Beam by Design

Customized X-rays from Free Electron Lasers

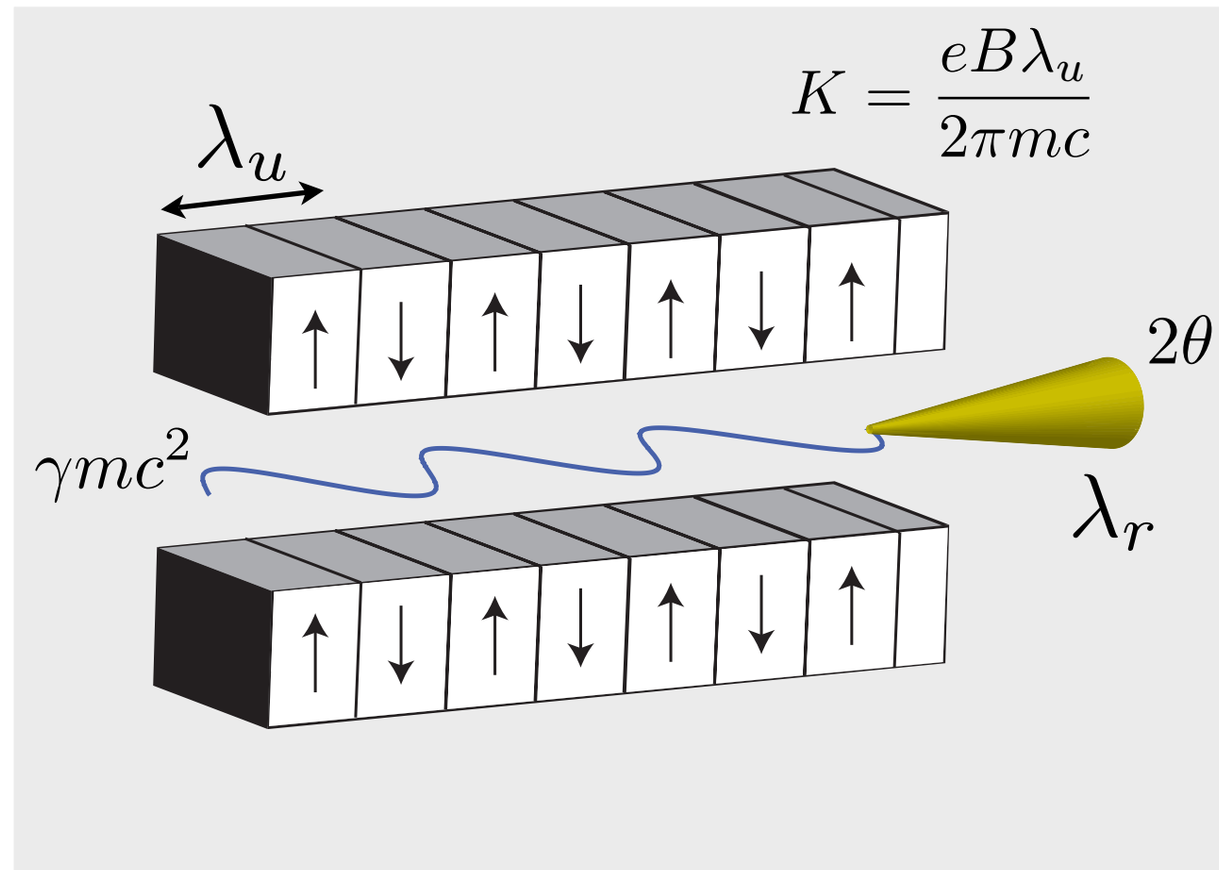
Erik Hemsing
SLAC National Accelerator Laboratory
Fermilab Colloquium,
Nov 2 2016

U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

What is a Free Electron Laser?

- FELs use relativistic electron beams to generate light in an undulator
- An undulator is a series of alternating dipole magnets that make the beam wiggle and radiate
- In a high-gain FEL, the emitted radiation acts back on the electrons, which then radiate more light, which acts back on the electrons... the *FEL instability* develops
- The radiation **grows exponentially**, taking energy from the electrons and increasing their energy spread until saturation



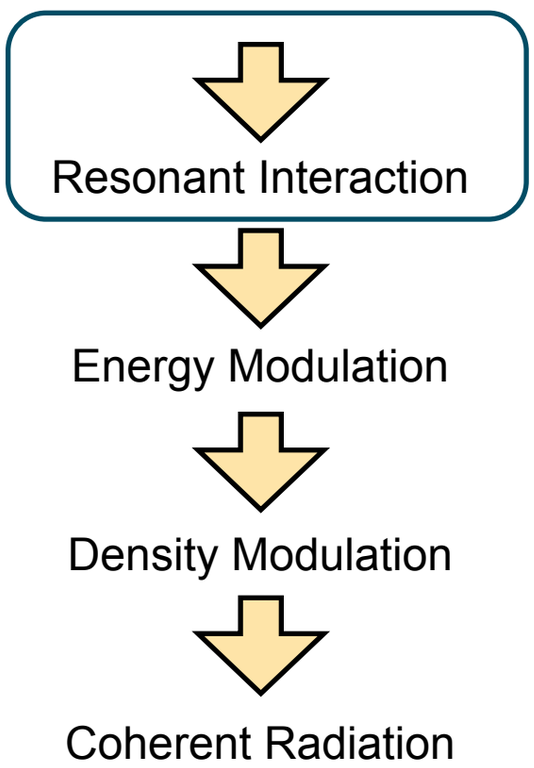
$$\lambda_r = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

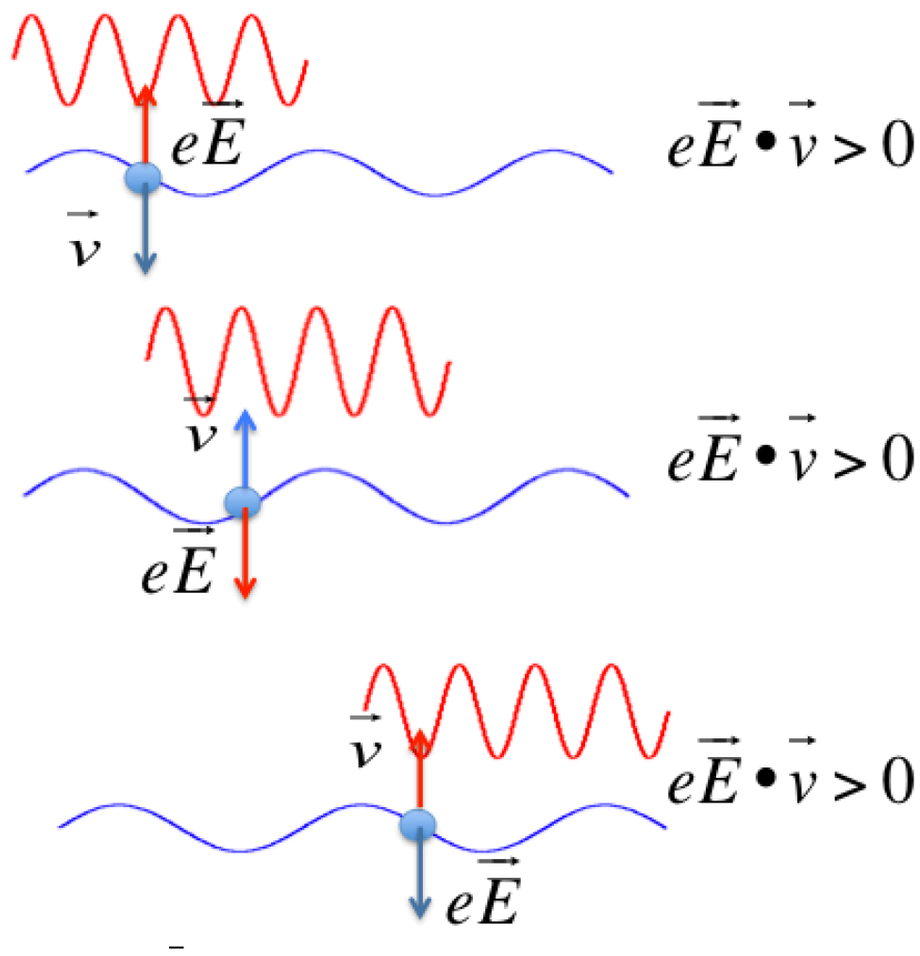
FEL resonant wavelength

Characteristics of FELs

- Invented by John Madey in the 1970s.
- Tunable, high power radiation 10 orders of magnitude brighter than storage ring based synchrotron light sources
- Electrons interact with the radiation field in vacuum.
- Unlike conventional lasers restricted to fixed transitions between atomic energy levels, FELs use unbound electrons and have no such limitation on their output wavelength.
- Broad frequency tunability over ~ 8 orders of magnitude
- No thermal lensing, birefringence or heat dissipation issues.
- Radiation is essentially diffraction limited, with a low angular divergence and narrow bandwidth.

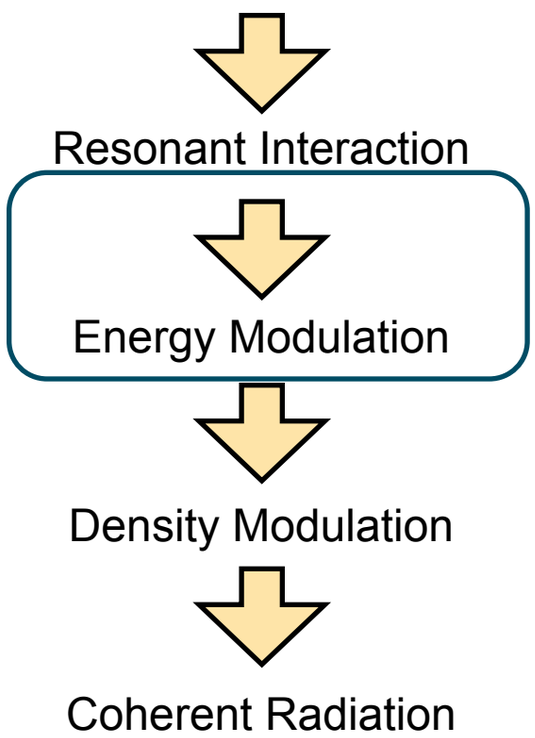
Working Principle



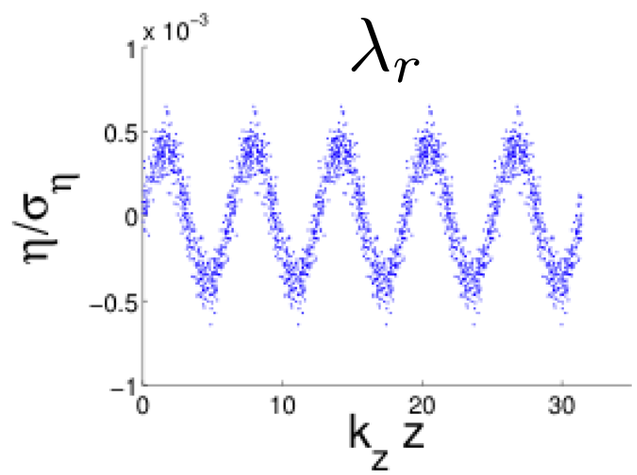


As electron wiggles, the light slides past. At a specific wavelength, as the velocity of the electron reverses, so does the E-field. The energy exchange is maintained: RESONANCE

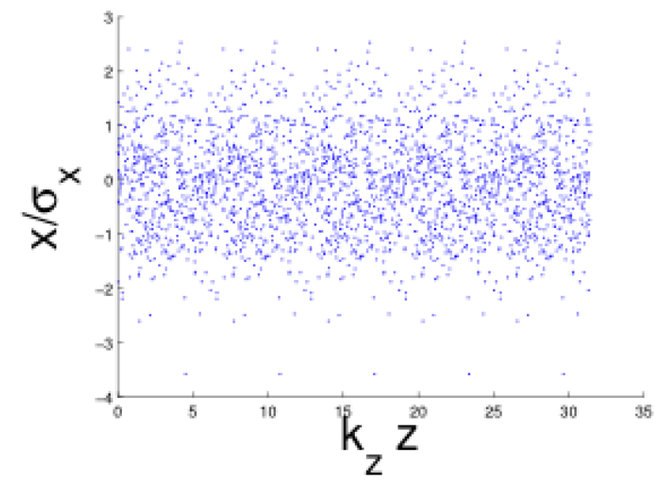
Working Principle



e-beam
phase space

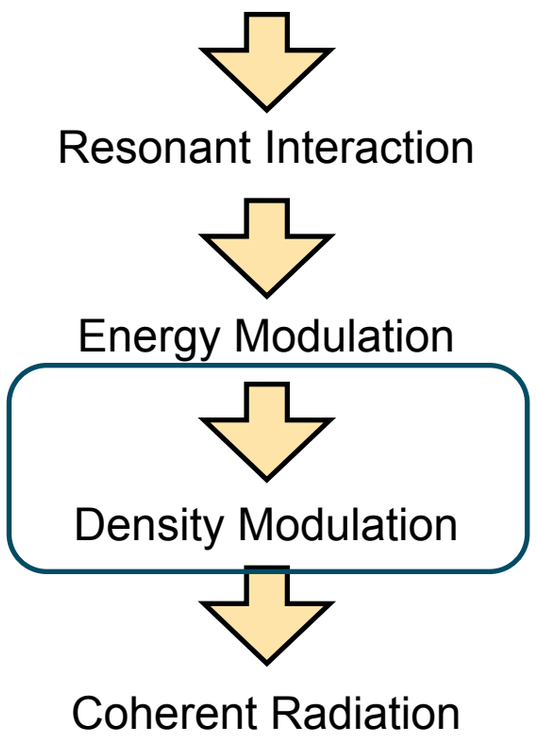


e-beam
position space

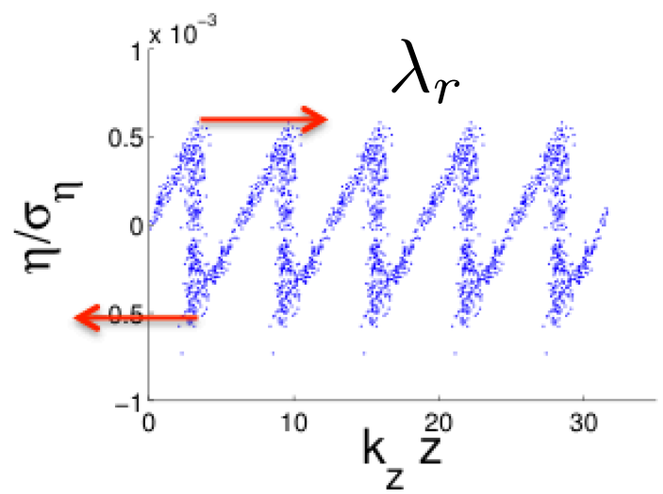


Resonant energy transfer generates sinusoidal modulation of electron energies.

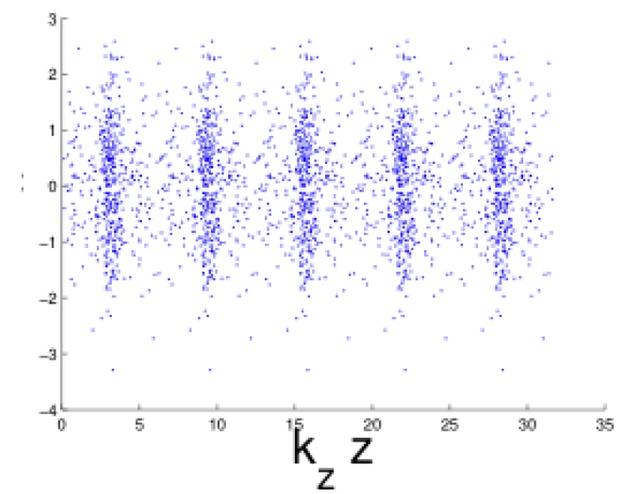
Working Principle



e-beam
phase space

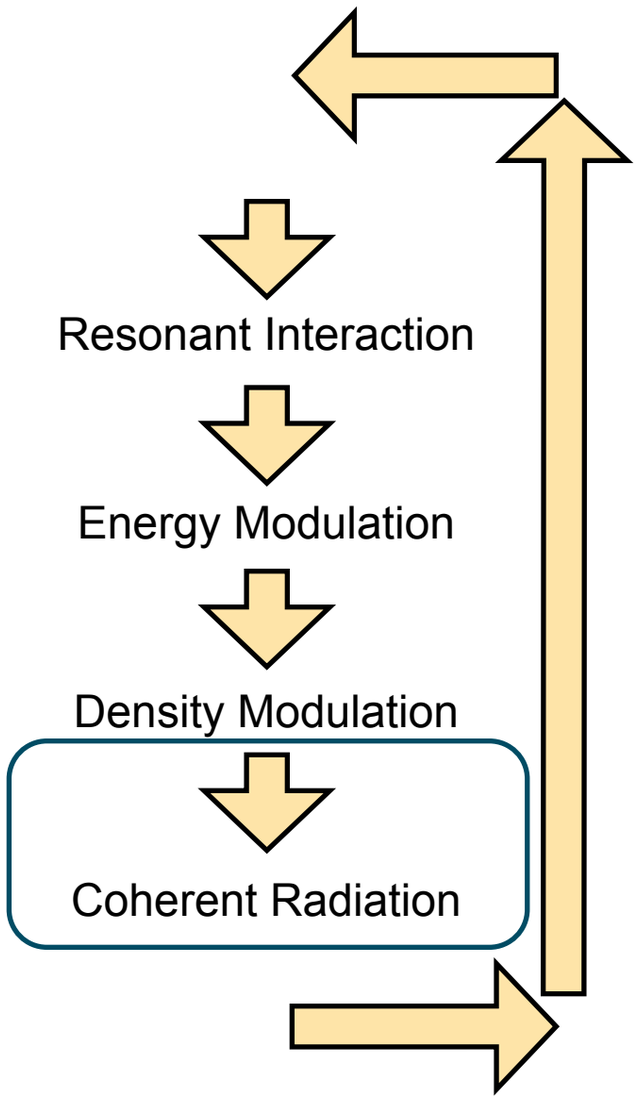


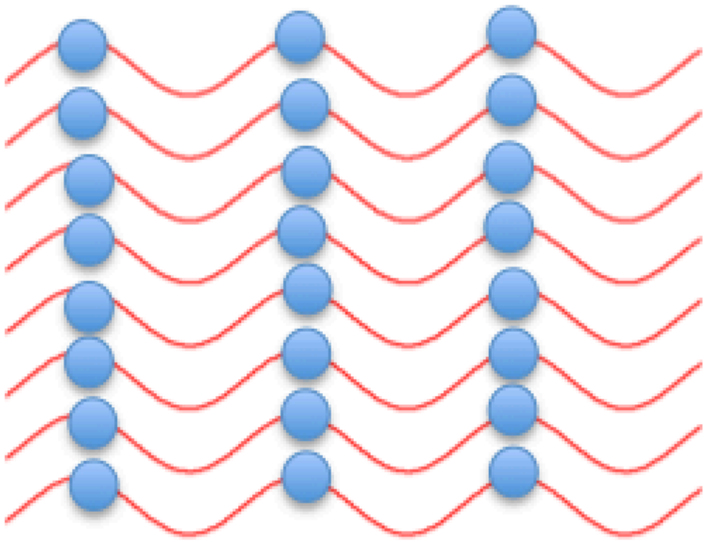
e-beam
position space



Higher energy electrons move forward, lower energy electrons move backward.
This DISPERSION generates bunching.

Working Principle



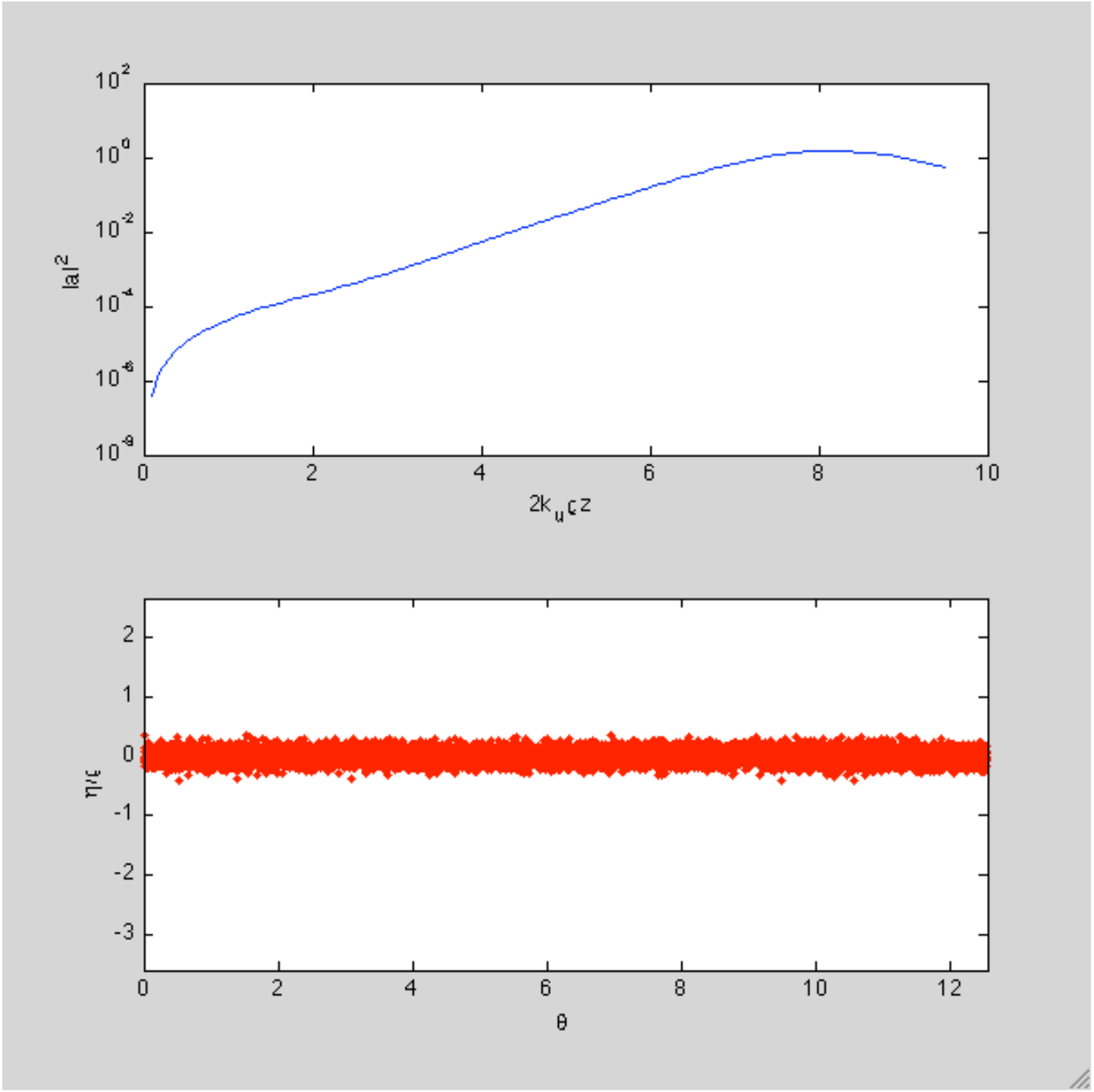


Bunched electrons radiate coherently, generating stronger fields. FEL INSTABILITY

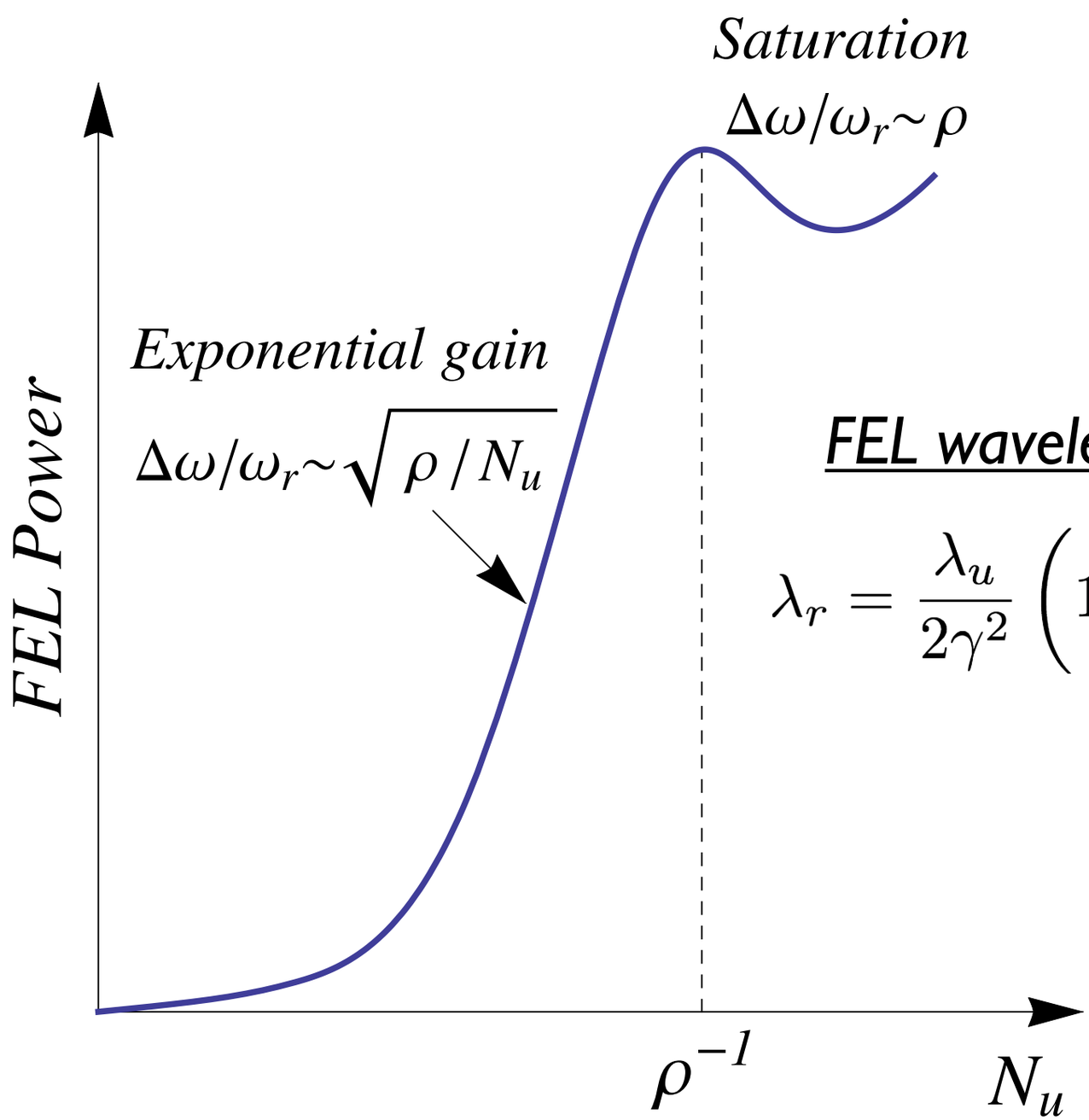
Evolution of electron beam in high gain FEL

FEL Power

e-beam
phase space



High Gain FEL Growth and Scaling



FEL parameter

$$\rho = \left(\frac{K^2 J J^2 \lambda_u^2}{32 \lambda_p^2} \right)^{1/3}$$

FEL wavelength

$$\lambda_r = \frac{\lambda_u}{2\gamma^2} \left(1 + \frac{K^2}{2} \right)$$

Gain length

$$L_g = \frac{\lambda_u}{4\pi\sqrt{3}\rho}$$

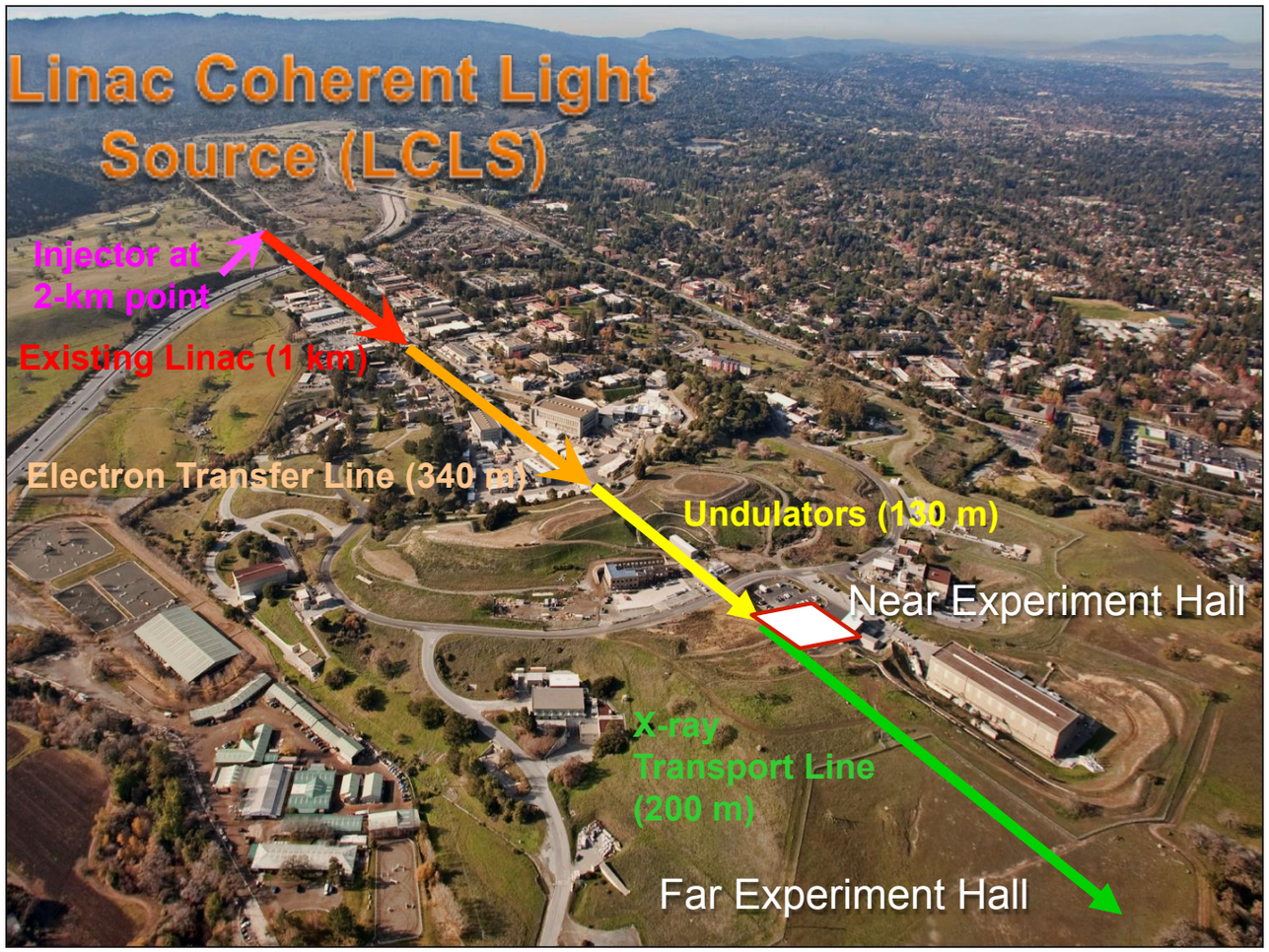
Saturation length

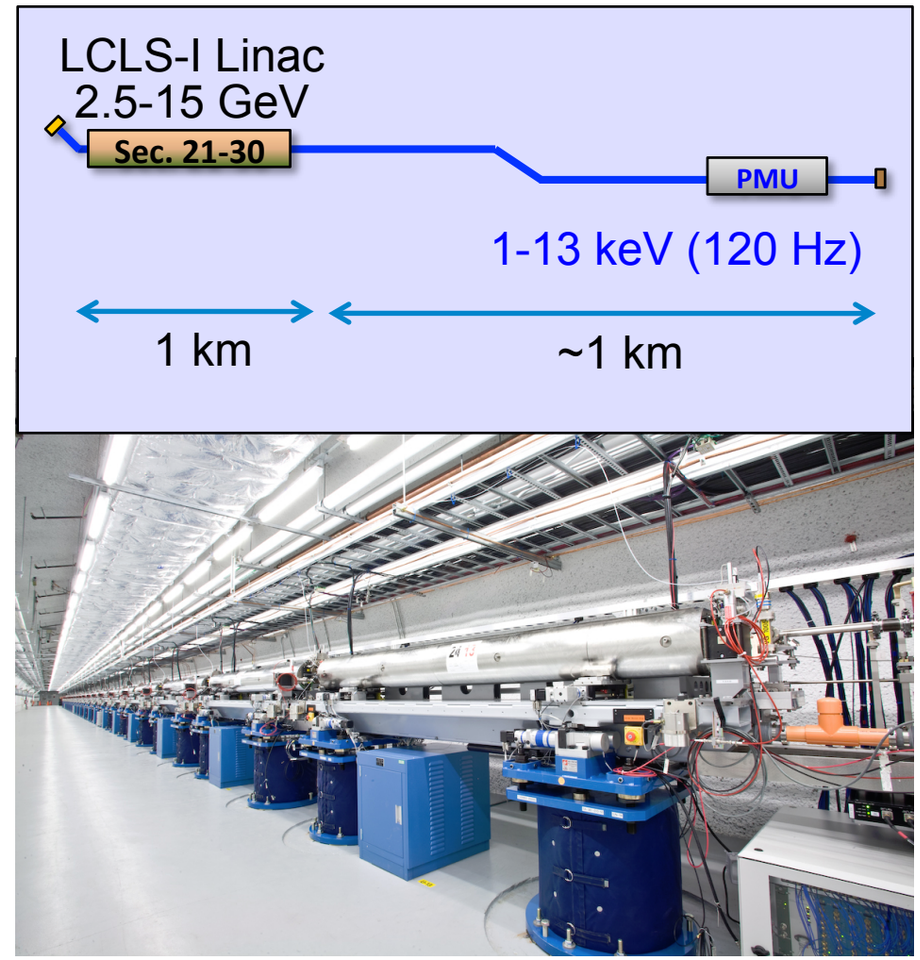
$$L_s \sim \lambda_u / \rho$$

Saturation power

$$P_s \sim \rho P_b = \rho \mathcal{E} I_0 / e$$

Linac Coherent Light Source @ SLAC

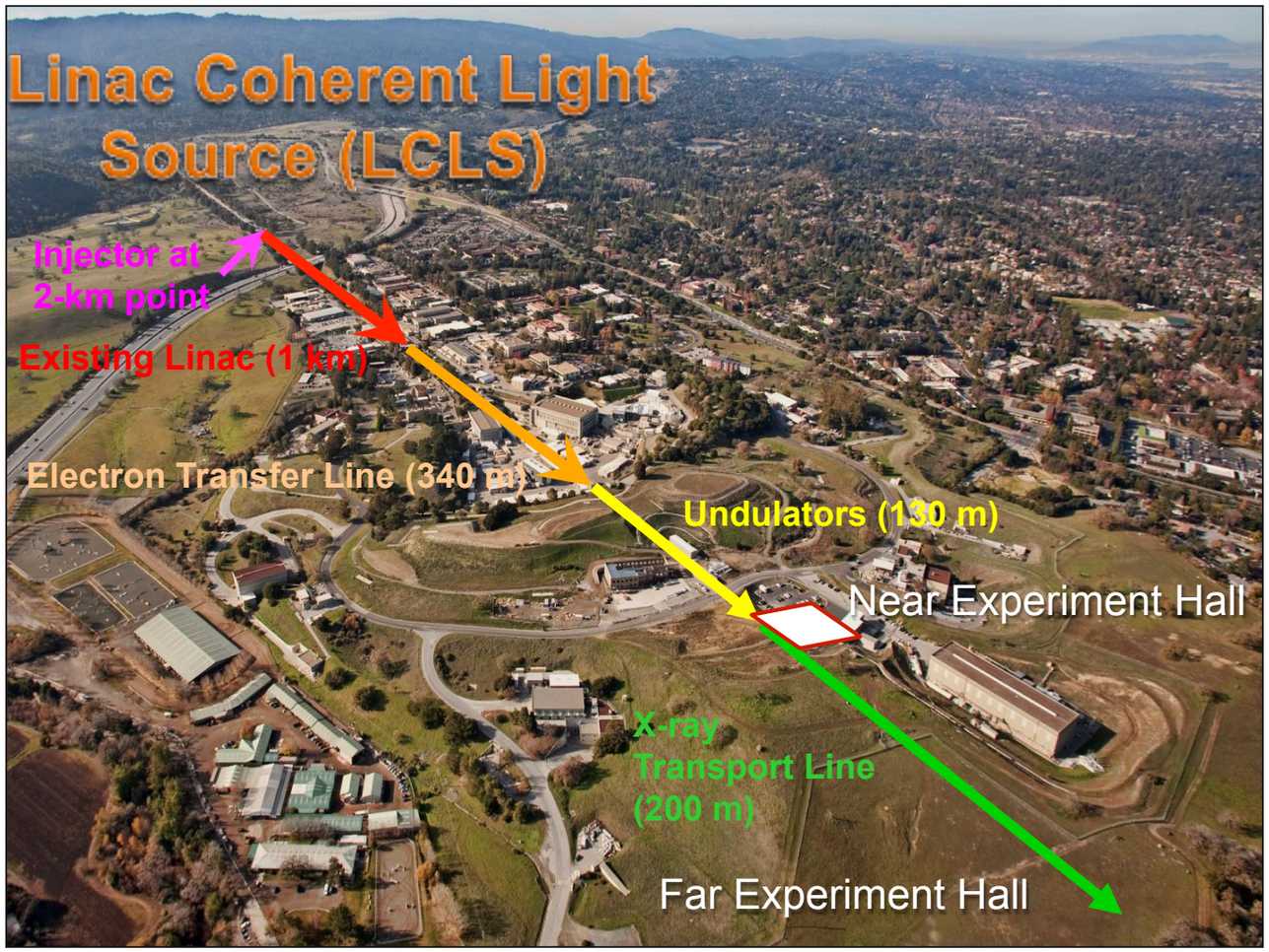


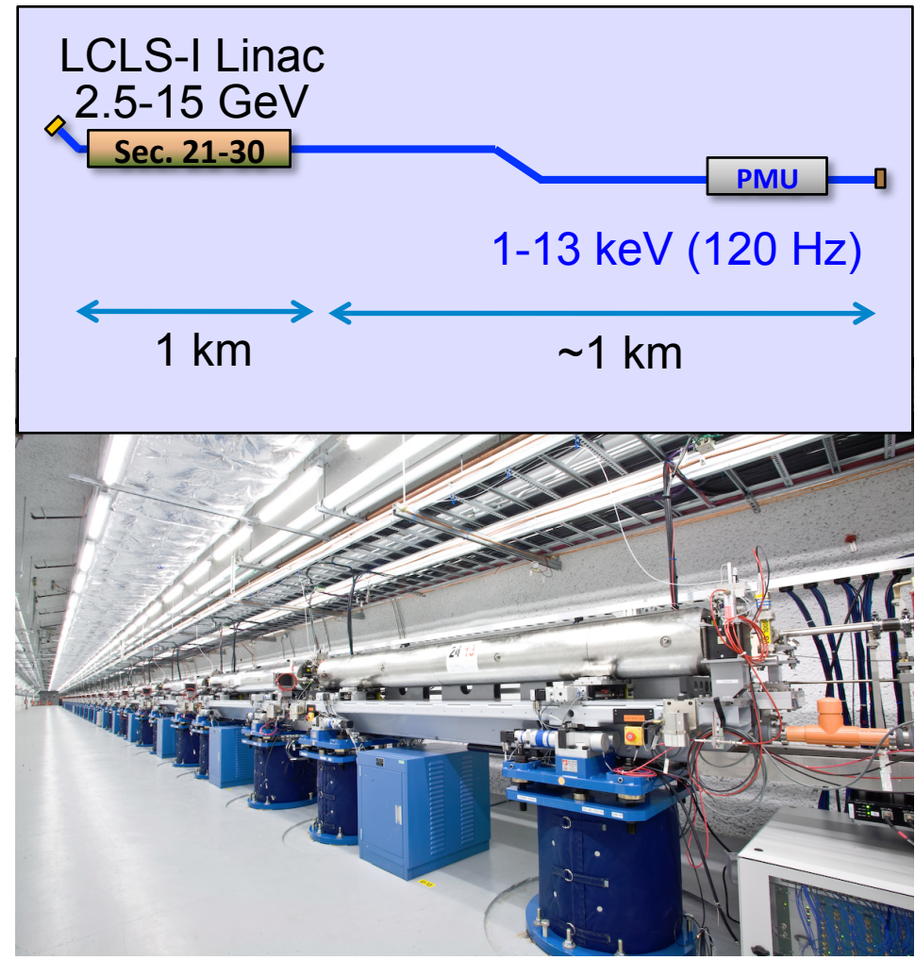


- LCLS is world's 1st x-ray FEL (start 2009)
- uses final 1/3 of SLAC linac to produce <15 GeV e- to drive FEL
- soft-hard x-rays (10-100 GW) to 6 experimental stations

X-ray Range	**250 to 12,600 eV**
FEL Pulse Length	**< 5 - 100 fs**
Rel. Bandwidth	**0.1%-0.005%**
FEL Pulse Energy	**~3 mJ (2 x10^{12} @ 10 keV)**
Repetition Rate	**120 Hz**

Linac Coherent Light Source @ SLAC





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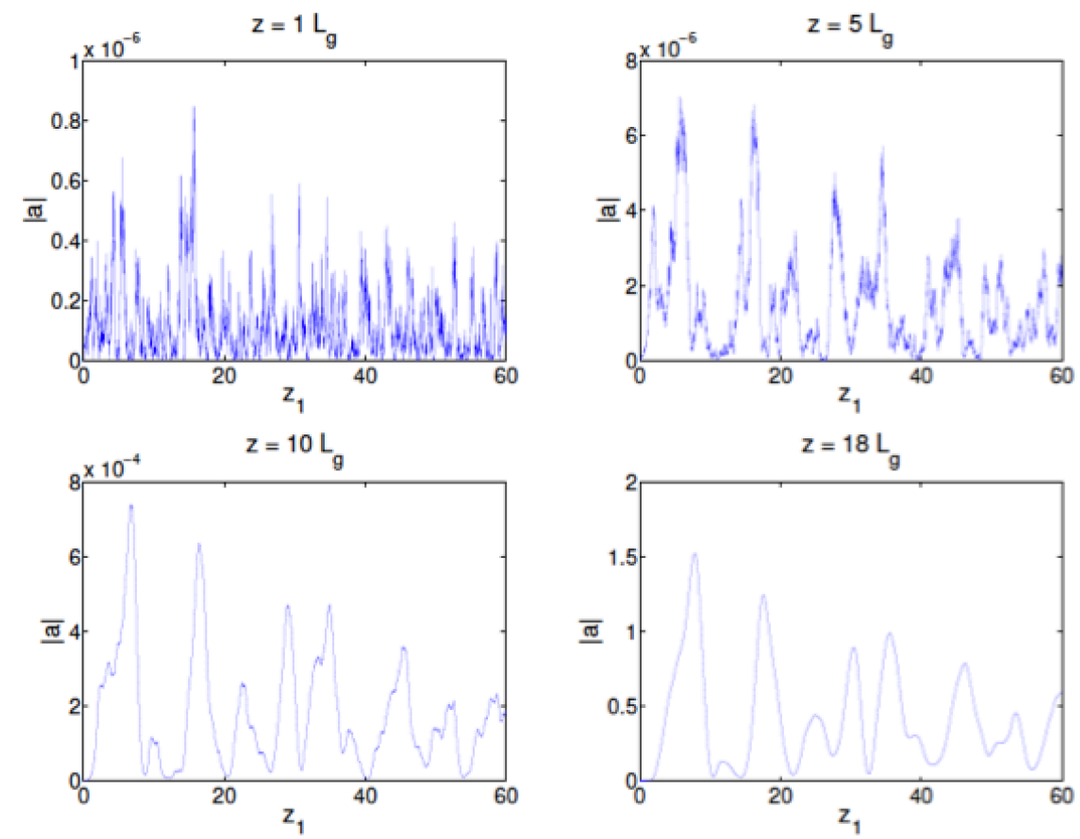
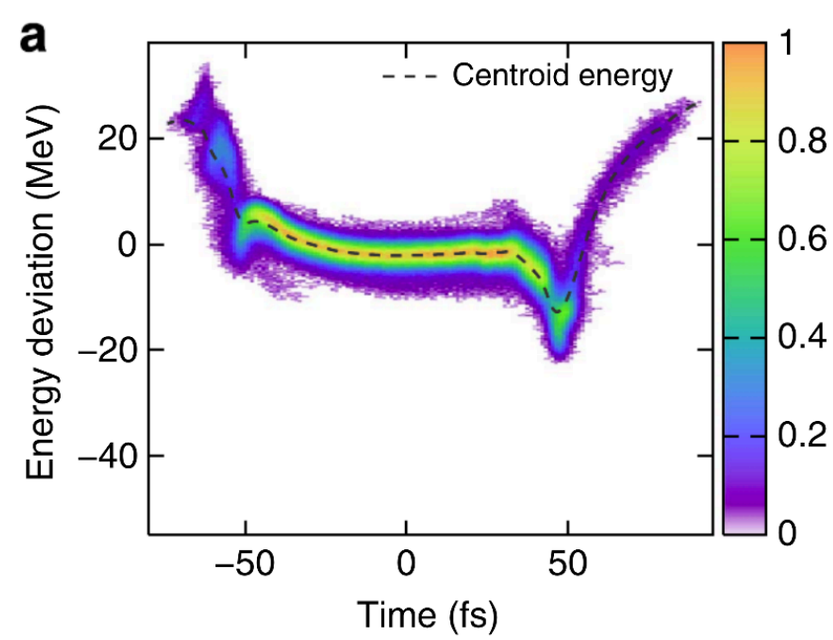
Other XFELs underway in S.Korea, Germany, Switzerland...
+LCLS-II

Temporal Characteristics

Most x-ray FELs generate light by **Self Amplified Spontaneous Emission** (SASE)

- Shot noise in e-beam seeds FEL
- **Noise is broadband** so it is coherent over very **short time scales**
- At resonance, light slips forward one wavelength per undulator period.
- Over **one gain length**, the light slips forward **one cooperation length**, extending the coherence length
- Typically the **e-beam is long** compared to cooperation length, there are **many coherent spikes** in FEL pulse

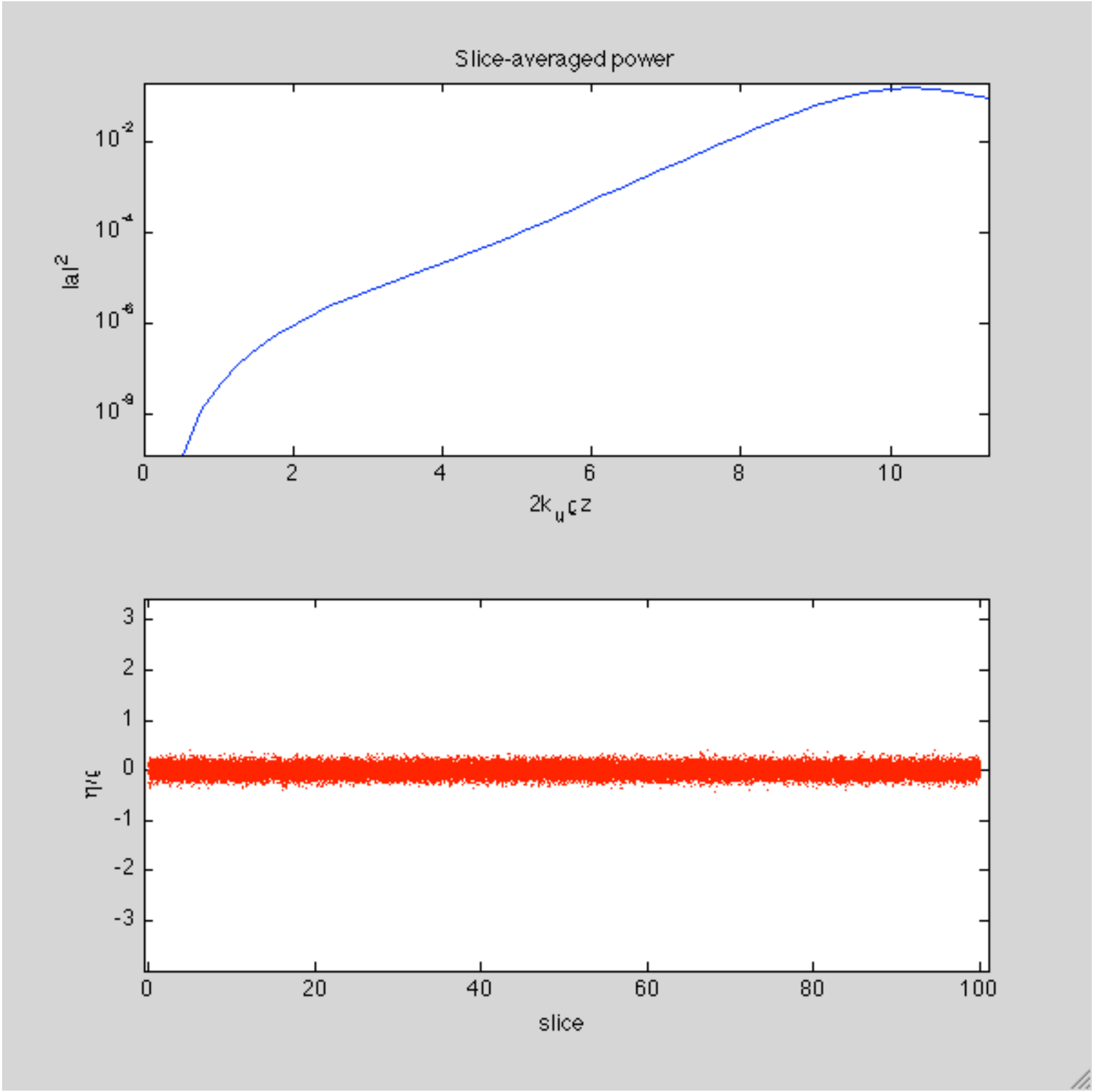




Evolution of SASE FEL (starting from noise)

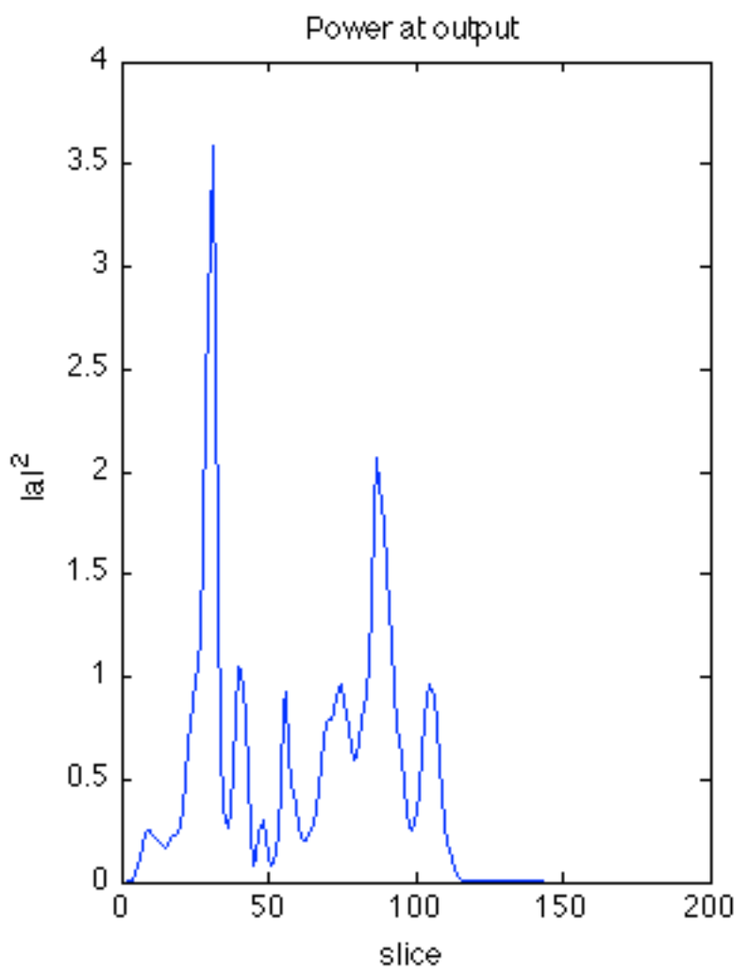
Radiation power along undulator

e-beam phase space

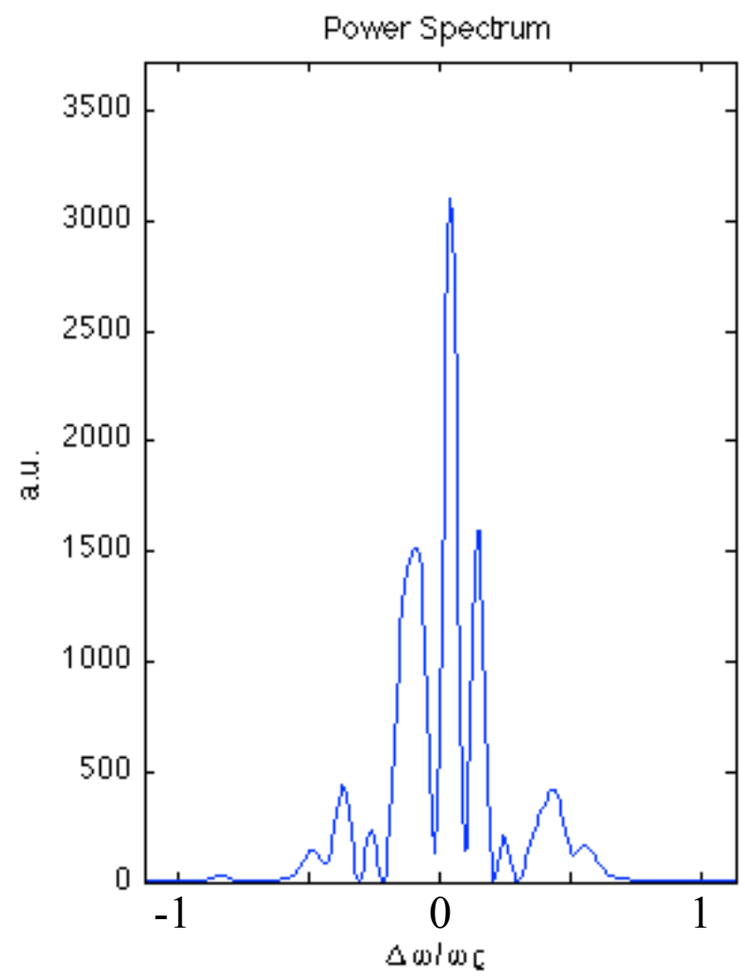


SASE FEL Output pulse

Multiple spikes at saturation



time



spectrum

Challenges/Opportunities in modern FELs

- Improved Temporal Coherence
  - Despite excellent transverse coherence, SASE FELs have limited temporal coherence and exhibit large statistical fluctuations in the output power spectrum.
- Control over the x-ray pulse duration.
  - Electron bunch length is typically longer than the cooperation length (tens of fs), but resolution of electron motion in atoms, for example, needs x-ray pulses down to attoseconds (10^{-18} s).
- Customizable pulse shaping
  - Tunable transform-limited time/bw trade off
  - Central frequency control
  - Multicolor operations
  - Higher order transverse modes with new photon degrees of freedom

FEL Pulse Tailoring

- Many techniques for transforming the FEL output by directly shaping electron beam or exploiting features of the emitted radiation
- "Beam by Design" now possible where light can be precisely tailored to suit wide-ranging needs

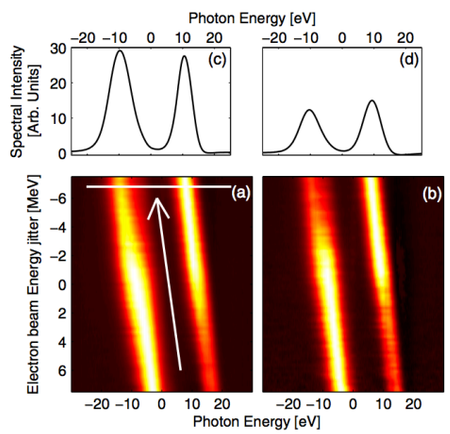
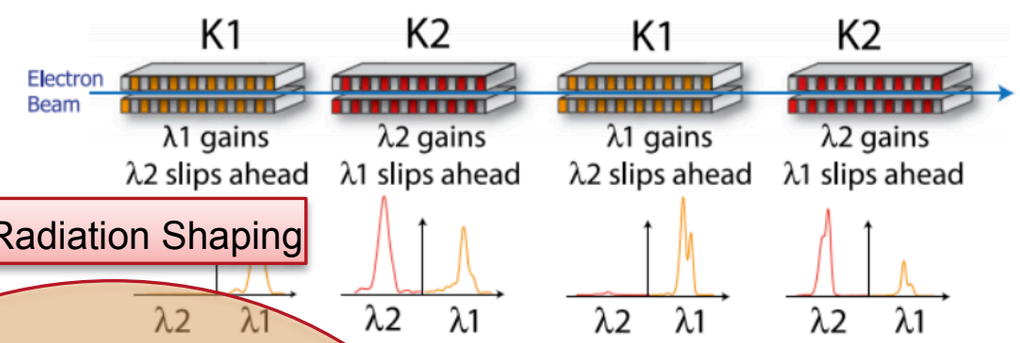
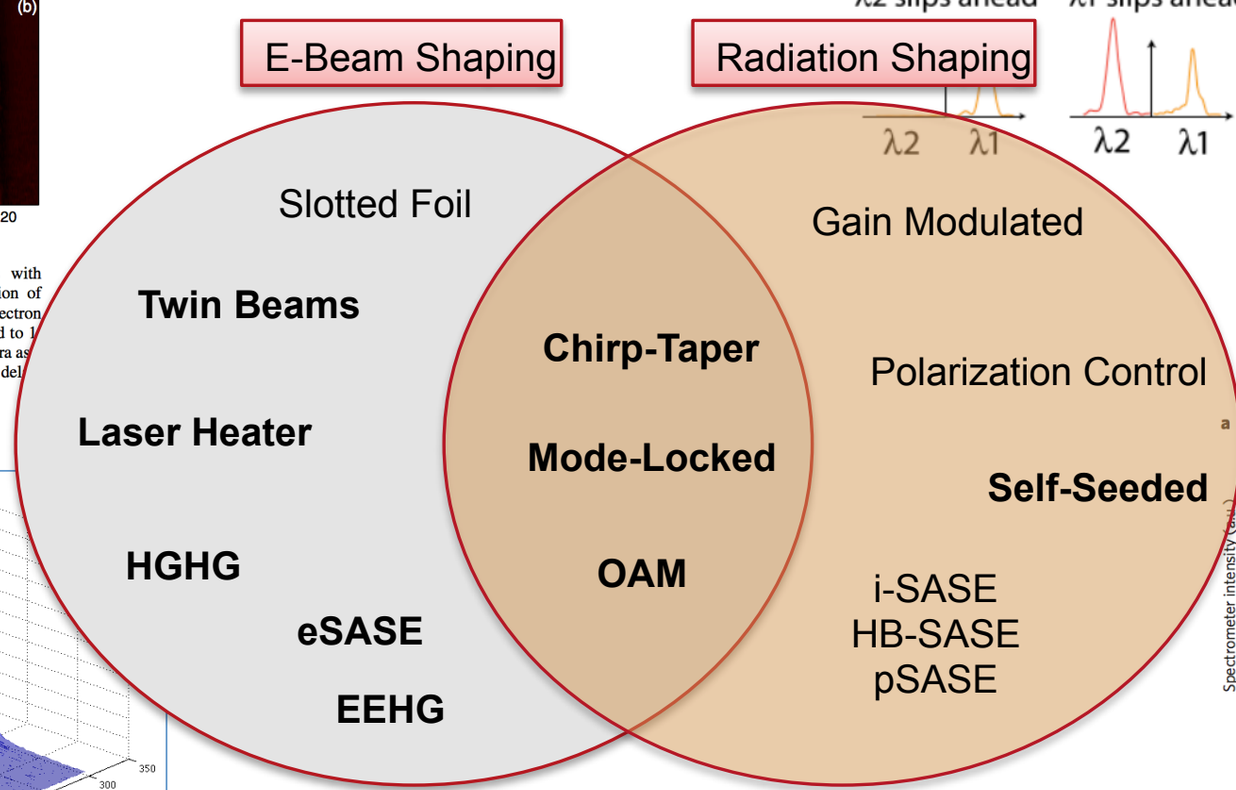
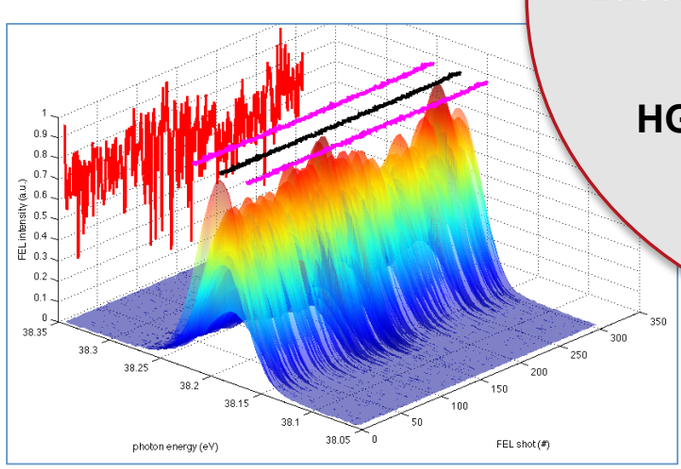
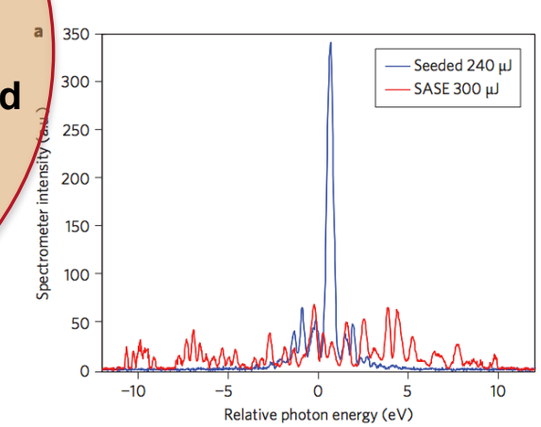


FIG. 3 (color online). Results for two-color beams with scheme I. (a),(b) Average spectral intensity as a function of the electron beam energy and photon energy. For each electron beam energy, the maximum intensity has been normalized to 1. (a) 0 fs delay. (b) 25 fs delay. (c,d) Average realigned spectra as function of the photon energy offset from 1.5 keV. (c) 0 fs del (d) 25 fs delay.









Bold: Laser-based

Short Pulses through Beam Shaping

- Want a short FEL pulse? Make the electron beam short!
- Single spike SASE output for beams shorter than the FEL cooperation length
- Low charge
- Diminishing returns in making the beam shorter

Nuclear Instruments and Methods in Physics Research A 593 (2008) 39–44

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Generation of ultra-short, high brightness electron beams for single-spike SASE FEL operation

J.B. Rosenzweig [a,*], D. Alesini [c], G. Andonian [a], M. Boscolo [c], M. Dunning [a], L. Faillace [b,c], M. Ferrario [c], A. Fukusawa [a], L. Giannessi [e], E. Hemsing [a], G. Marcus [a], A. Marinelli [b,c], P. Musumeci [a], B. O'Shea [a], L. Palumbo [b,c], C. Pellegrini [a], V. Petrillo [d], S. Reiche [a], C. Ronsivalle [e], B. Spataro [c], C. Vaccarezza [c]

[a] UCLA Department of Physics and Astronomy, 405 Hilgard Ave., Los Angeles, CA 90095, USA

nature COMMUNICATIONS

ARTICLE

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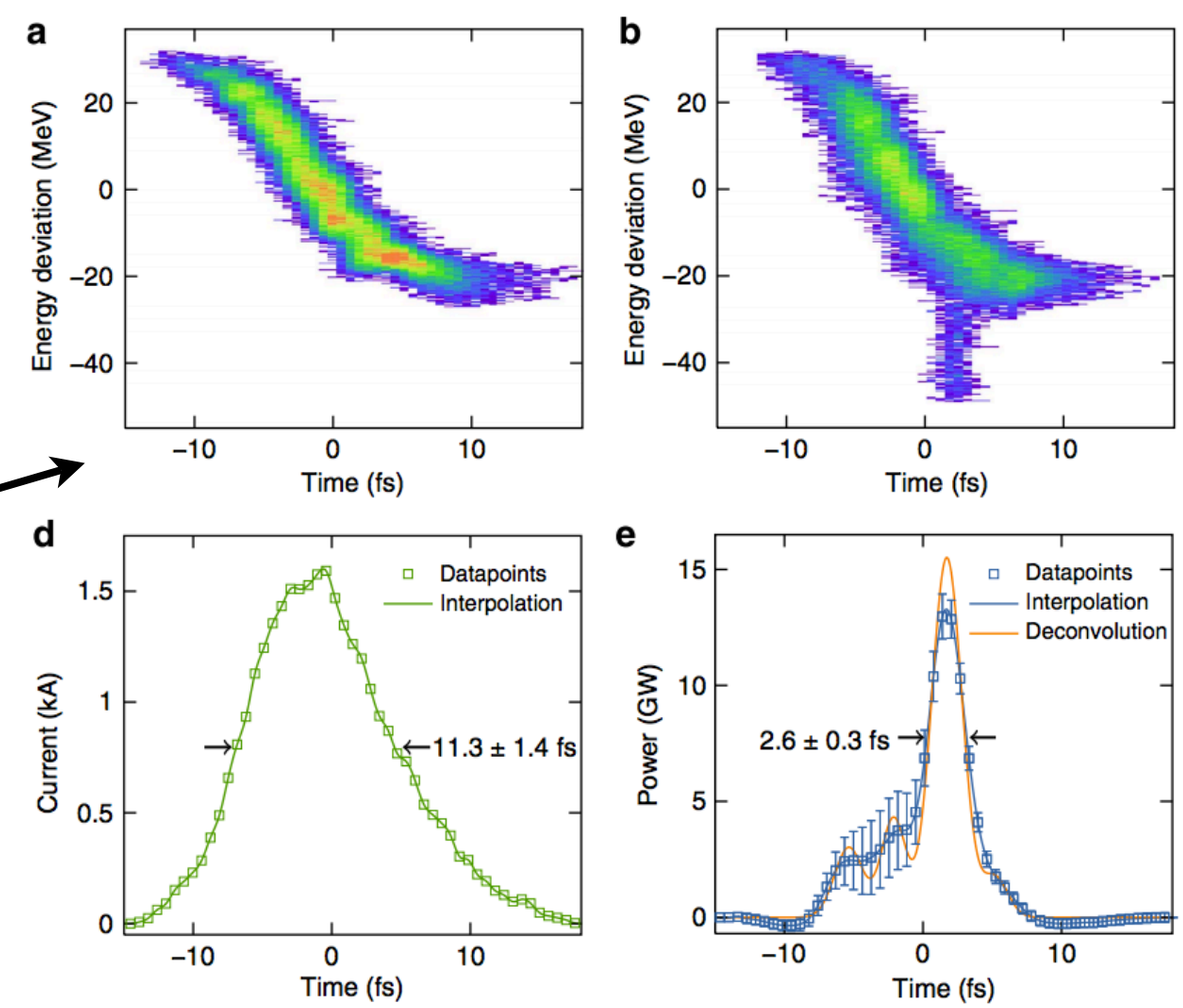
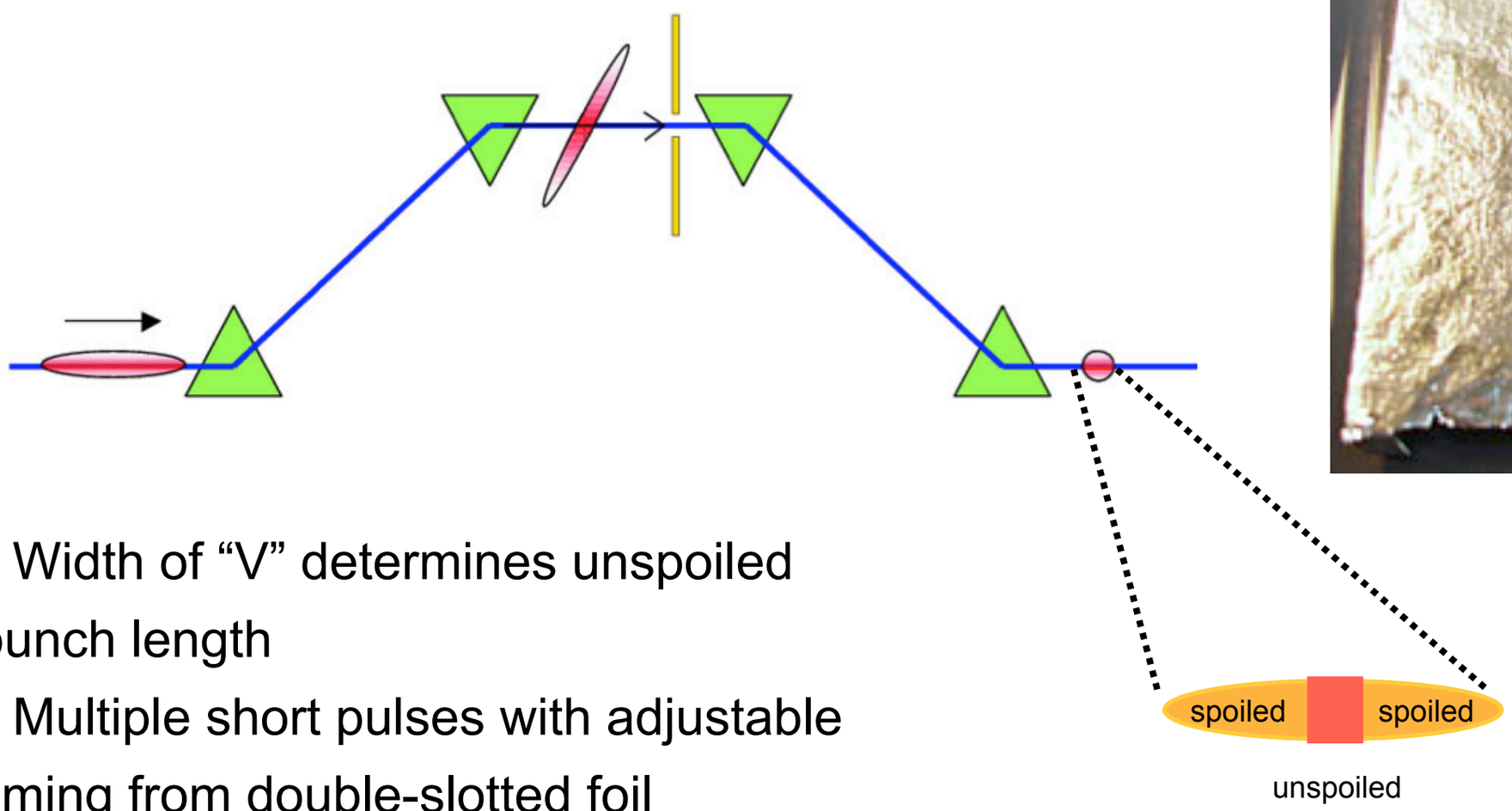
Few-femtosecond time-resolved measurements of X-ray free-electron lasers

C. Behrens[1,2], F.-J. Decker[1], Y. Ding[1], V.A. Dolgashev[1], J. Frisch[1], Z. Huang[1], P. Krejcik[1], H. Loos[1], A. Lutman[1], T.J. Maxwell[1], J. Turner[1], J. Wang[1], M.-H. Wang[1], J. Welch[1] & J. Wu[1]



Short Pulses through Beam Shaping

- Slotted Foil aka “Emittance Spoiler”
- x-t correlation in chicane during compression
- Only portion of beam that passes through hole retains properties suitable for lasing



- Width of “V” determines unspoiled bunch length
- Multiple short pulses with adjustable timing from double-slotted foil

P. Emma, et al Phys. Rev. Lett. **92**, 074801 2004

Self Seeding at soft x-rays

J. Feldhaus et al. / Optics Communications 140 (1997) 341–352

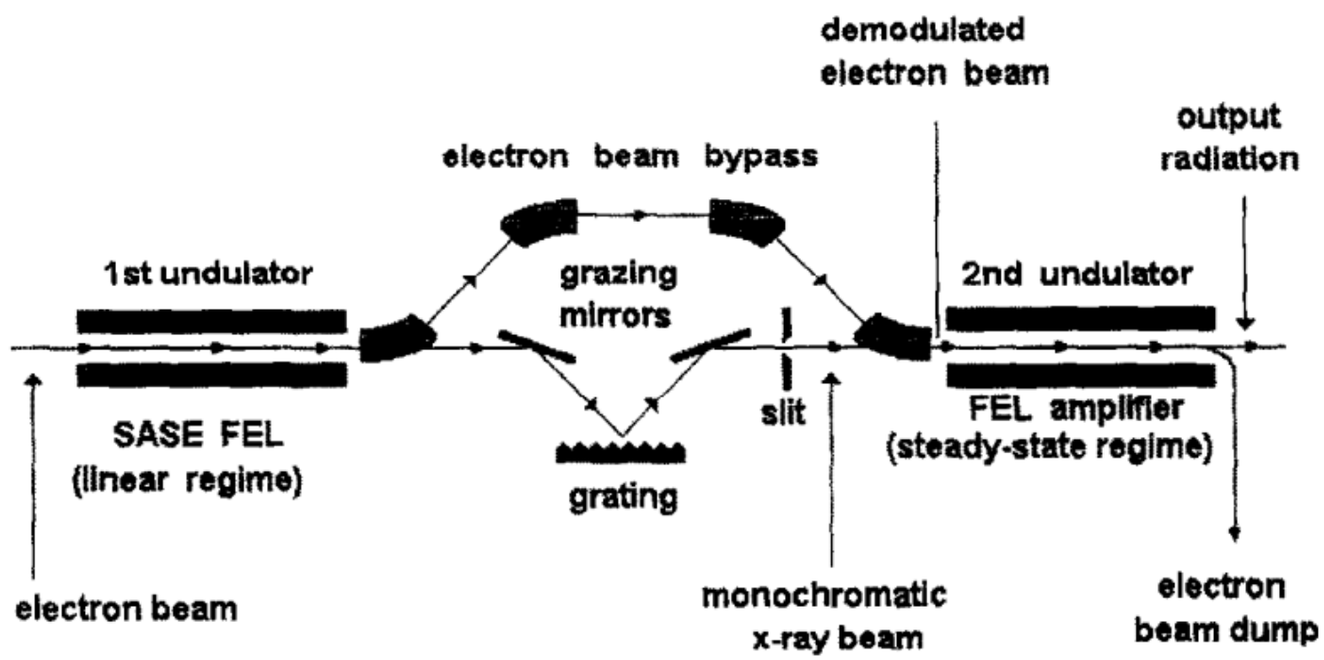
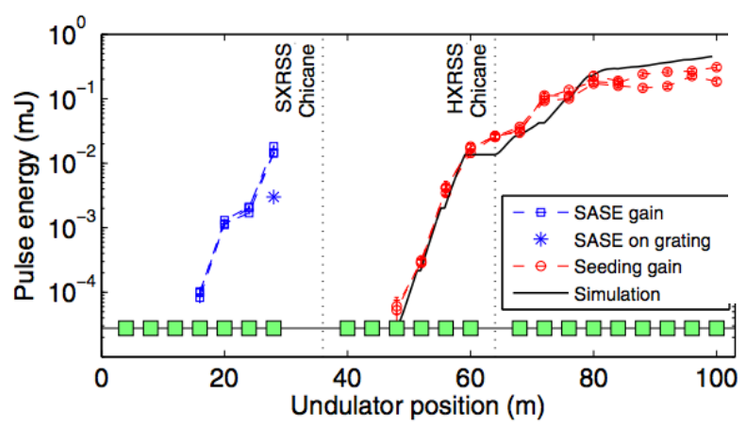


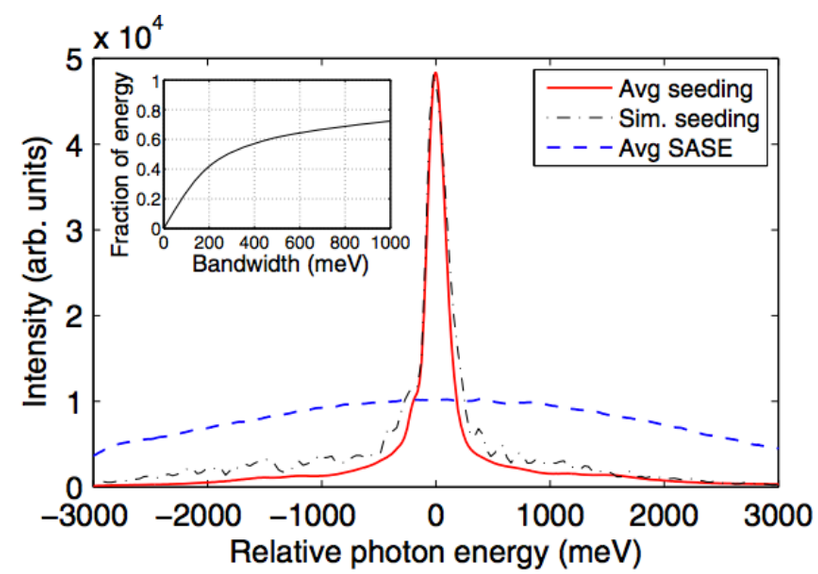
Fig. 3. The principal scheme of a single-pass two-stage SASE X-ray FEL with monochromator.

PRL **114,** 054801 (2015) PHYSICAL REVIEW LETTERS week ending 6 FEBRUARY 2015

Experimental Demonstration of a Soft X-Ray Self-Seeded Free-Electron Laser

D. Ratner,[1,*] R. Abela,[2] J. Amann,[1] C. Behrens,[1] D. Bohler,[1] G. Bouchard,[1] C. Bostedt,[1] M. Boyes,[1] K. Chow,[3] D. Cocco,[1] F. J. Decker,[1] Y. Ding,[1] C. Eckman,[1] P. Emma,[1] D. Fairley,[1] Y. Feng,[1] C. Field,[1] U. Flechsig,[2] G. Gassner,[1] J. Hastings,[1] P. Heimann,[1] Z. Huang,[1] N. Kelez,[1] J. Krzywinski,[1] H. Loos,[1] A. Lutman,[1] A. Marinelli,[1] G. Marcus,[1] T. Maxwell,[1] P. Montanez,[1] S. Moeller,[1] D. Morton,[1] H. D. Nuhn,[1] N. Rodes,[3] W. Schlotter,[1] S. Serkez,[4] T. Stevens,[3] J. Turner,[1] D. Walz,[1]





Self Seeding at hard x-rays

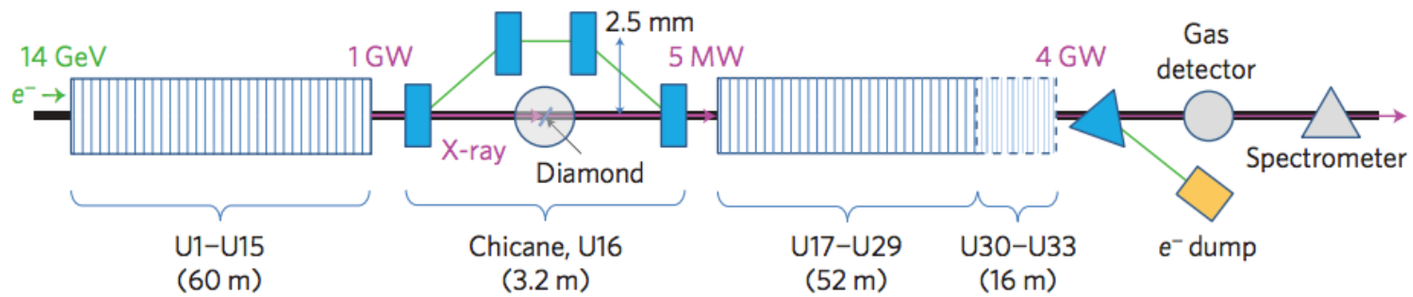
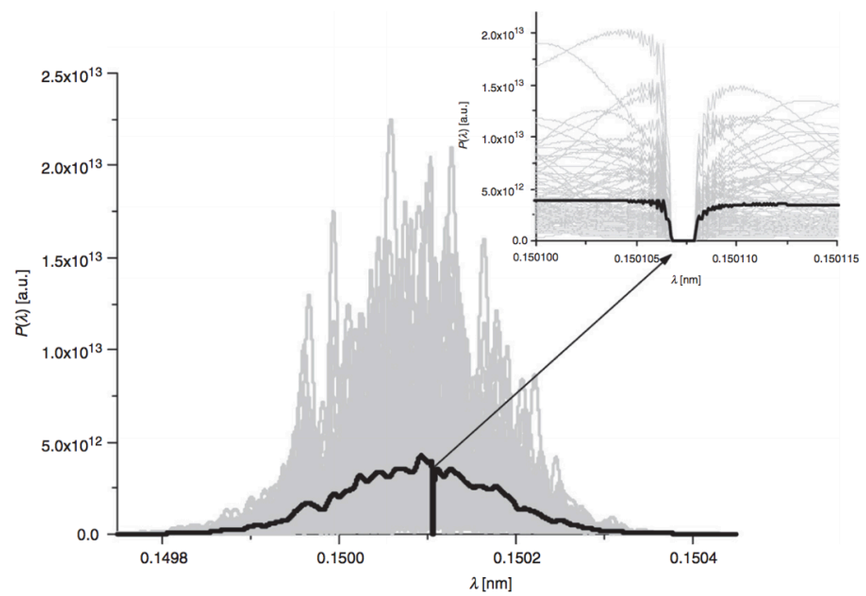


Figure 1 | Layout of the LCLS undulator with a self-seeding chicane, diamond monochromator, gas detector and hard-X-ray spectrometer. The chicane is greatly exaggerated in scale. The last four LCLS undulators (U30–U33) were previously modified as second-harmonic afterburners[15] and were not used in this experiment.

Crystal monochromator instead of grating to reduce required e-beam delay



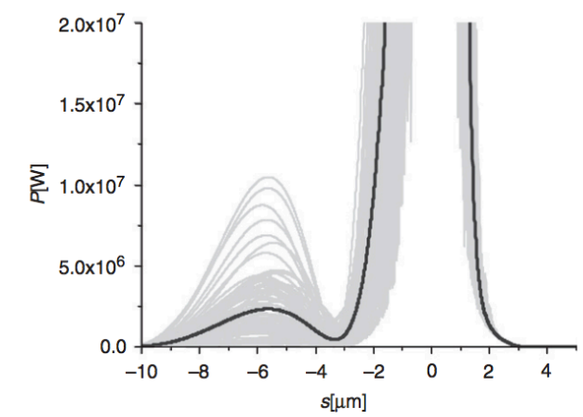


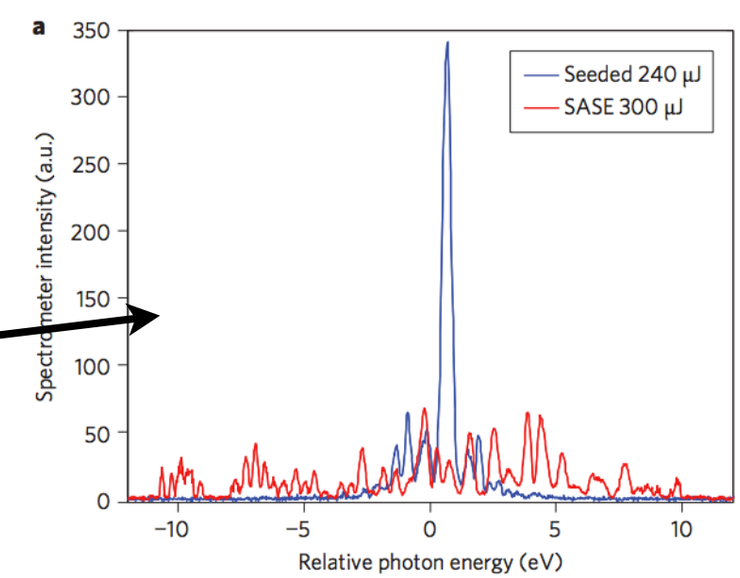
Figure 10. Feasibility study for the LCLS. Power distribution after the diamond crystal. The monochromatic tail due to the transmission through the bandstop filter is now evident on the left of the figure. Gray lines refer to single shot realizations, the black line refers to the average over 100 realizations.

Gianluca Geloni ,Vitali Kocharyan & Evgeni Saldin (2011) A novel self-seeding scheme for hard X-ray FELs, Journal of Modern Optics, 58:16, 1391-1403,

nature photonics
ARTICLES
PUBLISHED ONLINE: 12 AUGUST 2012 | DOI: 10.1038/NPHOTON.2012.180

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

J. Amann[1], W. Berg[2], V. Blank[3], F.-J. Decker[1], Y. Ding[1], P. Emma[4]*, Y. Feng[1], J. Frisch[1], D. Fritz[1], J. Hastings[1], Z. Huang[1], J. Krzywinski[1], R. Lindberg[2], H. Loos[1], A. Lutman[1], H.-D. Nuhn[1], D. Ratner[1], J. Rzepiela[1], D. Shu[2], Yu. Shvyd'ko[2], S. Spampinati[1], S. Stoupin[2], S. Terentyev[3], E. Trakhtenberg[2], D. Walz[1], J. Welch[1], J. Wu[1], A. Zholents[2] and D. Zhu[1]



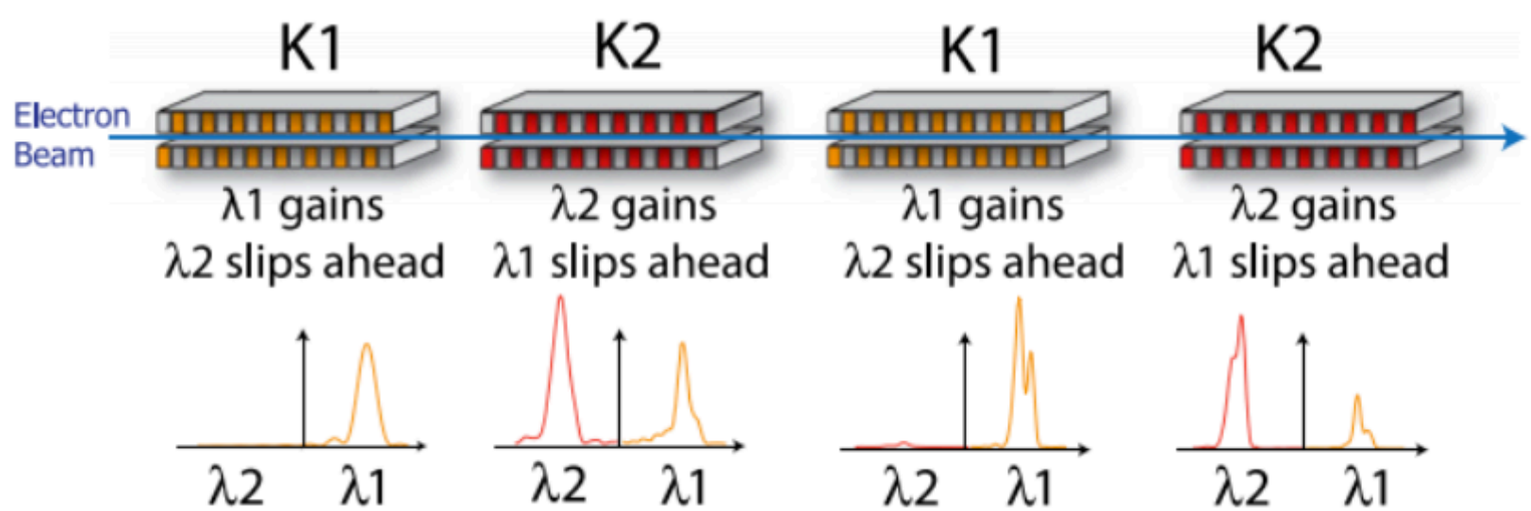
Multicolor x-ray FEL pulses

Multicolor x-rays have numerous uses in, e.g., pump-probe experiments. Two of the basic scenarios relevant to two-color x-ray applications are:

- The generation of a pair of sequential x-ray pulses with independent control of timing and spectrum.
- One x-ray pulse with two discrete wavelengths.

Ex: Two colors by alternating undulator resonance

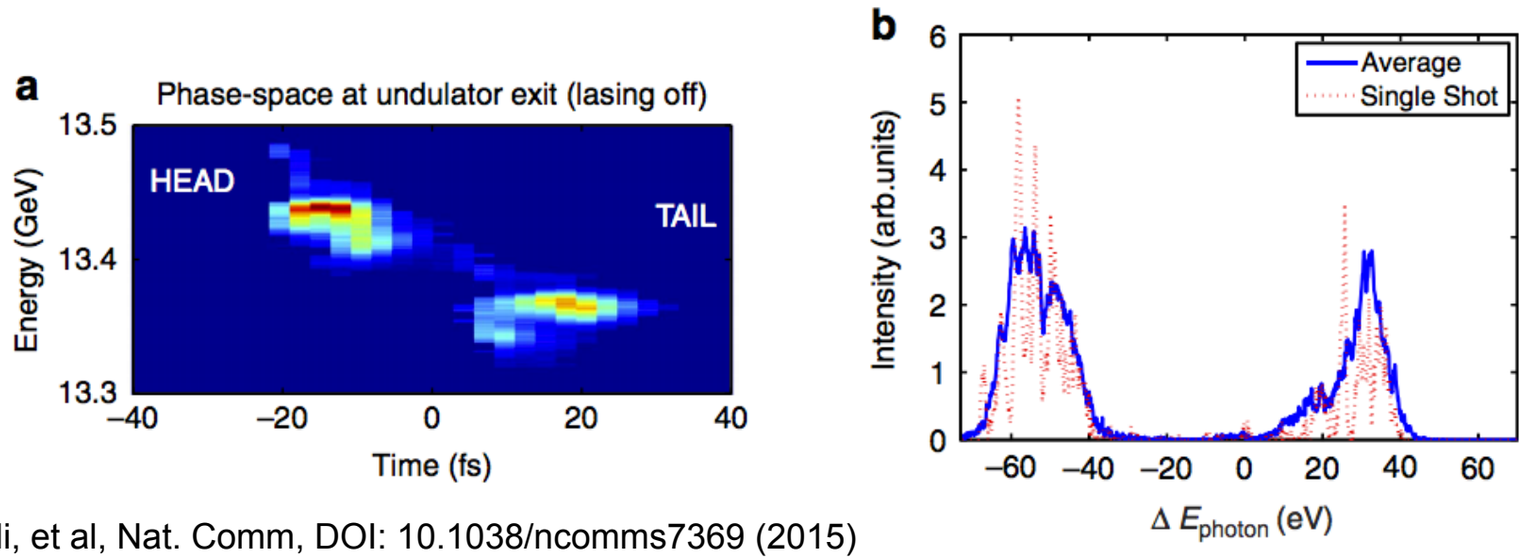
$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$



A. Marinelli, PRL, 111, 134801, (2013)

Multicolor FELs

Ex 2: Split/delay ~1ps photocathode laser pulse to create two beams within same RF bucket. ΔE and Δt adjusted by compression and phase



A. Marinelli, et al, Nat. Comm, DOI: 10.1038/ncomms7369 (2015)

Ex 3: Split undulators and use chicanes to delay different colors

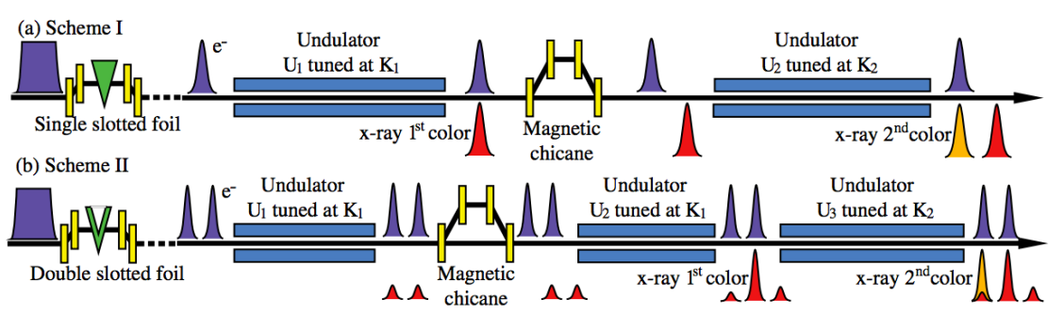


FIG. 1 (color online). Two-color FEL schemes tested at the LCLS. A single-slot (in scheme I) or double-slot (in scheme II) emittance spoiling foil was used to generate ultrashort single or double electron bunches. The emittance-spoiling foil is located in the second bunch compressor. A magnetic chicane, designed for hard x-ray self-seeding purpose, was adopted here to control the temporal delay between the two-color pulses.

A. Lutman, et al, PRL, 110, 134801, (2013)

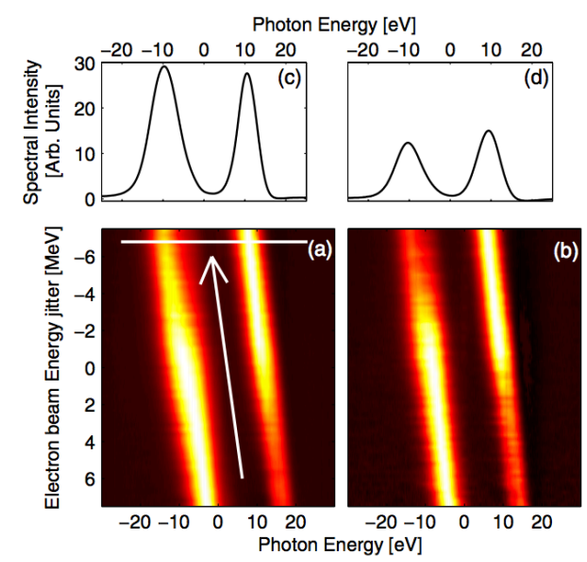
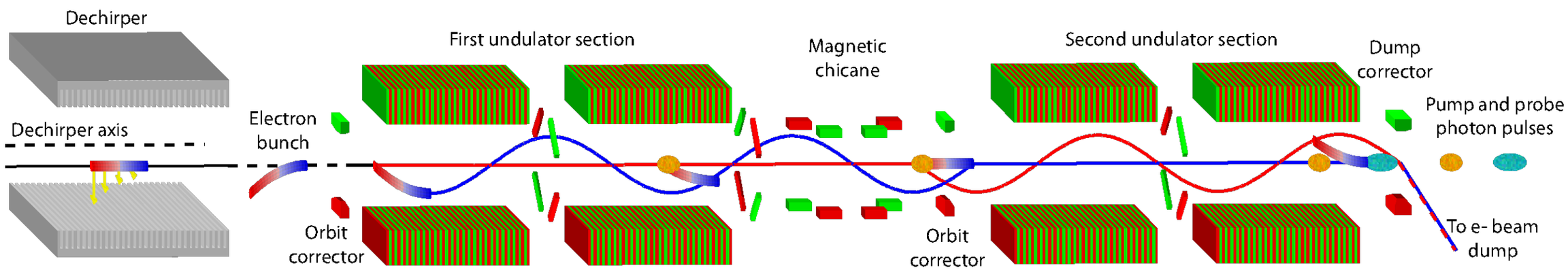


FIG. 3 (color online). Results for two-color beams with scheme I. (a),(b) Average spectral intensity as a function of the electron beam energy and photon energy. For each electron beam energy, the maximum intensity has been normalized to 1. (a) 0 fs delay. (b) 25 fs delay. (c,d) Average realigned spectra as a function of the photon energy offset from 1.5 keV. (c) 0 fs delay. (d) 25 fs delay.

Fresh-slice X-ray free-electron lasers

Wakefield “dechirper” gives e-beam correlated y-t kick that enables control over lasing portion.

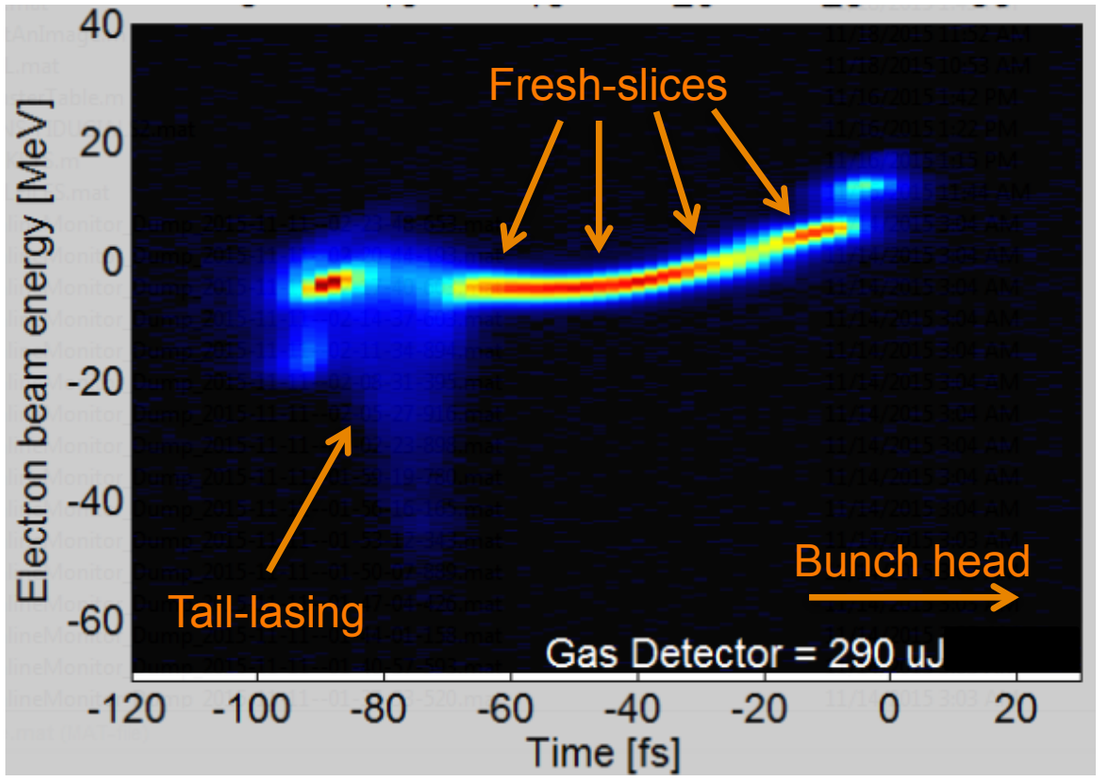


nature photonics
ARTICLES
PUBLISHED ONLINE: 17 OCTOBER 2016 | DOI: 10.1038/NPHOTON.2016.201

Fresh-slice multicolour X-ray free-electron lasers

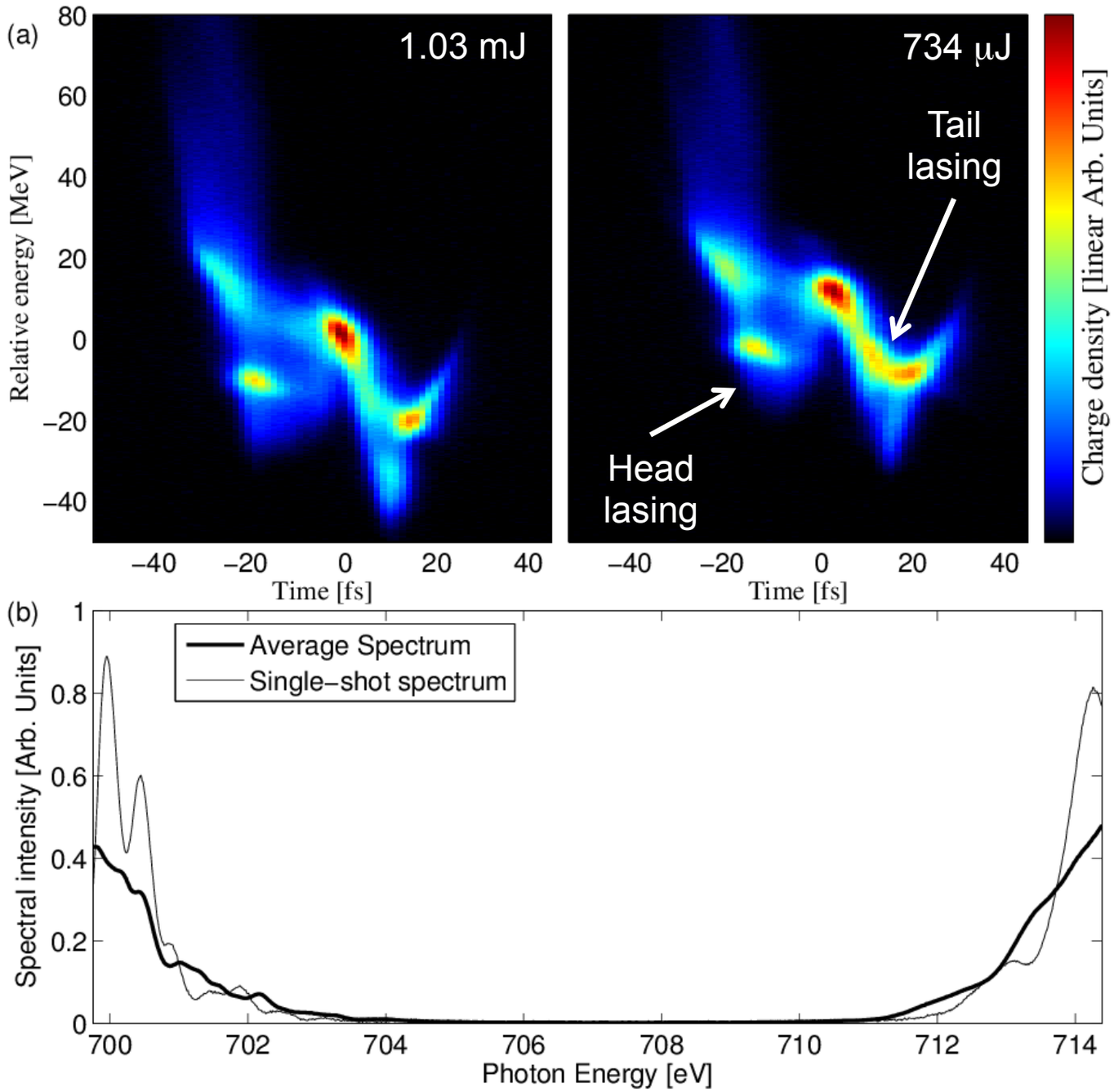
Alberto A. Lutman[1]*, Timothy J. Maxwell[1], James P. MacArthur[1], Marc W. Guetg[1], Nora Berrah[2], Ryan N. Coffee[1,3], Yuantao Ding[1], Zhirong Huang[1,3], Agostino Marinelli[1], Stefan Moeller[1] and Johann C. U. Zemella[1,4]

- Fresh-slice allows one temporal slice to lase.
- Differently than with other schemes to achieve short pulses (slotted foil, low charge), non-lasing slices remain fresh and can still lase in downstream undulator sections

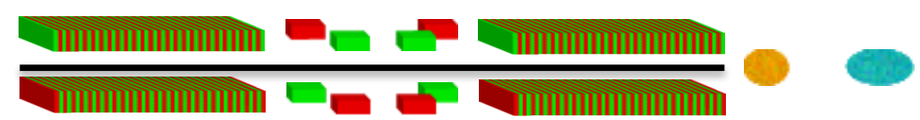


Courtesy A. Lutman

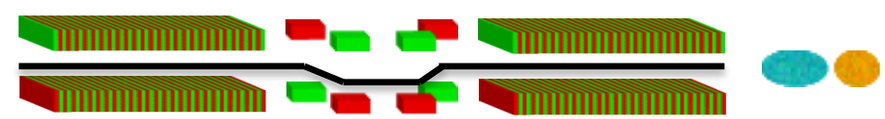
Dechirper applications: Two-color x-rays



	Tail Pulse	Head Pulse
Energy [μJ]	248 ± 83	484 ± 91
Duration	~ 5 fs	~ 17 fs
Wavelength	715 eV	699 eV
Undulators	U1-U8, K~3.455	U26-U33, K~3.505



No chicane delay, pulse on head arrives first



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

Scheme features:

+ Very easy to setup
+ Fully saturated short pulses
+ Delay controlled by chicane
+ Color separation controlled by undulator K
+ Scan through zero delay if tail lases first
+ Independent pointing in each section
+ Polarization control with Delta

A. A. Lutman *et al.,* Fresh-slice multicolour X-ray free-electron lasers, *Nature Photonics,* DOI 10.1038/NPHOTON.2016.201

Seeding to Generate Transform-Limited Pulses

- Coherent FEL pulses can be produced if the FEL starts from a fully coherent seed that has sufficient power to dominate over the electron beam shot noise.
- **Ultimate goal:** Generate **transform limited**, stable, and controllable x-ray pulses with **tunable time/BW** tradeoff

Seeding approaches

Direct Seeding - High Harmonic Generation (HHG) – [State Of The Art: 38 nm]

FEL amplification EM input, usu. harmonic of 800nm generated in noble gas

Limited to >20nm by 10^{-6} conversion efficiency. Seed must exceed shot noise in beam.

High Gain Harmonic Generation (HGHG) – [4 nm, 65th harm from 260nm]

Harmonic density bunching. Limited to <15th harmonic in single stage

Cascade multiple stages w/fresh beam to reach soft x-rays.

Demonstrated and soon in use @4nm

Echo-Enabled Harmonic Generation (EEHG) – [32 nm, 75th harm from 2.4um]

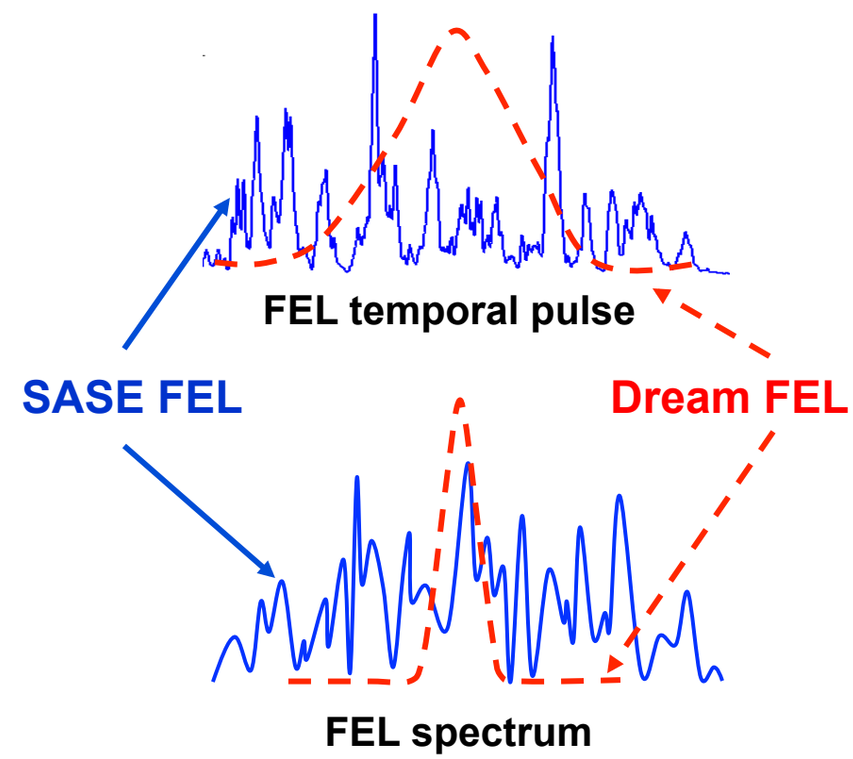
Harmonic density bunching. Small energy modulations required. Reach soft x-rays from UV lasers in single stage.

Highly nonlinear phase space manipulation and preservation challenging.

Self Seeding (HXRSS & SXRSS)

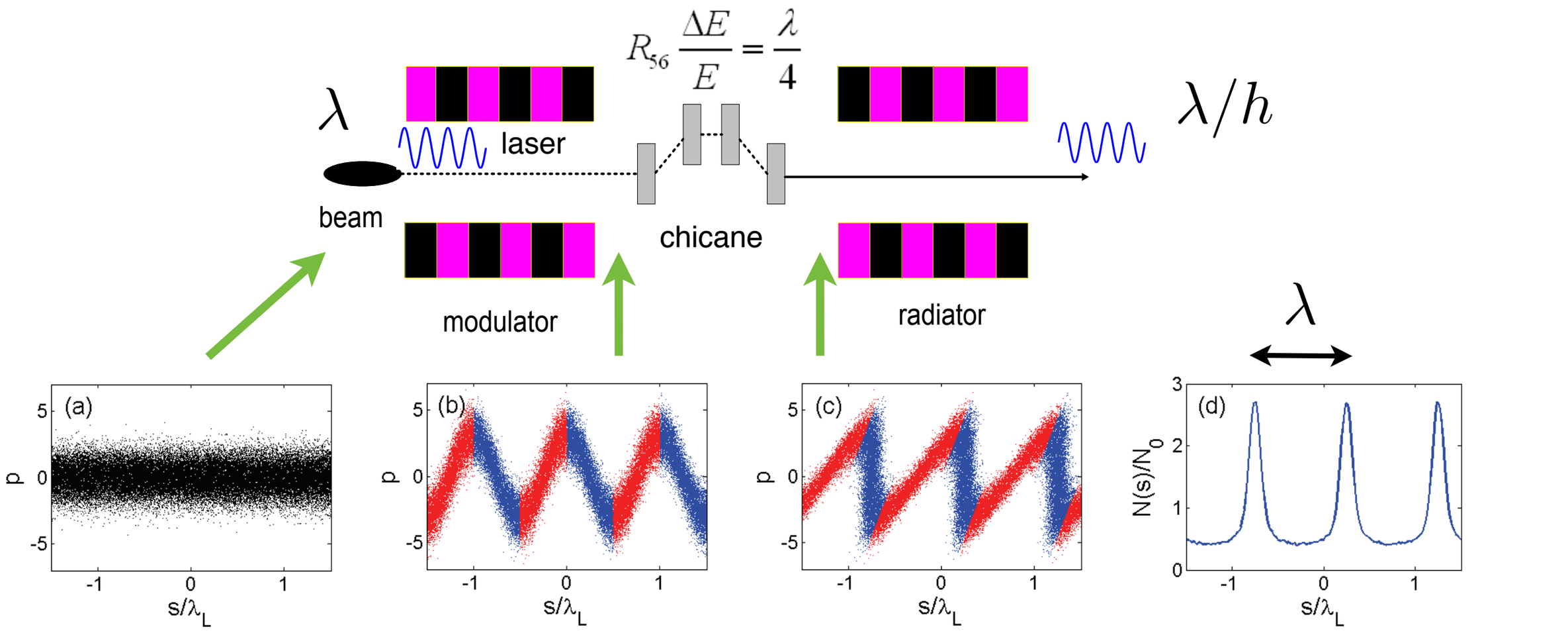
Monochromatized FEL seeds itself. **Demonstrated and in use.**

No direct pulse length control. Damage & rep rate limits. Spectral pedestal.



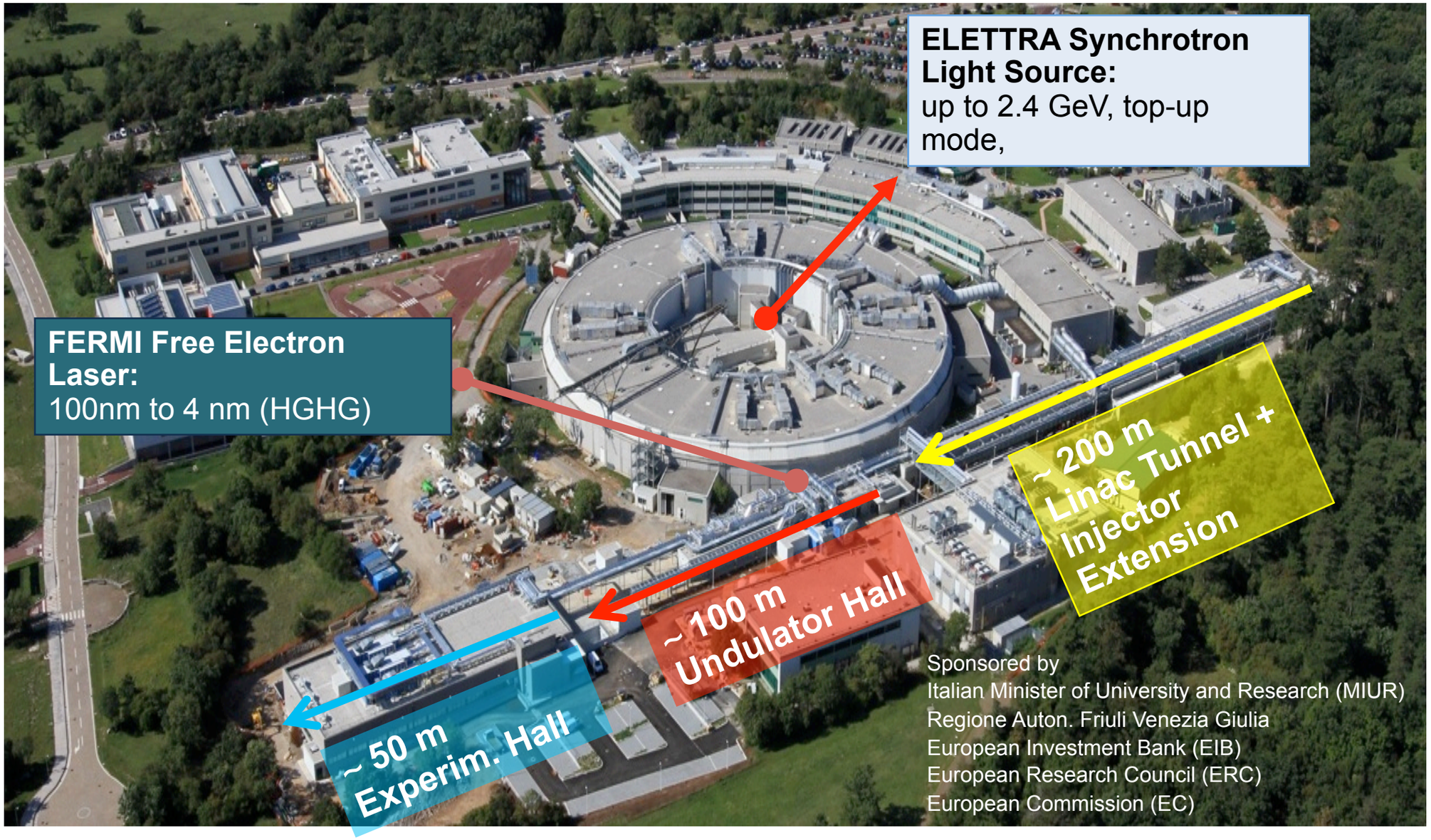
High Gain Harmonic Generation (HGHG)

- Laser generates energy modulation in electron beam phase space
- Energy modulation converted to density modulation in dispersive section (chicane)
- Coherent radiation at wavelength amplified to saturation in FEL



density distribution

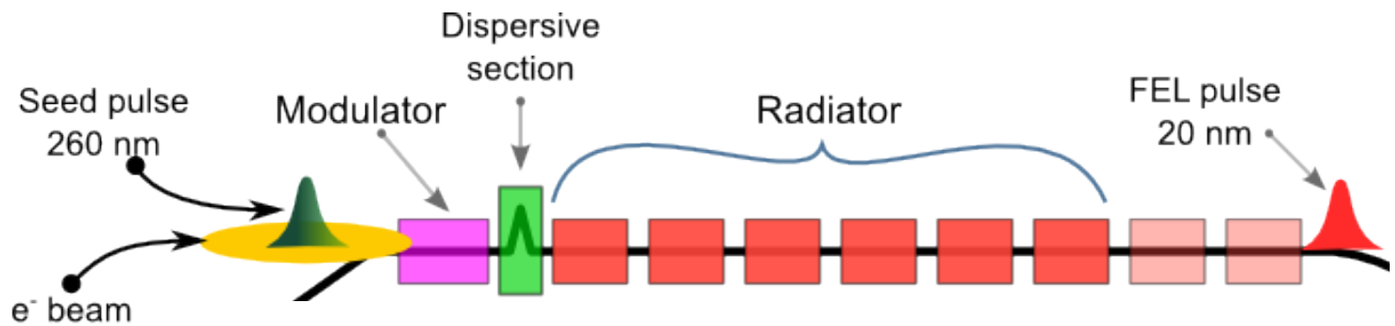
HGHG-based FEL: FERMI@Elettra (Italy)



- FERMI (Free Electron laser Radiation for Multidisciplinary Investigations)
- HGHG FEL 4-65th harmonic of 260 nm
- 0.9-1.5 GeV e- to drive FEL
- 700pC, 700 Amps/pulse

Wavelength Range	**4 to 100 nm**
FEL Pulse Length	**10 - 100 fs**
Rel. Bandwidth	**~0.1%**
FEL Pulse Energy	**<100 uJ**
Repetition Rate	**10-50 Hz**

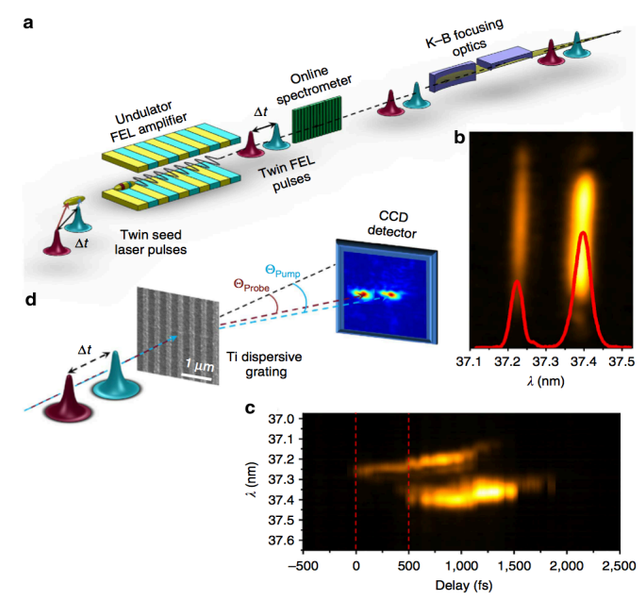
HGHG-based FEL pulse control @ FERMI



HGHG seeding provides significant control over FEL output, eg:

- stable central wavelength **and power**
- narrow bandwidth
- multicolor operations (two harmonics, or two different seeds with different wavelengths)
- phase-locked pulses
- FEL chirp compensation by laser shaping
- chirped pulse amplification, etc.

multicolor pulses



nature photonics ARTICLES
PUBLISHED ONLINE: 23 SEPTEMBER 2012 | DOI: 10.1038/NPHOTON.2012.233

Highly coherent and stable pulses from the FERMI seeded free-electron laser in the extreme ultraviolet

E. Allaria et al.*

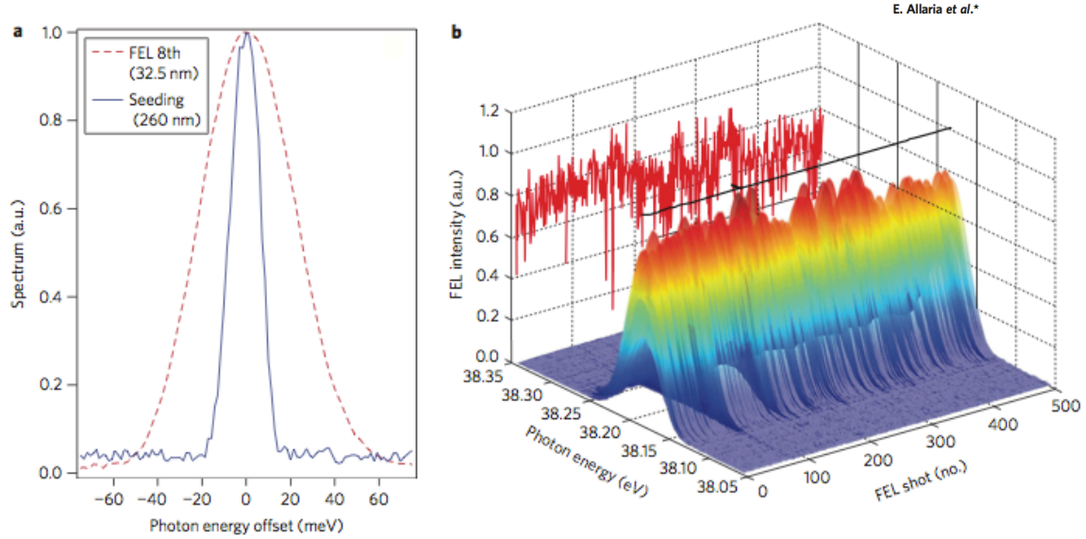
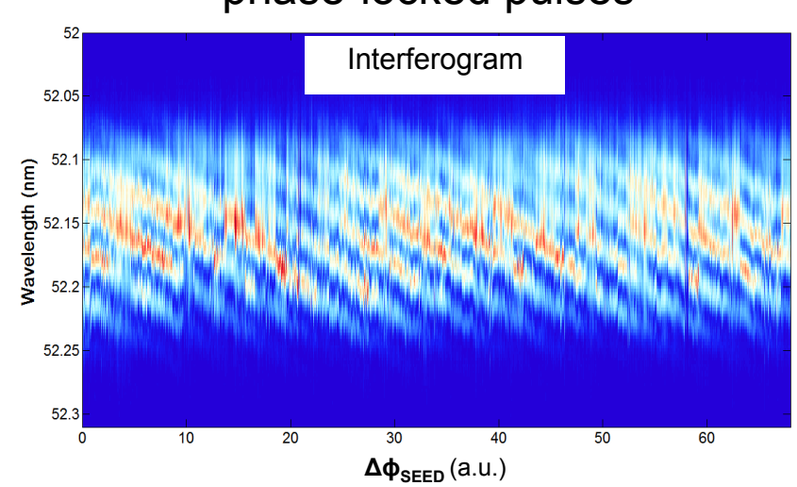


Figure 4 | Single-shot and multi-shot spectra at 32.5 nm. a, Measured FEL and seed laser spectrum (dashed red and continuous blue lines respectively). **b**, Acquisition of 500 consecutive FEL spectra.

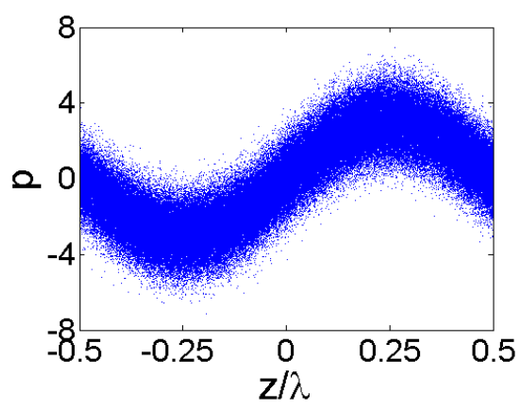
phase-locked pulses

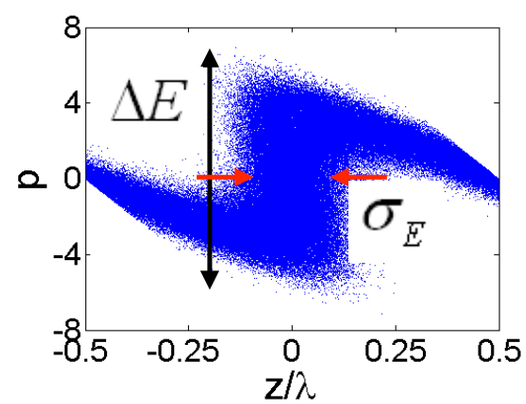


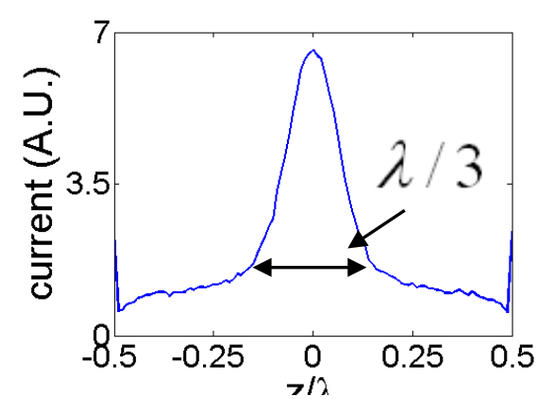
Limitations on single stage HGHG

- **Low up-frequency conversion efficiency:** $\Delta E / \sigma_E \approx n$

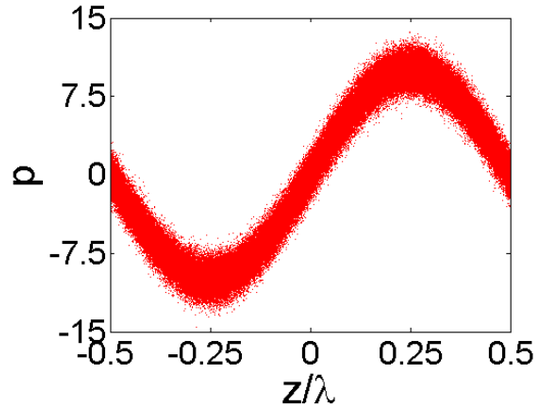
$\Delta E / \sigma_E = 3$

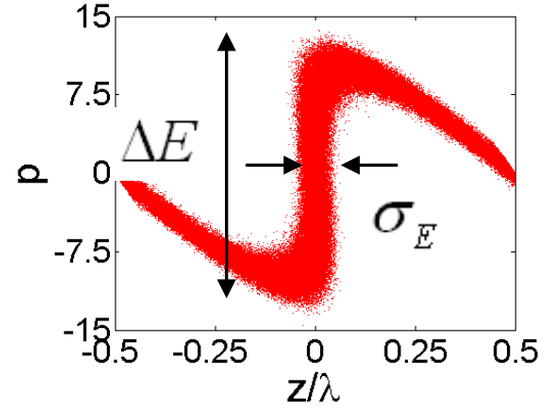


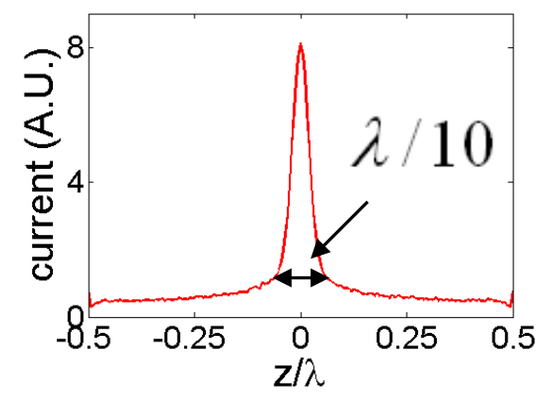




$\Delta E / \sigma_E = 10$





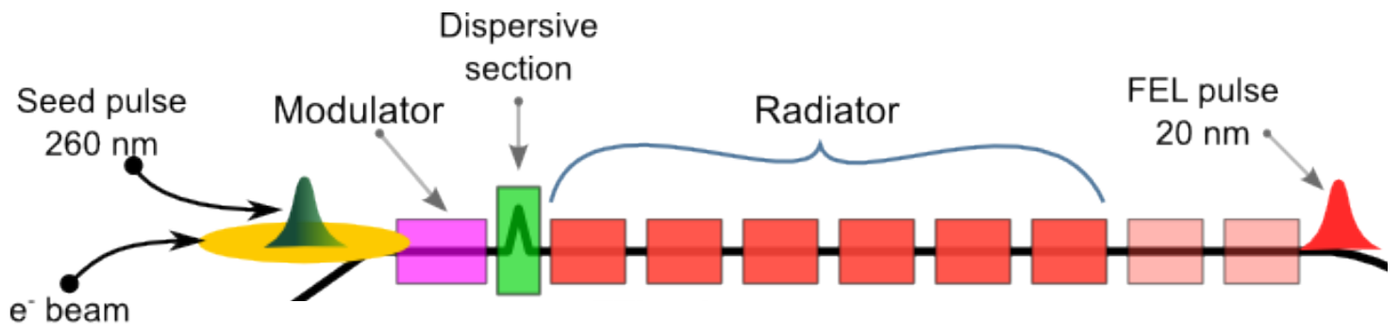


Modulator exit **Chicane exit** **Current distribution**

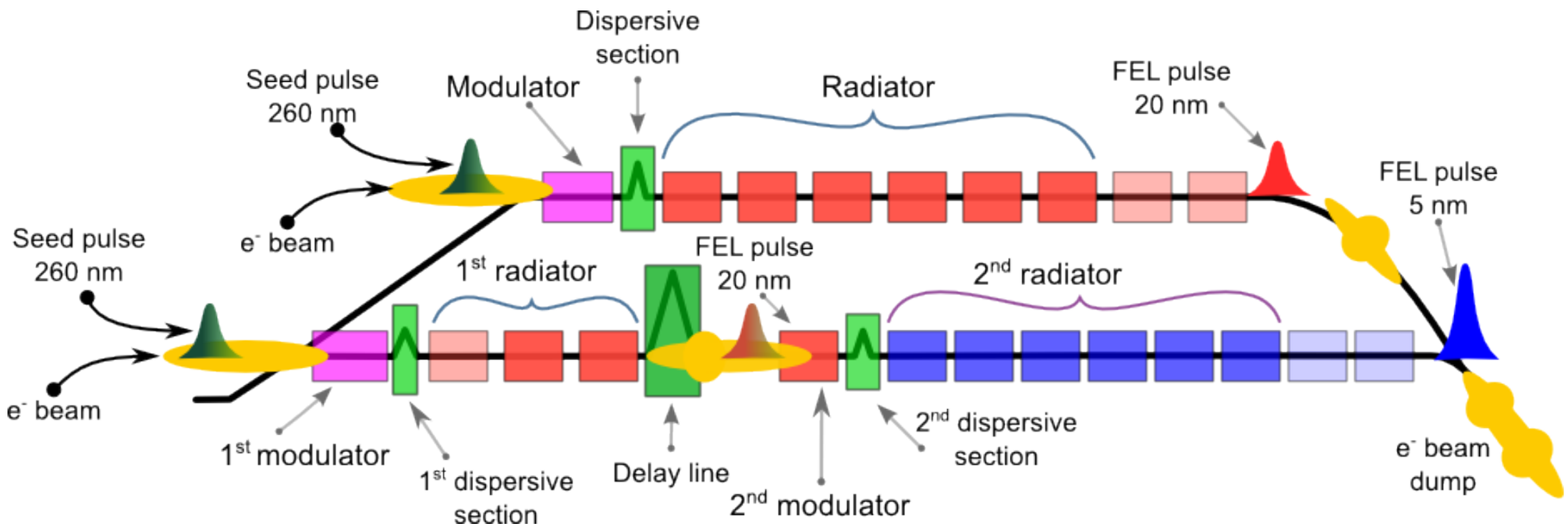
- **Outcome: Bunching (large ΔE) OR Gain (small ΔE)**
- **But seeded FEL wants: Bunching AND Gain**

(Slide courtesy D. Xiang)

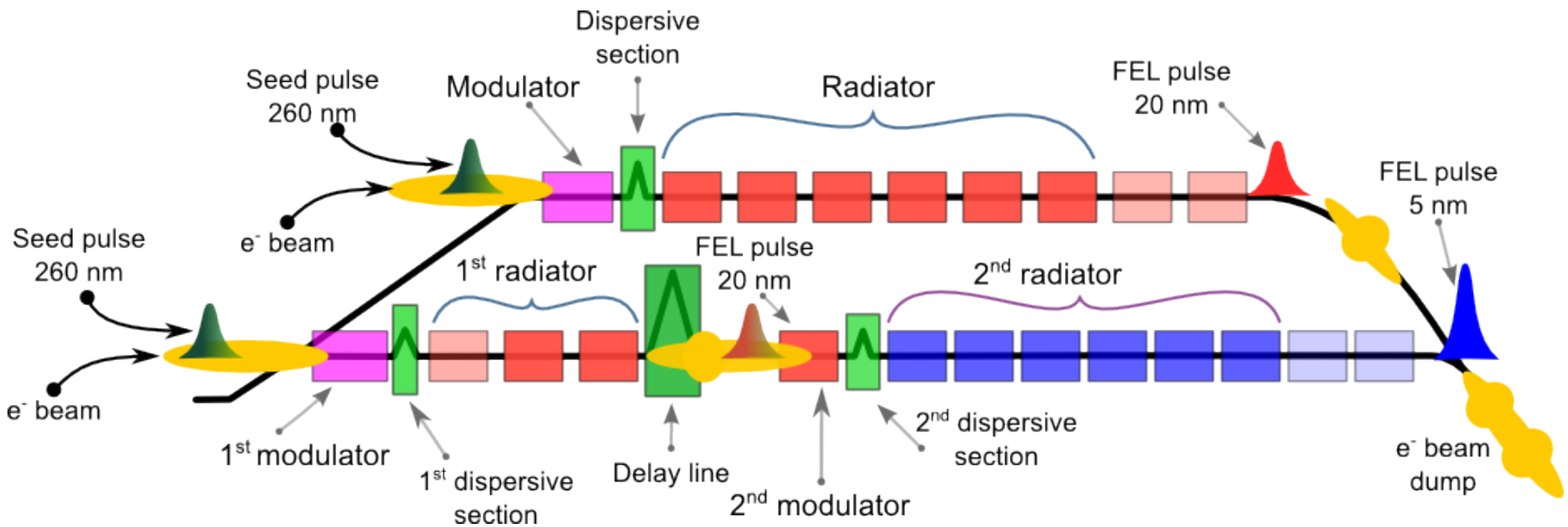
Reaching shorter wavelengths - cascaded HGHG



Reaching shorter wavelengths - cascaded HGHG



Reaching shorter wavelengths - cascaded HGHG



$$\lambda \Rightarrow \frac{\lambda}{h_1} \Rightarrow \frac{\lambda}{h_1 h_2}$$

Two Stages <65th harmonic @ FERMI

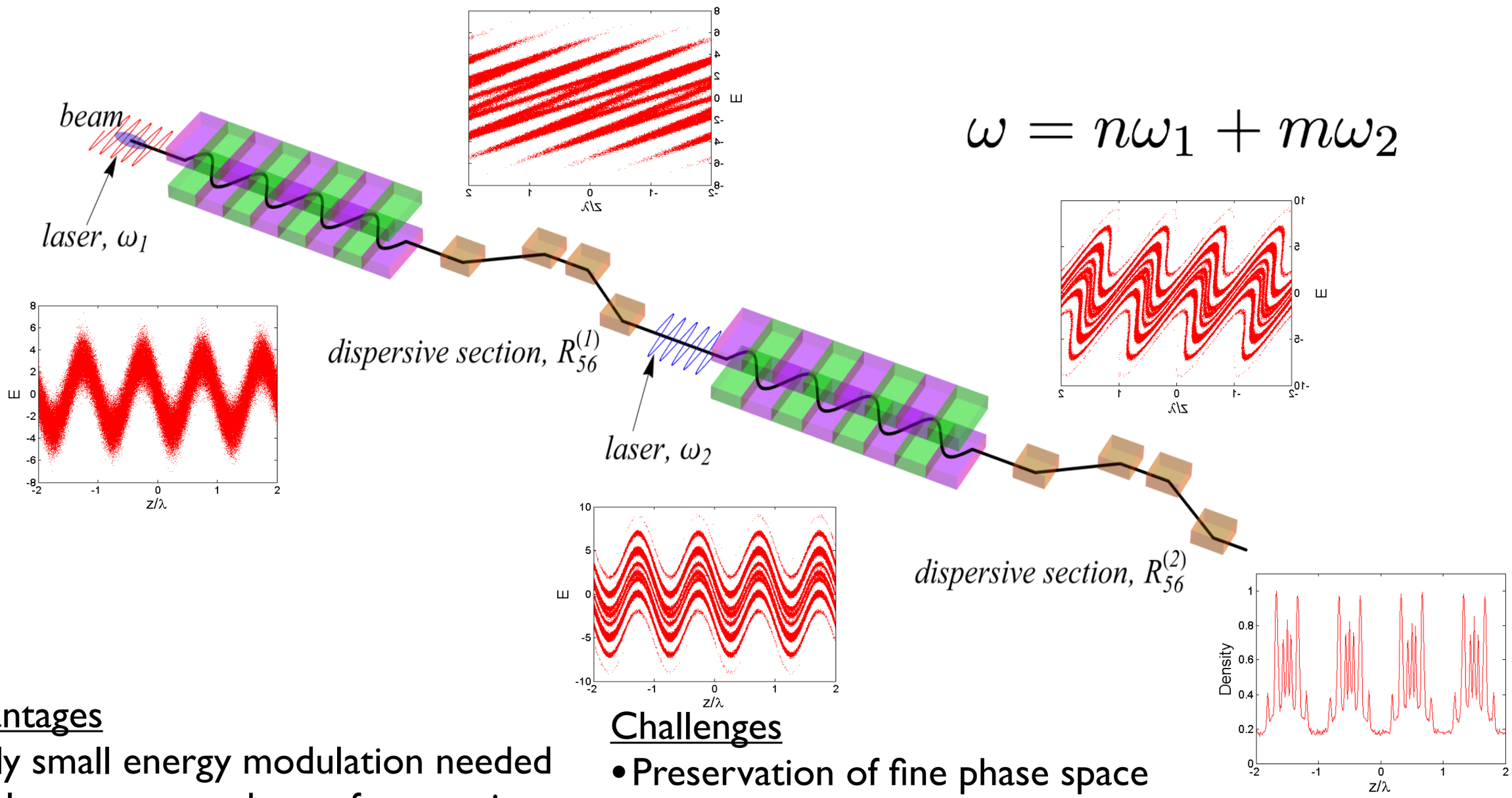
nature photonics
ARTICLES
PUBLISHED ONLINE: 20 OCTOBER 2013 | DOI: 10.1038/NPHOTON.2013.277

Two-stage seeded soft-X-ray free-electron laser

E. Allaria[1], D. Castronovo[1], P. Cinquegrana[1], P. Craievich[1†], M. Dal Forno[1,2], M. B. Danailov[1], G. D'Auria[1], A. Demidovich[1], G. De Ninno[1,3], S. Di Mitri[1], B. Diviacco[1], W. M. Fawley[1]*, M. Ferianis[1], E. Ferrari[1], L. Froehlich[1], G. Gaio[1], D. Gauthier[1,3], L. Giannessi[1,4]*, R. Ivanov[1], B. Mahieu[1,5], N. Mahne[1], I. Nikolov[1], F. Parmigiani[1,2], G. Penco[1], L. Raimondi[1], C. Scafuri[1], C. Serpico[1], P. Sigalotti[1], S. Spampinati[1,3], C. Spezzani[1], M. Svandrlik[1], C. Svetina[1,2], M. Trovo[1], M. Veronese[1], D. Zangrando[1] and M. Zangrando[1,6]

- Cascaded multiple stages to reach soft x-rays
- Each stage degrades e-beam, so fresh beam needed each time
- Staging reduces pulse control flexibility (harder to control FEL properties through cascade, limited fresh beam length...)

Combination of two modulators and two chicanes: Echo Enabled Harmonic Generation (EEHG)



Advantages

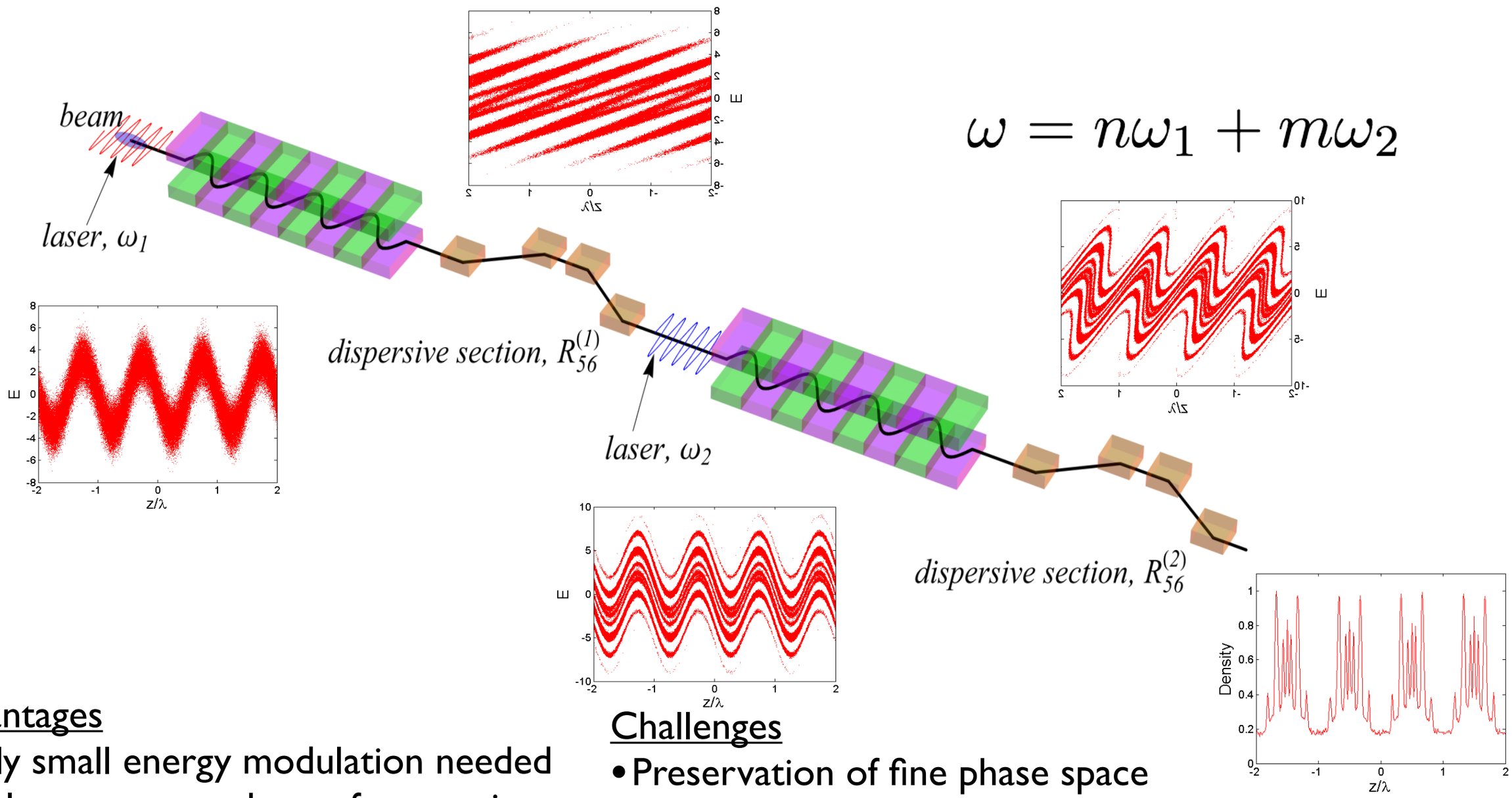
- Only small energy modulation needed
- UV laser converted to soft x-rays in single stage
- Tunable through dispersion
- Relatively insensitive to e-beam phase space distortions

Challenges

- Preservation of fine phase space correlations
- Sensitive to intrabeam scattering, diffusion, and laser quality

G. Stupakov, PRL 102, 074801 (2009)
D. Xiang and G. Stupakov, 12, 030702 (2009)

Combination of two modulators and two chicanes: Echo Enabled Harmonic Generation (EEHG)



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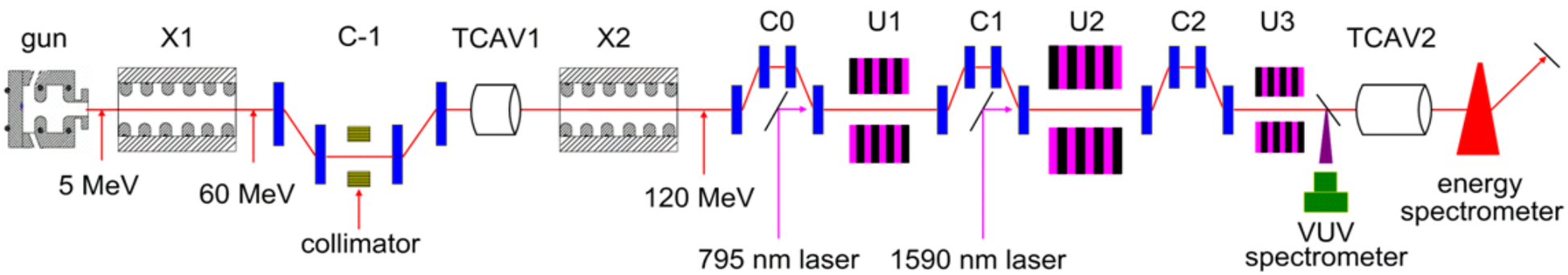
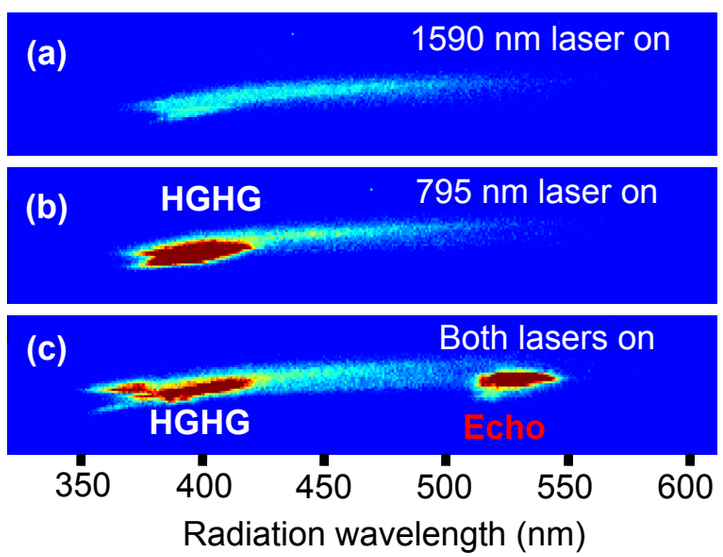
G. Stupakov, PRL 102, 074801 (2009)
D. Xiang and G. Stupakov, 12, 030702 (2009)

First EEHG experiments at SLAC's NLCTA

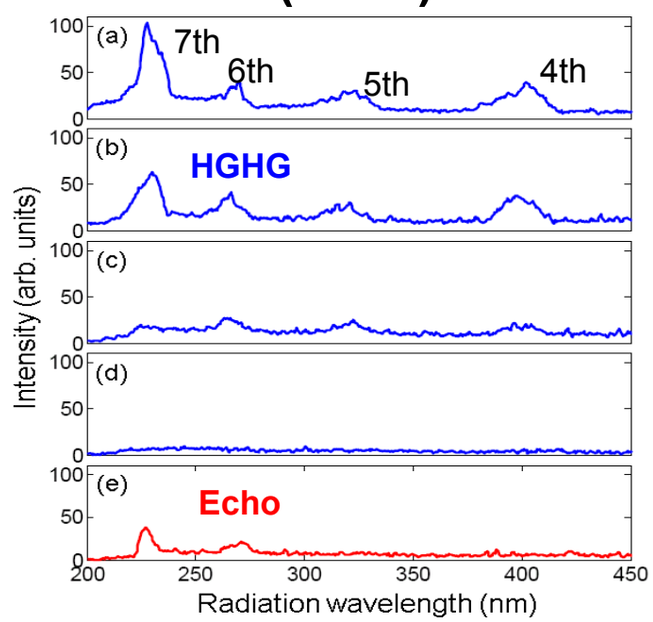


ECHO-3 (2010)



D. Xiang *et al., PRL 105, 114801* (2010)

ECHO-7 (2012)



D. Xiang, et al, PRL 108, 024802 (2012).

ECHO-15 (2014)

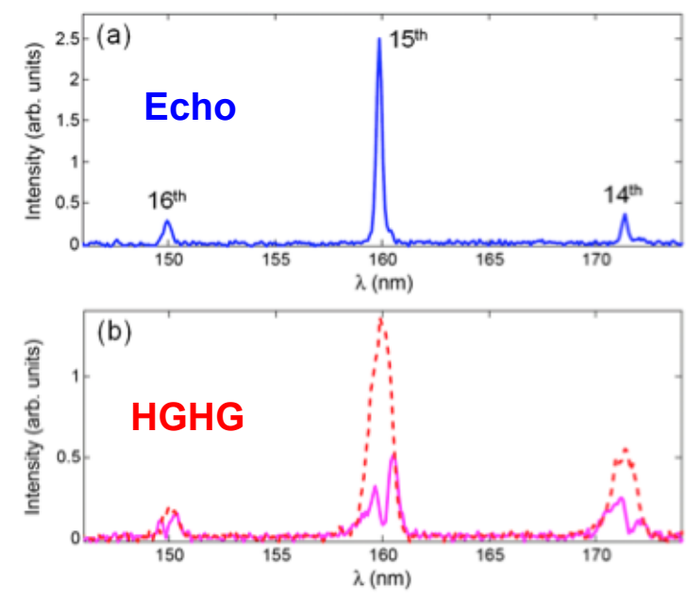
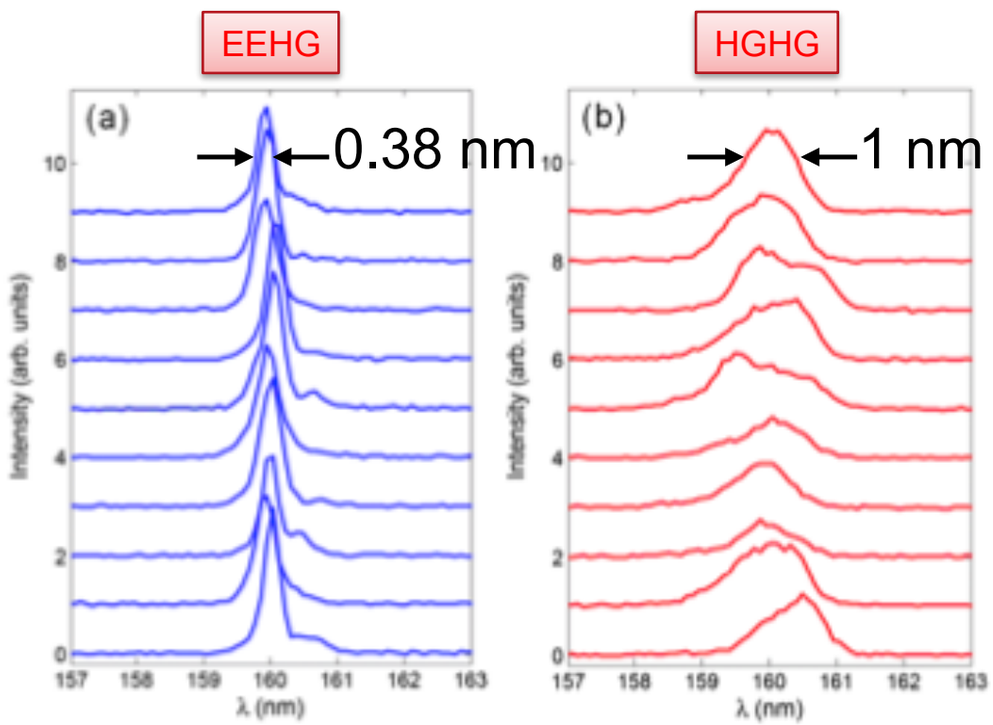


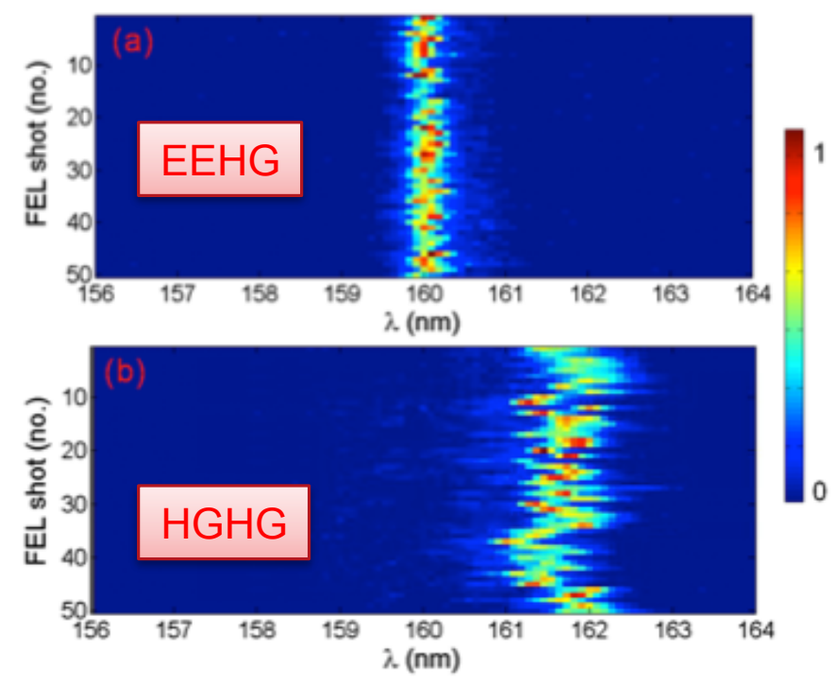
FIG. 4. Representative single-shot radiation spectrum for EEHG (a) and HGHG (b).

E. Hemsing, et al PRST-AB 17, 070702 (2014)

15th harmonic: EEHG vs HGHG comparison

EEHG has better spectral performance than HGHG due to the strong nonlinear frequency mixing





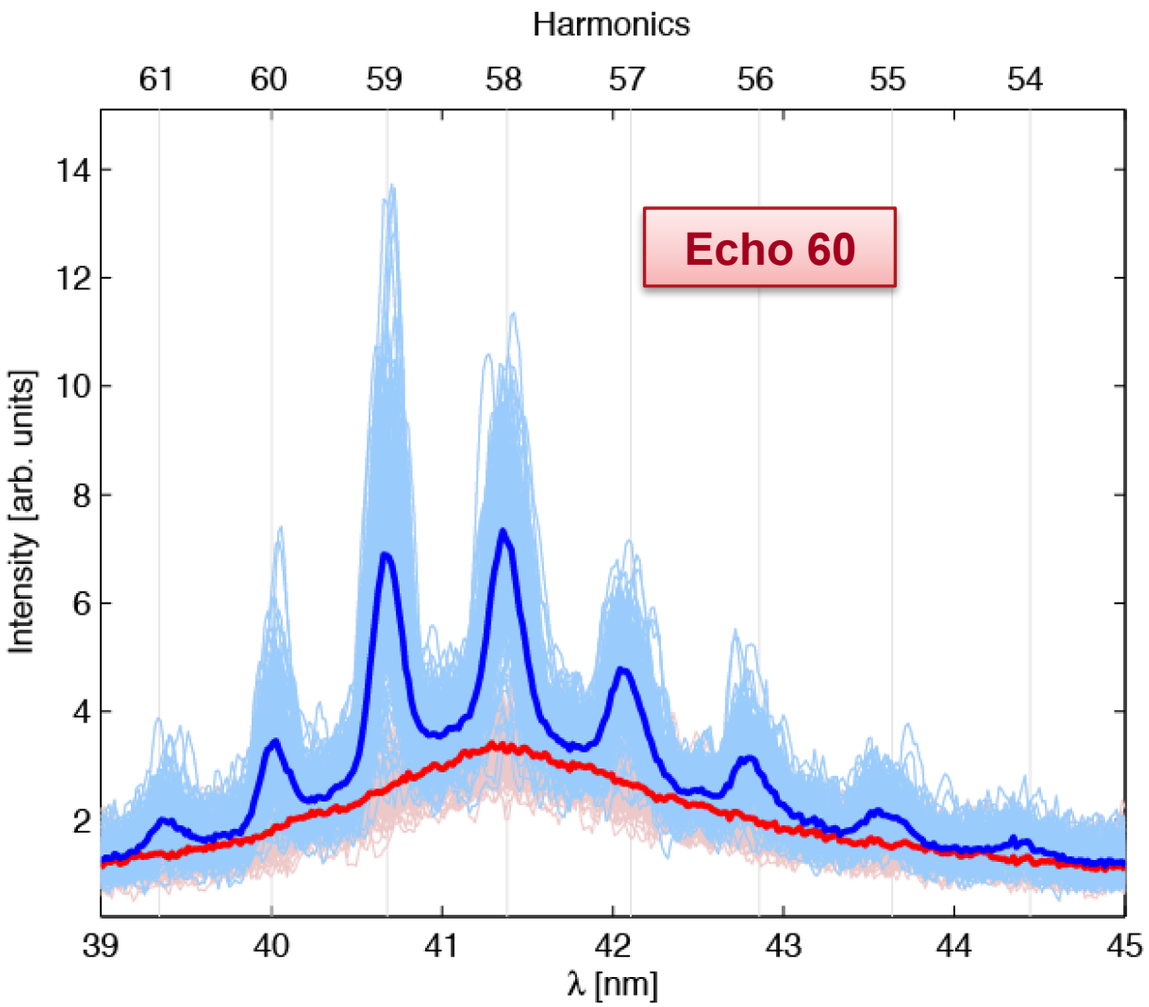
- Non-linear curvature adds more bandwidth to HGHG by shifting wavelengths across the beam
- front is compressed, back is decompressed
- EEHG less sensitive because strong initial R_{56} removes this smooth variation

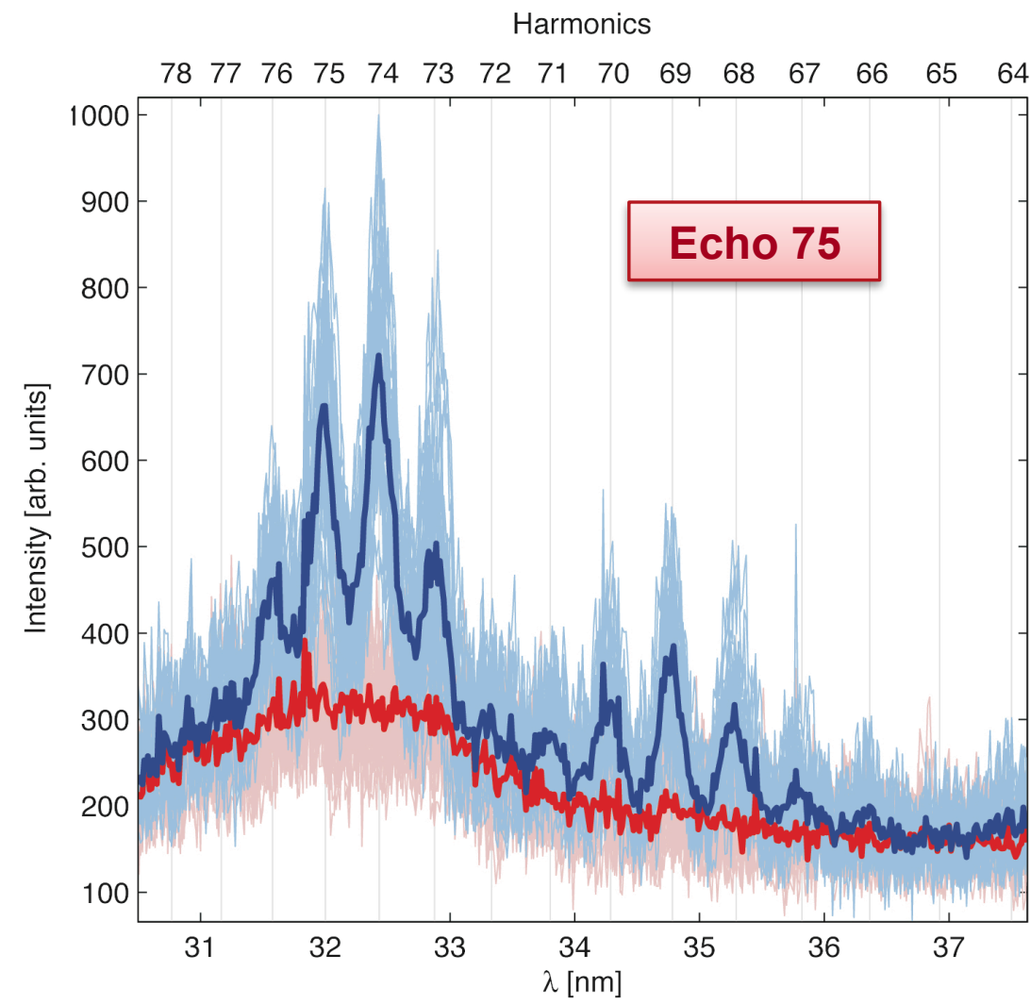
- Reduced sensitivity of EEHG to phase space distortions stabilizes central wavelength
- RF timing drift or jitter in e-beam can change chirp –> shift in central wavelength
- OR, timing jitter between laser and e-beam (ie, energy jitter) changes laser overlap and selects differently chirped region

EEHG in the high-harmonic regime

- **2400 nm to 40nm, 32 nm (190 MeV)**
- **Signals at undulator harmonics**

E.H, et. al., Nature Photonics 10, 512–515 (2016)





ΔE_1	ΔE_2	$R_{56}^{(1)}$	$R_{56}^{(2)}$
38 keV	84 keV	12.5 mm	600um

ΔE_1	ΔE_2	$R_{56}^{(1)}$	$R_{56}^{(2)}$
60 keV	100 keV	12.5 mm	484 um

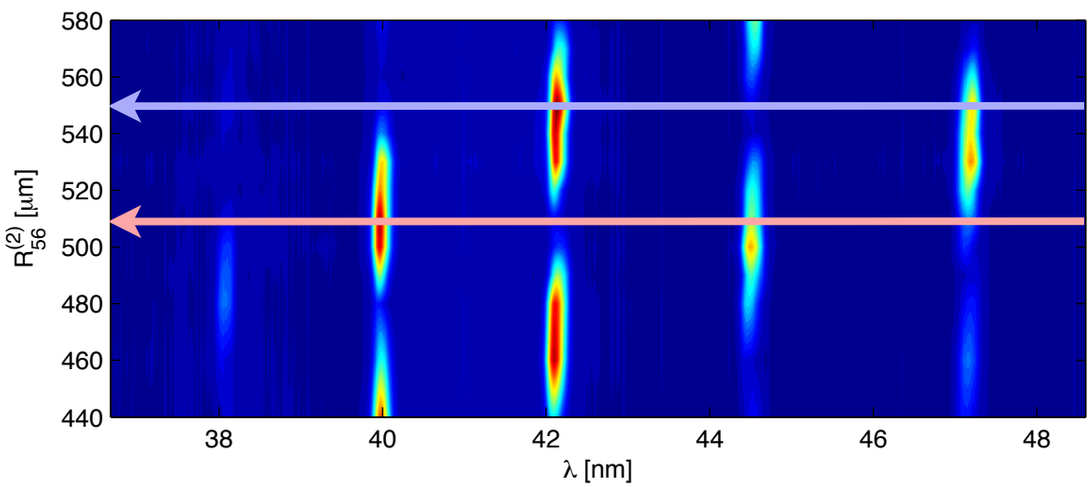
Precision control of multicolor spectrum with EEHG

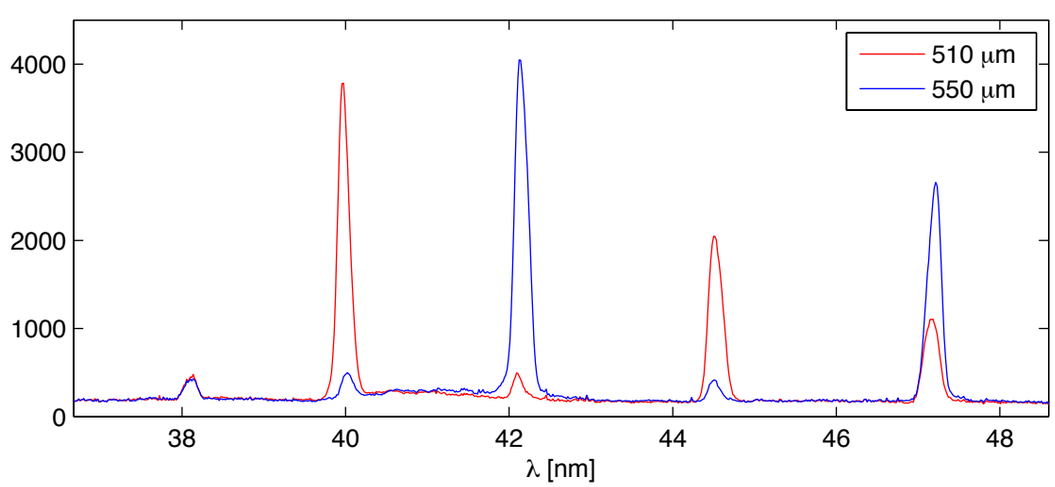
Via dispersion:

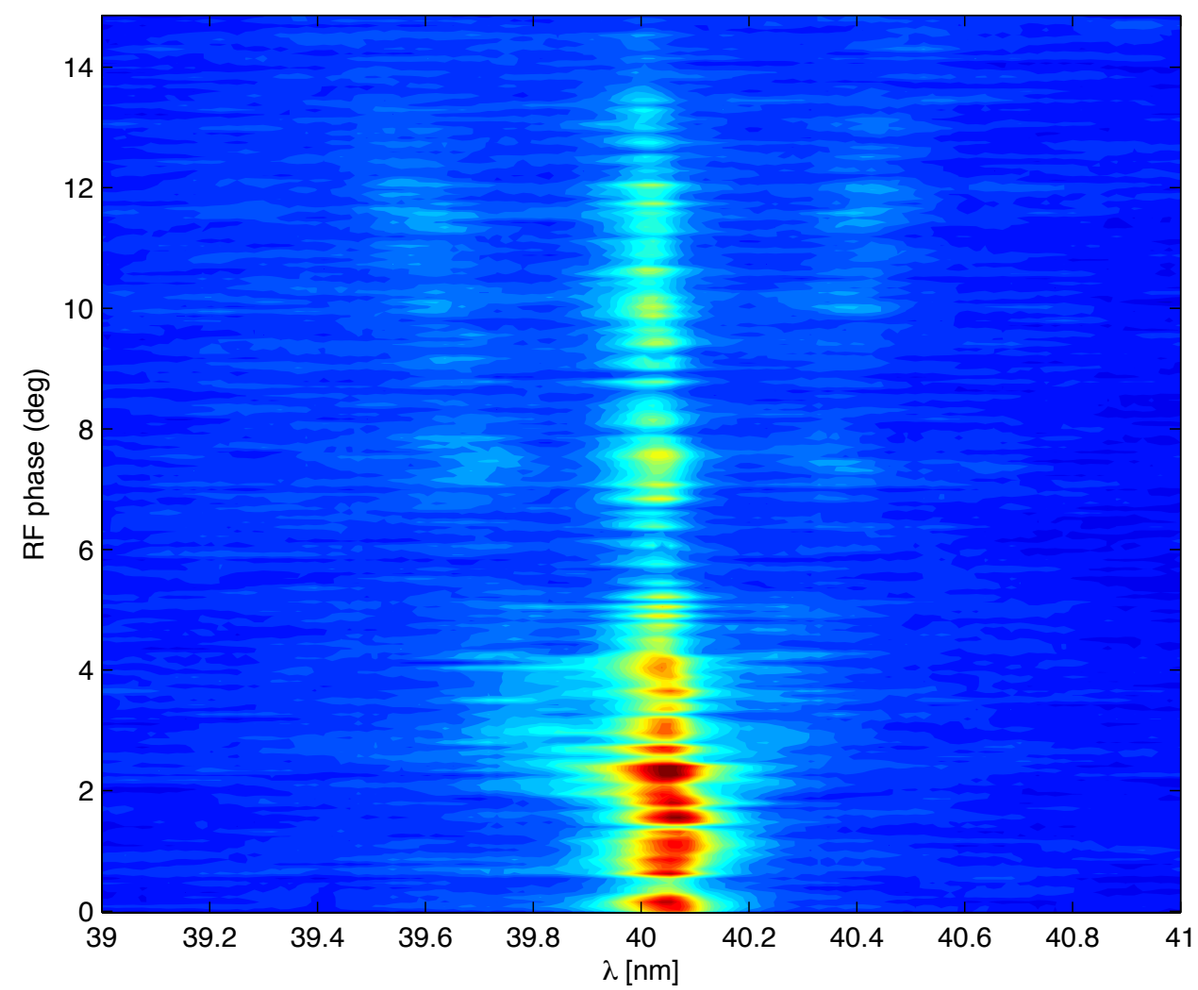
- Each harmonic has slightly different dependence on dispersion
- Individual harmonics can be selectively excited/suppressed
- nm-scale control of multicolor spectrum

Via e-beam chirp:

- Harmonics at given wavelength can be excited by different n,m bunching indices, but have different dependence on e-beam chirp
- Chirp splits central wavelength into sidebands
- sub nm-scale control of multicolor spectrum







harmonics of 800 nm laser

Exotic Light Production

Virtually all e-beam manipulation and improved FEL lasing techniques modify the longitudinal phase space (with good results!)…

But other coordinates of the 6D phase space of high-brightness beams can also be manipulated through laser based interactions.

Can we generate higher-order light ?

LCLS

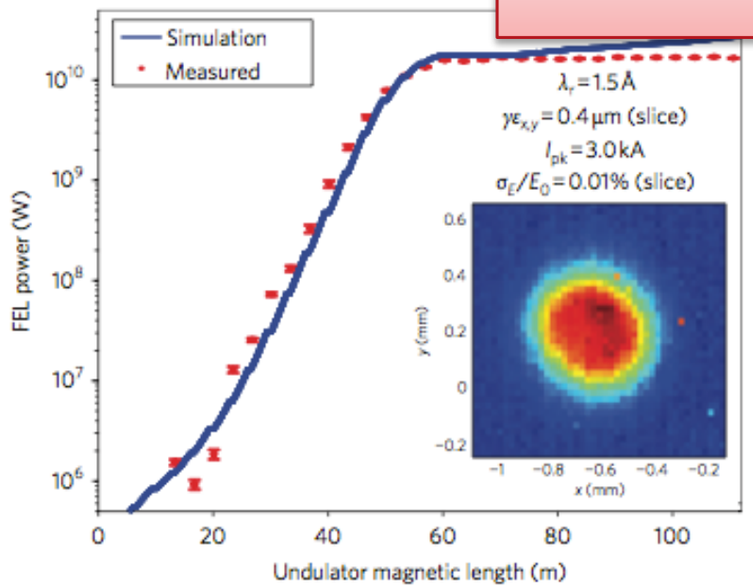
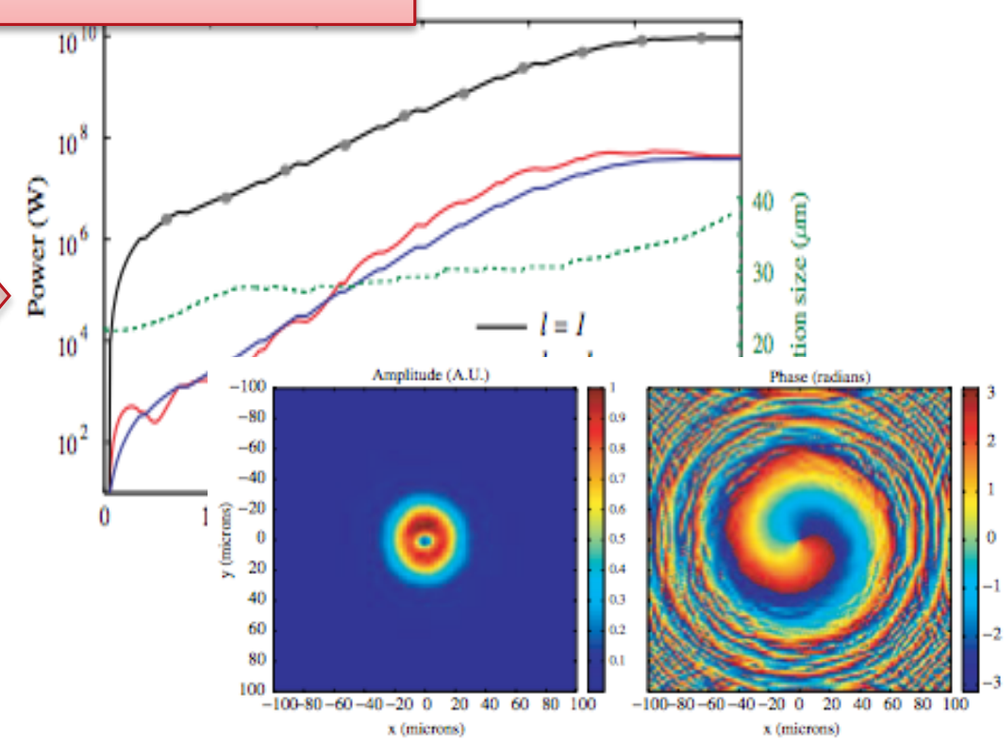


Figure 4 | FEL gain length measurement at 1.5 Å. Measured FEL power (rec

P. Emma, et al, Nature Photonics 4, 641 - 647 (2010)

LCLS w/OAM



E. H et al, PRL 106, 164803 (2011)

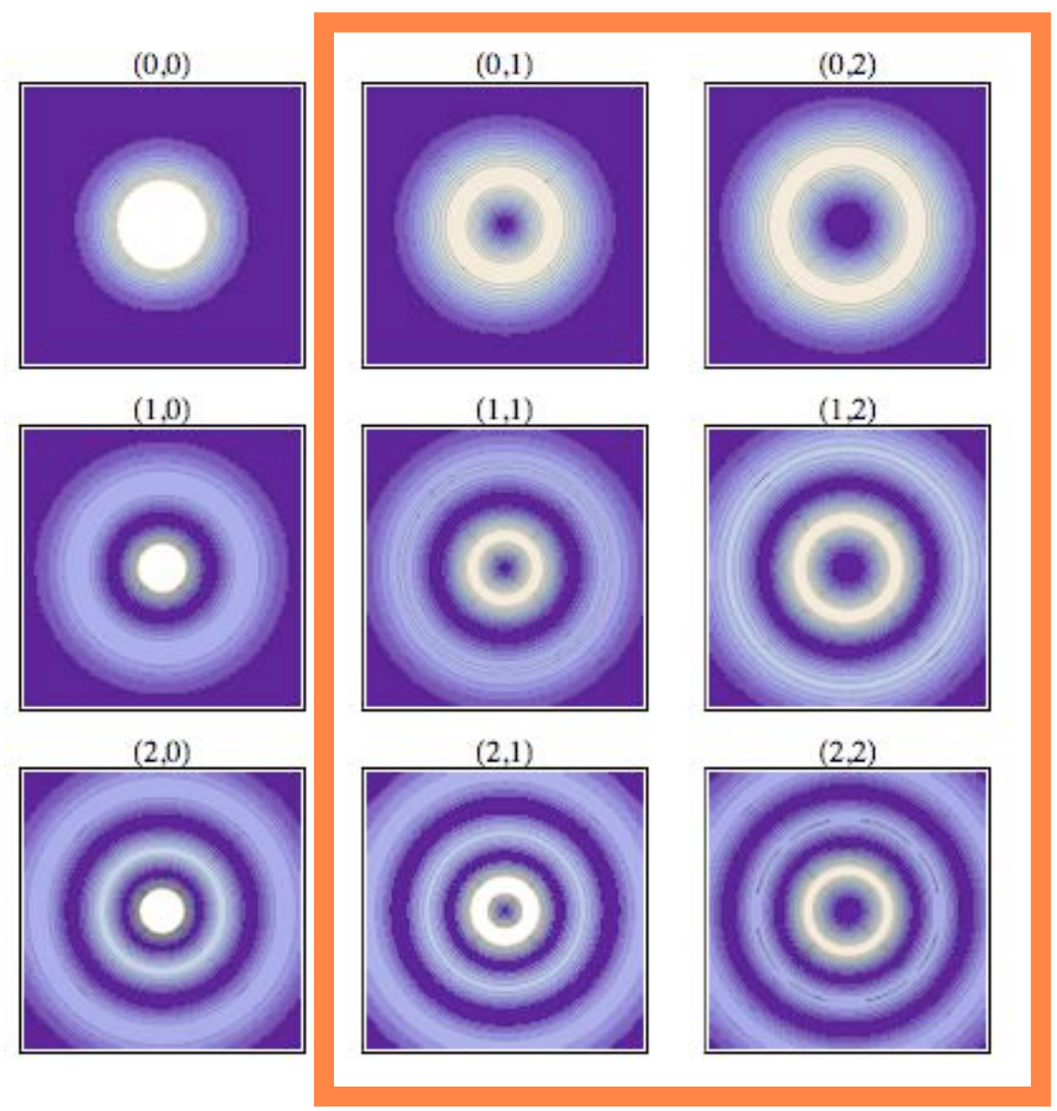
Ex: high order light modes

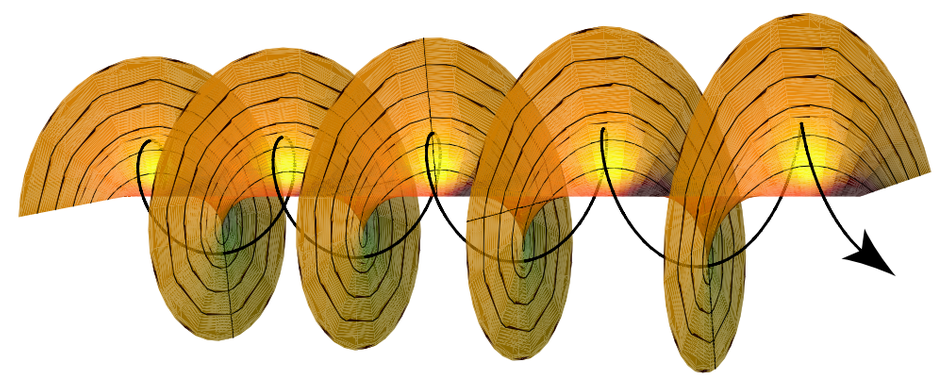
Cylindrical solutions to the paraxial wave equation yield modes that carry orbital angular momentum (OAM) in helical phase

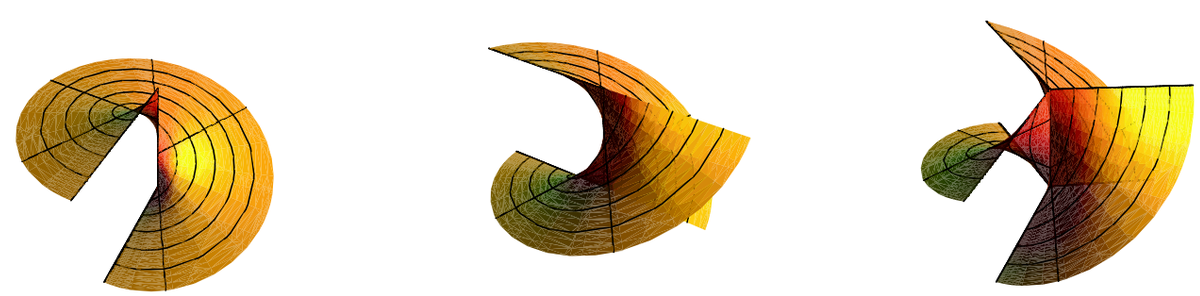
$$\nabla_\perp^2 E + 2ik\frac{\partial}{\partial z}E = 0$$

$$E_{p,l}(r,\phi) \sim e^{-\frac{r^2}{w^2}+il\phi}\left(\frac{r\sqrt{2}}{w}\right)^{|l|} L_p^l\left(\frac{2r^2}{w^2}\right)$$

OAM modes: Photon momentum spirals about the axis







l=1 *l=2* *l=3*

L. Allen, et al, PRA, 45, 11, 1992

OAM SAM

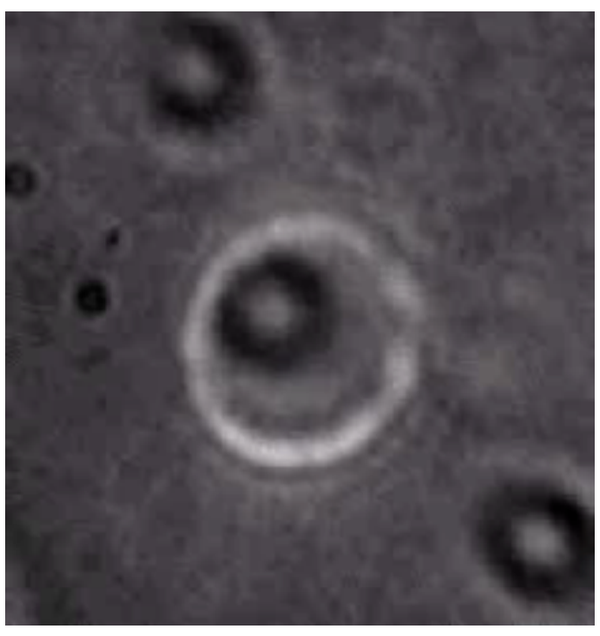
$$J_z = (l \pm 1)\hbar$$

Applications for OAM modes

- Mechanical micro manipulation: precision transfer of quantized torque to samples (proteins, molecules, BECs, etc)

- Photon Science: Enhanced resolution and contrast in microscopy and diffraction imaging, two mode pump-probe, X-ray magnetic dichroism and angle-resolved spectrometry

- Quantum States: Quantum entanglement and encryption in OAM state (n-dimensional storage space), BECs



U. of Glasgow

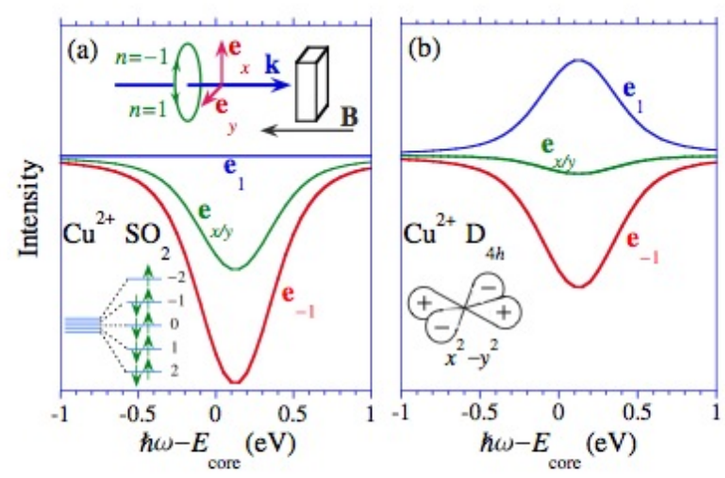
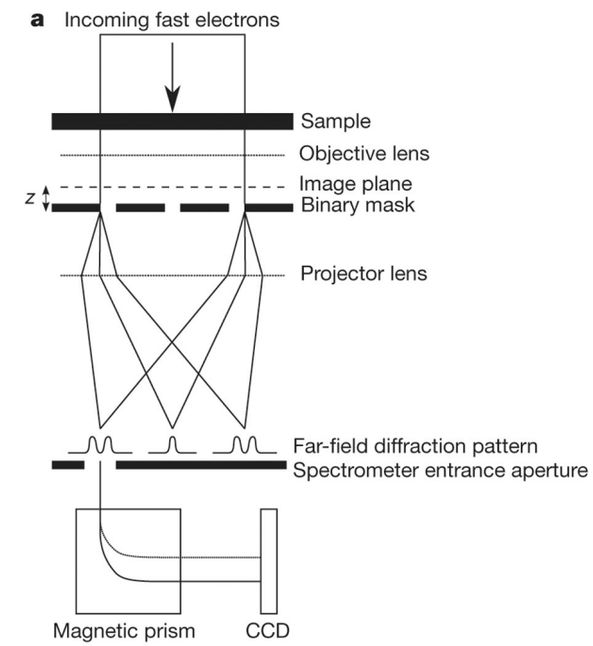
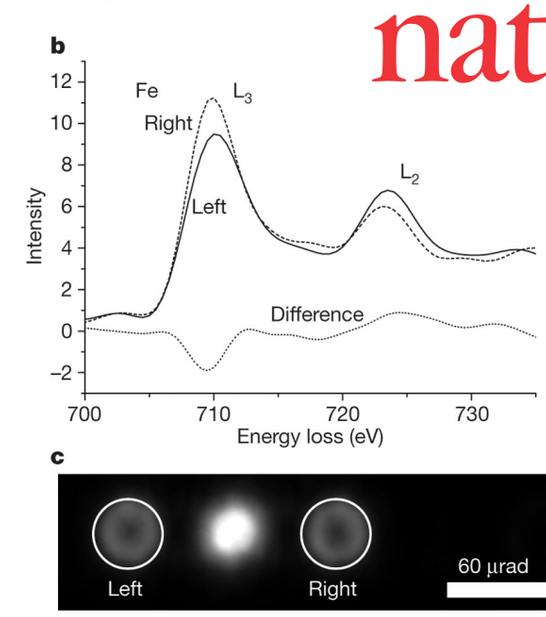


FIG. 1 (color online). (a) The dichroic OAM signal for circular ($\mathbf{e}_1$ and $\mathbf{e}_{-1}$) and linear ($\mathbf{e}_{x/y}$) polarization of the incoming x-rays for a divalent copper ion in spherical symmetry with a magnetic field along the z axis. (b) The same, but for a Cu^{2+} atom in a crystal field with D_{4h} symmetry.

Veenendaal and McNulty, PRL 98, 157401 (2007)



nature



Application of the vortex beam to energy-loss spectrometry.

J Verbeeck et al. Nature 467, 301-304 (2010)

Generating OAM light in FELs

Optics can be used to mode-convert at optical wavelengths, but different solution is needed for FELs at short wavelengths, high peak power, etc.

Solution: **Harmonic emission** from helical undulators has **helical phase**

Therefore, a **bunched e-beam** will radiate **coherent OAM light at harmonics**

Sasaki and McNulty, PRL., 100, 124801 (2008)

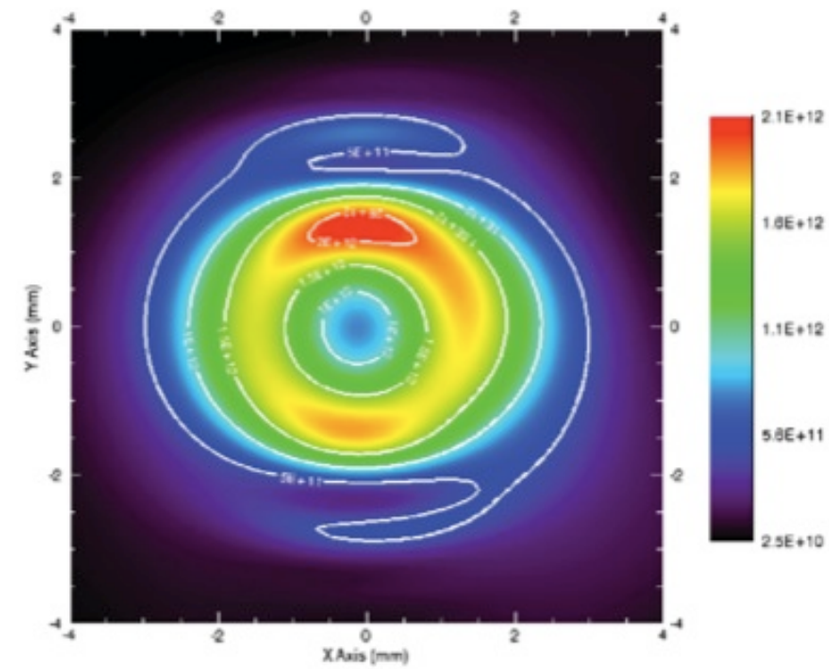
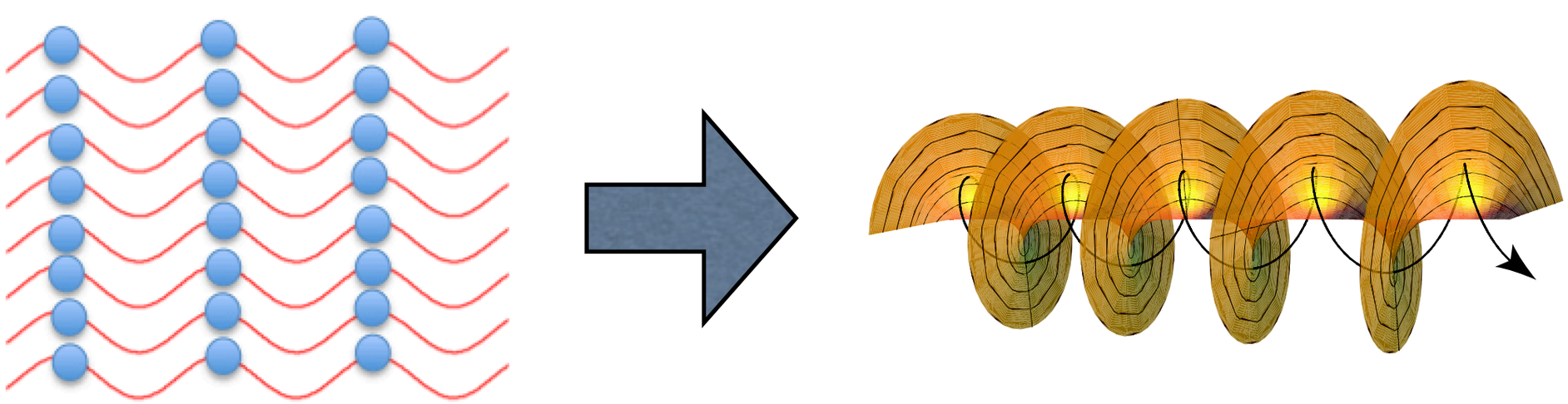
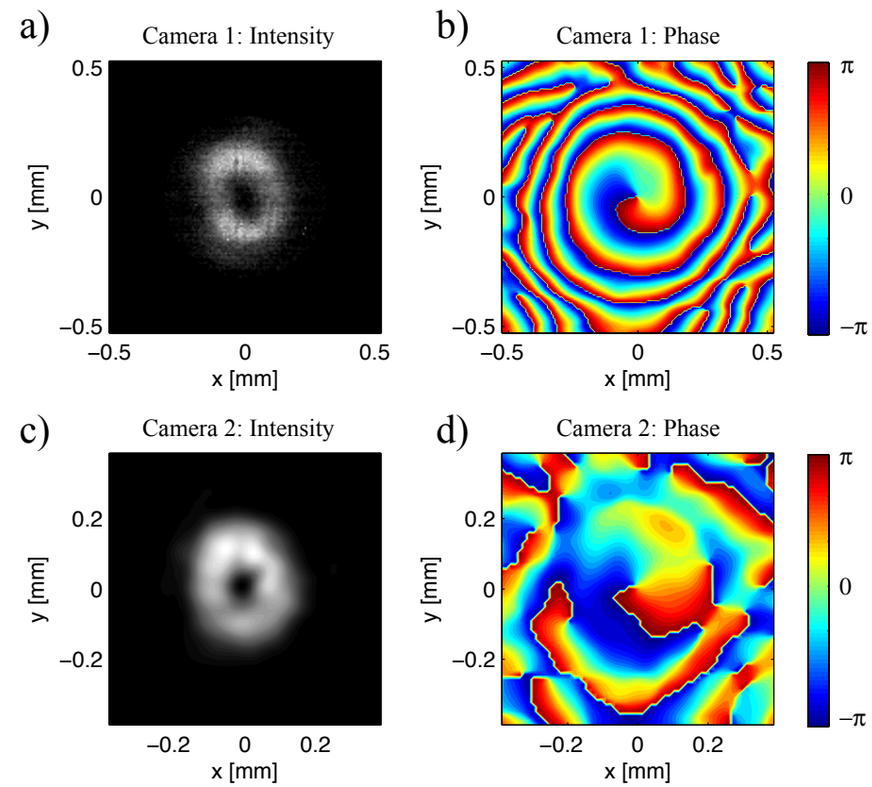


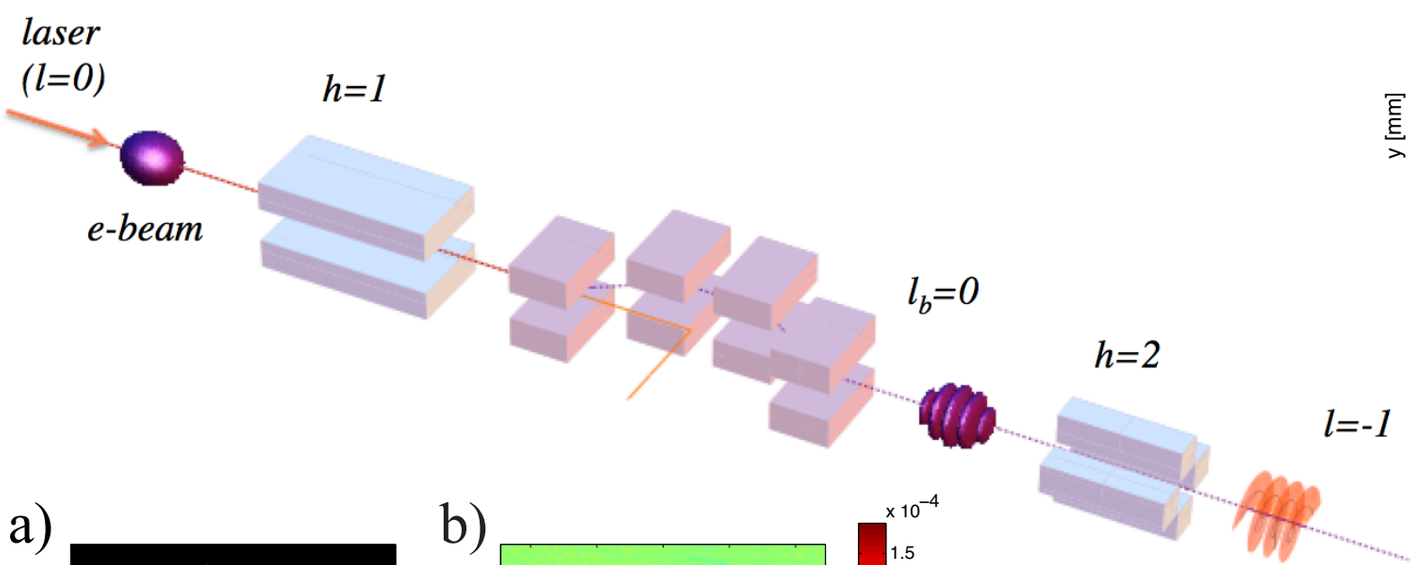
FIG. 5 (color). Calculated intensity distribution of the second harmonic from the APS CPU for $K = 2.77$, a photon energy of 830 eV, at a distance of 50 m.

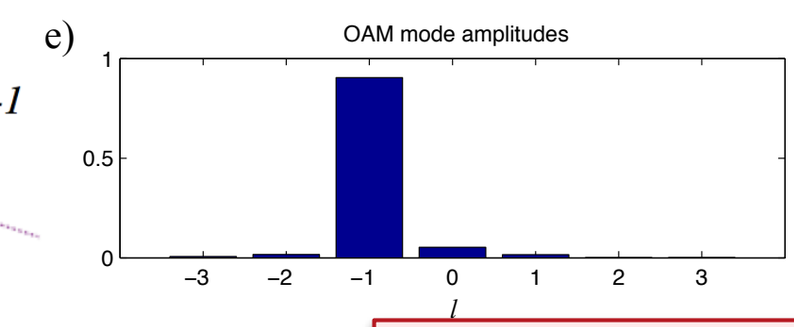


Coherent OAM light production in FELs

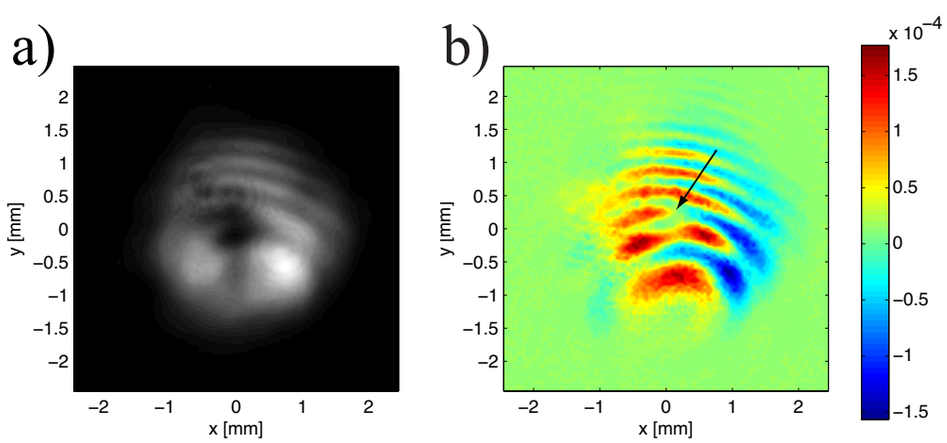
Proof of principle experiment @ SLAC
- 800 nm laser modulates e-beam
- Chicane dumps seed laser and converts beam energy modulation into density modulation
- e-beam emits coherent OAM light in helical undulator tuned so that 800 nm is 2nd harmonic
- straightforward to implement at x-rays







OAM mode power distribution shows 91% in l=-1



Interference between CUR and off-axis CTR reveals signature fork of a l=-1 vortex

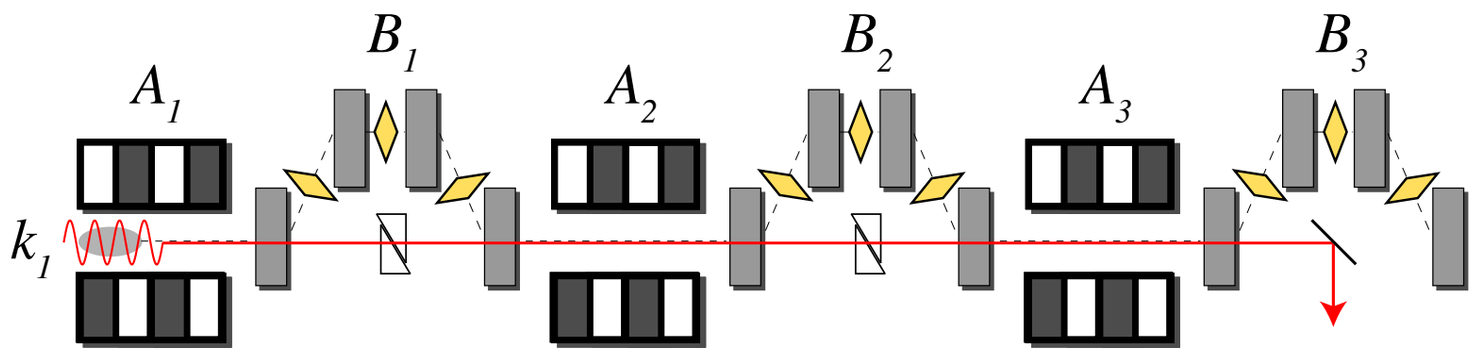
E. H, et al, PRL 113, 134803, (2014)

Summary

- ✦ FELs are highly flexible and versatile!
- ✦ Numerous schemes and techniques exist to manipulate the electron beam distribution to precisely tailor the FEL output
- ✦ These days, good ideas can rapidly mature from concept to experiment to implementation
- ✦ Many more good ideas are yet to come. The future is bright (and coherent)!

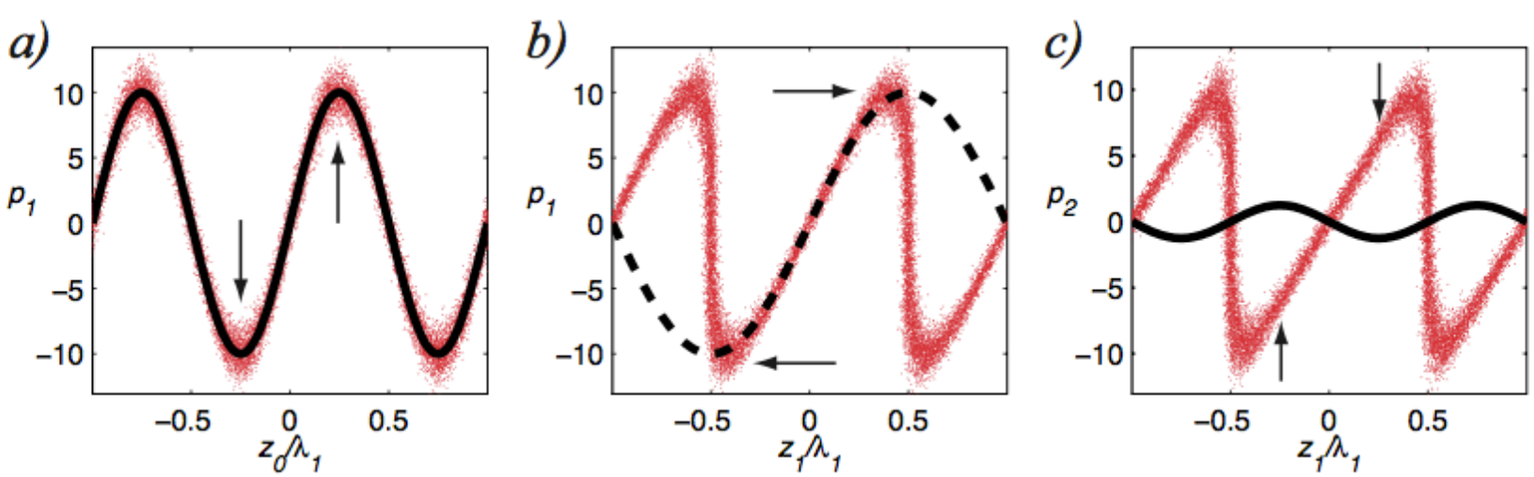
Waveform synthesis with cascaded modulators/chicanes

Multiple modulators and dispersive sections with only a **single laser wavelength can mimic** the effect of harmonic modulations from **multiple lasers** on the longitudinal phase space.



E. H and D. X, PRST-AB, 16, 010706 (2013)

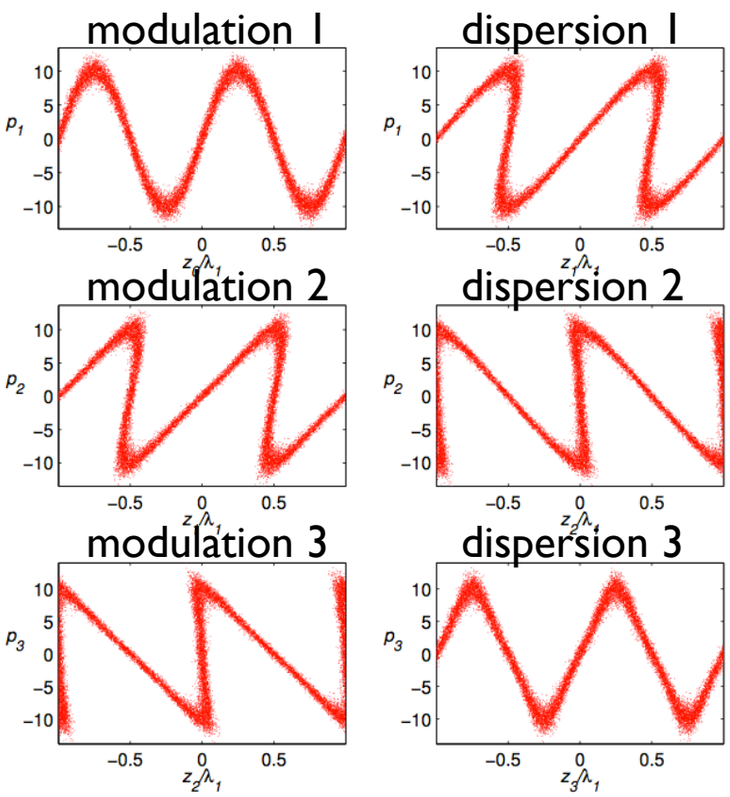
Longitudinal dispersion acts to compress and decompress and different regions of chirp between modulations, such that the arrangement acts as a **waveform synthesizer** through **linearization of local regions**



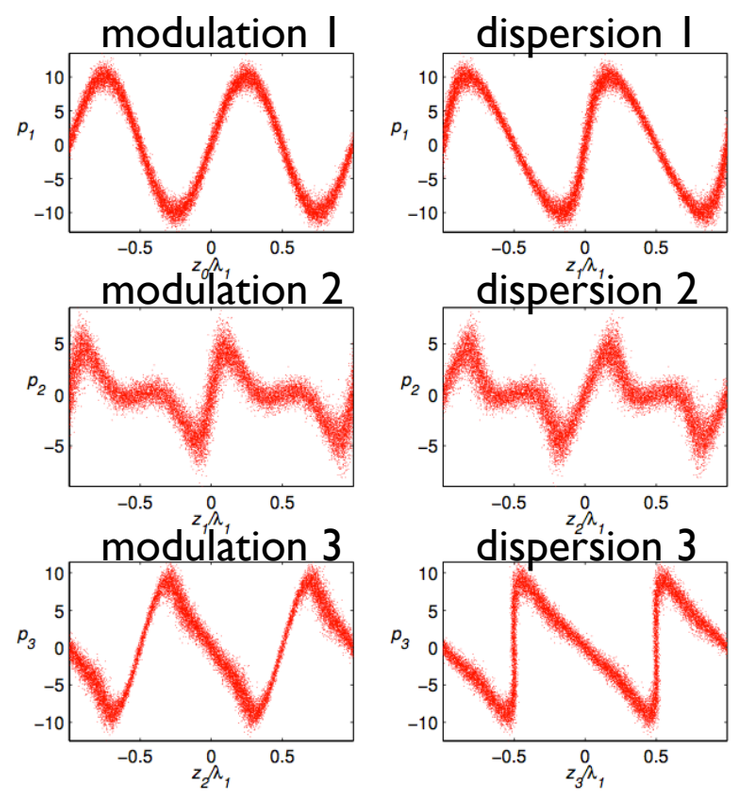
- Better control of optical scale beam structure
- Improved harmonic bunching
- Increased capture efficiency for laser-based accelerators

Waveform synthesis with cascaded modulators/chicanes

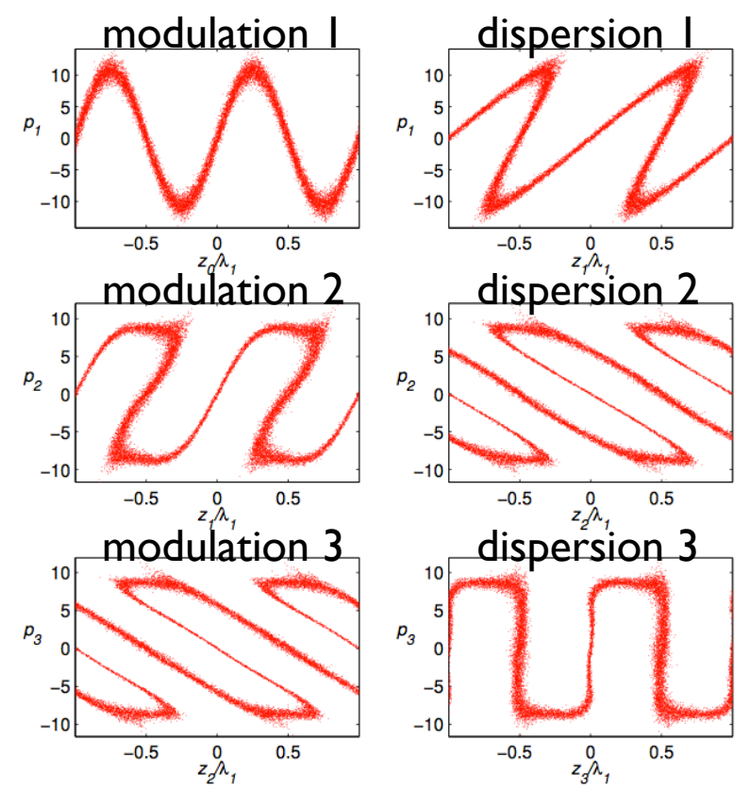
The effect on the phase space is an optical analog of an RF function generator to generate triangular, sawtooth, and square wave-type distributions. Requires both positive and negative R_{56}s, and stable phase between modulation sections.



Triangle



Sawtooth



Square

Waveform synthesis with cascaded modulators/chicanes

The effect on the phase space is an optical analog of an RF function generator to generate triangular, sawtooth, and square wave-type distributions. Requires both positive and negative R_{56}s, and stable phase between modulation sections.

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PAPER

Free electron lasers using 'beam by design'

J R Henderson[1,2], **L T Campbell**[1,2] **and B W J McNeil**[1,3]

[1] SUPA, Department of Physics, University of Strathclyde, Glasgow G4 0NG, UK
[2] ASTeC, STFC Daresbury Laboratory and Cockcroft Institute, Warrington WA4 4AD, UK
[3] Author to whom any correspondence should be addressed.

E-mail: j.r.henderson@strath.ac.uk, lawrence.campbell@strath.ac.uk and b.w.j.mcneil@strath.ac.uk

Keywords: free electron laser, accelerator, un

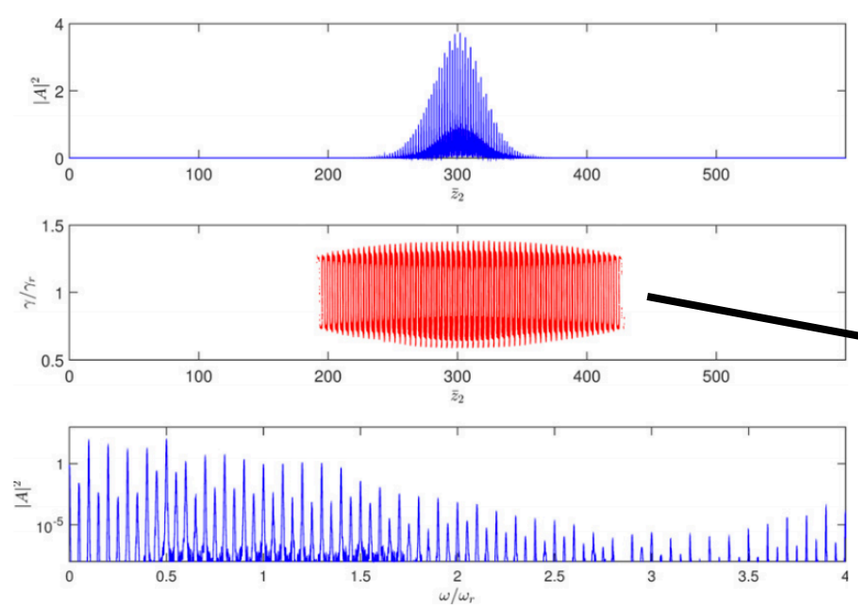
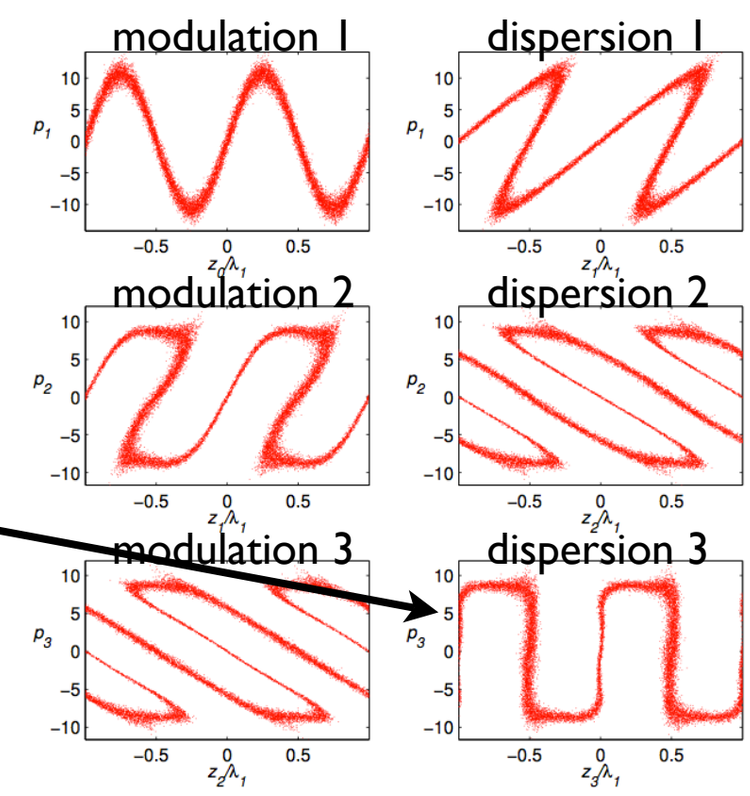


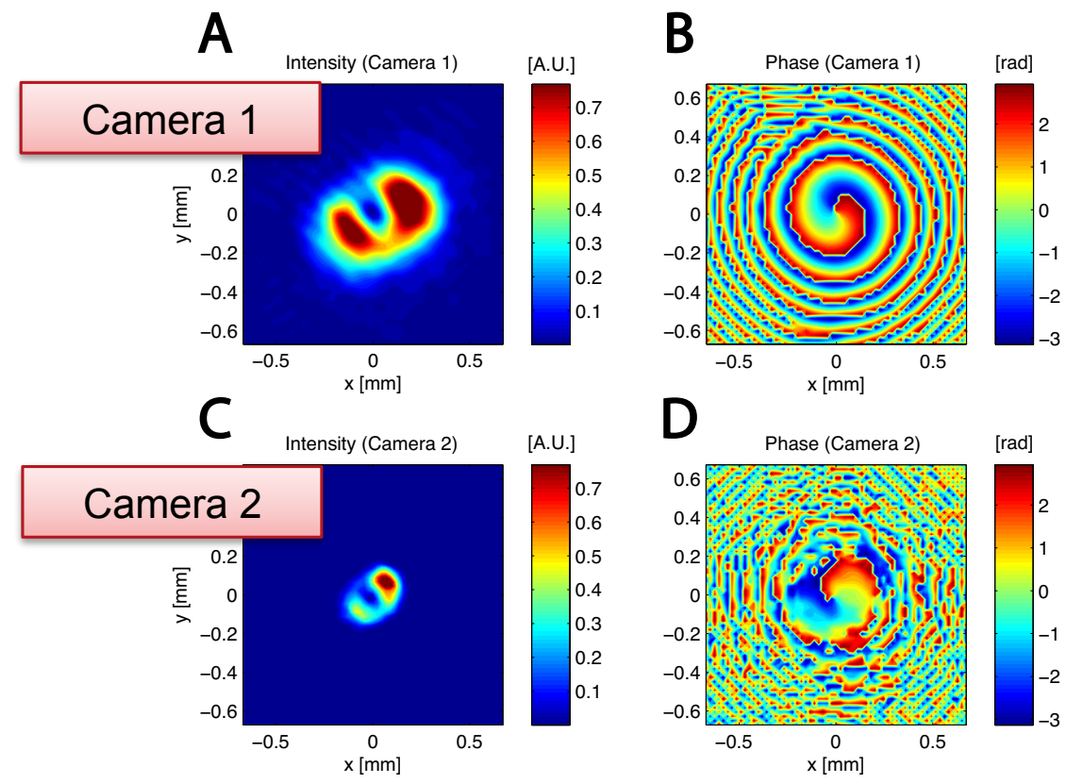
Figure 10. As figure 9, but now using an optimized chicane which maintains the rectangular waveform electron pulse structure in phase-space as it propagates through the undulator-chicane lattice. The rectangular electron waveform emits coherent radiation in each new undulator module which constructively interferes with the radiation in subsequent undulator modules.



Square

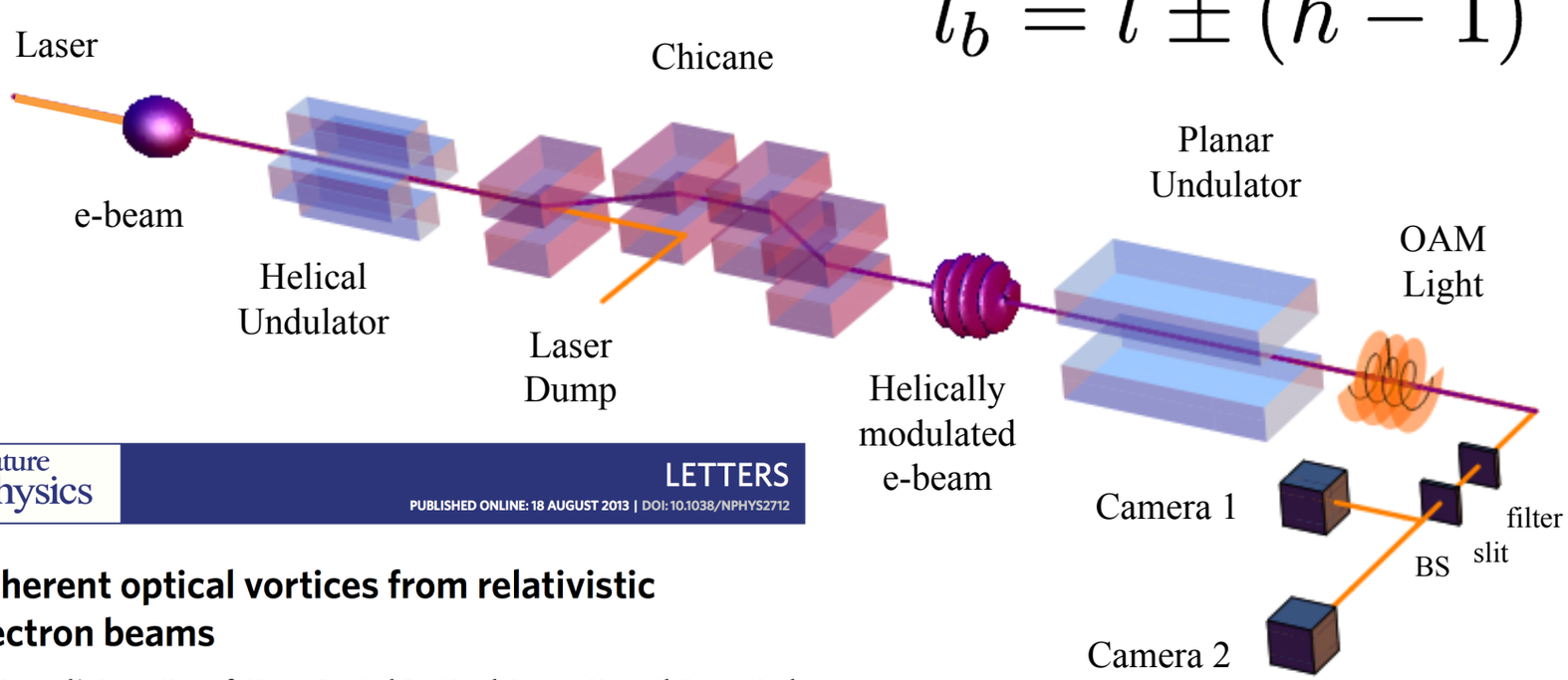
OAM light production with beam shaping

- 800 nm laser modulates e-beam in helical undulator at 2nd harmonic resonance (tuned to 1.6 um fundamental)
- Chicane dumps seed laser and converts beam energy modulation into 800 nm helical density modulation
- e-beam emits coherent OAM light in planar undulator tuned to 800 nm at resonant frequency

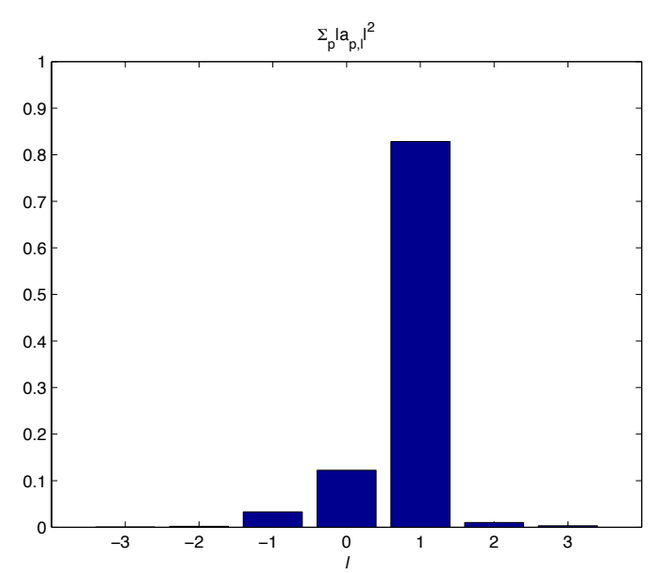


Satisfies

$$l_b = l \pm (h - 1)$$



OAM mode power distribution shows 85% in l=1

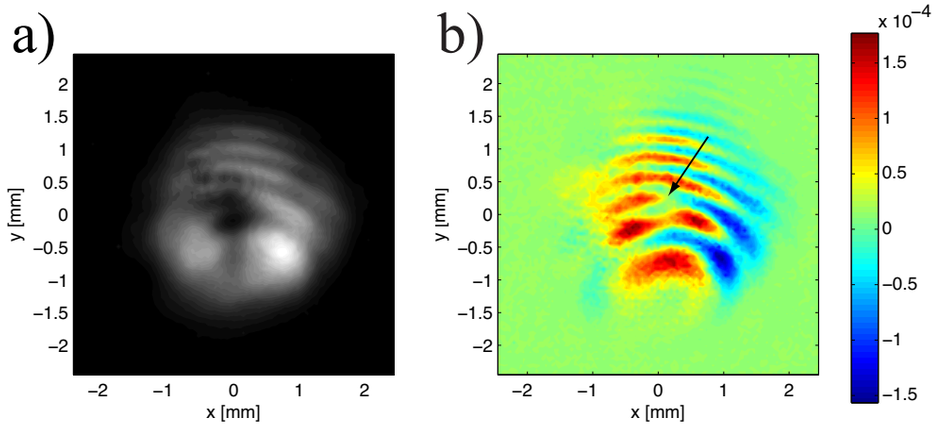


nature physics
LETTERS
PUBLISHED ONLINE: 18 AUGUST 2013 | DOI: 10.1038/NPHYS2712

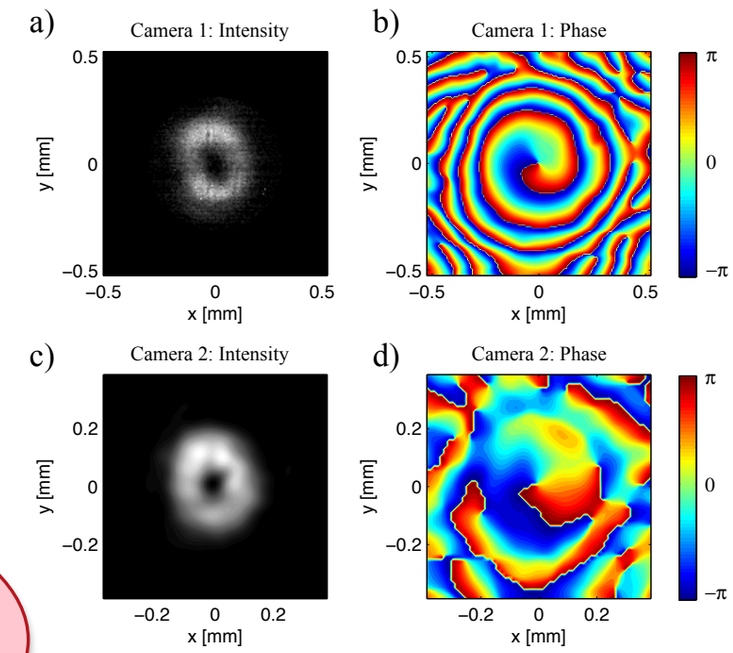
Coherent optical vortices from relativistic electron beams

Erik Hemsing[1]*, Andrey Knyazik[2], Michael Dunning[1], Dao Xiang[1], Agostino Marinelli[1], Carsten Hast[1] and James B. Rosenzweig[2]

OAM light production with radiation shaping "OAM afterburner"

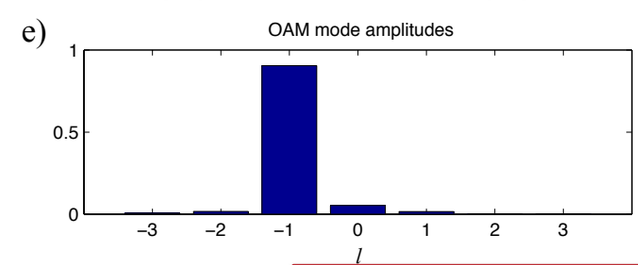


Interference between CUR and off-axis CTR reveals signature fork of a *l*=-1 vortex

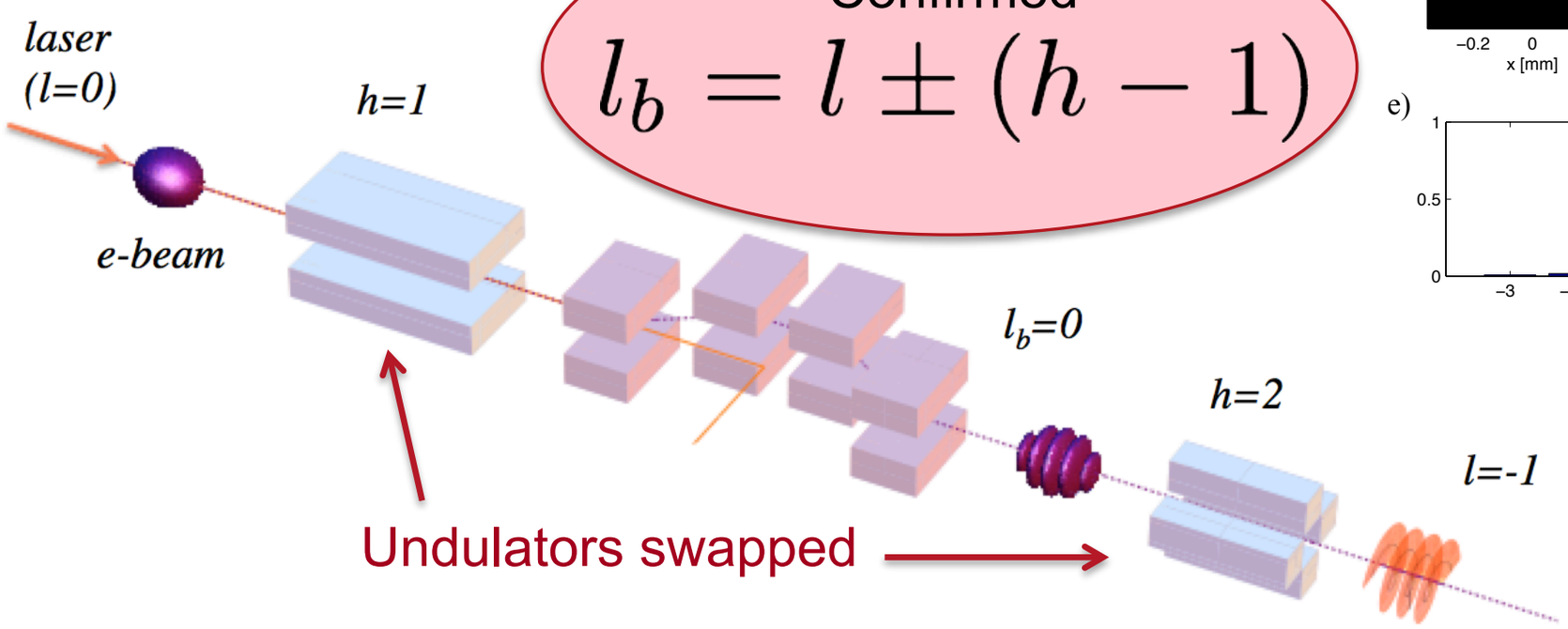


Confirmed

$$l_b = l \pm (h-1)$$



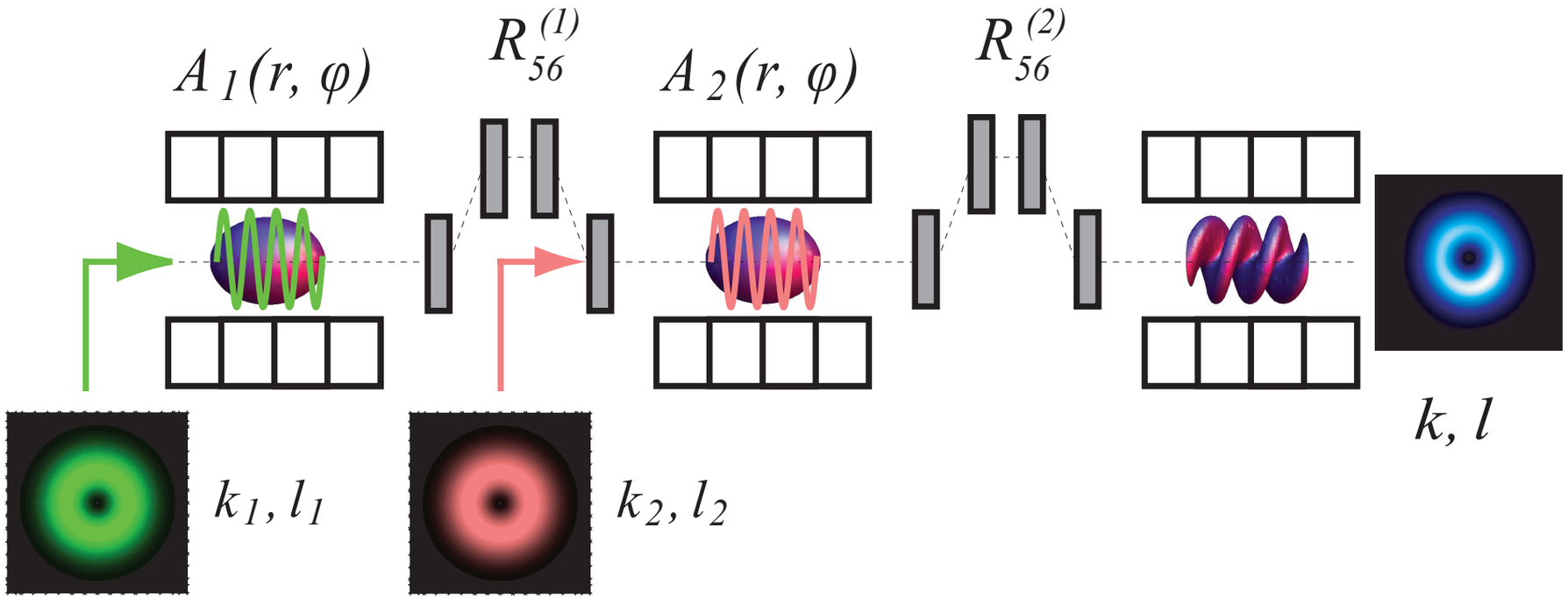
OAM mode power distribution shows 91% in *l*=-1



E. H, et al, PRL 113, 134803, (2014)

Future possibilities: EEHG with a twist

Cascaded helical microbunching in EEHG for frequency and mode up-conversion



Frequency up-conversion

$$k \equiv ak_1 = nk_1 + mk_2,$$

OAM mode up-conversion

$$l = nl_1 + ml_2.$$

E. Hemsing and A. Marinelli, PRL 109, 224801 (2012)

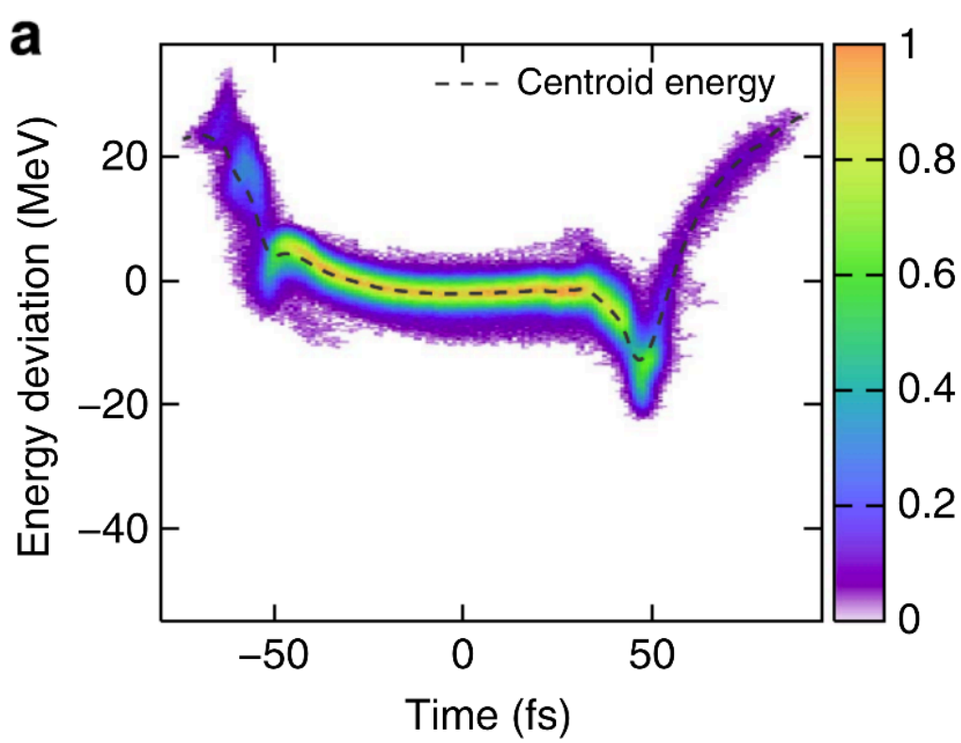
Extra slides

Electron beam phase space

Typical parameters

- Energy ~ GeV (γ~10^4)
- relative energy spread ~10^{-4} (before lasing)
- bunch length ~100 fs
- Current few kA (10^8-10^9 electrons)
- transverse emittance $\varepsilon_{nx,ny}$ ~0.4 mm-mrad

Before Lasing

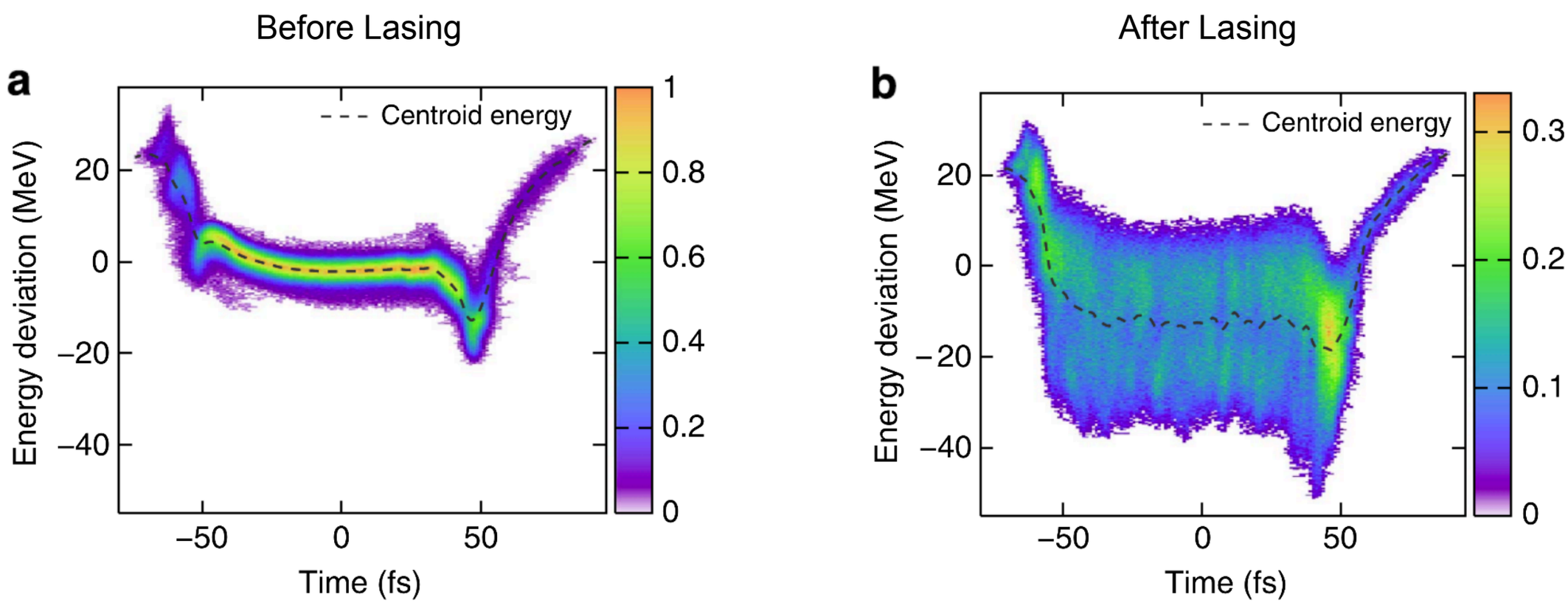


After Lasing

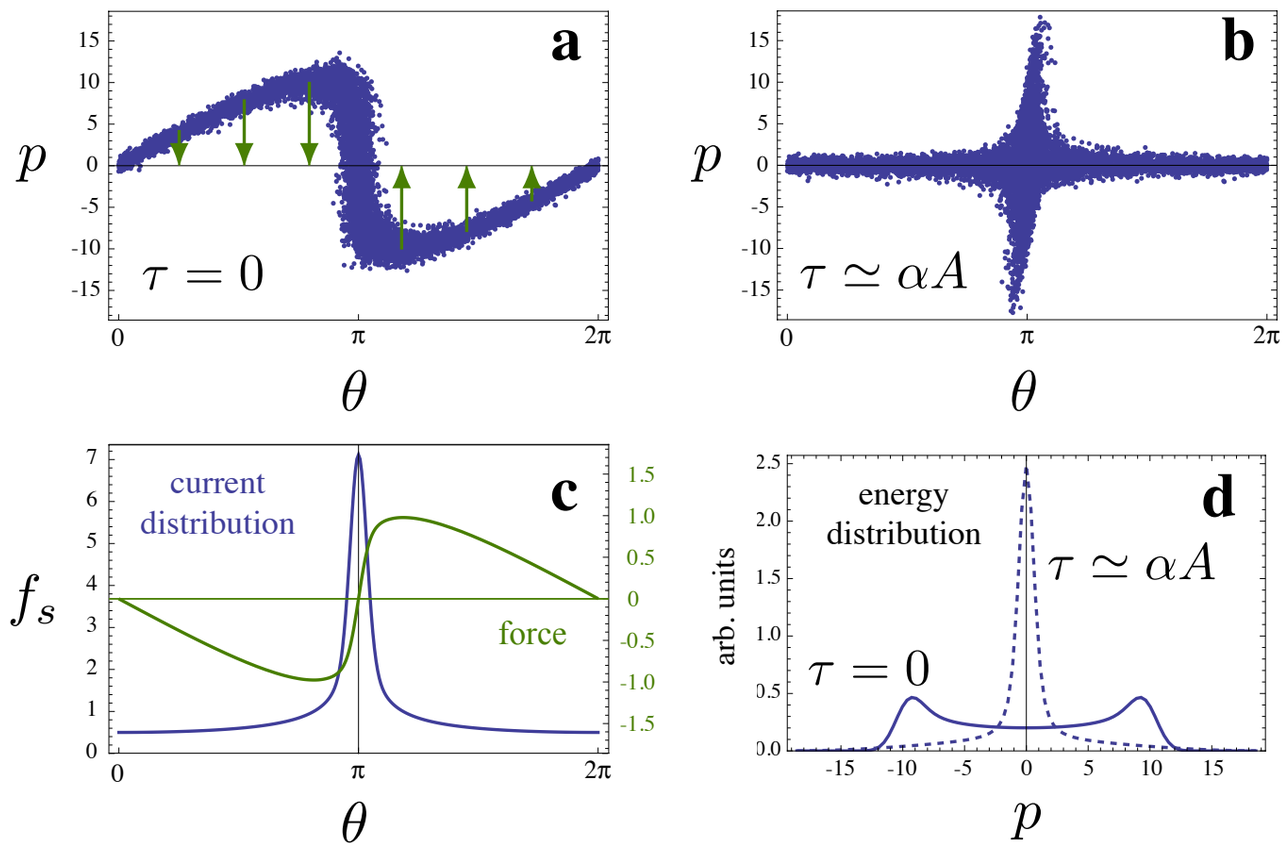
Electron beam phase space

Typical parameters

- Energy ~ GeV (γ~10^4)
- relative energy spread ~10^{-4} (before lasing)
- bunch length ~100 fs
- Current few kA (10^8-10^9 electrons)
- transverse emittance $\varepsilon_{nx,ny}$ ~0.4 mm-mrad



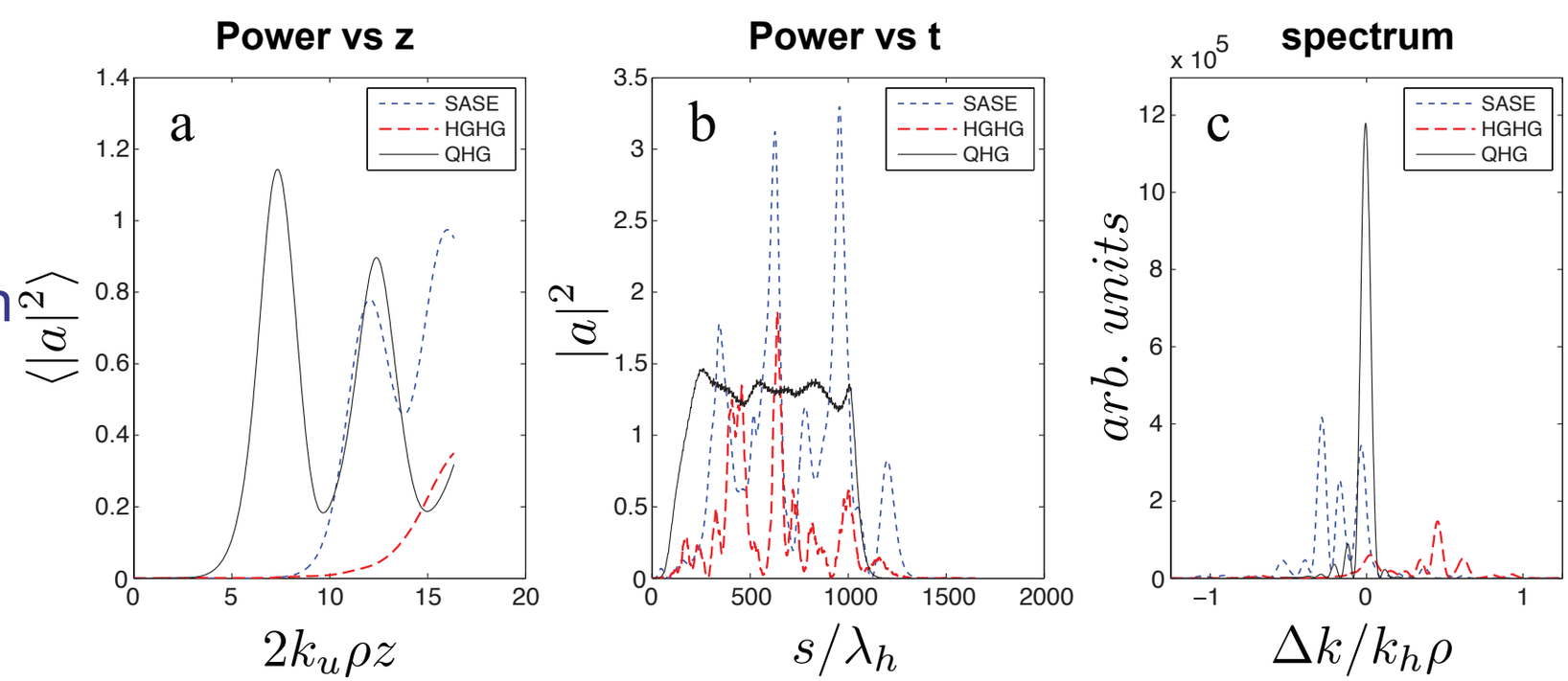
Quieting the energy modulation in HGHG



- Longitudinal space charge near density spikes acts to remove energy chirp during drift
- Energy spread is reduced while harmonic bunching is preserved

E. Hemsing, et al, PRL 113, 134802 (2014)

- Higher harmonics accessible by using larger induced energy modulation
- Lasing portion of beam is linearized so FEL performance enhanced

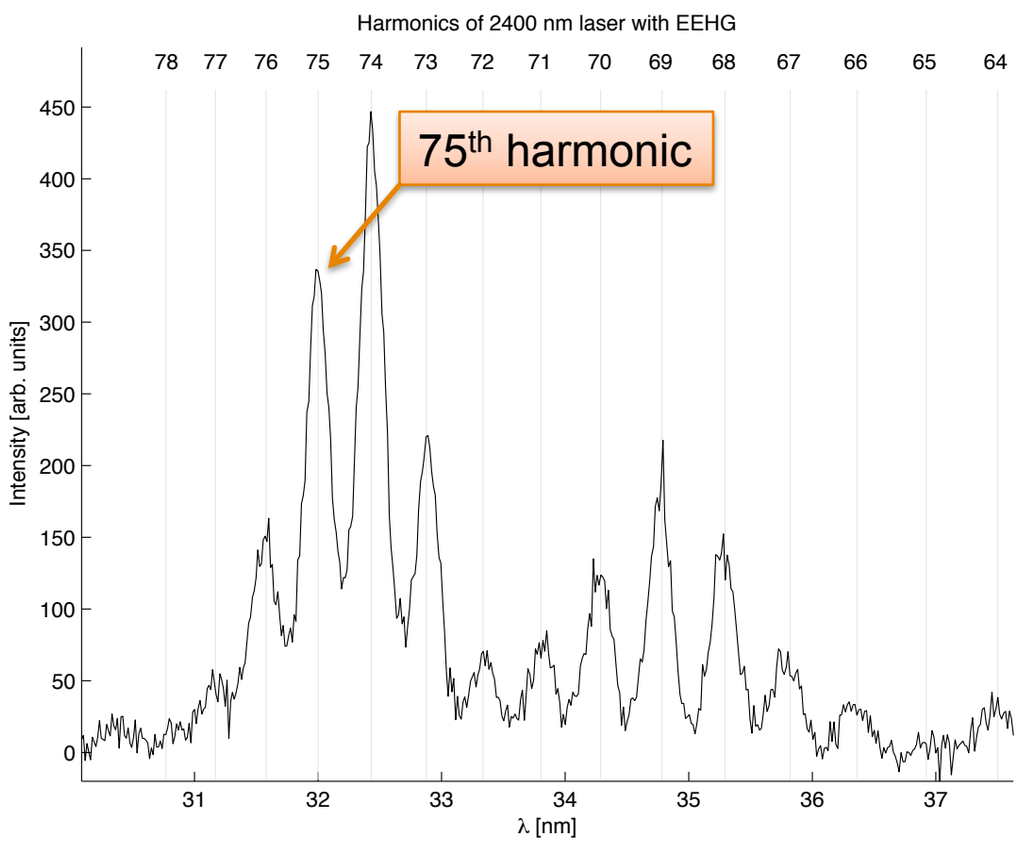


EEHG harmonics determined by dispersion

Broad spectrum of EEHG harmonics generated by adjusting second chicane strength

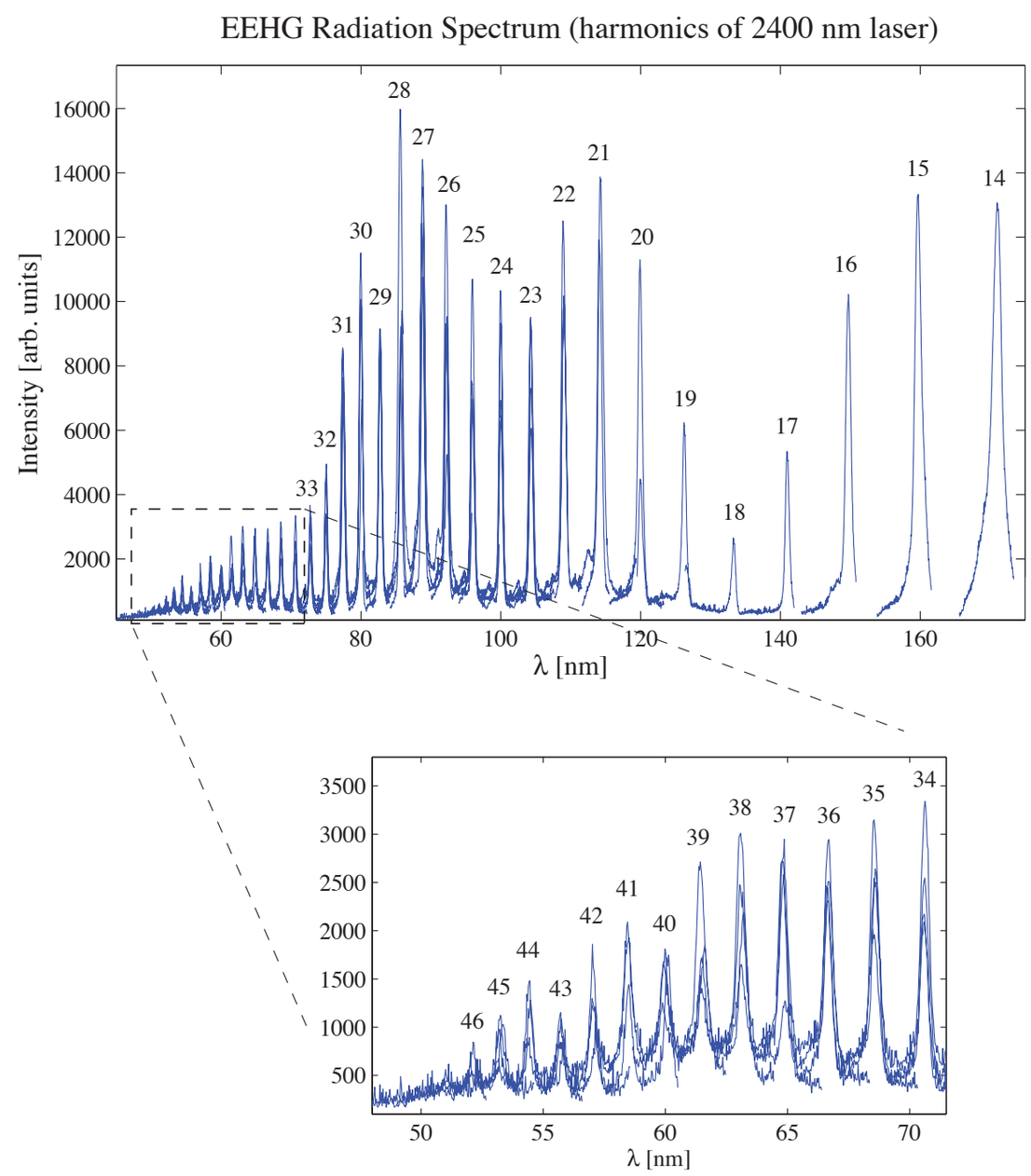
$$h \simeq \frac{\lambda_2}{\lambda_1} \frac{n R_{56}^{(1)}}{R_{56}^{(2)}}$$

- 75th harmonic: conversion from 2400 nm to 32 nm in single stage



E.H, et. al., Nature Photonics 10, 512–515 (2016)

$$hk_2 = nk_1 + mk_2$$

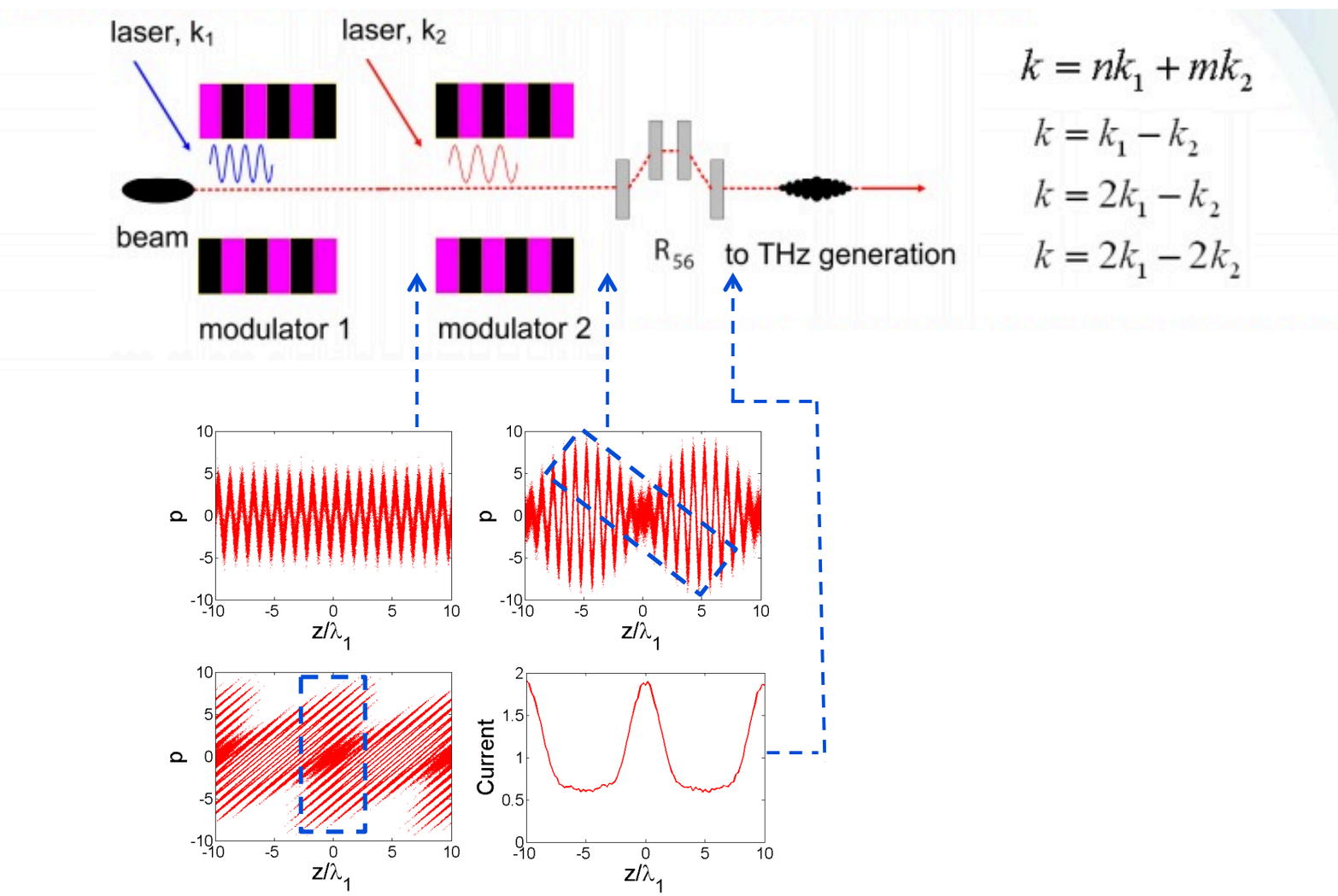


$$\longleftarrow R_{56}^{(2)} \longrightarrow$$

Using EEHG for narrowband THz density modulations

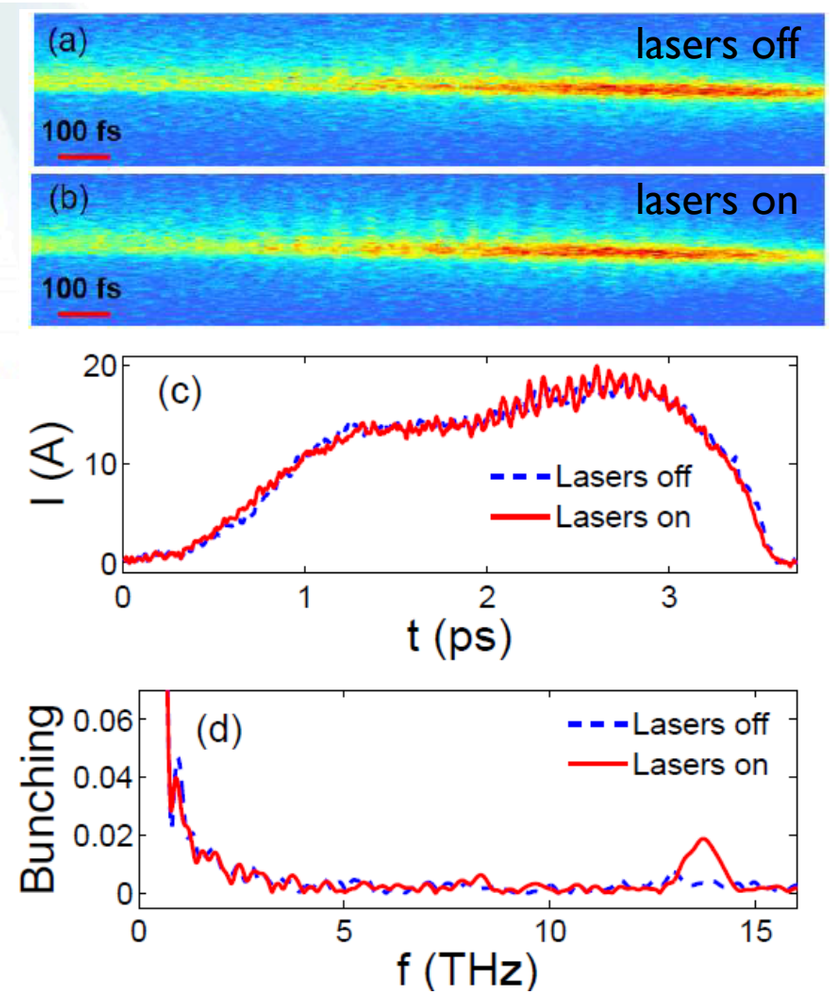
Beams with density modulations at sub-mm wavelengths (THz frequencies) can be produced with a set of modulators and chicanes using optical lasers using the beatwave modulations. Such beams may be used to resonantly excite wakefields for advanced accelerators and for the generation of narrow-band THz radiation.

Electron beam acts as nonlinear medium



Xiang and Stupakov, PRST-AB, 12, 080701 (2009)

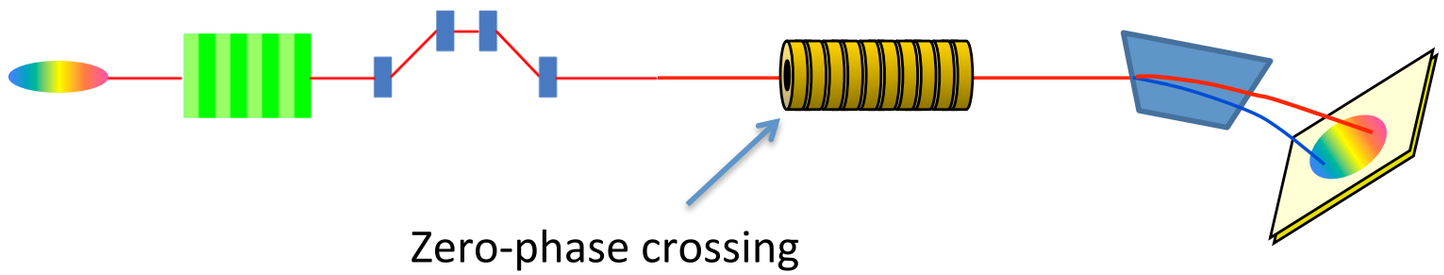
Temporal profile (w/RF deflector)

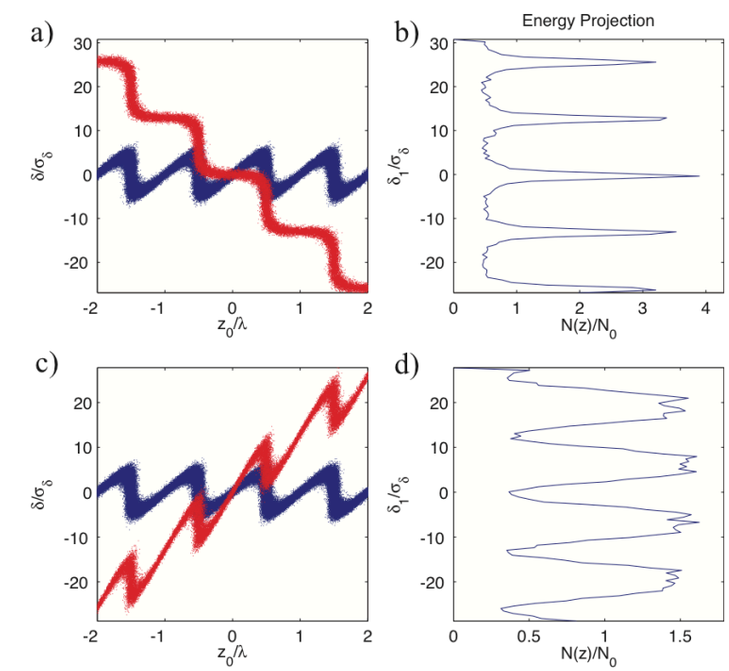


M. Dunning et al, Phys. Rev. Lett., 109, 074801 (2012)

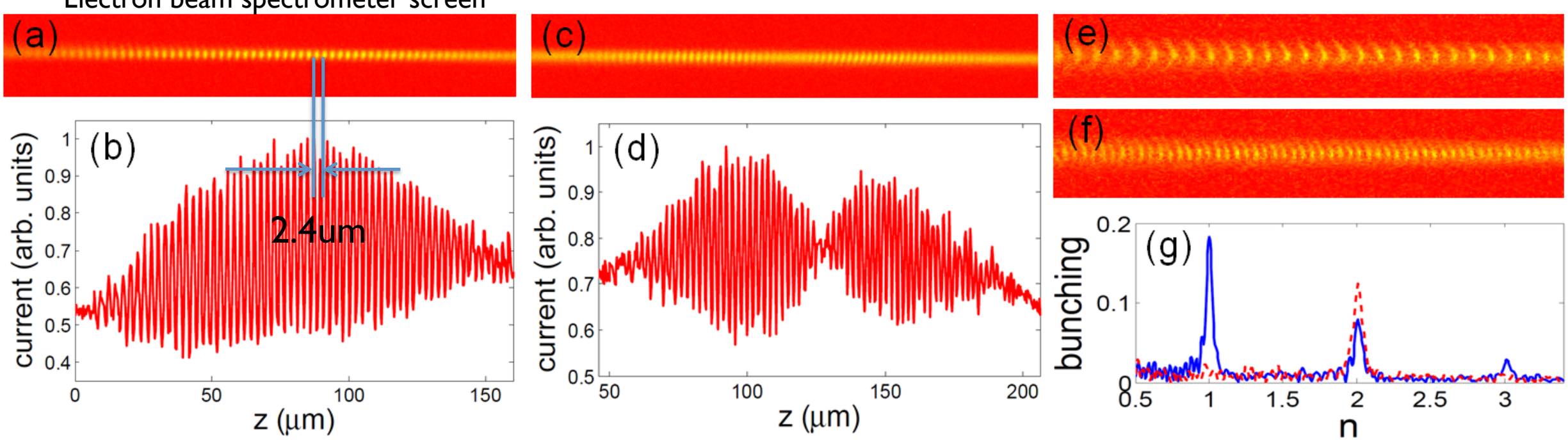
Femtosecond visualization of microbunching

Bunching spectrum characterization with modified zero-phasing technique





Dispersion followed by linear energy chirp rotates phase space so that energy maps directly to time

Crosson el al., AIP Conf. Proc., 367, 397 (1996)
Ricci and Smith, PRST-AB, 3, 032801 (2000)
Z. Huang, et al, PRST-AB 13, 092801 (2010)
D. Xiang, E. Hemsing, et al, PRL 113, 184802 (2014)

Electron beam spectrometer screen