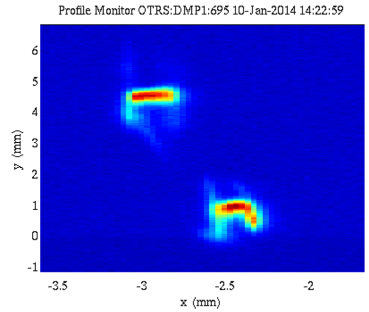
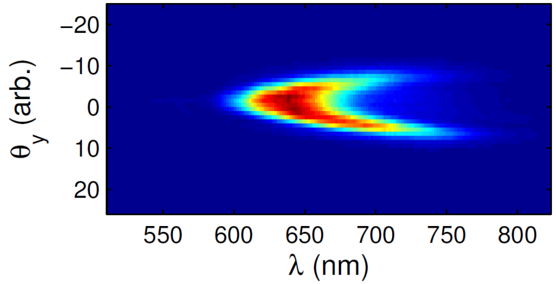
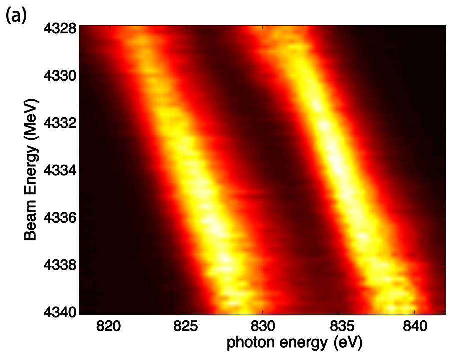
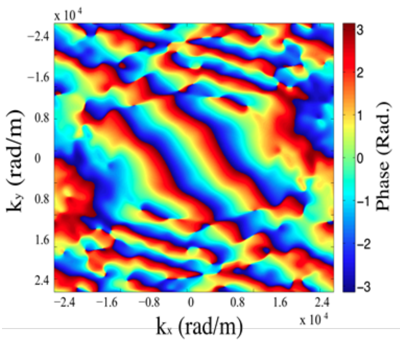




FEL R&D Initiatives at the SLAC National Accelerator Laboratory





Agostino Marinelli

SLAC

IPAC 2014,

June, 19 - Dresden

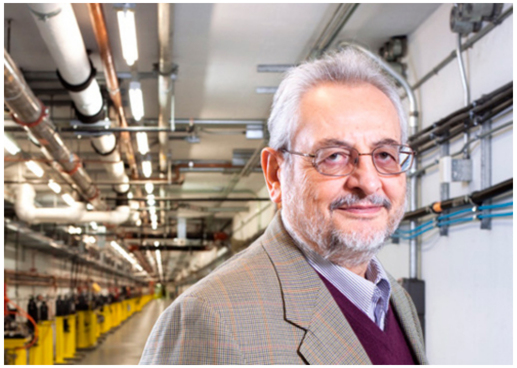
U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Acknowledgements

Gigi Palumbo

Jamie Rosenzweig



Claudio Pellegrini

Zhirong Huang

Acknowledgements

- All my colleagues and friends at SLAC, UCLA, University of Rome and INFN.
- The IPAC prize committee for honoring me with the Frank Sacherer prize and inviting me here.

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- The IPAC prize committee for honoring me with the Frank Sacherer prize and inviting me here.
- My family for their constant love and support.

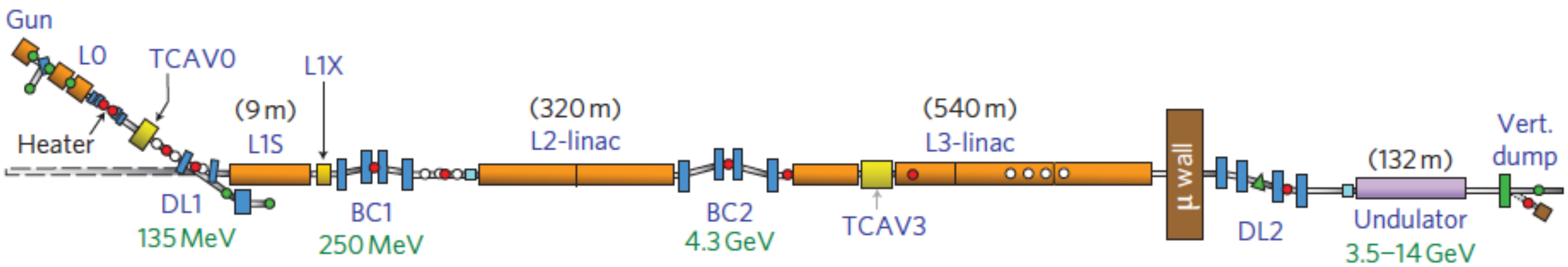
Outline of the Talk

1) The X-Ray Free-Electron Laser

2) Research and Development Activities on X-FELs:
   - -LCLS: multicolor/multibunch operation
   - -NLCTA: longitudinal space-charge amplifier

3) Conclusions

The X-Ray Free Electron Laser



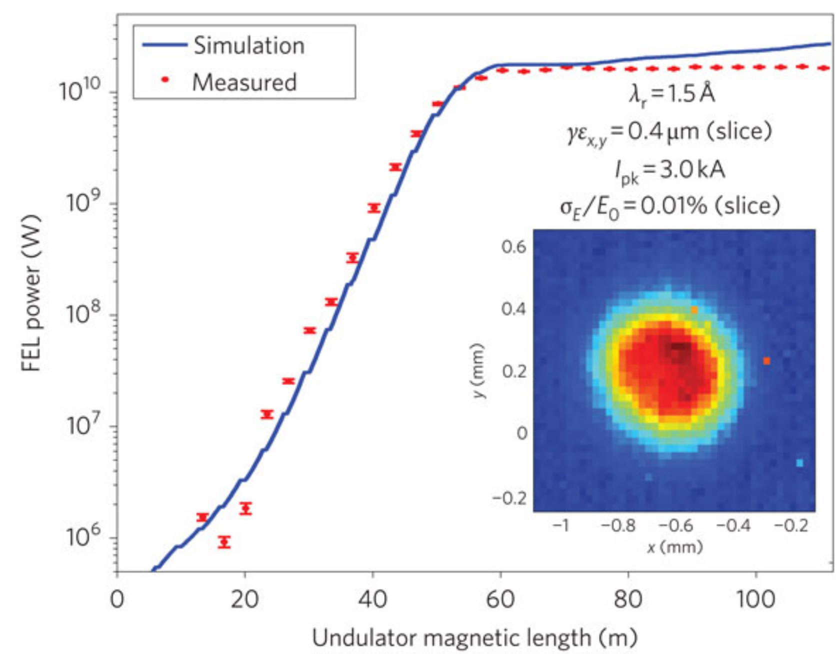
X-FEL shares properties of conventional lasers:

-High Power (~ 100 GW)
-Short Pulse (~5-100 fs)
-Narrow Bandwidth (~0.1% to 0.005%)
-Transverse Coherence

nature photonics
ARTICLES
PUBLISHED ONLINE: 1 AUGUST 2010 | DOI: 10.1038/NPHOTON.2010.176

First lasing and operation of an ångstrom-wavelength free-electron laser

P. Emma[1]*, R. Akre[1], J. Arthur[1], R. Bionta[2], C. Bostedt[1], J. Bozek[1], A. Brachmann[1], P. Bucksbaum[1], R. Coffee[1], F.-J. Decker[1], Y. Ding[1], D. Dowell[1], S. Edstrom[1], A. Fisher[1], J. Frisch[1], S. Gilevich[1], J. Hastings[1], G. Hays[1], Ph. Hering[1], Z. Huang[1], R. Iverson[1], H. Loos[1], M. Messerschmidt[1], A. Miahnahri[1], S. Moeller[1], H.-D. Nuhn[1], G. Pile[3], D. Ratner[1], J. Rzepiela[1], D. Schultz[1], T. Smith[1], P. Stefan[1], H. Tompkins[1], J. Turner[1], J. Welch[1], W. White[1], J. Wu[1], G. Yocky[1] and J. Galayda[1]



FEL R&D at SLAC: LCLS

Spectral Manipulation of FELs:

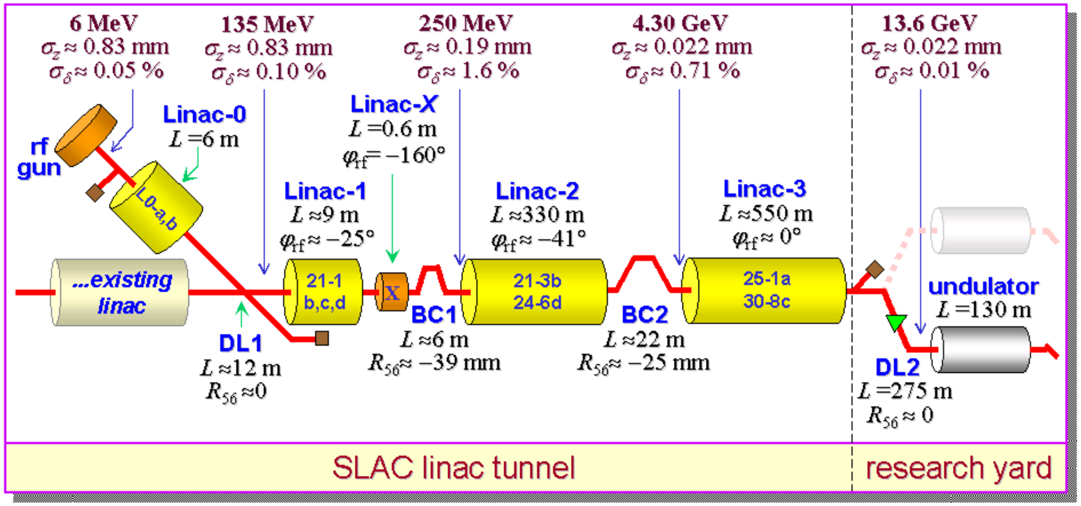
-Self seeding (HXR and SXR)
-Multicolor Operation
(split undulator, gain-modulation, multi-bunch mode)
-iSASE

Temporal Diagnostics:

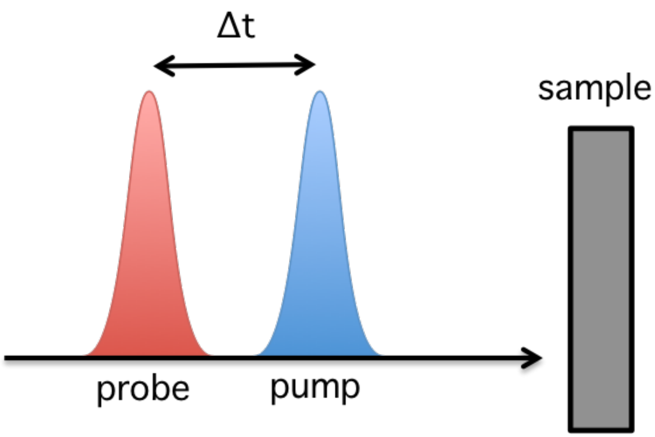
-X-ray pulse reconstruction with x-band deflector and coherent radiation.

Photon Science User facility:
R&D mostly oriented towards improving/expanding user operation.

IDEA ->
EXPERIMENTAL DEMONSTRATION -> TRANSITION TO USER OPERATION



2 Color Free-Electron Lasers



$$\lambda_{1,2} = \lambda_w \frac{1+K_{1,2}^2}{2\gamma^2}$$

$$\lambda_{1,2} = \lambda_w \frac{1+K^2}{2\gamma_{1,2}^2}$$

2 pulses with

-tunable energy difference

-tunable arrival time

Many applications!

- x-ray pump/x-ray probe
- 2 color diffraction imaging

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
SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA
(Received 13 December 2012; published 25 March 2013)

PRL 111, 134801 (2013) PHYSICAL REVIEW LETTERS week ending 27 SEPTEMBER 2013

Multicolor Operation and Spectral Control in a Gain-Modulated X-Ray Free-Electron Laser

A. Marinelli,[1,*] A. A. Lutman,[1] J. Wu,[1] Y. Ding,[1] J. Krzywinski,[1] H.-D. Nuhn,[1] Y. Feng,[1] R. N. Coffee,[1] and C. Pellegrini[2,1]

PRL 110, 064801 (2013) PHYSICAL REVIEW LETTERS week ending 8 FEBRUARY 2013

Chirped Seeded Free-Electron Lasers: Self-Standing Light Sources for Two-Color Pump-Probe Experiments

Giovanni De Ninno,[1,2] Benoît Mahieu,[1,2,3] Enrico Allaria,[2] Luca Giannessi,[2,4] and Simone Spampinati[2]

ARTICLE

Received 8 Sep 2013 | Accepted 12 Nov 2013 | Published 4 Dec 2013 DOI: 10.1038/ncomms3919

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

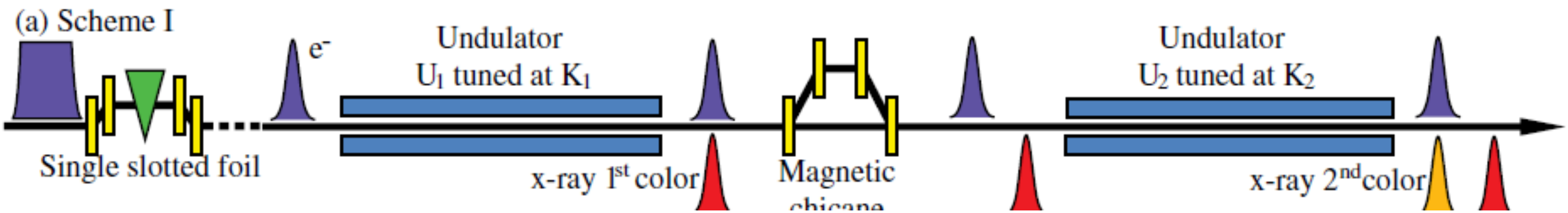
Toru Hara[1], Yuichi Inubushi[1], Tetsuo Katayama[2], Takahiro Sato[1,†], Hitoshi Tanaka[1], Takashi Tanaka[1], Tadashi Togashi[2], Kazuaki Togawa[1], Kensuke Tono[2], Makina Yabashi[1] & Tetsuya Ishikawa[1]

PRL 111, 114802 (2013) PHYSICAL REVIEW LETTERS week ending 13 SEPTEMBER 2013

Observation of Time-Domain Modulation of Free-Electron-Laser Pulses by Multipeaked Electron-Energy Spectrum

V. Petrillo,[1] M. P. Anania,[2] M. Artioli,[3] A. Bacci,[1] M. Bellaveglia,[2] E. Chiadroni,[2] A. Cianchi,[4] F. Ciocci,[3] G. Dattoli,[3] D. Di Giovenale,[2] G. Di Pirro,[2] M. Ferrario,[2] G. Gatti,[2] L. Giannessi,[3] A. Mostacci,[5] P. Musumeci,[6] A. Petralia,[3] R. Pompili,[4] M. Quattromini,[3] J. V. Rau,[7] C. Ronsivalle,[3] A. R. Rossi,[1] E. Sabia,[3] C. Vaccarezza,[2] and F. Villa[2]

Split Undulator Scheme



$$\lambda_{1,2} = \lambda_w \frac{1 + K_{1,2}^2}{2\gamma^2}$$

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

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

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

(Received 13 December 2012; published 25 March 2013)

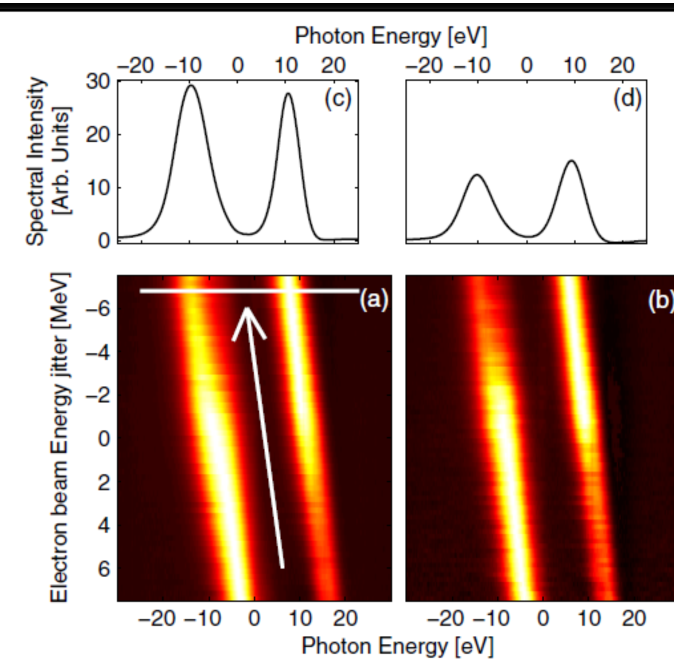
Split undulator in 2 parts.

Use magnetic chicane to introduce delay

Easy to tune!

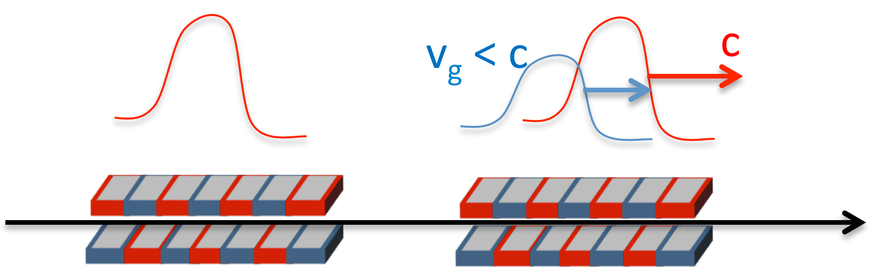
~1/10 to 1/5 of SASE power

Controllable delay up to 40 fs.



2 Color SASE vs Gain-Modulation

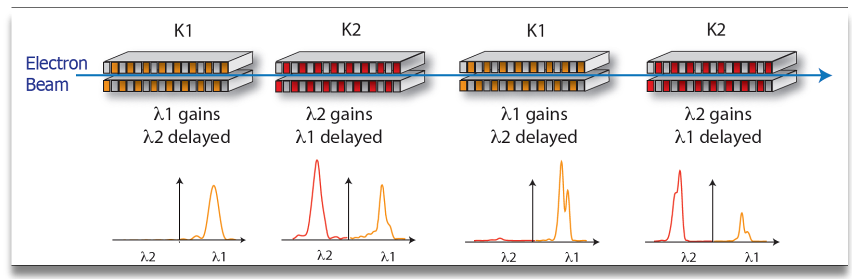
Split undulator yields minimum delay of 2/3 slippage length



At soft x-rays that's ~ a few fs

For short pulse applications it's a real problem!

Solution: discretely modulate undulator



2 colors catch up to each other -> 0 delay!

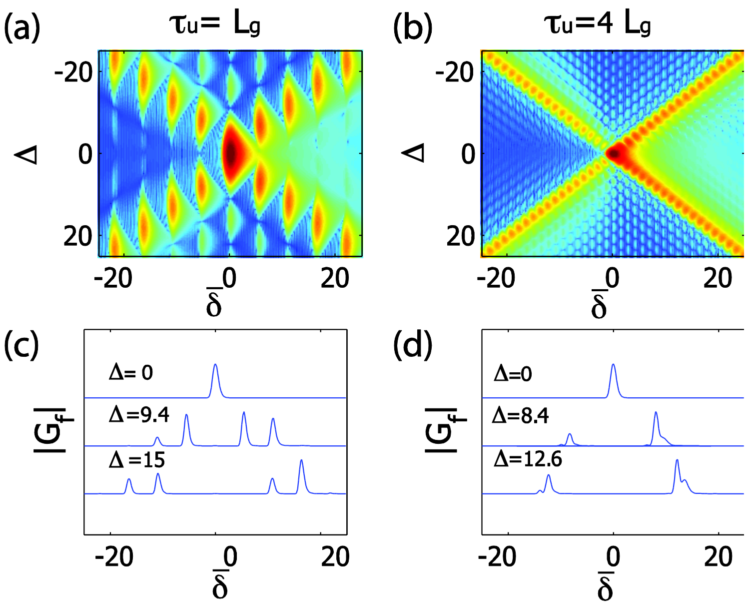
$$\lambda_{1,2} = \lambda_w \frac{1 + K_{1,2}^2}{2\gamma^2}$$

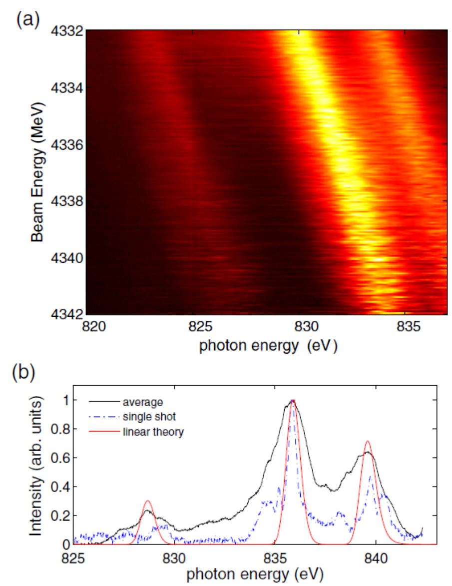
PRL **111,** 134801 (2013) PHYSICAL REVIEW LETTERS week ending 27 SEPTEMBER 2013

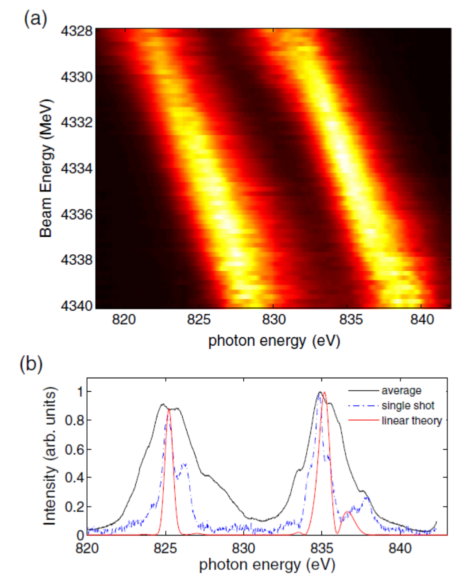
Multicolor Operation and Spectral Control in a Gain-Modulated X-Ray Free-Electron Laser

A. Marinelli,[1,*] A. A. Lutman,[1] J. Wu,[1] Y. Ding,[1] J. Krzywinski,[1] H.-D. Nuhn,[1] Y. Feng,[1] R. N. Coffee,[1] and C. Pellegrini[2,1]

Experimental Demonstration







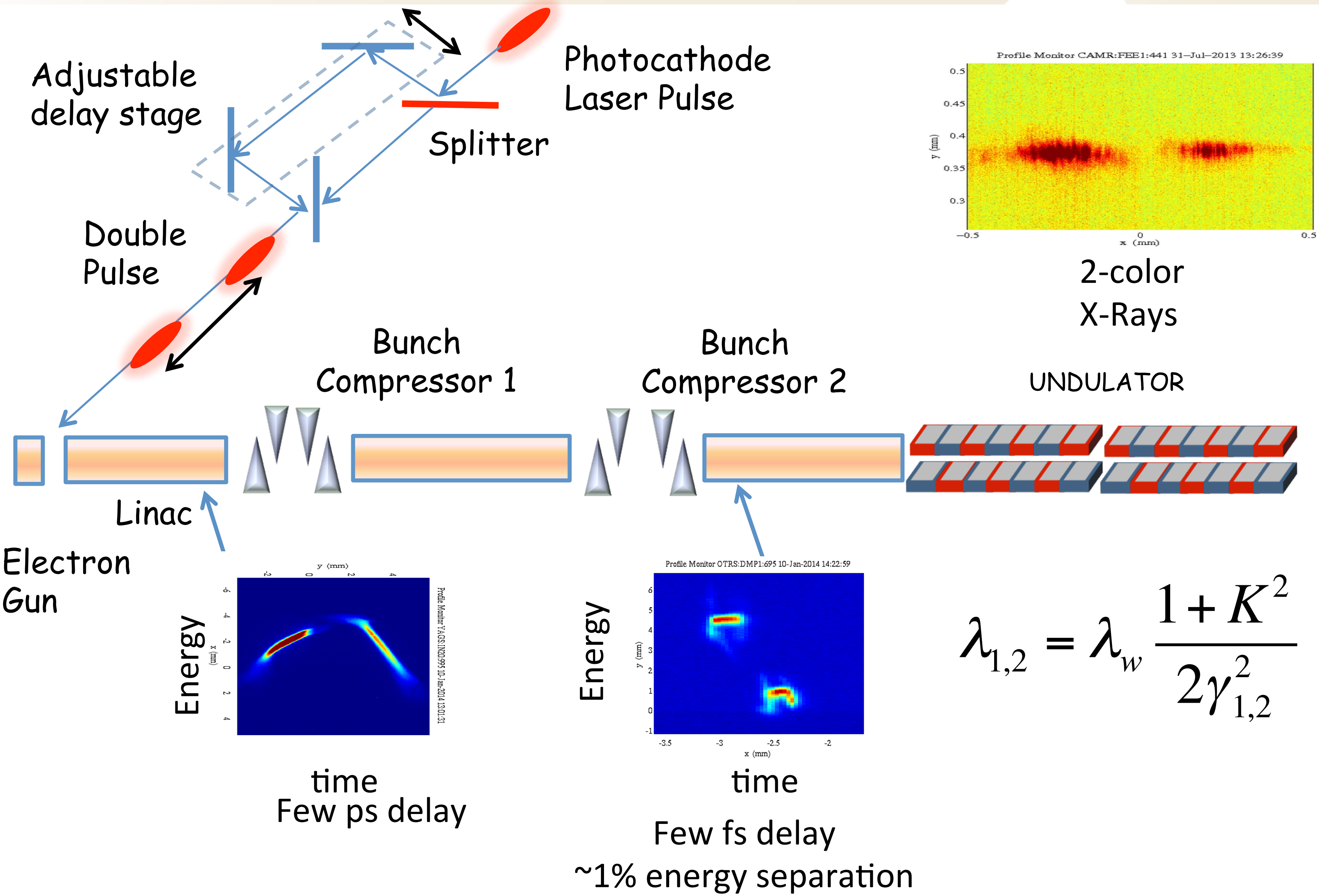
E_{pulse} = 18 μJ
T_{pulse} = 10fs
E_{photon} =830 eV
(~1/10 of saturation power, consistently with 3-D simulations)

PRL **111,** 134801 (2013) PHYSICAL REVIEW LETTERS week ending 27 SEPTEMBER 2013

Multicolor Operation and Spectral Control in a Gain-Modulated X-Ray Free-Electron Laser

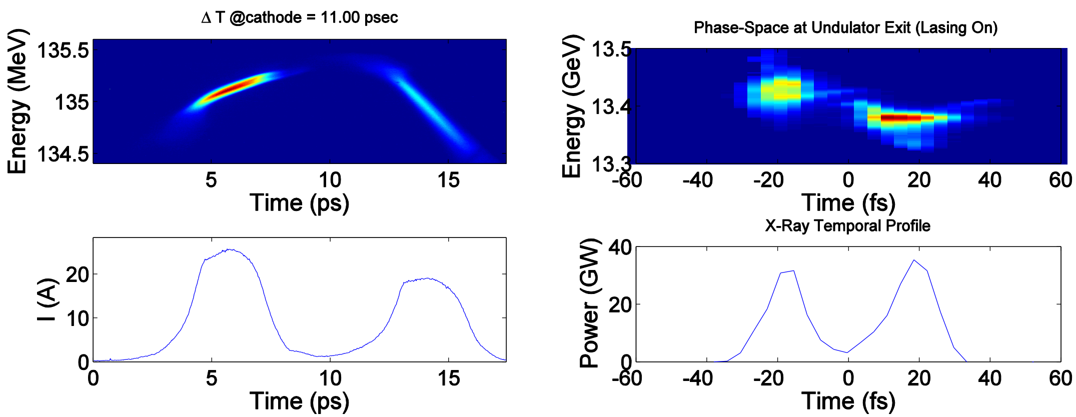
A. Marinelli,[1,*] A. A. Lutman,[1] J. Wu,[1] Y. Ding,[1] J. Krzywinski,[1] H.-D. Nuhn,[1] Y. Feng,[1] R. N. Coffee,[1] and C. Pellegrini[2,1]

Two-Bunch xFEL



$$\lambda_{1,2} = \lambda_w \frac{1 + K^2}{2\gamma_{1,2}^2}$$

2 Bunch Lasing



Already delivered to
4 user experiments

~ 3 kA peak current

Energy separation 50 MeV
(tunable parameter!)

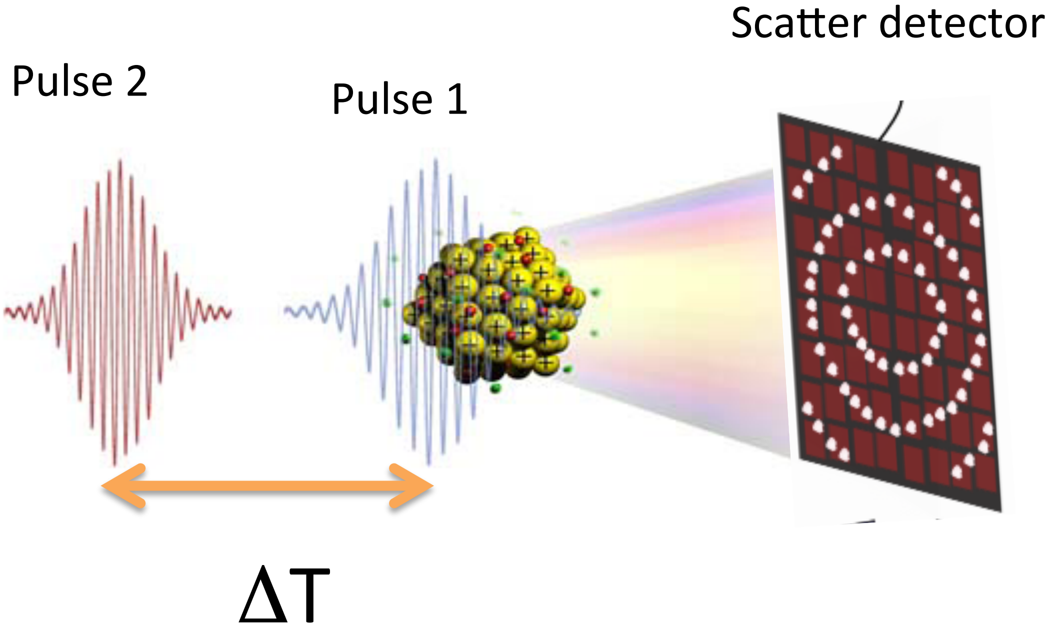
35 fs peak to peak distance
(tunable parameter!)

Lasing at 8.4 keV

Peak Power ~ 35 GW
(comparable to standard
single color operation)

Pulse duration ~15 fs fwhm

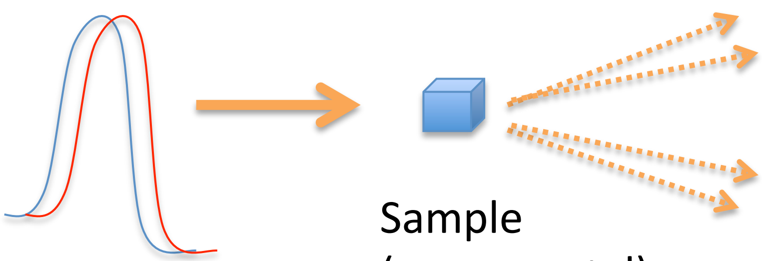
2 Color X-Rays:
X-Ray Pump/X-Ray Probe



Courtesy of K. Ferguson

Two Color X-FELs: Multi-Wavelength Anomalous Dispersion

Two pulses ~ simultaneous



1st pulse: tuned above absorption edge -> Does not diffract off of heavy atoms

2nd pulse: below absorption-edge -> Diffracts off of all atoms

De novo phase reconstruction from the two split diffraction patterns…

FEL R&D at SLAC: NLCTA

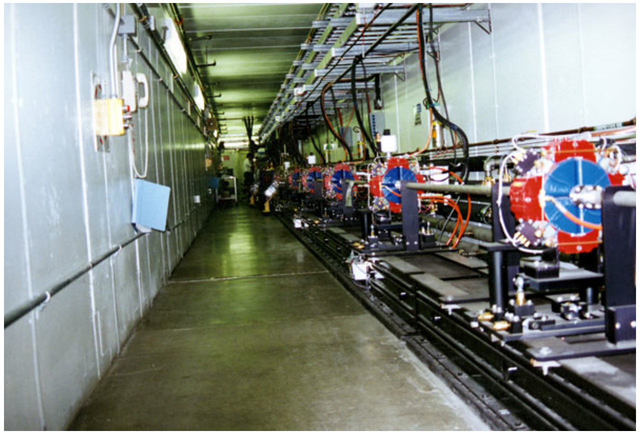
Laser-Electron interaction:

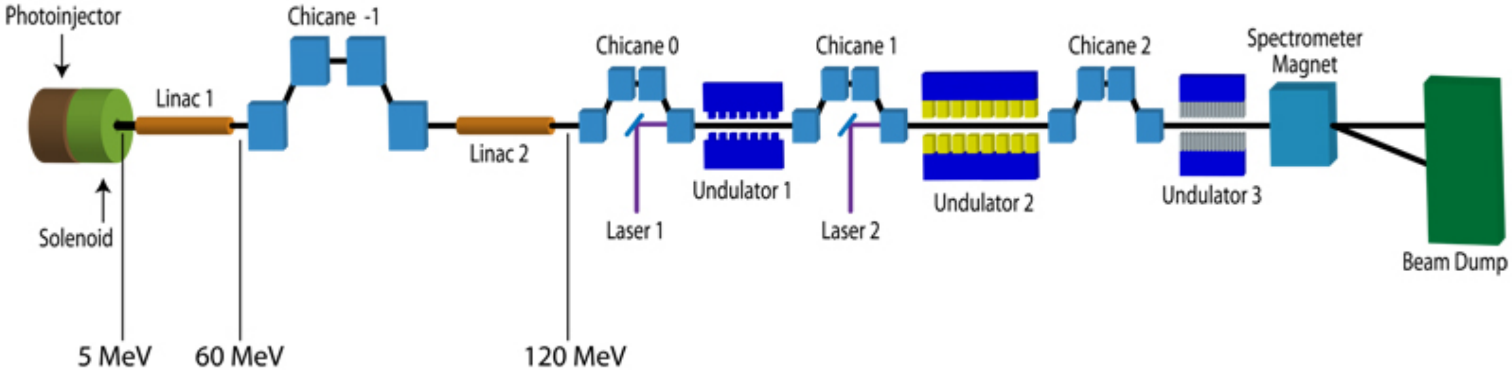
-Echo enabled harmonic generation
-Orbital angular momentum in FELs
-Coherent diffraction imaging of microbunched beams

Collective instabilities in high-brightness beams:

-Cascaded longitudinal space-charge amplifier

120 MeV test accelerator:
R&D oriented towards manipulation of electron beams for advanced seeding schemes.





The Longitudinal Space-Charge Amplifier

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 13, 110701 (2010)

Using the longitudinal space charge instability for generation of vacuum ultraviolet and x-ray radiation

E. A. Schneidmiller and M. V. Yurkov

Deutsches Elektronen-Synchrotron (DESY), Notkestrasse 85, D-22607 Hamburg, Germany

(Received 1 April 2010; published 13 November 2010)

PRL 111, 084802 (2013) PHYSICAL REVIEW LETTERS week ending 23 AUGUST 2013

Microbunched Electron Cooling for High-Energy Hadron Beams

D. Ratner*

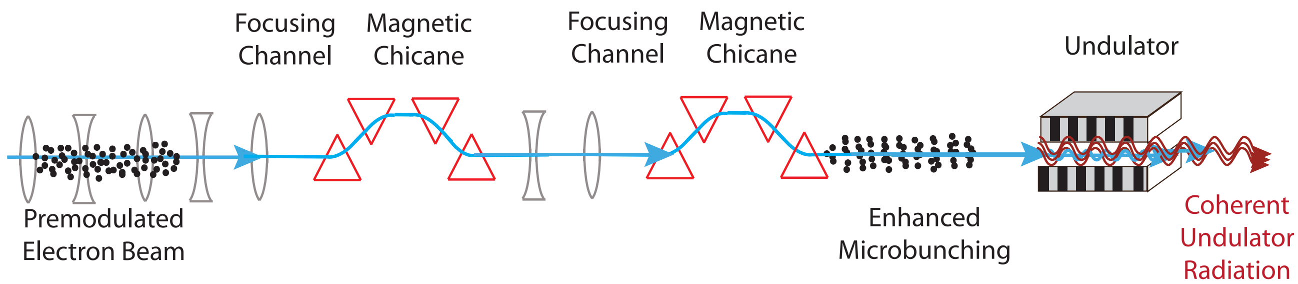
SLAC, Menlo Park, California 94025, USA

(Received 11 April 2013; published 20 August 2013)

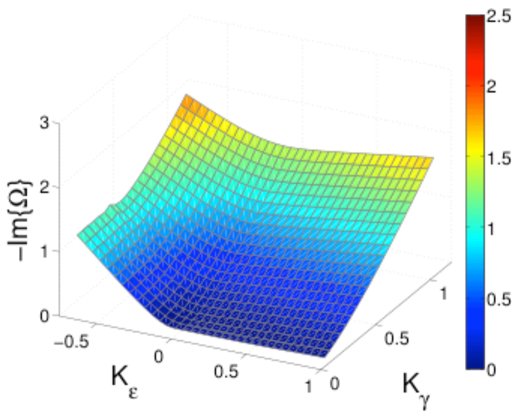
-Inexpensive (short undulator)

-Alternative to FEL for broadband (e.g. attosecond pulses)

-Can be used for coherent electron cooling



6-Dimensional Theory of Space-Charge Interactions

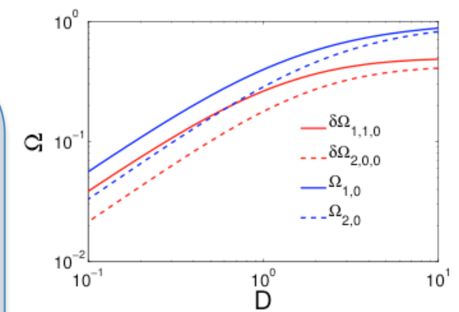


Emittance induced anisotropic Landau damping

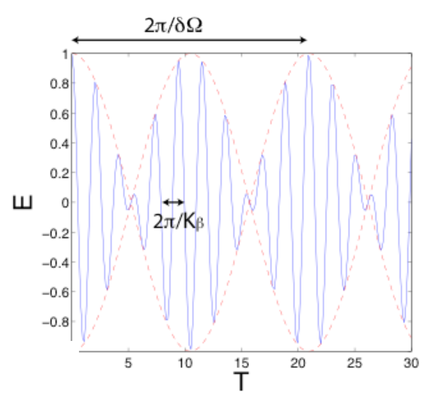
Analysis of space-charge interactions in terms of plasma-waves

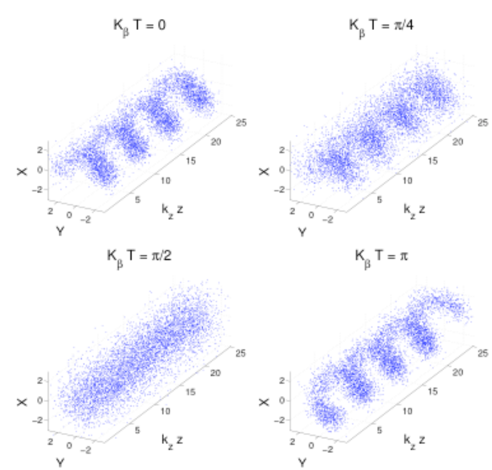
$$\left(\frac{1}{D^2}\nabla_\perp^2 - 1\right) E_z = -\int E_z(\vec{X}')\Pi(\vec{X},\vec{X}')d^2\vec{X}'$$

$$\Pi(\vec{X},\vec{X}') = \int_{-\infty}^{0} \frac{Te^{-\frac{(K_\gamma T)^2}{2} - i\Omega T} e^{-\left(\vec{X}^2+\vec{X}'^2-2\vec{X}\cdot\vec{X}'\cos K_\beta T\right)\frac{(1+iK_\epsilon T)}{2\sin^2 K_\beta T}}}{2\pi \sin^2 K_\beta T} dT.$$



Suppression of higher order modes from betatron motion





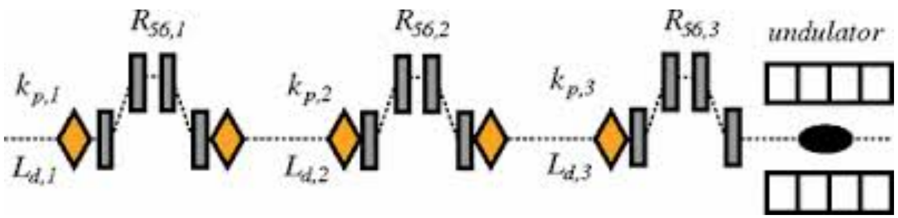
Plasma-Betatron Beatwaves

PHYSICS OF PLASMAS 18, 103105 (2011)

Three dimensional analysis of longitudinal plasma oscillations in a thermal relativistic electron beam

Agostino Marinelli,[1,2] Erik Hemsing,[1] and James B. Rosenzweig[1]

Experimental Demonstration @ Optical Wavelengths

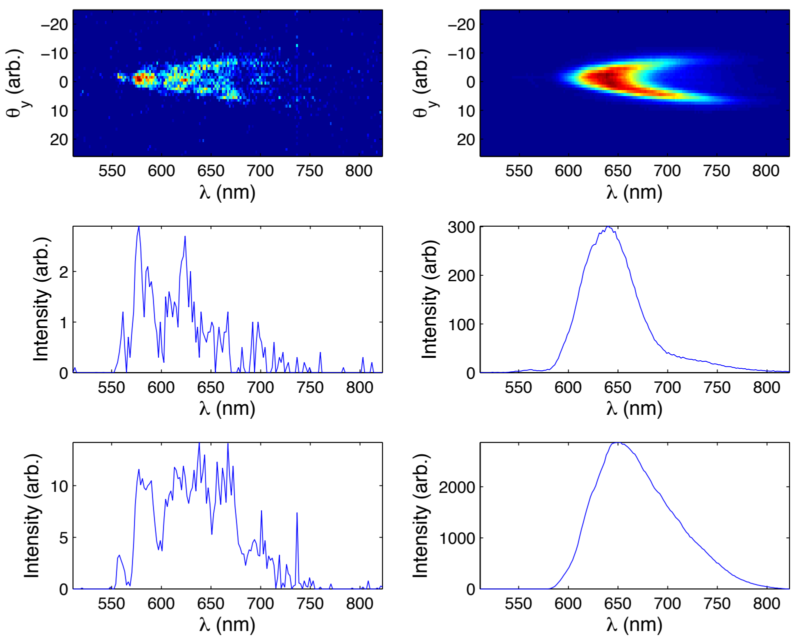


3 chicanes + 10 period undulator
R56 = 4mm, 2.5mm, 1.5 mm

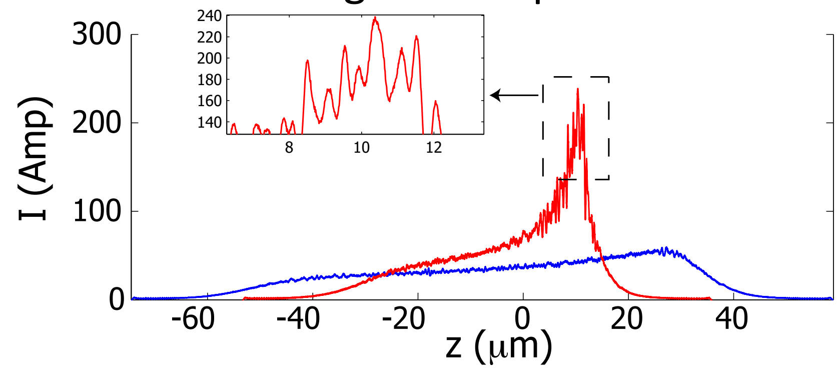
Microbunching gain confined to leading peak containing ~20% charge…
Local microbunching gain ~ 15000

Moderate compression

High Compression



Single-spike from compression:
-short leading current peak



PRL 110, 264802 (2013) PHYSICAL REVIEW LETTERS week ending 28 JUNE 2013

Generation of Coherent Broadband Photon Pulses with a Cascaded Longitudinal Space-Charge Amplifier

A. Marinelli,[1,*] E. Hemsing,[2] M. Dunning,[2] D. Xiang,[2] S. Weathersby,[2] F. O'Shea,[1] I. Gadjev,[1] C. Hast,[2] and J. B. Rosenzweig[1]

Conclusions

1) Despite being a well established experimental tool, research on X-FELs is still very active.

2) Two-color X-FEL schemes are now operational or at very advanced stage of development

3) More forward looking experiments at NLCTA are opening new avenues for ultra-fast science.