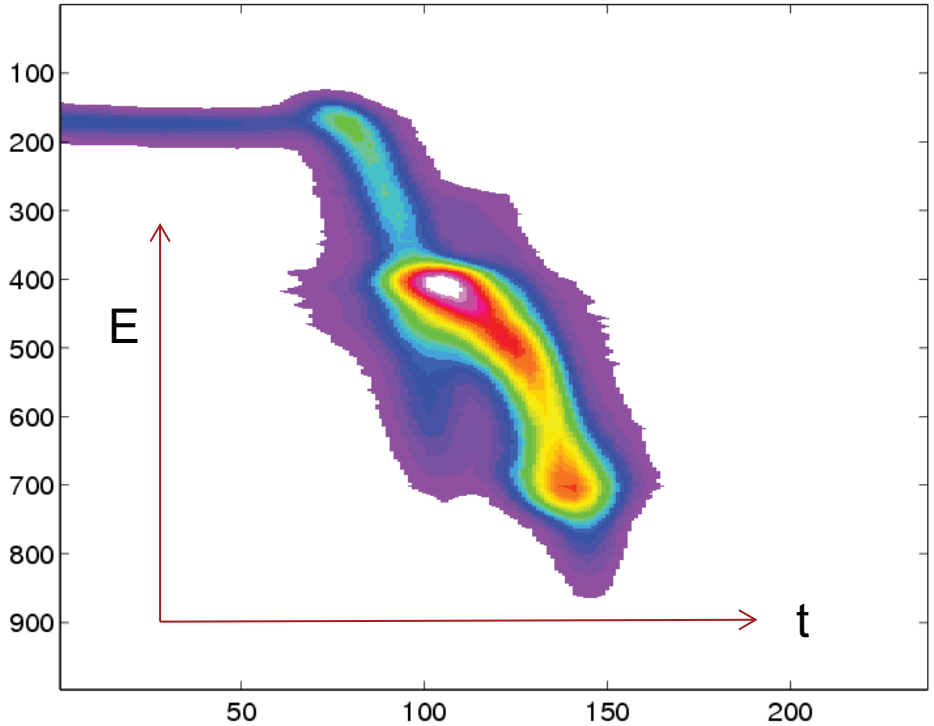


+ This allows:
+ Two pulses with variable delay, energy, seeding (not yet done), …

Longitudinal Phase Space Comparison with XTCAV

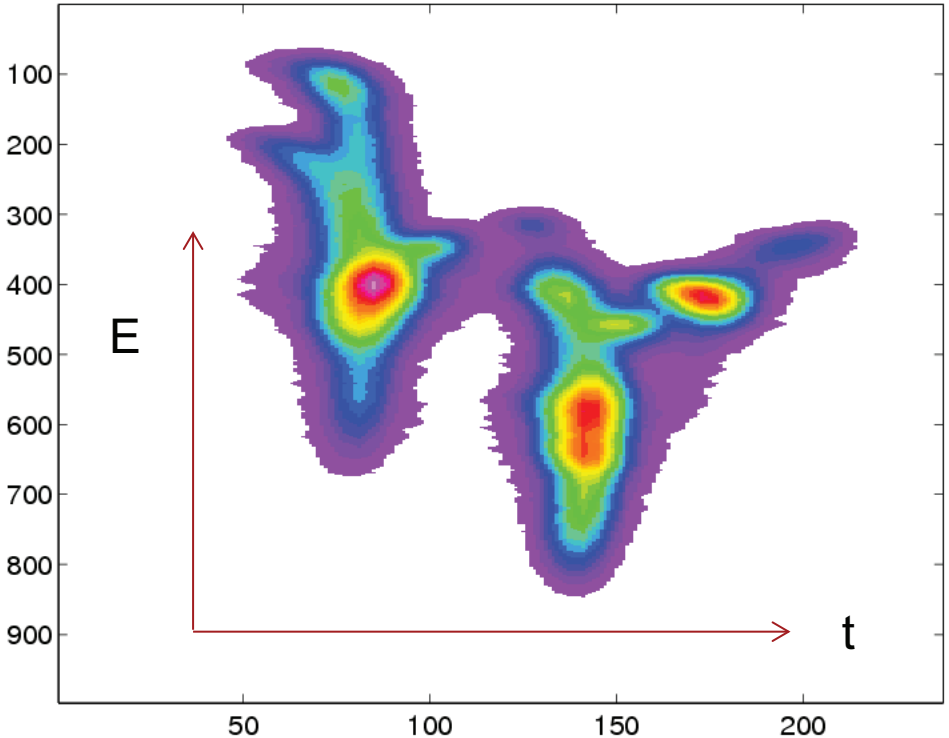
Two-Color Seeded

L1X low amplitude (14.4 MeV)



Double pulse: SASE

Double pulse = 2 bunchlets



Summary

- Two-Color schemes were experimentally demonstrated at LCLS

- Soft x-ray: Two-Color SASE with *K*1 and *K*2,
  iSASE
- Hard x-ray: Two-Color Self Seeding on out-of-plane Bragg lines
- Double energy electron distribution:
  - with one bunch (L1X)
  - two bunchlets (Double Pulse)

- Combinations of these different approaches are very promising