From femtosecond to attosecond coherent undulator pulses

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Acknowledgements

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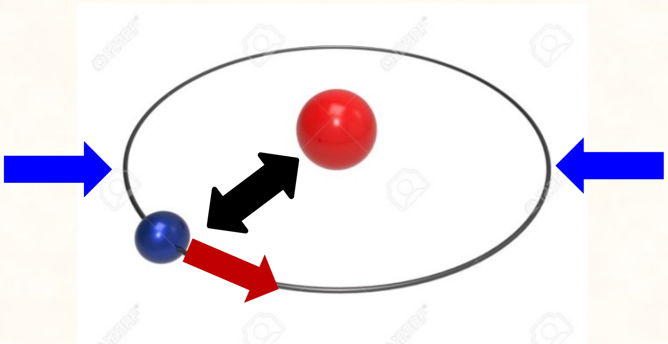
Outline of the talk

- a taste of attosecond science;
- state-of-the-art of short pulse generation;
- FEL concepts for reaching femtosecond and attosecond pulse duration.

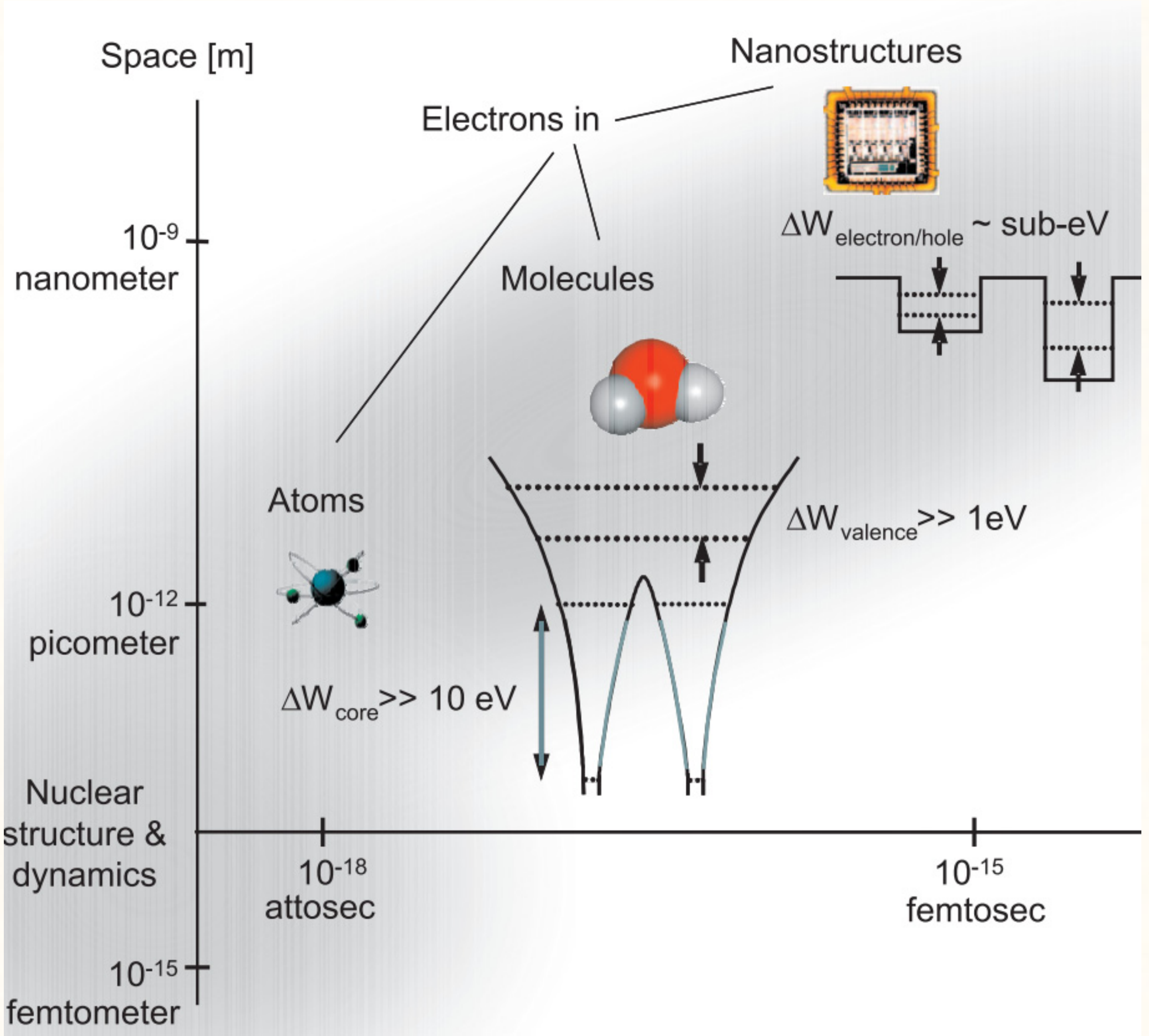
Characteristic time and space scales in the nanoworld

Ground state of Hydrogen atom



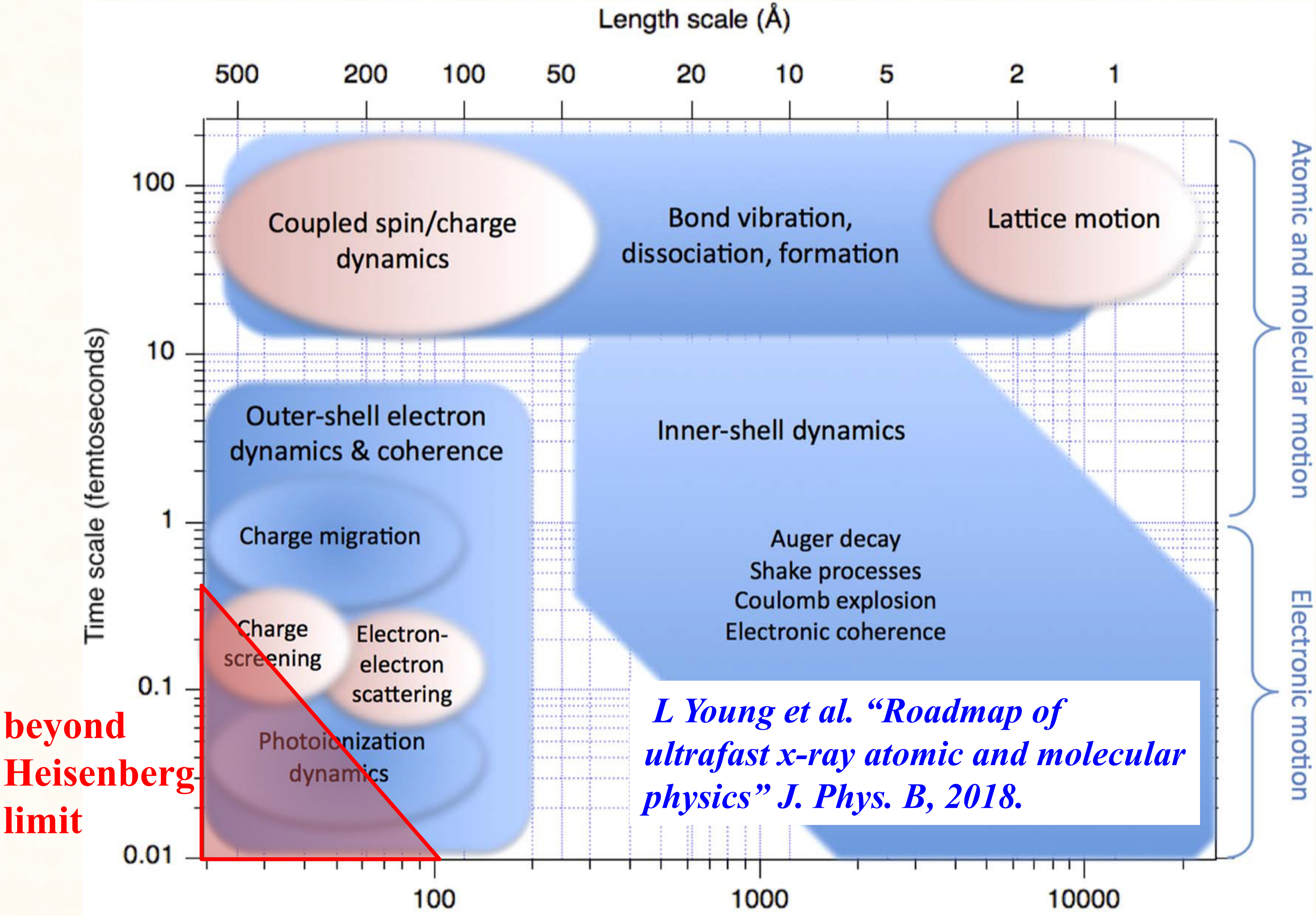
Energy scale ~ 10 eV
Spatial scale ~ 1 Å
Time scale ~ 150 as

Heisenberg uncertainty
$\Delta t\ \Delta E \geq h/2$,
$\Delta t\ \Delta E \geq$ 2 eV fs

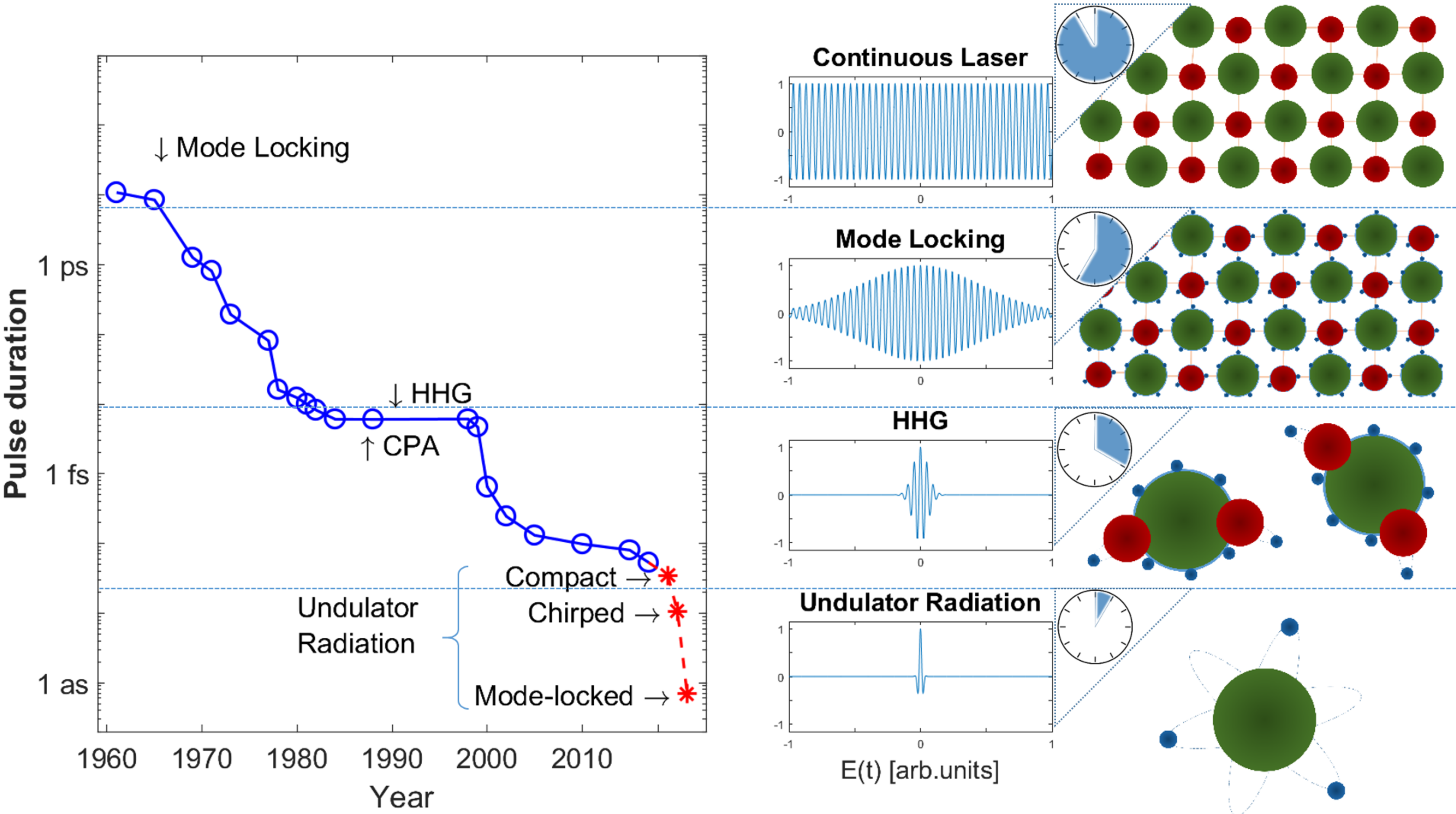


F. Krausz and M. Ivanov: Attosecond physics. Rev. Mod. Phys. 2009

Science drivers for femtosecond & attosecond FELs



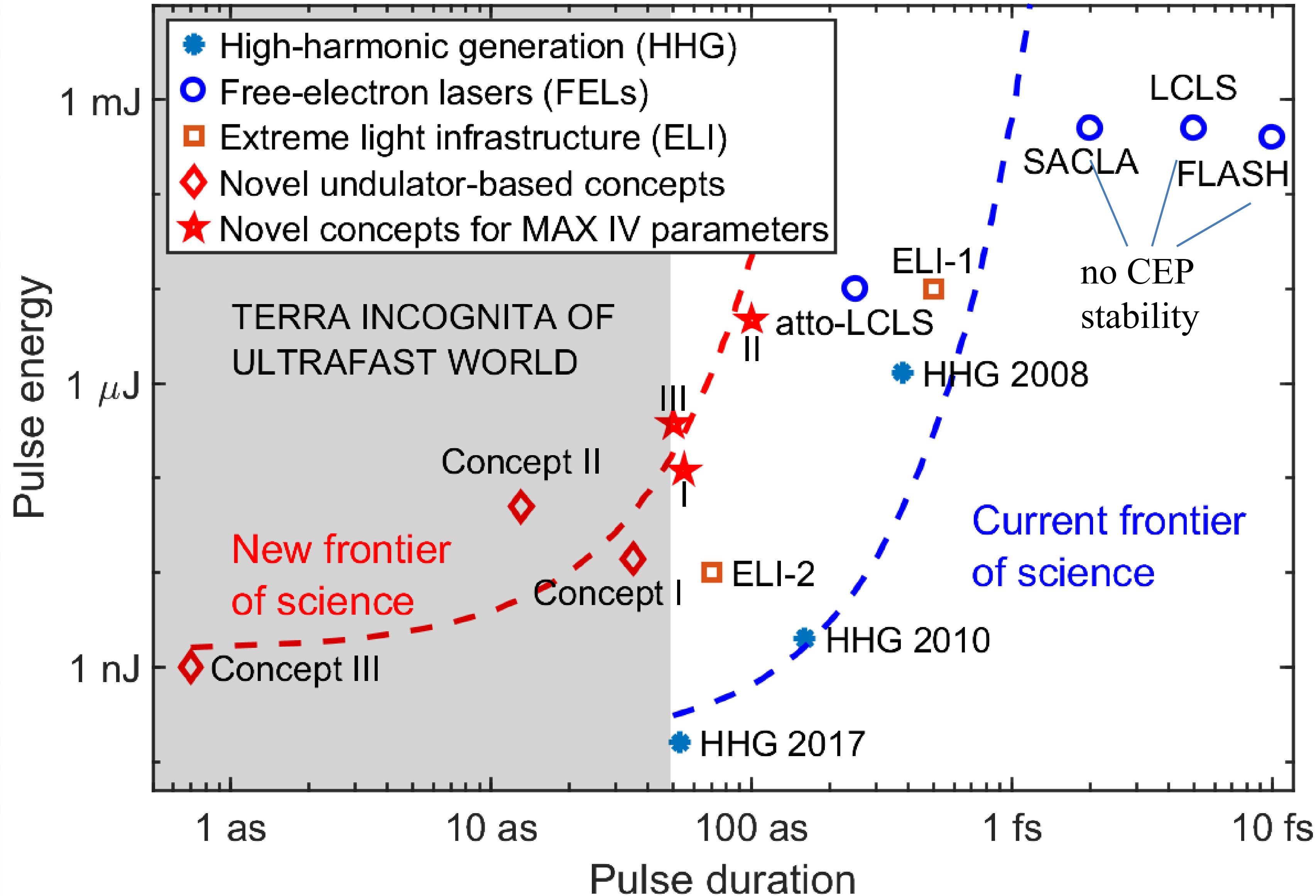
Progress on ultrashort generation



HHG sources are facing saturation. New methods are needed.

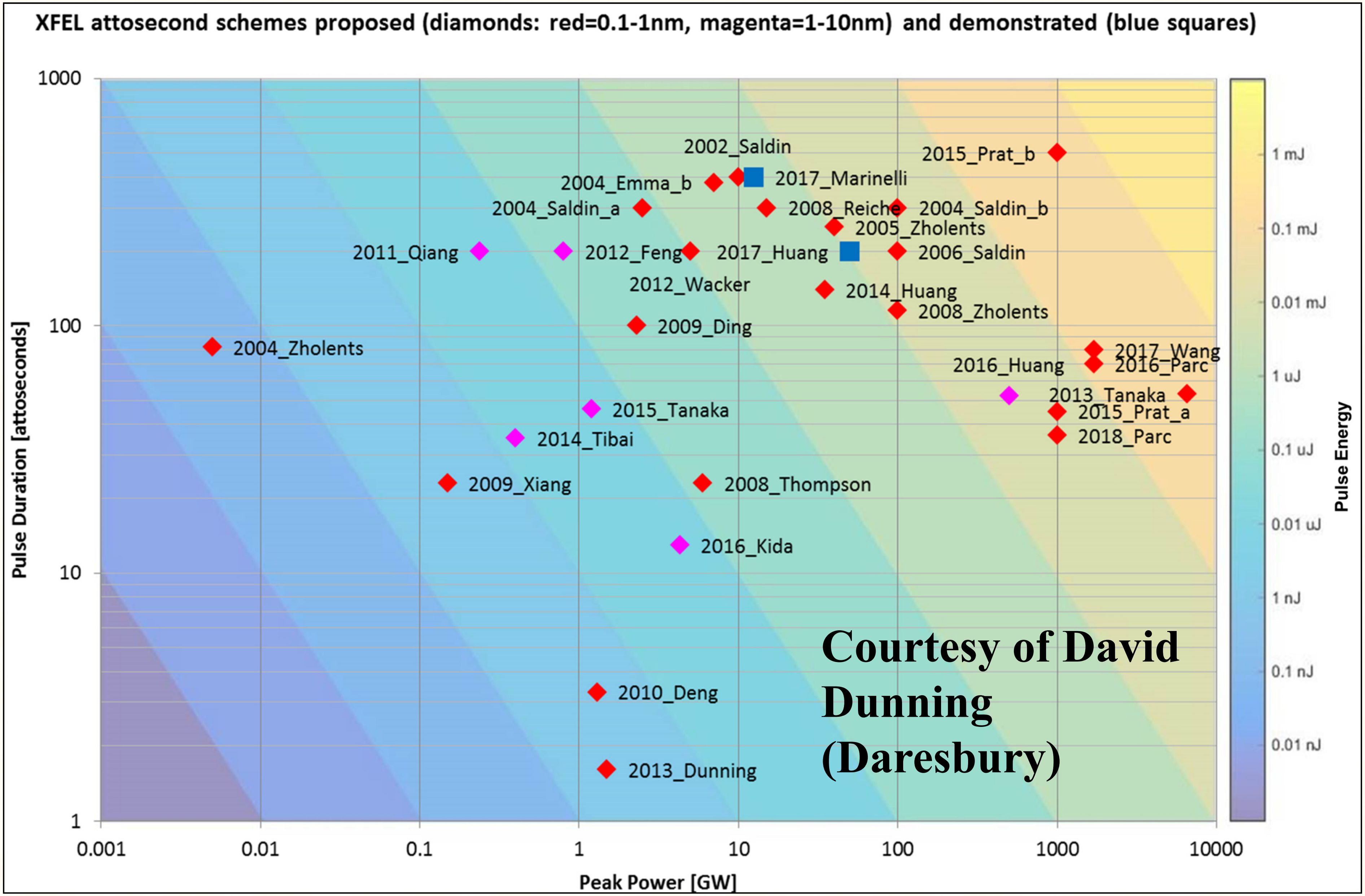
A. Mak et al. & V. Goryashko, Reports on Progress in Physics, 2018.

State-of-the-art of short-pulse, CEP-stable generation



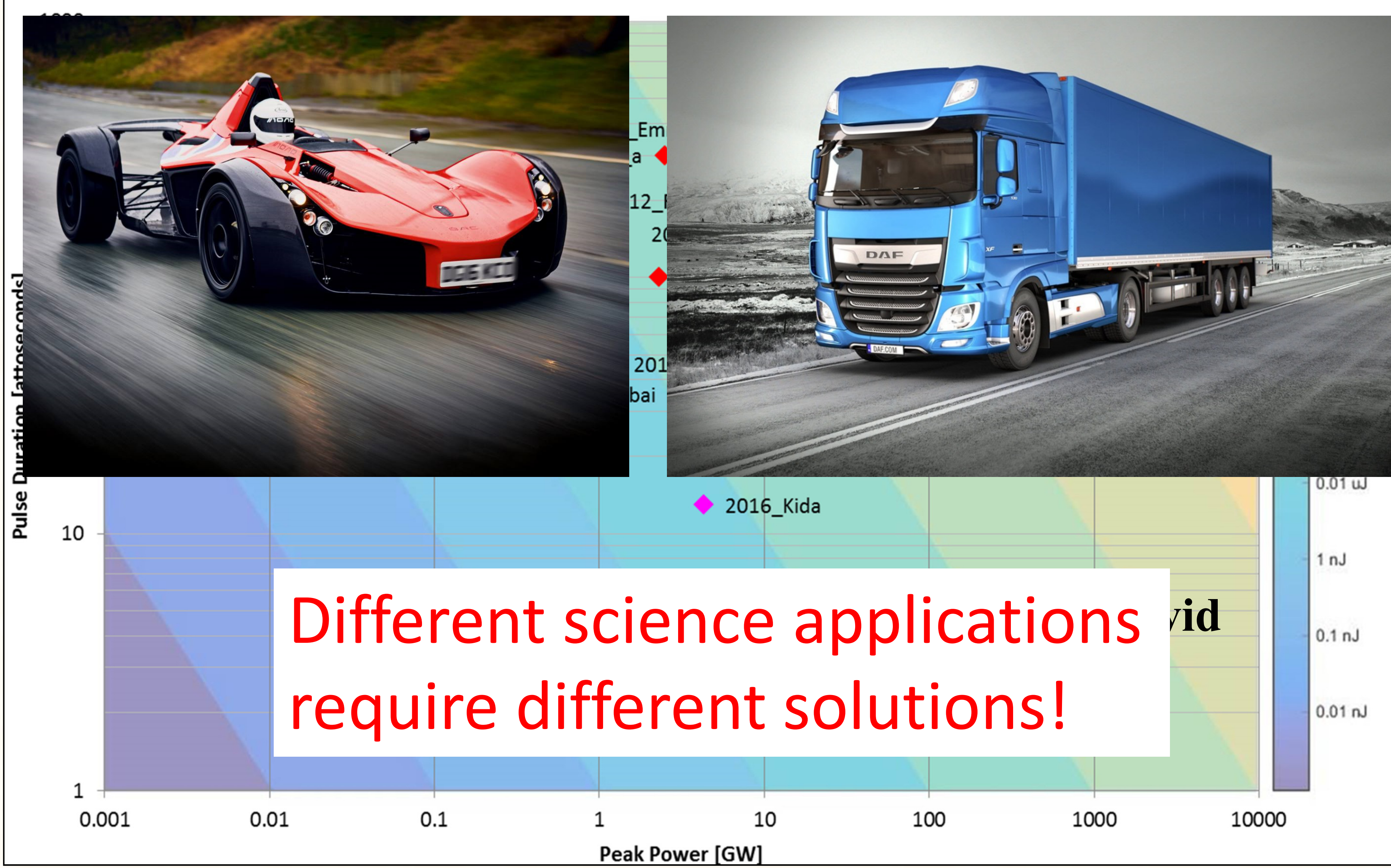
Undulator light source is a promising way to the attosecond region.

Concepts for short-pulse generation with FELs



Concepts for short-pulse generation with FELs

XFEL attosecond schemes proposed (diamonds: red=0.1-1nm, magenta=1-10nm) and demonstrated (blue squares)



Different science applications require different solutions!

Examples of science requirements and FEL solutions

Example of science applications	Essential requirements	Comments	Suitable FEL schemes
Imaging of biomolecules & matter under extreme conditions	$10^{12} - 10^{13}$photons ~ 0.5 fs resolution 0.3-10 keV	No major changes on the detector side	?
Spectroscopic mapping of electronic structure	$\sim 10^{11}$ photons > 10 fs resolution wavelength stability ~1 keV	Traditional synchrotron community	?
Probing electronic wavefunctions with attosecond interferometry	$\sim 10^{8}$ photons CEP stability (?) ~ 100 eV ~ 0.1 fs resolution	HHG user community	?
Electronic dynamics by attosecond transient absorption	$\sim 10^{7}$ photons ~ 0.1-1 keV ~ 0.1 fs resolution	HHG user community	?

Generation of short pulses in FELs

FEL mechanisms for generation of short pulses:

- Single-spike SASE regime
- Pulse self-compression in the superradiant regime
- Tapered FEL and bandwidth control
- Mode-locking
- CEP-stable, coherent spontaneous undulator radiation

Beam preparation for generation of short pulses:

- Emittance spoiling and its derivatives
- Current enhancement and its derivatives
- Beam energy modulation
- Beam tilt, orbit mismatch, ..
- Beam self-modulation through long-wavelength, coherent undulator radiation (*see A. Marinelli talk*)

Single-spike SASE regime

For bunches shorter than $2\pi t_c$, a single SASE spike is generated*

$$t_c = \frac{1}{2\rho\omega} \leftrightarrow l_c = \lambda_r \frac{L_g}{\lambda_u} .$$

Minimum pulse duration is limited by the coherence time**

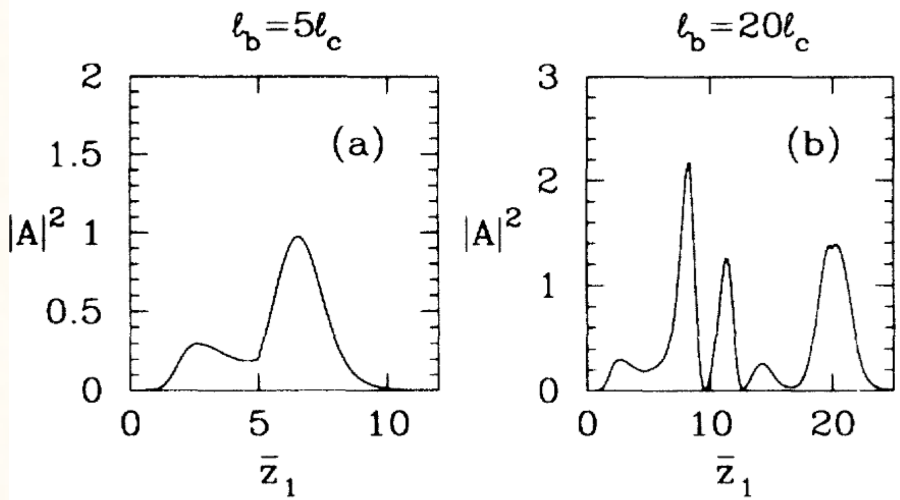
$$\tau_c = \frac{1}{\rho\omega}\sqrt{\frac{\pi \ln N_c}{18}} \propto \frac{1}{\sqrt{E_{ph}}}.$$

For soft X-ray FELs τ_c~ 0.5-1.5 fs

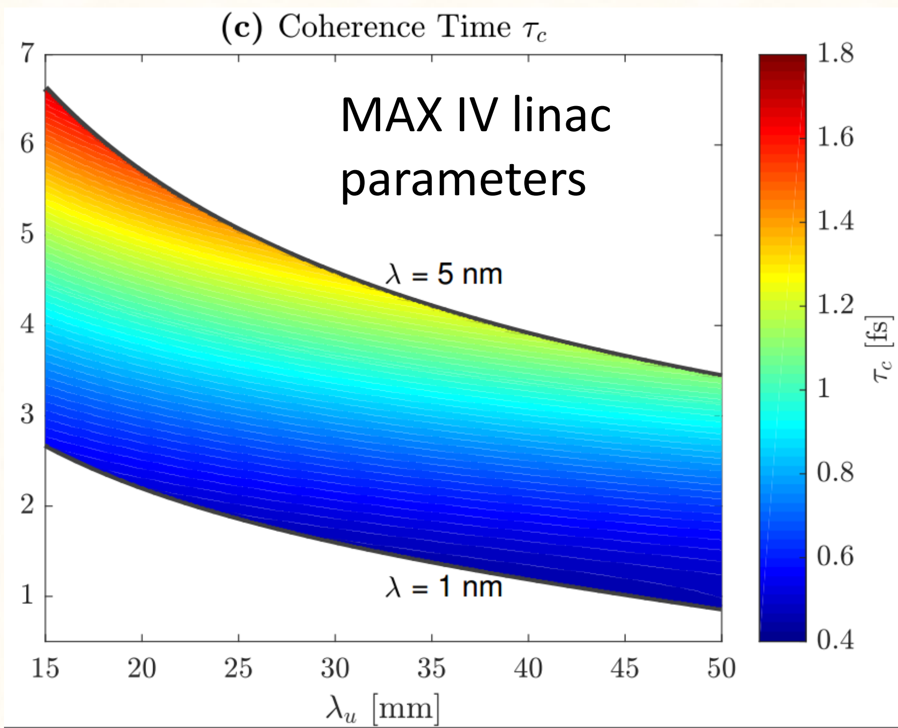
For hard X-ray FELs τ_c~ 0.15-0.4 fs

The challenge is to prepare a short bunch.

***E.L. Saldin et al. Optics Communications **148** (1998), 383.*

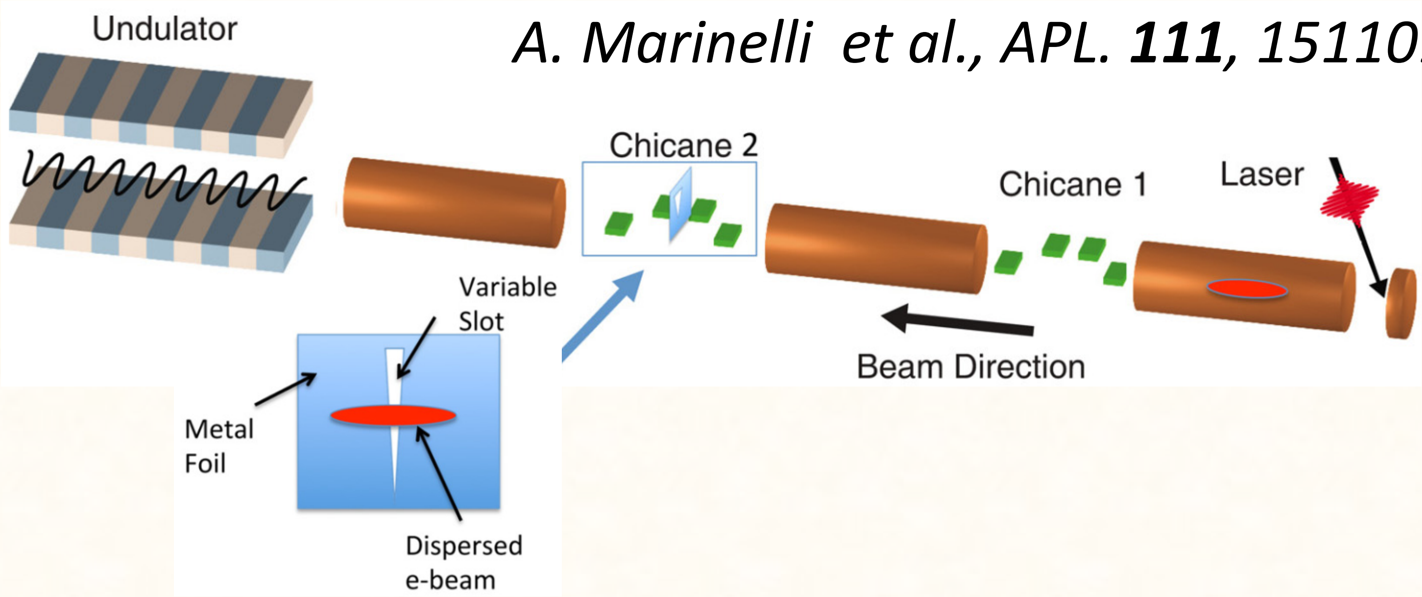


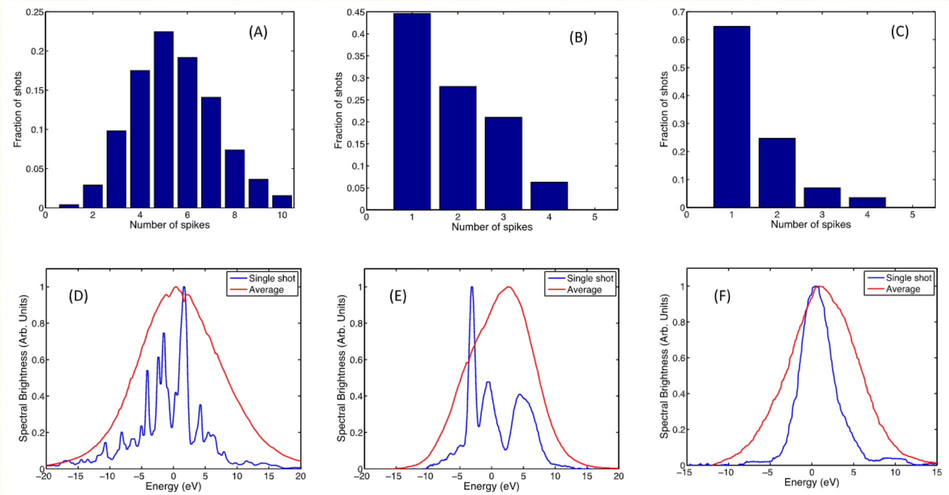
**R. Bonifacio, PRL 73 (1994), 70*



Single-spike generation with a slotted foil

A. Marinelli et al., APL. ***111****, 151101 (2017)*

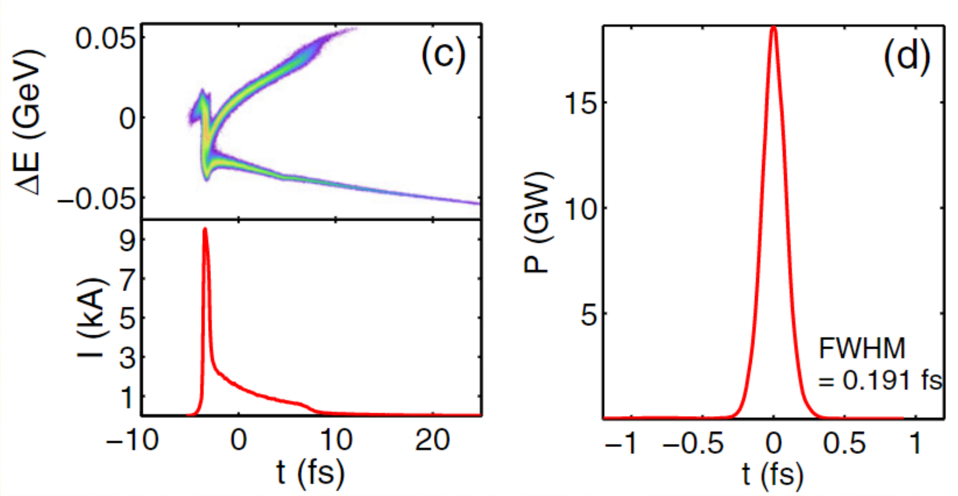




unspoiled　220 um　130 um

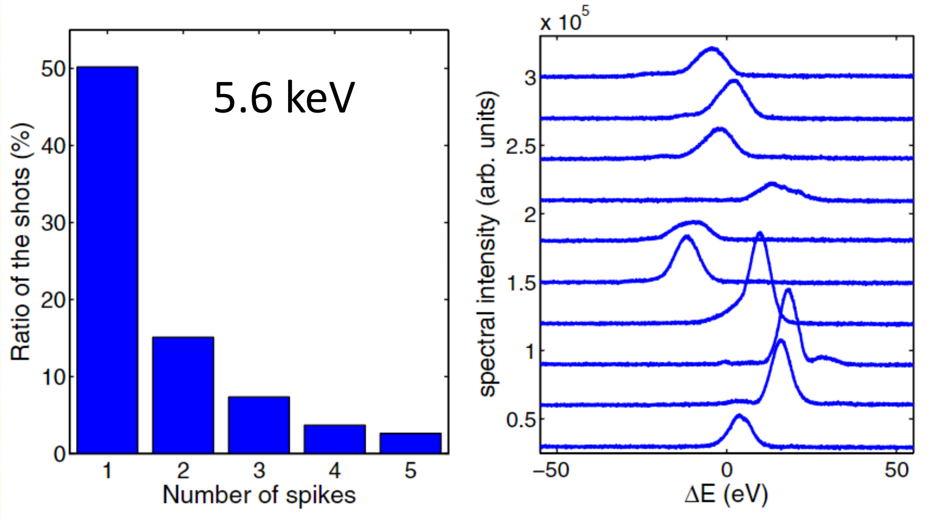
- demonstrated at 5.6 keV
- bunch duration ~ 1 fs
- 65% of shots being single spike
- average pulse energy 5 uJ
- 30% of the shots above 10 uJ
- intensity fluctuation level 76%
- single-spike bandwidth 4.5 eV
- duration ~ 400 as FWHM

Single-spike generation via nonlinear compression



S. Huang et al. PRL. ***119****, 154801 (2017)*

Reversed taper undulator operation to compensate for the time-energy chirp in the bunch.



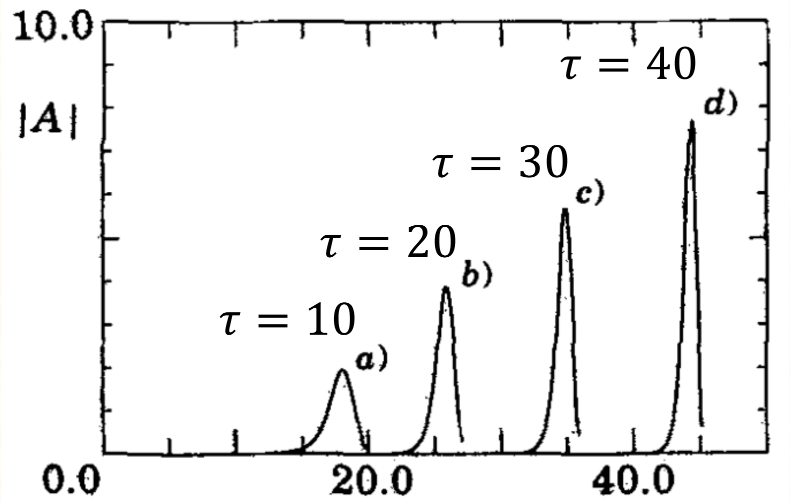
- 20 pC at 11.5 GeV
- demonstrated at 5.6 & 9 keV
- bunch duration ~ 3 fs FWHM
- 50% of shots being single spike
- average pulse energy 10 uJ
- intensity fluctuation level 76%
- bandwidth 11.3 $\pm$ 4.2 eV
- duration ~ 230 $\pm$ 82 as FWHM

Pulse self-compression in the superradiant regime

R. Bonifacio, Rivista del Nuovo Cimento 15 (1992) 1.

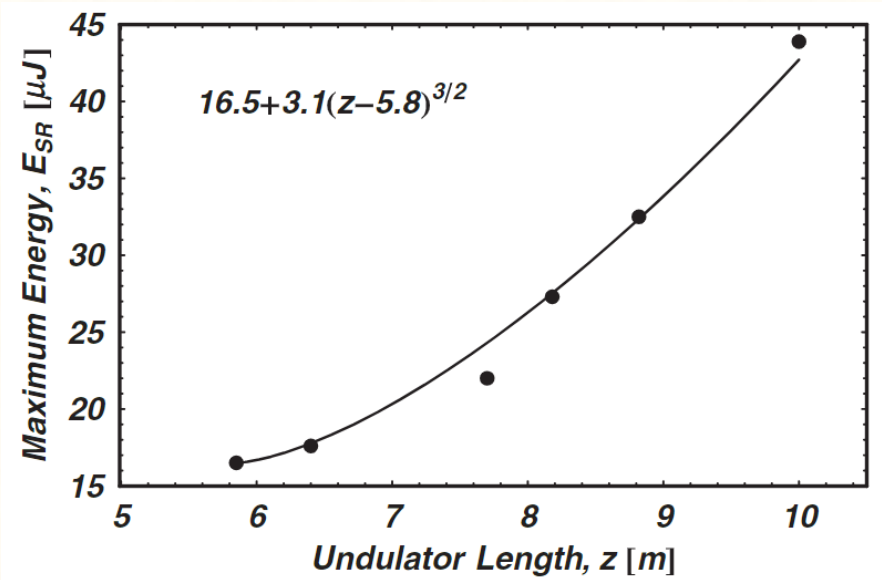
In the superradiant regime $P \propto I^2$:

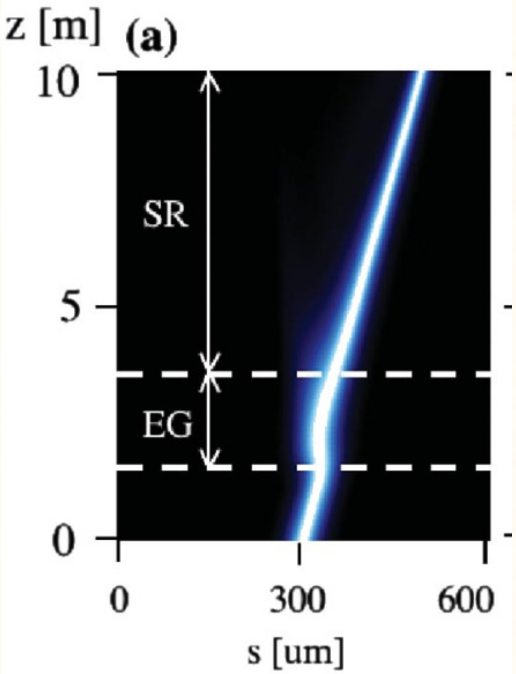
- Pulse energy $\propto z^{3/2}$
- Pulse duration $\propto z^{-1/2}$
- Peak power $\propto (z - v_z t)^2$
- Soliton-like solution



Distance in units of l_c

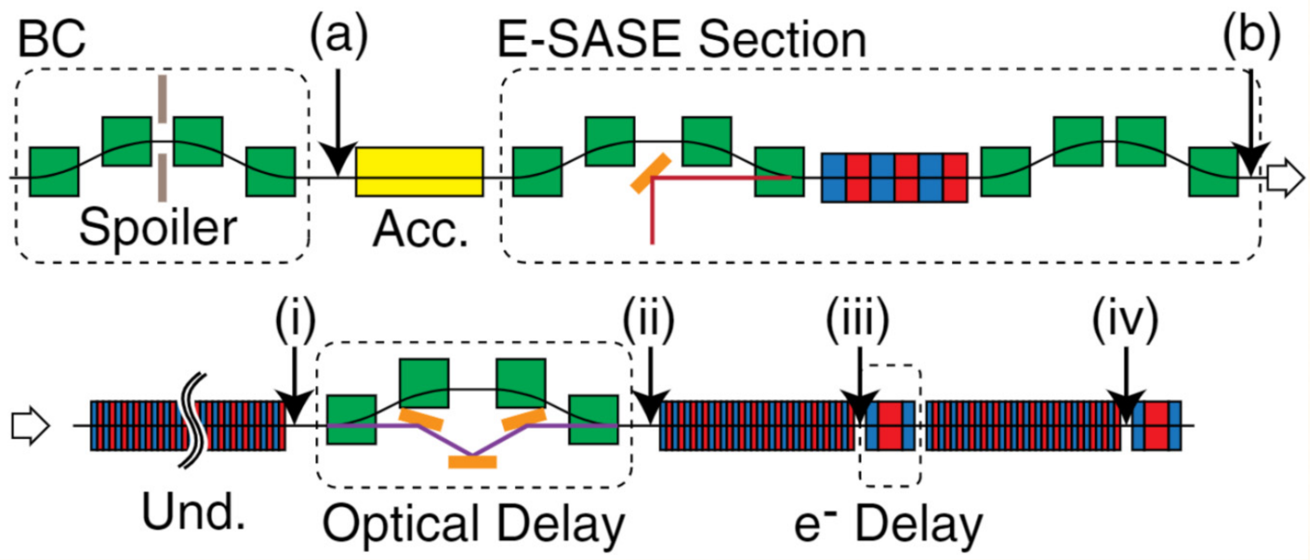
T. Watanabe et al. PRL 98 (2007) 034802.





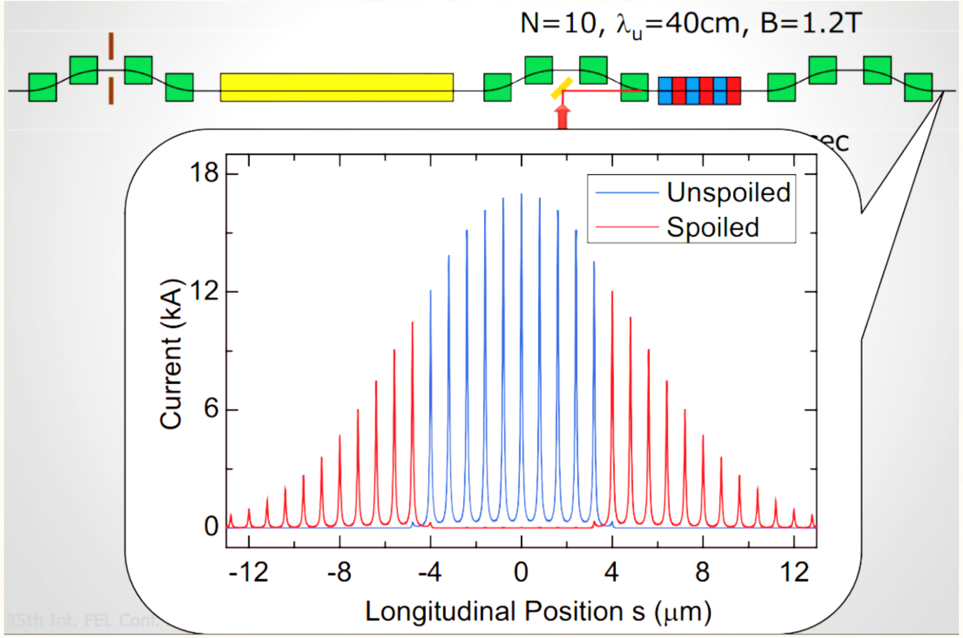
Genesis simulation

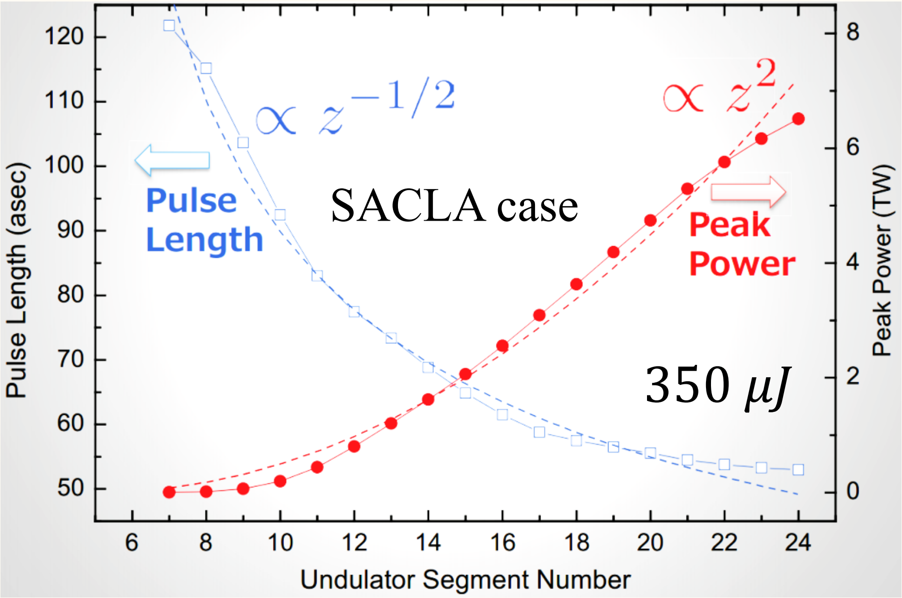
Superradiant regime: *Tanaka, PRL 110 (2013) 084801*



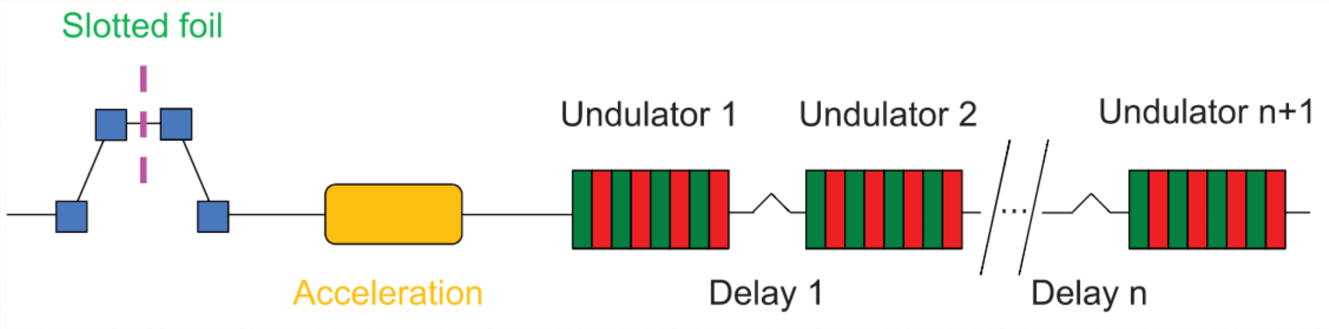
- *P. Emma et al. PRL 92 (2004) 074801.*
- *A. Zholents PRST-AB 8 (2005) 040701*
- *F. Geloni et al., DESY 10-004.*

Allows for time-locking

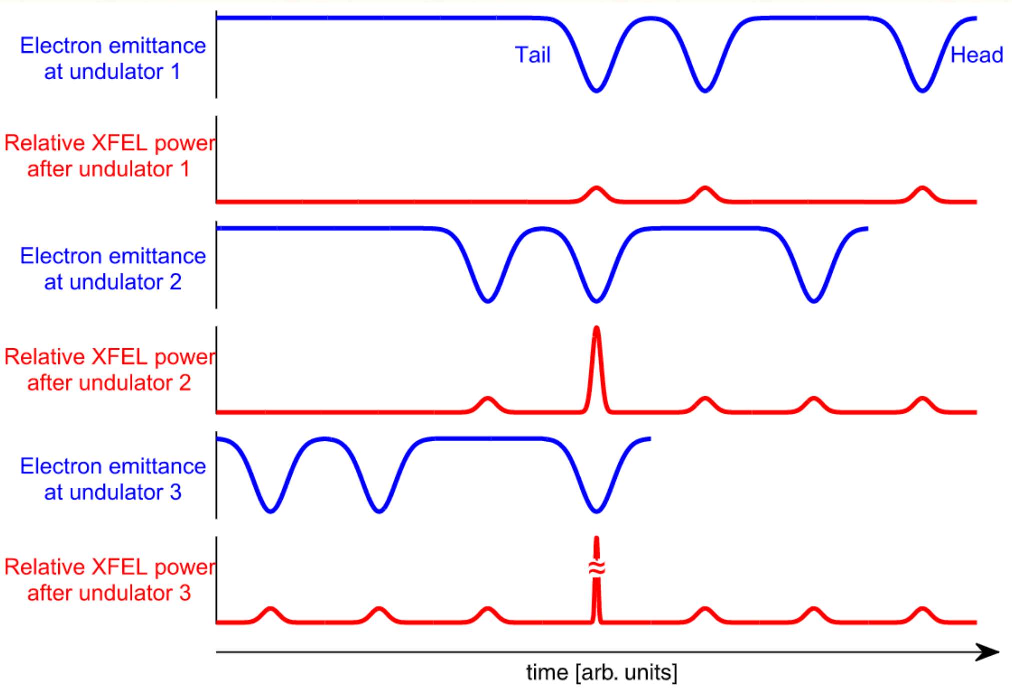




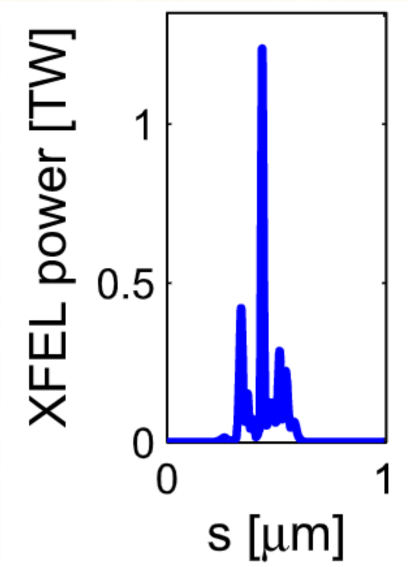
Superradiant regime: E. *Prat, PRL 114 (2015) 244801*

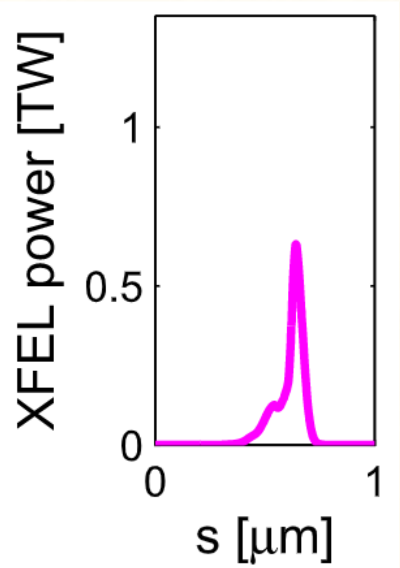


Uses a foil with multiple, unevenly located slots.



SwissFEL case

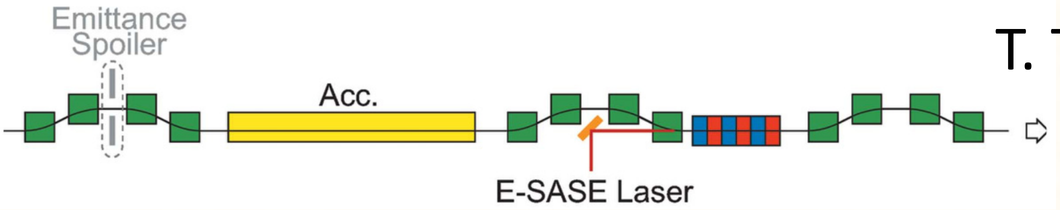




~ 200 as & $200\ \mu J$

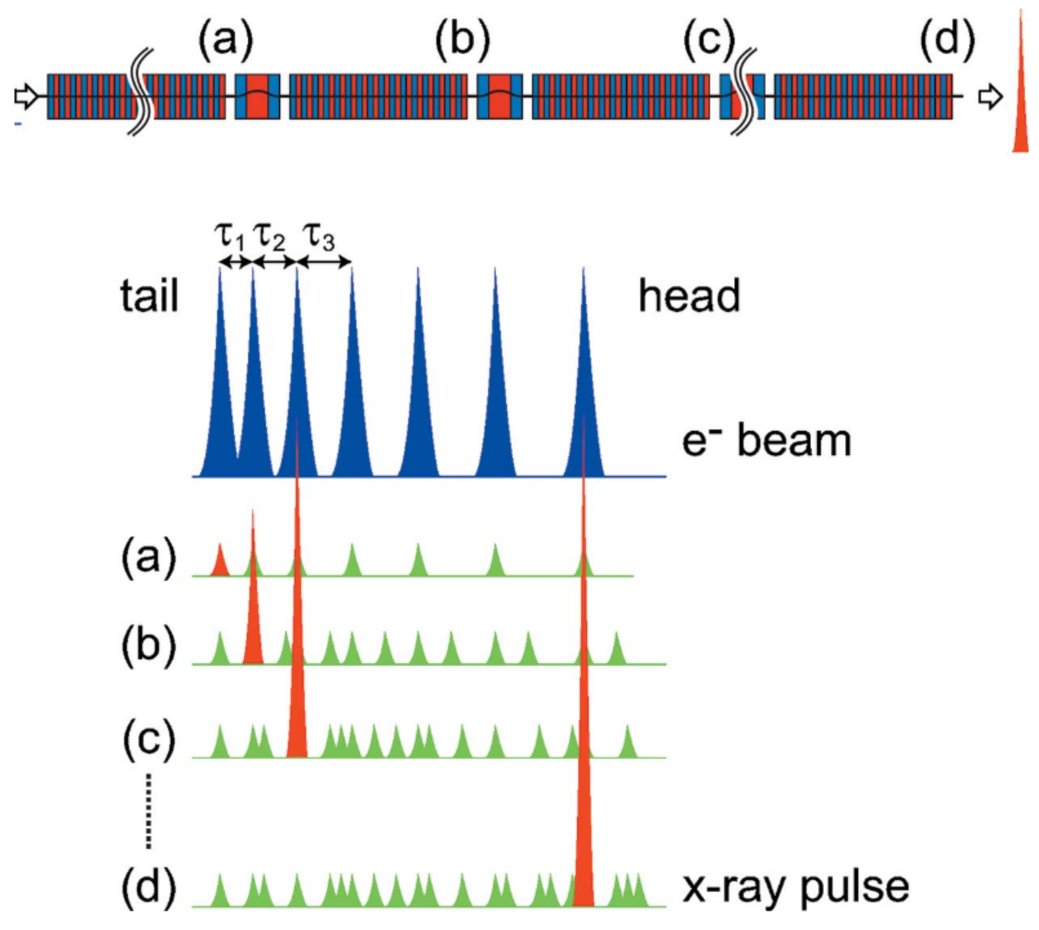
Simple compared to other schemes but no time-locking.

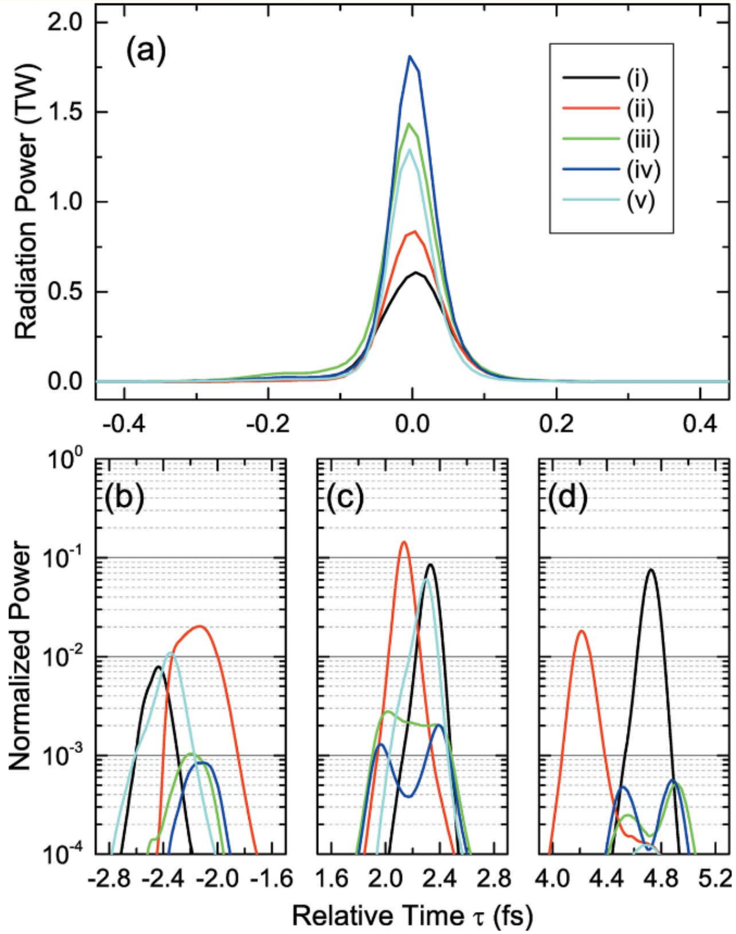
Further development of Tanaka's superradiant scheme



T. Tanaka et al, JSR 23 (2016), 1273

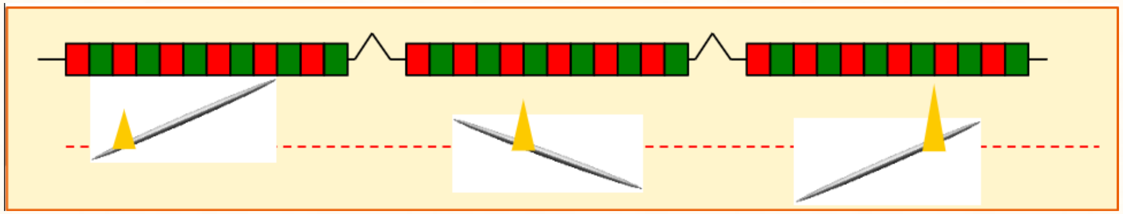
- SACLA-like case
- 7.7 keV, 50 as, 1.7 TW
- Contrast ~ 100:1





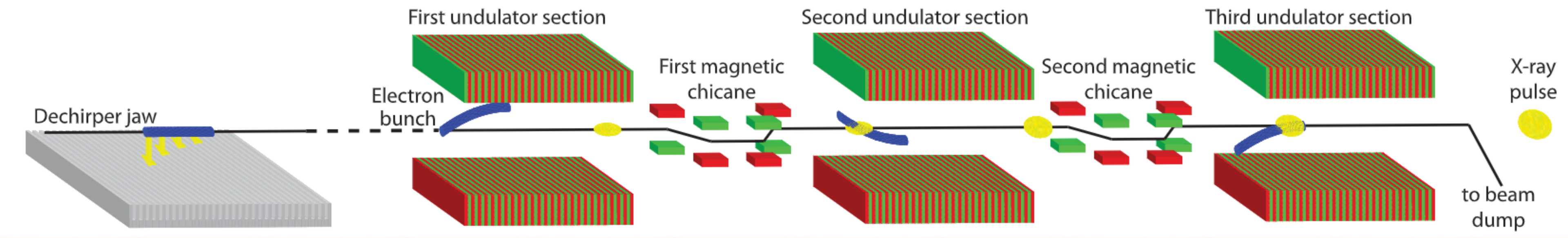
Very similar idea by Z. Wang PRAB 20 (2017) 040701.

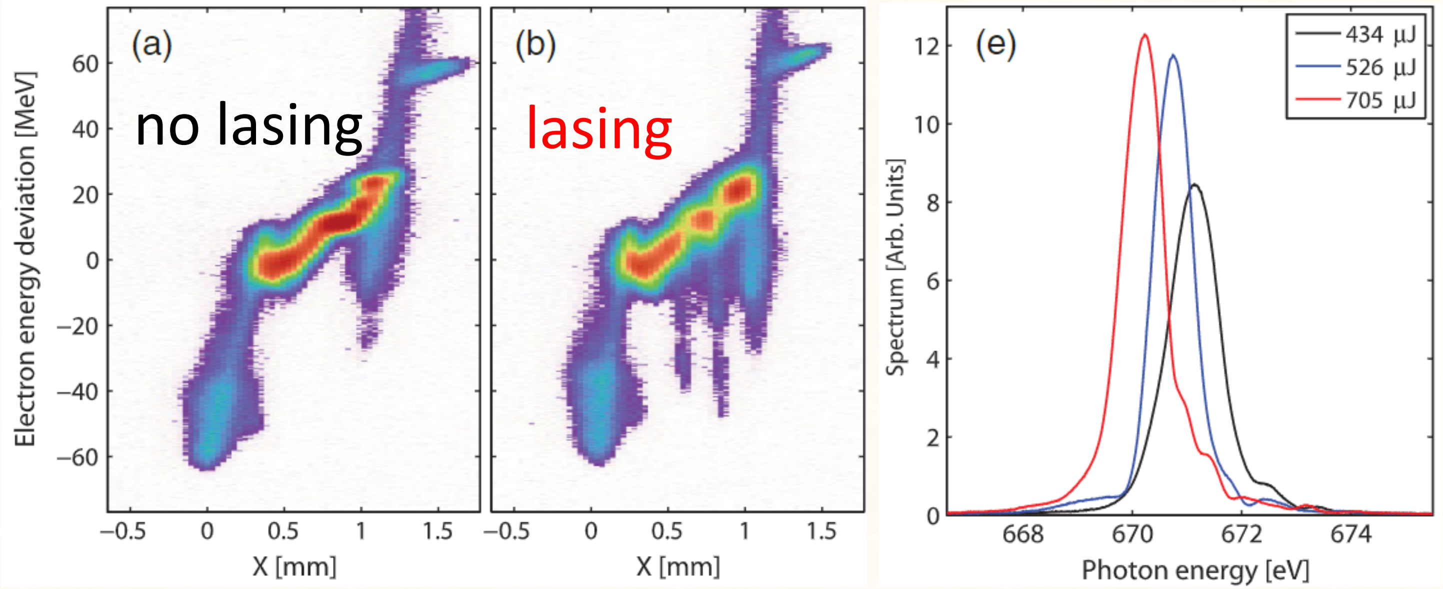
Transversely tilted beam: E. Prat et al. (2015)



Idea: E. Prat et al, PRSTAB 18 (2015), 100701.

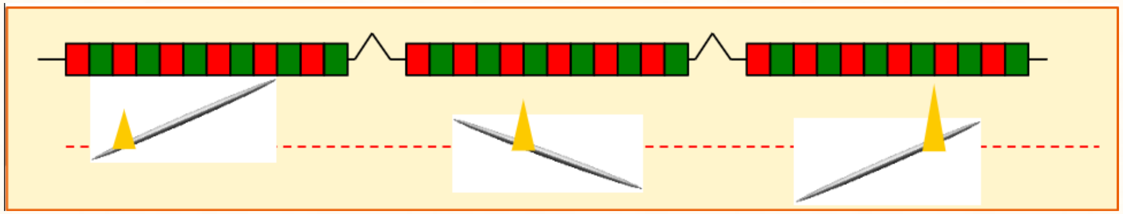
Experiment: A. Lutman et al, PRL 120, (2018) 264801.





- 670 eV
- ~ 1 eV FWHM
- ~ 2 fs FWHM
- 13% single spike
- 300 uJ

Transversely tilted beam: E. Prat et al. (2015)



Idea: E. Prat et al, PRSTAB 18 (2015), 100701.

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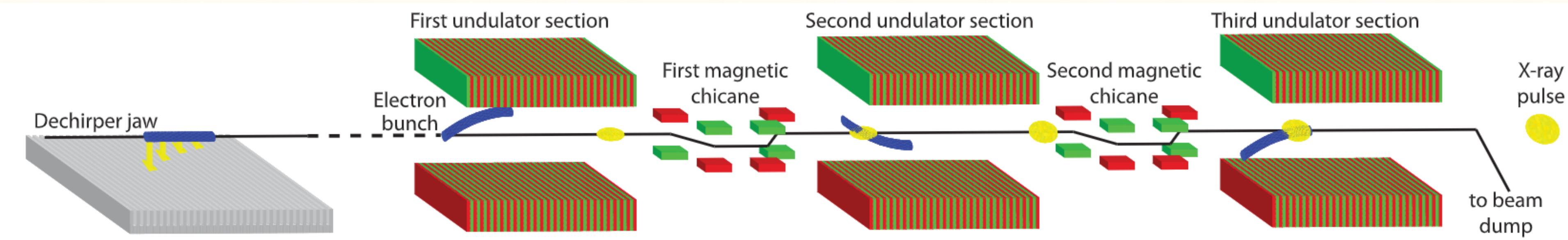
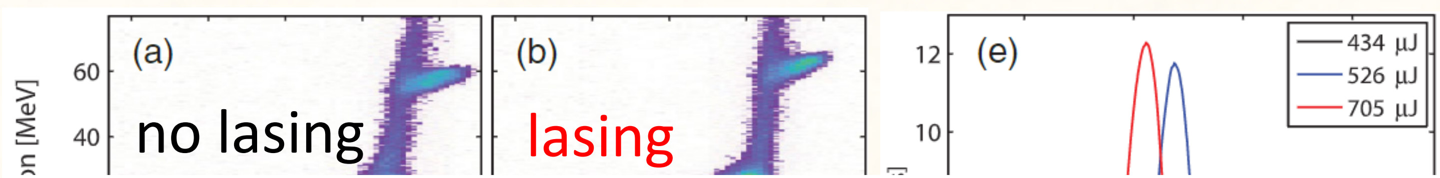
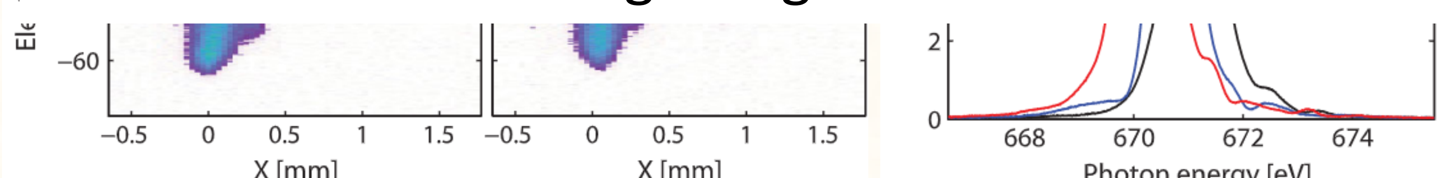


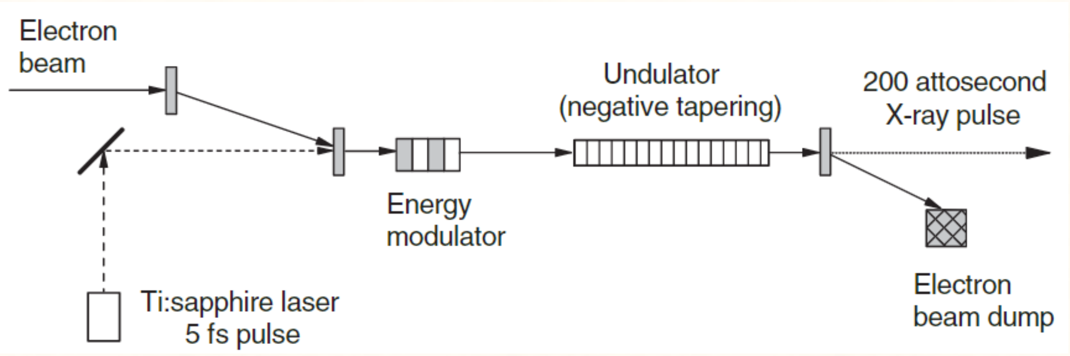


In another **experiment** "Y. Chao et al, PRL 121 (2018) 064802" slice-selective lasing is demonstrated using transverse mismatching along the beam.

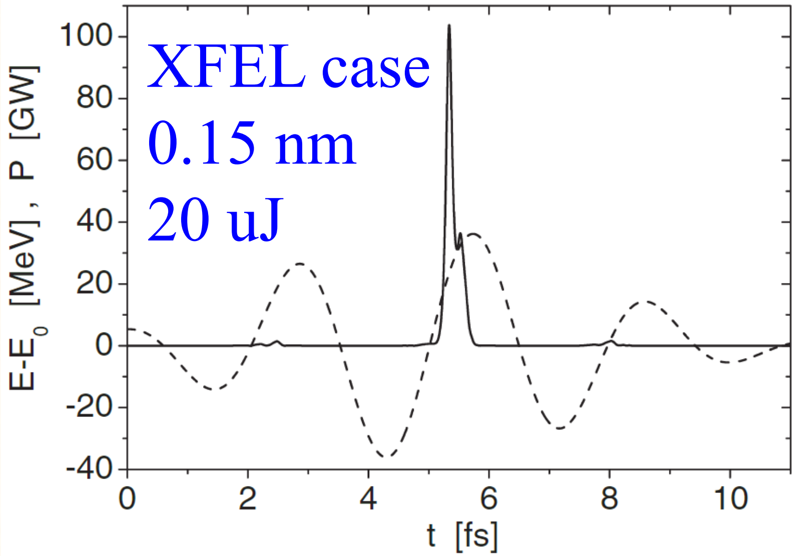


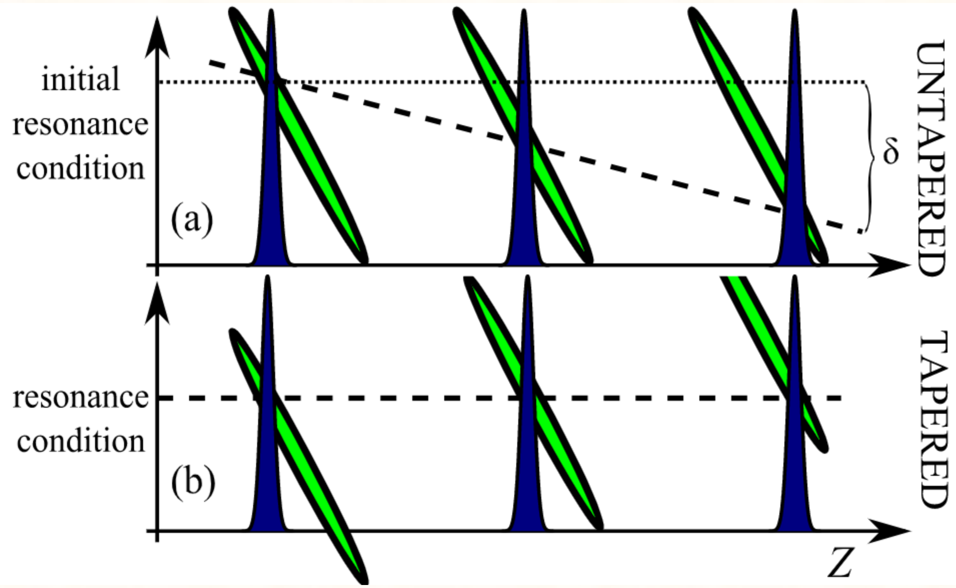
- 670 eV
- ~ 1 eV FWHM
- ~ 2 fs FWHM
- 13% single spike
- 300 uJ

Tapered FEL with an energy chirped beam

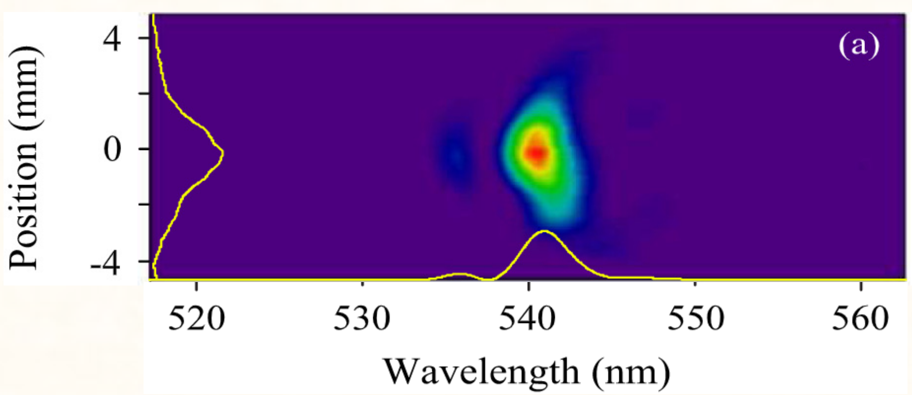


E.L. Saldin et al. PRSTAB 9,050702 (2006).

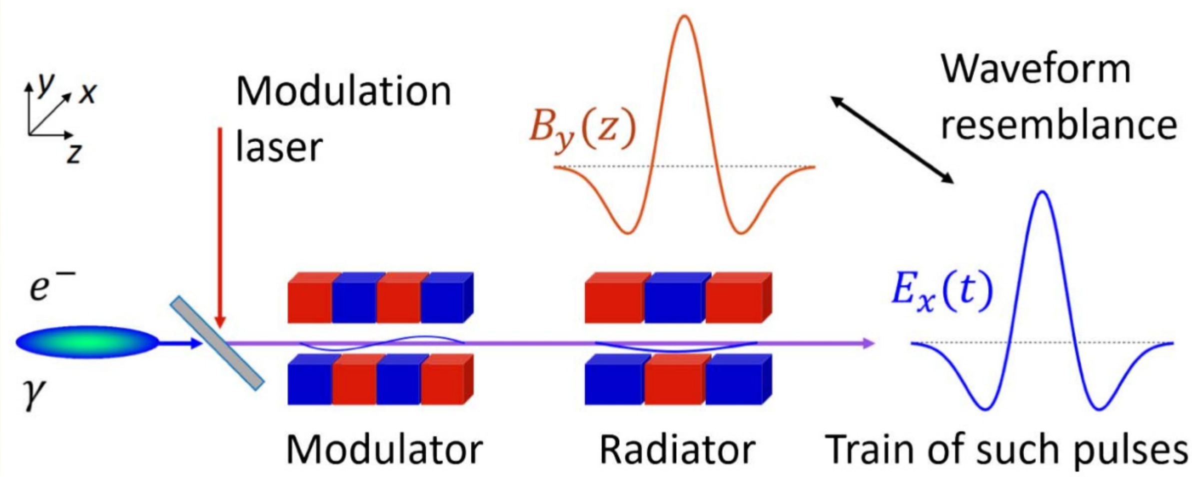




Experiment in the visible range: L. Giannessi et al. PRL**106**,144801 (2011).

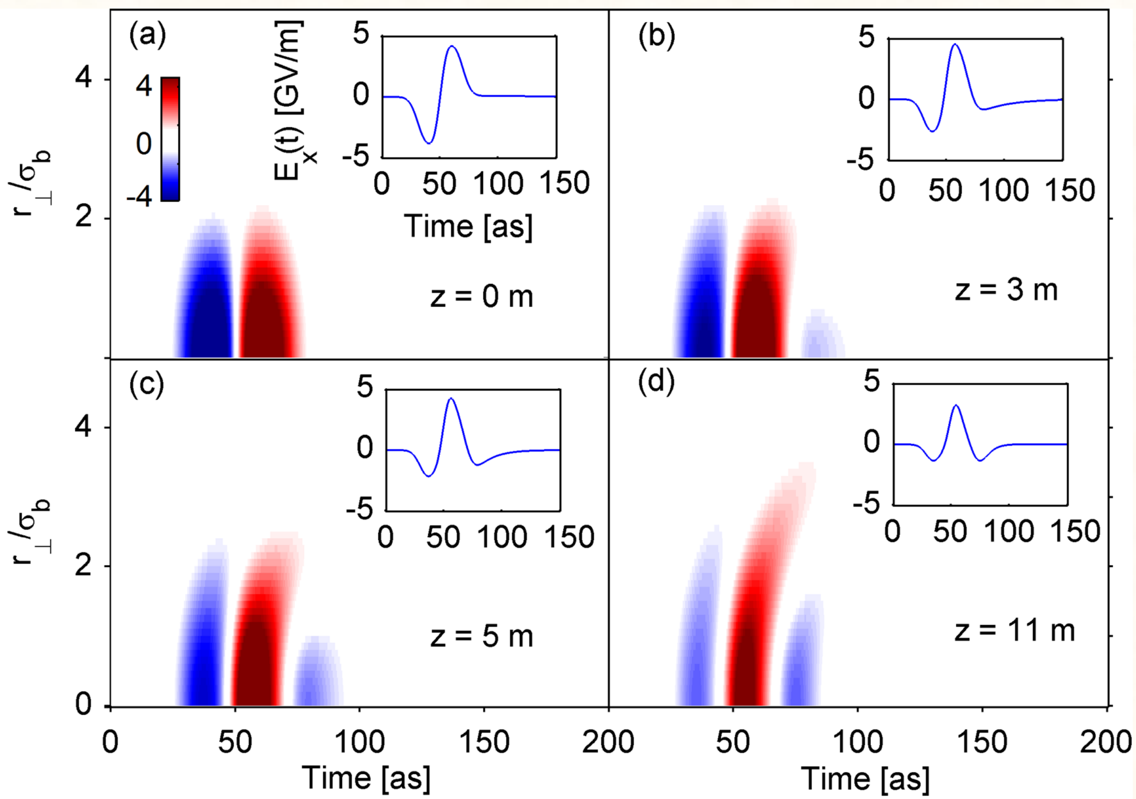


CEP-stable radiation from a single-period undulator



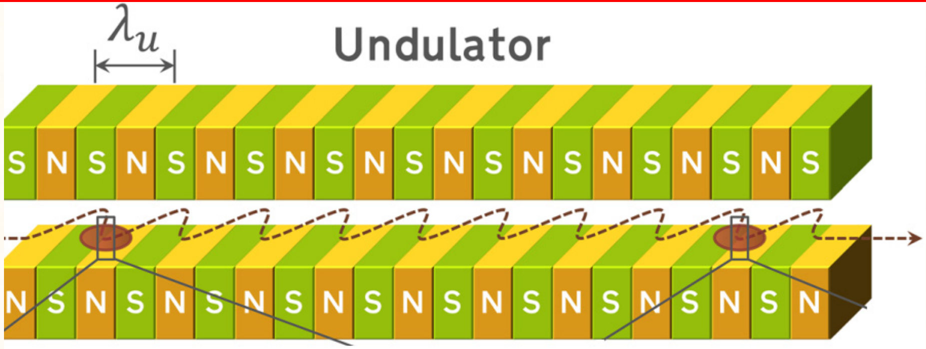
Tibai et al., PRL 113 (2014) 104801.

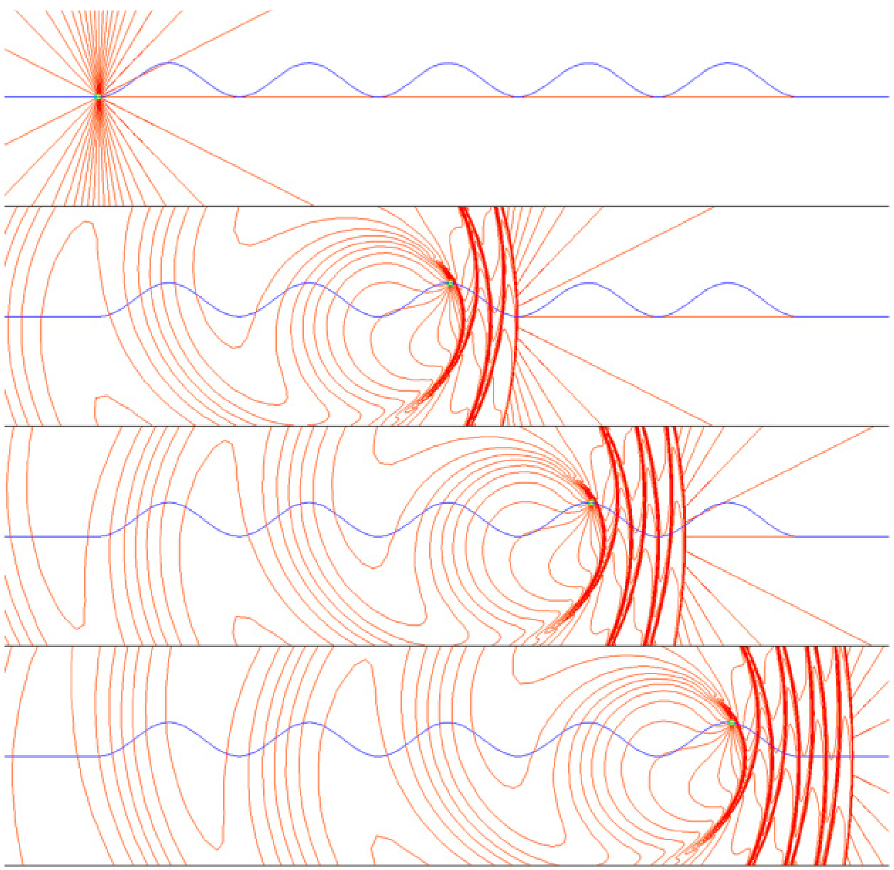
G. Shamuilov et al., Optics Lett. 43 (2018) 819.



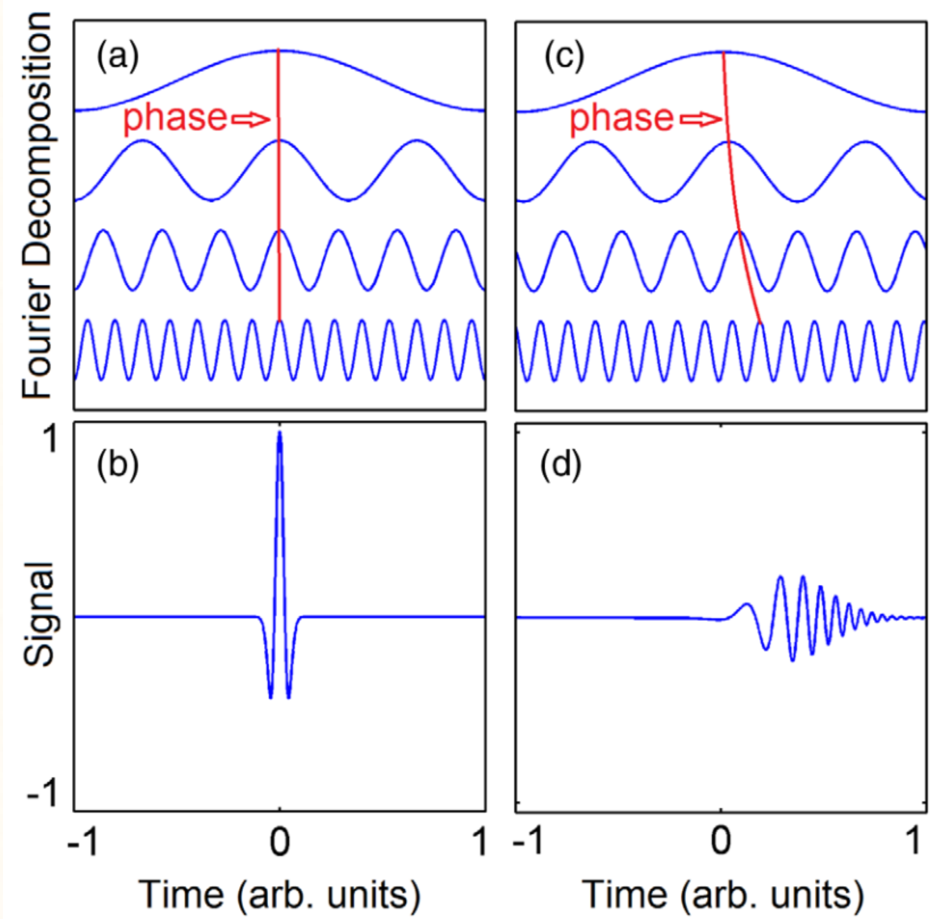
- Bunch energy 1.5 GeV
- Bunch radius 150 µm,
- Charge 4 pC,
- K of radiator 1
- Radiator period 4 cm
- Wavelength 18 nm
- Pulse energy 68 nJ
- Pulse duration 26 as FWHM

From multi-cycle to CEP-stable single-cycle pulses



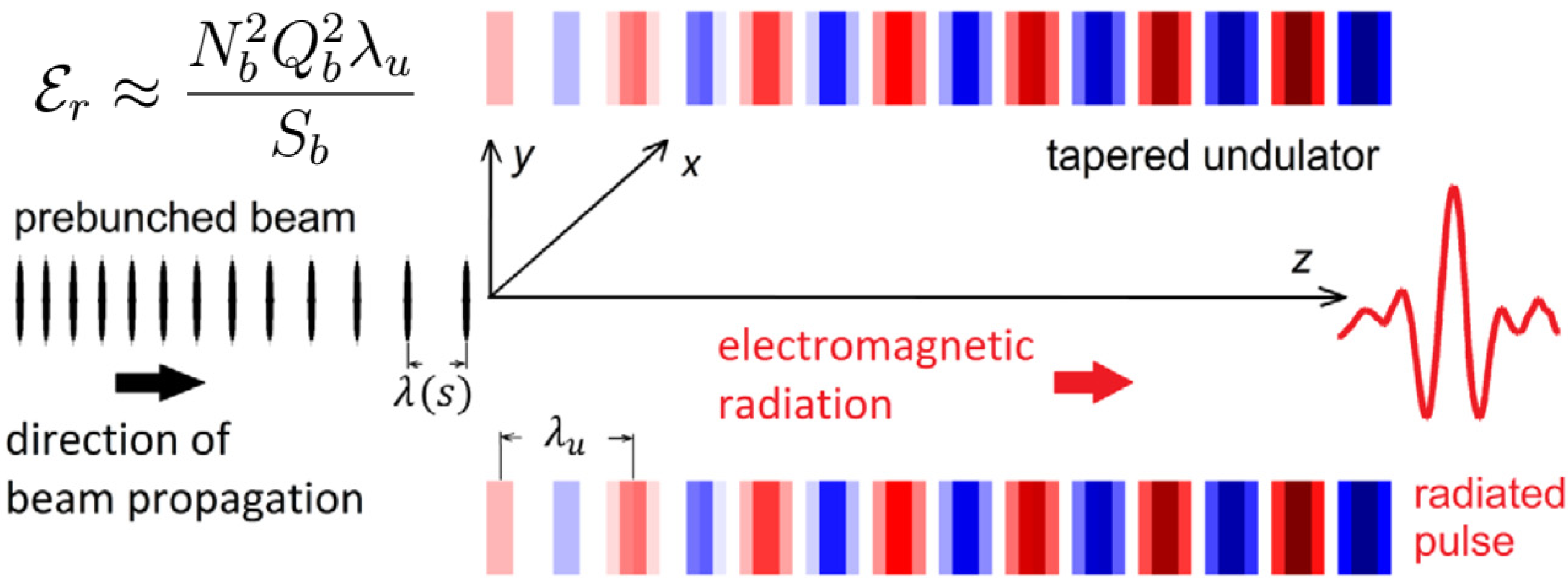


$$f(t) = \left(1-\frac{t^2}{\sigma_t^2}\right)\mathrm{e}^{-t^2/2\sigma_t^2},$$



Single-cycle pulses from tapered undulator: Tanaka, PRL (2015)

$$\mathcal{E}_r \approx \frac{N_b^2 Q_b^2 \lambda_u}{S_b}$$

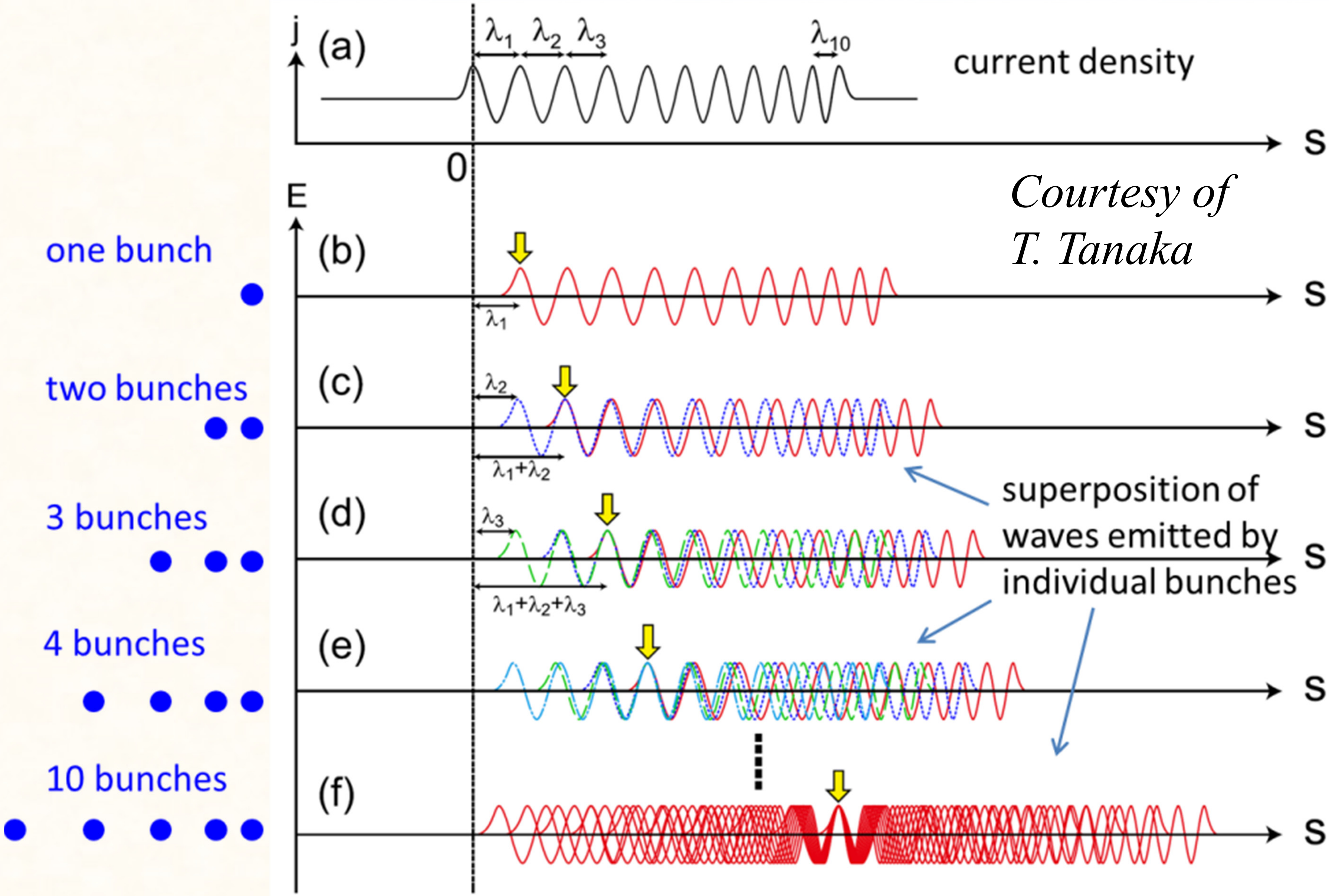


- Periodic undulator field with varying strength $B_0(z)\cos(2\pi z/\lambda_u)$
- A train of electron bunches (prebunched beam)
- Radiation wavelength changes along the pulse

$$\lambda(z) = \frac{\lambda_u}{2\gamma^2}\left[1 + \frac{\mathcal{K}(z)^2}{2}\right], \qquad \mathcal{K}(z) \propto B_0(z).$$

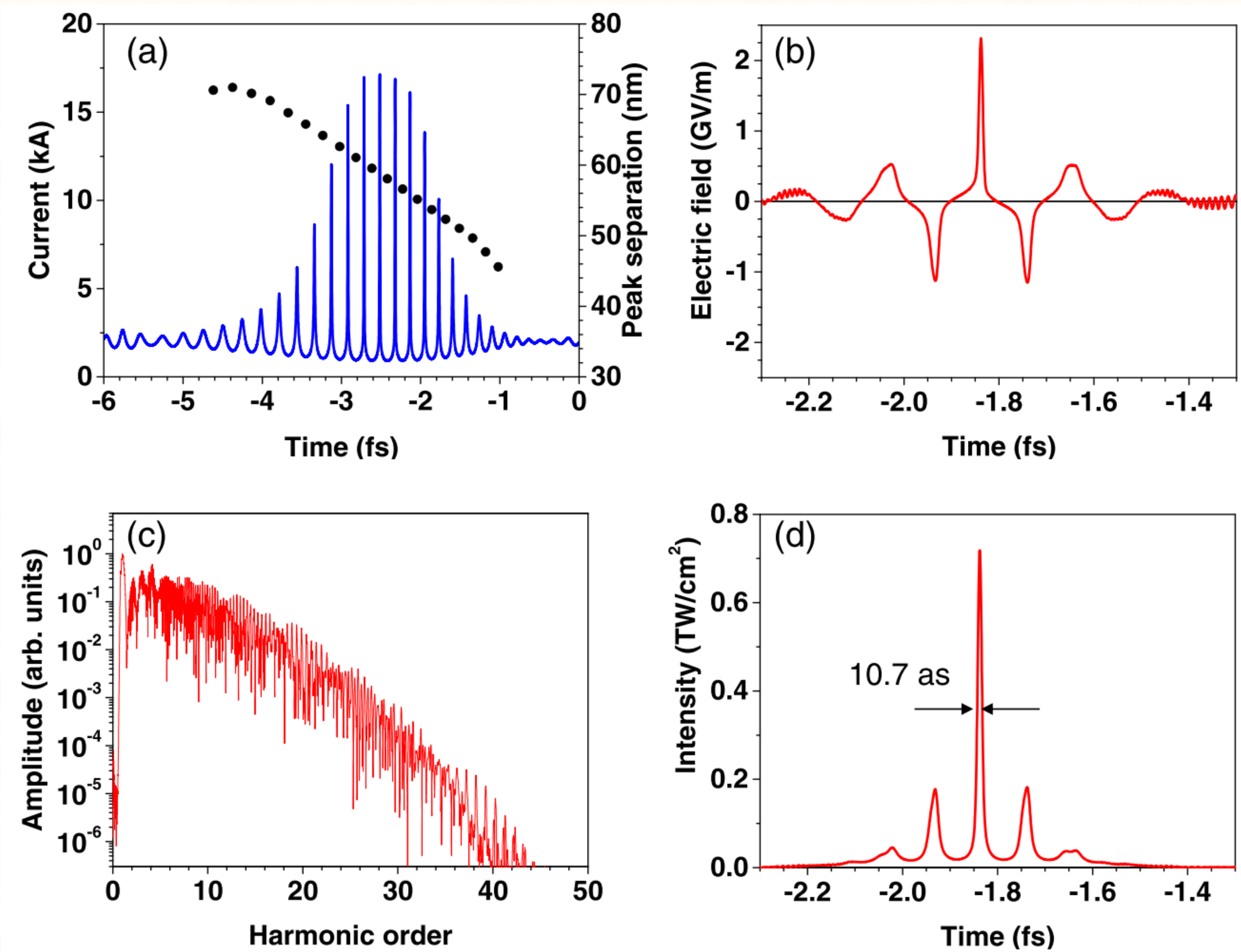
See also V. Goryashko "Quasi-half-cycle pulses of light from a tapered undulator," Phys. Rev. Acc. & Beams, 2017.

How it really works



Pulse waveform can be controlled by taper profile.

Pushing the limit: Y. Kida et al. APL 109, 151107 (2016)



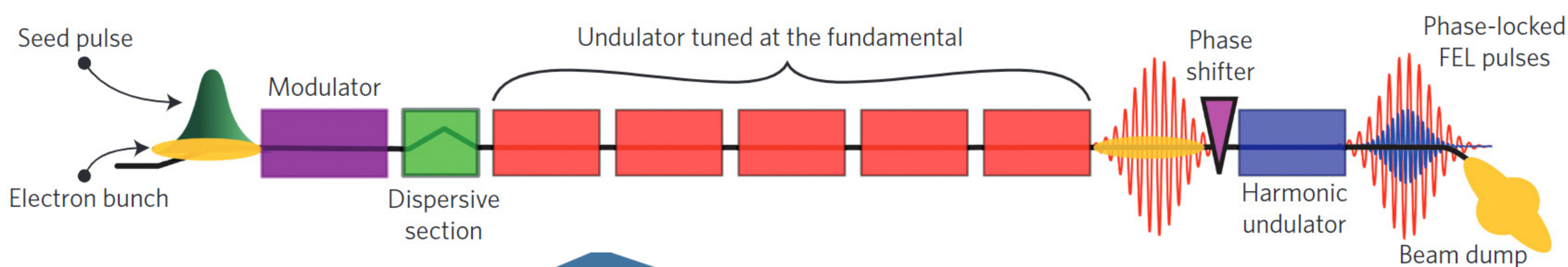
Beam:
2 GeV
2 kA
0.4 um
10^{-4} spread

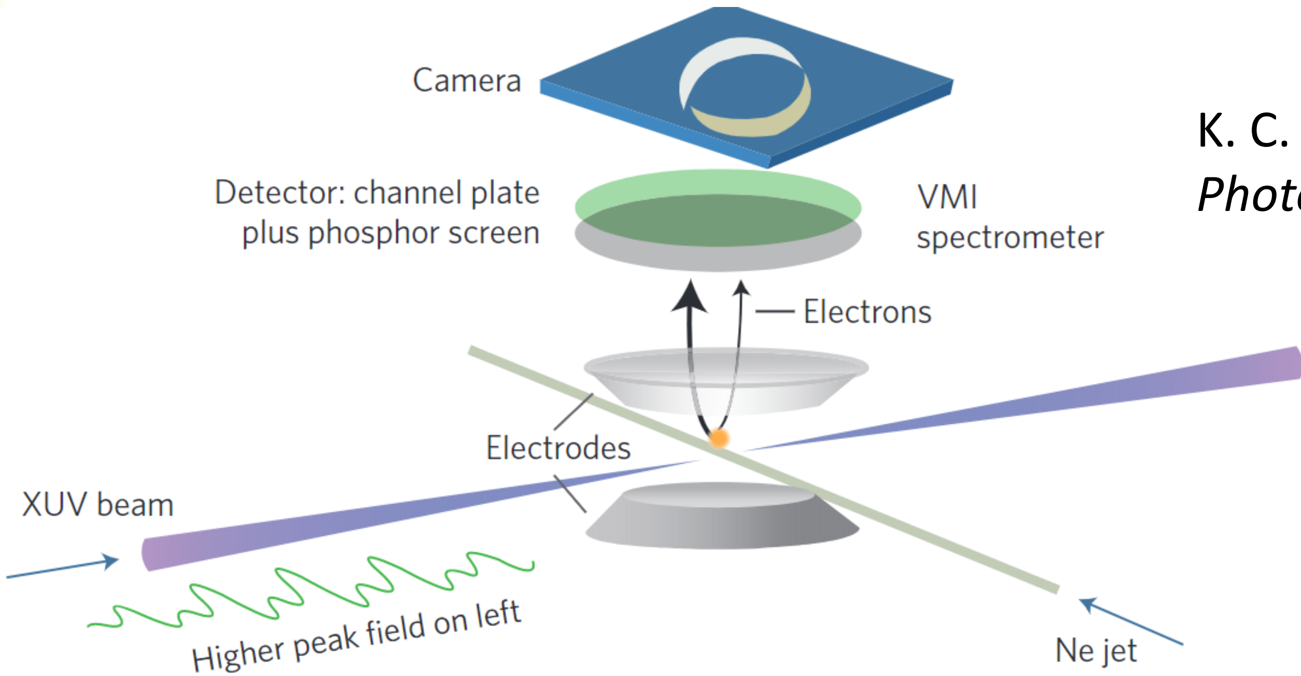
Undulator:
K = 3.5-4.5
λ_u =17cm
30 periods

Seed:
HHG
60 nm
0.38 fs
25 TW/cm^2

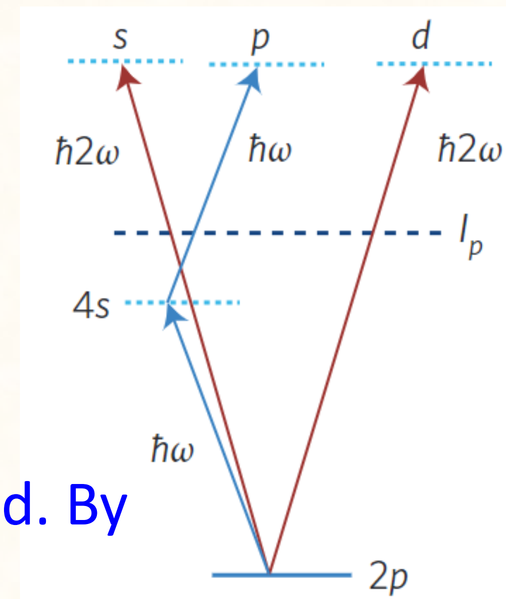
Photon energy range extents to ~ 850 eV

CEP-stable attosecond interference at FERMI



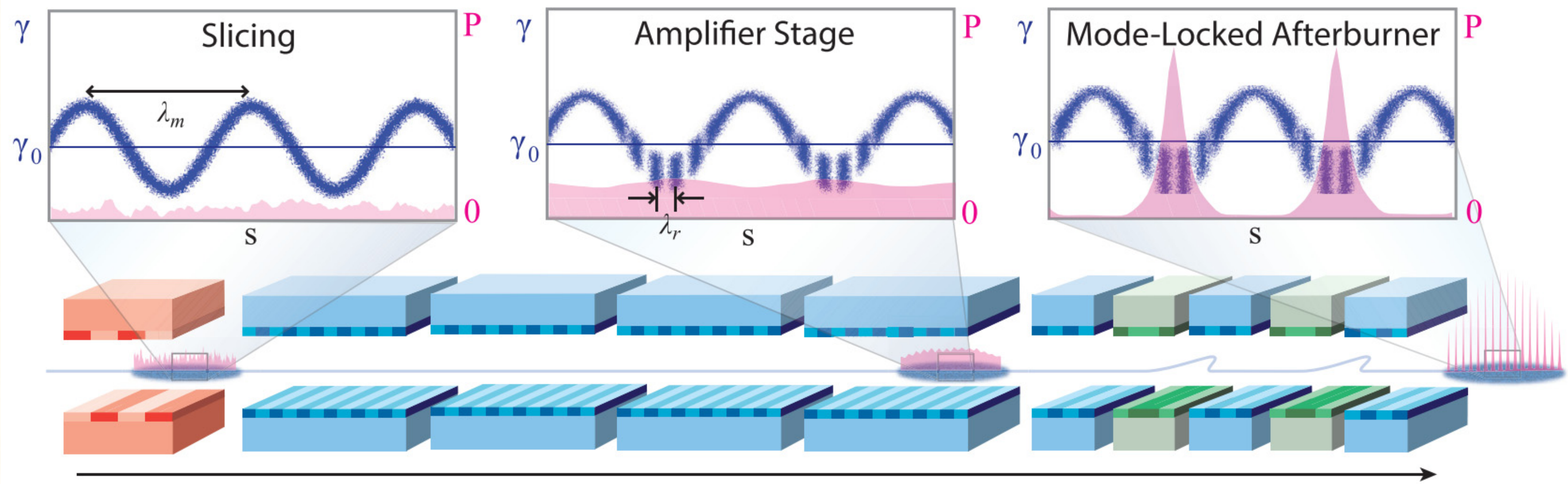


K. C. Prince *et al.*, *Nature Photonics* **10**, 176–179 (2016).

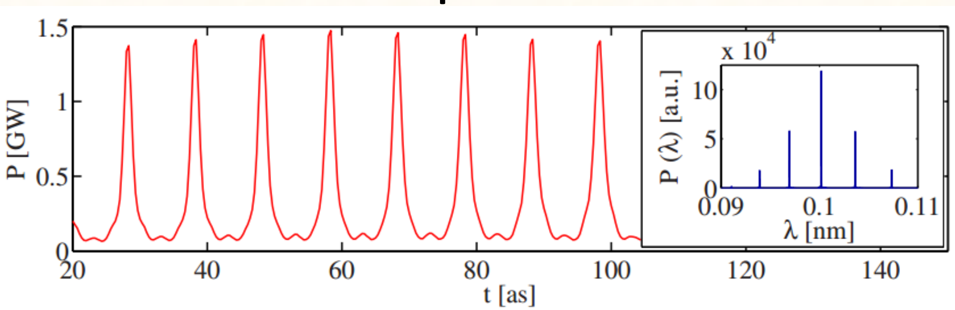


Two colors produce a beat wave with 105 as period. By adjusting the relative phase with 3 as precision, a quantum system is driven into a specific final state.

Mode-locked afterburner



SACLA-like parameters



Thanks to mode locking, the FEL pulse has internal CEP stability. No stability from shot to shot.

The mode-locked afterburner "D. J. Dunning et al., PRL 110, 104801 (2013)" may extend FERMI-type experiments on the coherent control of the quantum path to the hard X-ray region.

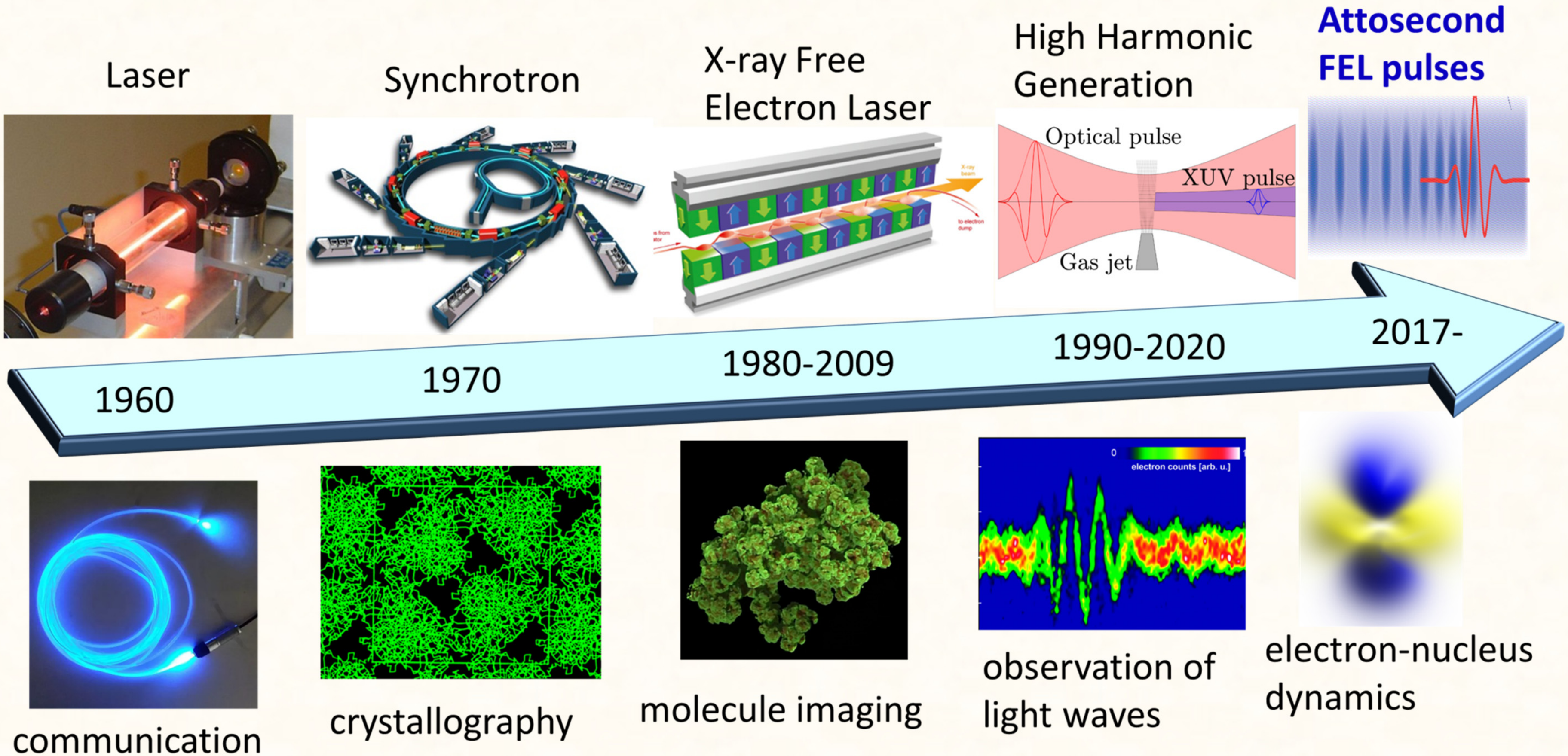
See C. Feng et al. PRSTAB 15, 080703 (2012) for a mode-locked seeded FEL.

Examples of science requirements and FEL solutions

Example of science applications	Essential requirements	Comments	Suitable FEL schemes
Imaging of biomolecules & matter under extreme conditions	$10^{12} - 10^{13}$photons ~ 0.5 fs resolution 0.3-10 keV	No major changes on detector side	• Beam tilt • Current enhancement
Spectroscopic mapping of electronic structure	$\sim 10^{11}$ photons > 10 fs resolution wavelength stability ~1 keV	Traditional synchrotron community	• single-spike SASE • XLEAP
Probing electronic wavefunctions with attosecond interferometry	$\sim 10^{8}$ photons CEP stability (?) ~ 100 eV ~ 0.1 fs resolution	HHG user community	• Mode-locked FEL • Short-pulse seeded FEL
Electronic dynamics by attosecond transient absorption	$\sim 10^{7}$ photons ~ 0.1-1 keV ~ 0.1 fs resolution	HHG user community	• Coherent undulator radiation

Different FEL schemes may find their niche applications.

Summary: looking towards the bright future



FELs capable of producing *tailored light pulses at the highest intensities and shortest time scales.*

Thank you for your attention!