Review of Coherent SASE Schemes

Lawrence Campbell[1], David Dunning[1,2],
James Henderson[1], <u>Brian McNeil</u>[1] & Neil Thompson[2]

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36th International Free Electron Laser Conference, Basel, August 25-29, 2014

Outline

- Types of Seeding – direct; indirect; self;
- HB-SASE; i-SASE; p-SASE….
- UK CLARA FEL Test Facility

The issue: SASE photon output

- SASE output is amplified noise
  - Spontaneous emission generated by electron beam in first few gain lengths is the 'seed' which is amplified via an exponential instability.
  - Pulses noisy temporally and spectrally: poor temporal coherence
  - No pulse-to-pulse reproducibility

SIMULATED XFEL OUTPUT*
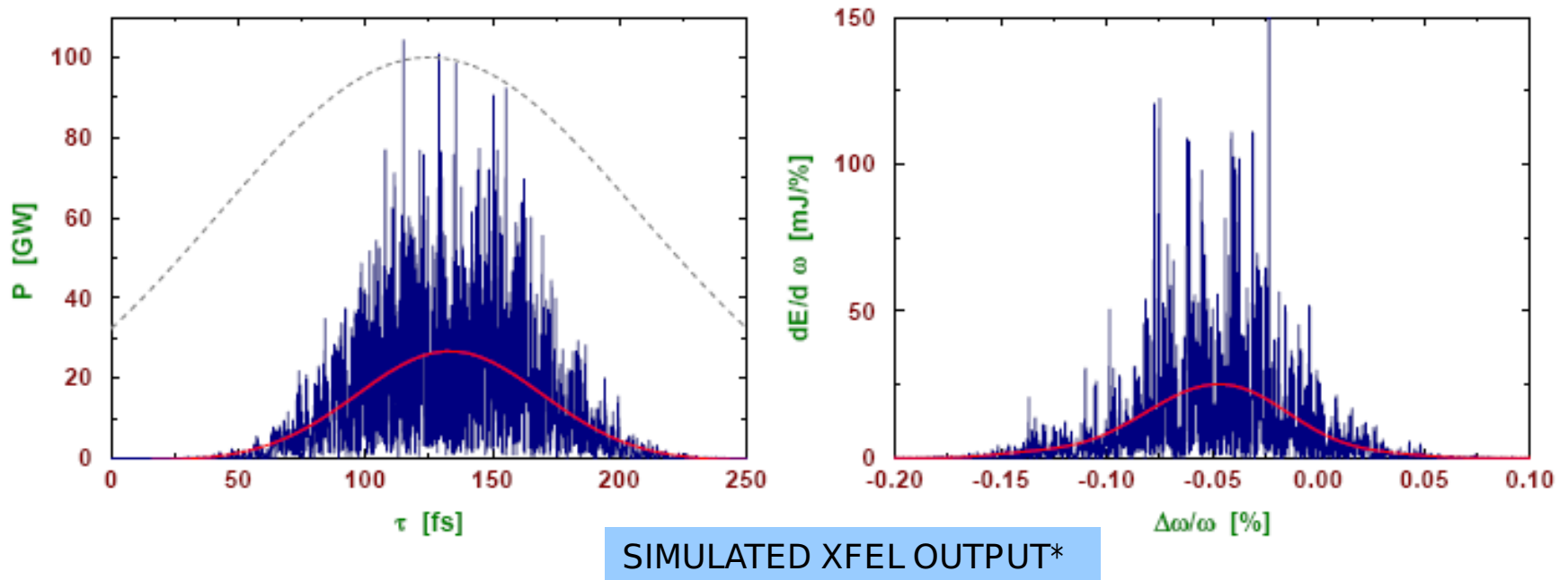
*Taken from DESY report

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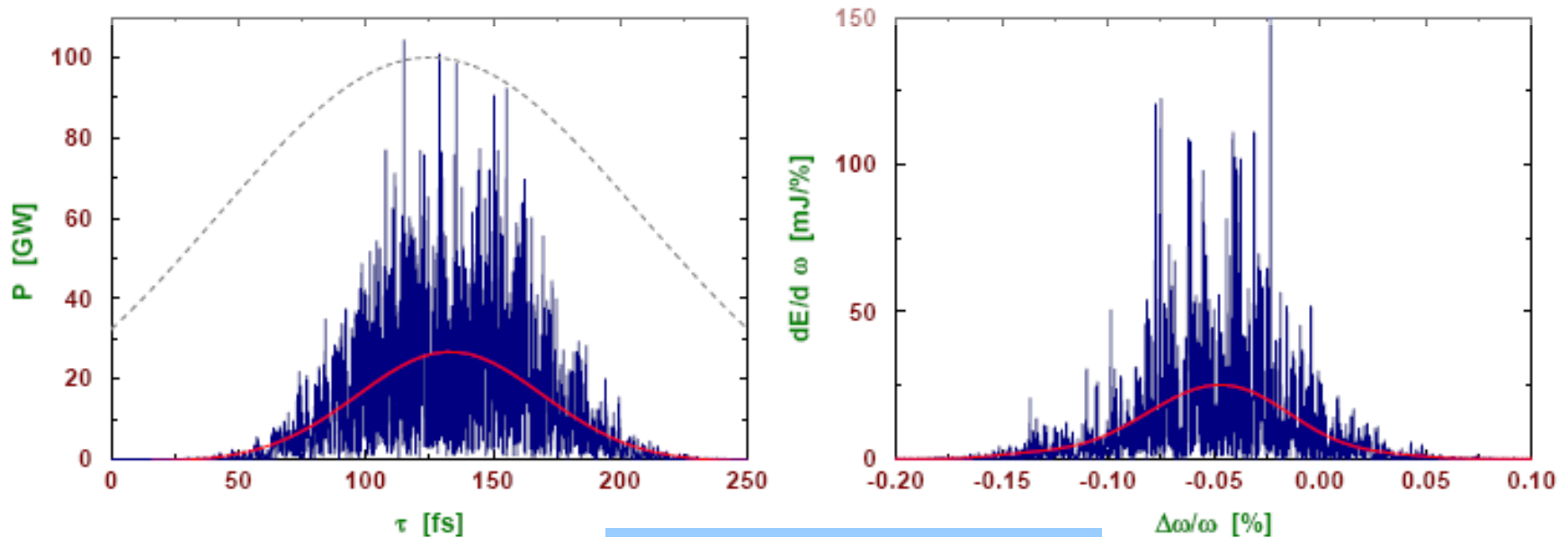   - No pulse-to-pulse reproducibility

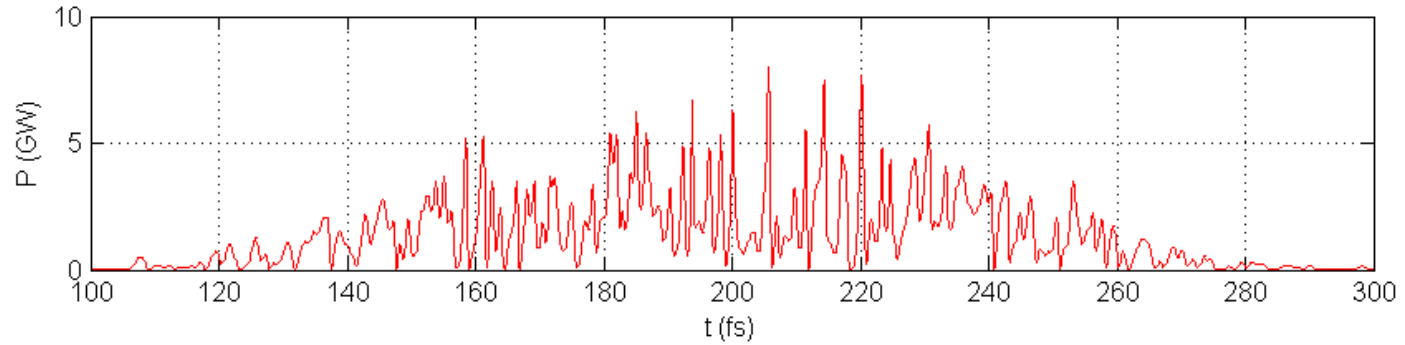# Far from FT limited: $\Delta\nu\,\Delta t >> 1$
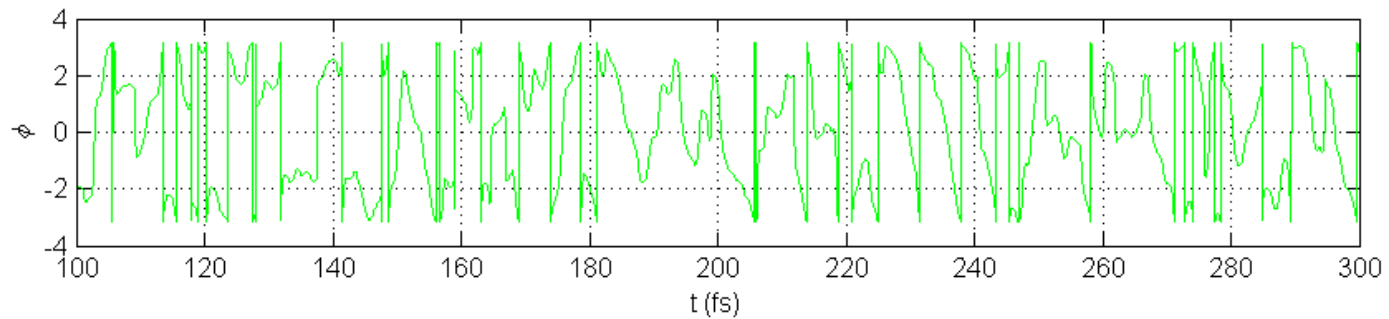
SIMULATED XFEL OUTPUT*
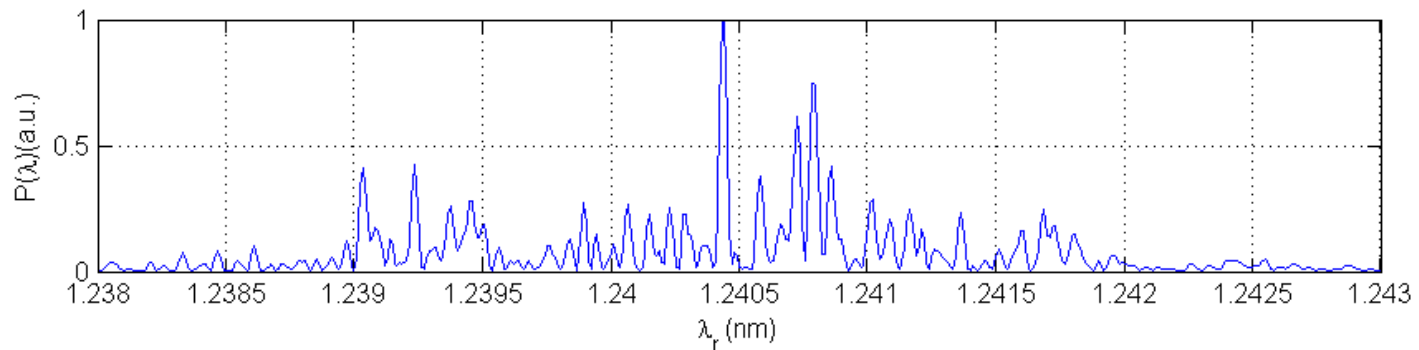
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SASE Coherence
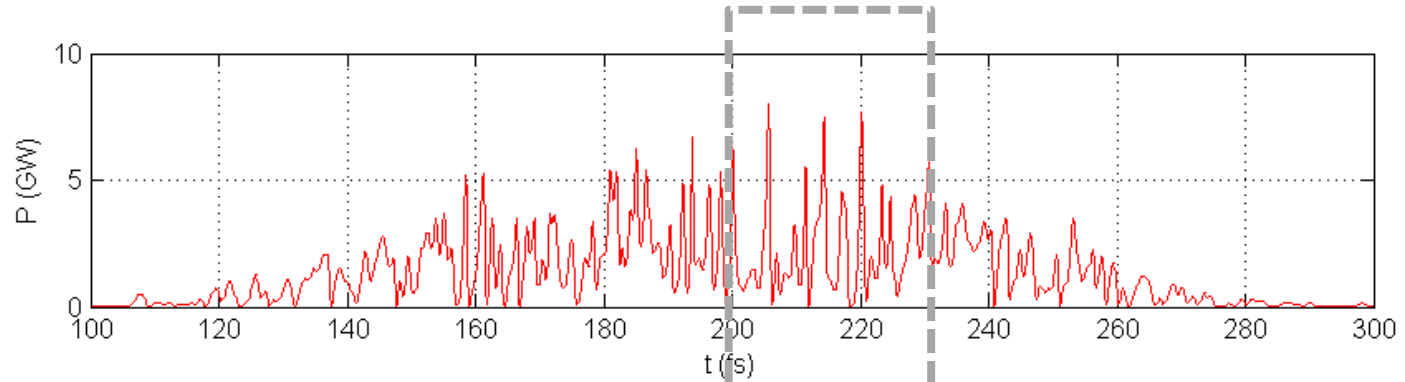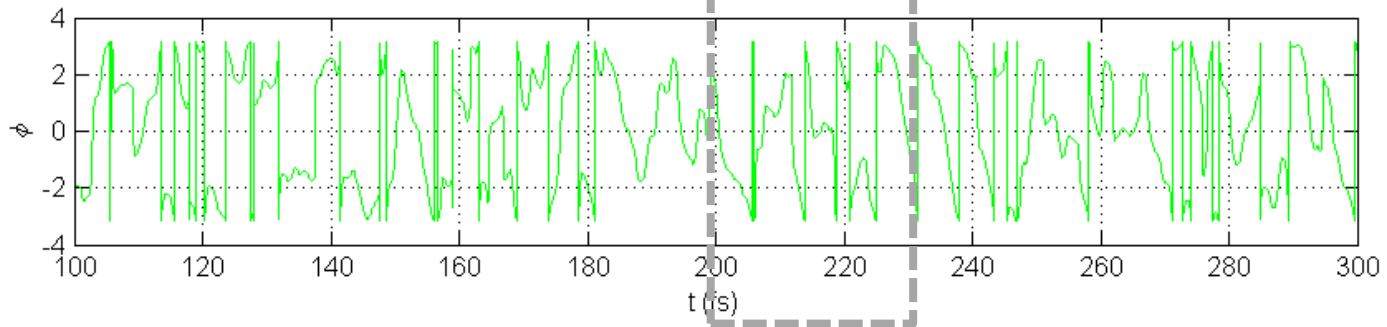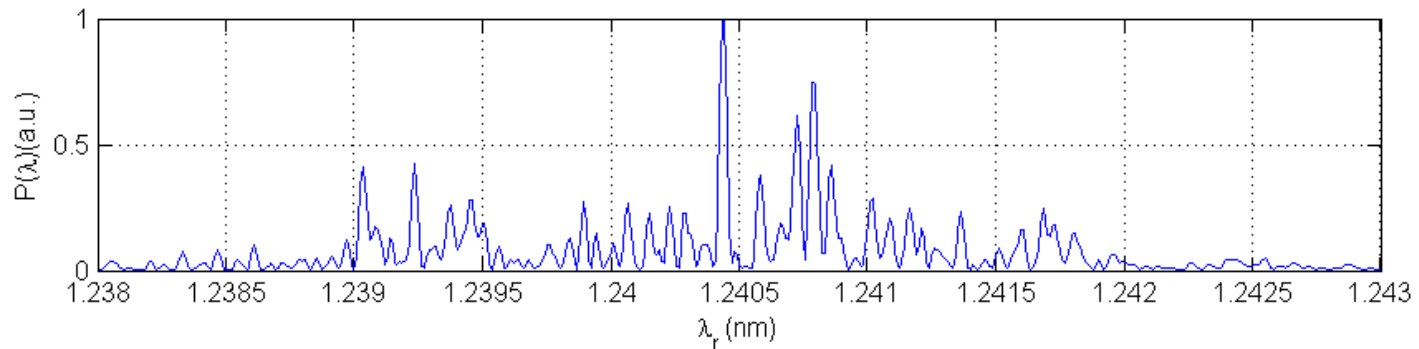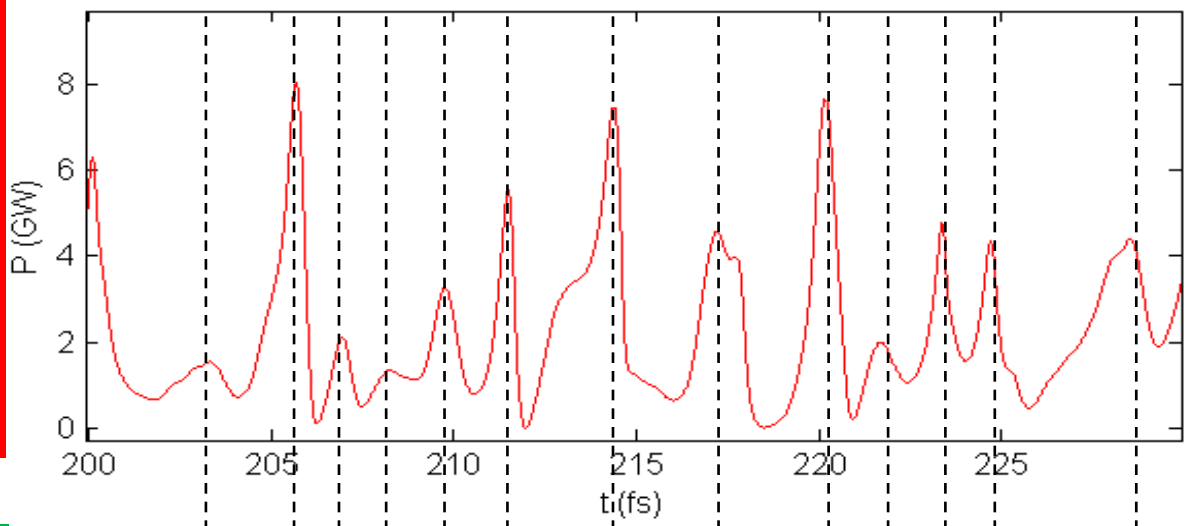
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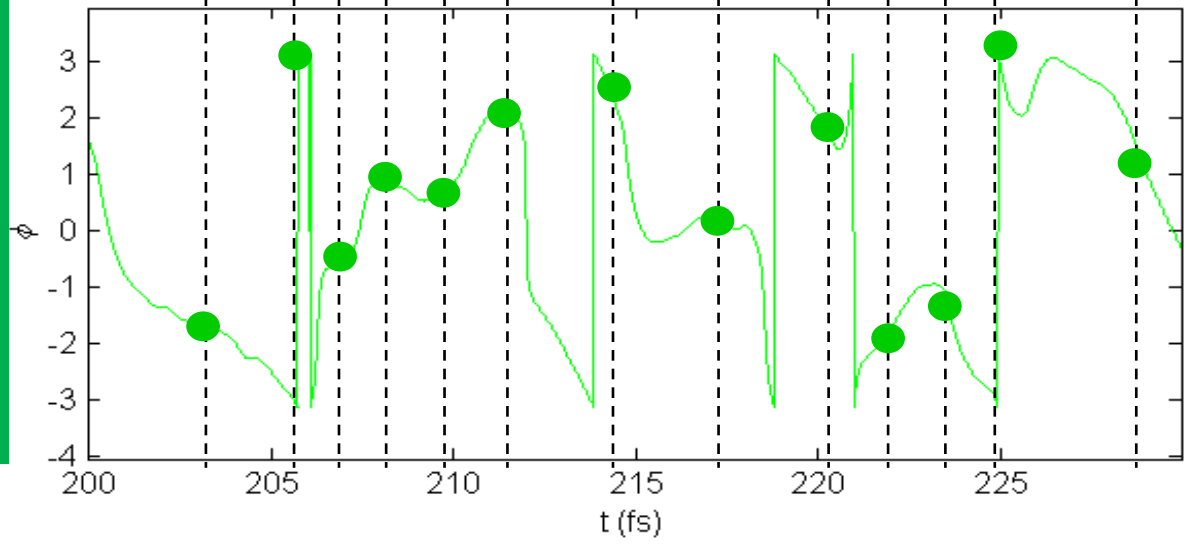
Direct seeding at fundamental

Injection of harmonics generated in gas in a free-electron laser providing intense and coherent extreme-ultraviolet light

G. LAMBERT[1,2,3]*, T. HARA[2,4], D. GARZELLA[1], T. TANIKAWA[2], M. LABAT[1,3], B. CARRE[1], H. KITAMURA[2,4], T. SHINTAKE[2,4], M. BOUGEARD[1], S. INOUE[4], Y. TANAKA[2,4], P. SALIERES[1], H. MERDJI[1], O. CHUBAR[3], O. GOBERT[1], K. TAHARA[2] AND M.-E. COUPRIE[3]
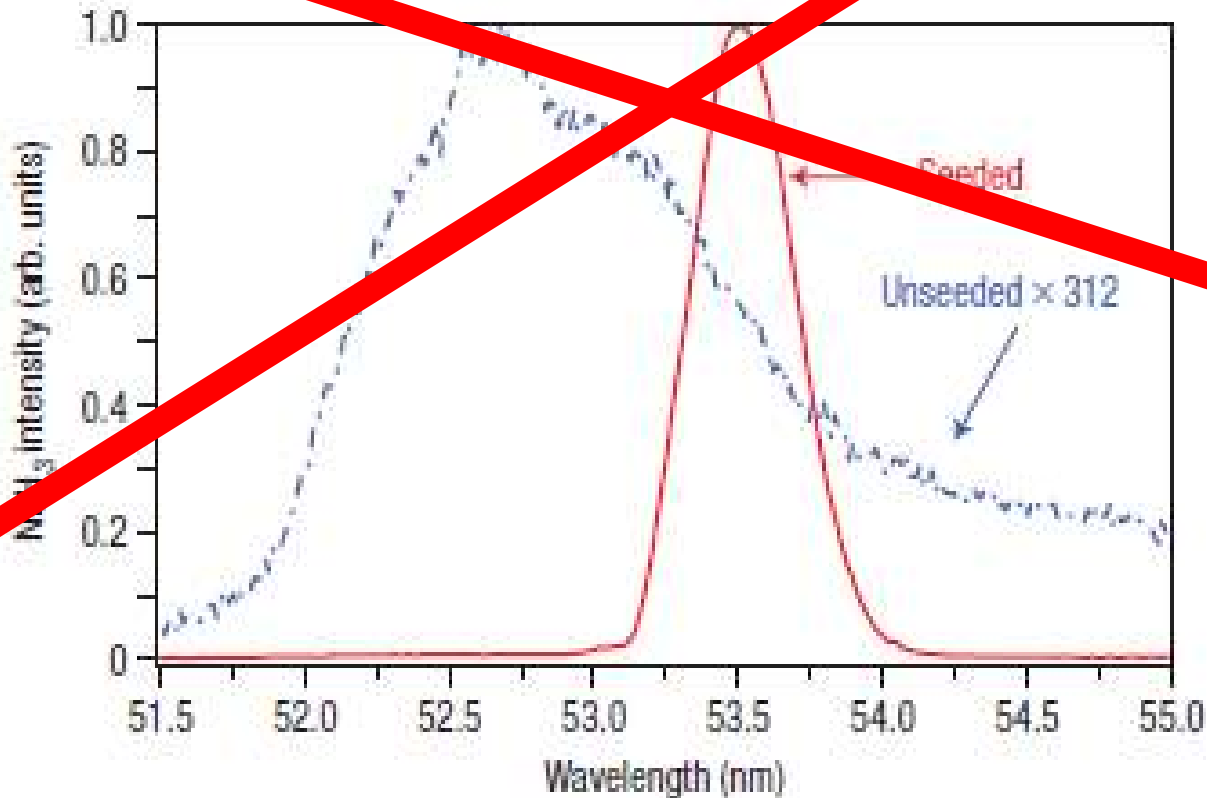
Indirect Seeding
Using Harmonics

'Use good temporal coherence of a longer wavelength to seed coherence at shorter harmonic wavelength '

Harmonic Generation via a longer wavelength seeded beam

R. Bonifacio, L. De Salvo Souza, P. Pierini, and E. T. Scharlemann, NIM A **296**, 787 (1990).

L.-H. Yu *et al.*, Science **289**, 932 (2000).

$$D = k\rho R_{56}$$

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L.-H. Yu *et al.*, Science **289**, 932 (2000).

λ_1 - fundamental

$\lambda_n = \lambda_1/n$ - fundamental

Good coherence at λ_1 transferred to harmonic λ_n

Seed laser λ_1

D

e⁻

Bunched electrons

$$D = k\rho R_{56}$$

Harmonic Generation via a longer wavelength seeded beam

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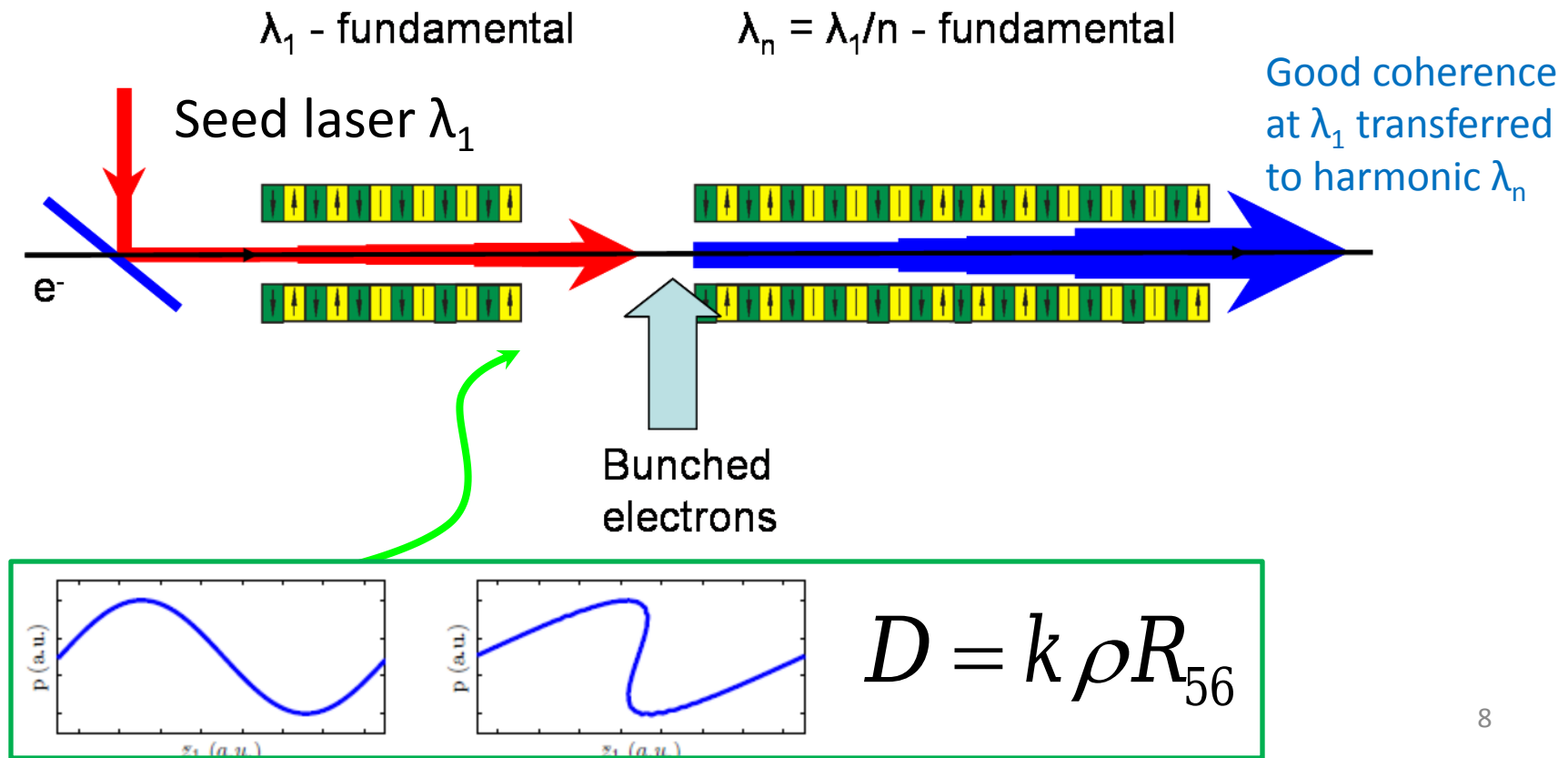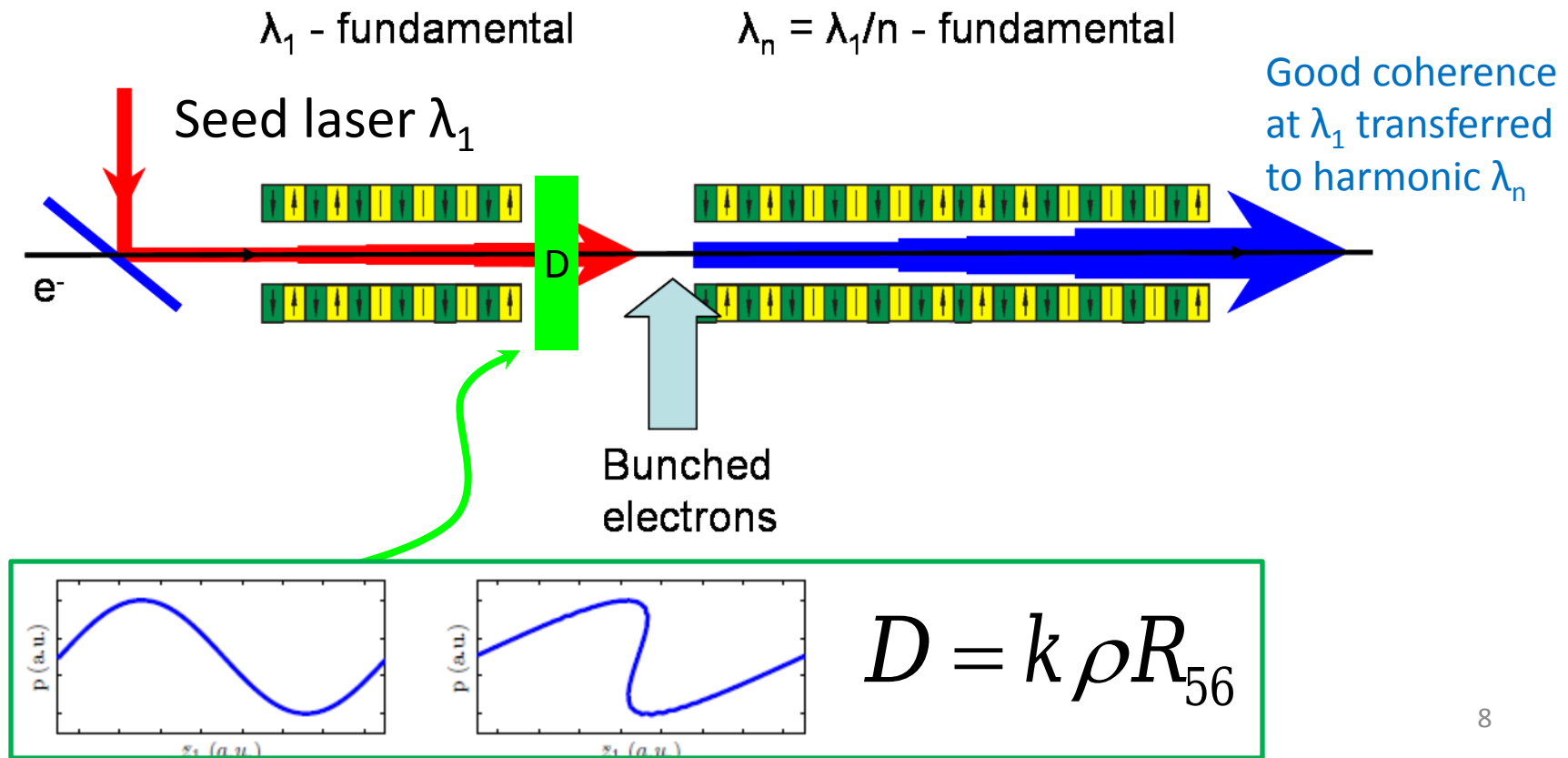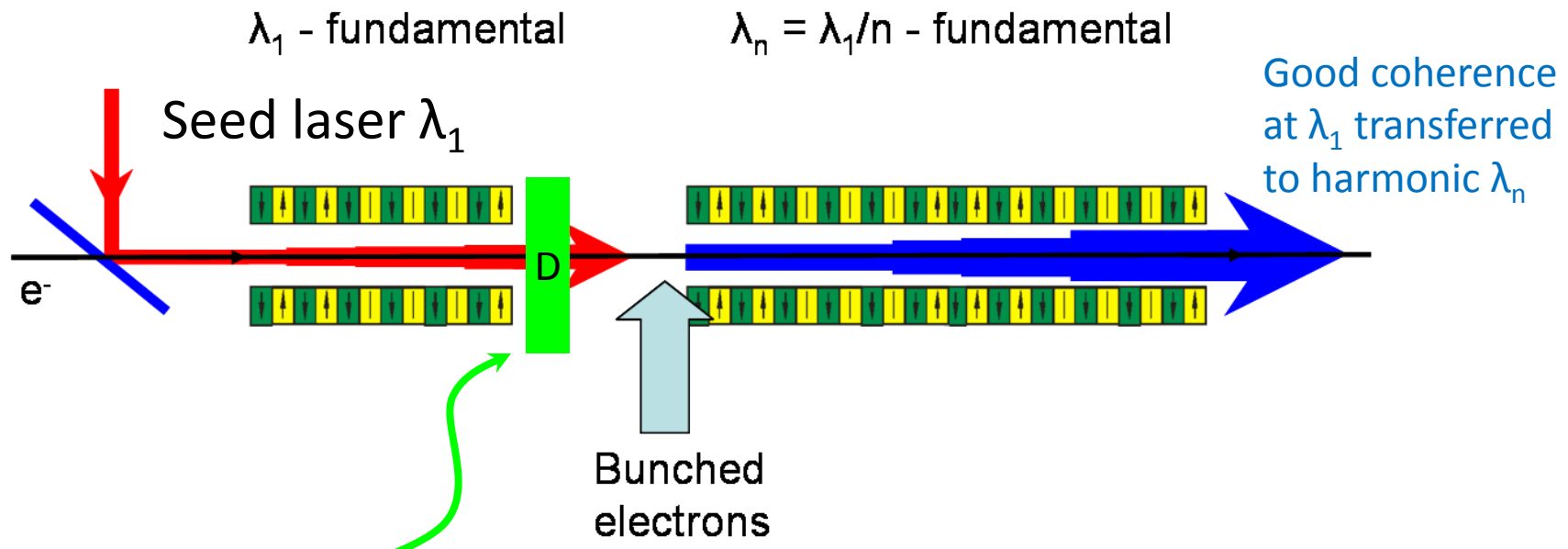
$$\frac{\Delta\gamma}{\rho\gamma} < \frac{1}{nD} \qquad D = k\rho R_{56}$$

X-rays require a HGHG Cascade

λ_1=260nm

24th Harmonic

However…

Study of a noise degradation of amplification process in a multistage HGHG FEL

E.L. Saldin[a,*], E.A. Schneidmiller[a], M.V. Yurkov[b]

always been an important problem. The majority of communication and radar engineers are familiar with the fact that inserting the amplifier prior to frequency multiplication has the disadvantage that the phase noise contribution of the amplifier is multiplied by n^2, where n is a frequency multiplication factor (see, for example [19]). In the case of HGHG FEL this means that the effect of frequency multiplication by a factor of N multiplies the first FEL amplifier noise power to carrier ratio by N^2. This prevents operation of HGHG FEL at very short wavelength range. The results presented in this paper have demonstrated that the HGHG FEL approach is quite adequate for a 10–100 nm coherent source, but not scalable to an X-ray device.

Recently, various HGHG schemes have been proposed to improve the performance of X-ray FEL. The basic theory of these schemes does not take into account the shot noise effect, meanwhile it leads to a dramatic degradation of the quality of the output radiation when applying frequency multiplication schemes. The arguments discussed above, based on our results of numerical simulations, seem to be strong enough to suggest that the HGHG FEL schemes for reaching hard X-rays proposed in the literature so far will not work.

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Study of a noise degradation of amplification process in a multistage HGHG FEL

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Problems in X-ray

10

Indirect Seeding:
Echo Enabled Harmonic Gain

Using the Beam-Echo Effect for Generation of Short-Wavelength Radiation

G. Stupakov

SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA
(Received 22 October 2008; published 17 February 2009)

Echo-enabled harmonic generation free electron laser

Dao Xiang and Gennady Stupakov

SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA
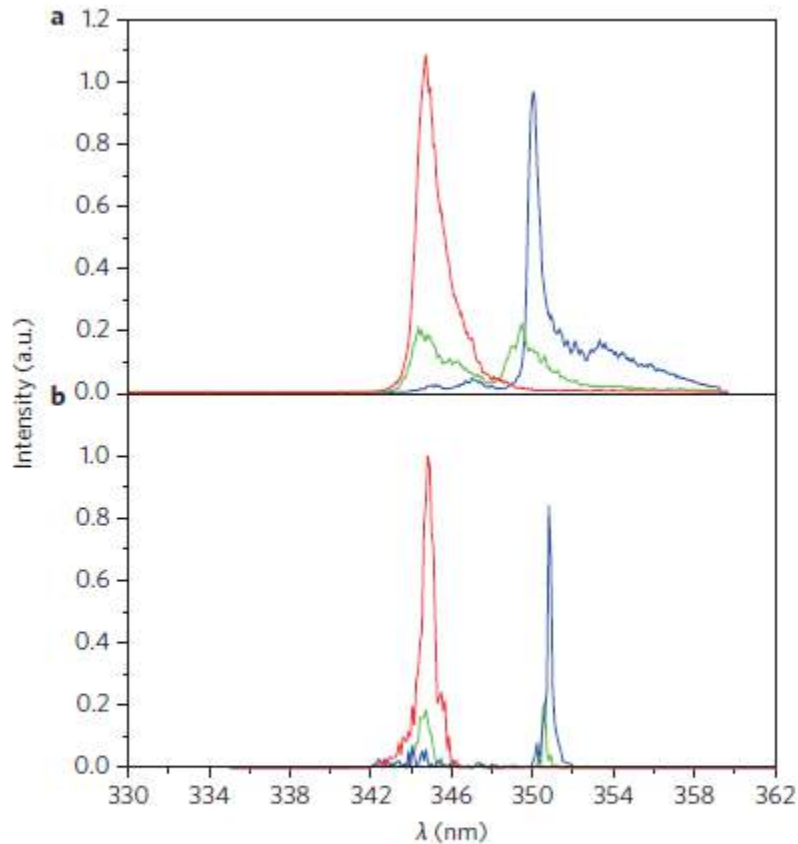(Received 2 December 2008; published 4 March 2009)

First lasing of an echo-enabled harmonic generation free-electron laser

Z. T. Zhao, D. Wang, J. H. Chen, Z. H. Chen, H. X. Deng, J. G. Ding, C. Feng, Q. Gu, M. M. Huang, T. H. Lan, Y. B. Leng, D. G. Li, G. Q. Lin, B. Liu, E. Prat, X. T. Wang, Z. S. Wang, K. R. Ye, L. Y. Yu, H. O. Zhang, J. Q. Zhang, Me. Zhang, Mi. Zhang, T. Zhang, S. P. Zhong ✚ et al.
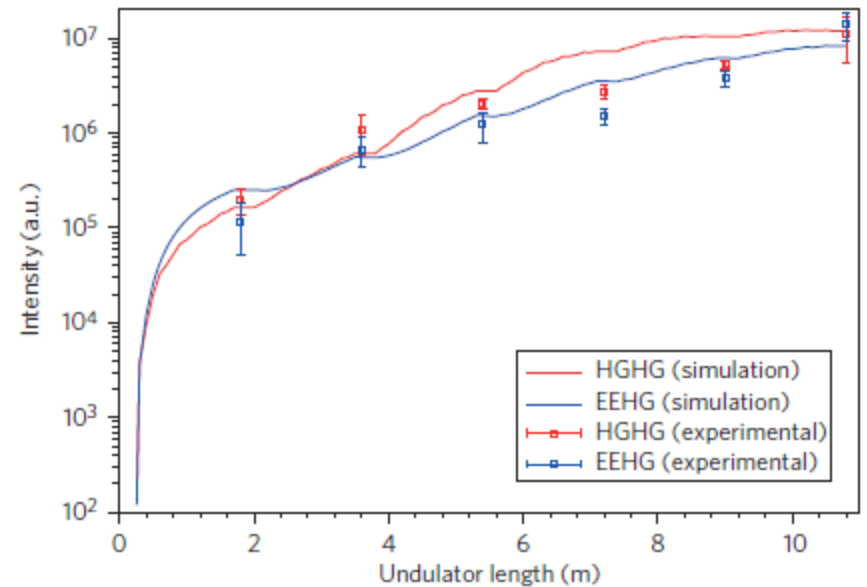
Affiliations | Contributions | Corresponding author

Figure 3 | Spectra for FEL radiation. a, Experimental results (red line, HGHG; blue line, EEHG; green line, intermediate state between HGHG and EEHG). b, Simulation results (red line, HGHG; blue line, EEHG; green line, intermediate state between HGHG and EEHG).
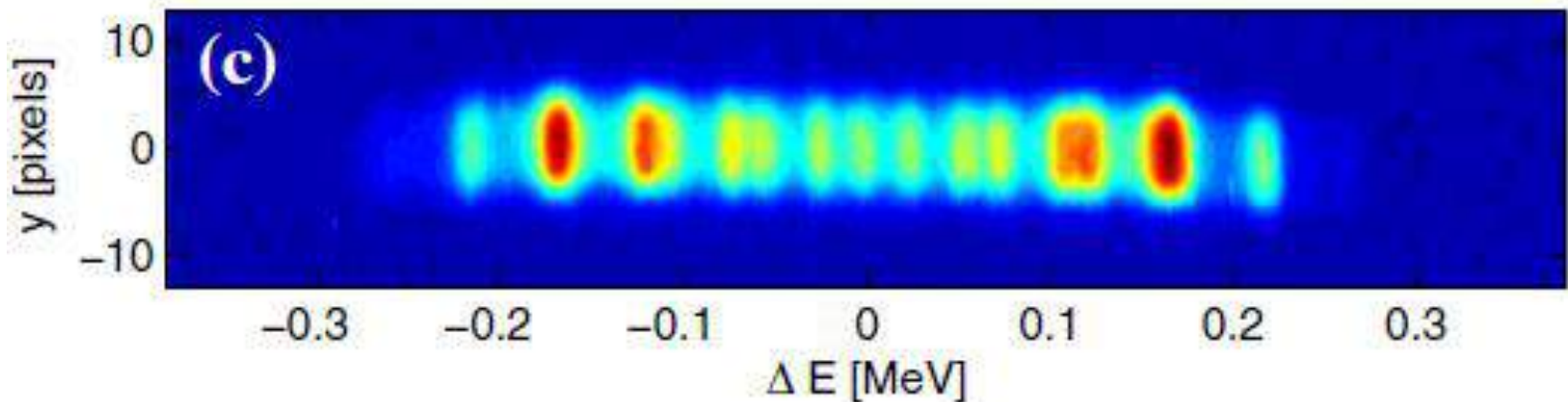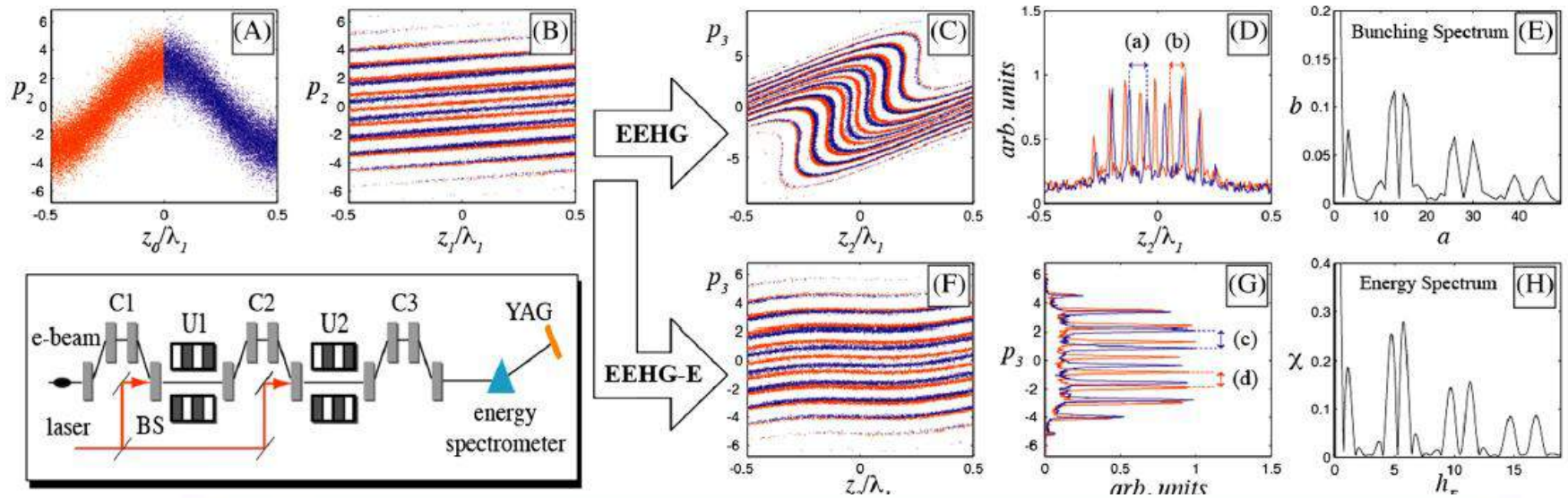

Figure 5 | Gain curves of the EEHG and HGHG FEL at SDUV-FEL. Intensity is measured with a calibrated CCD at the end of the radiator (red open squares, HGHG; blue open squares, EEHG). Error bars correspond to the peak-to-peak intensity statistics of 100 measurements. Simulation results are shown as a red line (HGHG) and a blue line (EEHG).

13

Direct observation of fine-scale energy banding in echo-enabled harmonic generation
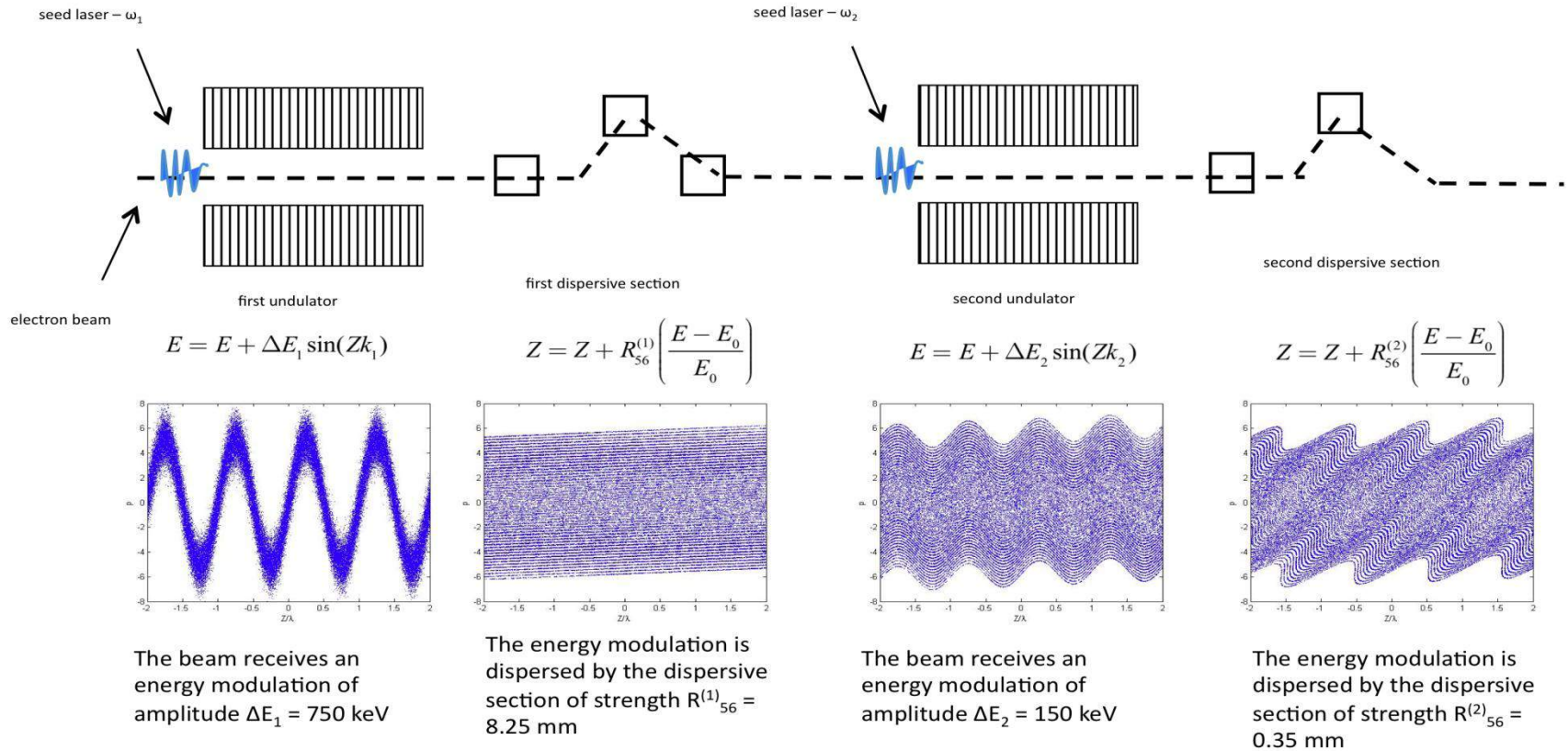
E. Hemsing, D. Xiang, M. Dunning, S. Weathersby, C. Hast, and T. Raubenheimer

SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA
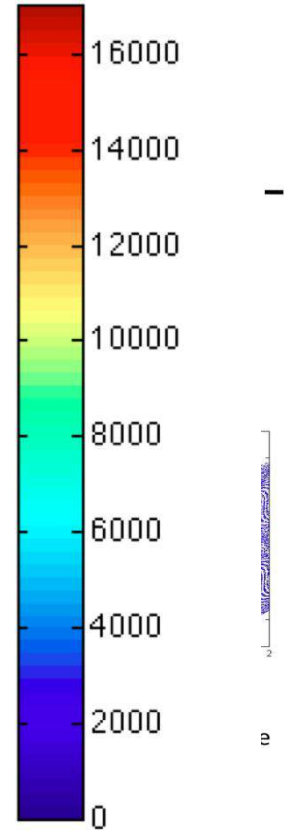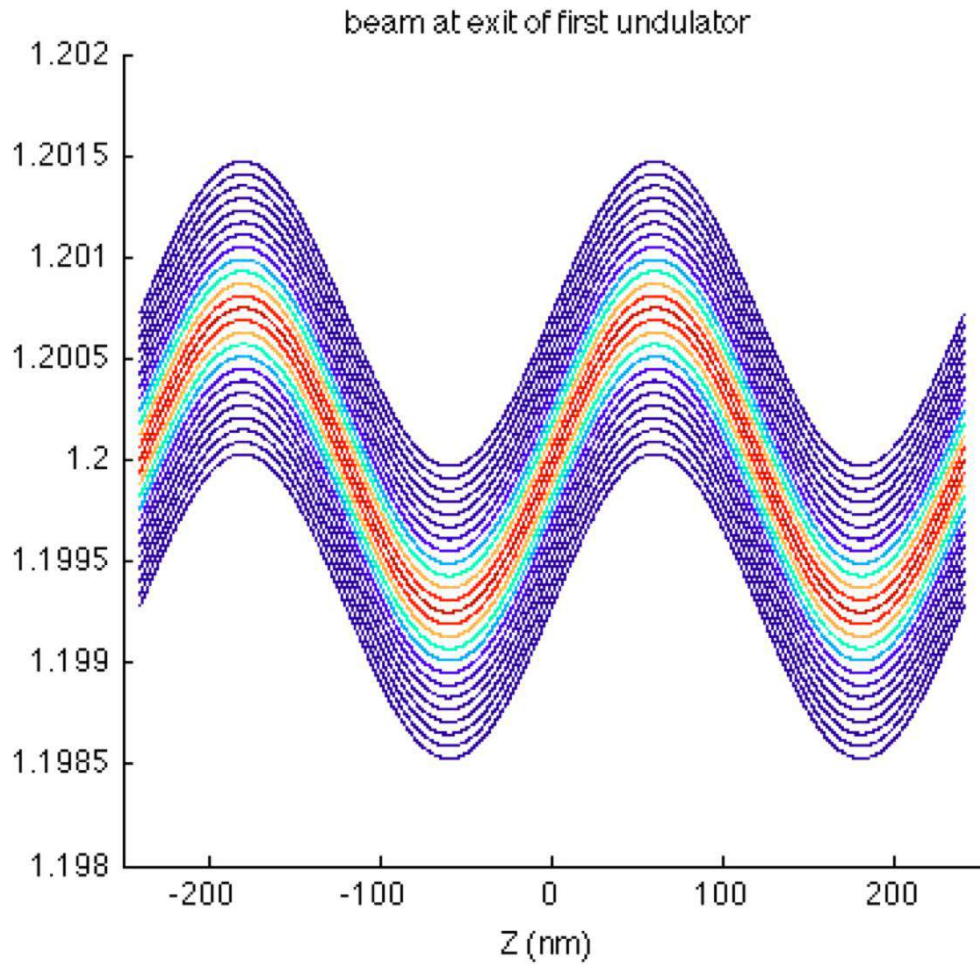(Received 5 July 2013; published 30 January 2014)

14

Mechanism

seed laser – ω_1

seed laser – ω_2

electron beam

first undulator

first dispersive section

second undulator

second dispersive section

$$E = E + \Delta E_1 \sin(Zk_1)$$

$$Z = Z + R^{(1)}_{56}\left(\frac{E - E_0}{E_0}\right)$$

$$E = E + \Delta E_2 \sin(Zk_2)$$

$$Z = Z + R^{(2)}_{56}\left(\frac{E - E_0}{E_0}\right)$$

The beam receives an energy modulation of amplitude ΔE_1 = 750 keV

The energy modulation is dispersed by the dispersive section of strength $R^{(1)}_{56}$ = 8.25 mm

The beam receives an energy modulation of amplitude ΔE_2 = 150 keV

The energy modulation is dispersed by the dispersive section of strength $R^{(2)}_{56}$ = 0.35 mm

Mechanism

seed laser – ω_1

first undu

electron beam

$$E = E + \Delta E_1$$

The beam receiv
energy modulati
amplitude $\Delta E_1 =$

beam at exit of first undulator

15

Mechanism

seed laser – ω_1

first undula...

electron beam

$E = E + \Delta E_1$ si...

The beam receive...
energy modulatio...
amplitude $\Delta E_1 = 7$...

beam at exit of first dispersive section

E (GeV)

Z (nm)

$\left. \dfrac{E - E_0}{E_0} \right)$

ion

...ulation is
...e dispersive
...th $R^{(2)}_{56}$ =

Mechanism

seed laser – ω_1

electron beam

first undulator

$E = E + \Delta E_1 \sin$

The beam receives energy modulation amplitude $\Delta E_1 = 75$

beam at exit of second undulator

E (GeV)

Z (nm)
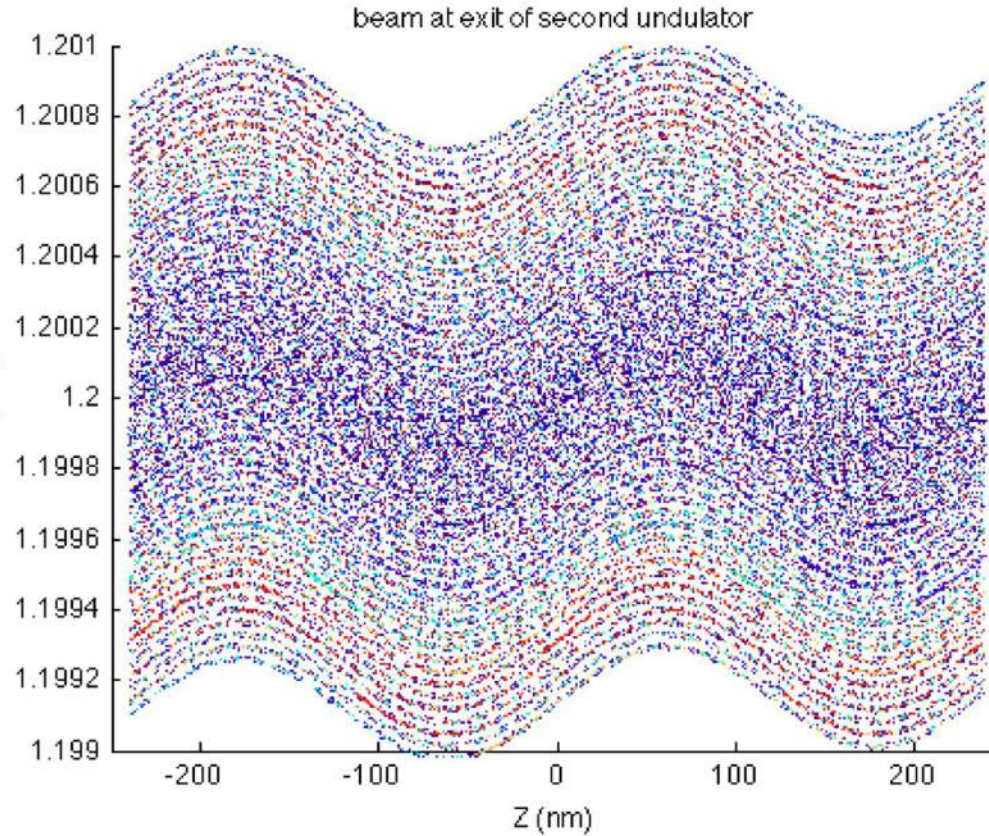
e section

$R^{(2)}_{56} \left(\dfrac{E - E_0}{E_0} \right)$
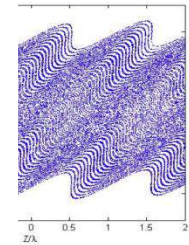
modulation is the dispersive rength $R^{(2)}_{56} =$

0.35 mm

Mechanism

seed laser – ω_1

first undu

electron beam

$$E = E + \Delta E_1$$

The beam receiv
energy modulati
amplitude $\Delta E_1 =$

beam at exit of second dispersive section
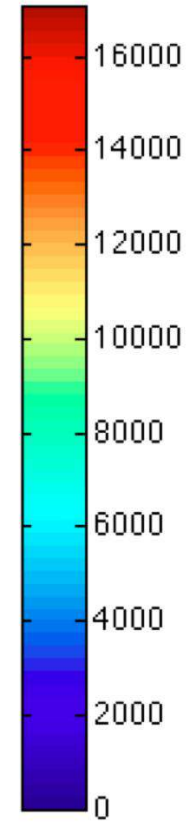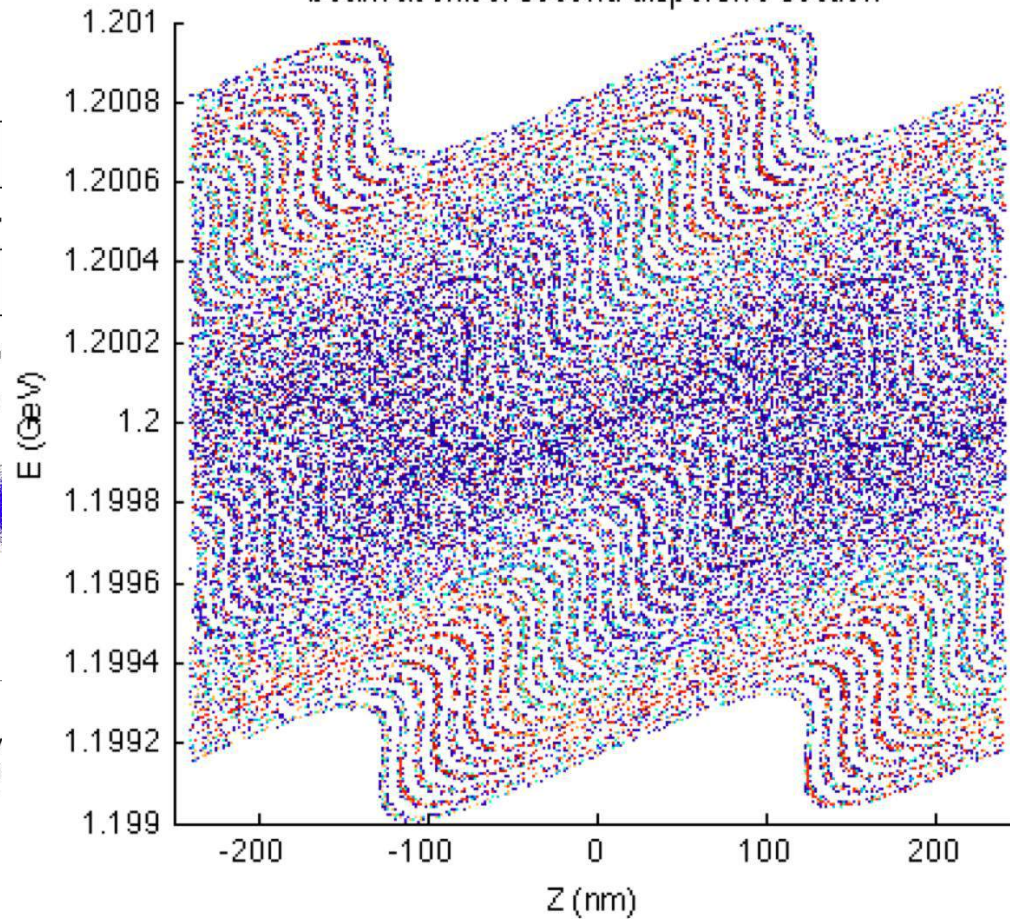
Indirect Seeding:
Echo Enabled Harmonic Gain
- Also results in modal bunching

Echo enabled harmonic generation free electron laser in a mode-locked configuration

J. R. HENDERSON[1,2] and B. W. J. MCNEIL[1]
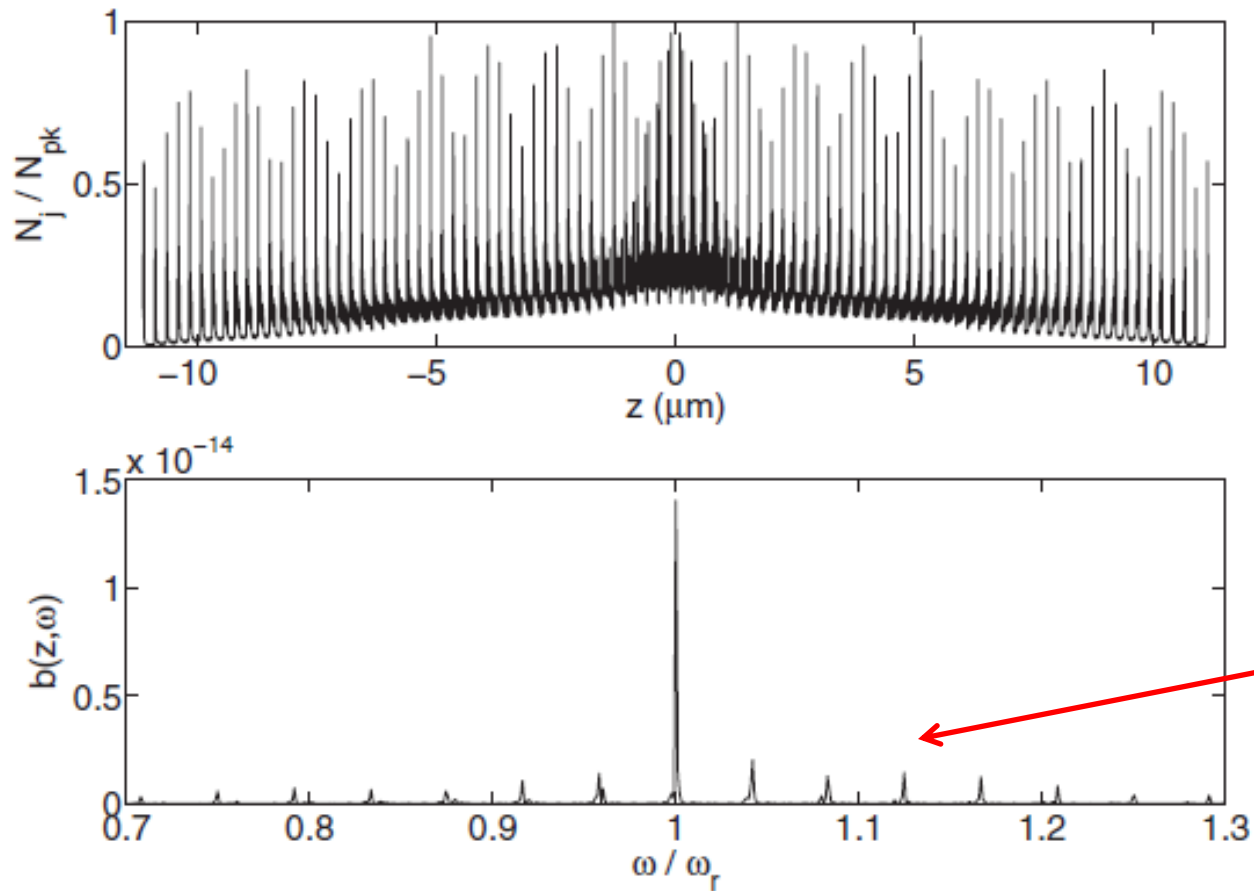
Fig. 4: Histogram of electron numbers (top) normalised with respect to the peak, and the Fourier transform of the bunching parameter $b(z, \omega)$ for the full electron beam distribution showing the modal structure at the end of the EEHG pre-bunching process.

Modal bunching with separation of initial modulation laser.

Mode locked FEL interaction

$\lambda_r \approx 10$ nm
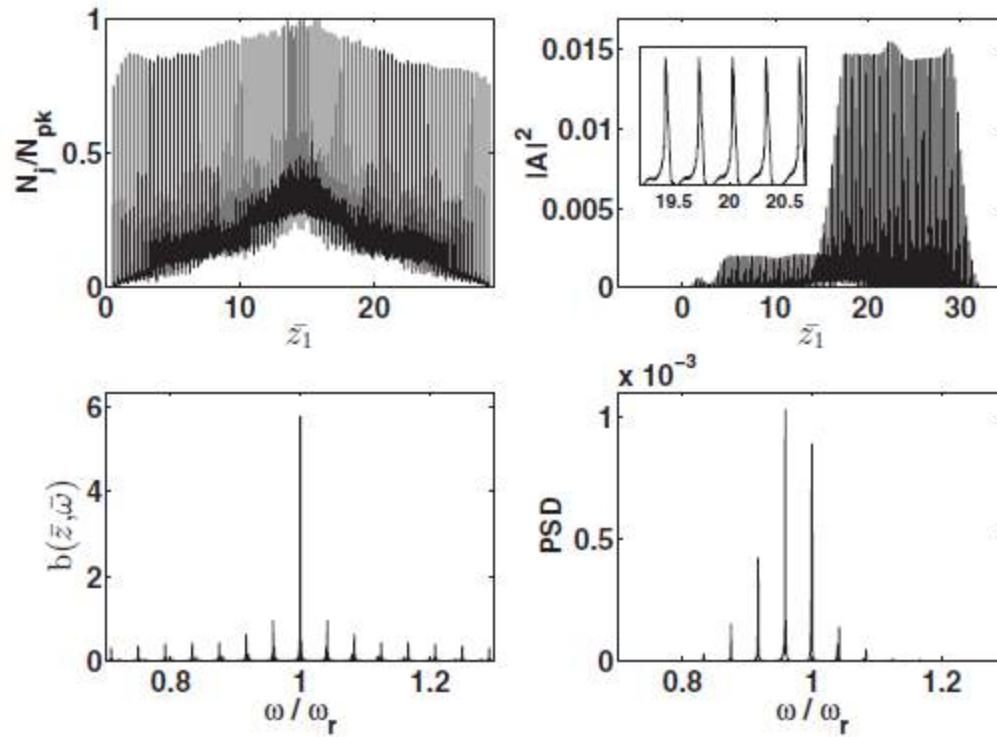
Fig. 6: As fig. 5, but for the MLOK undulator at saturation ($\bar{z} \approx 0.6$). The inset (top, right) shows more detail expanded in $\bar{z}_1$. A well-defined set of phase-matched radiation modes has developed resulting in a train of short radiation pulses. In unscaled units the individual pulse widths are ~ 106 attoseconds (FWHM) and separated by ~ 0.8 femtoseconds corresponding to $\bar{s} = 0.3$ in scaled units of $\bar{z}_1$.

Self-Seeding

Self-seeding

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]

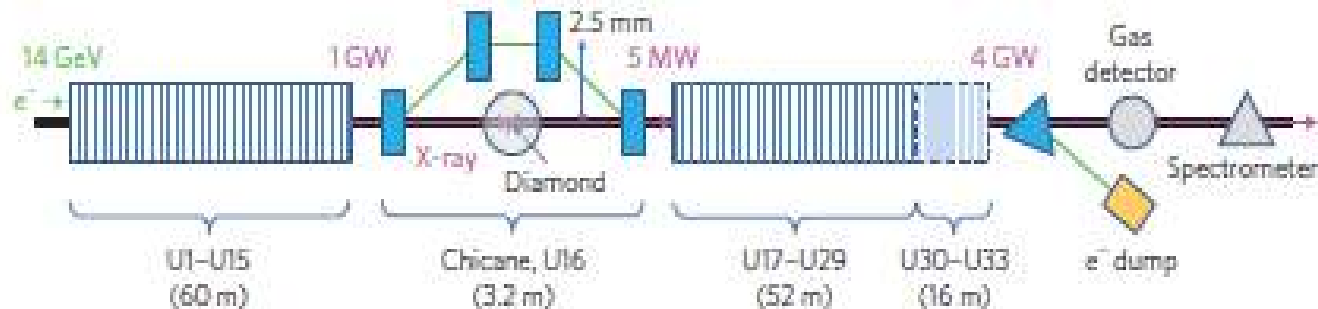**Figure 1 | Layout of the LCLS undulator with a self-seeding chicane, diamond monochromator, gas detector and hard-X-ray spectrometer.** The chicane i greatly exaggerated in scale. The last four LCLS undulators (U30–U33) were previously modified as second-harmonic afterburners[15] and were not used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

Feldhaus, J., Saldin, E. L., Schneider, J. R., Schneidmiller, E. A. & Yurkov, M.V. *Opt. Commun.* **140**, 341 (1997)

A novel self-seeding scheme for hard X-ray FELs *Journal of Modern Optics*
Gianluca Geloni[a]*, Vitali Kocharyan[b] and Evgeni Saldin[b] Vol. 58, No. 16, 20 September 2011

Self-seeding*

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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.

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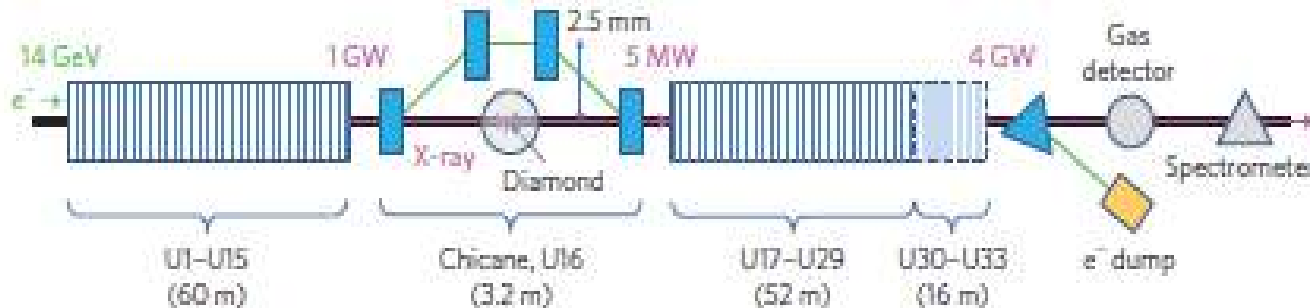
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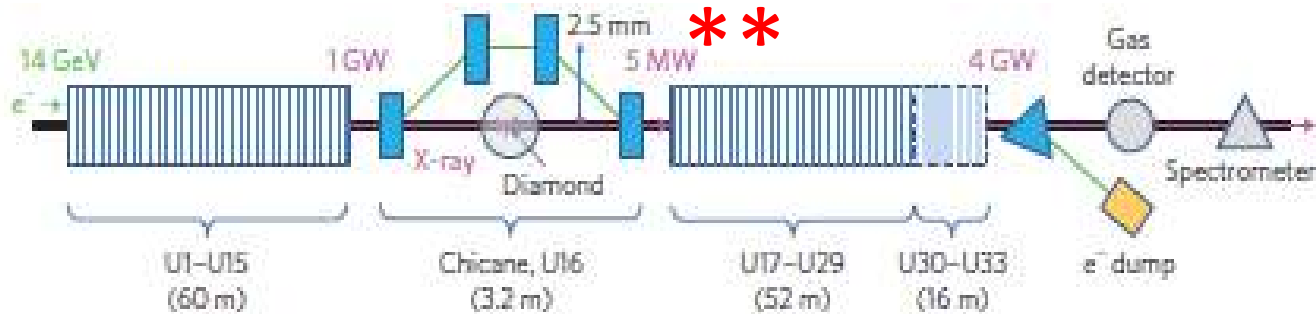
** A novel self-seeding scheme for hard X-ray FELs *Journal of Modern Optics*
Gianluca Geloni[a]*, Vitali Kocharyan[b] and Evgeni Saldin[b] Vol. 58, No. 16, 20 September 2011

Diamond crystal optics for self-seeding of hard X-rays in X-ray free-electron lasers

S. Stoupin[a], V.D. Blank[b], S.A. Terentyev[b], S.N. Polyakov[b], V.N. Denisov[b], M.S. Kuznetsov[b], Yu.V. Shvyd'ko[a], D. Shu[a], P. Emma[c], J. Maj[a], J. Katsoudas[d]
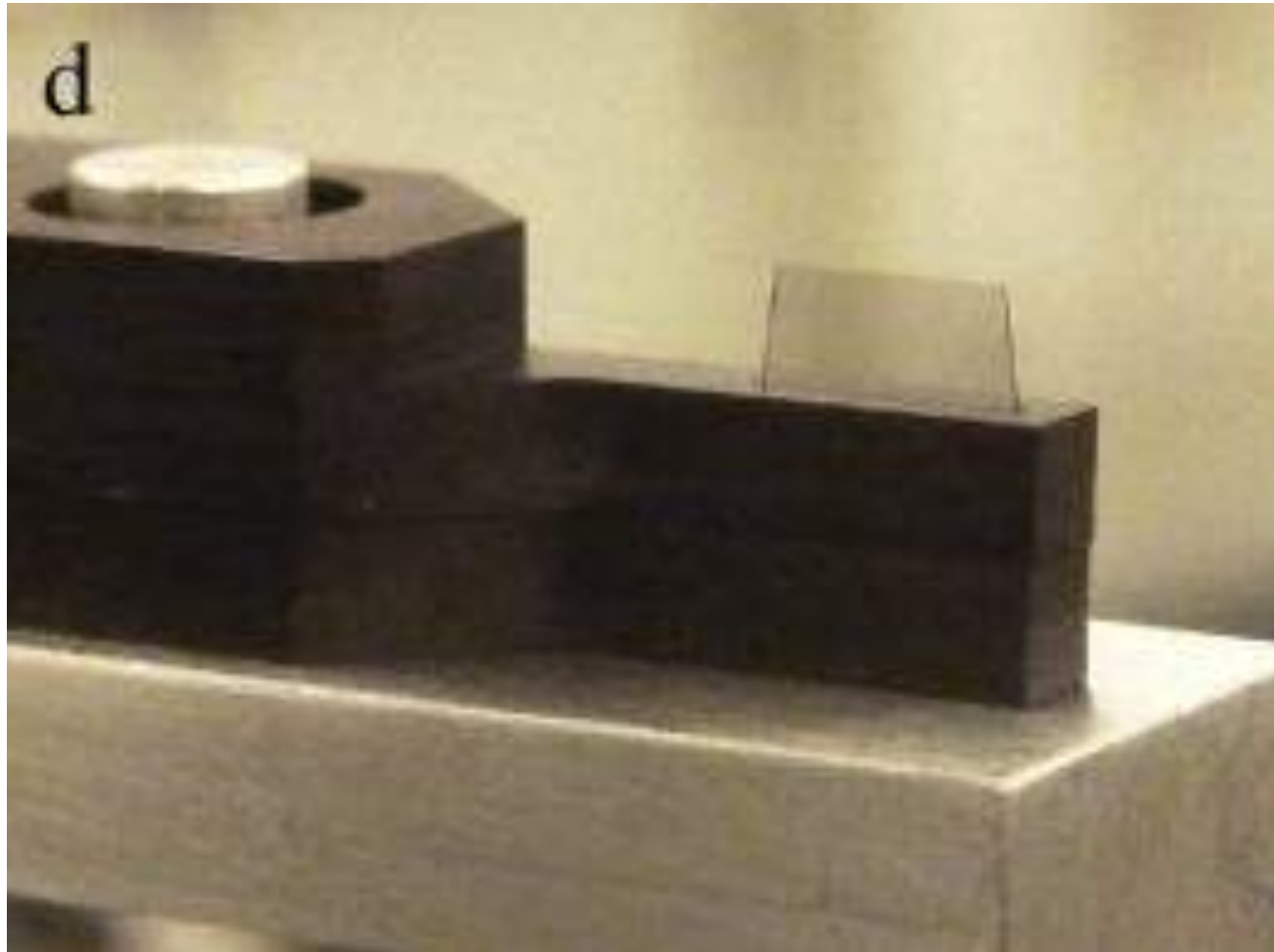
Results from LCLS Experiment* based on:

A novel self-seeding scheme for hard X-ray FELs *Journal of Modern Optics*
Gianluca Geloni[a*], Vitali Kocharyan[b] and Evgeni Saldin[b] Vol. 58, No. 16, 20 September 2011

Figure 5 | Measured X-ray spectra. a,b, Single-shot (**a**) and averaged (**b**) X-ray spectrum in SASE mode (red) and self-seeded mode (blue). The FWHM single-shot seeded bandwidth is 0.4 eV, whereas the SASE FWHM bandwidth is ~20 eV. Vertical scales have the same arbitrary units in both **a** and **b**. The chicane is turned off for the SASE measurements, but necessarily switched on for the self-seeded mode.

*J. Amann et al, NATURE PHOTONICS **6**, 693 (2012)

22

Results from LCLS Experiment* based on:

A novel self-seeding scheme for hard X-ray FELs *Journal of Modern Optics*

Gianluca Geloni[a]*, Vitali Kocharyan[b] and Evgeni Saldin[b] Vol. 58, No. 16, 20 September 2011

It works!

May have heating issues that need sorted at high rep-rates?

Single-shot

Averaged

Figure 5 | Measured X-ray spectra. **a,b**, Single-shot (**a**) and averaged (**b**) X-ray spectrum in SASE mode (red) and self-seeded mode (blue). The FWHM single-shot seeded bandwidth is 0.4 eV, whereas the SASE FWHM bandwidth is ~20 eV. Vertical scales have the same arbitrary units in both **a** and **b**. The chicane is turned off for the SASE measurements, but necessarily switched on for the self-seeded mode.

*J. Amann et al, NATURE PHOTONICS **6**, 693 (2012)

22

HB-SASE; i-SASE; p-SASE….

HB-SASE; i-SASE; p-SASE….

?? HiBp-SASE ??

HB-SASE developed from numerical experiments on studies of phase shifting in the FEL

Small shifts < λ_r
(Phase shifts)

INDUCING STRONG DENSITY MODULATION WITH SMALL ENERGY DISPERSION IN PARTICLE BEAMS AND THE HARMONIC AMPLIFIER FREE ELECTRON LASER

B. W. J. McNeil, G. R. M. Robb, Department of Physics, University of Strathclyde, Glasgow, UK
M. W. Poole, ASTeC, Daresbury Laboratory, Warrington WA4 4AD, UK
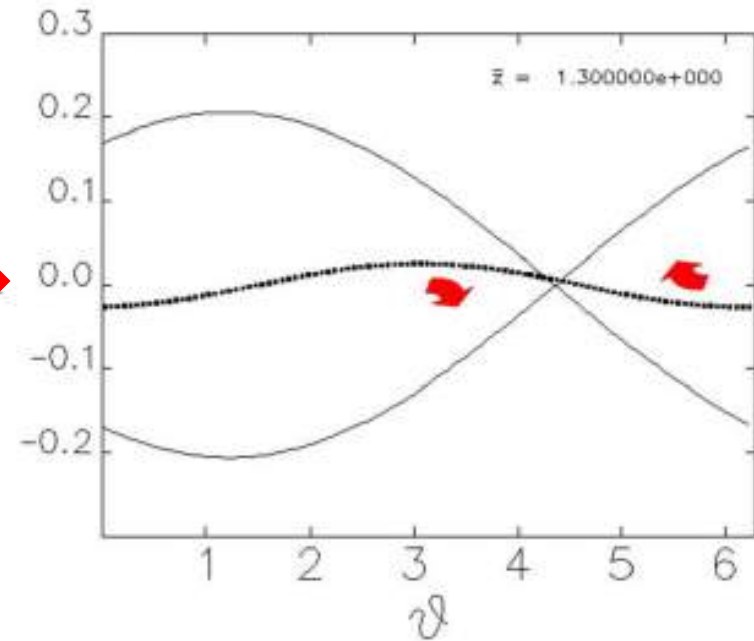
Figure 1: Electron trajectories in phase-space (ϑ, p) at beginning of FEL-type interaction. The solid line is the instantaneous separatrix and the red arrows indicate the direction of electron phase flow.

$\lambda_r/2$ (π-shift)

Figure 2: Electron trajectories in phase-space at beginning of FEL-type interaction as Fig. 1 but immediately following a relative $\Delta\vartheta = \pi$ phase change between electrons and radiation.

26

Phase shifting

Electron delay

π-shift

Use chicanes to delay electrons

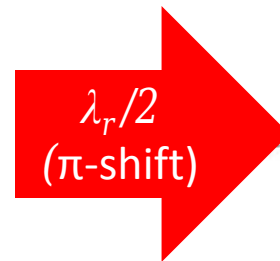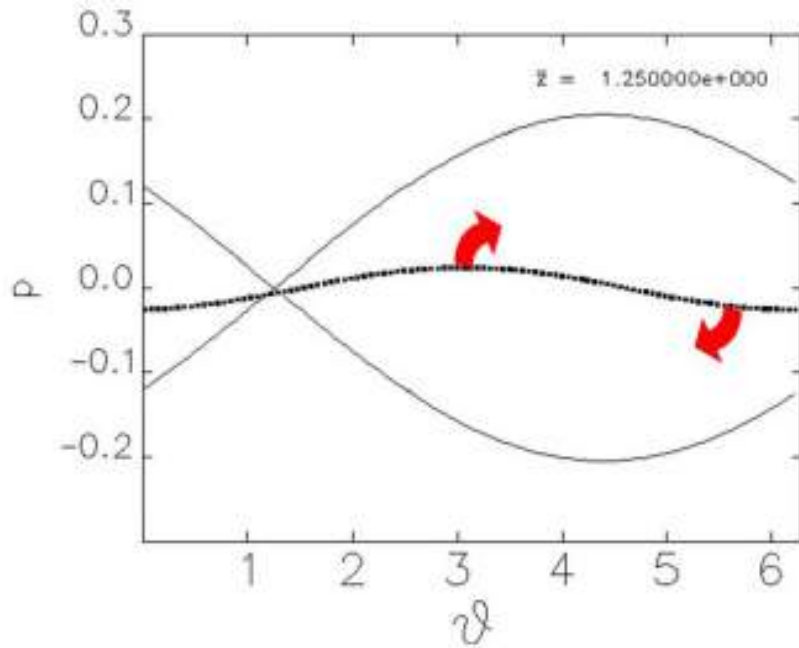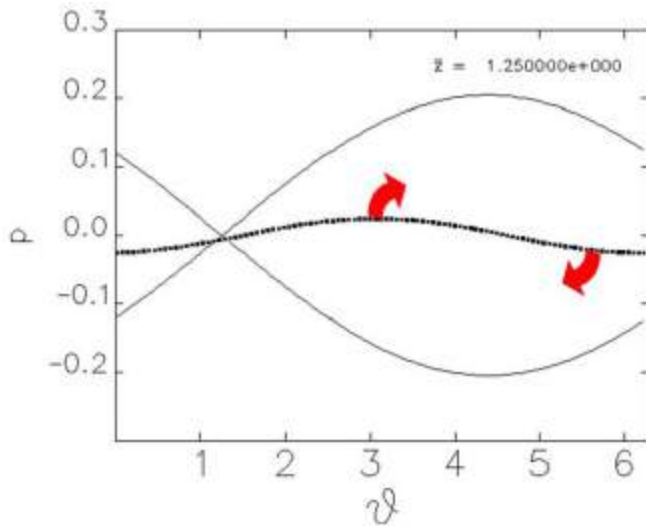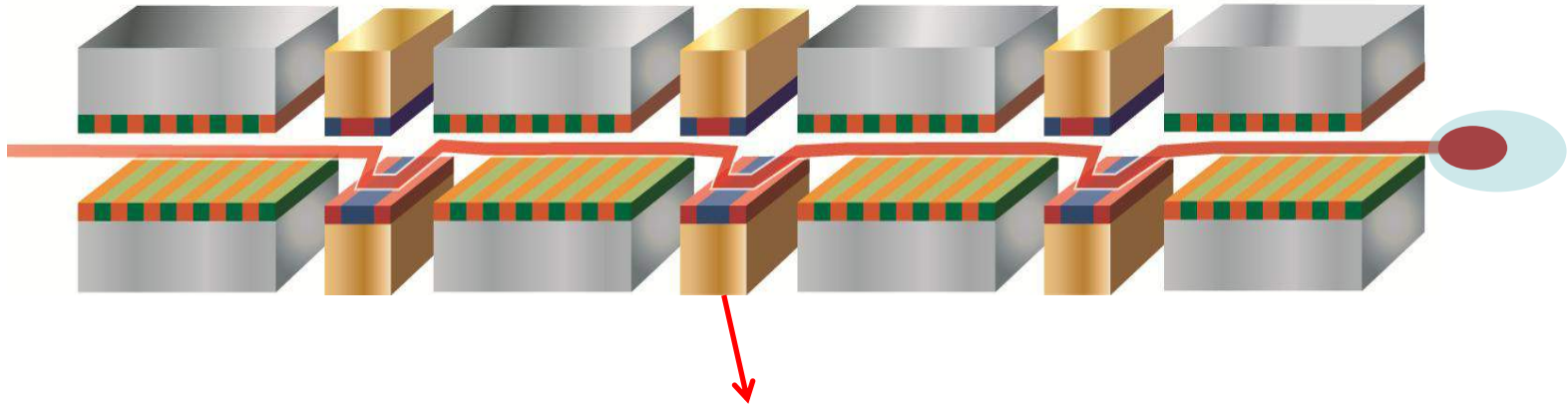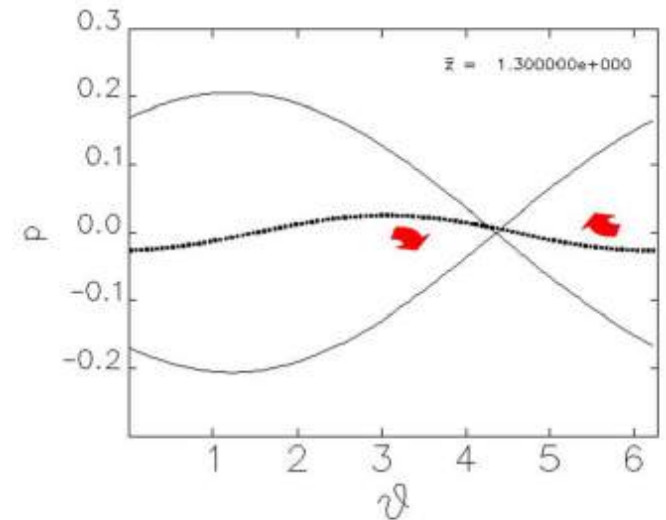Figure 1: Electron trajectories in phase-space (ϑ, p) at beginning of FEL-type interaction. The solid line is the instantaneous separatrix and the red arrows indicate the direction of electron phase flow.

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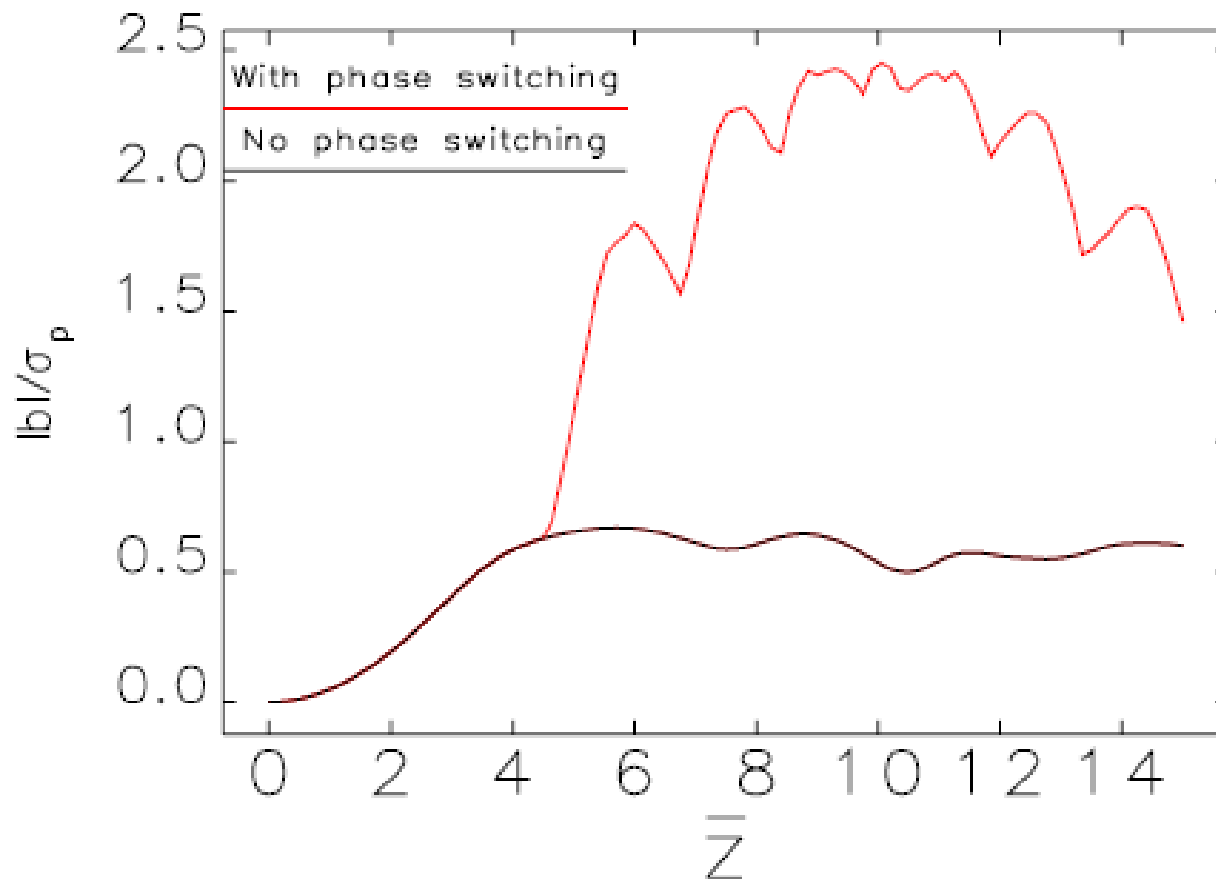
Figure 5: FEL type evolution of the quantity $|b|/\sigma_p$ as a function of scaled distance, $\bar{z}$, through the interaction region.

Result: bunching with reduced energy spread

Can also get Harmonic Amplifier FEL*

fundamental

$\bar{z} = 3.000000e+000$

3rd harmonic

$\bar{z} = 3.100000e+000$

$2\pi/3$
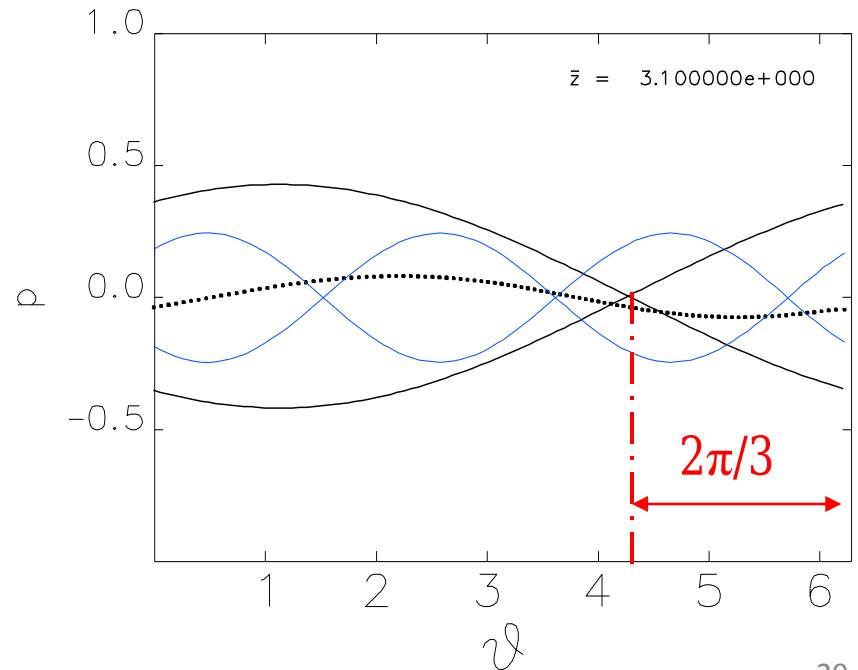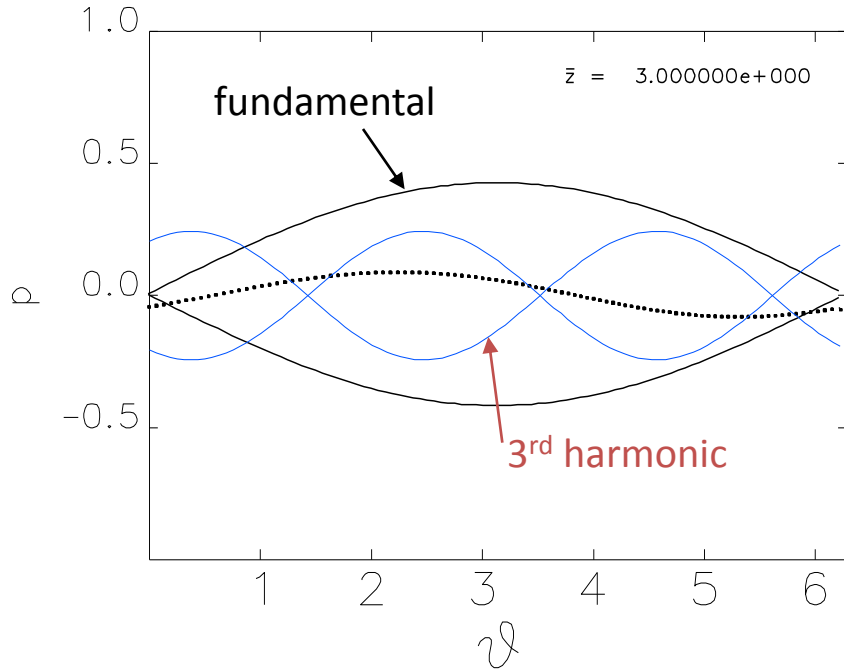
*McNeil, Robb & Poole, PAC 2005, Knoxville, Tennessee, 1718-20

Can also get Harmonic Amplifier FEL*

fundamental

$\bar{z} = 3.000000e+000$

3rd harmonic

A relative phase change between electrons and fundamental radiation of $n2\pi/3$ (n - integer) will disrupt the fundamental-electron coupling and so the fundamental's growth.

$\bar{z} = 3.100000e+000$

$2\pi/3$

*McNeil, Robb & Poole, PAC 2005, Knoxville, Tennessee, 1718-20

29

Can also get Harmonic Amplifier FEL*

A relative phase change between electrons and fundamental radiation of $n2\pi/3$ (n - integer) will disrupt the fundamental-electron coupling and so the fundamental's growth.

However, a $n2\pi/3$ phase change for the fundamental is a $n2\pi$ phase change for the 3rd harmonic – The 3rd harmonic interaction therefore suffers no disruption.

*McNeil, Robb & Poole, PAC 2005, Knoxville, Tennessee, 1718-20
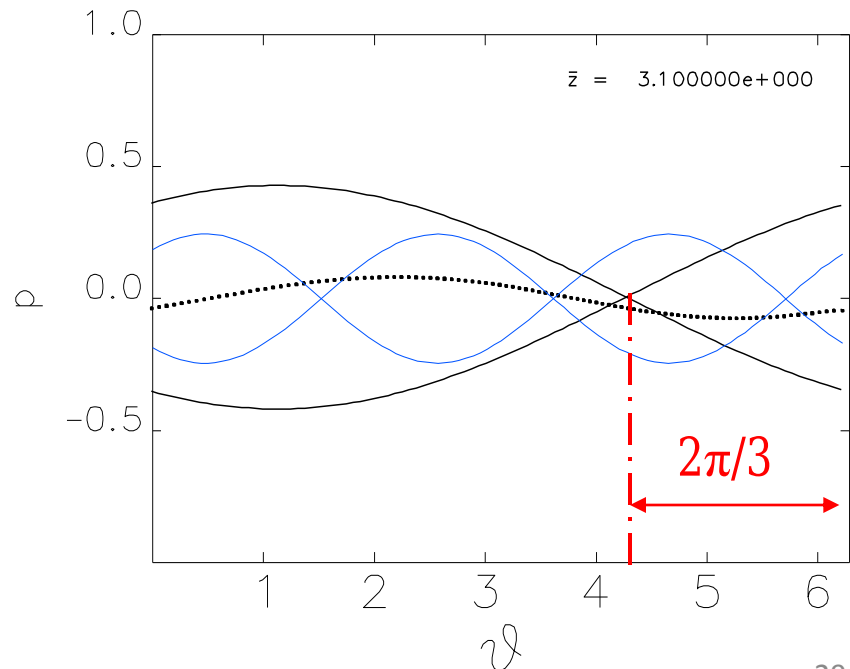
Using a seeded steady-state model* (i.e. no pulses effects):

FIG. 2. Scaled powers of fundamental $|A_1|^2$ (solid line) and third harmonic $|A_3|^2$ (dotted line) for wiggler parameter $a_1 = 4$ demonstrating the effects of relative phase changes of $\Delta\theta = 2\pi/3$ at $\bar{z} = 4, 5, 6, \ldots, 24$. For the wiggler parameter retuned to $a_3 = 2.16$, A_3 is the fundamental and a separate simulation shows how $|A_3|^2$ (dashed line) evolves.
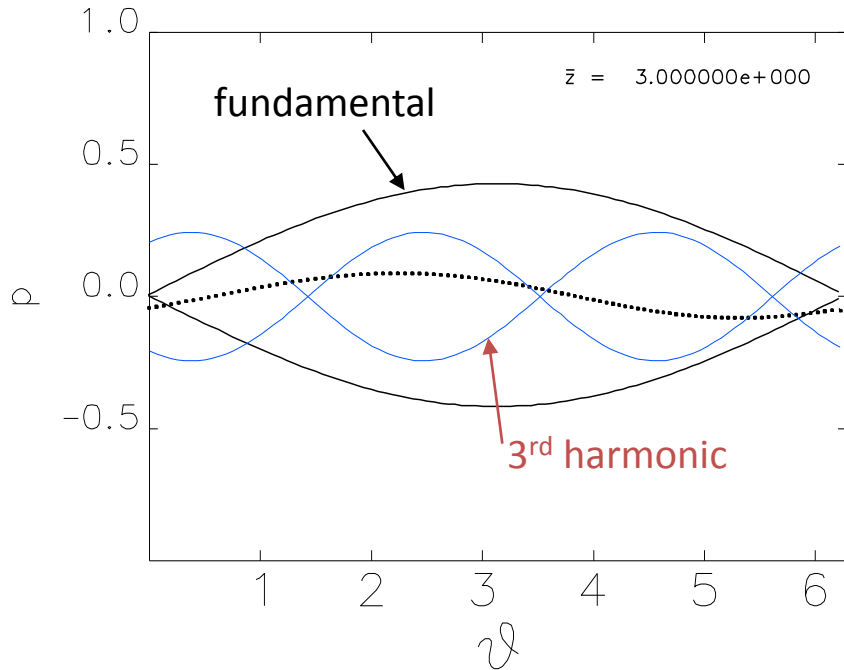
*McNeil, Robb, Poole & Thompson, PRL **96**, 084801 (2006)
Schneidmiller & Yurkov, PRST-AB **15,** 080702 (2012) - For SASE

Using a seeded steady-state model* (i.e. no pulses effects):
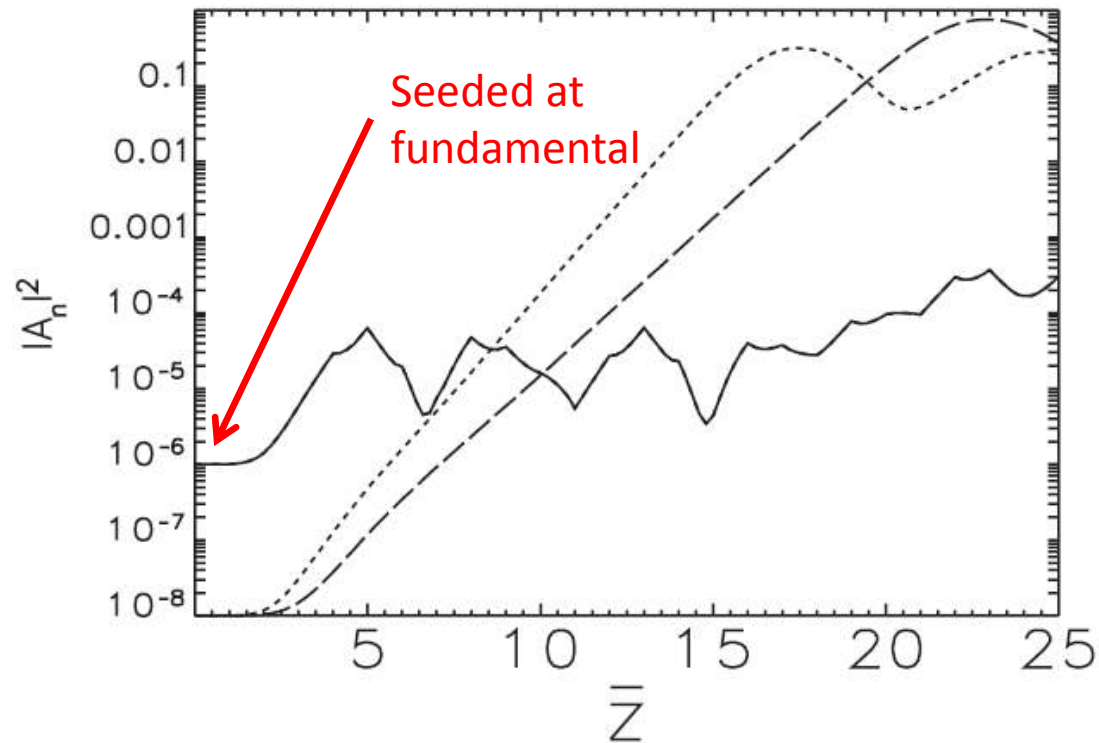
Seeded at fundamental

FIG. 2. Scaled powers of fundamental $|A_1|^2$ (solid line) and third harmonic $|A_3|^2$ (dotted line) for wiggler parameter $a_1 = 4$ demonstrating the effects of relative phase changes of $\Delta\theta = 2\pi/3$ at $\bar{z} = 4, 5, 6, \ldots, 24$. For the wiggler parameter retuned to $a_3 = 2.16$, A_3 is the fundamental and a separate simulation shows how $|A_3|^2$ (dashed line) evolves.

*McNeil, Robb, Poole & Thompson, PRL **96**, 084801 (2006)
Schneidmiller & Yurkov, PRST-AB **15,** 080702 (2012) - For SASE

Large shifts >> λ_r
(But no phase shifting)

The introduction of longer shifts, $>> \lambda_r$ over many wavelengths, was subject of PhD study from Oct. 2005 to improve SASE coherence:

Year One/Two Report

N. R. Thompson

13 January 2007

Abstract

This report summarises the research carried out until January 2007. The main thrust has been the development of techniques and ideas to improve the longitudinal (or temporal) coherence of Self-Amplified Spontaneous Emission (SASE) Free-Electron Lasers. Some satisfactory progress has been made in this area, as well as observation of new phenomena which are not yet understood but which promise to be interesting fields for future research.

Method: Stretch out the interaction and the coherence length:
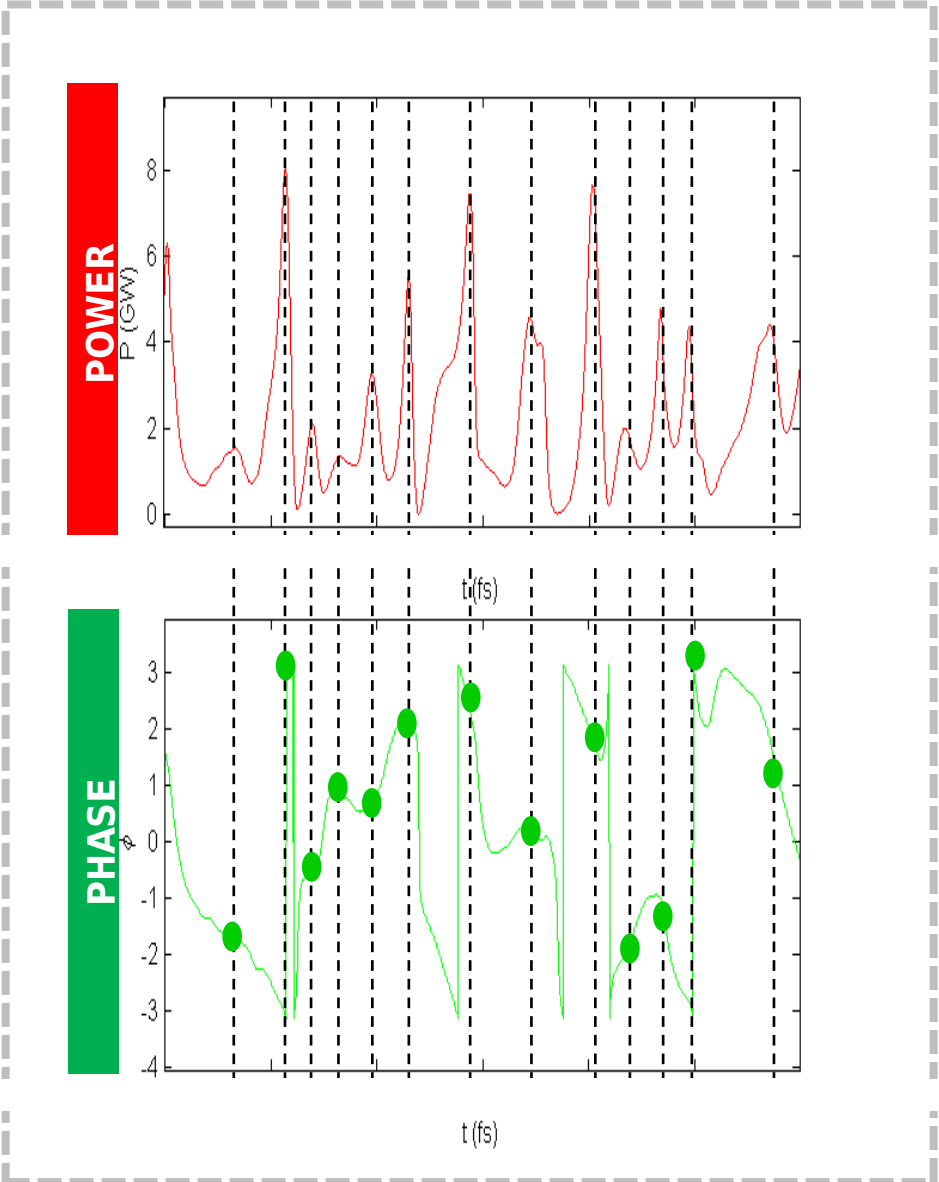
Method: Stretch out the interaction and the coherence length:

t (fs)

t (fs)

Large shifts >> $\lambda_{r,}$

Electron delay

N_w period undulator

$\bar{l}$

$\bar{l} + \bar{\delta}$

$\bar{s}$ $\bar{s}$

$$\bar{s} = \bar{l} + \bar{\delta}$$

Large shifts >> $\lambda_{r,}$

Electron delay

N_w period undulator

e

$\overline{l}$

e

$\overline{l} + \overline{\delta}$

e

e

$\overline{s}$ $\overline{s}$

$$\overline{s} = \overline{l} + \overline{\delta}$$

$\overline{S}$

$\overline{S}$

Module 4

$\overline{S}$

Module 3

Wavefront

$\overline{S}$

Module 2

Module 1

e⁻ beam
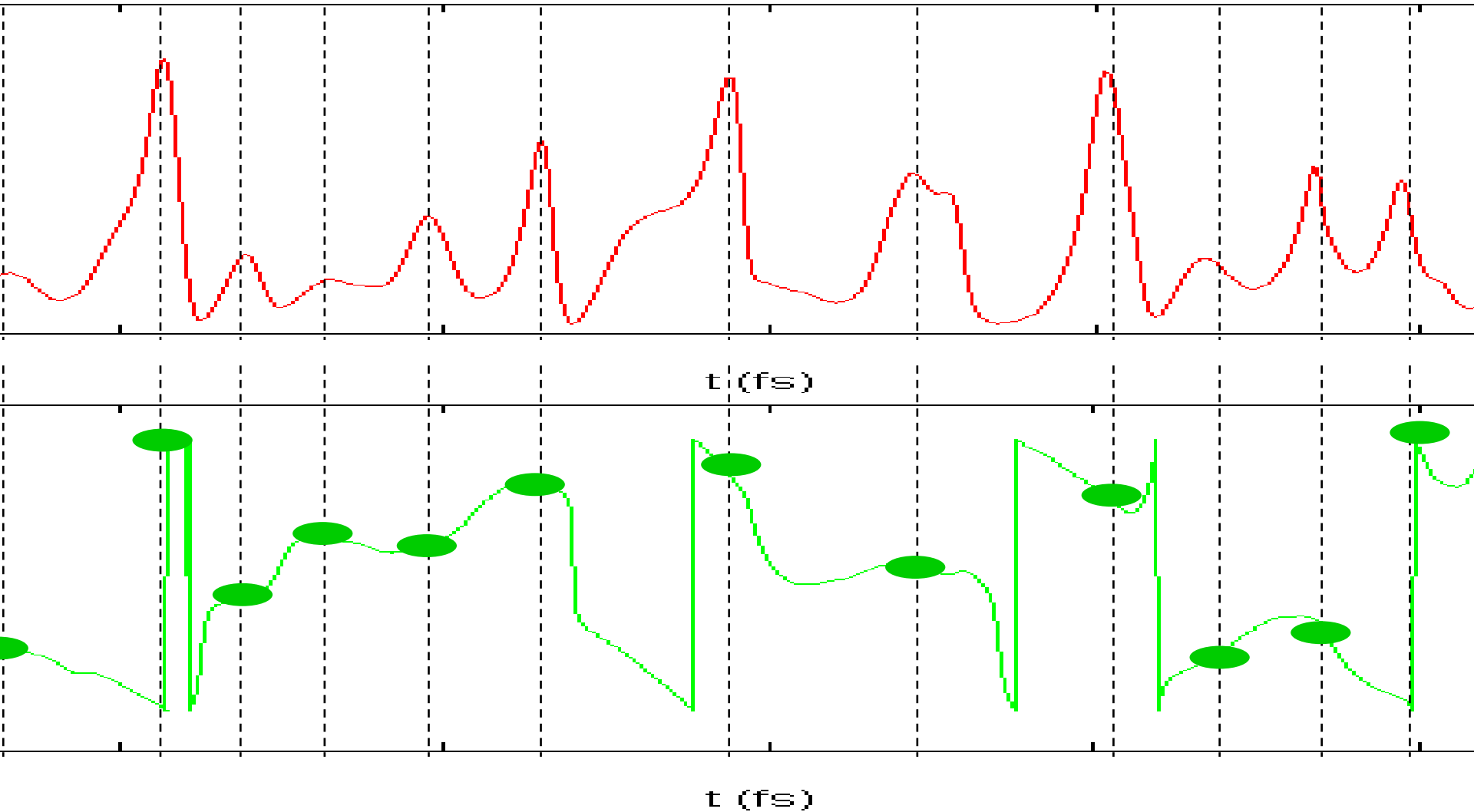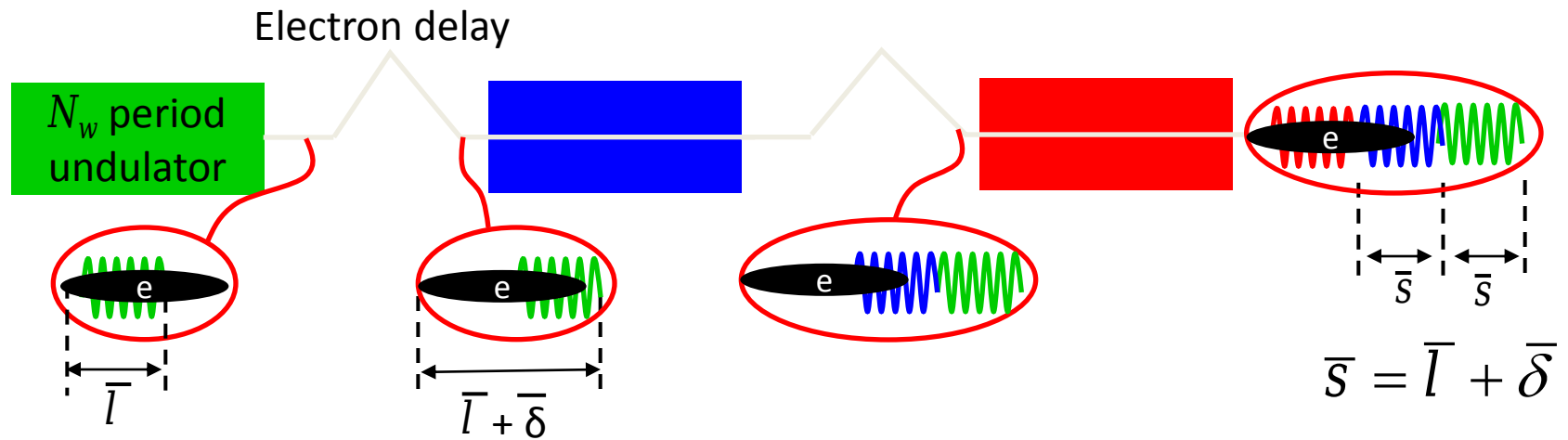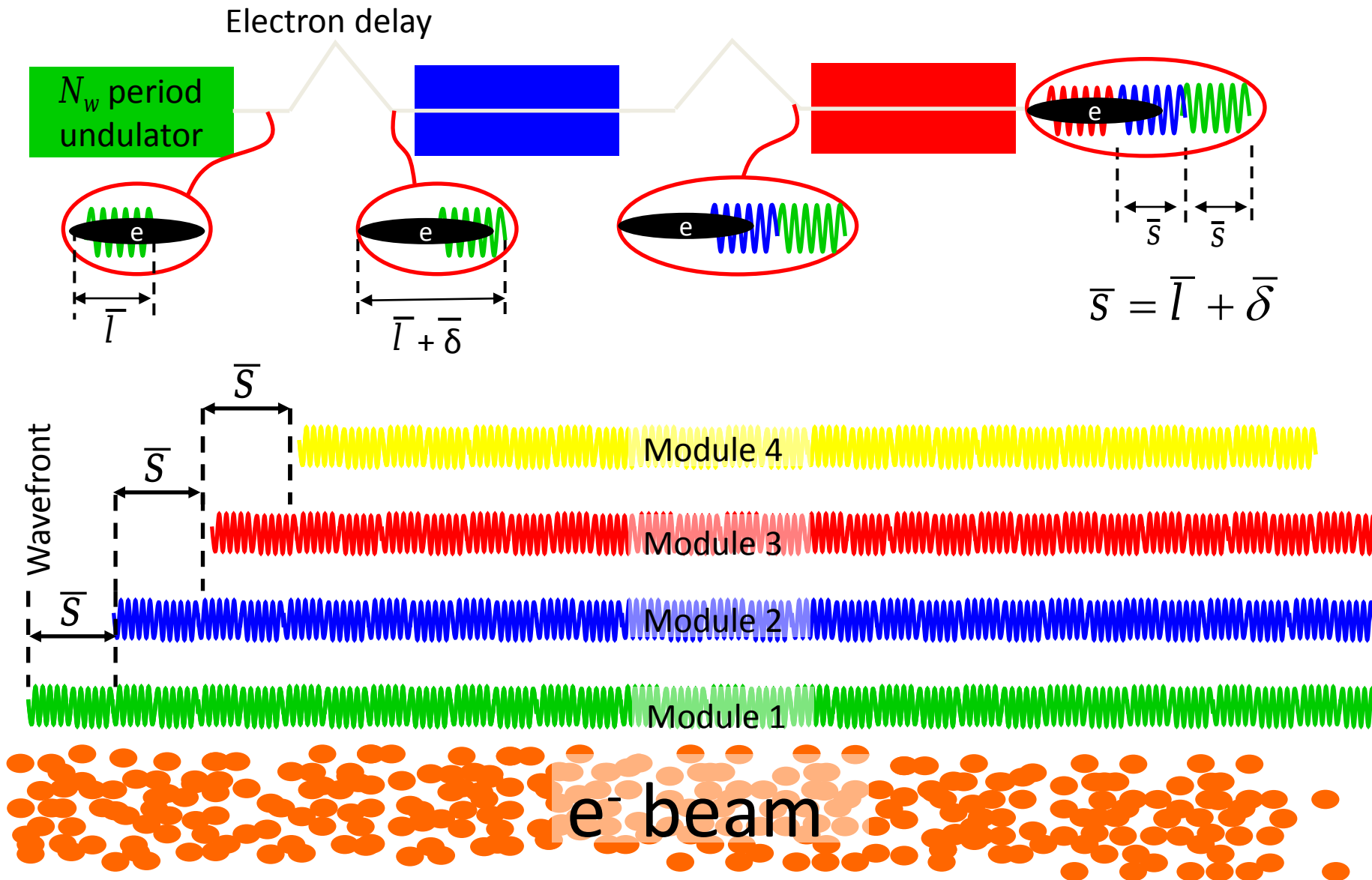
Chicanes with equal electron delays $>> \lambda_r$

Electron delay
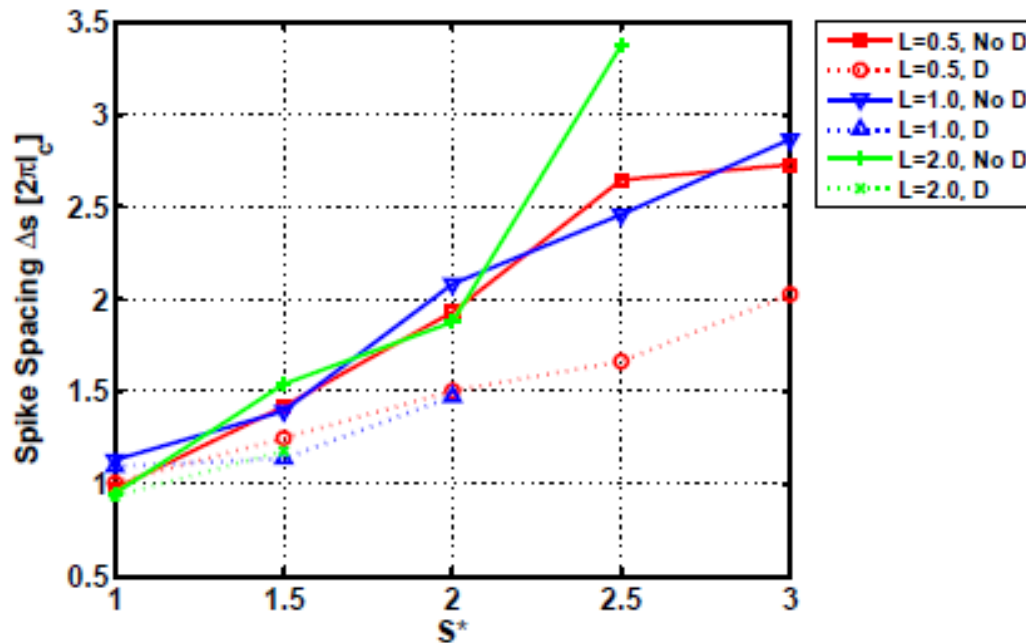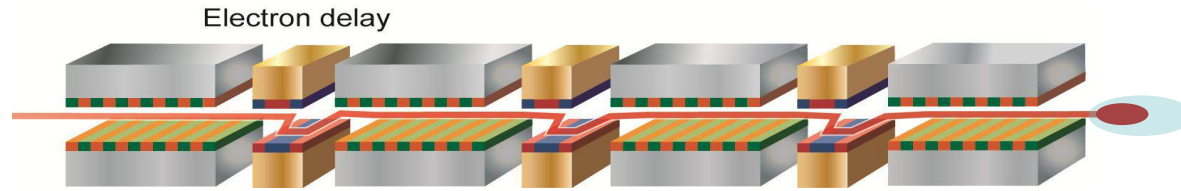
Increased cooperation length:

$$\hat{l}_c \simeq l_c S_e$$

$$S_e = (l + \delta)/l$$

Undulator slippage   Chicane slippage

Legend:
- L=0.5, No D
- L=0.5, D
- L=1.0, No D
- L=1.0, D
- L=2.0, No D
- L=2.0, D

(Plot y-axis: Spike Spacing Δs [$2\pi l_c$], x-axis: S^*)

Figure 2: The mean spacing between spikes in units of $2\pi l_c$ for rectangular electron bunch current profile, as a function of the slippage enhancement factor S^*.

Summarising:

Increasing spike separation => Increasing cooperation length
                             => Improved temporal coherence

35

Chicanes with equal electron delays $>> \lambda_r$

Figure 1: Pulse intensity profiles for a rectangular electron bunch, with undulator section length $L = 0.5$. The z-shifts are non-dispersive, with $S^* = 1$ (i.e. SASE) at the top, then $S^* = 1.5$, $S^* = 2.0$, $S^* = 2.5$. It is clear that the spikes broaden and separate as S^* increases, accompanied by the appearance of small-period oscillations. The bottom plot shows the Fourier transform of the pulse intensity for the case $S^* = 2.5$ where $\delta_c = 1.25$. It is seen that the small oscillations on the intensity plot have a period of 1.25 and that the longer scale oscillation has a period of ~ 16.5 which is close to $2\pi S^* = 15.7$.
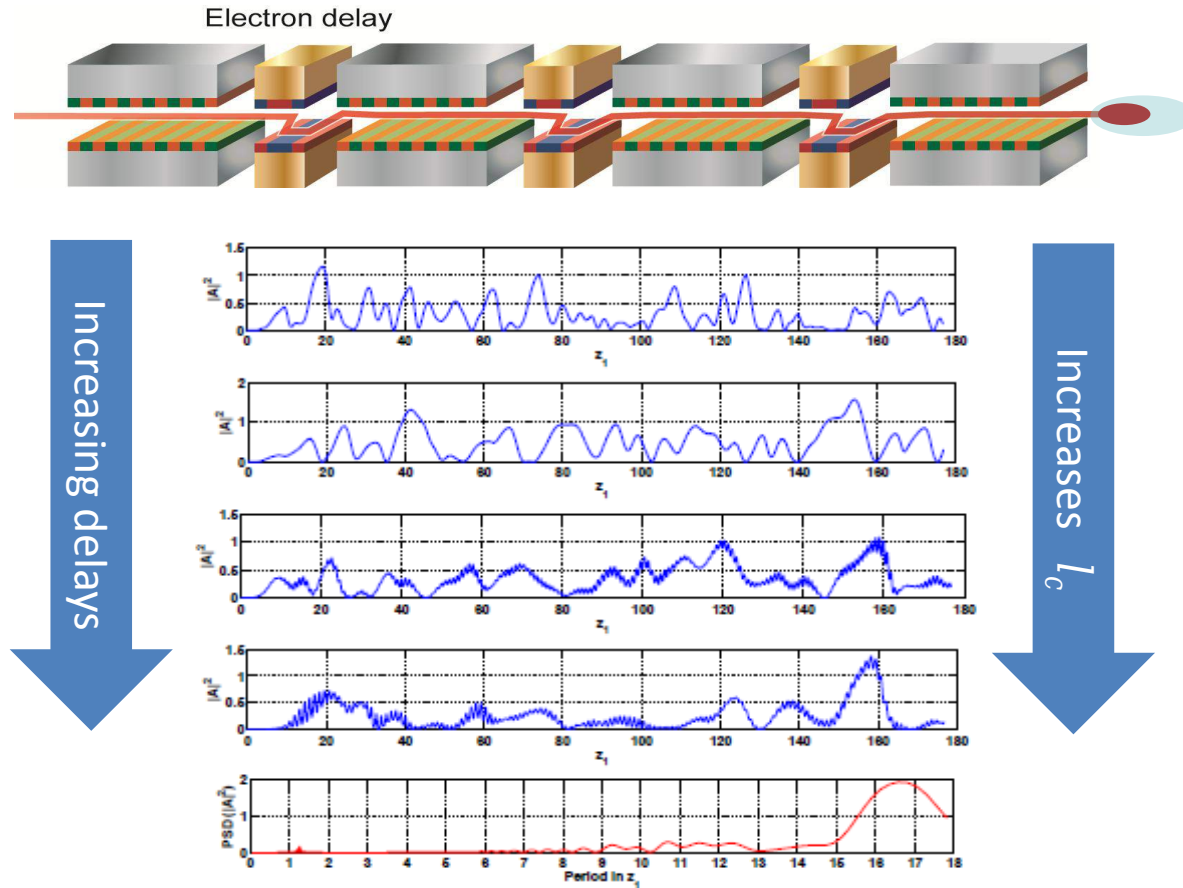
Chicanes with equal electron delays $>> \lambda_r$

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Chicanes with equal electron delays $>> \lambda_r$

Electron delay

Increasing delays

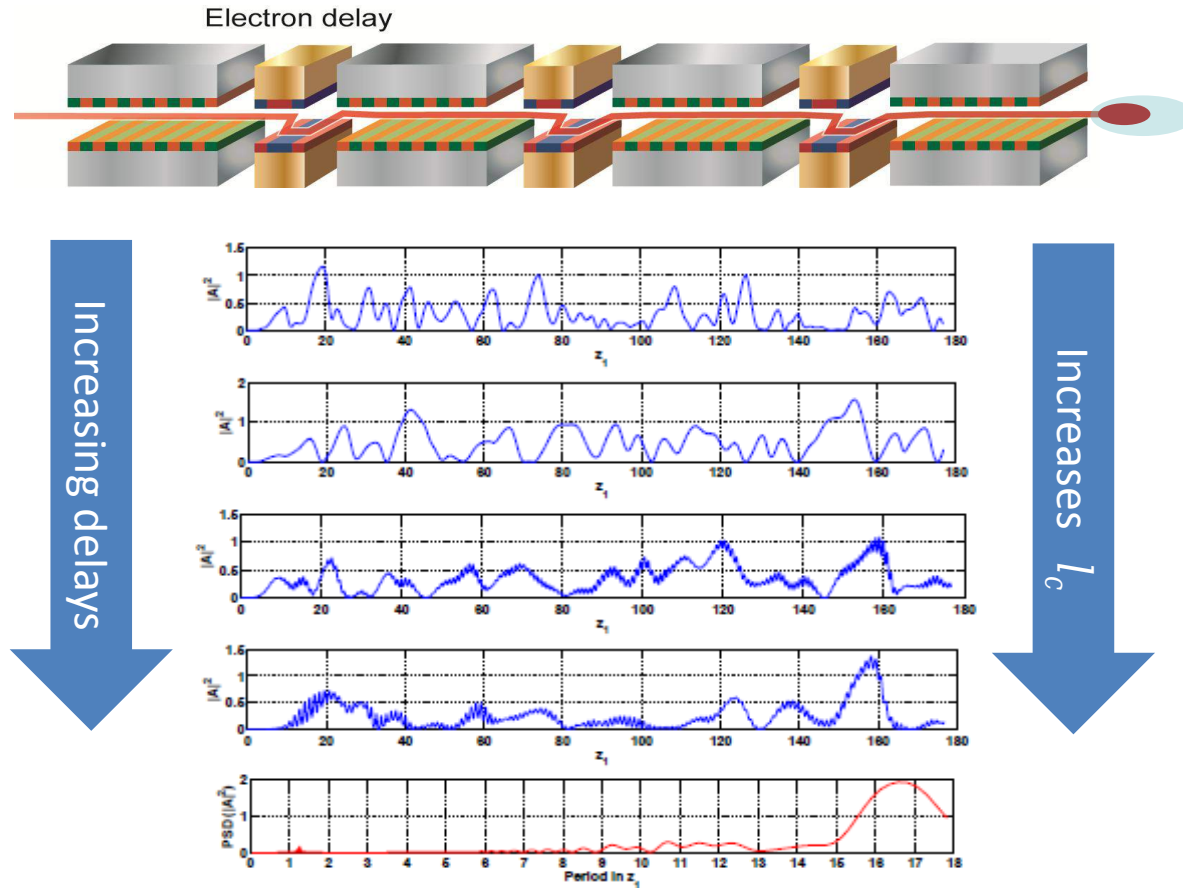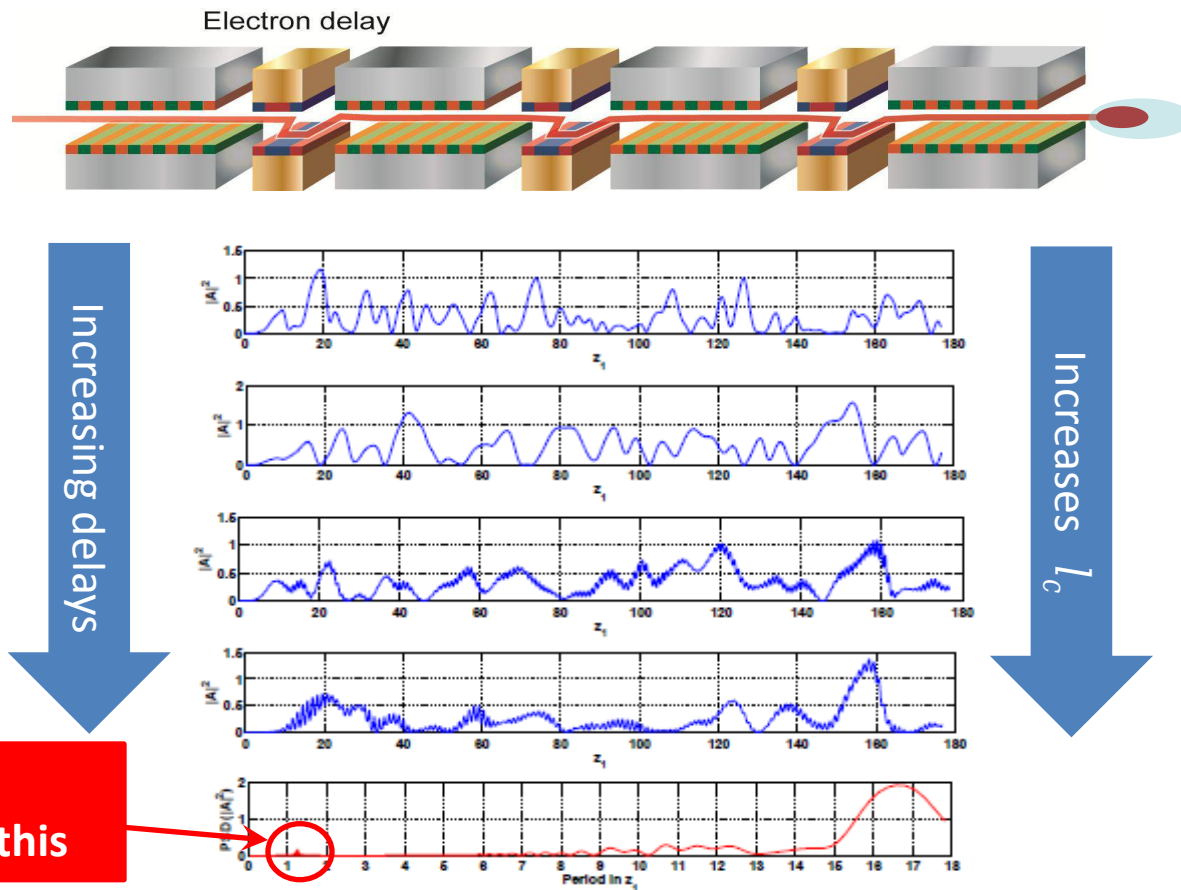Increases l_c

We became distracted by this

Some success!

Figure 1: Pulse intensity profiles for a rectangular electron bunch, with undulator section length $L = 0.5$. The z-shifts are non-dispersive, with $S^* = 1$ (i.e. SASE) at the top, then $S^* = 1.5$, $S^* = 2.0$, $S^* = 2.5$. It is clear that the spikes broaden and separate as S^* increases, accompanied by the appearance of small-period oscillations. The bottom plot shows the Fourier transform of the pulse intensity for the last $S^* = 2.5$ where $q = 1.25$. It is seen that the small oscillations on the intensity plot have a period of 1.25 and that the longer scale oscillation has a period of ~ 16.5 which is close to $2\pi S^* = 15.7$.

COHERENCE OF E-BEAM RADIATION SOURCES AND FELS –
A THEORETICAL OVERVIEW

Avi Gover, Egor Dyunin, Tel-Aviv University, Ramat Aviv, Israel.

A third scheme that should be considered for phase locking and increasing the coherence of the radiation in a SASE FEL consists of imposing periodic perturbation on the wiggler (e.g. periodic dispersive sections) [20]. The filtering effect of the periodic structure may be viewed as the analogue of linewidth narrowing of radiation emitted in a Fabri-Perot resonator. It is speculated (but needs further study) that if the SASE FEL in such a structure arrives to saturation within the wiggler length, nonlinear process of mode competition between the filtered spikes will lead to further increase of coherence and stability in analogy to the CW FEL oscillator case discussed previous.
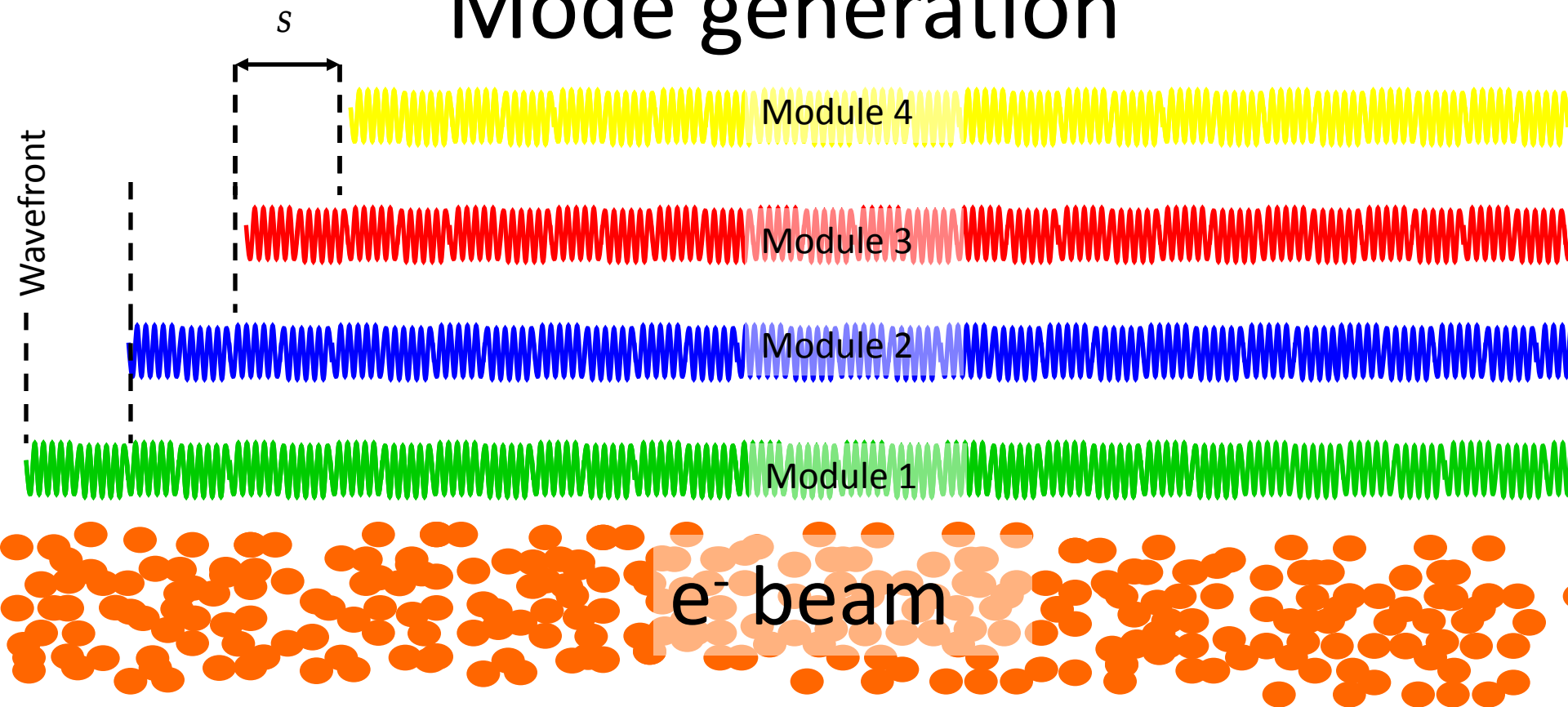
Also get 'cavity' modes

Linear process

Clearly thinking along the same lines, but did not pursue further?
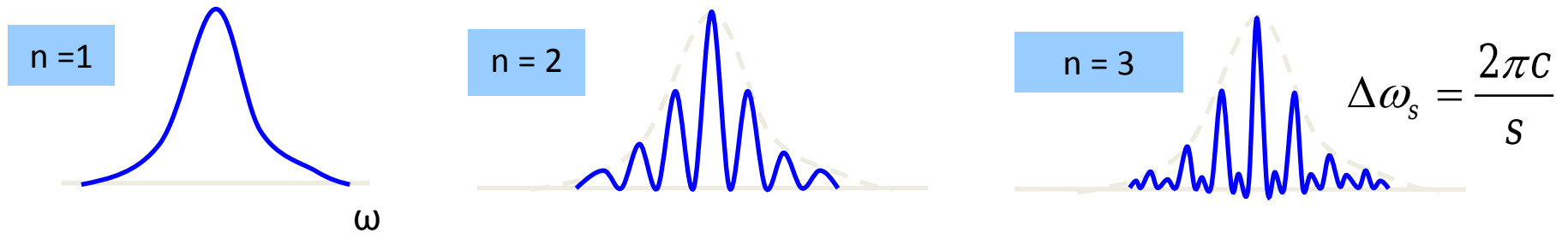
Generating Modes

Mode generation
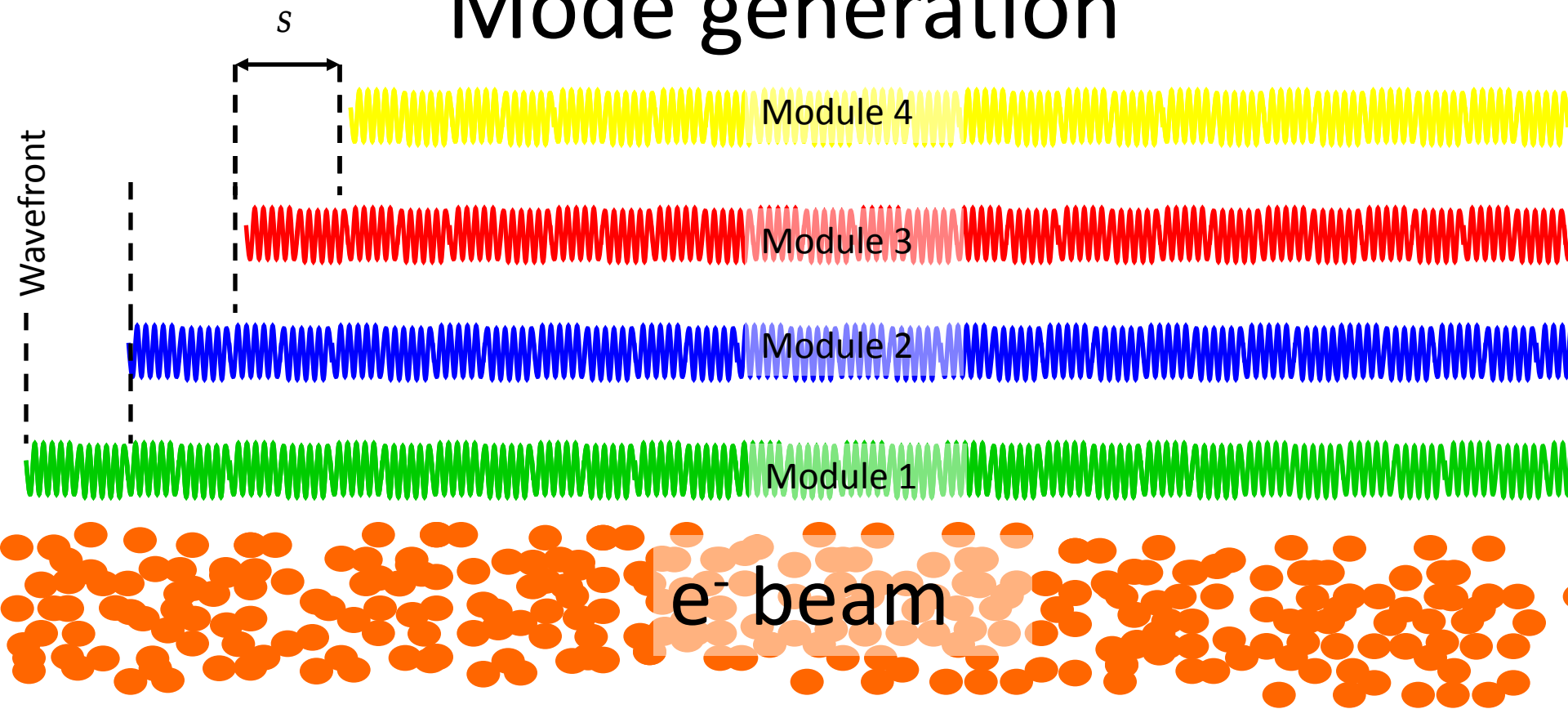

For continued slips of distance s, only those wavelengths with an integer number of periods in distance s will survive after many such slips. For s an integer of λ_j:

$$s = N\lambda_j = (N+1)\lambda_{j-1}$$

$$\Rightarrow \omega_j = \frac{2\pi c N}{s}; \omega_{j-1} = \frac{2\pi c(N+1)}{s} \quad \Rightarrow \Delta\omega_s = \omega_{j-1} - \omega_j = \frac{2\pi c}{s}$$

Mode generation

s

Wavefront

Module 4

Module 3

Module 2

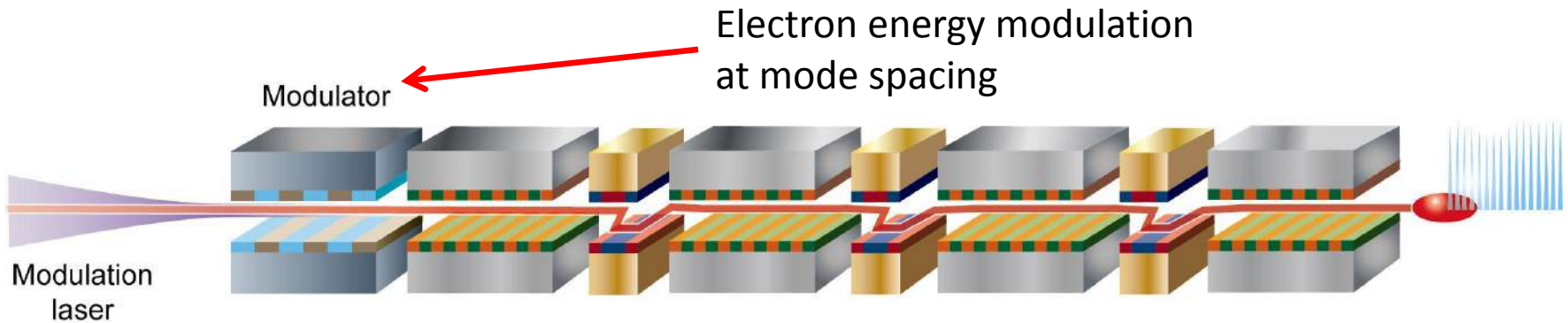Module 1

e⁻ beam

n = 1

n = 2

n = 3

$$\Delta\omega_s = \frac{2\pi c}{s}$$

ω

The spectrum is the same as a ring cavity of length S. A ring cavity of length equal to the total slippage in each undulator/chicane module has been synthesized
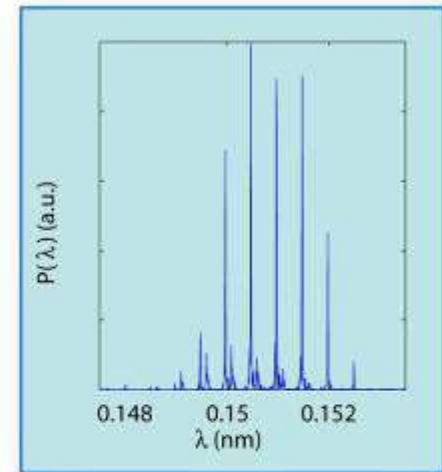
39

X-ray FEL amplifier with mode-locking*

Electron energy modulation at mode spacing

*Thompson, McNeil, PRL **100,** 203901 (2008)
Kur, Dunning, McNeil, Wurtele & Zholents, NJP **13**, 063012 (2011)

X-ray FEL amplifier with mode-locking*
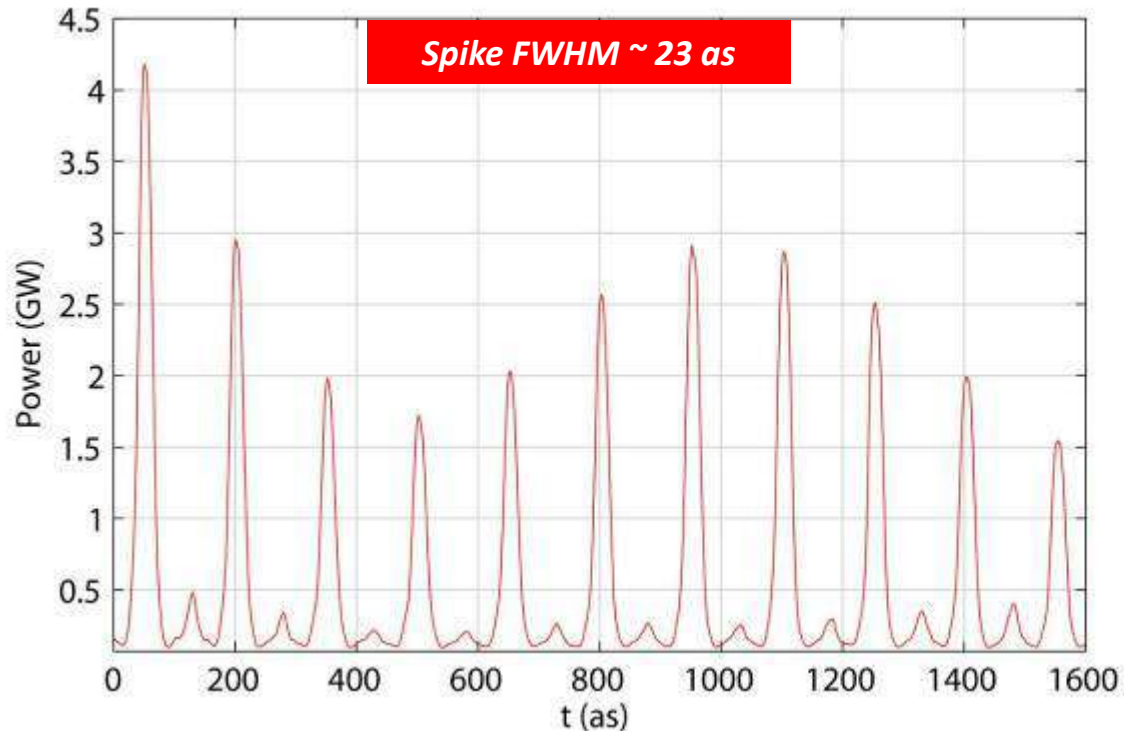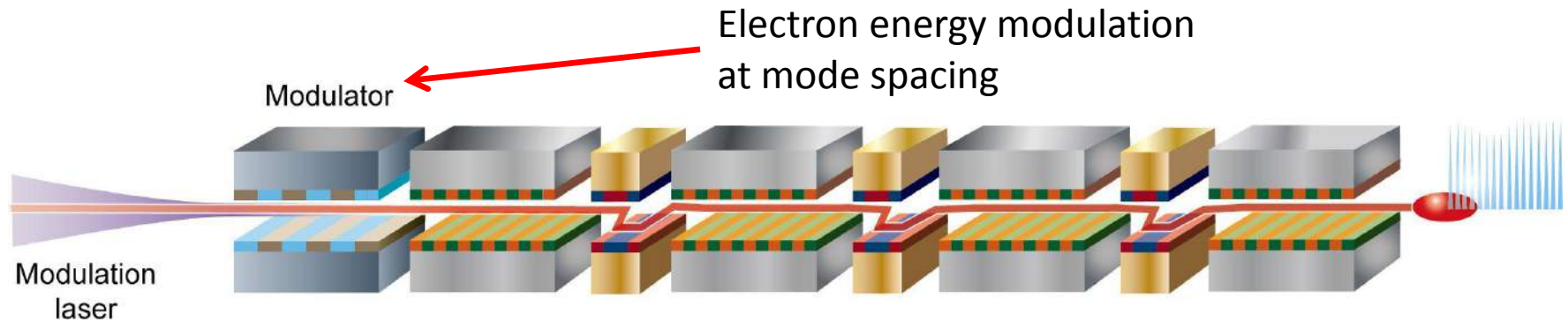
Electron energy modulation at mode spacing

Modulator

Modulation laser
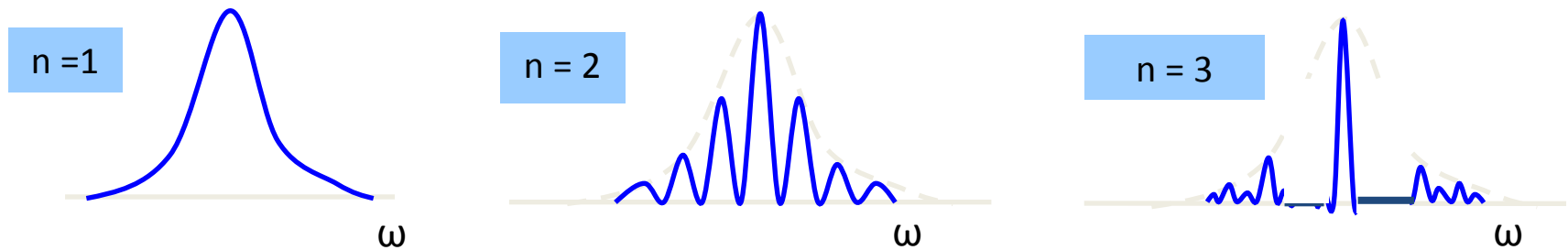
Spike FWHM ~ 23 as

*Thompson, McNeil, PRL **100,** 203901 (2008)
  Kur, Dunning, McNeil, Wurtele & Zholents, NJP **13**, 063012 (2011)

Removing the modes

Different chicane delays* introduce **different** integer resonant wavelength delay to e⁻:

$$\Rightarrow \Delta\omega_s = \frac{2\pi c}{s_n}$$ is different for each module, to leave

only the central resonant wavelength.

$< l_g$ $< l_g$ $< l_g$

n =1   n = 2   n = 3

ω   ω   ω
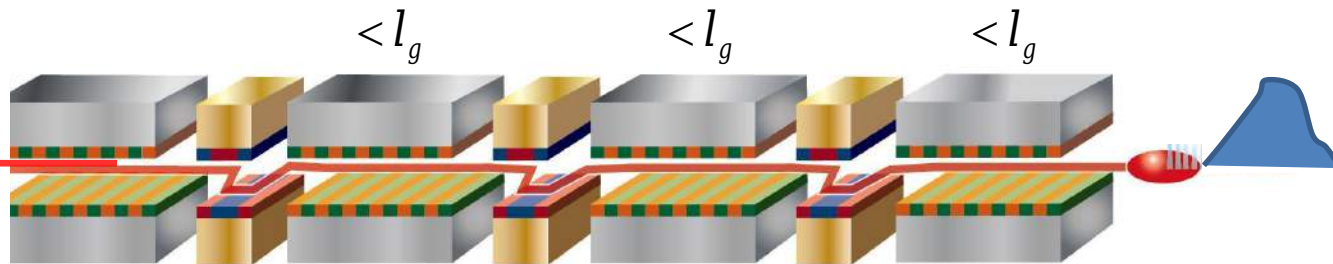
*Thompson, Dunning & McNeil, '*Improved temporal coherence in SASE FELs*', **TUPE050**, Proceedings of IPAC'10, Kyoto, Japan

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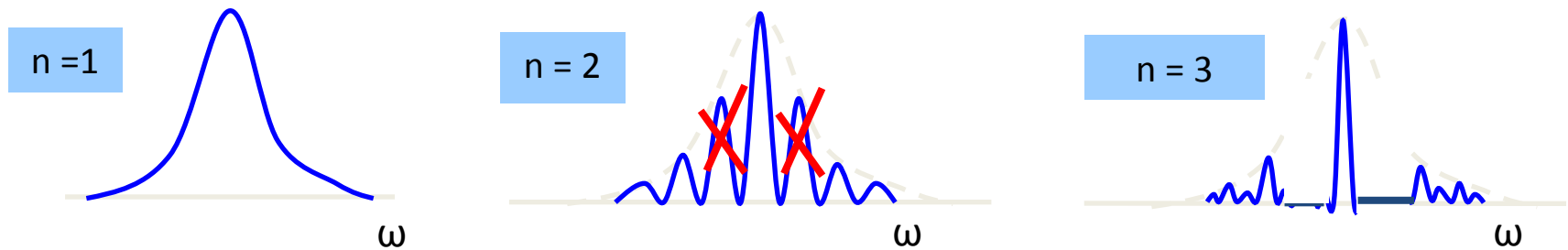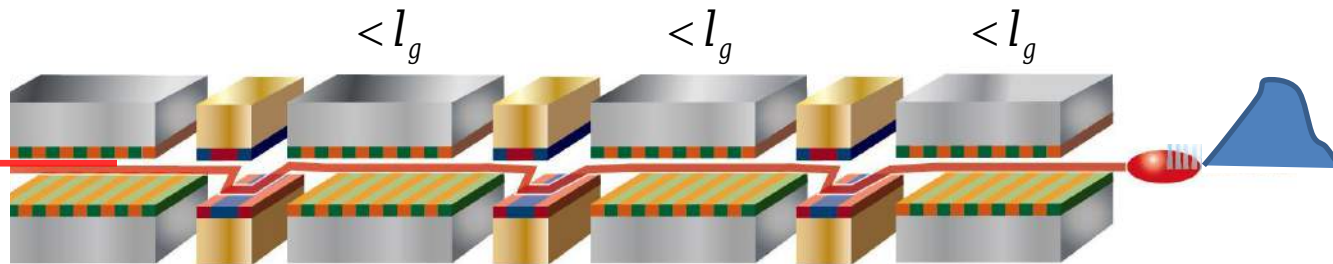
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*Thompson, Dunning & McNeil, '*Improved temporal coherence in SASE FELs*', **TUPE050**, Proceedings of IPAC'10, Kyoto, Japan

High-Brightness SASE – Stage I*

IMPROVED TEMPORAL COHERENCE IN SASE FELS

N.R. Thompson and D. J. Dunning, ASTeC/CI, STFC Daresbury Laboratory, UK
B. W. J. McNeil, University of Strathclyde, Scotland, UK

Electron delay $< l_g$ $< l_g$ $< l_g$
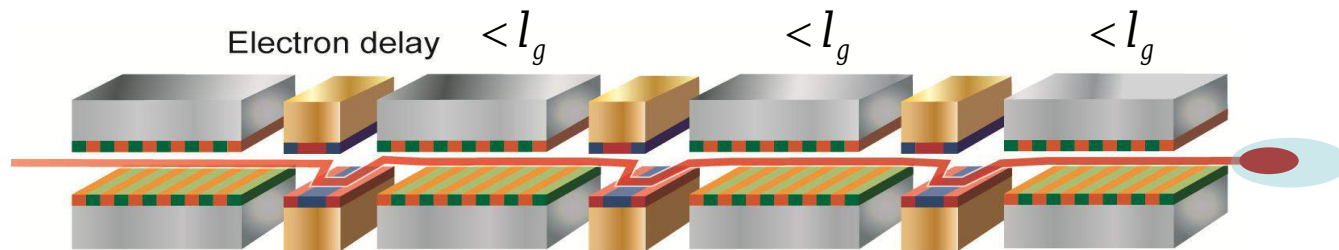
To remove the modes , a randomness in the chicane delays was introduced :

$$\bar{\delta}_n = \bar{\delta} + \bar{\delta}_r$$

where: $\bar{\delta}$ is a constant and $\bar{\delta}_r$ is a uniform random variate $\left|\bar{\delta}_r\right| < \bar{\delta}$

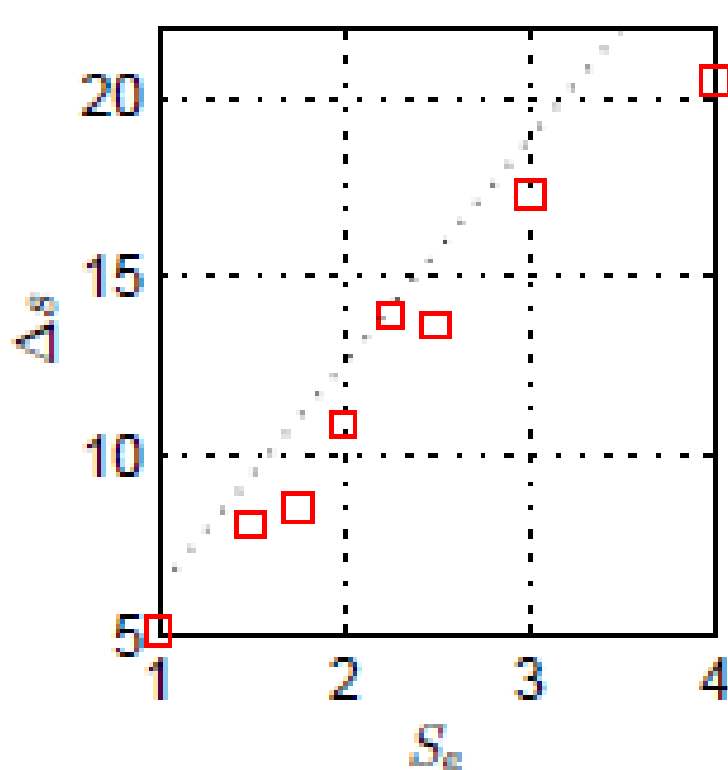# High-Brightness SASE – Stage I*

IMPROVED TEMPORAL COHERENCE IN SASE FELS

N.R. Thompson and D. J. Dunning, ASTeC/CI, STFC Daresbury Laboratory, UK
B. W. J. McNeil, University of Strathclyde, Scotland, UK
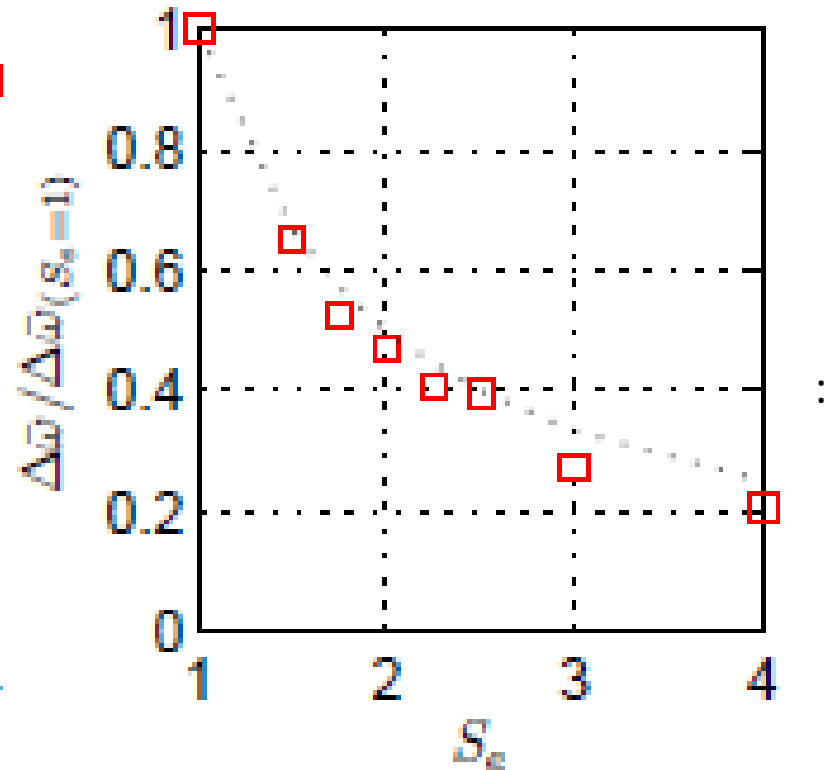
Mean spike spacing   Bandwidth reduction

High-Brightness SASE – Stage II

– The following results are for a delay sequence based on *Prime Numbers,* as a method of prohibiting the sidebands:

As the frequency spacing of the axial modes is inversely proportional to the delay s:

- ***no common supported sidebands between any two delays***

- The prime delay sequence is defined as

$$\bar{s}_n = \mathbb{P}_n \bar{s}_1/2 \qquad \mathbb{P}_n \text{ is sequence of primes beginning with } \mathbb{P}_1 = 2$$

- Setting s_1 scales the whole sequence.

Transform-Limited X-Ray Pulse Generation from a High-Brightness Self-Amplified Spontaneous-Emission Free-Electron Laser

B. W. J. McNeil,[1,*] N. R. Thompson,[1,2,†] and D. J. Dunning[1,2,‡]

[1]*University of Strathclyde (SUPA), Glasgow G4 0NG, United Kingdom*
[2]*ASTeC, Daresbury Laboratory, Warrington WA4 4AD, United Kingdom*
(Received 23 December 2012; published 26 March 2013)

– The following results are for a delay sequence based on *Prime Numbers,* as a method of prohibiting the sidebands:

As the frequency spacing of the axial modes is inversely proportional to the delay s:
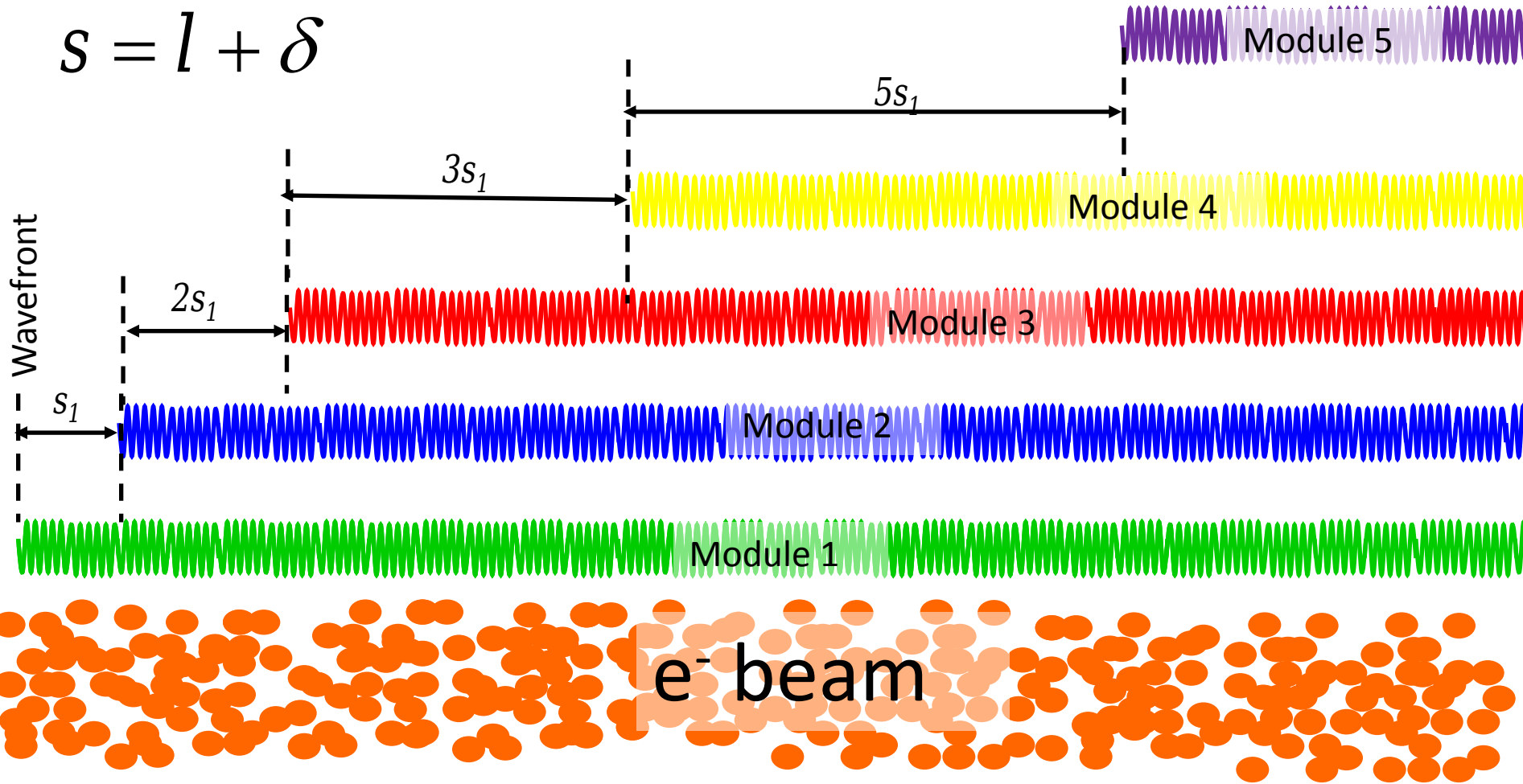
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- Setting s_1 scales the whole sequence.

HB-SASE Mechanism I

$$s = l + \delta$$

Module 5

Module 4

Module 3

Module 2

Module 1

$5s_1$

$3s_1$

$2s_1$

s_1

Wavefront

e⁻ beam

Undulator modules have lengths $l_g \lesssim 1$

Radiation wavefronts then propagate $\lesssim l_c$ through electrons in each module

Due to extra slippage , no radiation wavefront propagates through electrons within local range l_c in successive undulators – NO LOCALISED COOPERATIVE EFFECTS
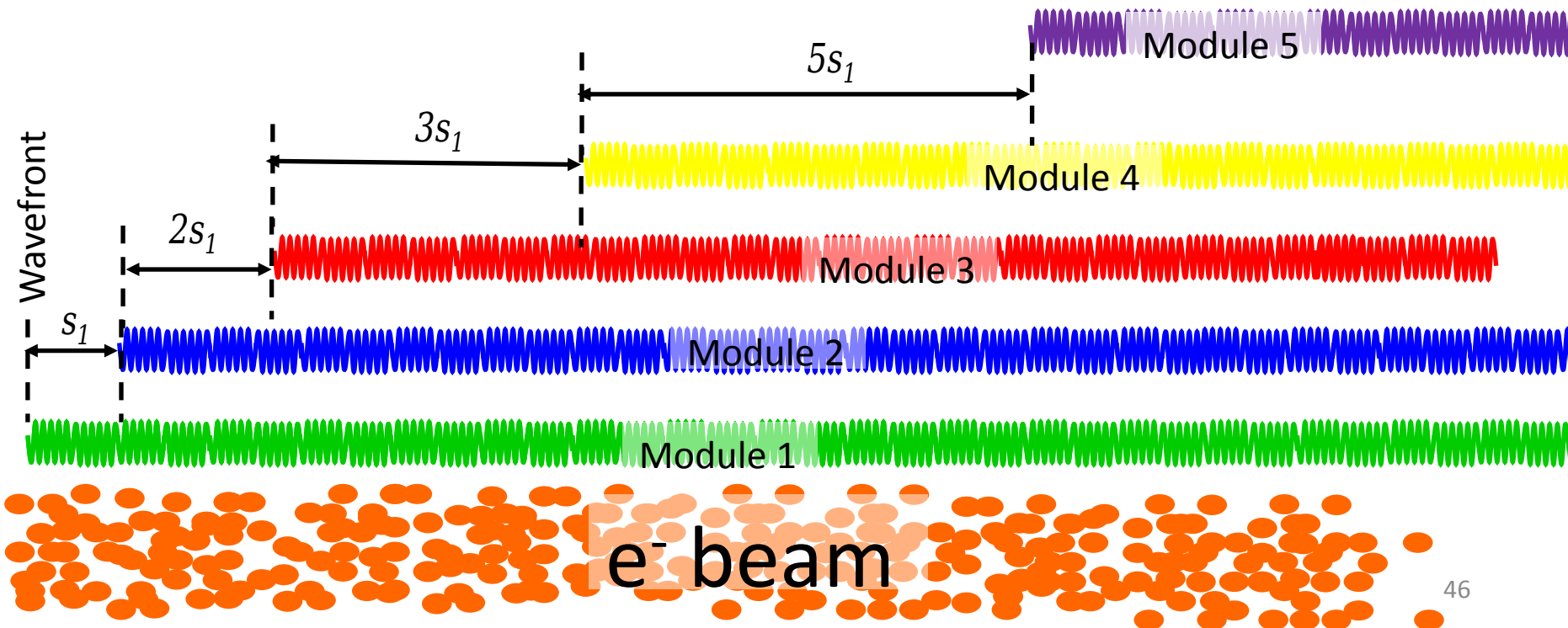
45

HB-SASE Mechanism II

From Maxwell's wave equation:

$$\frac{da}{d\bar{z}} = \langle \cos(\theta + \phi) \rangle; \quad \frac{d\phi}{d\bar{z}} = -\frac{1}{a}\langle \sin(\theta + \phi) \rangle$$

The phase can adapt rapidly in linear regime due to the $1/a$ term.

The phase coherence propagates rapidly at the enhanced slippage rate throughout the pulse

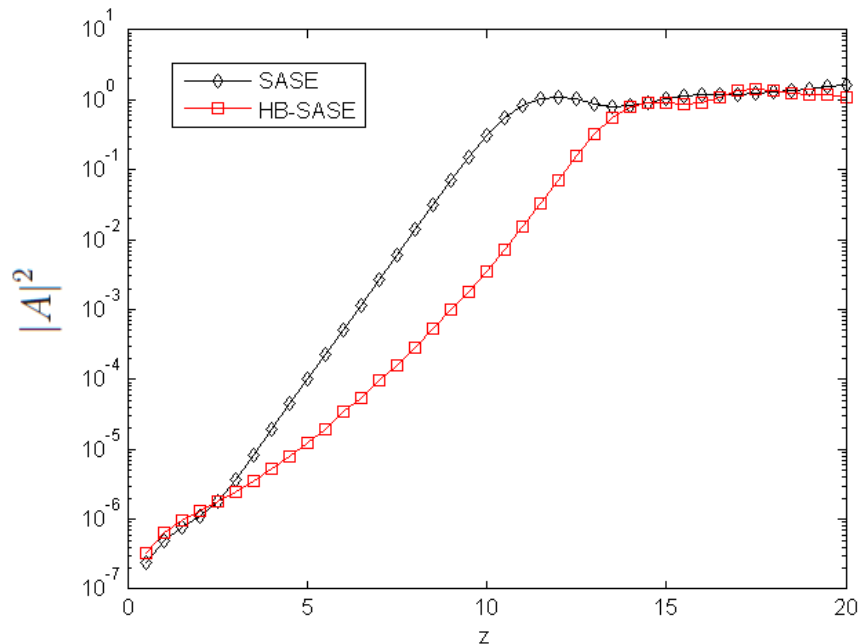# HB-SASE: Simulation Results, Long Pulse, Scaled Units

- Constant current, l_e = 4000, module length l = 0.5, delay sequence with $s_1 = 4l$
- Coherence length calculated using:

$$\bar{l}_{coh} = \int |g(\bar{\tau}_1)|^2 d\bar{\tau}_1 \qquad g(\bar{\tau}_1) = \frac{\langle A^*(\bar{z}_1) A(\bar{z}_1 + \bar{\tau}_1) \rangle}{\langle A^*(\bar{z}_1) A(\bar{z}_1) \rangle}$$

HB-SASE: Simulation Results, Long Pulse, Scaled Units

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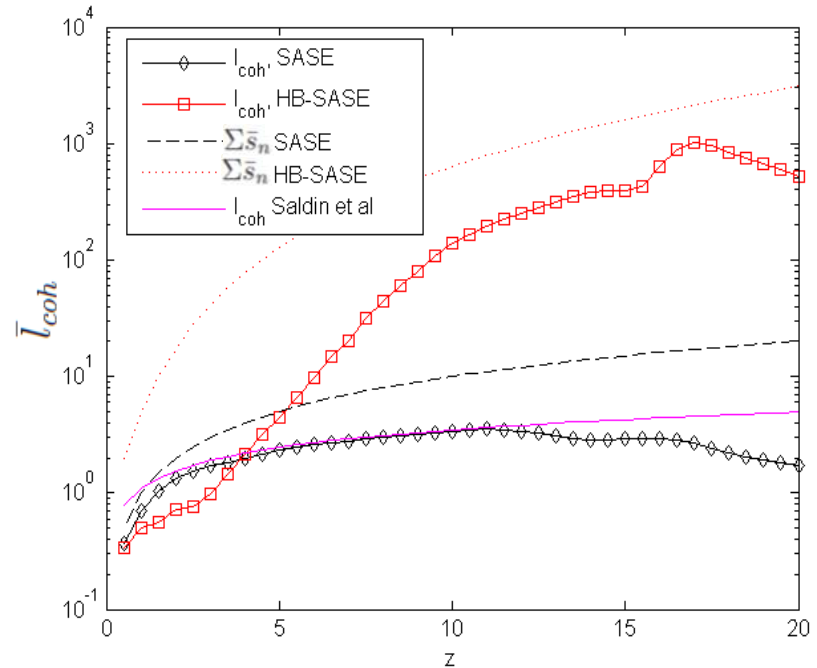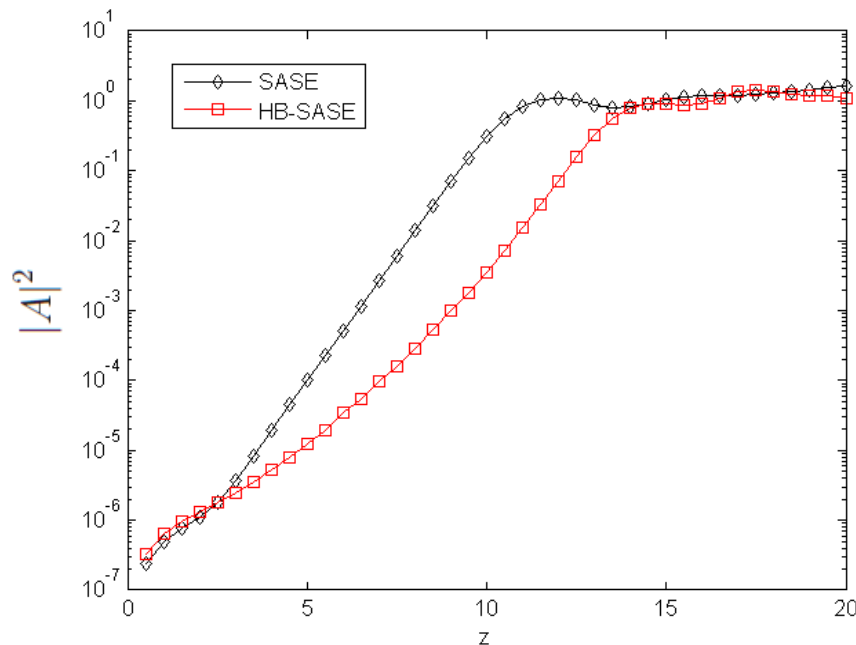
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- Constant current, l_e = 4000, module length l = 0.5, delay sequence with $s_1 = 4l$
- Coherence length calculated using:

$$\bar{l}_{coh} = \int |g(\bar{\tau}_1)|^2 d\bar{\tau}_1 \qquad g(\bar{\tau}_1) = \frac{\langle A^*(\bar{z}_1)A(\bar{z}_1 + \bar{\tau}_1)\rangle}{\langle A^*(\bar{z}_1)A(\bar{z}_1)\rangle}$$
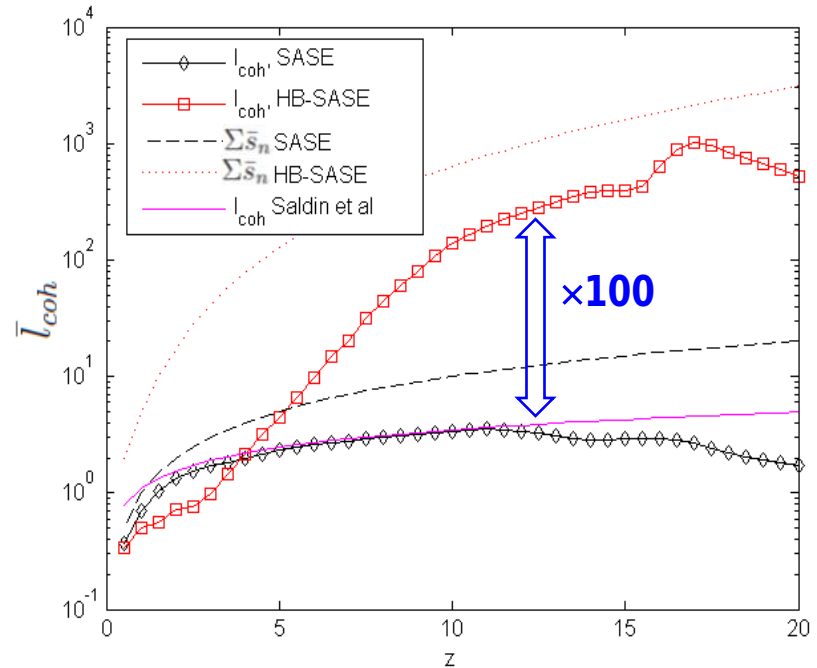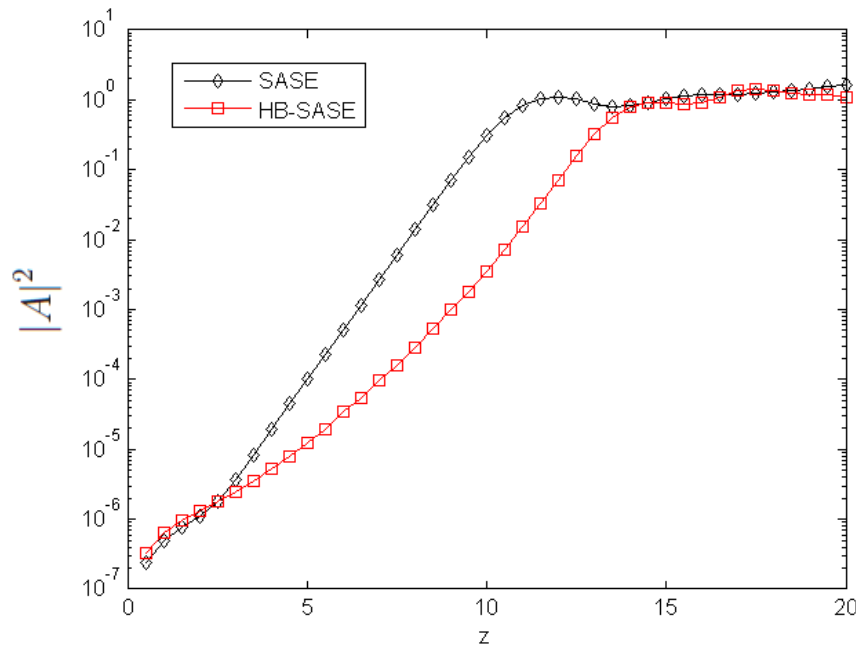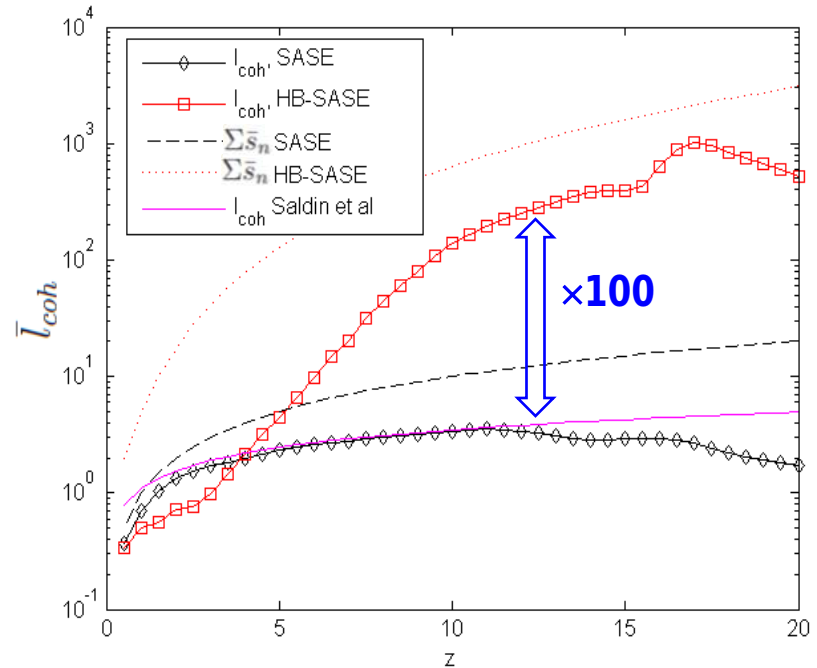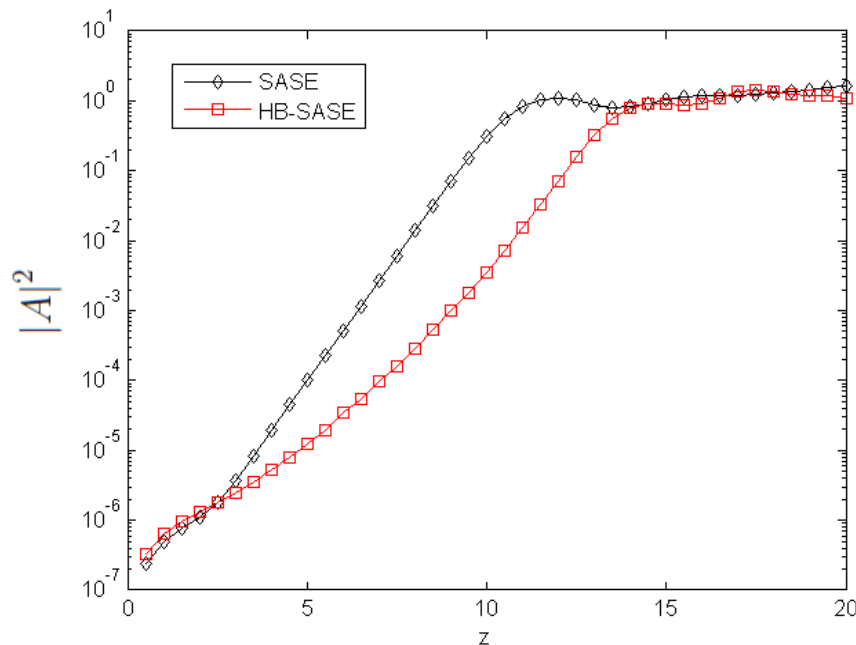
HB-SASE: Simulation Results, Long Pulse, Scaled Units

- Constant current, l_e = 4000, module length l = 0.5, delay sequence with $s_1 = 4l$
- Coherence length calculated using:

$$\bar{l}_{coh} = \int |g(\bar{\tau}_1)|^2 d\bar{\tau}_1 \qquad g(\bar{\tau}_1) = \frac{\langle A^*(\bar{z}_1)A(\bar{z}_1 + \bar{\tau}_1)\rangle}{\langle A^*(\bar{z}_1)A(\bar{z}_1)\rangle}$$

	$\bar{L}_{sat}$	$\bar{l}_{coh}$	$\bar{\sigma}_{\bar{\omega}}$	$\bar{l}_{coh} \times \bar{\sigma}_{\bar{\omega}}$
SASE	12.0	3.4	0.5	$1.7\,(\simeq \sqrt{\pi})$
HB-SASE	14.5	393	0.0045	$1.8\,(\simeq \sqrt{\pi})$

HB-SASE Vs SASE: Comparison of Coherence Development

- ## *SASE*
  - Coherence length evolves little after first three gain lengths, reaching half its saturation value by $\bar{z} = 3$, and always grows **more slowly** than the accumulated slippage

- ## *HB-SASE*
  - Coherence length evolves more slowly for first three gain lengths, **then grows exponentially**
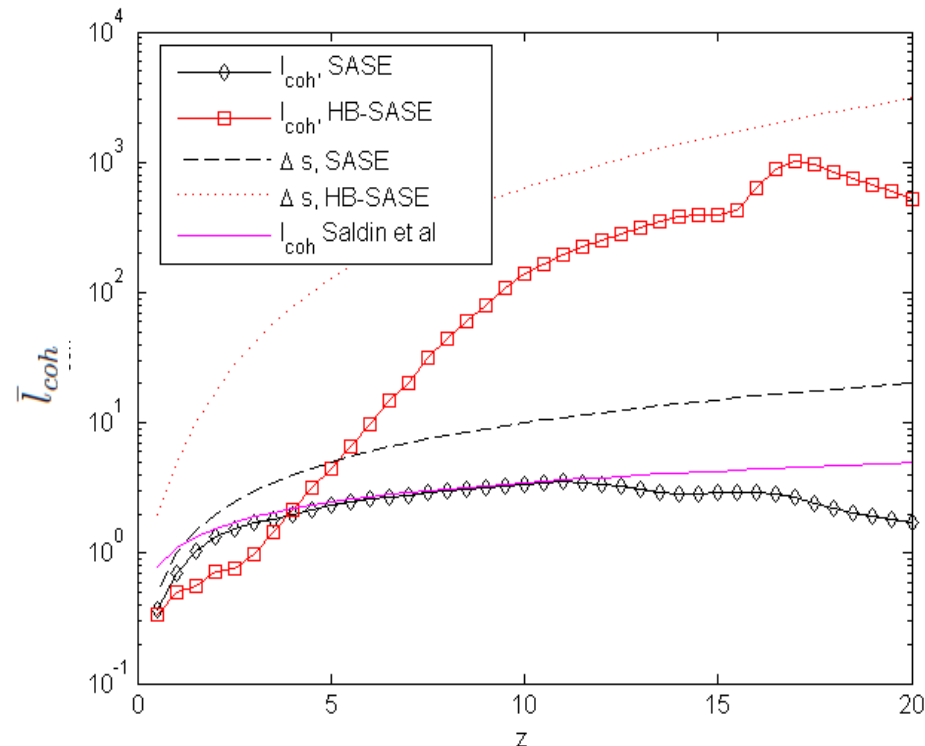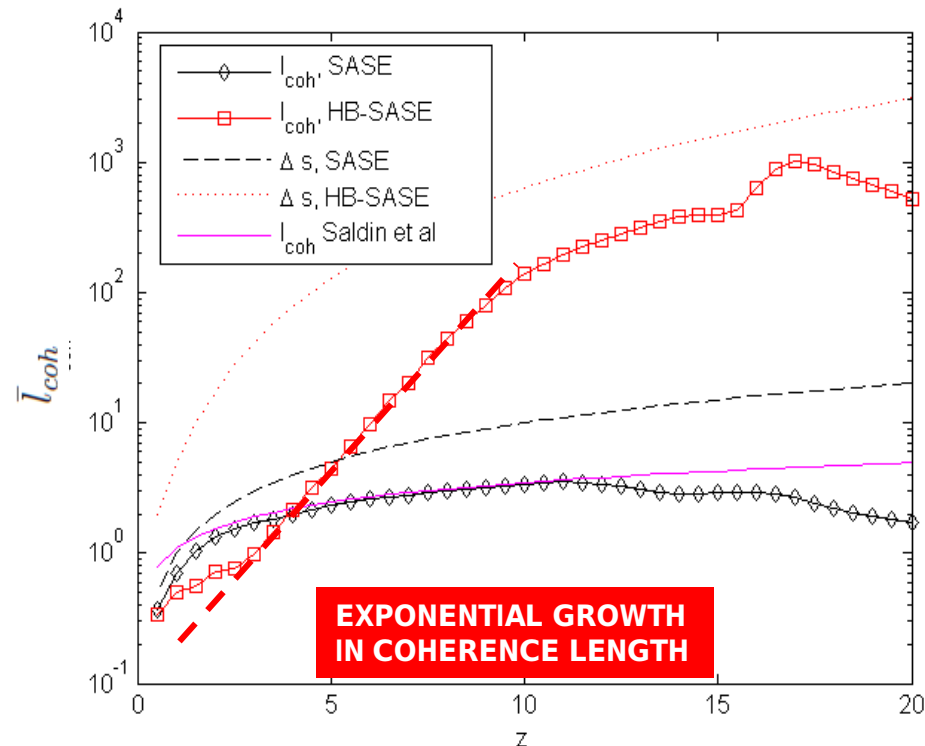
HB-SASE Vs SASE: Comparison of Coherence Development

▶ **SASE**

  ▸ Coherence length evolves little after first three gain lengths, reaching half its saturation value by $\bar{z} = 3$, and always grows **more slowly** than the accumulated slippage

▶ **HB-SASE**

  ▸ Coherence length evolves more slowly for first three gain lengths, **then grows exponentially**

HB-SASE Spectrum for simulation in soft X-ray at 1.24 nm*

FIG. 3: Comparison of linear theory predictions of FEL spectra with simulation results, for the output after 3 modules (top) and 25 modules (bottom). Note the The x-axis range is adjusted on the bottom plot for clarity.

*McNeil, Thompson and Dunning, Phys. Rev. Lett., **110**, 134802 (2013)

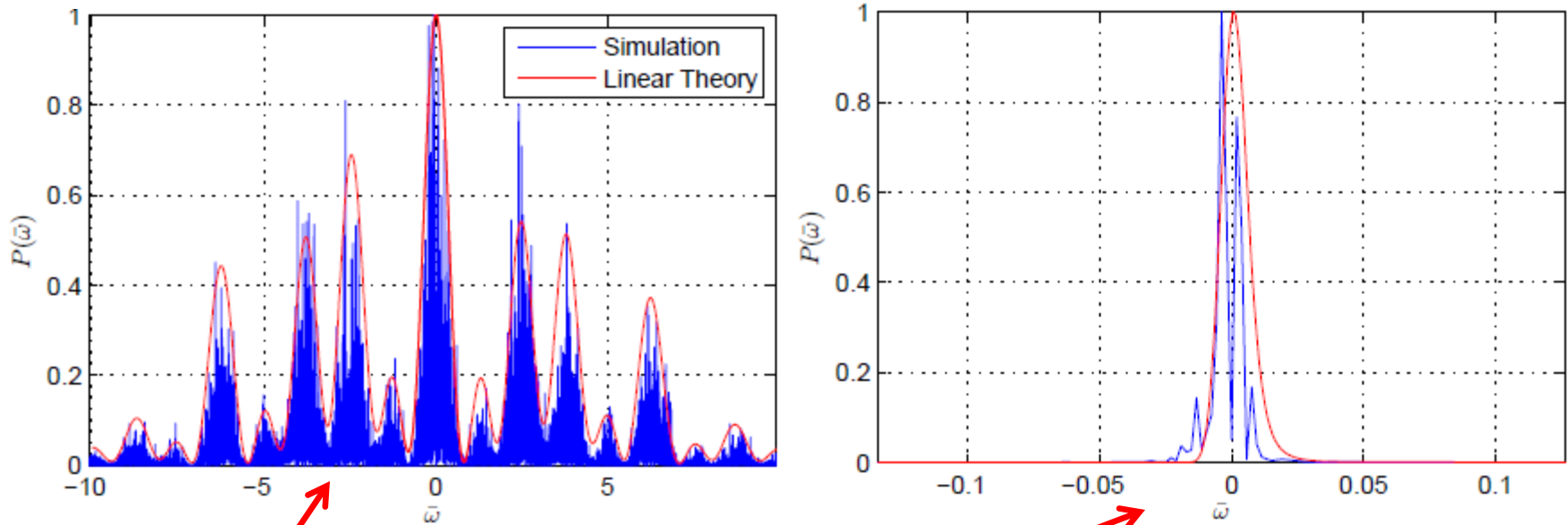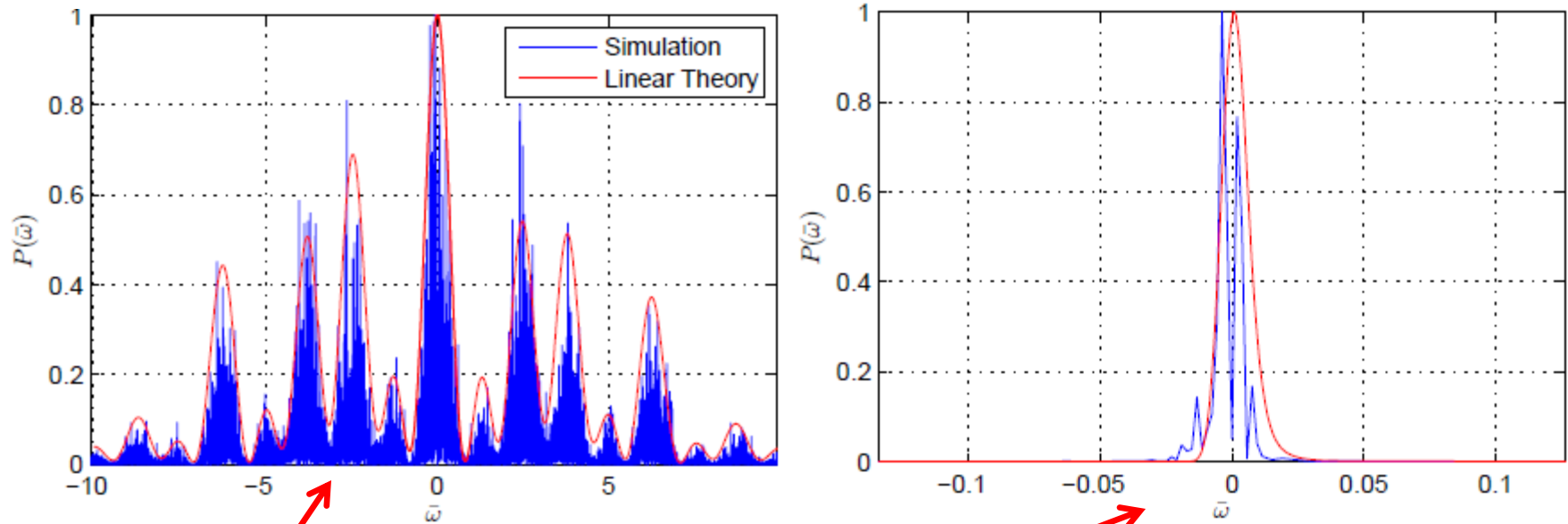# HB-SASE Spectrum for simulation in soft X-ray at 1.24 nm*

FIG. 3: Comparison of linear theory predictions of FEL spectra with simulation results, for the output after 3 modules (top) and 25 modules (bottom). Note the The x-axis range is adjusted on the bottom plot for clarity.

The system of shifts acts like a 'distributed monochronometer'.

*McNeil, Thompson and Dunning, Phys. Rev. Lett., **110**, 134802 (2013)

SASE & HB-SASE comparison*
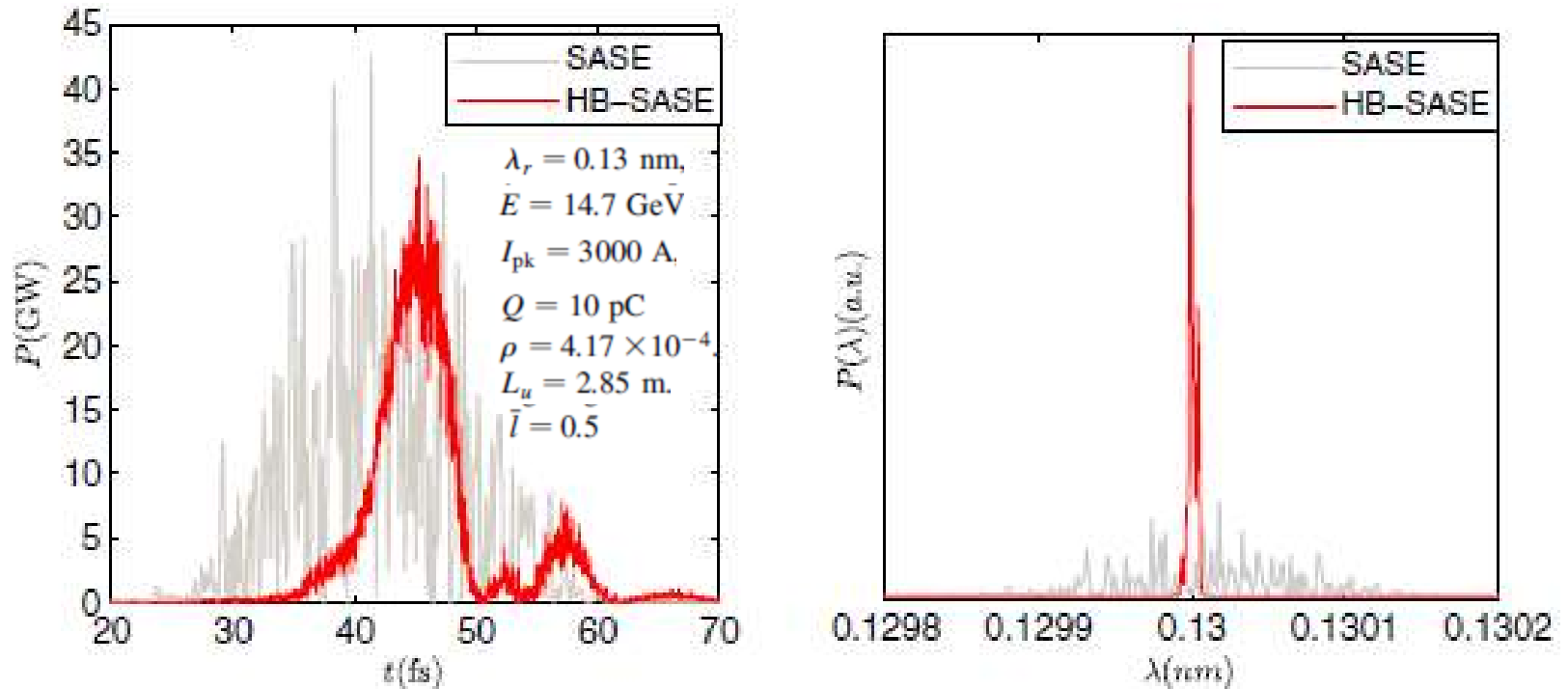
FIG. 3 (color online). Hard x-ray example at $\lambda_r = 0.13$ nm: the pulse profiles and spectra of SASE and HB-SASE.

SASE: $\Delta\nu\Delta t = 32$ Poor temporal coherence

HB-SASE: $\Delta\nu\Delta t = 0.85$ Excellent temporal coherence

*McNeil, Thompson and Dunning, Phys. Rev. Lett., **110**, 134802 (2013)

HB-SASE: 1.24nm Soft X-Ray Example

▶ **Parameters:** λ = 1.24nm, E = 2.25 GeV, I_{pk} = 1200 A, Q = 200 pC, ρ = 8.8×10⁻⁴
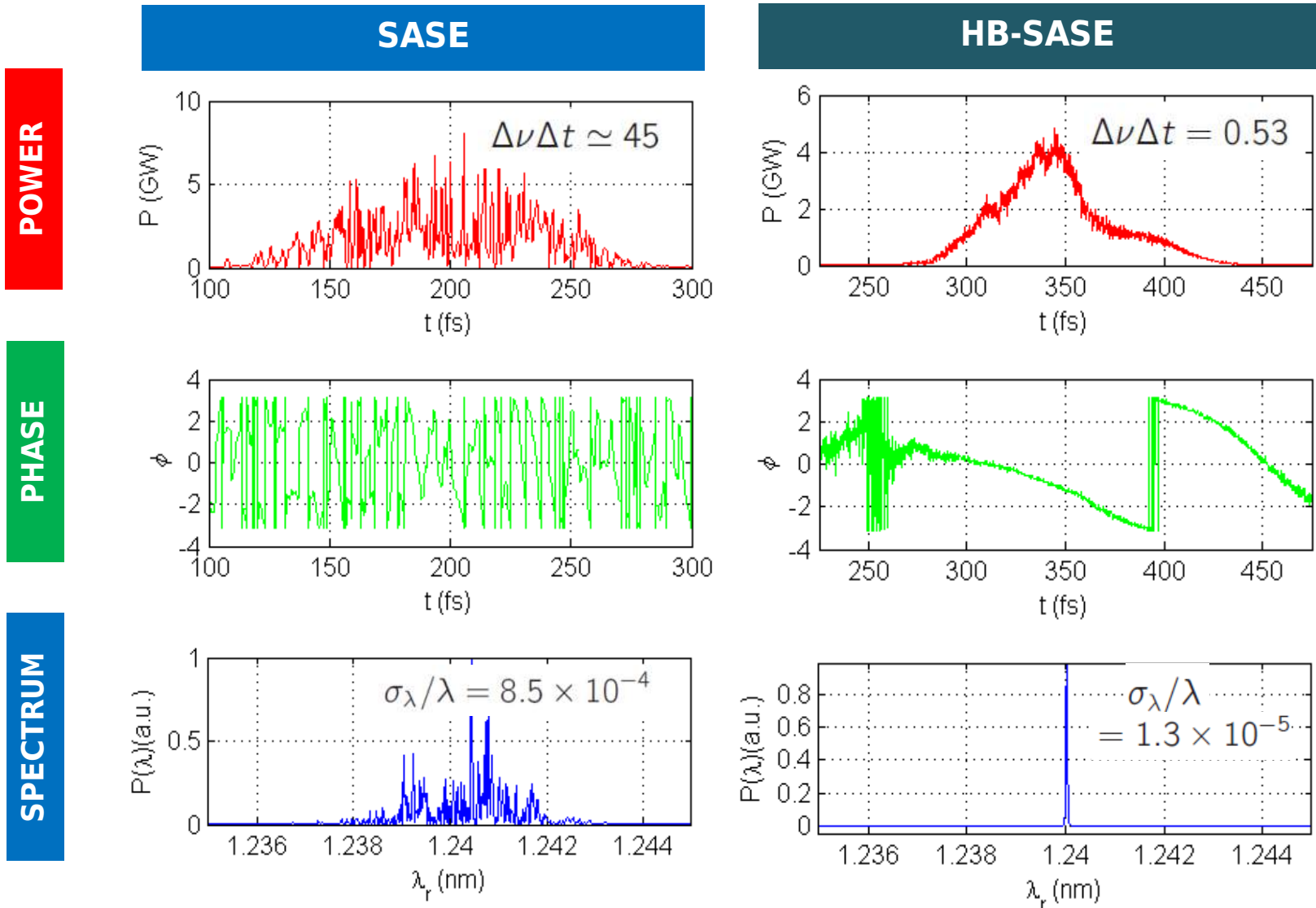
Very Related Research - iSASE

GENERATION OF LONGITUDINALLY COHERENT ULTRA HIGH POWER X-RAY FEL PULSES BY PHASE AND AMPLITUDE MIXING*

J. Wu[#], SLAC, Menlo Park, CA 94025, USA

A. Marinelli, UCLA, Los Angeles, California 90095-1547, USA

C. Pellegrini, UCLA, Los Angeles, CA 90095-1547, USA, SLAC, Menlo Park, CA 94025, USA

- *iSASE (Improved SASE)*
  - Chicanes used to delay electron bunches between undulator modules
  - Proposed a *Geometric* sequence of increasing delays
  - **Good temporal coherence (~constant phase) enables efficiently tapered undulator for ultra-high peak power – predict TW-level powers**
  - Proof-of-principle experiment on LCLS over a limited parameter range, using detuned undulators as delay sections, showed a threefold reduction in SASE linewidth, in agreement with expectation for the parameters used.
  - Demonstrated stability to electron beam energy jitter

Very Related Research - iSASE

GENERATION OF LONGITUDINALLY COHERENT ULTRA HIGH POWER X-RAY FEL PULSES BY PHASE AND AMPLITUDE MIXING*

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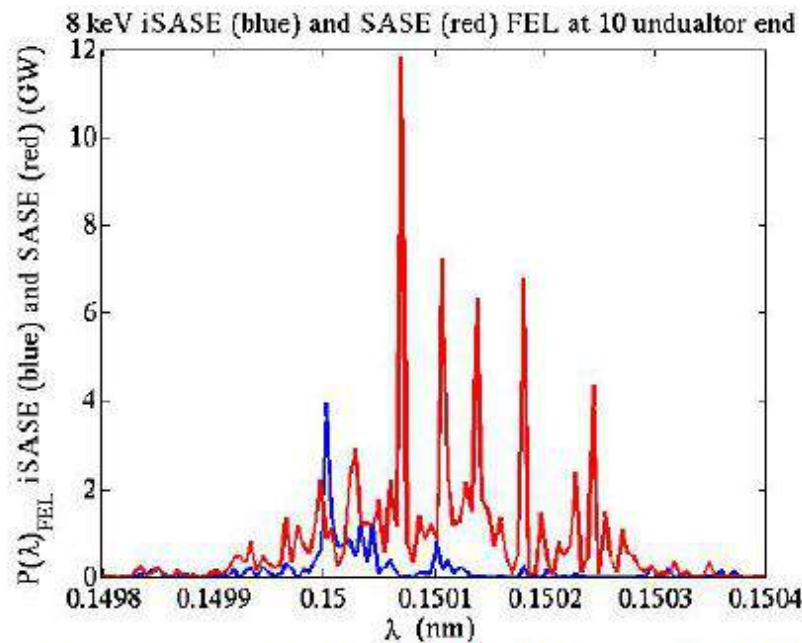
Figure 3: Spectrum of iSASE (blue) and SASE (red) radiation after 10 undulator modules. iSASE FWHM bandwidth is 5.1E-05, compared to 1.5E-03 for SASE.
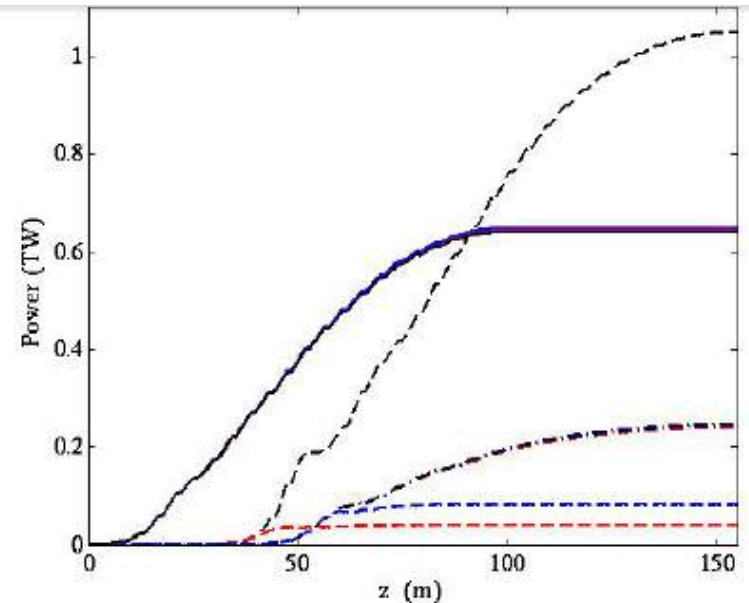
Figure 5: FEL power gain curve variation for a ±0.1 % energy jitter: on-energy (black), 0.1 % (red), and -0.1 % (blue), and SASE (dash-dotted), iSASE (solid), and Self-seeding (dashed).

52

Experiment!

X-RAY SPECTRA AND PEAK POWER CONTROL WITH ISASE*

J. Wu[†], C. Pellegrini, A. Marinelli, H.-D. Nuhn, F.-J. Decker, H. Loos, A. Lutman, D. Ratner, Y. Feng, J. Krzywinski, D. Zhang, D. Zhu, SLAC, Menlo Park, CA 94025, USA

Figure 3: Undulator setup for SASE experiment at LCLS.   Figure 4: A SASE FEL spectrum with undulator in Fig. 3.

SASE

53

Experiment!

X-RAY SPECTRA AND PEAK POWER CONTROL WITH ISASE*

J. Wu[†], C. Pellegrini, A. Marinelli, H.-D. Nuhn, F.-J. Decker, H. Loos, A. Lutman, D. Ratner, Y. Feng, J. Krzywinski, D. Zhang, D. Zhu, SLAC, Menlo Park, CA 94025, USA
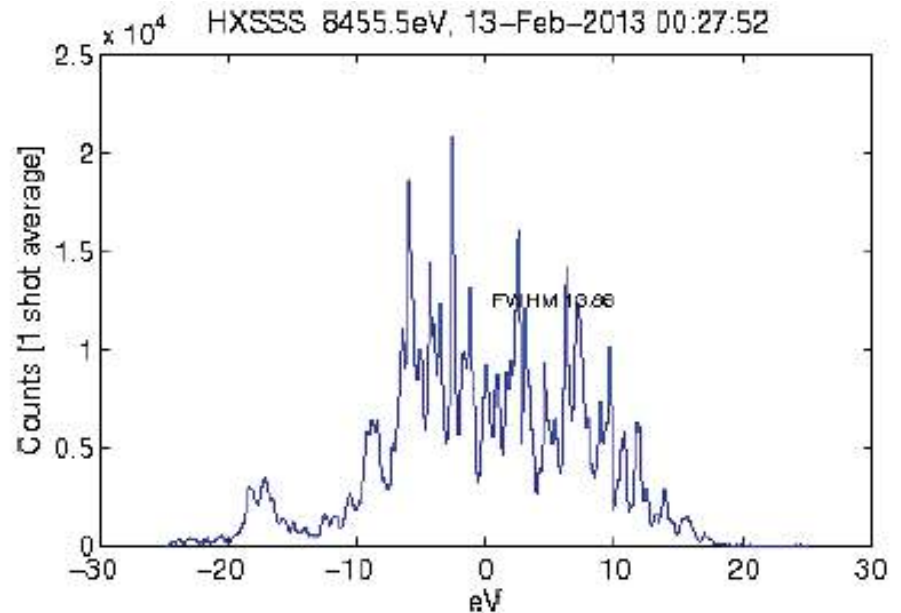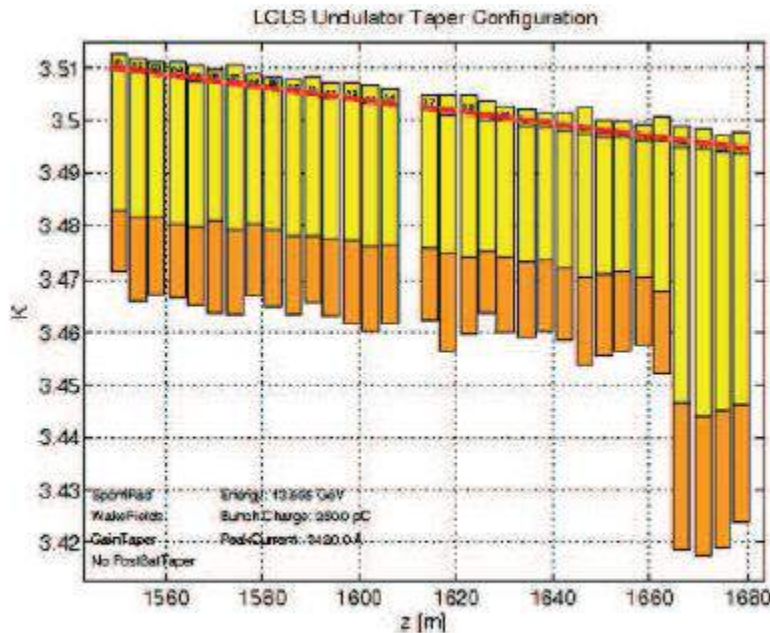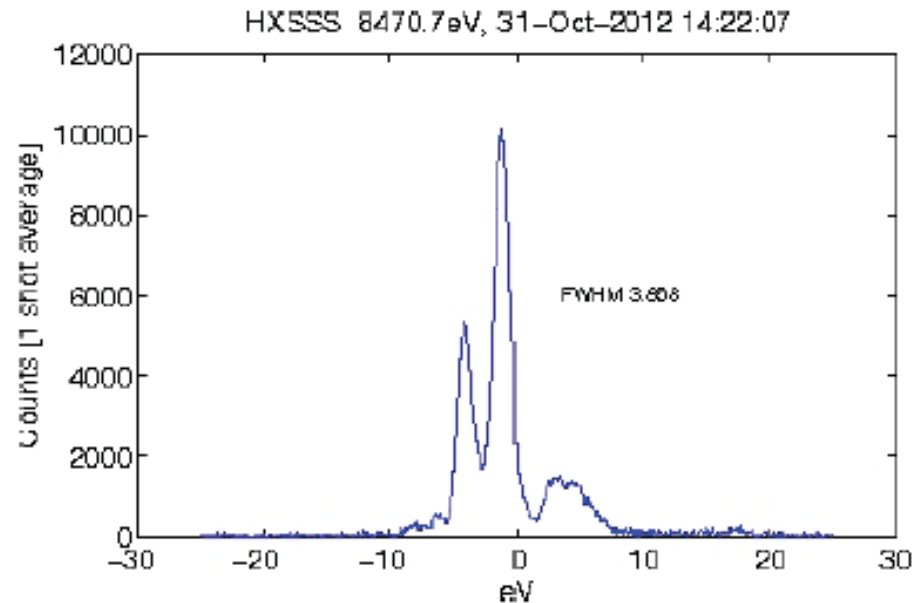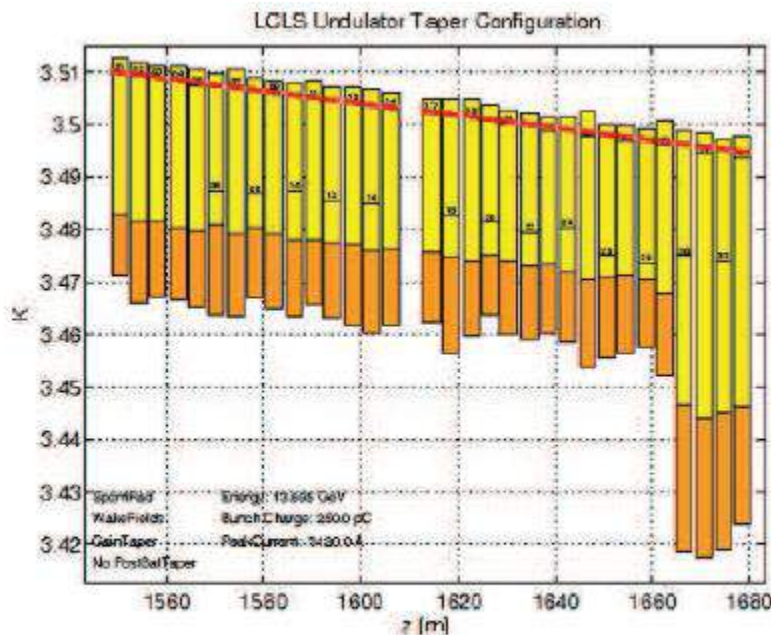

Figure 5: Undulator setup for iSASE experiment at LCL Figure 6: An iSASE FEL spectrum with undulator in Fig. 5.

iSASE

54

Purified self-amplified spontaneous emission free-electron lasers with slippage-boosted filtering

Dao Xiang, Yuantao Ding, and Zhirong Huang

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

Haixiao Deng

- ***pSASE (Purified SASE)***
  - A few undulator sections (called slippage boosted sections – U2 below), resonant at a sub-harmonic of the FEL, are used in the middle stage of the exponential growth regime to amplify the radiation while simultaneously reducing the bandwidth

FIG. 2.   Schematic layout of a pSASE FEL.

Purified self-amplified spontaneous emission free-electron lasers with slippage-boosted filtering

LCLS-II type parameters

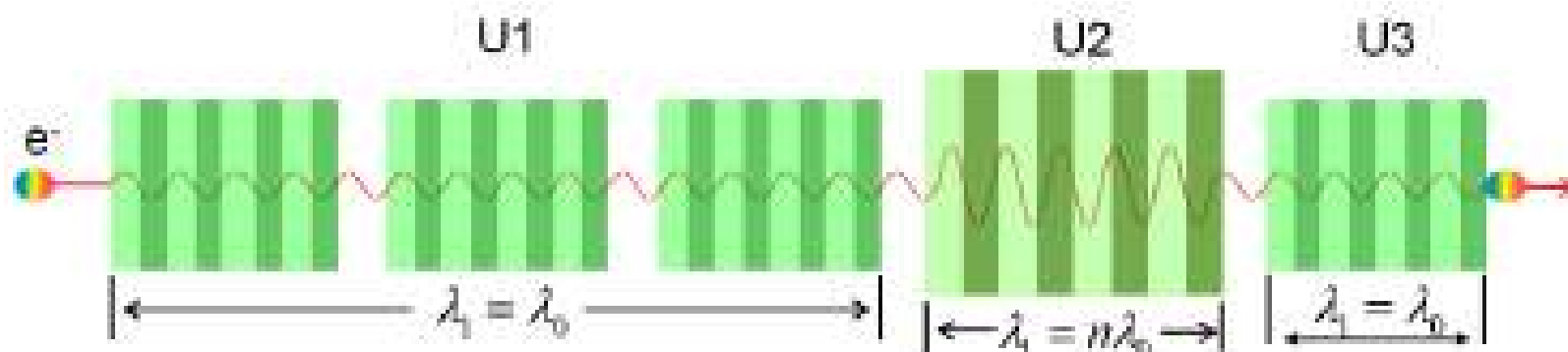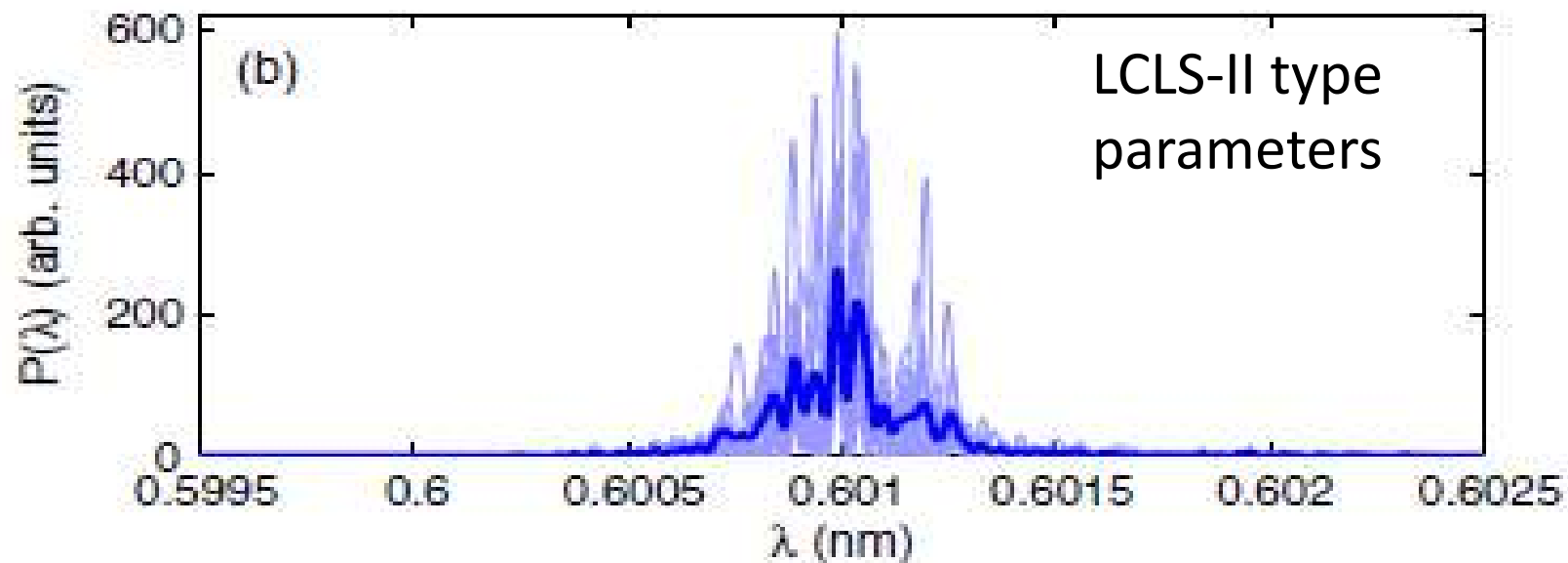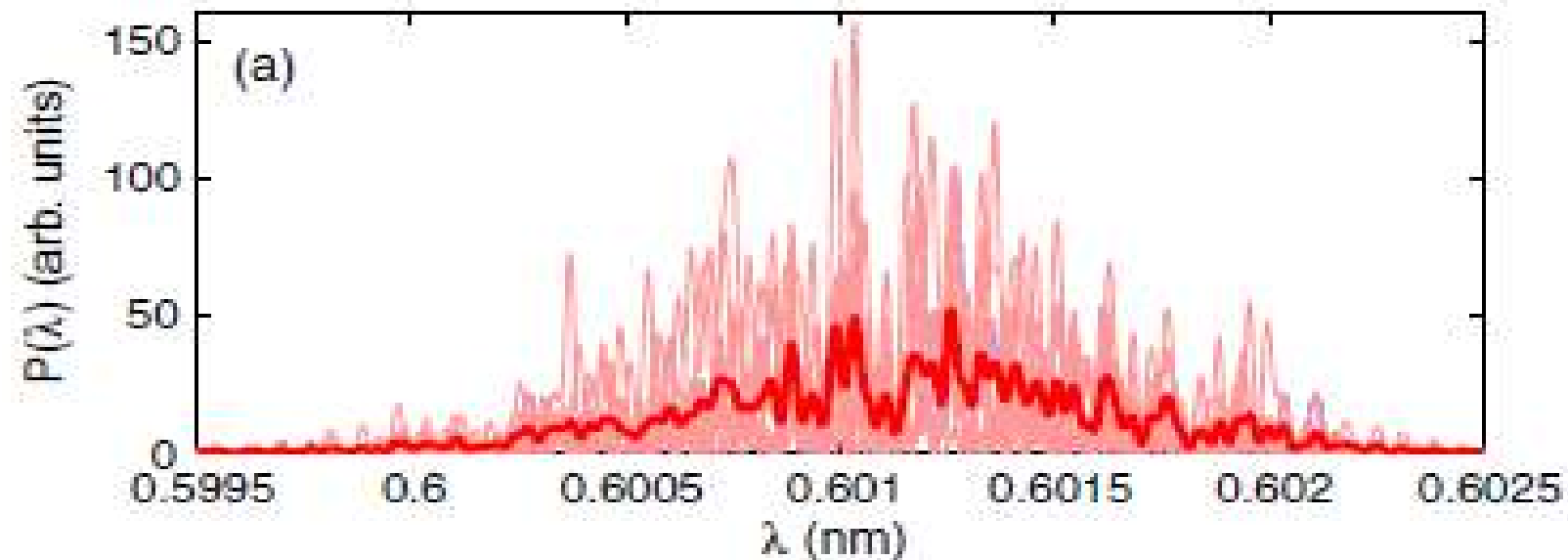# Practical Issues

- **Undulator module lengths**
  - Undulator modules should ideally be less than a gain length to prohibit localised effect

Scaled Undulator Length $\bar{l}$	0.5	1.0	2.0
Maximum $\frac{l_{coh}(HB-SASE)}{l_{coh}(SASE)}$	> 100	$\simeq 50$	$\simeq 10$

- **Electron Beam Delays**
  - Our work shown here uses isochronous chicanes which do not affect rate of electron microbunching
  - Small deviation from non-isochronicity is OK. Simulation studies over limited parameter ranges have shown so far that the chicane must have R_{56} < 10% of that of a standard 4-dipole chicane
  - A design was developed at ASTeC* that meets R_{56} < 10% for the hard x-ray case shown here.
  - For standard non-isochronous chicanes, increase in coherence length over SASE limited to *approximately $\times 5$*
  - An alternative might be to use standard dipole chicanes with correction in occasional negative R_{56} delays – yet to be investigated.....

- **Electron Beam Stability**
  - For isochronous delays, if beam energy jitters the FEL wavelength will change but delay remain constant. This will destroy phase matching.
  - For hard x-ray parameters shown here, for the largest delay to remain phase matched to λ/4, electron beam energy must jitter relatively by less than 5×10^{-5}

*J. K. Jones *et al.*, Proc. IPAC, TUPPP069 1759 (2012) .

HB-SASE Summary

- ***HB-SASE***
  - May be an alternative or additional method for improving the longitudinal coherence of SASE FELs.
  - **Requires no optics** and could in principle work at **any wavelength and repetition rate**.
  - May enable generation of transform limited X-ray FEL pulses
  - Delocalises the collective FEL interaction and breaks the dependence of the radiation coherence length on the FEL cooperation length
  - Exhibits exponential growth of radiation coherence length
  - Can be adapted for ML-SASE: equal chicanes→ few-cycle pulse trains
- Work so far based on some analysis and one-dimensional simulations (but HB-SASE is a longitudinal effect, which is well modelled in 1D)
- Further study required to include 3D effects and full tracking through isochronous chicanes

CLARA – a new UK test facility

[**C**ompact **L**inear **A**ccelerator for **R**esearch and **A**pplications]

CLARA conceptual design report

J.A. Clarke,[a,b,*] D. Angal-Kalinin,[a,b] N. Bliss,[a] R. Buckley,[a,b] S. Buckley,[a,b] R. Cash,[a]
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J.K. Jones,[a,b] A.S. Kalinin,[a,b] W. Liggins,[a,b] L. Ma,[a,b] K.B. Marinov,[a,b] B. Martlew,[a]
P.A. McIntosh,[a,b] J.W. McKenzie,[a,b] K.J. Middleman,[a,b] B.L. Militsyn,[a,b] A.J. Moss,[a,b]
B.D. Muratori,[a,b] M.D. Roper,[a,b] R. Santer,[a,b] Y. Saveliev,[a,b] E. Snedden,[a,b]
R.J. Smith,[a,b] S.L. Smith,[a,b] M. Surman,[a,b] T. Thakker,[a,b] N.R. Thompson,[a,b]
R. Valizadeh,[a,b] A.E. Wheelhouse,[a,b] P.H. Williams,[a,b] R. Bartolini,[c,d] I. Martin,[c]
R. Barlow,[e] A. Kolano,[e] G. Burt,[b,f] S. Chattopadhyay,[b,f,g,h] D. Newton,[b,g] A. Wolski,[b,g]
R.B. Appleby,[b,h] H.L. Owen,[b,h] M. Serluca,[b,h] G. Xia,[b,h] S. Boogert,[i] A. Lyapin,[i]
L. Campbell,[j] B.W.J. McNeil[j] and V.V. Paramonov[k]

58

CLARA – a new UK test fac...

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Research and...

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...y,[a,b] S. Buckley,[a,b] R. Cash,[a]
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...D.M.P. Holland,[a,b] S.P. Jamison,[a,b]
...[b] L. Ma,[a,b] K.B. Marinov,[a,b] B. Martlew,[a]
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...by,[b,h] H.L. Owen,[b,h] M. Serluca,[b,h] G. Xia,[b,h] S. Boogert,[i] A. Lyapin,[i]
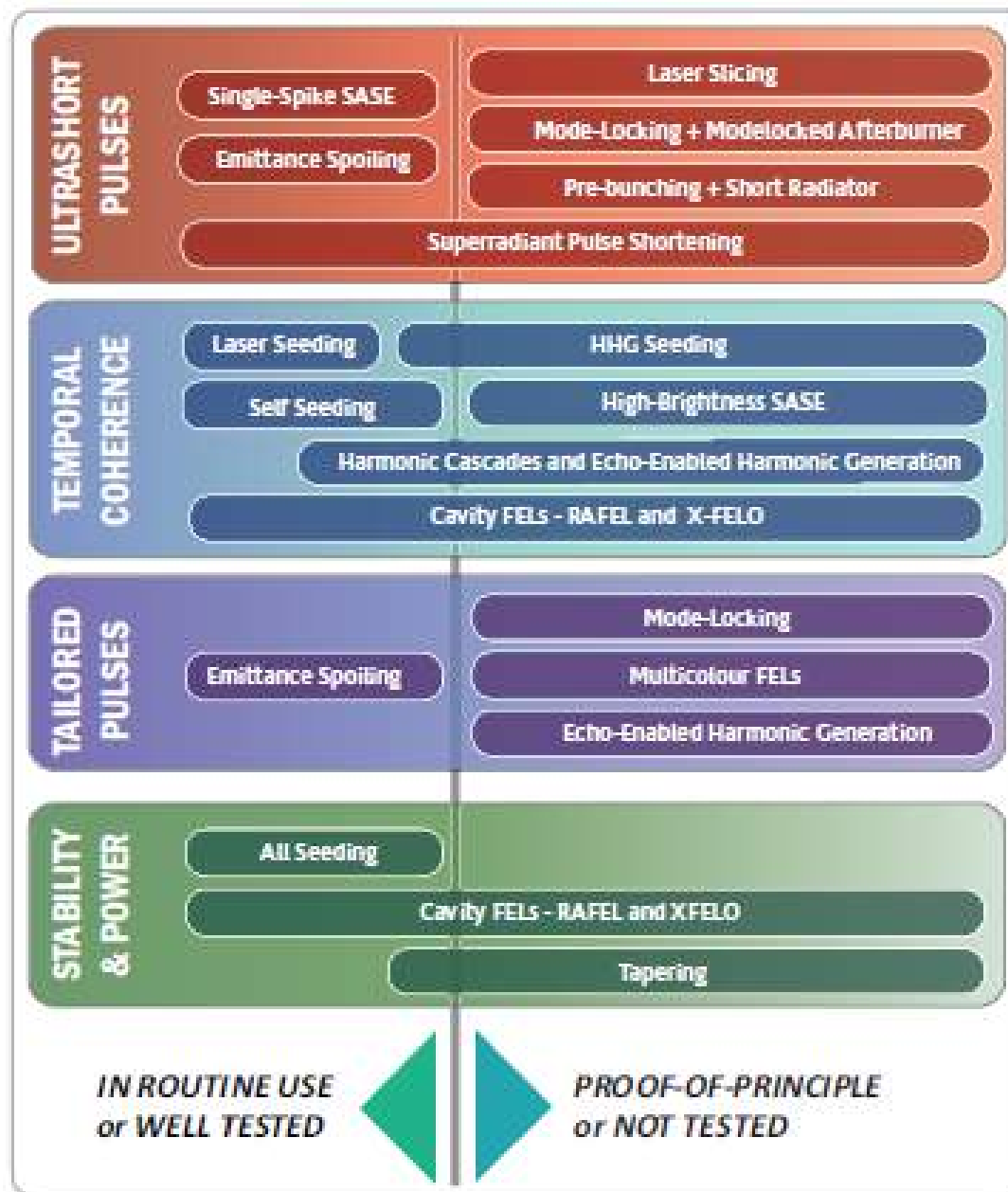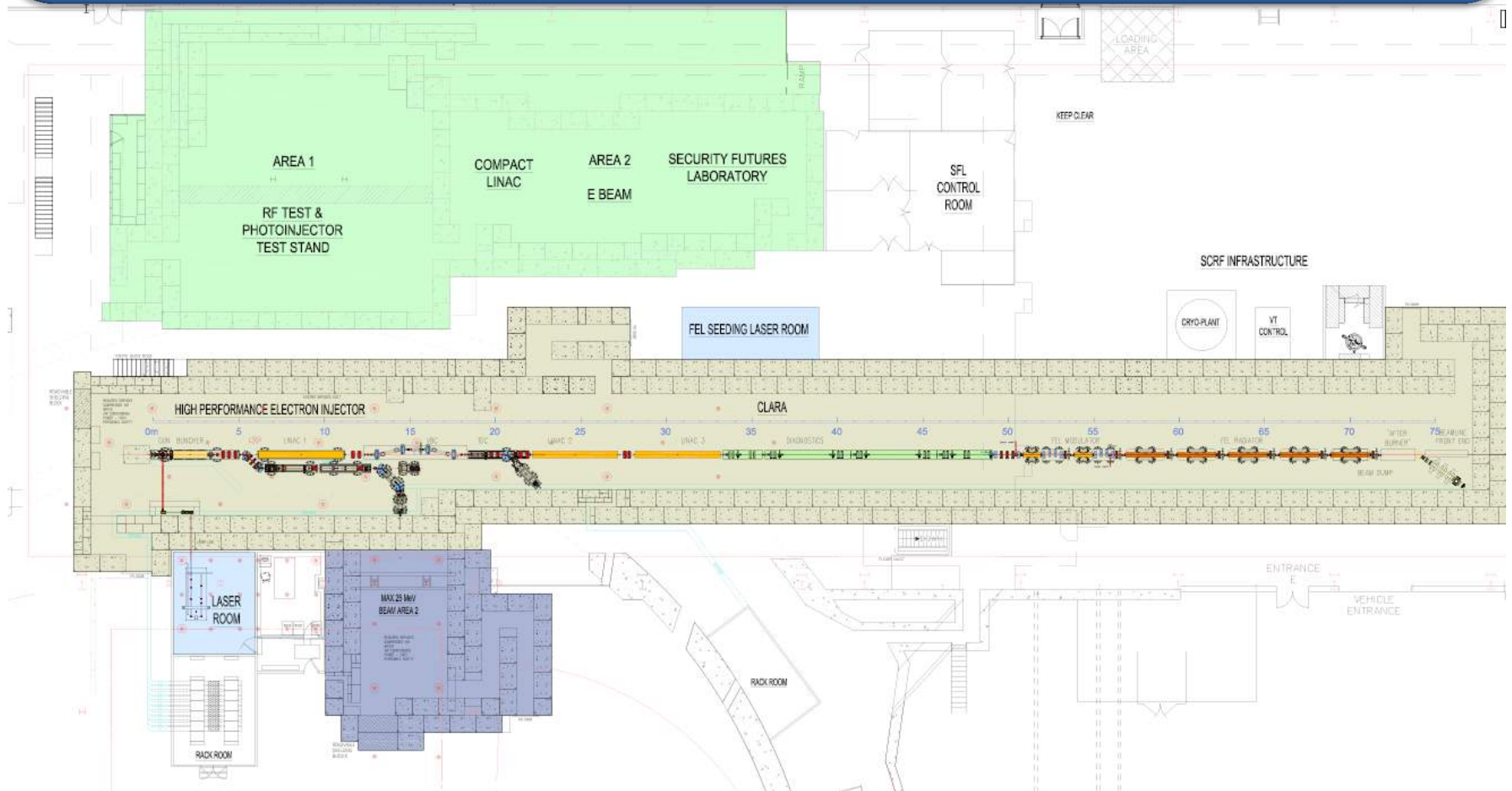...mpbell,[j] B.W.J. McNeil[j] and V.V. Paramonov[k]

58

Figure 1.2. Schematic representation of the FEL landscape in terms of potential improvements to particular output properties against progress to date.

To develop a normal conducting test accelerator able to generate longitudinally and transversely bright electron bunches and to use these bunches in the experimental production of **stable**, **synchronised**, **ultra short** photon pulses of coherent light from a single pass FEL with techniques directly applicable to the future generation of light source facilities.

Top diagram labels (left to right):

6 MeV, 20 MeV, 60 MeV, 150 MeV, 250 MeV

Gun, Buncher, Linac 1, Linac 2, Linac 3, Diagnostics, Bunch Compression, Diagnostics, Modulator Undulators, Radiator Undulators, Beamline Front End, Shield Wall, Switching Mirror

Laser

Laser

Beamlines
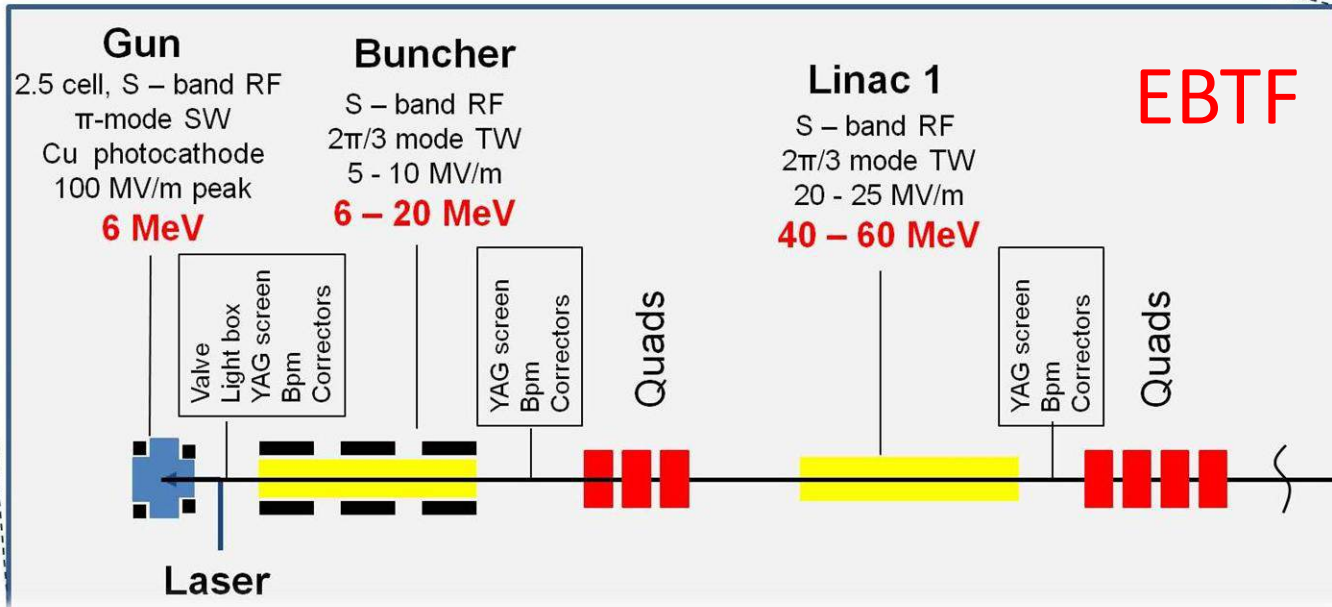
Dump

Scale: 0m, 10m, 20m, 30m, 40m, 50m, 60m, 80m, 90m, 100m

Work In Progress

EBTF

Gun
2.5 cell, S – band RF
π-mode SW
Cu photocathode
100 MV/m peak
6 MeV

Buncher
S – band RF
$2\pi/3$ mode TW
5 - 10 MV/m
6 – 20 MeV

Linac 1
S – band RF
$2\pi/3$ mode TW
20 - 25 MV/m
40 – 60 MeV

Valve
Light box
YAG screen
Bpm
Correctors

YAG screen
Bpm
Correctors

Quads

YAG screen
Bpm
Correctors

Quads

Laser

6 MeV
20 MeV
60 MeV
150 MeV
250 MeV

Gun
Buncher
Linac 1
Linac 2
Linac 3
Diagnostics
Bunch Compression
Diagnostics
Modulator Undulators
Radiator Undulators
Beamline Front End
Shield Wall
Switching Mirror

Laser

Laser

Beamlines

Dump

0m   10m   20m   30m   40m   50m   60m   80m   90m   100m

Work In Progress

2.5 ce
Cu
10

Laser

Now funded to 150 MeV!

TF

61

Thank You!