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Towards Zeptosecond-Scale Pulses from X-Ray Free-Electron Lasers

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The Cockcroft Institute of Accelerator Science and Technology

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- **History of short pulse development**
  - Lasers, HHG, present state-of-the-art
  - Uses
- **Short-pulse potential of FELs**
  - Potential to surpass present state-of-the-art
- **Existing short pulse concepts for FELs**
  - Issues in going to even shorter pulses
- **New method**
  - Particularly short pulses
  - Could be applied on existing facilities

Note: the motivation is to investigate what is possible to extend the versatility and flexibility of FELs. Possible applications may be in ways we don't expect – e.g. focus on ultra-short pulses also gives ultra-broad bandwidth.

Short pulses - a brief review

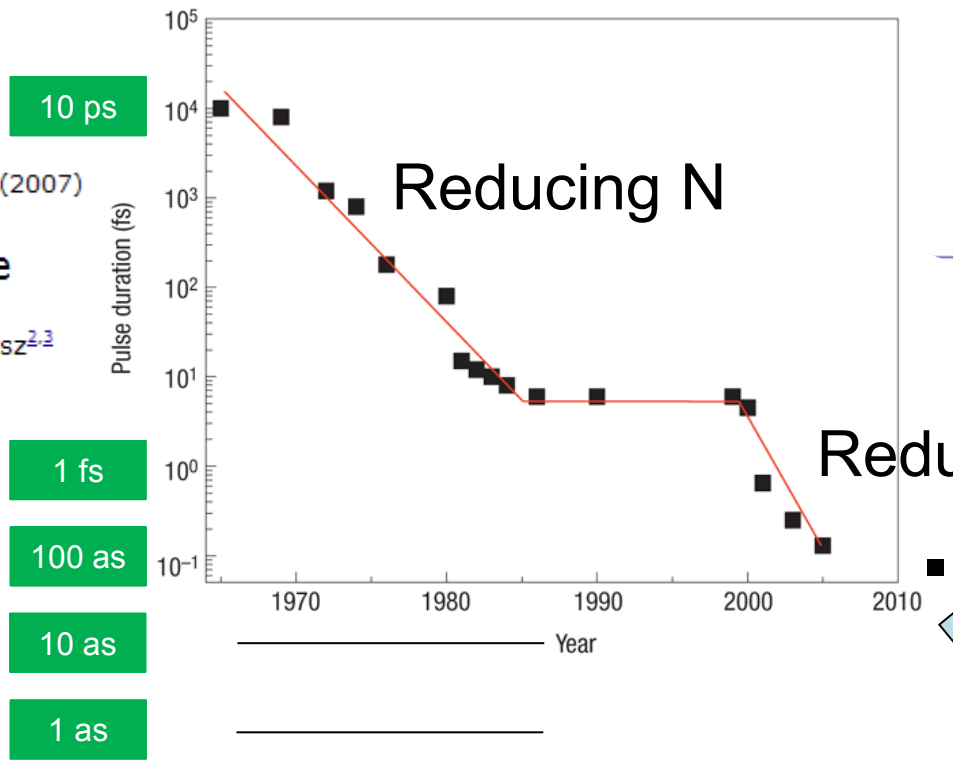
- Record for shortest pulse of light against year: ~10 ps in 1960's to ~67 as (1as=10^{-18}s) - five orders of magnitude reduction over five decades.
- Conventional lasers operating at ~fixed wavelength progressed in terms of number of cycles (N), until they could proceed little more.
- Transformative step for progress to continue: High Harmonic Generation (HHG) – reduced the wavelength (λ) and entered attosecond scale .
- Shorter wavelength required to progress further : e.g. HHG: C. Hernandez-Garcia et al. PRL 111, 033002 (2013) – FELs a promising candidate.

Nature Physics **3**, 381 - 387 (2007)
doi:10.1038/nphys620

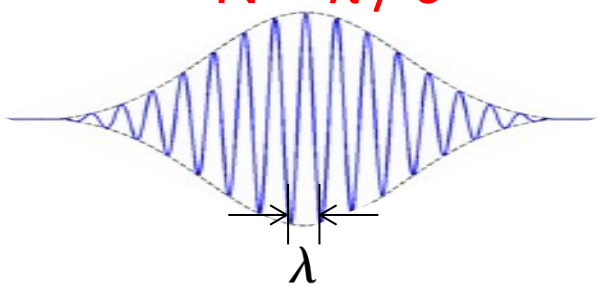
Attosecond science

P. B. Corkum[1] & Ferenc Krausz[2,3]

+ modified to include recent HHG result and possible future development



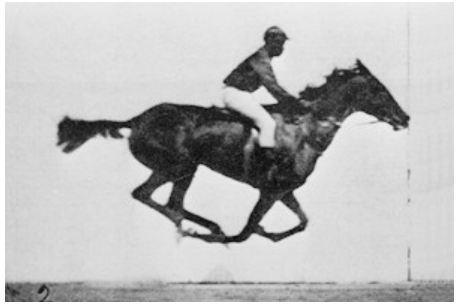
Pulse duration = N × λ / c

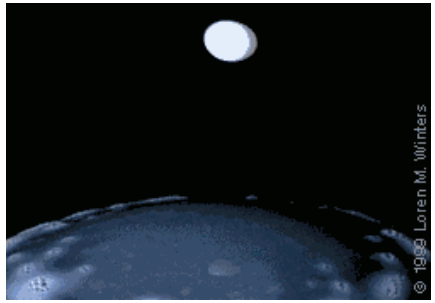


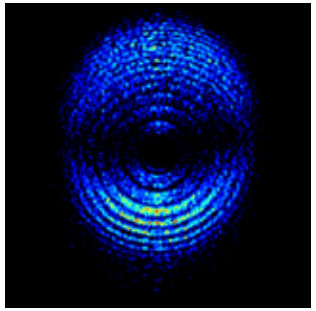
FELs?

Motivation for short pulses

- The motivation for short pulses is to study (and influence) ultra-fast dynamic processes – need radiation pulses on shorter scale than dynamics to be studied.







Left to Right:
E. Muybridge ~1878 Shutter time ~1e-3 sec

H.Edgerton ~1931 Flash ~1e-6 sec

J. Mauritson et al. PRL 100, 073003, 2008

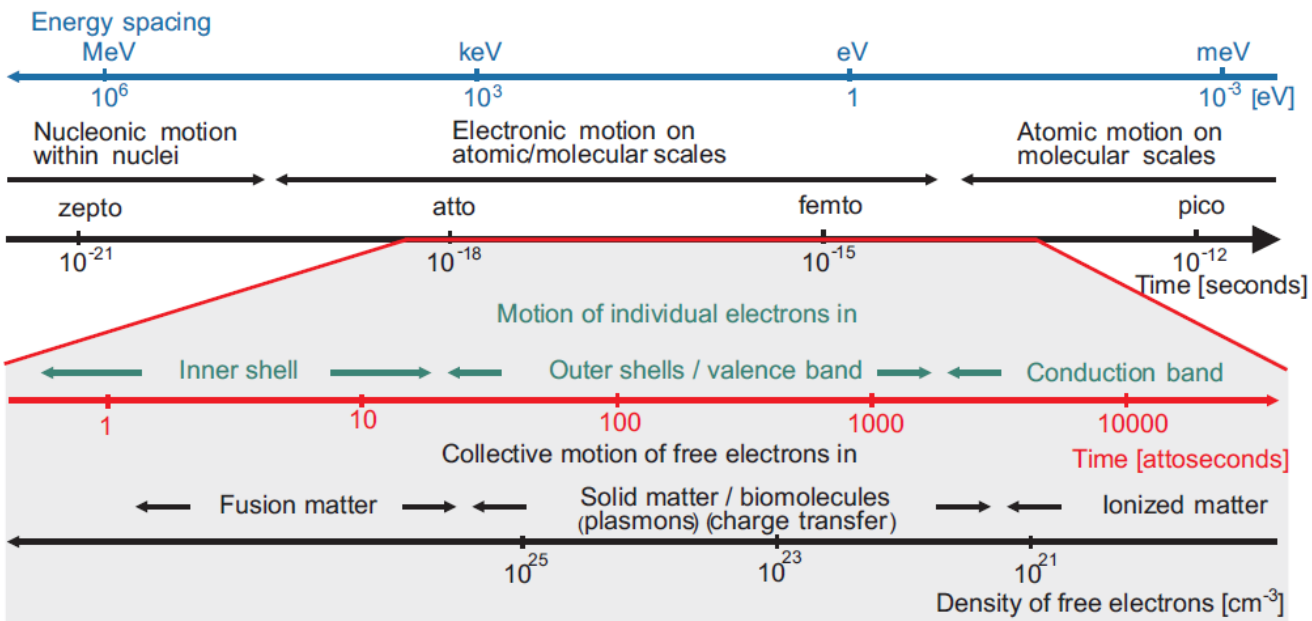


FIG. 2. (Color) Characteristic time scales for microscopic motion and its connection with energy spacing between relevant stationary states (upper panel); characteristic time scales for the motion of one or several electrons and for the collective motion of an electronic ensemble (lower panel).

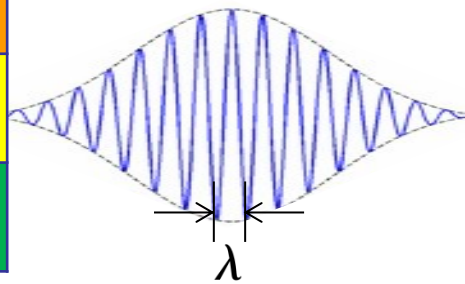
F.Krausz, M. Ivanov, Rev. Mod. Phys, 81, 163, 2009.

Short-pulse potential of free-electron lasers

- The FEL has two advantages giving it potential to push the short-pulse frontier.
- **Short wavelength** – a few-cycle pulse at 0.1 nm would correspond to pulses of ~1 attosecond duration, a factor of ~100 over present HHG sources operating at ~10 nm (~100 attoseconds) and a factor of ~10,000 over conventional lasers operating at ~800 nm (~10 fs).

	N=1000	N=100	N=10	N=1
Lasers @~800nm	3 ps	300 fs	30 fs	3 fs
HHG @~10nm	30 fs	3 fs	300 as	30 as
FEL @~0.1nm	300 as	30 as	3 as	300 zs

Pulse duration = N × λ / c



- **Peak power** – a hard x-ray (0.1 nm) FEL at 20 GW is 10^{25} photons/second – corresponds to 10^{7} photons/pulse for few-cycle (i.e. 1 attosecond) pulse. Very challenging for other sources to match this.
- The challenge for reaching the very shortest pulses from FELs will be to **minimise the number of cycles per pulse.**

SASE

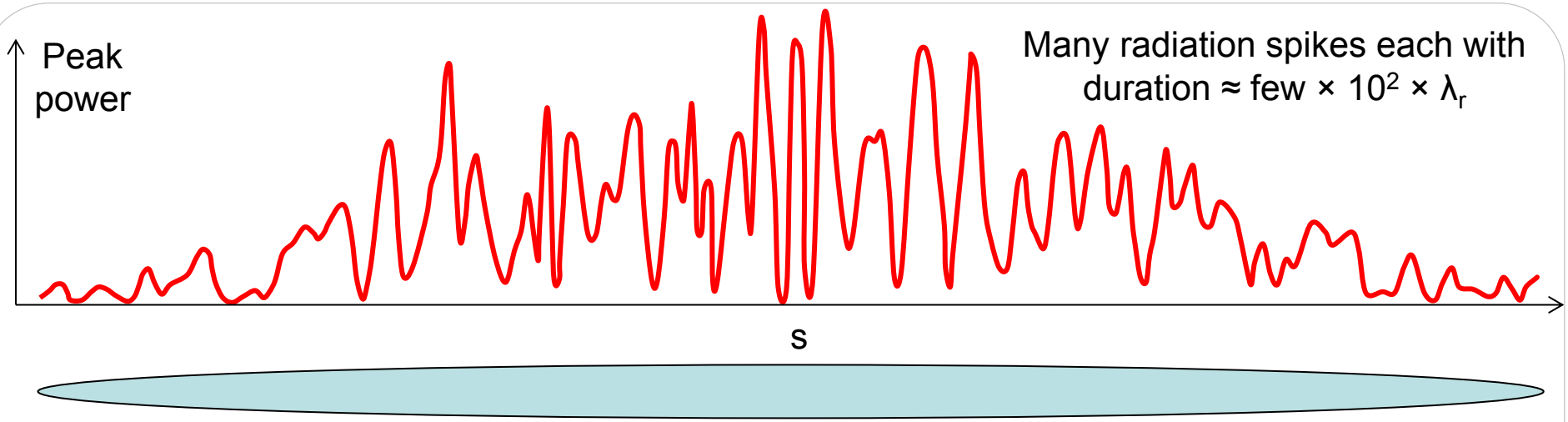
- First consider self-amplified spontaneous emission (SASE).
- A relativistic electron bunch traverses a long undulator and exponential amplification of both radiation intensity and electron beam micro-bunching, *b*, occurs, starting from noise.

$$b = \langle e^{-i\theta_j} \rangle$$

- The total length of the emitted radiation pulse is on the scale of the electron bunch and is relatively long in this context e.g. a few fs corresponds to ~$10^4 \times \lambda_r$ at 0.1nm.
- In an undulator a resonant radiation wave-front propagates ahead of the electrons at a rate of one radiation wavelength (λ_r) per undulator period (λ_u).

$$l_c = \lambda_r / 4\pi\rho$$

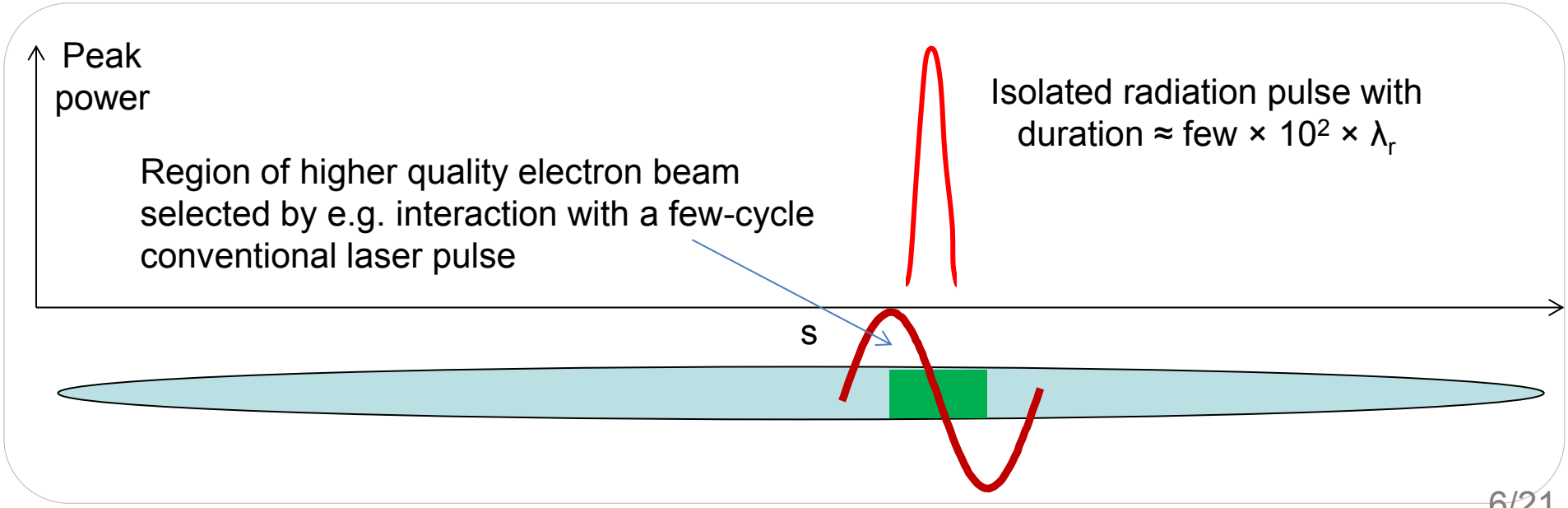
- The slippage in one gain length is called the **"co-operation length" - l_c** – and sets a much shorter-scale sub-structure in the radiation profile –~few hundred × λ_r in x-ray FELs.



The electron bunch is relatively long, e.g. ~few fs = ~ $10^4 \times \lambda_r$ (not to scale)

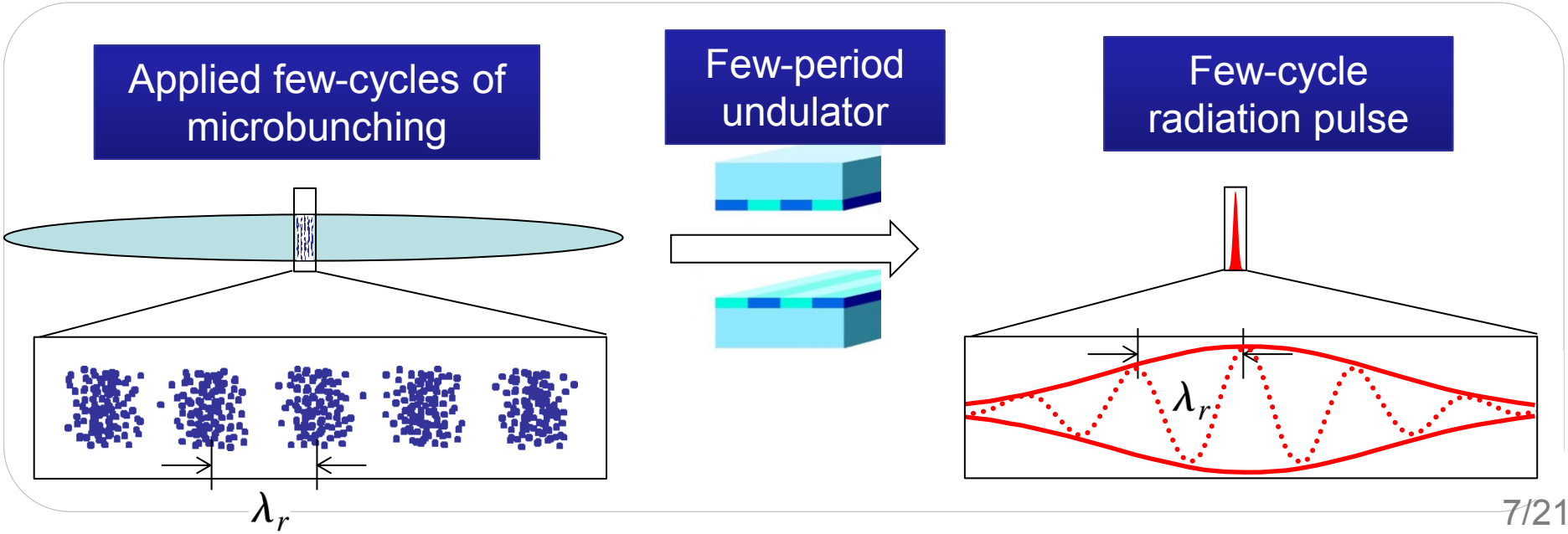
Slicing a single SASE spike

- Each SASE spikes acts independently - can reduce the bunch length or 'slice' the electron beam quality so only one spike occurs – several proposals and experiments:
  - Reducing bunch length: e.g. Y. Ding et al. PRL, 102, 254801 (2009).
  - Emittance spoiling: e.g. P. Emma et al. Proc. 26th FEL Conf. 333 (2004), Y. Ding et al. PRL, 109, 254802 (2012).
  - Current enhancement: e.g. A. Zholents et al. New J. Phys. 10, 025005, (2008).
  - Energy modulation: e.g. E.L. Saldin et al. PRST-AB 9, 050702, (2006), L. Giannessi et al. PRL 106, 144801, (2011).
- The minimum pulse duration is usually one SASE spike, for hard x-ray FEL parameters corresponds to a few hundred cycles or ~100 as – close to record from HHG – and at shorter wavelength and higher photon flux . Fantastic potential for experiments.
- Potential for a further two orders of magnitude reduction with fewer cycles per pulse.



Few-cycle pulses from amplifier FELs?

- A few-cycle radiation pulse can only interact with a fixed point in the electron beam for a few undulator periods before slipping ahead of it.
- Exponential amplification not possible? (requires a sustained interaction between radiation and electrons to develop micro-bunching)
- Even if a few-cycle region of high micro-bunching can be imposed then a very short (few-period) undulator must be used to avoid the slippage effect broadening the emitted pulse – such examples predict relatively low power but very short pulses (e.g. tens of attoseconds):
  - Alexander A. Zholents and William M. Fawley , Phys. Rev. Lett. 92, 224801 (2004)
  - D. Xiang et al. Phys. Rev. ST Accel. Beams 12, 060701, (2009)
- Many promising ideas in this area (see e.g. A. Zholents "Intense Attosecond Pulses from X-ray Free-Electron Lasers", UCLA Workshop (2009) for overview)



A new method for few-cycle pulse generation in an x-ray FEL

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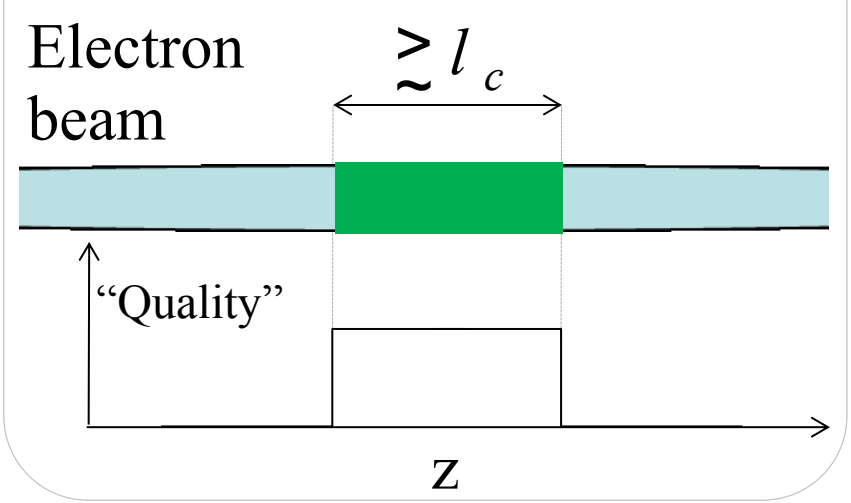
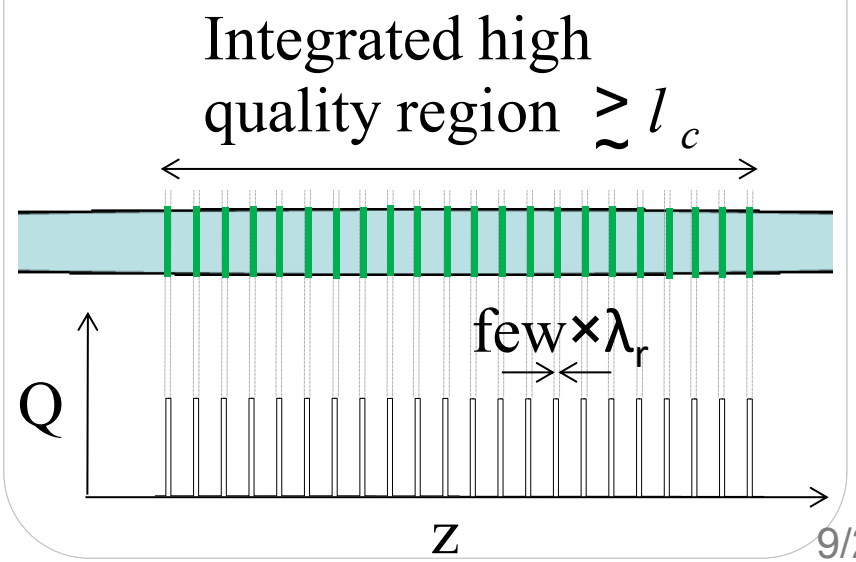
Introduction to new method

- Our proposal is to use FEL amplification but to do in such a way that we beat the limit imposed by the co-operation length.
- We still need a region of high quality electron beam with length on the scale of the co-operation length – but the key point is that it <u>does not need to be continuous.</u>
- We propose to slice a series of few-cycle regions
  - In isolation each is insufficient to support FEL amplification.
  - However by positioning a number of these regions fairly closely spaced they can interact via the radiation slipping between them, and amplification can occur.
- <u>Effectively trading isolated many-cycle pulse for multiple few-cycle pulses</u>

Single many-cycle region

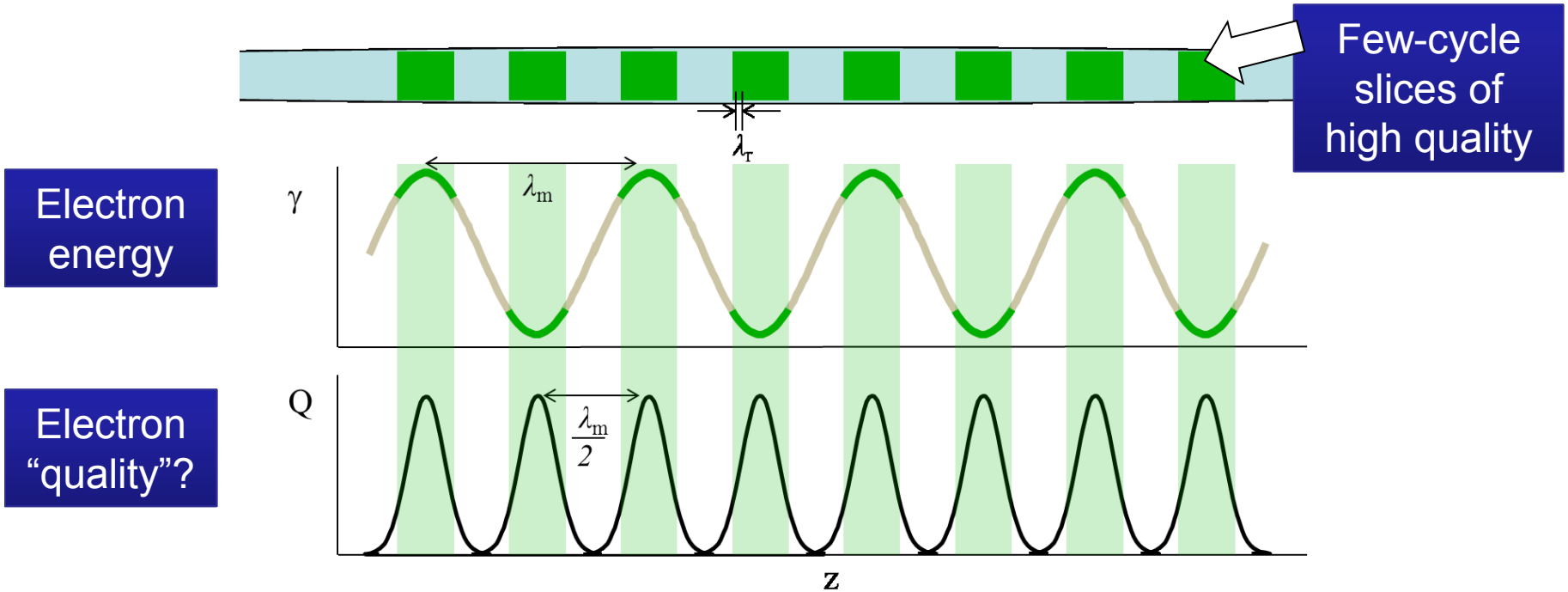


Multiple few-cycle regions



Generating a series of few-cycle slices

- Aiming to generate a series of few-cycle slices of higher quality beam.
- Could consider variation in emittance, current, energy modulation, etc.
- Here we propose to use energy modulation – with period typically ~10-100 times our operating FEL wavelength – so this should be feasible with HHG + short modulator undulator, already present at several facilities.
- The expectation was that this sinusoidal energy modulation would correspond to variation in electron beam quality in some way, e.g. higher quality beam (low energy chirp) and lower quality beam (high energy chirp).

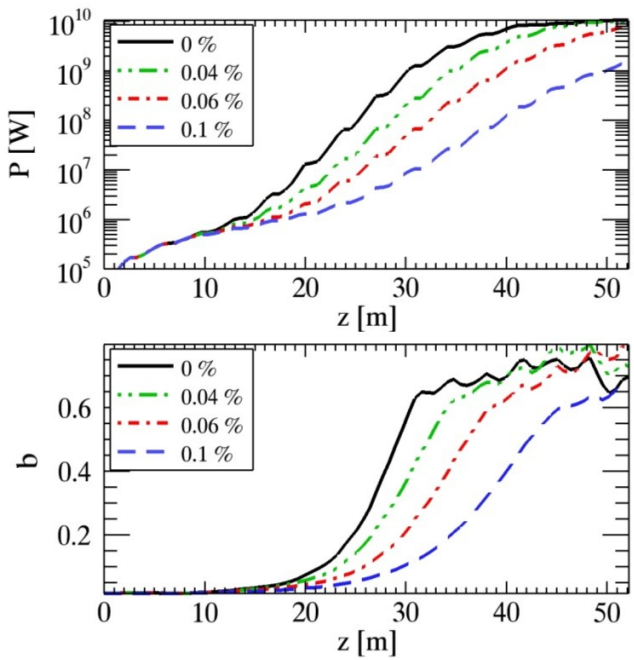


Modulated beam - simulation results

- Energy modulated beam in amplifier FEL gives interesting effects.
- Simulations of a soft x-ray FEL at 1.24 nm. Starts from noise.
- Applied sinusoidal energy modulation, period ~30xλ_r (=40nm).
- Varied modulation amplitude.
- Amplification rate reduces with increasing modulation amplitude.
- Only minor changes in radiation profile – increased I_c + 'ripple'
- Generates well-defined comb structure in e-beam micro-bunching.

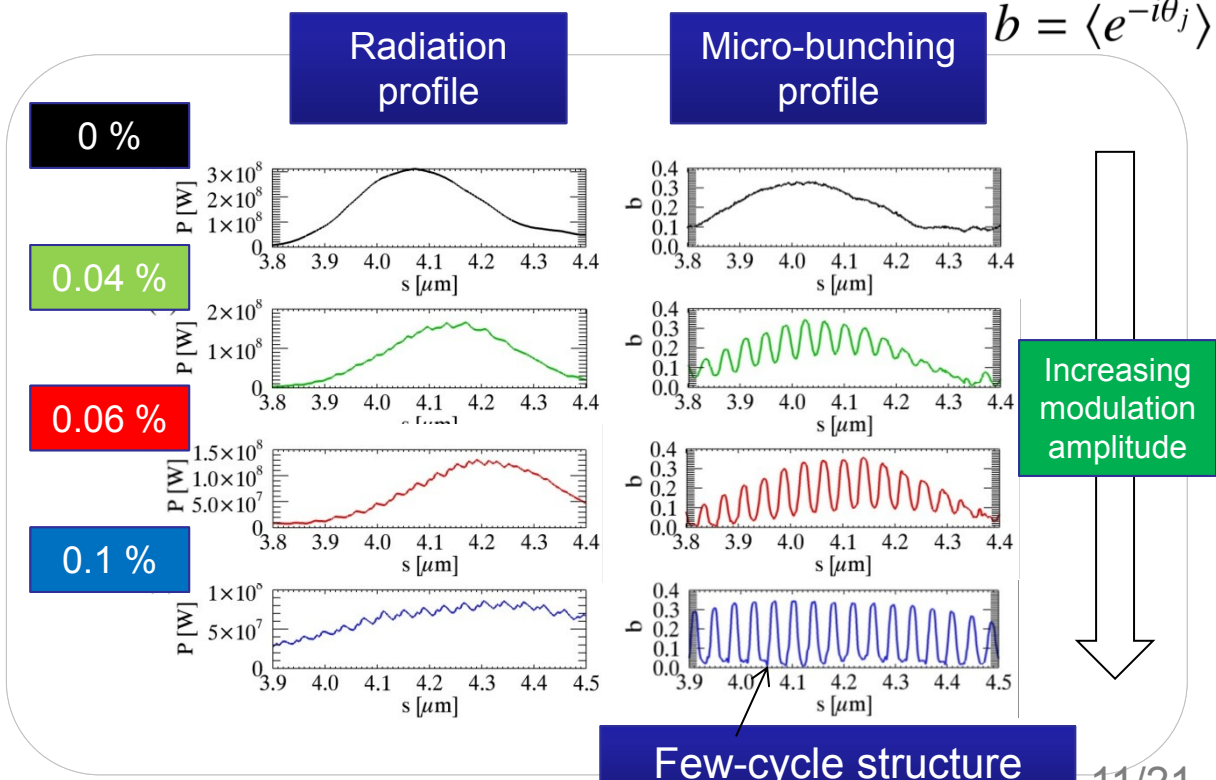
Soft x-ray 1.24 nm example

Parameter	Soft x ray
Amplifier stage	
Electron beam energy [GeV]	2.25
Peak current [kA]	1.1
ρ parameter	1.6×10^{-3}
Normalized emittance [mm-mrad]	0.3
rms energy spread, σ_γ/γ_0	0.007%
Undulator period, λ_u [cm]	3.2
Undulator periods per module	78
Resonant wavelength, λ_r [nm]	1.24
Modulation period, λ_m [nm]	38.44



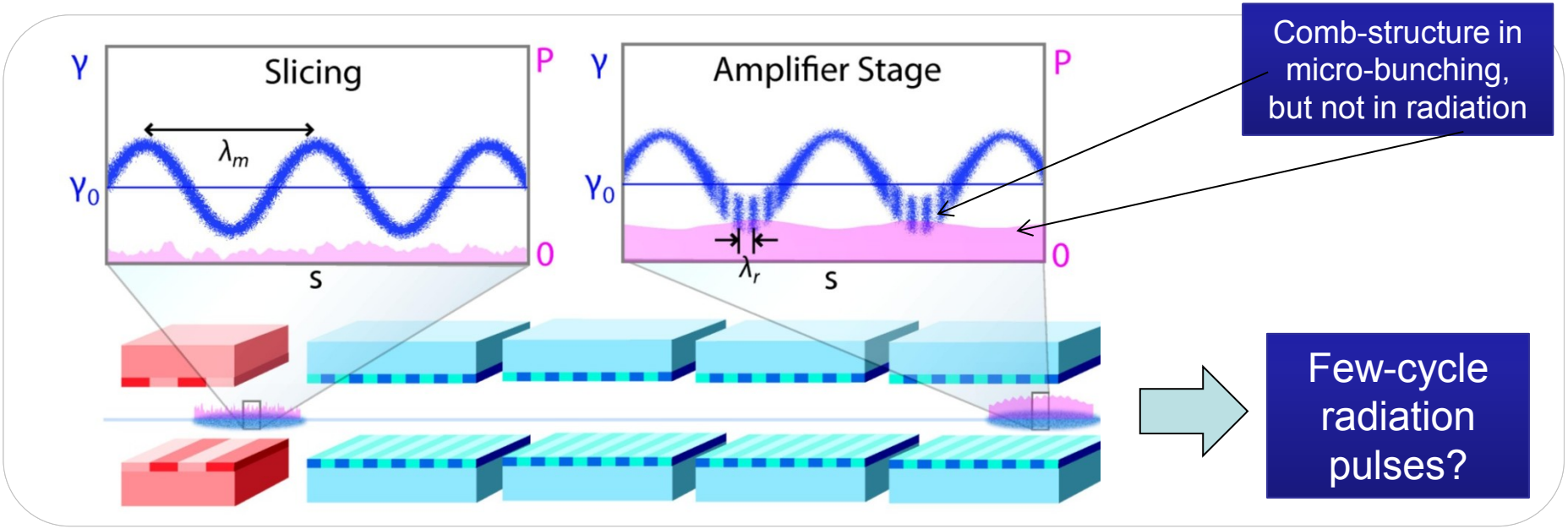
Maximum radiation power (top) and electron microbunching (bottom) with distance through FEL amplifier

$$b = \langle e^{-i\theta_j} \rangle$$



From few-cycle micro-bunching to few-cycle pulses

- The figure summarises the results so far:
  - Use HHG to apply energy modulation with period $\lambda_m >> \lambda_r$
  - Amplification from noise generates few-cycle structure in FEL micro-bunching (blue) but not in radiation (pink).
- How can we go from few-cycle micro-bunching structure to few-cycle pulses?
- We've developed two methods that could be added at the end of existing facilities to generate a train of few-cycle radiation pulses:
  - Few-period undulator - very simple but lower power
  - Series of few-period undulators (+ chicanes) to reach high power.

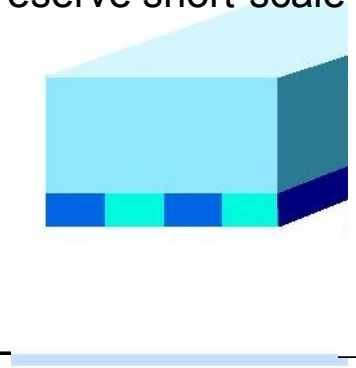


Blue trace shows schematic representation of electron beam energy (γ) variation and bunching. Pink trace shows radiation intensity (P).

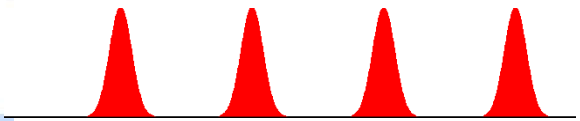
Simple method – single few-period undulator

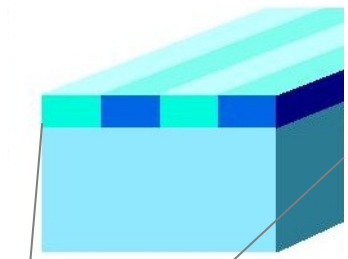
- The first idea is to simply block the radiation coming from the amplifier stage.
- And pass only the electron beam through a single short undulator – comb structure in micro-bunching generates a train of few-cycle radiation pulses.
- Undulator must be short to preserve short-scale structure – low power but simple.

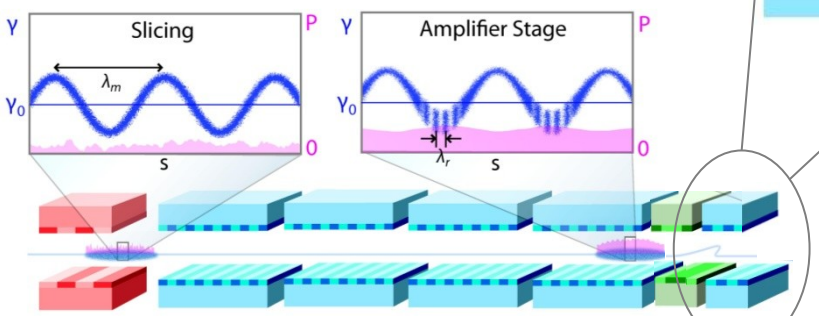
Comb of few-cycle regions with high microbunching



Train of few-cycle radiation pulses







Need to block/divert radiation emitted in amplifier – chicane to allow space for this.

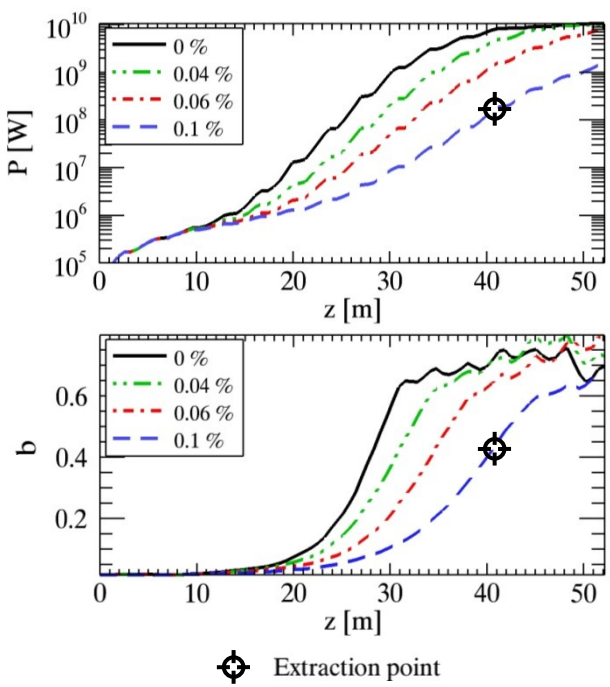
Single few-period undulator – simulations

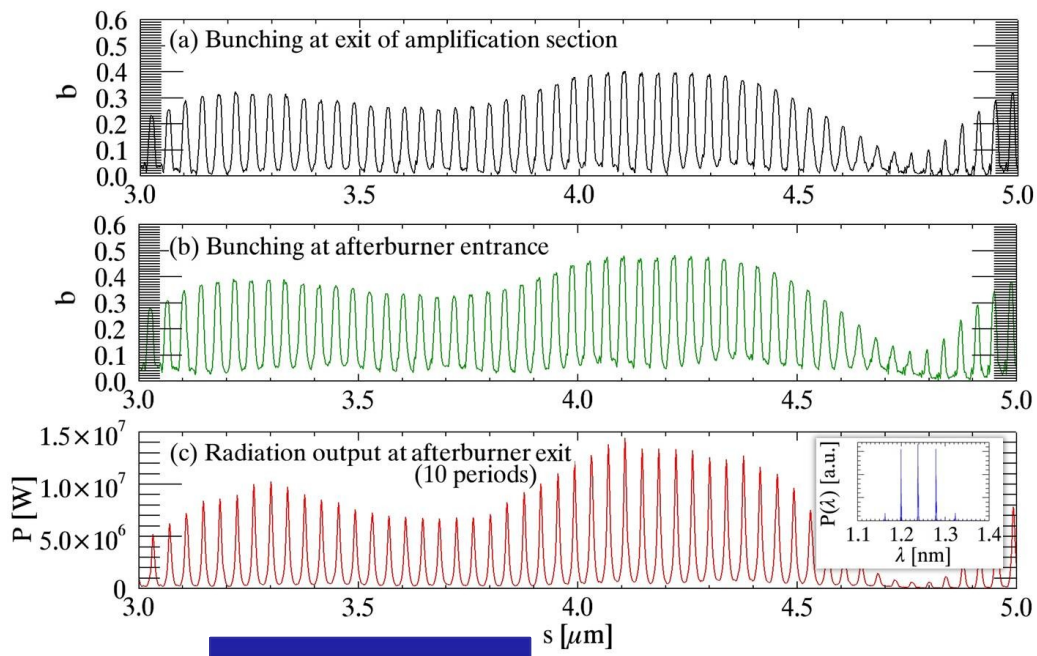
- We used the earlier soft x-ray simulation results for the case with 0.1% energy modulation amplitude which gave strong micro-bunching structure.
- We output the electron beam slightly before saturation and put it through a chicane (block amplifier radiation) which slightly enhanced the micro-bunching.
- Then used a 10-period undulator to get a train of radiation pulses. Pulse duration ~10 as rms and peak power ~10MW.
- Relatively low power but <u>a promising option for a proof-of-principle experiment</u>.

Soft x-ray 1.24 nm example

Parameter	Soft x ray
Amplifier stage	
Electron beam energy [GeV]	2.25
Peak current [kA]	1.1
ρ parameter	1.6×10^{-3}
Normalized emittance [mm-mrad]	0.3
rms energy spread, σ_γ/γ_0	0.007%
Undulator period, λ_u [cm]	3.2
Undulator periods per module	78
Resonant wavelength, λ_r [nm]	1.24
Modulation period, λ_m [nm]	38.44
Modulation amplitude, γ_m/γ_0	0.1%

$$b = \langle e^{-i\theta_j} \rangle$$

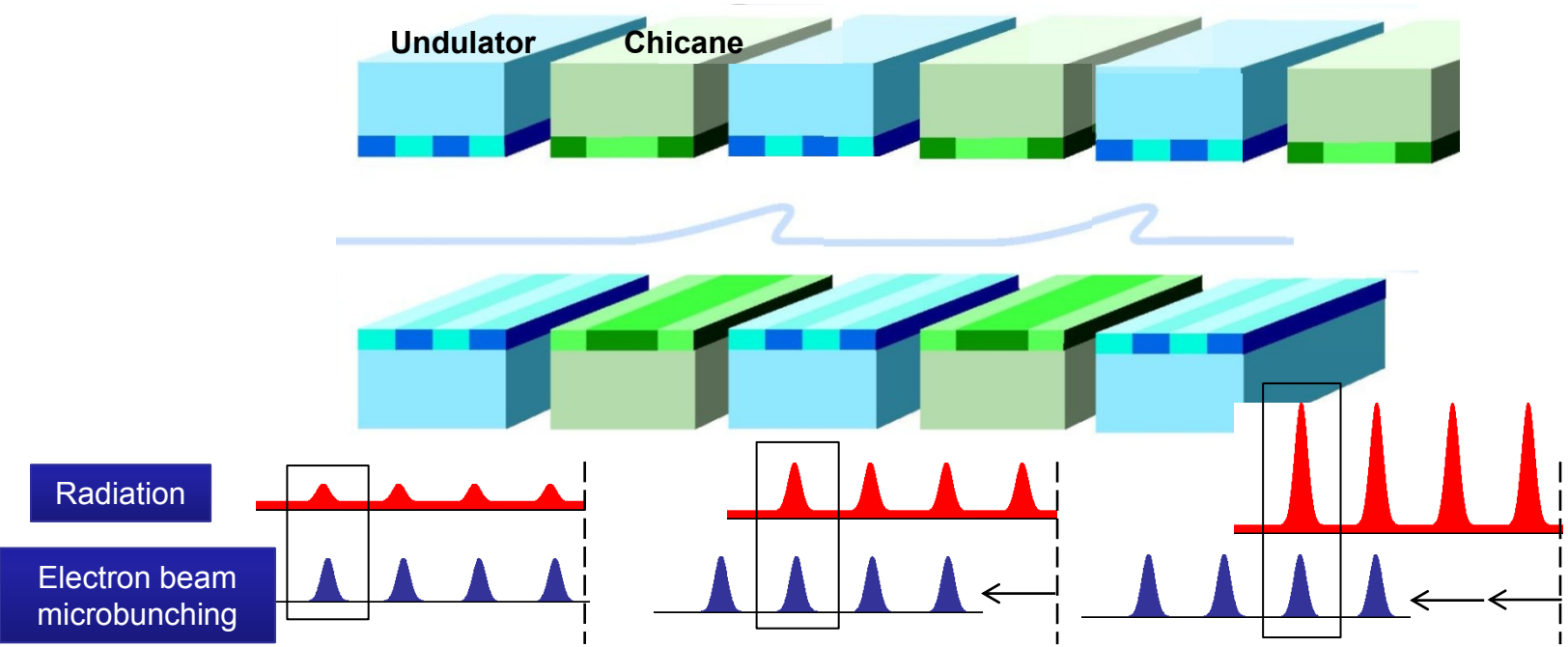




~10 as rms pulses

Method for high power few-cycle pulses

- To reach higher power requires a sustained interaction between radiation and e-beam – but such interaction in a long undulator washes out short-scale structure.
- Use concept from mode-locking in a FEL amplifier – use a series of short undulator sections with chicanes inserted between them to periodically delay the electrons.
- A train of radiation pulses can be amplified. Radiation pulses step from one micro-bunched region to the next, allowing high power while retaining the short-scale structure.



PRL **100,** 203901 (2008) PHYSICAL REVIEW LETTERS week ending 23 MAY 2008

Mode Locking in a Free-Electron Laser Amplifier

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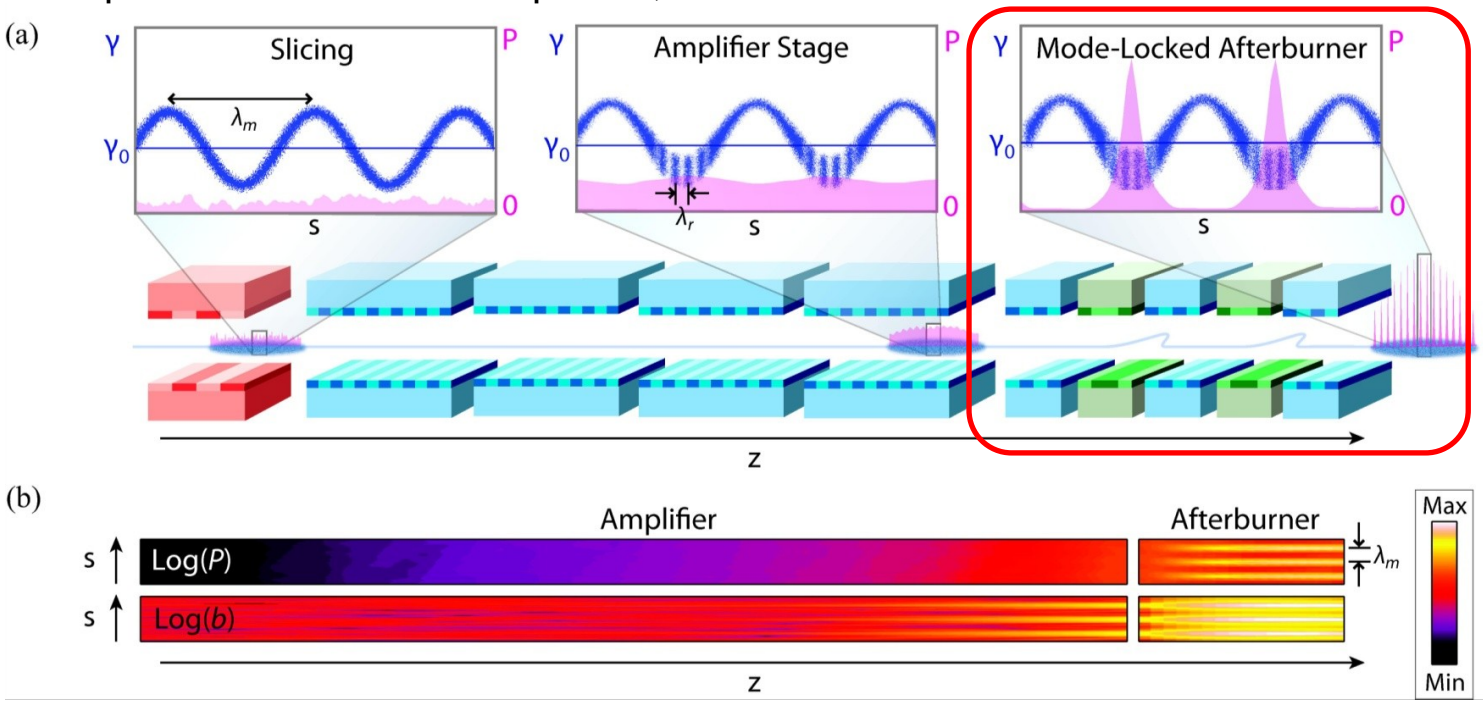
(Received 26 February 2008; published 21 May 2008)

“Mode-locked afterburner”

- Our new scheme uses this concept from the mode-locked FEL but it is applied after the usual FEL amplifier – so we refer to it as a “mode-locked afterburner”.
- To get the shortest pulses from these schemes requires minimising the number of periods per undulator module – so the advantage of the afterburner is that we’re free to optimise for the shortest pulses, with no modification of the main undulator.



PRL **110,** 104801 (2013) PHYSICAL REVIEW LETTERS week ending 8 MARCH 2013

Few-Cycle Pulse Generation in an X-Ray Free-Electron Laser

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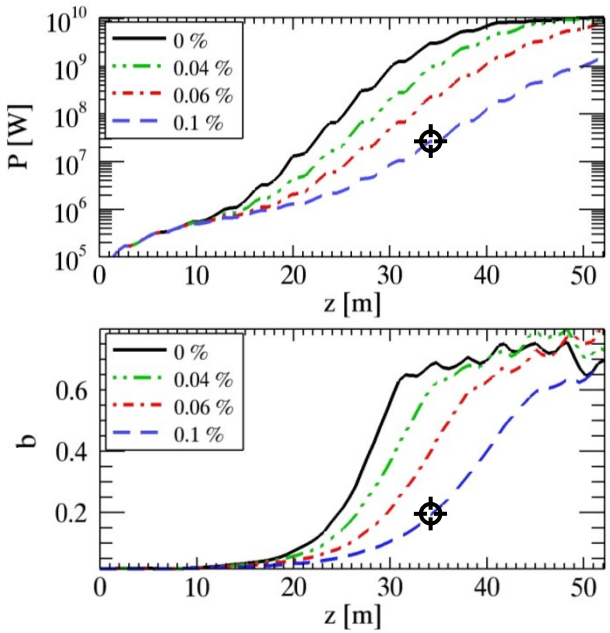
(Received 31 August 2012; published 5 March 2013)

Mode-locked afterburner soft x-ray simulation

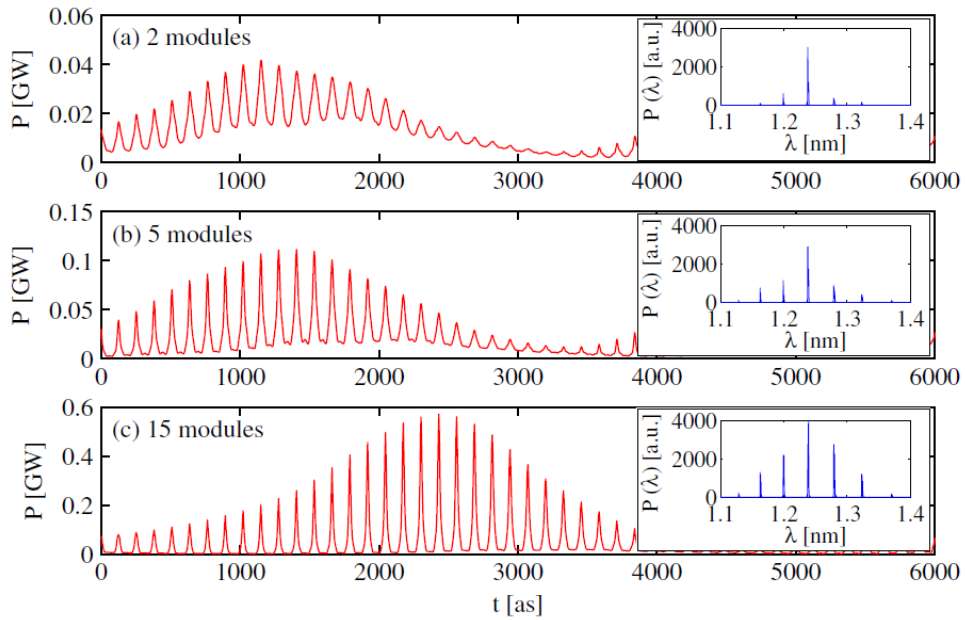
- We again used the earlier soft x-ray simulations for the case with 0.1% amplitude which gave strong micro-bunching structure.
- We want FEL amplification to continue into the mode-locked afterburner. To do this we need both the electron beam and the radiation from the amplifier and we extract before saturation.
- Choose 8-period undulators and set chicanes appropriately to maintain overlap.
- Pulse train emerges above the amplifier radiation within 15 modules (length of afterburner = 7 m) .
- Generates ~9 as rms pulses separated by 124 as, at ~0.6GW.

Soft x-ray 1.24 nm example

Parameter	Soft x ray
Amplifier stage	
Electron beam energy [GeV]	2.25
Peak current [kA]	1.1
ρ parameter	1.6×10^{-3}
Normalized emittance [mm-mrad]	0.3
rms energy spread, σ_γ/γ_0	0.007%
Undulator period, λ_u [cm]	3.2
Undulator periods per module	78
Resonant wavelength, λ_r [nm]	1.24
Modulation period, λ_m [nm]	38.44
Modulation amplitude, γ_m/γ_0	0.1%
Extraction point [m]	34.1
Mode-locked afterburner	
Undulator periods per module	8
Chicane delays [nm]	28.52
No. of undulator-chicane modules	~15



Extraction point for mode-locked afterburner

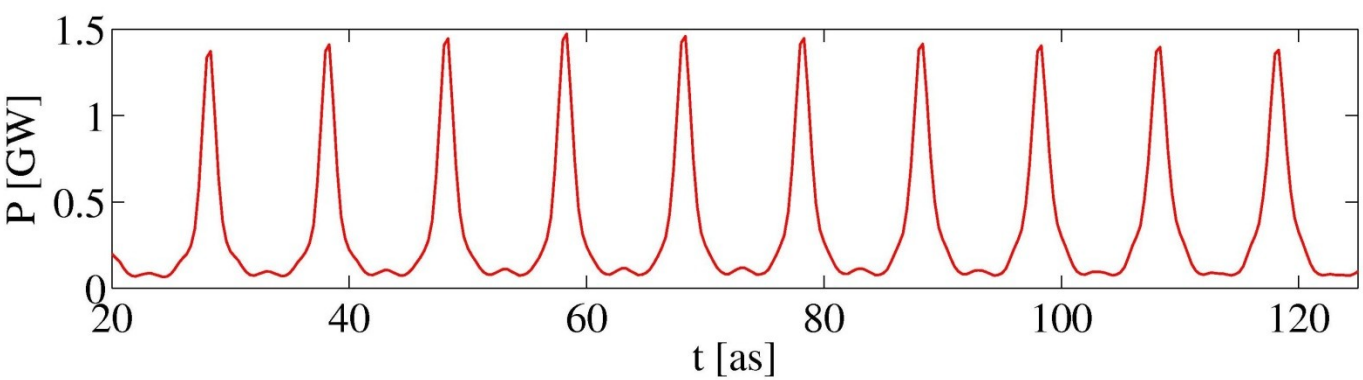


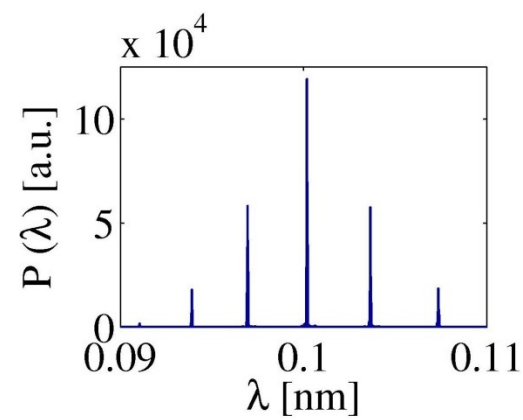
Mode-locked afterburner hard x-ray simulation

- A hard x-ray case of resonant FEL wavelength 0.1 nm was also simulated, with the aim of demonstrating shorter pulse generation.
- Used parameters similar to the SACLA facility.
- Aiming for shortest pulses so used 8-period undulator modules in afterburner and 3nm modulation period (30xλ_r).
- The results show pulse durations of ~700 zs rms pulses at ~1GW – the point at which we start to verge into zepto-scale.
- Future FELs at shorter wavelength could allow shorter still.
- We note for all these results that the spectrum is a set of discrete modes under a broad-bandwidth envelope – increased by ~2 orders of magnitude over SASE

Hard x-ray 0.1 nm example

Parameter	Hard x ray
Amplifier stage	
Electron beam energy [GeV]	8.5
Peak current [kA]	2.6
ρ parameter	6×10^{-4}
Normalized emittance [mm-mrad]	0.3
rms energy spread, σ_γ/γ_0	0.006%
Undulator period, λ_u [cm]	1.8
Undulator periods per module	277
Resonant wavelength, λ_r [nm]	0.1
Modulation period, λ_m [nm]	3
Modulation amplitude, γ_m/γ_0	0.06%
Extraction point [m]	36.0
Mode-locked afterburner	
Undulator periods per module	8
Chicane delays [nm]	2.2
No. of undulator-chicane modules	~40





~700 zs rms pulses

Future development

There are many possibilities for future development:

Further development of concept:

- Investigate flexibility in terms of changing pulse separation, increasing power etc.
- Combining with other techniques for e.g. improved temporal coherence/stability. Shorter pulses by tuning different undulator modules to different modes (e.g. MOPSO09).
- Modelling with non-averaged FEL code such as PUFFIN (L. Campbell and B. McNeil, Phys. Plasmas, 19, 093119, (2012).

Further investigation of potential applications:

- Ultra-fast dynamics – e.g. stroboscopic measurements as for HHG pulse trains.
- Also broad bandwidth/discrete modes could have applications.

Putting it into practice?

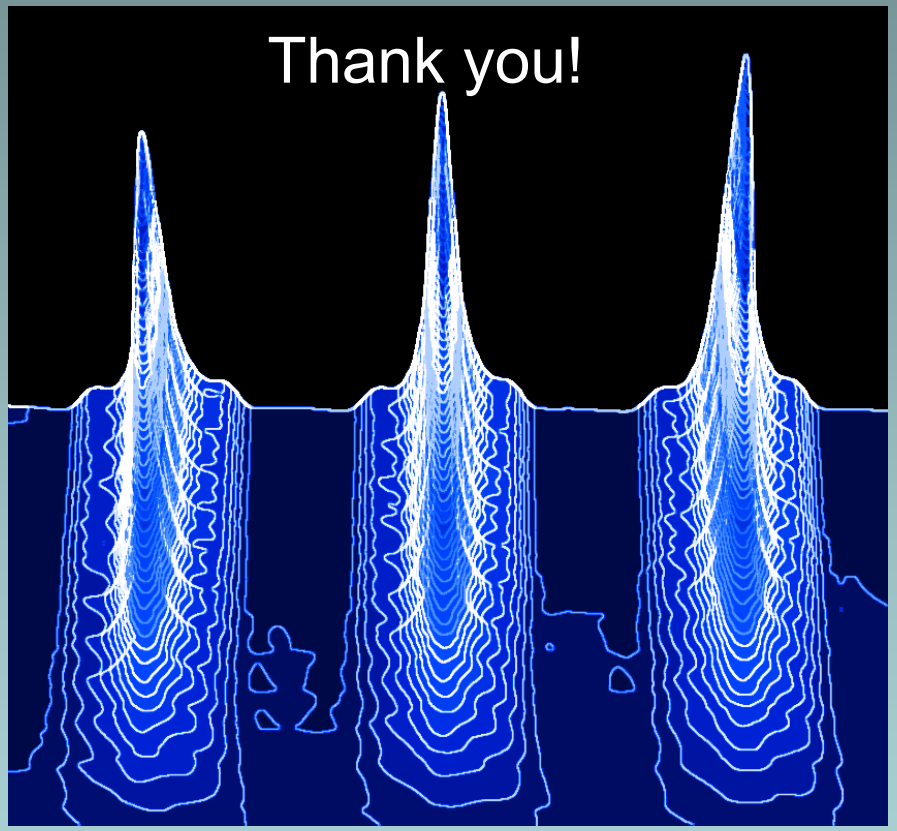
- The technique is very flexible. The single undulator scheme is a minimal addition to existing facilities – ideal for proof-of-principle. The mode-locked afterburner is also modular and could tested with a few modules before going to high power.
- How would we measure such short pulses?
  - Spectral measurements could be sufficient for first test.
  - Clearly measuring such temporal scales is challenging but the method is flexible to generate from hundreds of attoseconds down – so could enable development route from present methods e.g. HHG uses attosecond streaking.

Summary

- We have developed a method for generating trains of few-cycle pulses from FELs – which if applied at x-ray facilities could deliver GW powers + atto-to-zeptosecond-scale pulses + ultra-broad bandwidth envelope. We think this is a very promising option for future development.

On a more general note…

- There are clearly many promising ideas for pushing the frontier of short pulses on FELs. Each have their respective merits and could be better suited to different experiments.
- In the UK we're proposing a FEL test facility called CLARA (Compact Linear Accelerator for Research and Applications) at Daresbury which could be used to test such ideas:
  - CDR available now: http://www.stfc.ac.uk/ASTeC/resources/PDF/CLARA_CDRv2.pdf
  - Posters/papers at this conference:
  - WEPSO04 The Conceptual Design of *CLARA*, a Novel FEL Test Facility for Ultra-short Pulse Generation
  - MOPSO40 *CLARA* Accelerator Design and Simulations
  - WEPSO41 Feasibility Studies for Echo-enabled Harmonic Generation on *CLARA*
- we're keen to collaborate on this and other areas.
- We look forward with excitement to future progress in this field!



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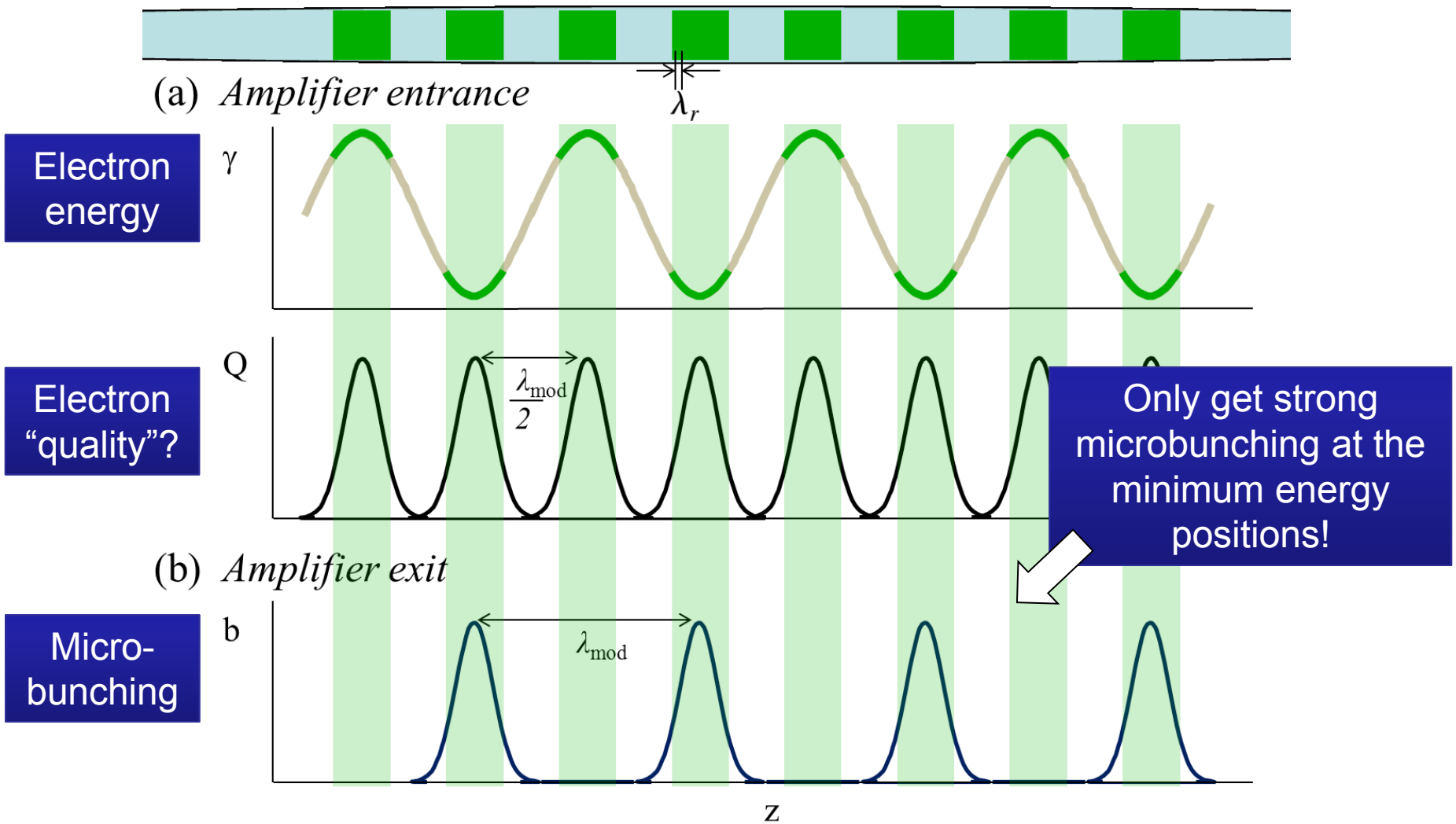
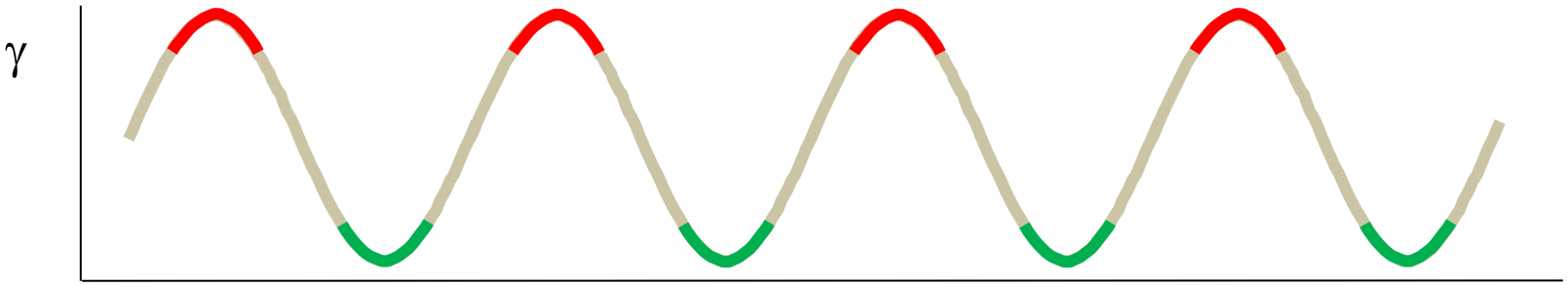
Interesting effects in microbunching structure (1)

- We were interested to note that the strong micro-bunching develops only at the minima – separation of bunching spikes equal to the modulation period.



Interesting effects in microbunching structure (2)

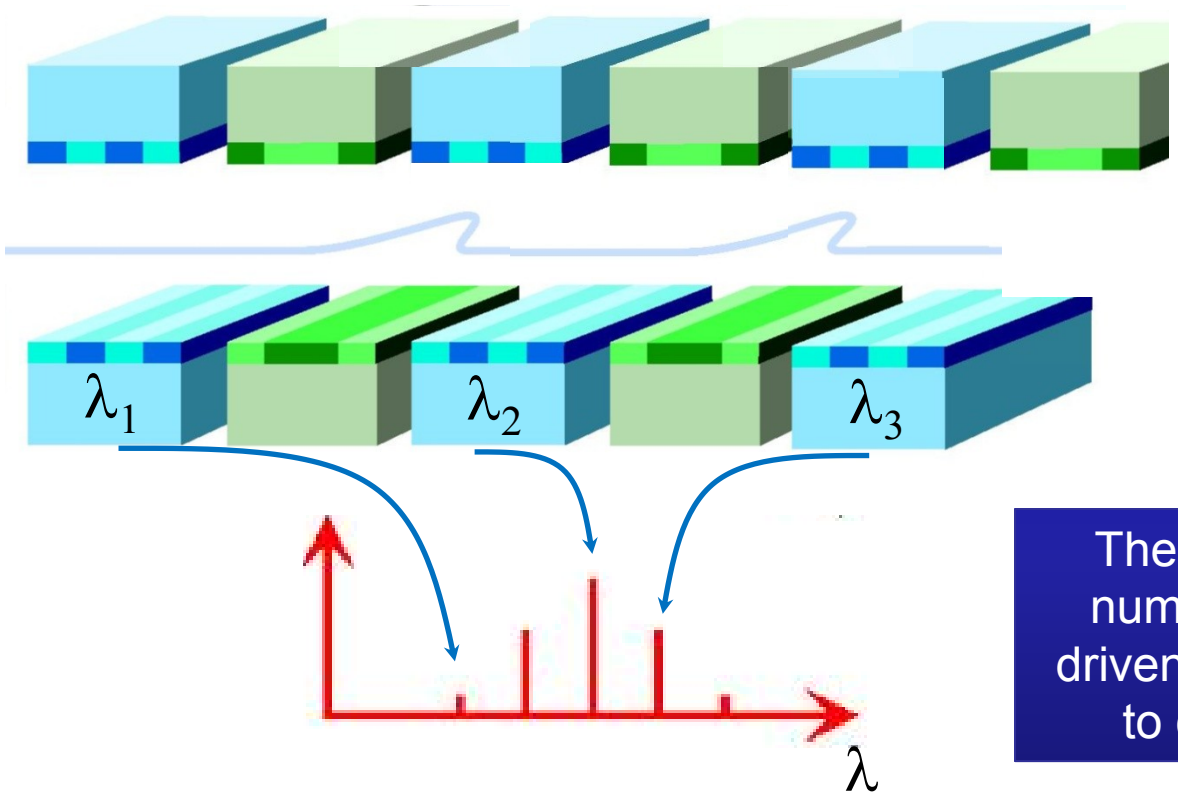
- Why does strong micro-bunching occur only at the minimum energy positions?



- Regions of high energy chirp slightly 'spoiled'
- Two 'sets' of 'higher quality' low-chirp positions with different energies.
- Radiation slips through it all – putting the two energies 'in competition'.
- Electrons at minima experience radiation from higher energy electrons (i.e. greater than their resonant frequency).
- Electrons at maxima experience radiation from lower energy electrons (i.e. lower than their resonant frequency).
- Well know asymmetry in the FEL interaction from FEL linear theory – critical frequency below which no exponential instability exists.
- Suggest that asymmetry in FEL interaction favours the lower energy set, so strong FEL interaction (bunching) at this energy while not elsewhere.
- Required modulation amplitude to generate comb structure is ~ρ - higher energy electrons are outside bandwidth of interaction occurring at the lower energy.

Possible method to generate shorter pulses

- The greater the number of phase coupled modes being driven, the shorter duration will be the individual radiation pulses in the train.
- By tuning the different undulator modules to neighbouring modes, the number of modes driven to saturation may be able to be increased.



The ordering and number of modes driven will be subject to optimisation

Short pulse techniques – pulse duration vs power