Two-Pulse Schemes in Soft and Hard X-Ray FELs: Robustness Analysis of State-of-the-Art Solutions

Alberto Lutman

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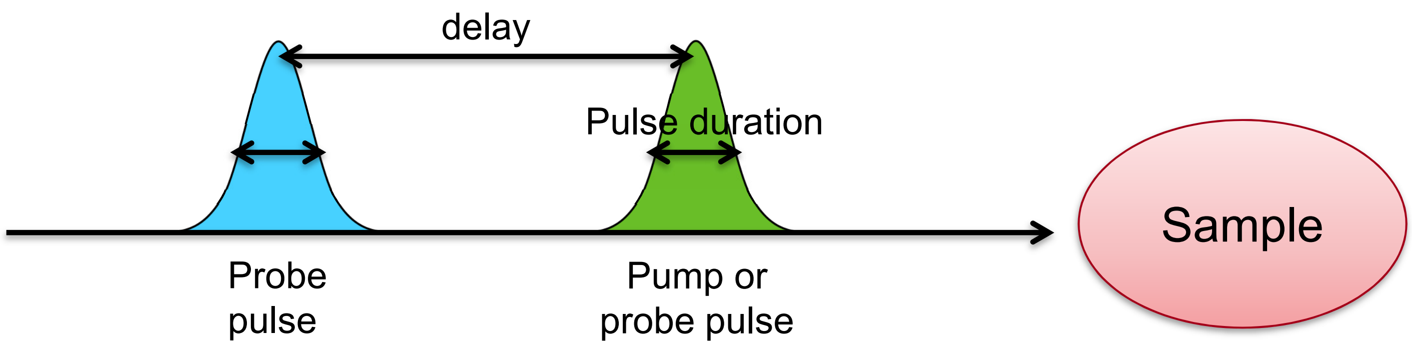
U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Two-pulses XFELs



Requirements:

- Color separation
- Delay
- Pulse Duration
- Power
- Bandwidth
- Polarization
- Pointing

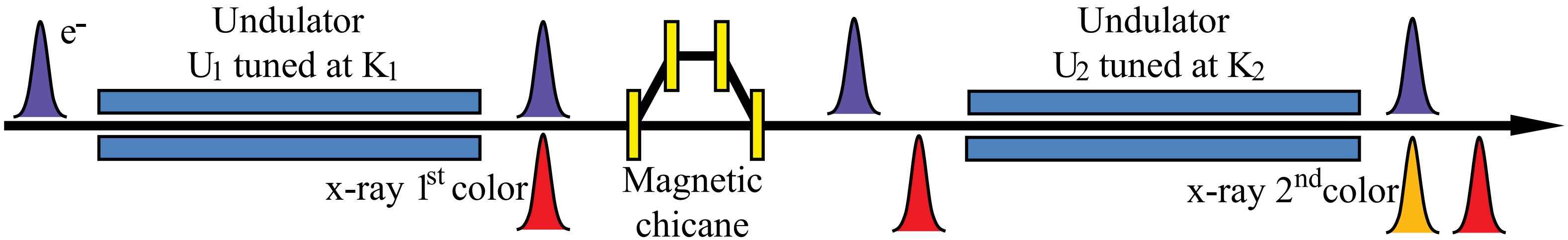
- Controlling pulse intensity and turning on/off
- Scanning delay
- Scanning color separation

Without impact on Anything else

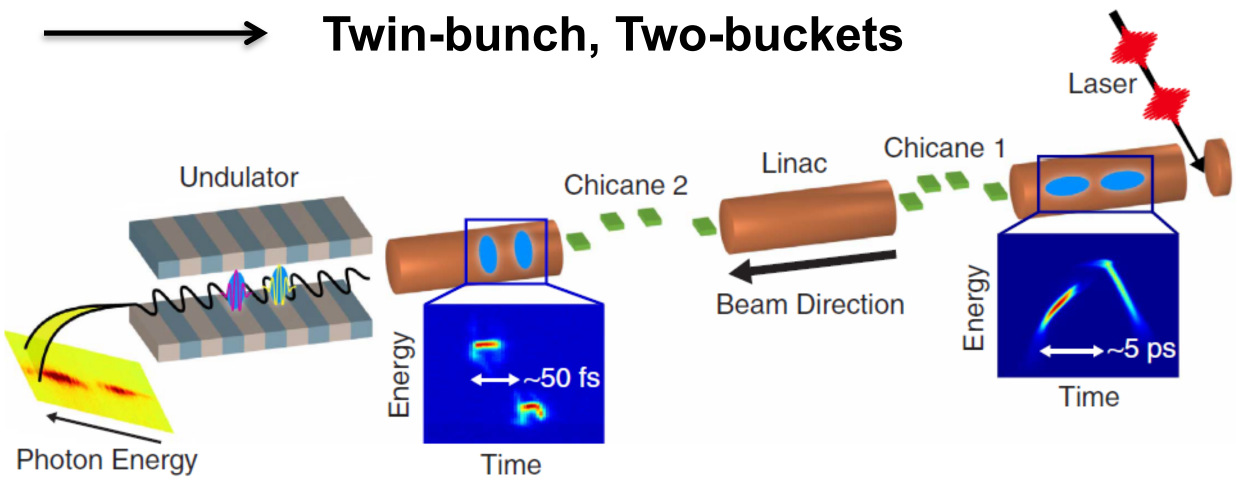
Two-color XFELs

$$\lambda_r = \lambda_u \frac{1 + K^2/2}{2\gamma^2}$$

By undulator K → **Split undulator, Fresh-slice**

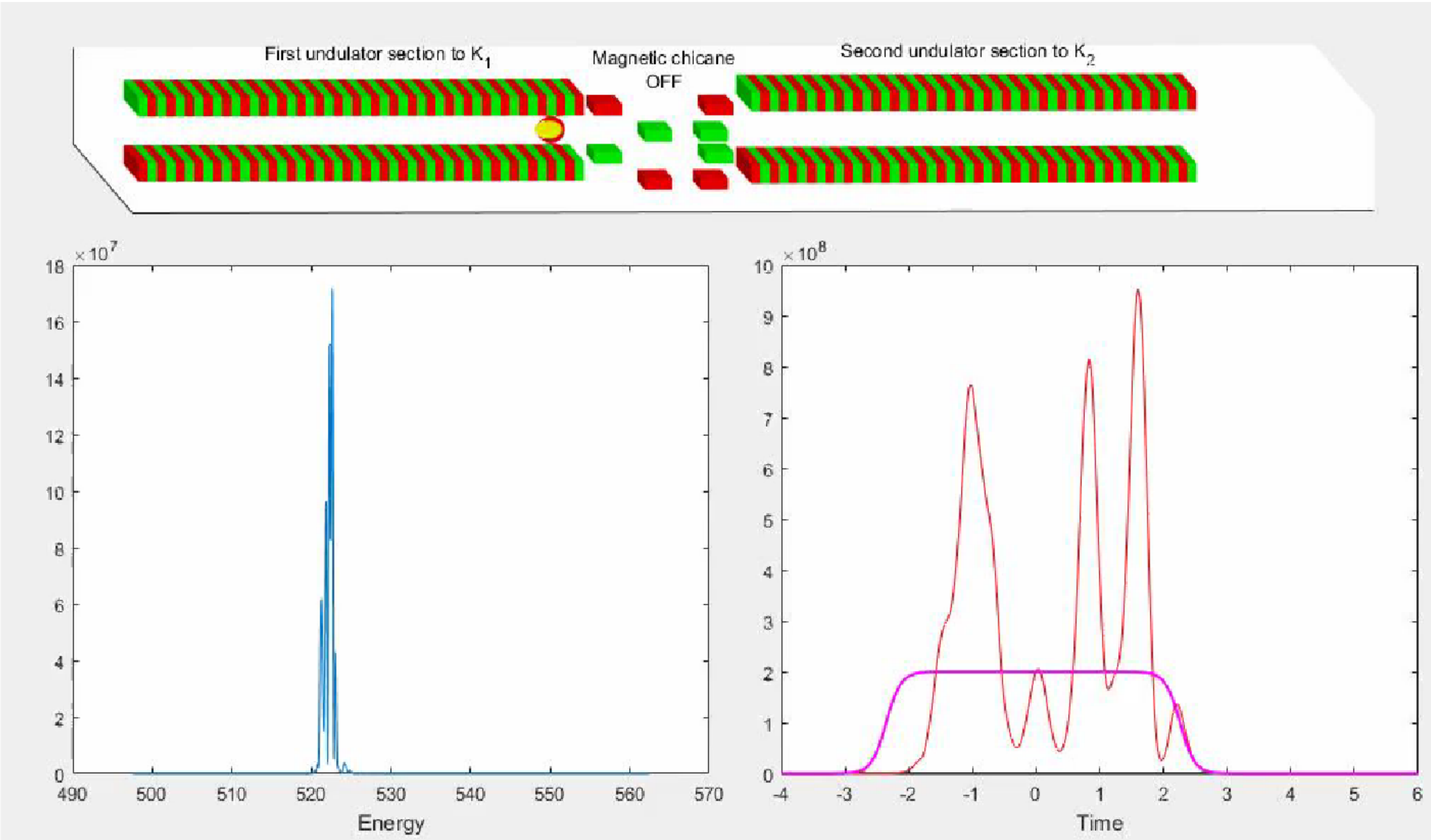


By beam energies γ → **Twin-bunch, Two-buckets**



Split undulator scheme

Split undulator scheme

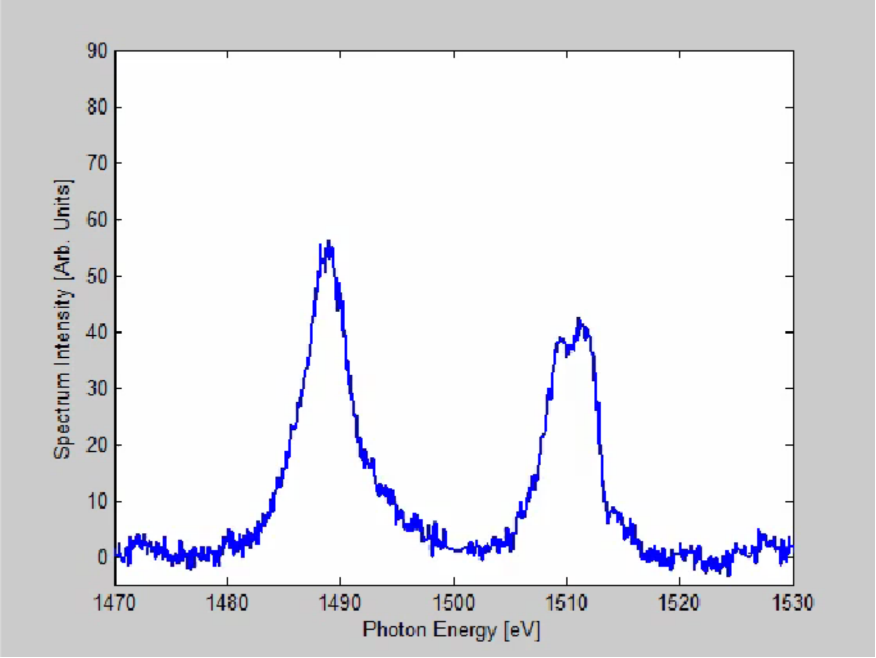


Instrinsic delay: $\tau \approx (N_1\lambda_1 + 2N_2\lambda_2)/3$ (~ 6 fs at 530 eV at LCLS)

Split undulator scheme

Strengths:

- Easy to setup
- Robust
- Large color separation (variable gap undulators)
- Delay and color separation scanned independently
- Chicane controls delay
- Undulator K controls color separation



PRL 110, 134801 (2013) PHYSICAL REVIEW LETTERS week ending 29 MARCH 2013

Experimental Demonstration of Femtosecond Two-Color X-Ray Free-Electron Lasers

A. A. Lutman, R. Coffee, Y. Ding,* Z. Huang, J. Krzywinski, T. Maxwell, M. Messerschmidt, and H.-D. Nuhn

nature COMMUNICATIONS

Two-colour hard X-ray free-electron laser with wide tunability

Toru Hara, Yuichi Inubushi, Tetsuo Katayama, Takahiro Sato, Hitoshi Tanaka, Takashi Tanaka, Tadashi Togashi, Kazuaki Togawa, Kensuke Tono, Makina Yabashi & Tetsuya Ishikawa

Nature Communications **4**, Article number: 2919 (2013)
Article | Published: 04 December 2013

Split undulator scheme

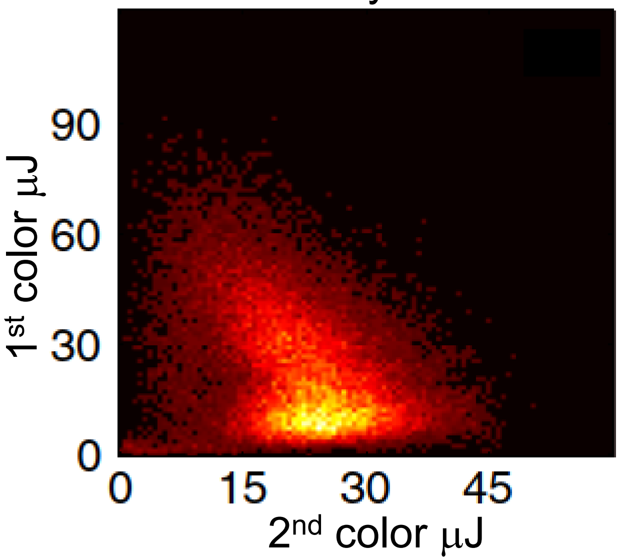
Scheme limitations:

- minimum intrinsic delay.
- first pulse cannot reach saturation
- Requires long undulator line (not suitable if gain-length is long, e.g. harder X-rays)

Limited reliability:

- Intensity anti-correlation
- anti-correlation can prevent any pulse overlap.
- Microbunching can influence second pulse for small delays.
- Scanning delay / color separation can influence pulse shape if partial time overlap or color separation is small.

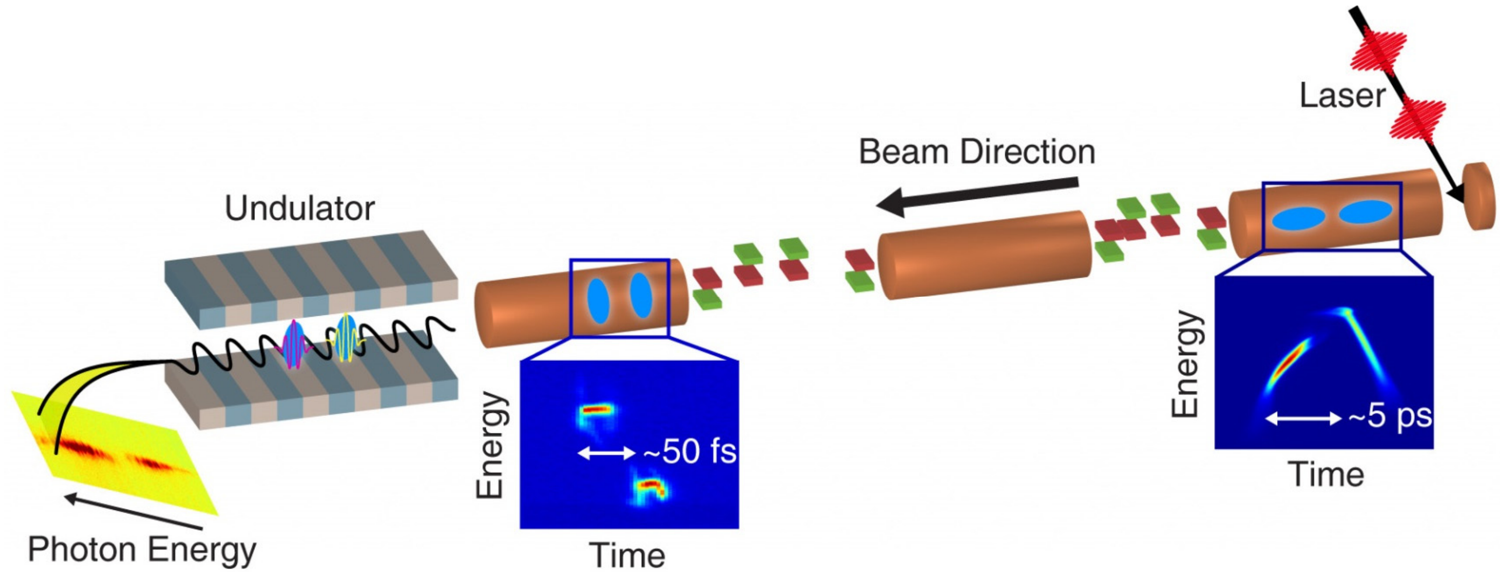
Pulse intensity correlation



Used as state-of-art:

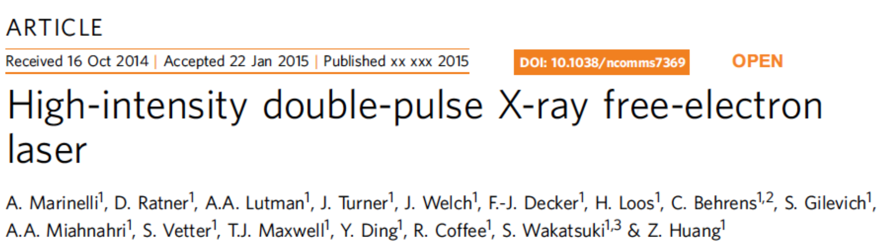
two-color with unbalanced intensities (weak pulse superposed with strong pulse)

Twin-Bunch scheme



Strengths:

- High power. Each pulse produced by an electron bunch
- Both colors use entire undulator line → suitable at any wavelength



ARTICLE

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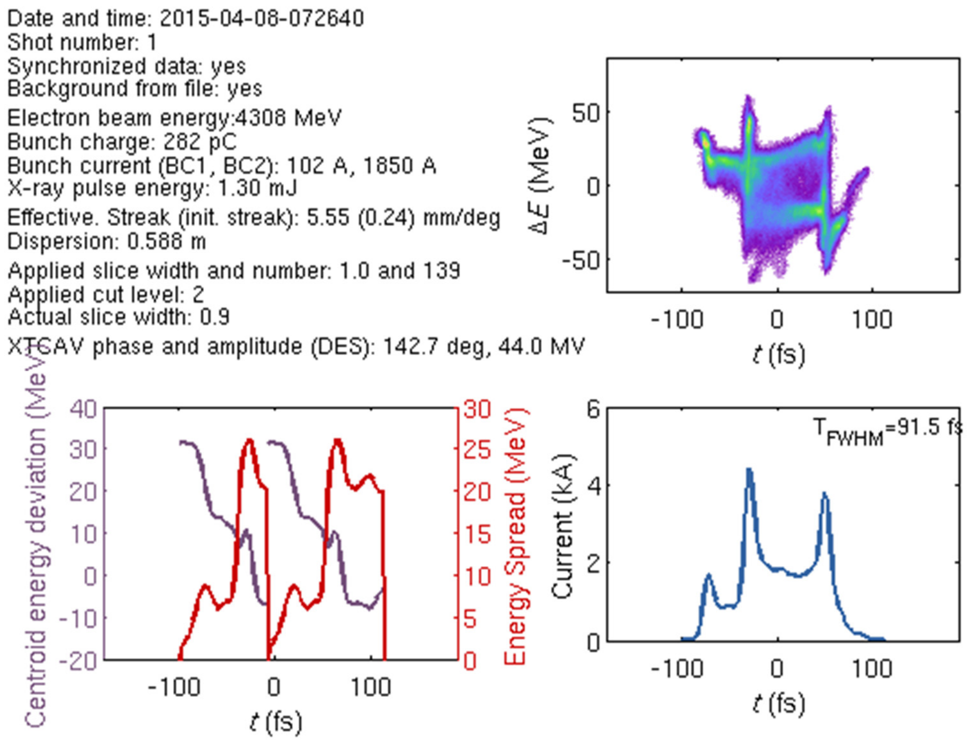
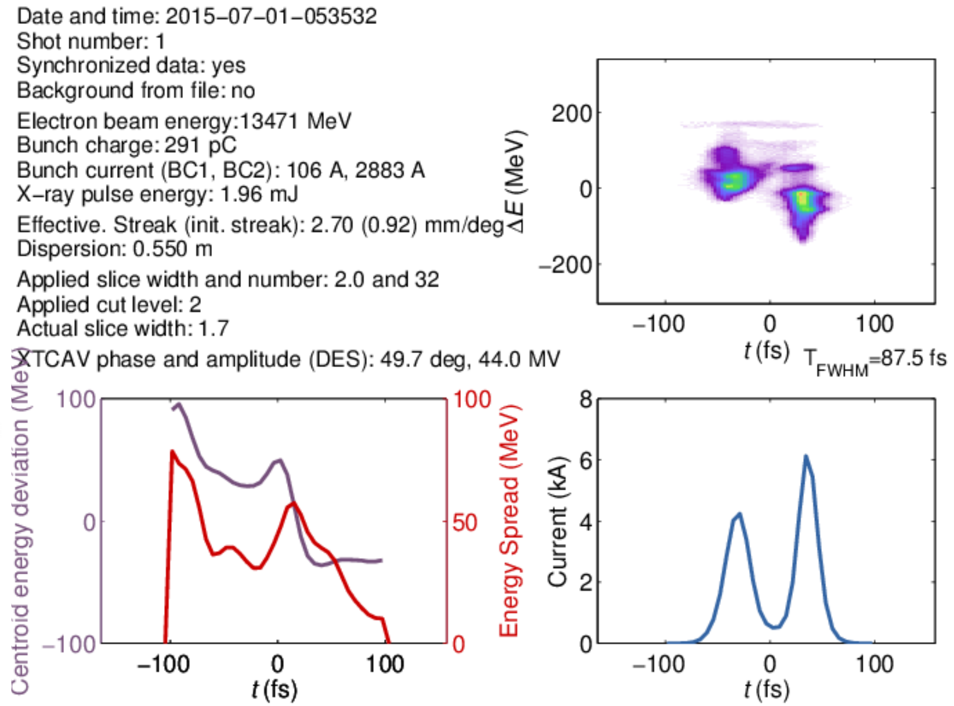
High-intensity double-pulse X-ray free-electron laser

A. Marinelli[1], D. Ratner[1], A.A. Lutman[1], J. Turner[1], J. Welch[1], F.-J. Decker[1], H. Loos[1], C. Behrens[1,2], S. Gilevich[1], A.A. Miahnahri[1], S. Vetter[1], T.J. Maxwell[1], Y. Ding[1], R. Coffee[1], S. Wakatsuki[1,3] & Z. Huang[1]

Twin-Bunch scheme





- SXR, 150+150 pC
- 1.3 mJ shot
- ~ 100 fs pulse duration per pulse
- 780 eV

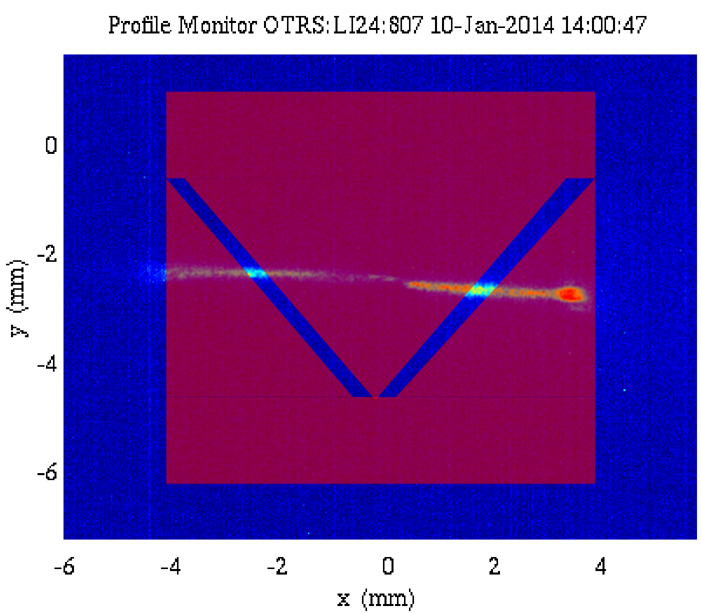
- HXR, 150+150 pC
- 1.96 mJ shot
- ~ 25 fs pulse duration per pulse
- 8 keV

Twin Bunch: Beam Carving

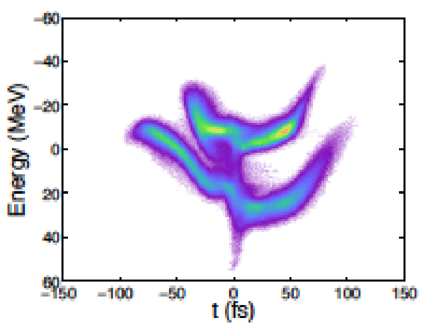
TUZA02 Proceedings of IPAC2016, Busan, Korea

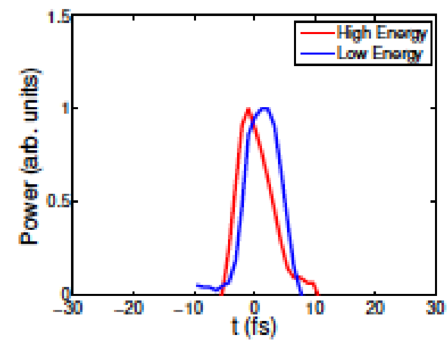
TWIN-BUNCH TWO-COLOUR FEL AT LCLS

A. Marinelli *, A. A. Lutman, T. J. Maxwell, Y. Ding, J. Turner, C. Field, D. Kharakh, F.-J. Decker, H. Loos, S. Gilevich, S. Vetter, R. Coffee, Z. Huang,
SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, California 94025, USA



X-Y distribution in BC2





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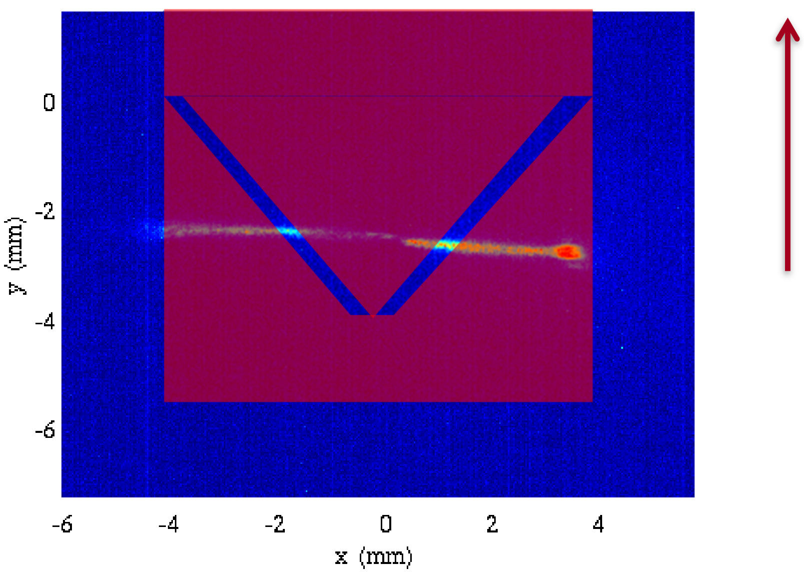

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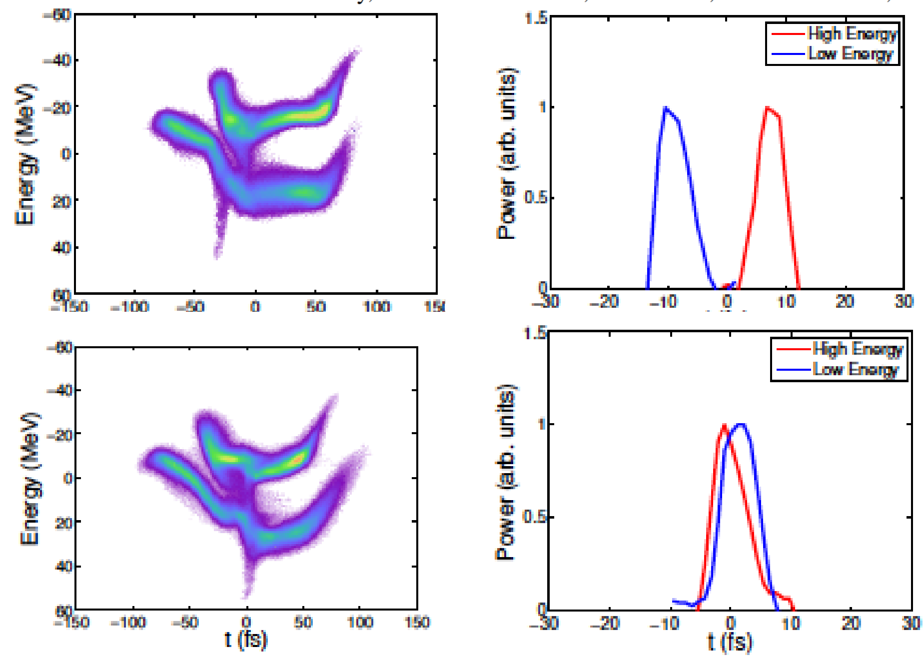

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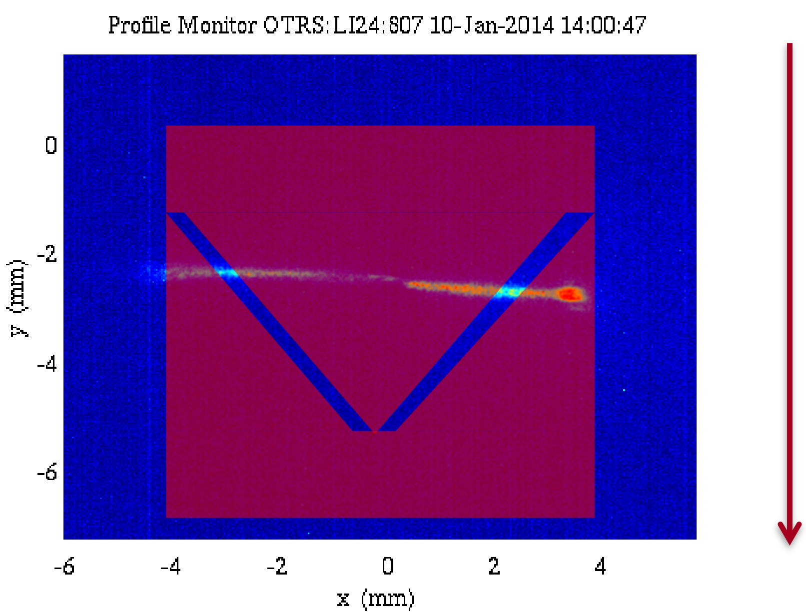

X-Y distribution in BC2

TUZA02 Proceedings of IPAC2016, Busan, Korea

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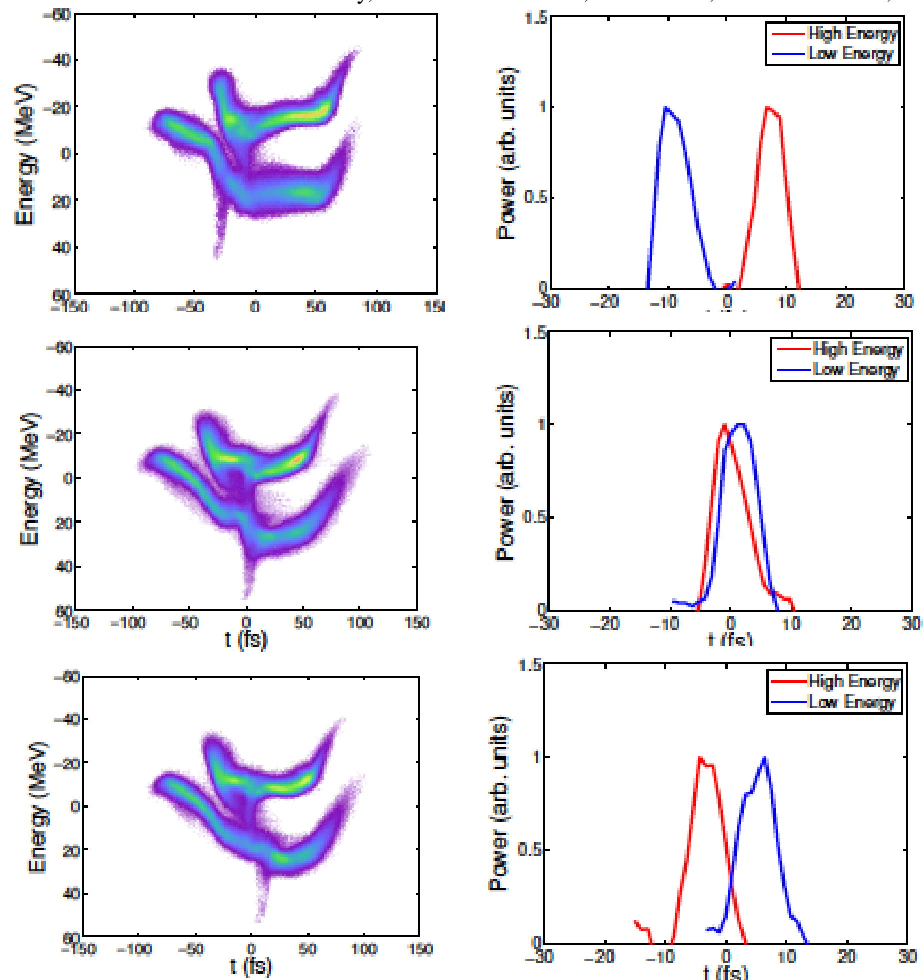


Twin-Bunch scheme: Robustness and reliability

- Beam setup requires change of entire machine.
- Delay and Color separation not on independent knobs.
  - Change requires some retuning
  - Pulses will not be identical after change

- Changing pulse intensity ratio / turning one pulse off
  - By matching, or by slotted foil.
  - In future could be improved with laser heater.

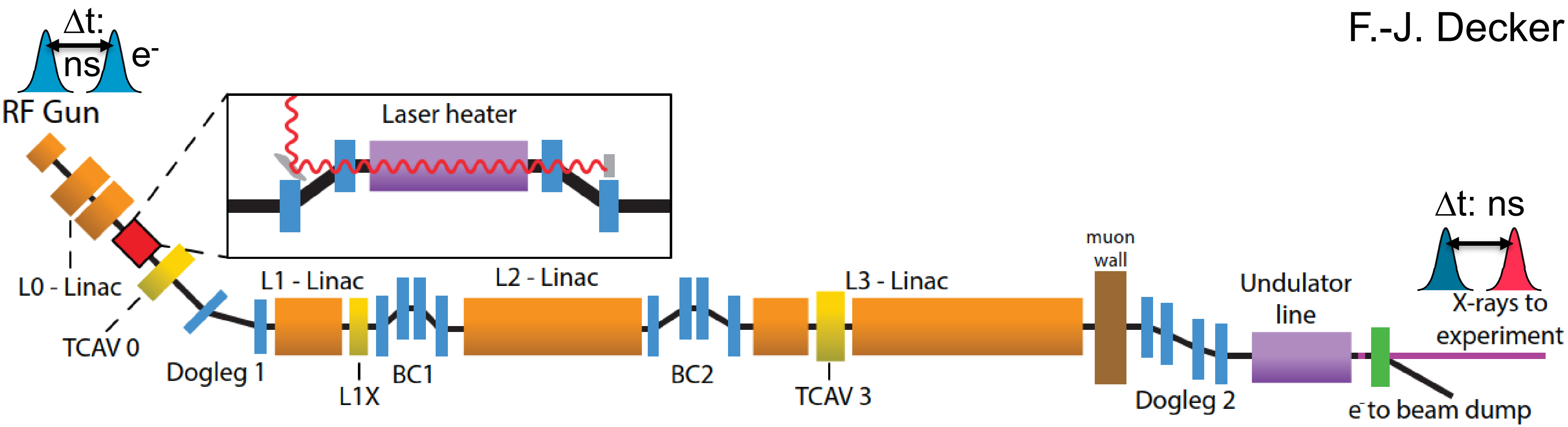
- Stable once setup, but historically some setups have failed, or have been lengthy
  - Injector laser issues
  - Attaining some delay/color separation setting
  - Lack of balance between color intensity (different compression / matching)
  - Non collinear-beams
  - Beam losses (with low energy and slotted foil)

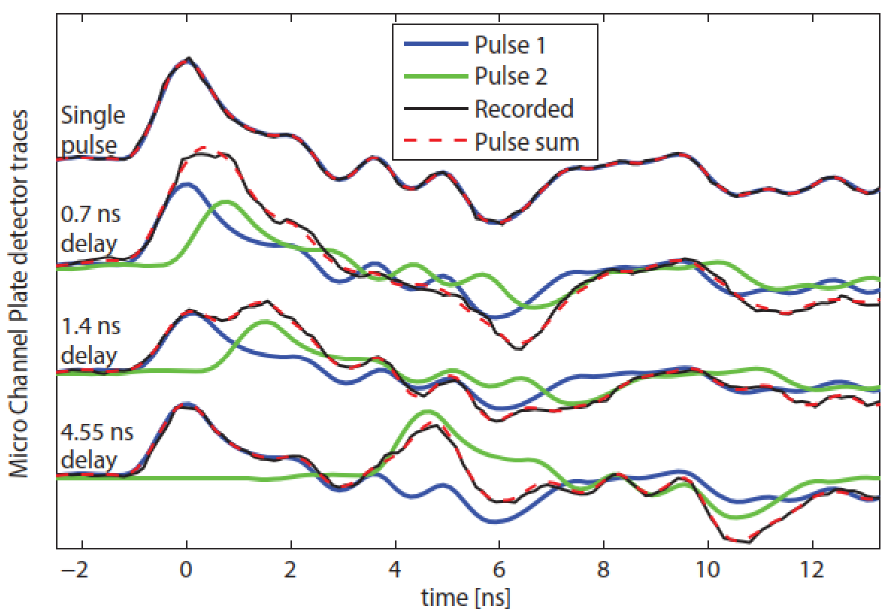
- Pulses cannot be same color

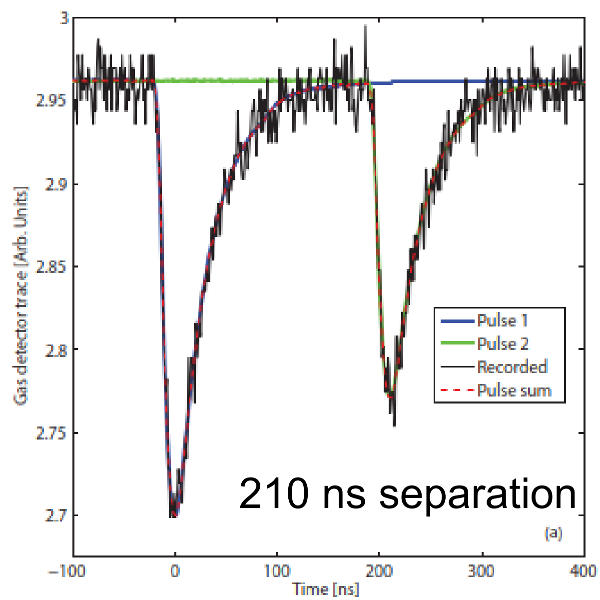
- Color separation limited by e-beam chromatic effects.

Two-Bucket Scheme

F.-J. Decker

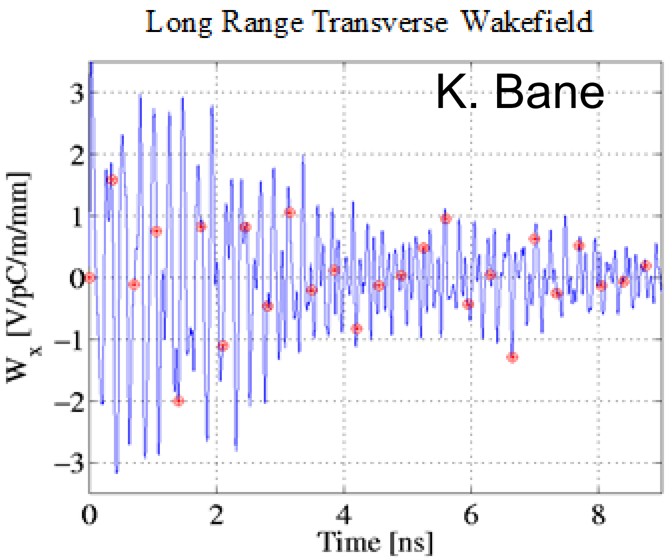






Two-Bucket Scheme. Wakefield issues short delays

Short delays (up to tens of nanoseconds), transverse wakefield problems.



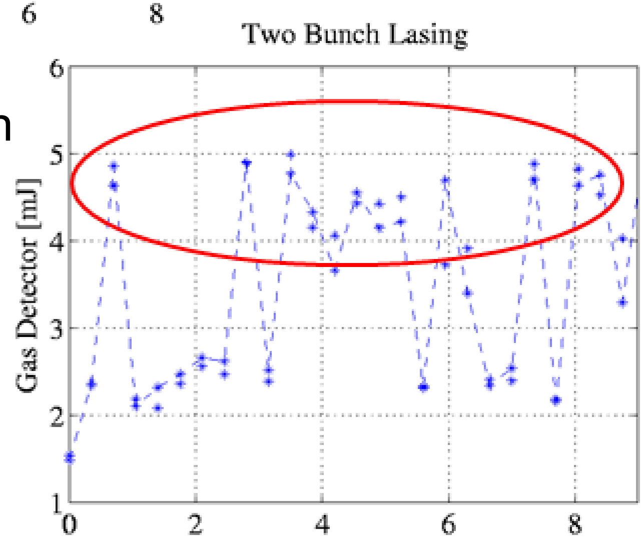
Transverse wake function

o 350 ns sampling

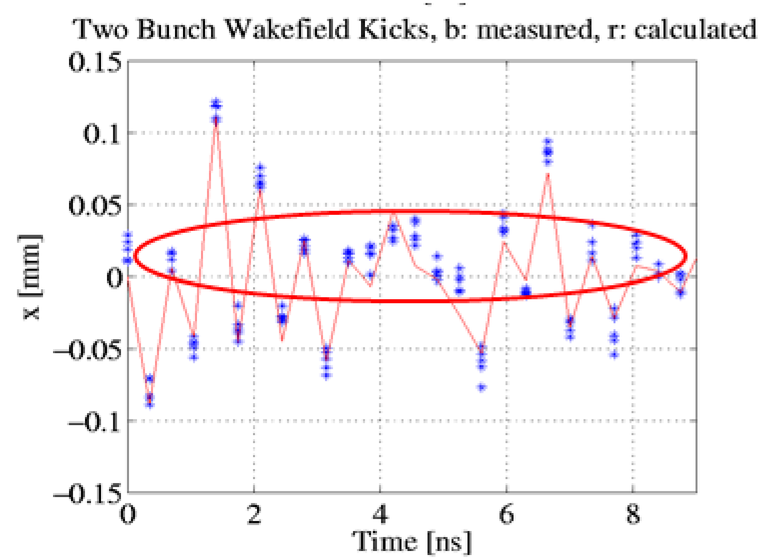
F.-J. Decker, K. Bane

Bucket separation scan

Transverse orbit feedback turned off



0 same bucket.

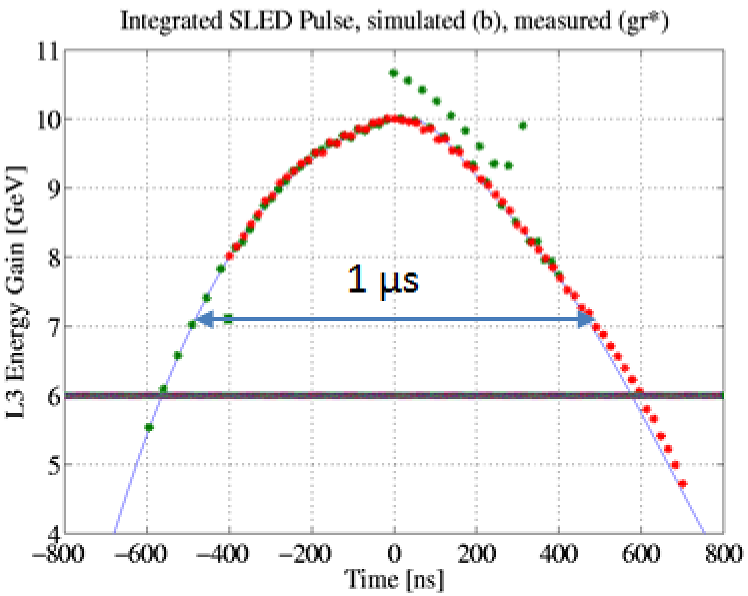


Two-Bucket Scheme

Long delays (~ 100 ns and above)

F.-J. Decker

- L0A, L0B pulses widened
- L1X, two pulses, one per bunch (lengthening increases temperature too much)
- L2,L3 might need unSLEDding.



By unSLEDding, 825 ns becomes 4000 ns, but with reduced energy gain.

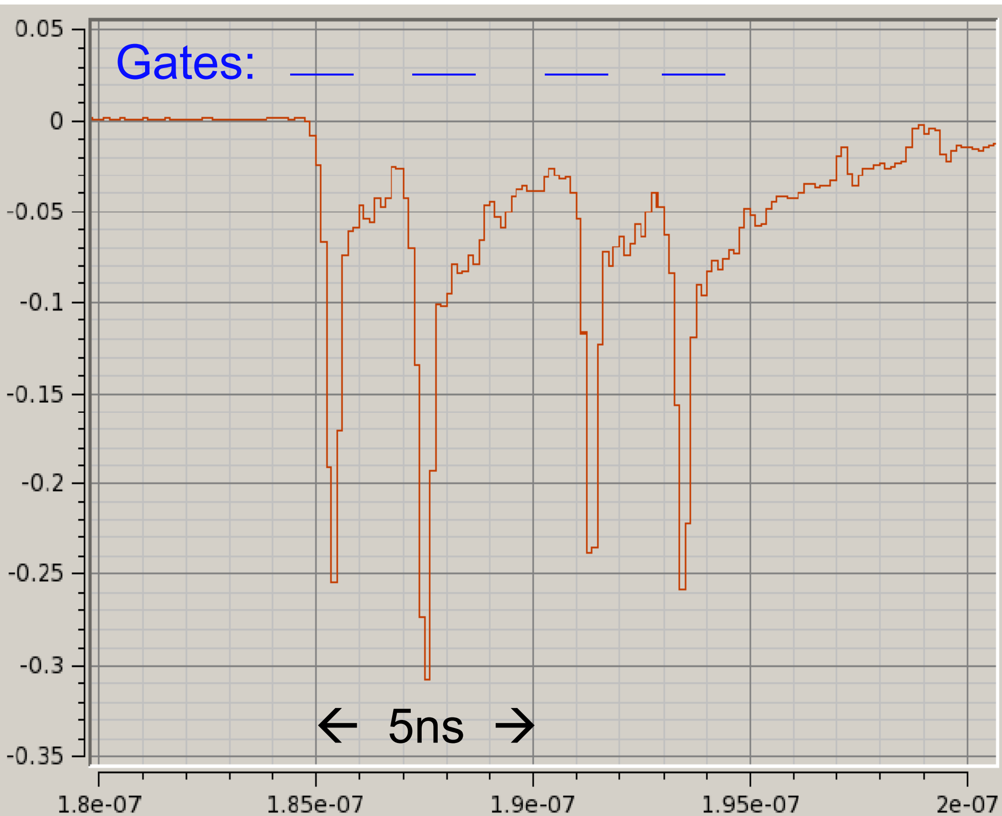
Not suitable for hard X-ray operation

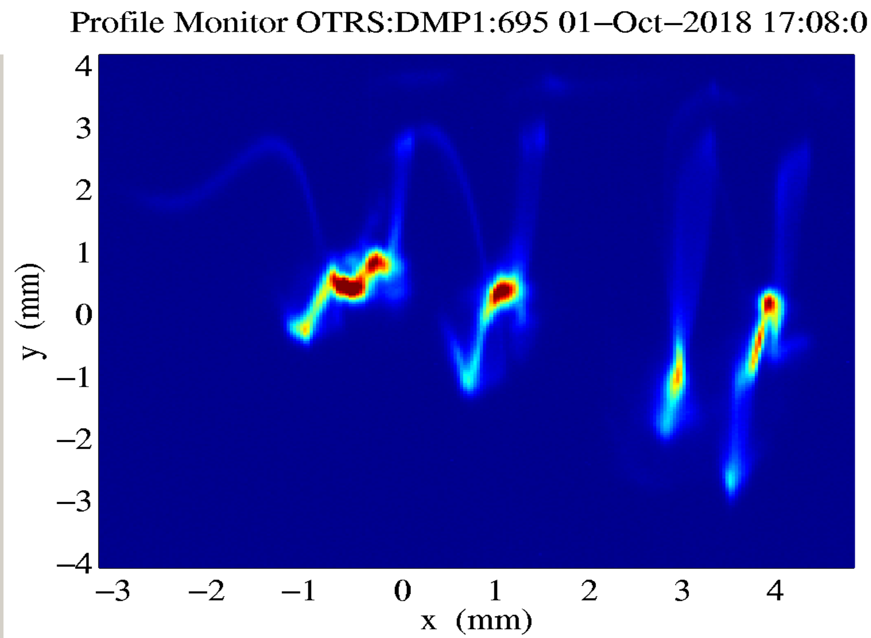
- XTCAV runs unSLEDded, just reduces streaking.

Two-Bucket Scheme
multiple bunches

F.-J. Decker

Fast-diode measurement at XCS endstation.





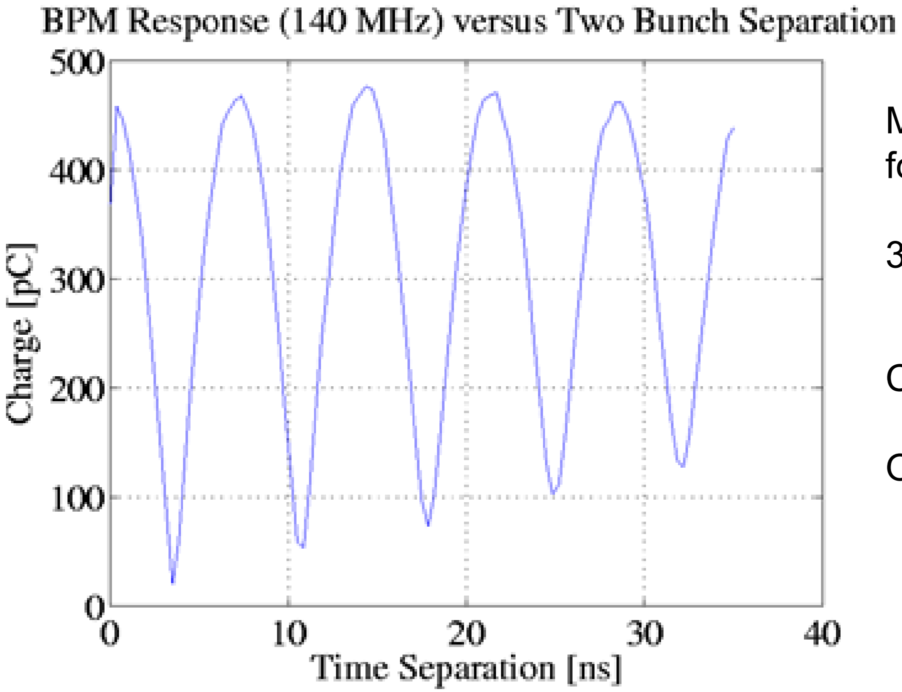
Time-resolved electron bunch phase spaces measurement of 4 bunches

MPPS Multi-Pulse Pulse-Stacker

Two-Bucket Scheme

Robustness and reliability:

- Beam setting up requires experts watching over many details.
- Anti-correlation between pulses
- Lasing at longer delays might fail.
- Energy scans are complicated, require re-tuning, pulses not identical.
- Feedback does not work for some delay.
- Pulse delay change ok, but not for all delays, need to be prepared beforehand.



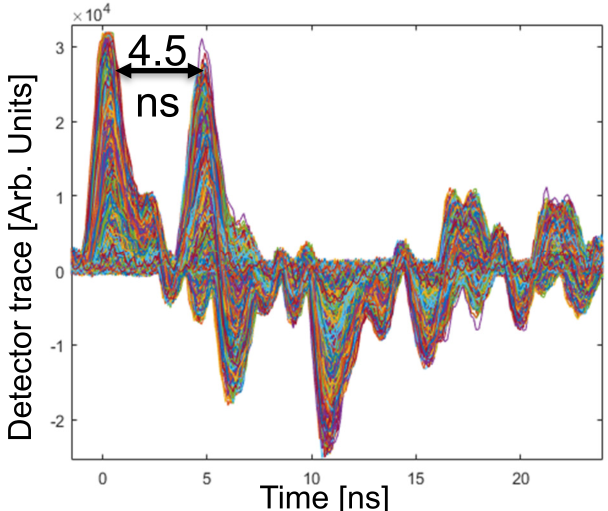
Measured charge as function of bucket delay. BPMs fail for delays of:

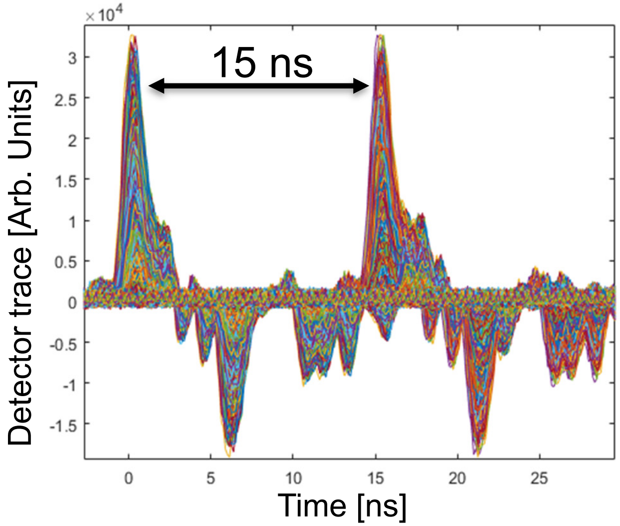
3.5 + 7 fs, for 140 MHz bandpass filtering

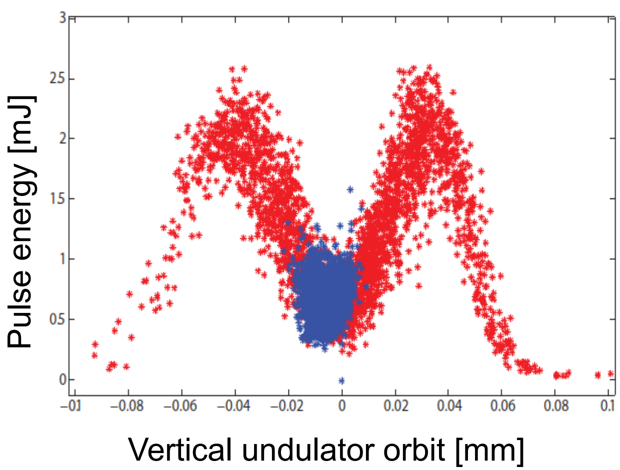
Cannot operate feedbacks for delays with failing BPMs.

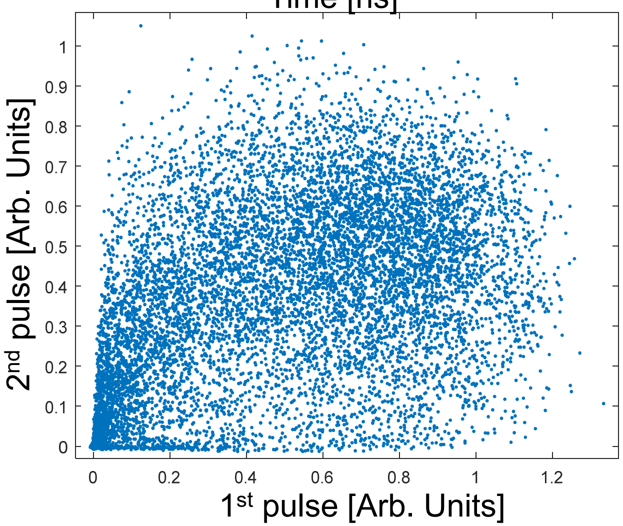
Ok to operate feedbacks far from notches.

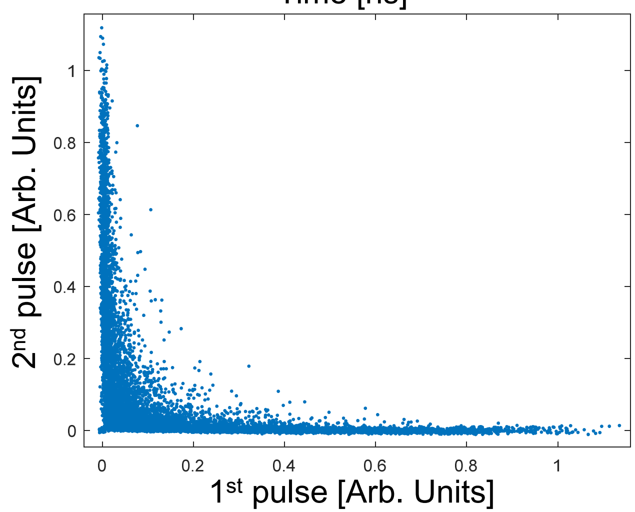
Two-Bucket Scheme pulse energy correlation.





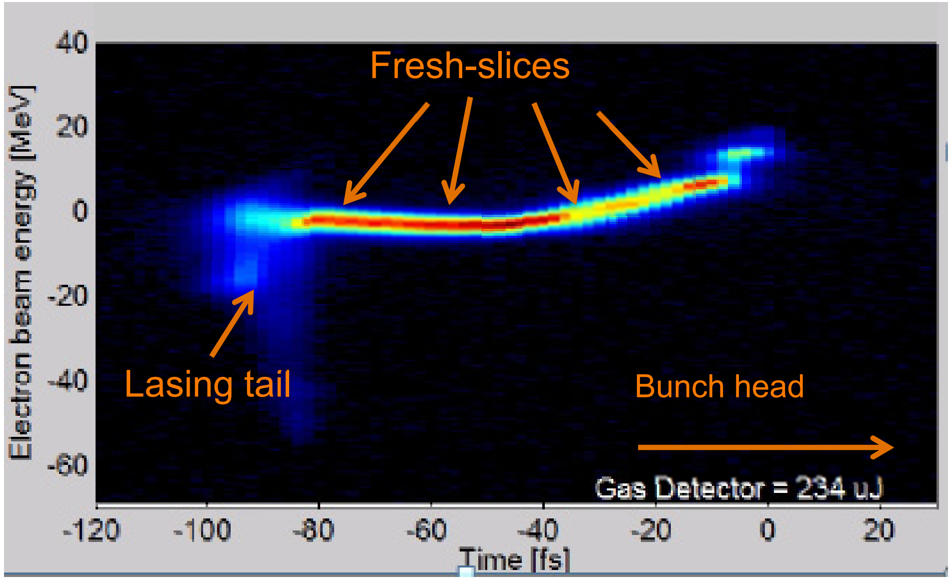






Fresh-slice Scheme

- Fresh-slice allows controlling which electron bunch slice lases in each undulator section, without spoiling the lasing-suppressed electron bunch slices.

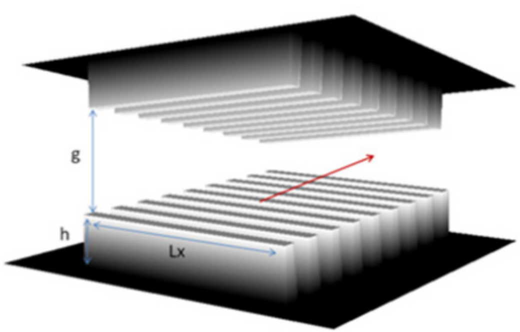


- Why Fresh-slice?

  Be more precise with bunch/slice definition.

  Avoid confusion with distinct bunches from the cathode.

- Fresh-slice lasing requires a time-dependent electron slice parameter that can be used to enable or disable the lasing process.



- Time-dependent orbit.
- Time-dependent focusing
- Time-dependent energy chirp

nature photonics ARTICLES
PUBLISHED ONLINE: 24 OCTOBER 2016 | DOI: 10.1038/NPHOTON.2016.201

Fresh-slice multicolour X-ray free-electron lasers

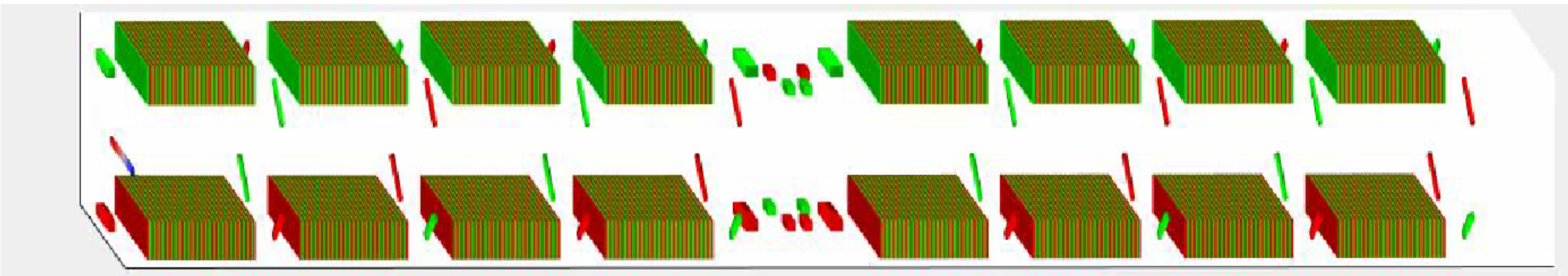
Alberto A. Lutman[1]*, Timothy J. Maxwell[1], James P. MacArthur[1], Marc W. Guetg[1], Nora Berrah[2], Ryan N. Coffee[1,3], Yuantao Ding[1], Zhirong Huang[1,3], Agostino Marinelli[1], Stefan Moeller[1] and Johann C. U. Zemella[1,4]

Fresh-slice Scheme (by time-dependent orbit)

First undulator section: K_1

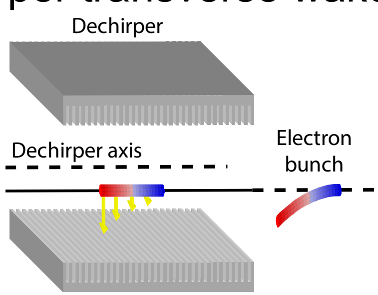
Correctors set
Head slice on axis

Second undulator section: K_2

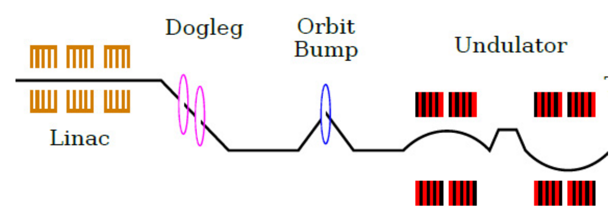


Time dependent orbit has been demonstrated by:

Dechirper transverse wakefield

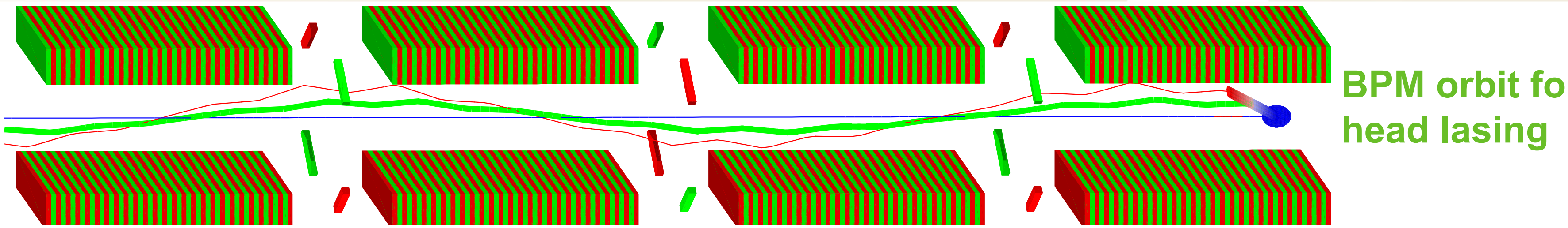


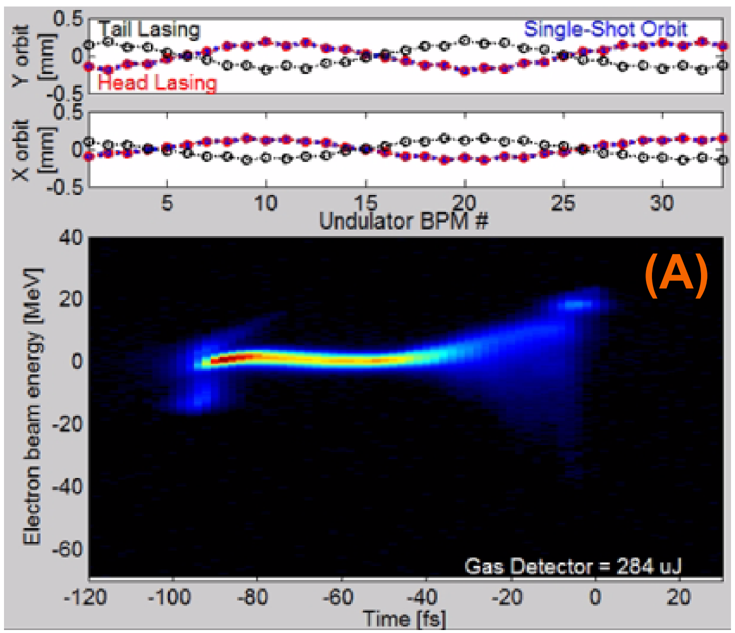
Energy chirp / dispersion.



Transverse Deflectors have been proposed

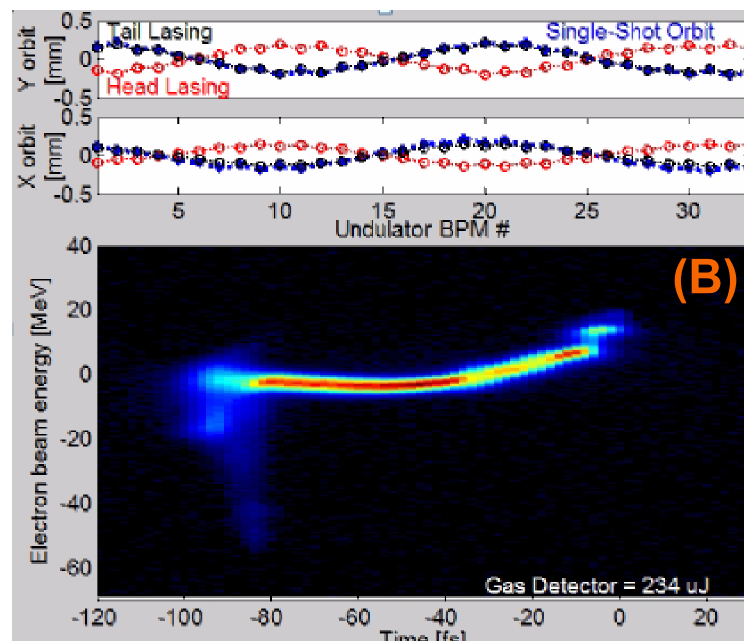
Fresh-slice Scheme (by time-dependent orbit)





1) The beam is tuned to lase uniformly on the entire phase space.

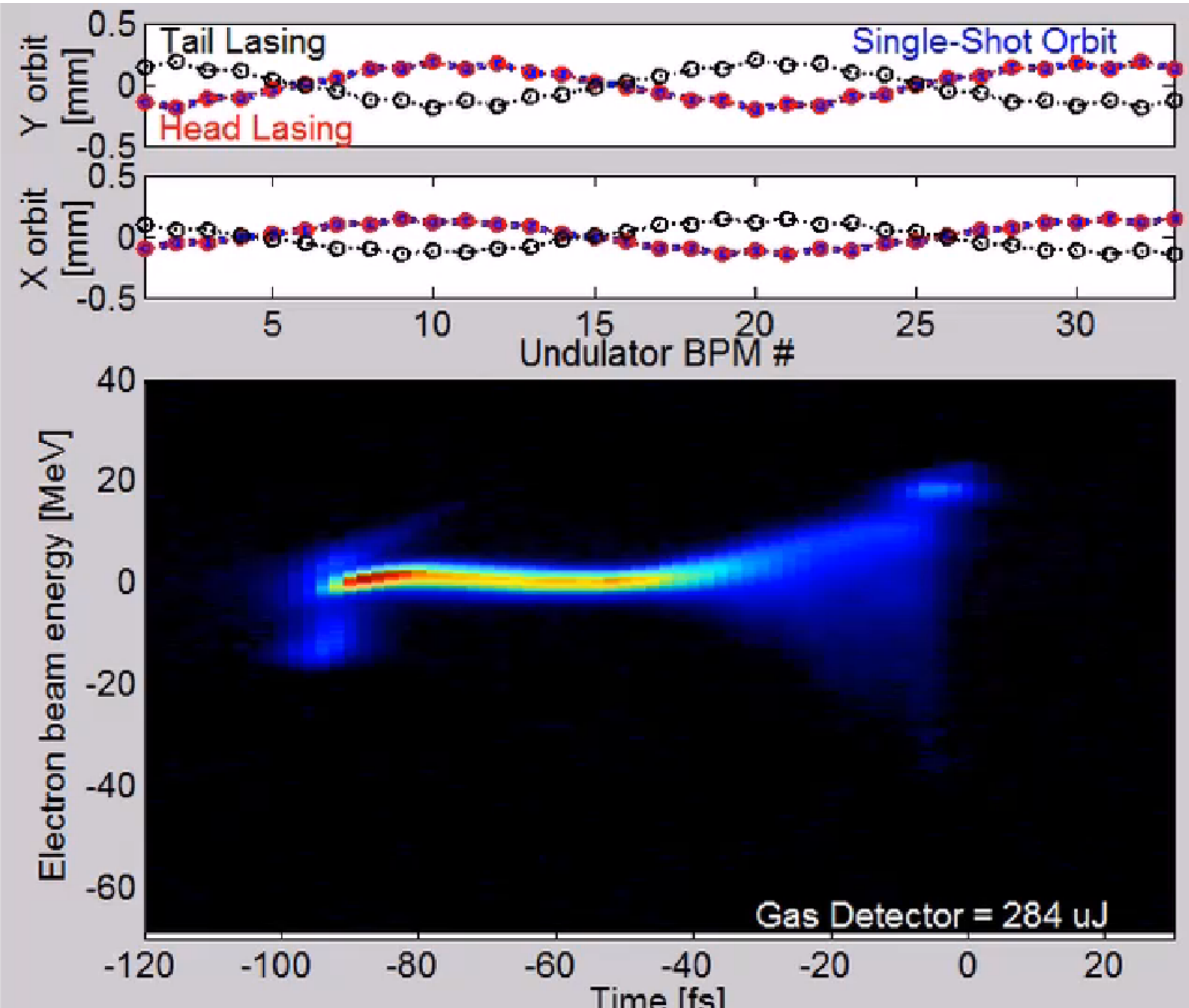
2) A dechirper jaw is set close to the bunch. The BPMs record the **Head Lasing** orbit. Only the head of the bunch lases **(A)**. The tail travels at an orbit about twice larger than the center-of-mass.



3) Orbit is controlled with correctors to select which slice is lasing. Different slices can lase in different undulator section.

4) **Tail Lasing** orbit is set, only the bunch tail lases. **(B)**. The head travels at an orbit about twice larger than the center-of-mass.

Fresh-slice Scheme
control of the lasing slice

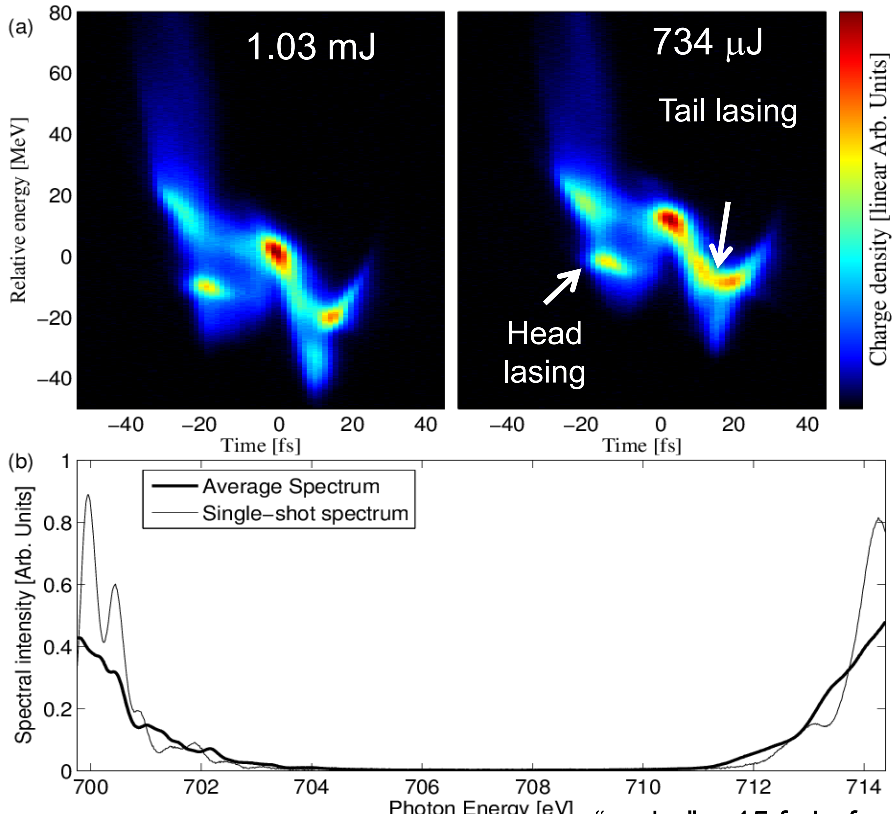


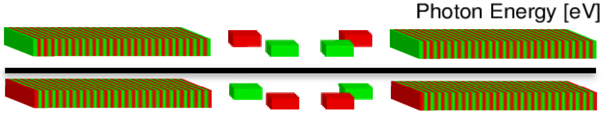
Red orbit: head lasing
Black orbit: tail lasing
Blue orbit: bunch orbit

- 1.8 keV operation
- Bunch head (right)

- Both dechirper used for increased suppression and quadrupole compensation

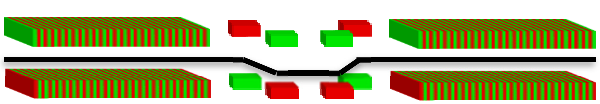
Fresh-slice Scheme two-color





“probe” ~ 15 fs before “pump”

No chicane delay, pulse on head arrives first



Chicane delays head pulse, scanning delay from small advance to large (1 ps) delays

Chicane delay >15 fs

pump before probe

With pump pulse in undulator 1-8 (allows long delays and zero delay crossing)

typical performance:

Pump ~ 150-200 uJ, 5-10 fs
Probe ~ 200-500 uJ, 8-15 fs

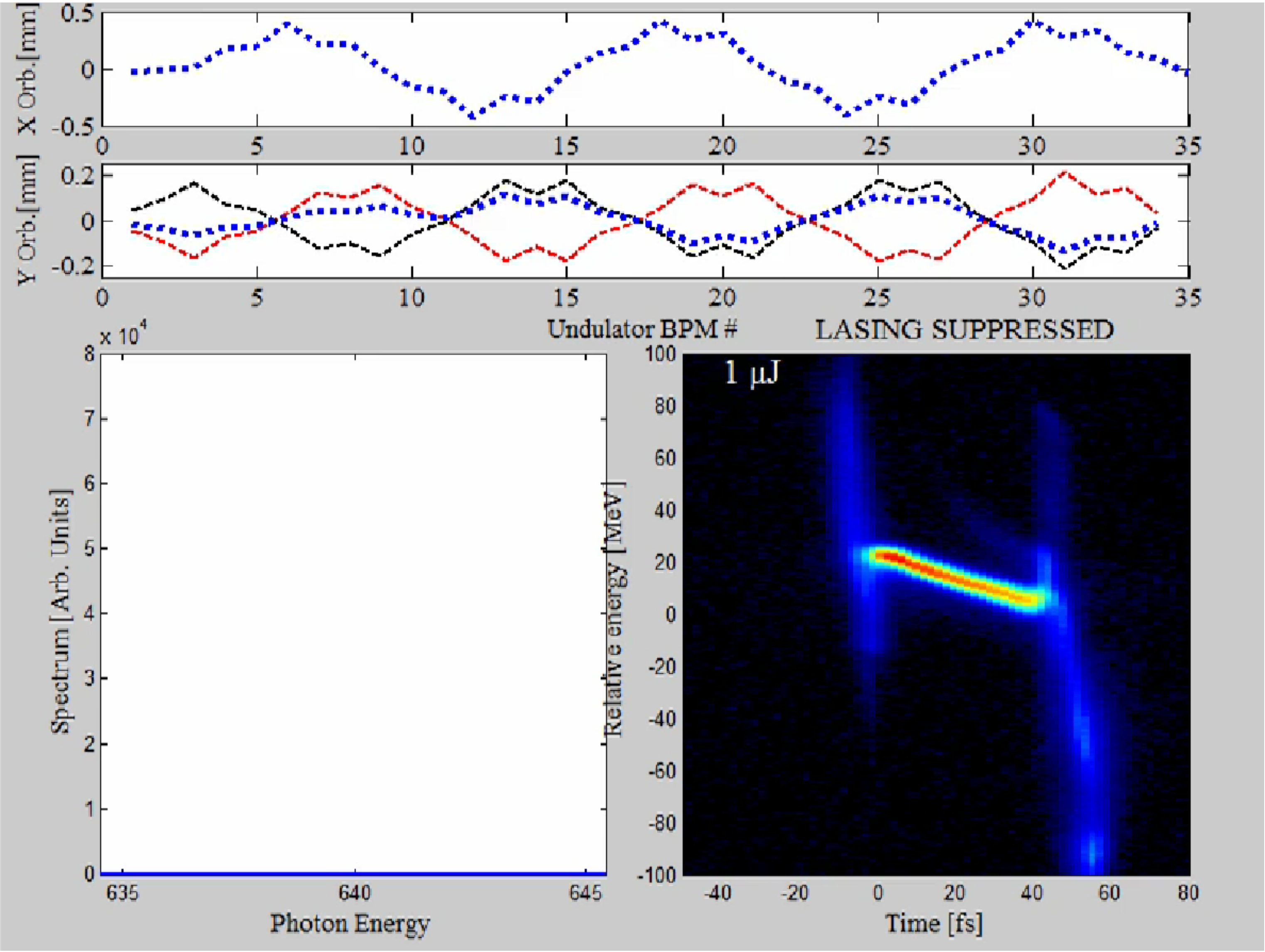
Max color separation ~2.5% (both sides)

Pulse on head (usually pump) may be up to 4% higher energy than pulse on tail (exploiting energy chirp)

> The transverse wake has approximately parabolic shape, therefore the lasing slice on the head has longer duration.

- Can scan through zero delay
- High power: different electron slices build up each pulse.

Fresh-slice double-pulses: Two color scheme.



Beam head

Head lasing in the first section for stronger pump pulse

Head lasing in U1-U8

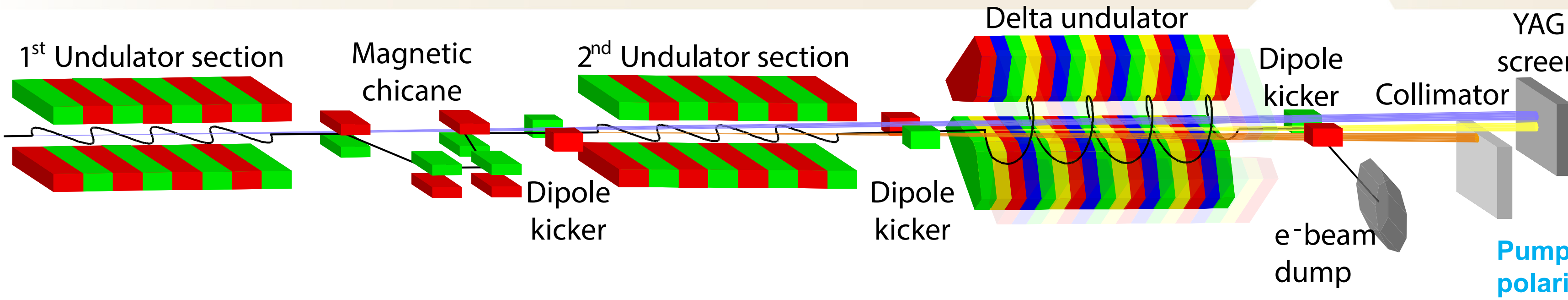
Tail lasing in U17-U33

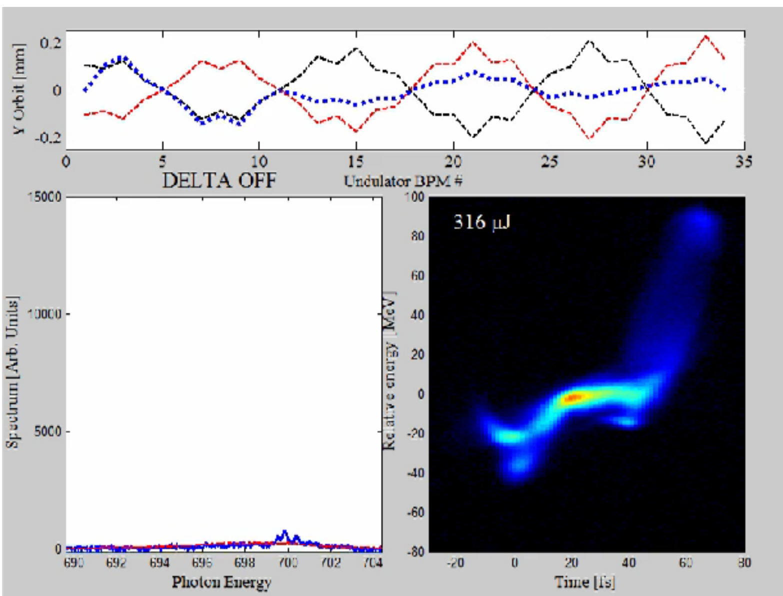
~ 500 uJ pump
~ 300 uJ probe

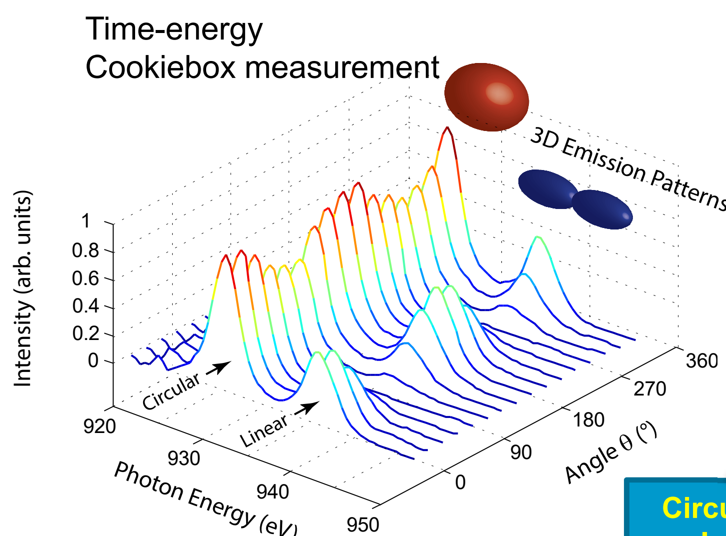
Chicane delay used up to 900 fs

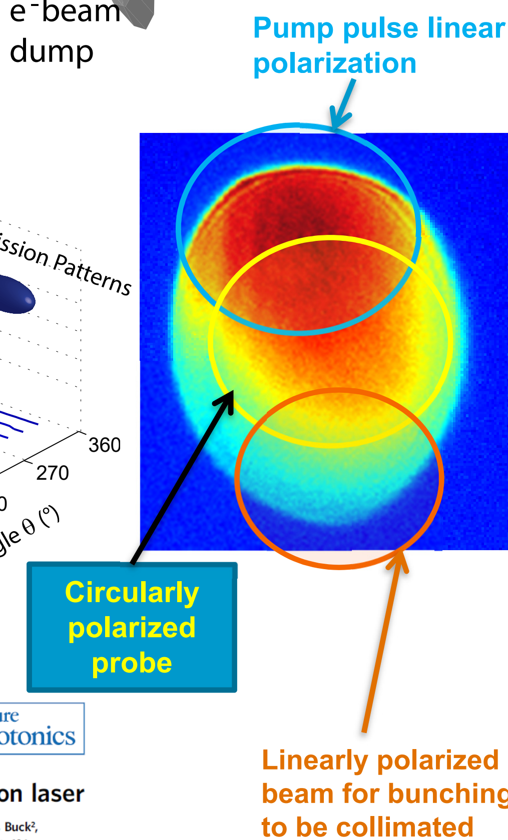
Small color separation required by the experiment

Each undulator line can be finely set: polarization, pointing, taper.









PHYSICAL REVIEW X 8, 041036 (2018)

Microbunch Rotation and Coherent Undulator Radiation from a Kicked Electron Beam

James P. MacArthur,[1,2,*] Alberto A. Lutman,[1] Jacek Krzywinski,[1] and Zhirong Huang[1,2,†]
[1]SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA
[2]Stanford University, Stanford, California 94305, USA

ARTICLES
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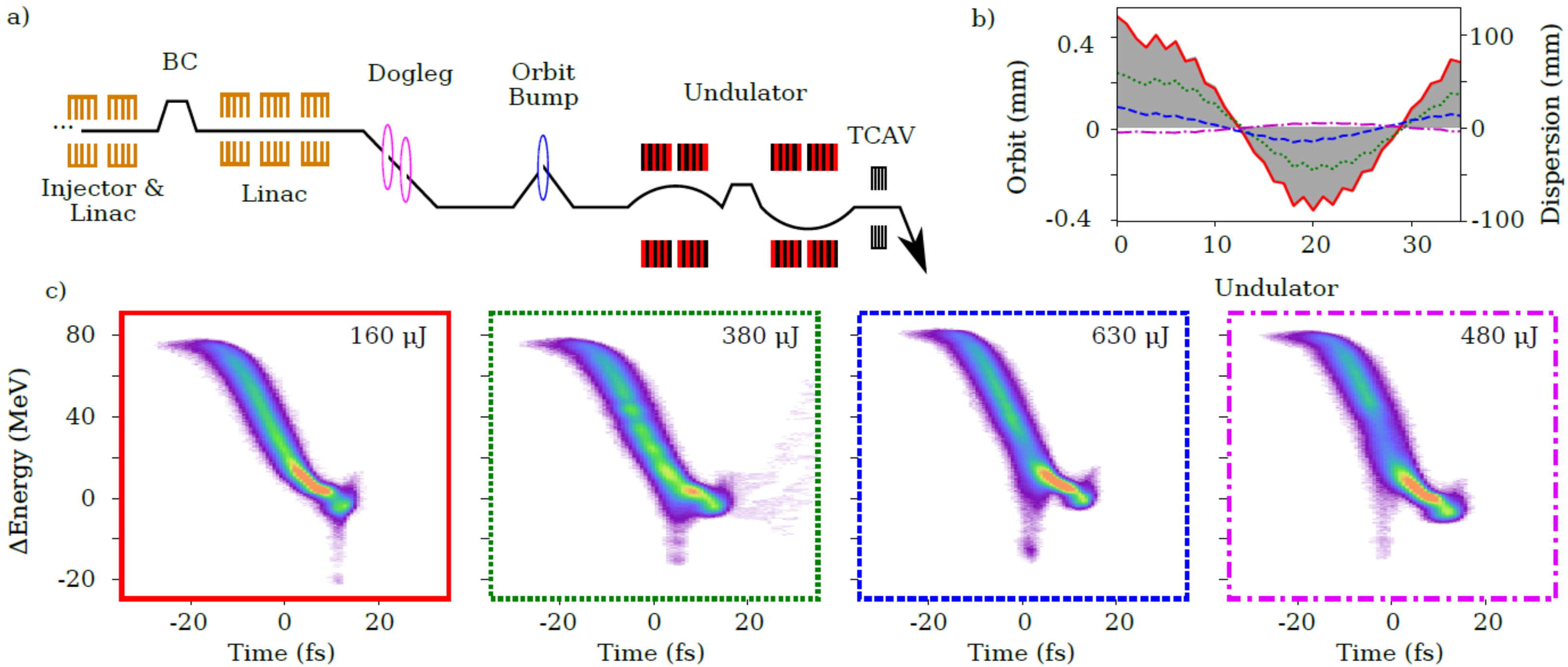
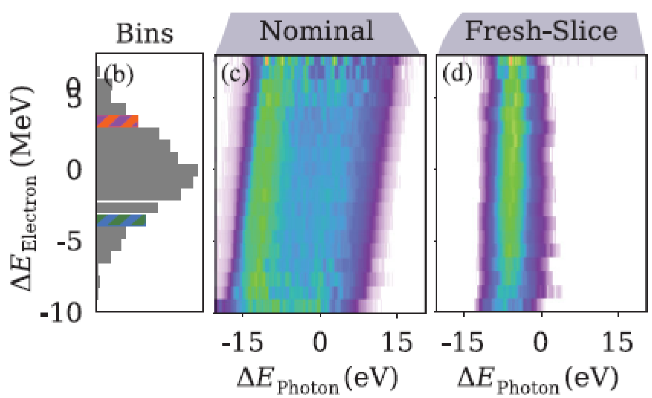
Polarization control in an X-ray free-electron laser

Alberto A. Lutman[1*], James P. MacArthur[1], Markus Ilchen[1,2,3], Anton O. Lindahl[3,4], Jens Buck[2], Ryan N. Coffee[1,3], Georgi L. Dakovski[1], Lars Dammann[5], Yuantao Ding[1], Hermann A. Dürr[1,3,6], Leif Glaser[5], Jan Grünert[2], Gregor Hartmann[5], Nick Hartmann[1,7], Daniel Higley[1], Konstantin Hirsch[1], Yurii I. Levashov[1], Agostino Marinelli[1], Tim Maxwell[1], Ankush Mitra[1], Stefan Moeller[1], Timur Osipov[1], Franz Peters[1], Marc Planas[2], Ivan Shevchuk[5], William F. Schlotter[1], Frank Scholz[5], Jörn Seltmann[5], Jens Viefhaus[5], Peter Walter[5], Zachary R. Wolf[1], Zhirong Huang[1,3] and Heinz-Dieter Nuhn[1]

Dispersion-orbit Fresh-slice.

Energy-chirped beam by over-compression, and quadrupole in dispersive section





Stabilizes emission wavelength

Doesn't require a dechirper

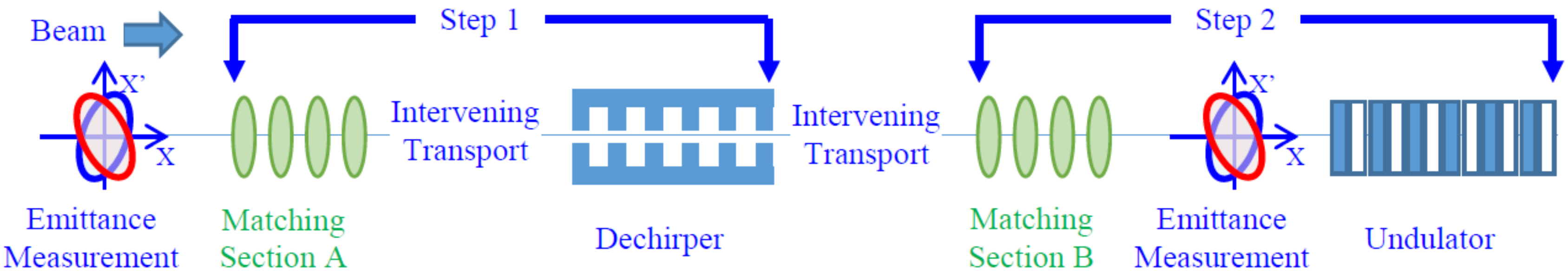
PHYSICAL REVIEW LETTERS **120,** 264802 (2018)

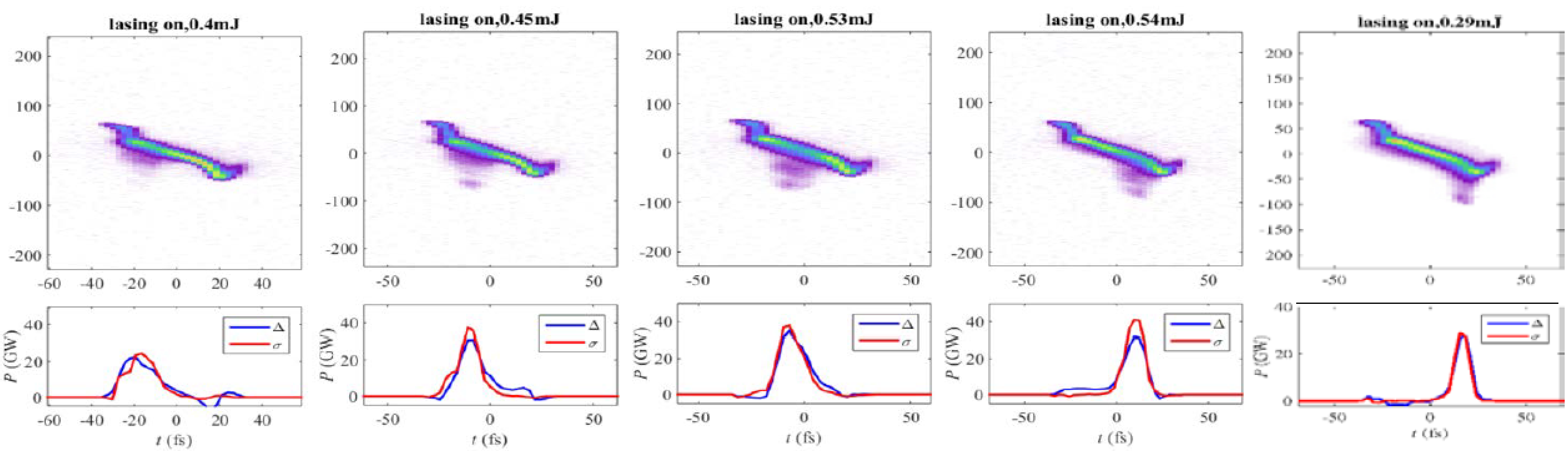
Dispersion-Based Fresh-Slice Scheme for Free-Electron Lasers

Marc W. Guetg,* Alberto A. Lutman, Yuantao Ding, Timothy J. Maxwell, and Zhirong Huang

SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA

Matching-based dechirper Fresh-slice control





PHYSICAL REVIEW ACCELERATORS AND BEAMS **20,** 090701 (2017)

Matching-based fresh-slice method for generating two-color x-ray free-electron lasers

Weilun Qin,[1,2] Yuantao Ding,[2] Alberto A. Lutman,[2] and Yu-Chiu Chao[2,*]

PHYSICAL REVIEW LETTERS **121,** 064802 (2018)

Control of the Lasing Slice by Transverse Mismatch in an X-Ray Free-Electron Laser

Yu-Chiu Chao,[1,*] Weilun Qin,[1,2] Yuantao Ding,[1] Alberto A. Lutman,[1] and Timothy Maxwell[1]
[1]*SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA*
[2]*Institute of Heavy Ion Physics, School of Physics, Peking University, Beijing 100871, China*

Robustness of the Fresh-slice methods LCLS experience.

Matching-based Fresh-slice:

- Matching far more difficult than controlling orbit.
- Re-matching in undulator line requires stronger quadrupoles / more space.
- Lasing control succeeded ~50% of attempts.
- Two-color were never demonstrated.

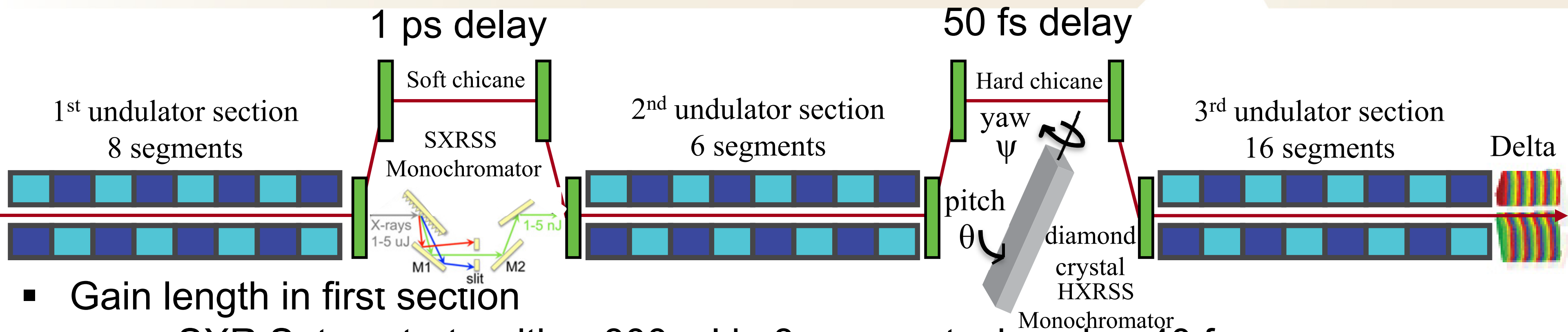
- Slice emittance measurement may improve setup.

Dispersion based Fresh-slice:

- Achieved performance for two color far below dechirper based method.
  (gain-length of over-compressed beam, matching)
- Time-dependent performance of chirped beam.
- Making tilt has impact on matching.
- Setup at lower energies did not succeed.

→ User deliveries have been all with dechirper based method.

Robustness of the dechirper/orbit Fresh-slice LCLS experience.



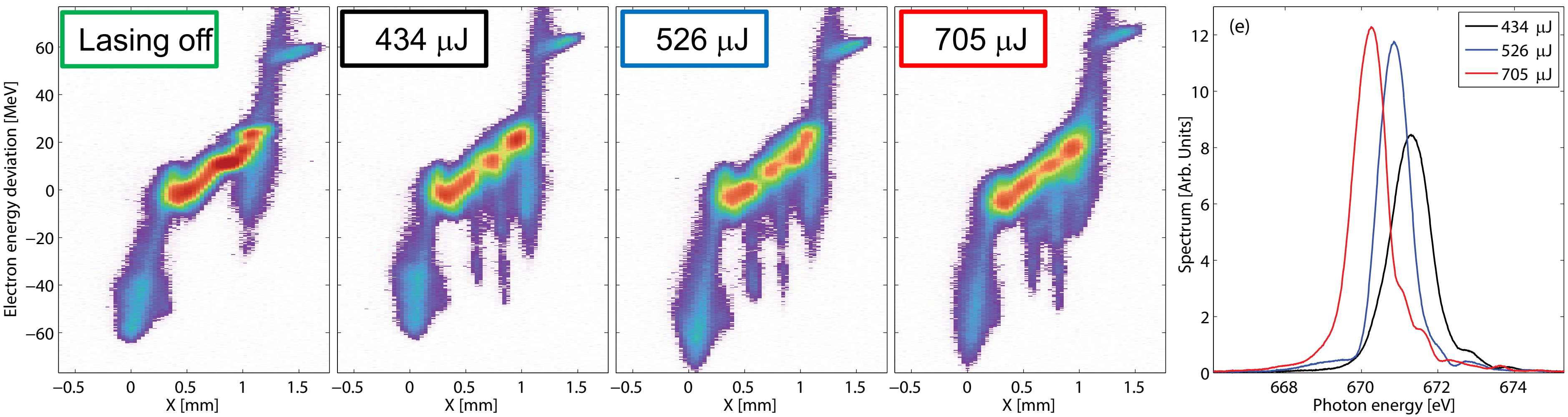
- Gain length in first section
  SXR Setup starts with ~ 800 uJ in 8 segments, bunch ~ 40 fs
  Reproducibility of this setup is the main issue.
- Losses downstream of dechirper to achieve required tilt.

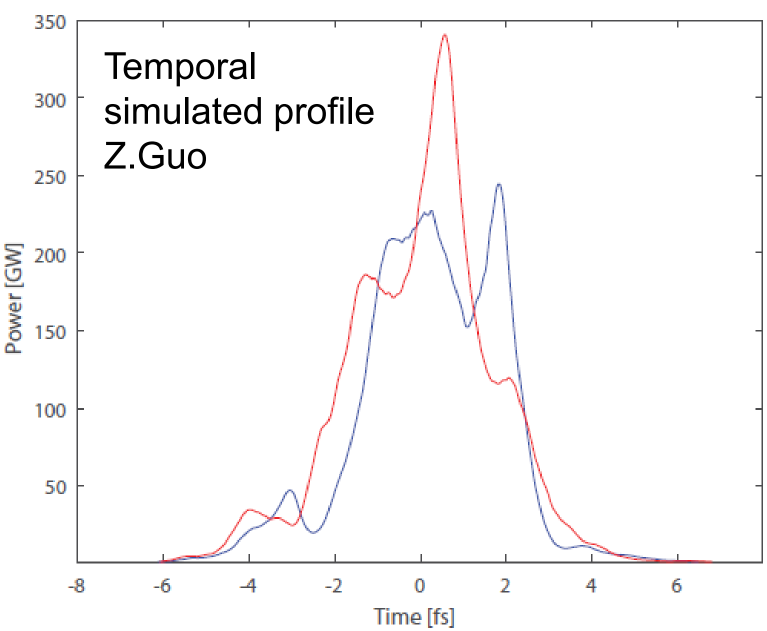
- Bunch tilt on X when dechirper is out
- Bad compensation of defocusing

- Downstream dechirper flattens orbit on tail.
- Pulse power control:
  - Second pulse easy (kick beam out)
  - First pulse, better pointing beam out
- Delay scan with same (close) color and 1st pulse overlaps with electrons.

- Longest delivery time ~ 6 hours, typical 1.5-3 hours.

Cascaded Fresh-slice schemes





1 Spike	2 Spikes	3 Spikes	>3 Spikes
13%	36%	36 %	15 %
304 μJ	299 μJ	289 μJ	235 μJ

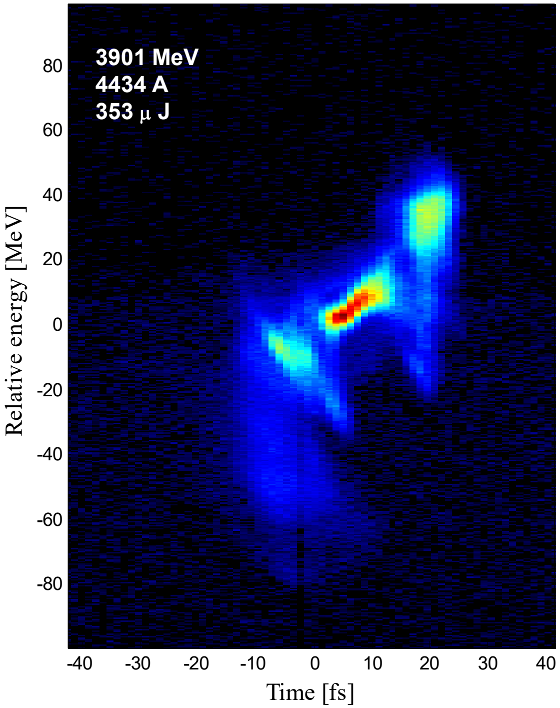
PHYSICAL REVIEW LETTERS **120,** 264801 (2018)

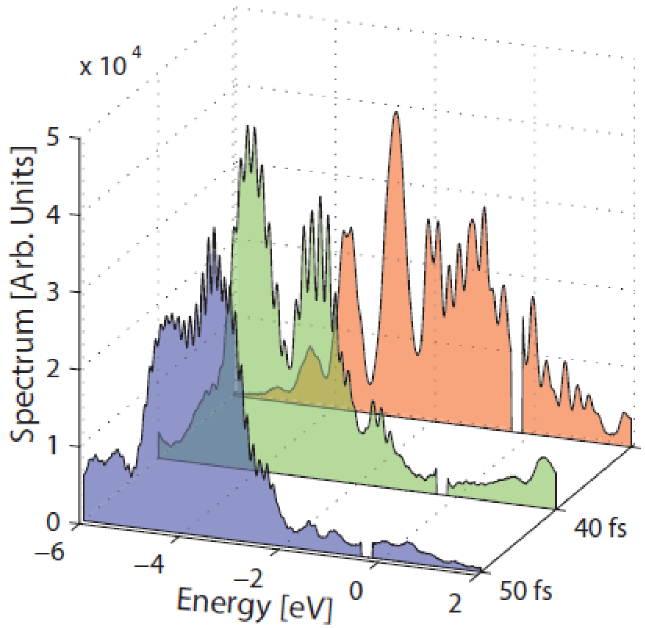
Featured in Physics

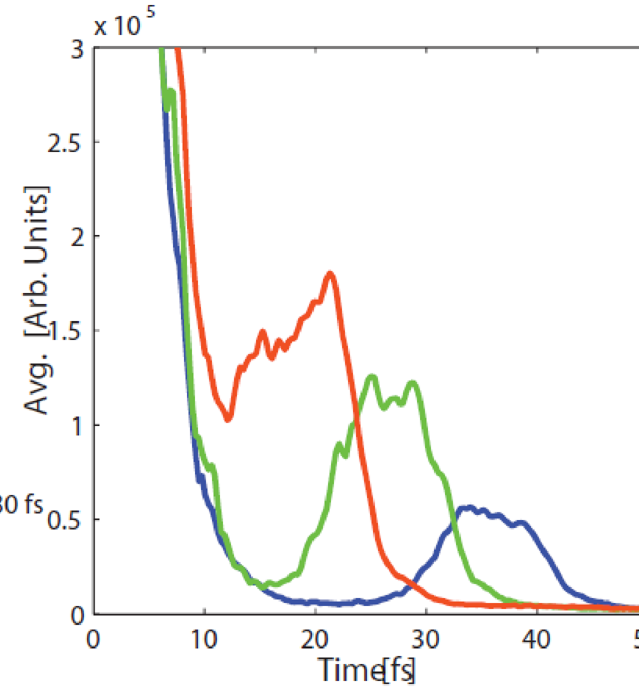
High-Power Femtosecond Soft X Rays from Fresh-Slice Multistage Free-Electron Lasers

Alberto A. Lutman,* Marc W. Guetg, Timothy J. Maxwell, James P. MacArthur, Yuantao Ding,
Claudio Emma, Jacek Krzywinski, Agostino Marinelli, and Zhirong Huang

Cascaded Fresh-slice schemes two-color SASE

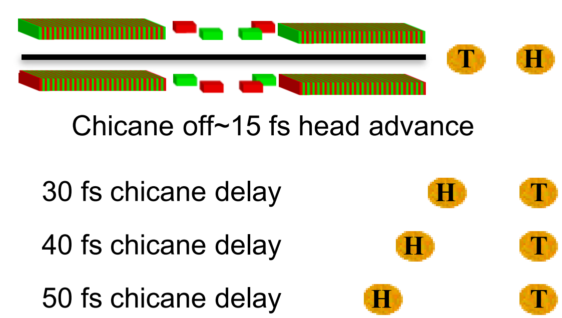






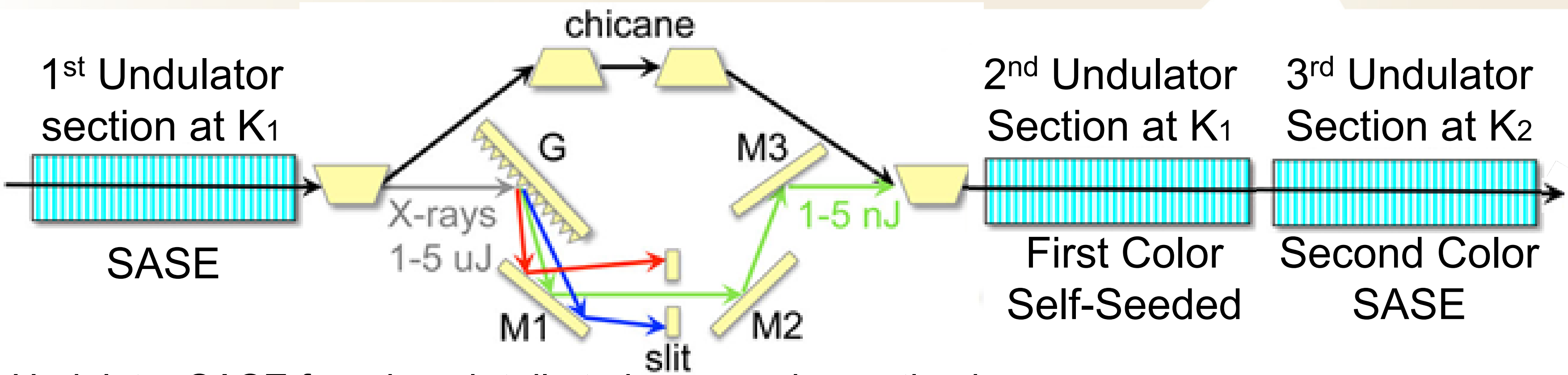
- 160 μJ total (on average)
- 2-stage pump, 1-stage probe
- ~30 fs chicane delay sets tail pulse ~15 fs before head pulse
- Same wavelength set by K.

Fringes Fourier analysis allows to determine the actual delay between x-ray pulses

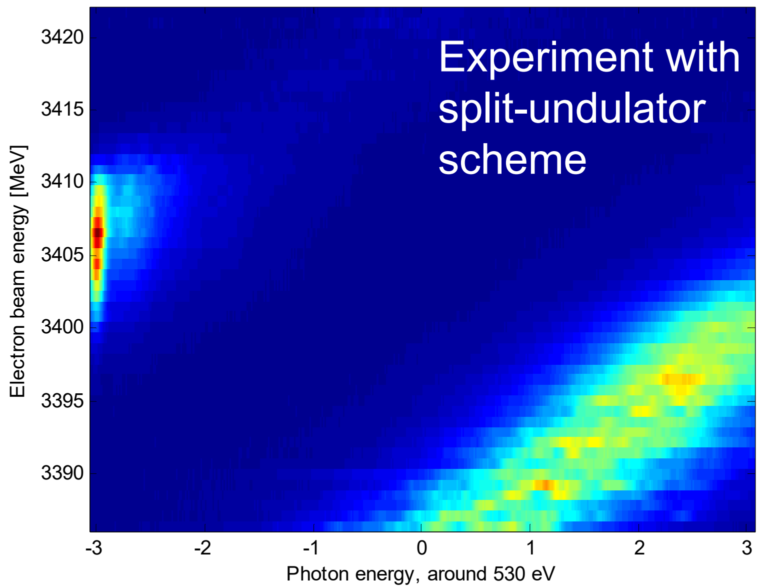


- Simple control of duration of both pulses

Cascaded Fresh-slice schemes two-color SASE+SEEDED



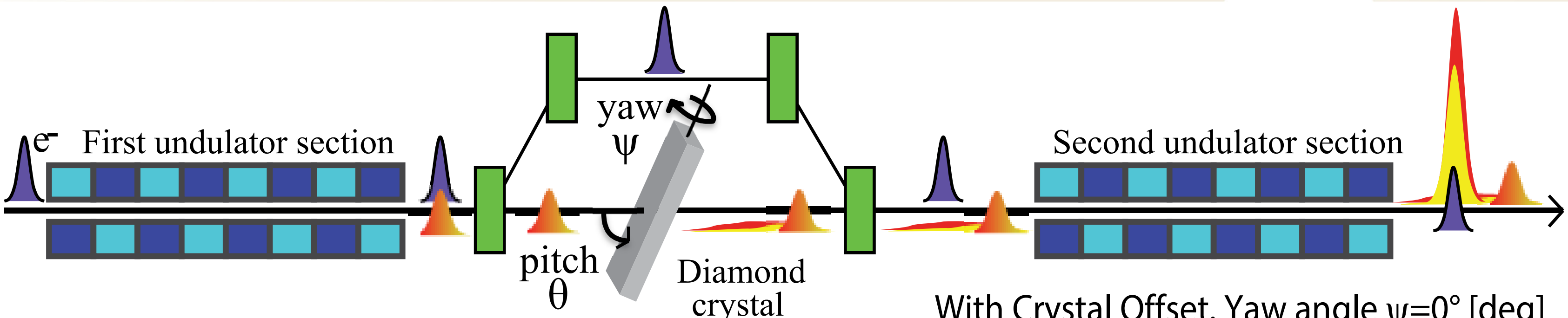
1st Undulator SASE from bunch tail, to be monochromatized.
2nd Undulator Self-seeding amplified on tail.
3rd Undulator SASE second color from shot noise. HXRSS chicane controls delay.

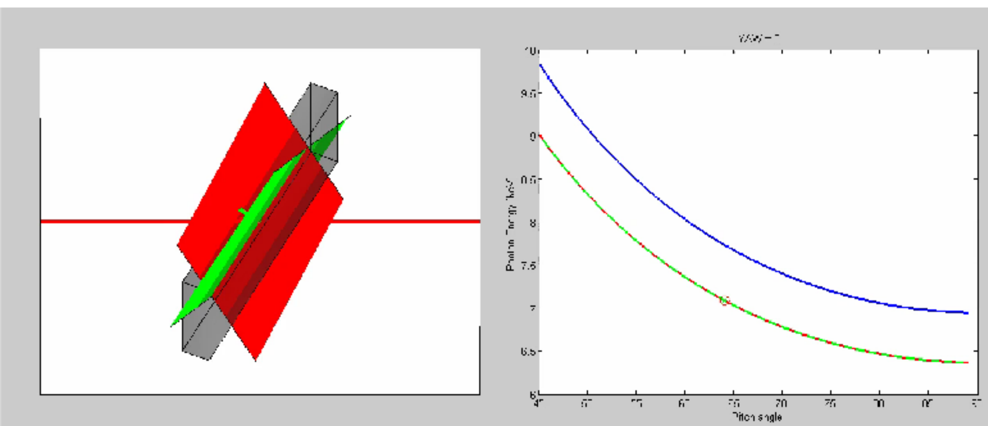


Two-color on collimator

Two-color self-seeding.

SLAC





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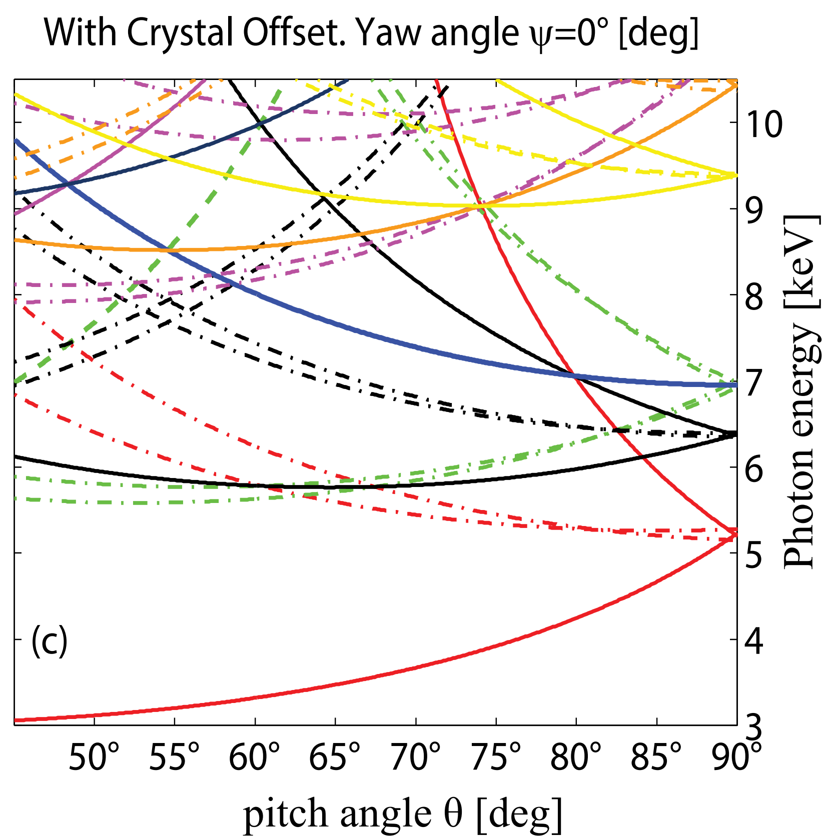


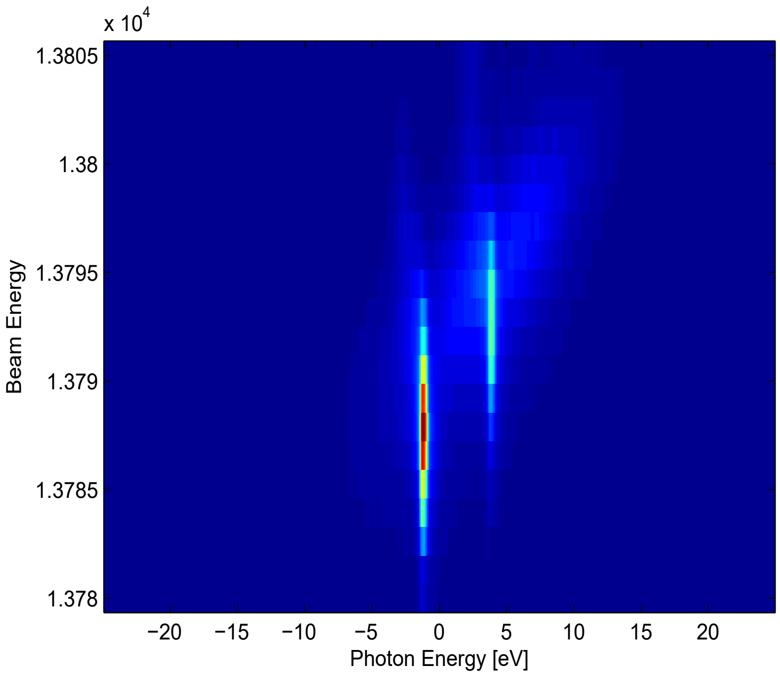
PRL 113, 254801 (2014) PHYSICAL REVIEW LETTERS week ending 19 DECEMBER 2014

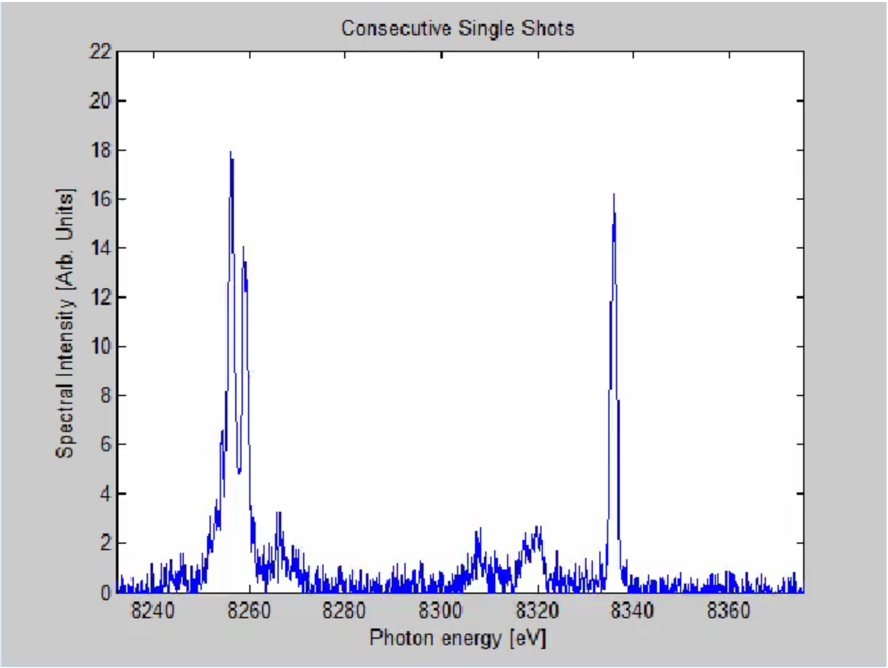
Demonstration of Single-Crystal Self-Seeded Two-Color X-Ray Free-Electron Lasers

A. A. Lutman,* F.-J Decker,† J. Arthur, M. Chollet, Y. Feng, J. Hastings, Z. Huang, H. Lemke, H.-D. Nuhn, A. Marinelli, J. L. Turner, S. Wakatsuki, J. Welch, and D. Zhu

Two-color self-seeding.

El. beam energy [MeV]





ph. energy [eV] (from central 8.4 keV)

Two-colors supported by
same electron bunch

No control on time-delay

Two-colors supported by
twin-bunch setup

Delay control, separation up to 1%

Conclusion

- The choice of two-color scheme depends mainly on photon beam requirements.

  Long ns delays → Two-buckets

  femtosecond delays → Fresh-slice or Twin-bunch
  - HXR, Twin-bunch preferred (as long as supports enough color separation and not same color)
  - SXR, Fresh-slice preferred (easier to setup, longer delay supported)

- Schemes can be often combined, this adds complication
  - Twin-bunch + self-seeding
  - Fresh-slice + polarization control

- Dechirper-orbit Fresh-slice is the only one that has been delivered to users:
  - easier setup
  - best performance
  - both basic scheme and cascaded 2 stage pump / 1 stage probe.

- Schemes are stable once setup, but setup requires experts.
- Understanding what schemes actually deliver may require experts.

FINE

THANK YOU FOR YOUR ATTENTION