Free-Electron Lasers II Advanced Techniques

Allan Gillespie

MAPS Group
Carnegie Laboratory of Physics
University of Dundee

LA^{3}NET 3rd School on Laser Applications, CLPU, Salamanca, 30 Sep 2014

Acknowledgements

This presentation has been prepared with significant help from the following colleagues within the FEL community:

- Neil Thomson and David Dunning of ASTeC, STFC Daresbury Laboratory and the Cockcroft Institute, UK
- Brian McNeil of the Department of Physics, SUPA, University of Strathclyde, UK
- Patrick Krejcik and colleagues of SLAC National Accelerator Laboratory, Menlo Park, CA, USA

ASTeC

The Cockcroft Institute
of Accelerator Science and Technology

University of
Strathclyde

SLAC
NATIONAL
ACCELERATOR
LABORATORY

Plan of Talk

- **Potential for short-pulse development of FELs**
- **The CLARA Facility at STFC Daresbury Laboratory, UK**
- **Methods for generating ultra-short pulses**
- **Examples using CLARA and other parameters**
- **The requirement for advanced FEL diagnostics**
  - “ probably the ultimate FEL diagnostic ”

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 reducing the 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 the attosecond scale.
- Shorter wavelength required to progress further. e.g. HHG: C. Hernandez-Garcia et al. PRL 111, 033002 (2013) – FEL is 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

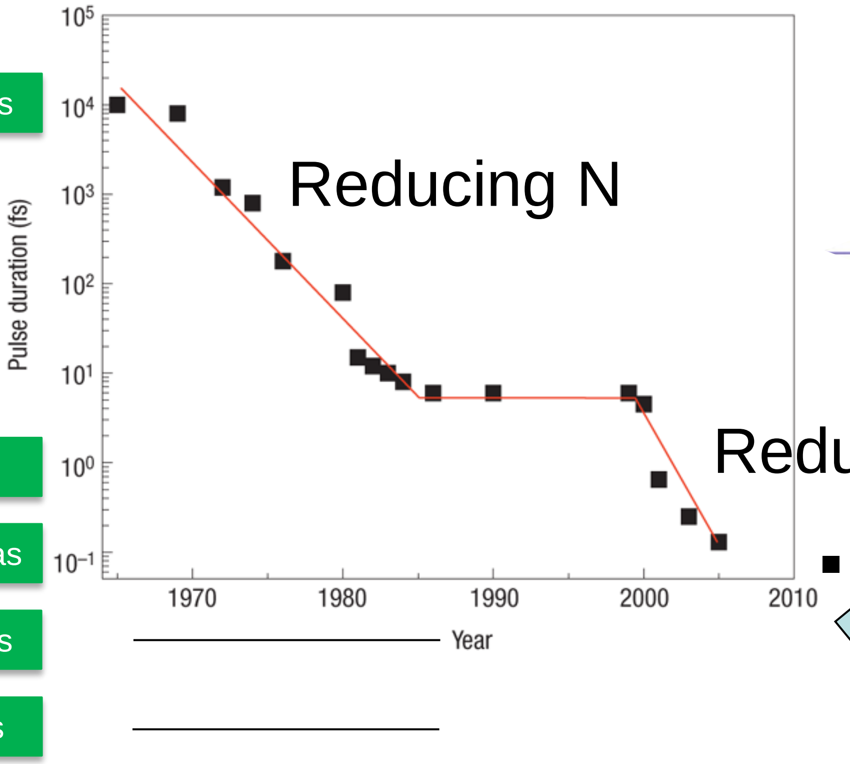
10 ps

1 fs

100 as

10 as

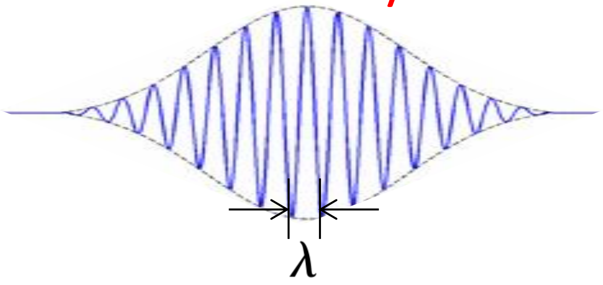
1 as



Reducing N

Reducing λ

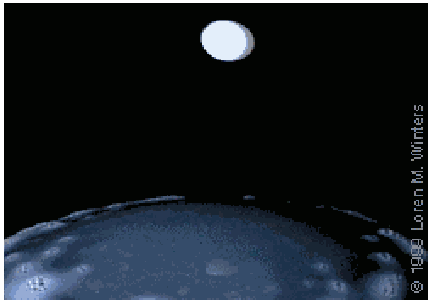
Pulse duration
= N × λ / c

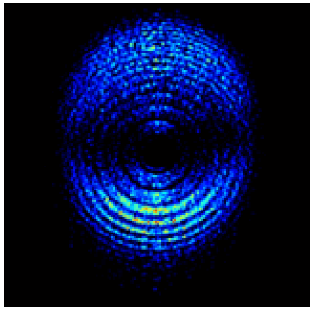


FELs ?

Motivation for short pulses

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





Left to Right:
E. Muybridge ~1878 Shutter time ~10^{-3} sec

H. Edgerton ~1931 Flash ~10^{-6} sec

J. Mauritsson et al. PRL 100, 073003, 2008 ~10^{-15} sec

Attosecond Quantum Stroboscope

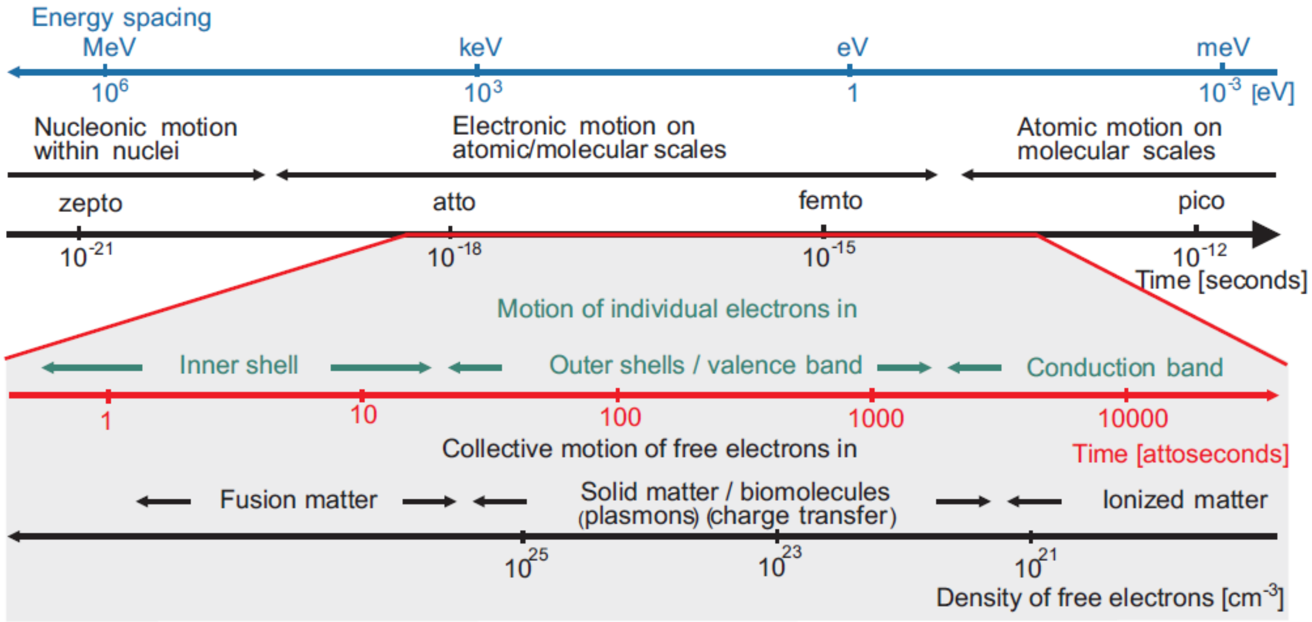


FIG. 2. (Color) Characteristic time scales for microscopic motion and its connection with energy spacing between relevant stationary states (upper panel); characteristic time scales for the motion of one or several electrons and for the collective motion of an electronic ensemble (lower panel).

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

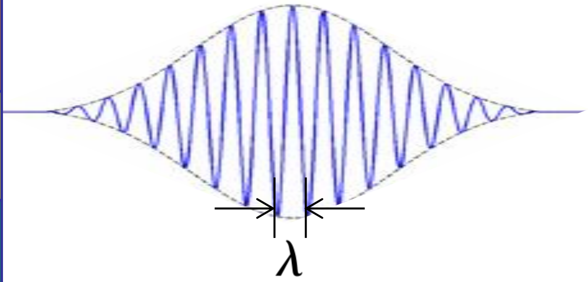
Short-pulse potential of free-electron lasers

The *X-ray FEL* has two advantages giving it the potential to push the short-pulse frontier:

- **Short wavelength** – a few-cycle pulse at 0.1 nm (1.0 Å) 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 around ~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**

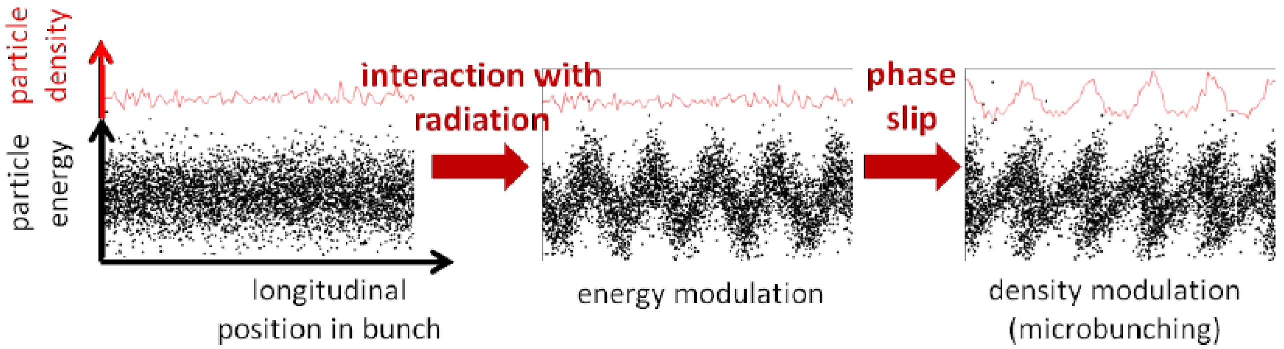
Pulse duration $= N \times \lambda / c$

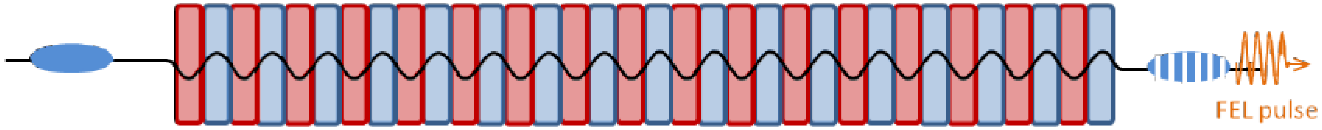


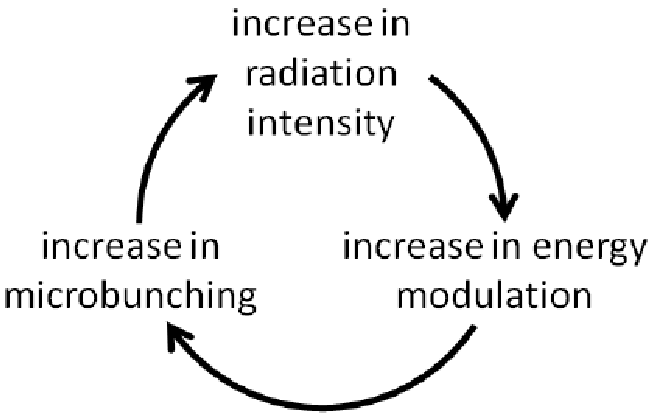
- **Peak power** – a hard x-ray (0.1 nm) FEL at 20 GW generates 10^{25} photons/second – corresponding to 10^{7} photons/pulse for a few-cycle (i.e. 1 attosecond) pulse.
  Very challenging for other sources to match this.

- The challenge for reaching the very shortest pulses from FELs will be to **minimise the number of cycles per pulse.**

SASE process





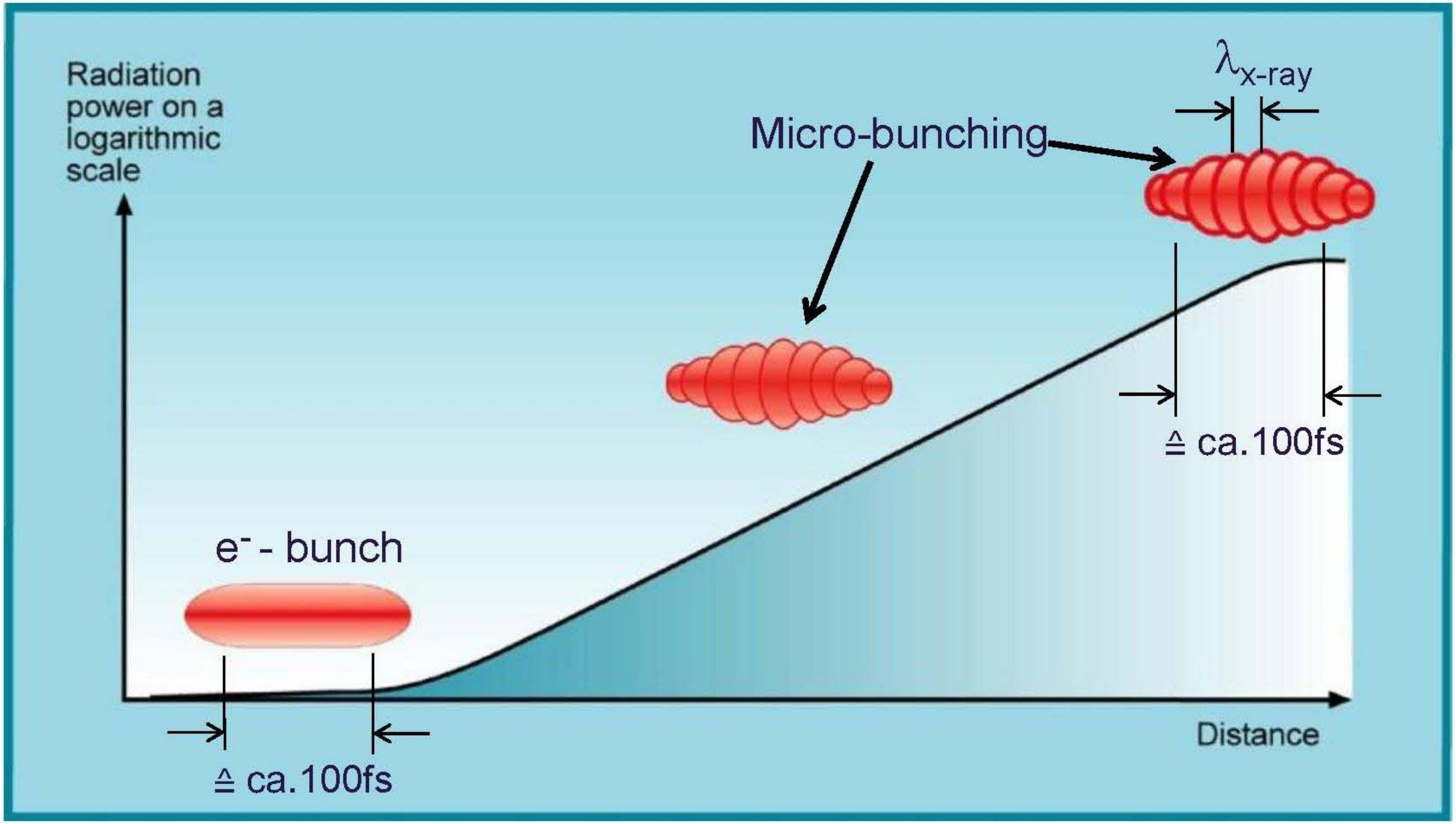


increase in radiation intensity

increase in energy modulation

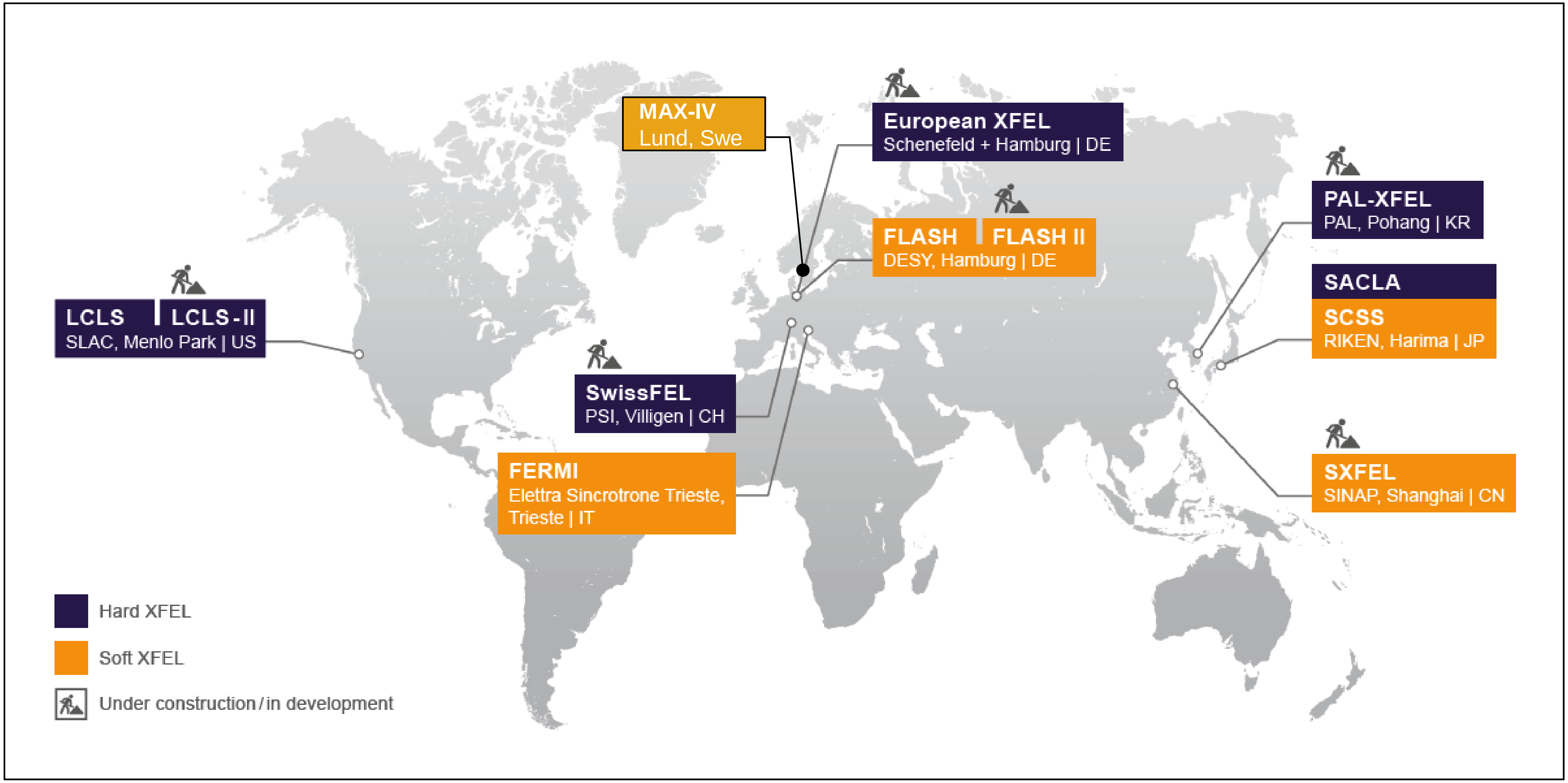
increase in microbunching

SASE-process



Light generation in the undulator:

SASE - Self-Amplified Spontaneous Emission



LCLS | **LCLS-II**
SLAC, Menlo Park | US

MAX-IV
Lund, Swe

SwissFEL
PSI, Villigen | CH

FERMI
Elettra Sincrotrone Trieste, Trieste | IT

European XFEL
Schenefeld + Hamburg | DE

FLASH | **FLASH II**
DESY, Hamburg | DE

PAL-XFEL
PAL, Pohang | KR

SACLA
SCSS
RIKEN, Harima | JP

SXFEL
SINAP, Shanghai | CN

🟪 Hard XFEL

🟧 Soft XFEL

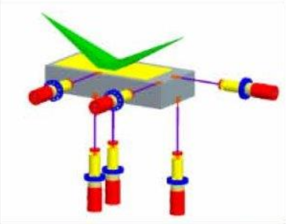
Under construction / in development

Technological challenges at European XFEL

Scientific instruments & ancillary instrumentation

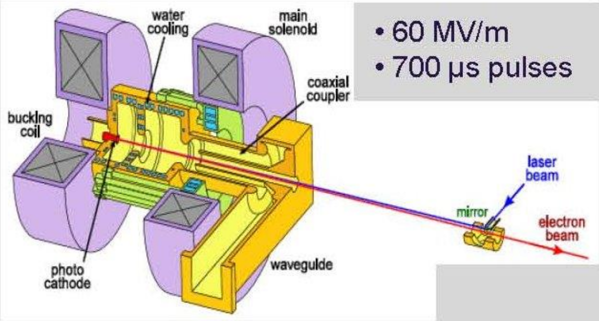

- 6 stations

X-ray optics & beam transport



- 3 systems
- ~2000 m
- 1m mirrors

Low emittance electron injector



- 60 MV/m
- 700 µs pulses

Undulator systems

- 3 systems
- >450 m

Superconducting electron accelerator

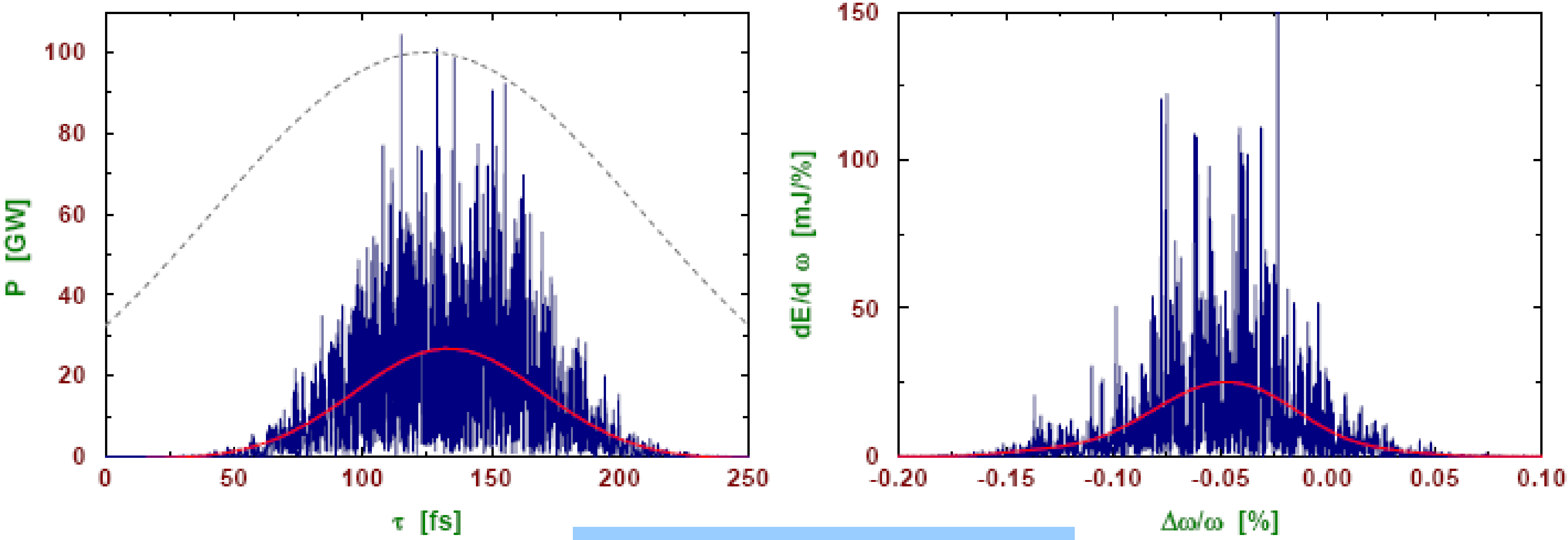
- 23 MV/m
- 800 cavities
- 17.5 GeV

Courtesy T. Tschentscher

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 are noisy temporally and spectrally: poor temporal coherence
  - No pulse-to-pulse reproducibility

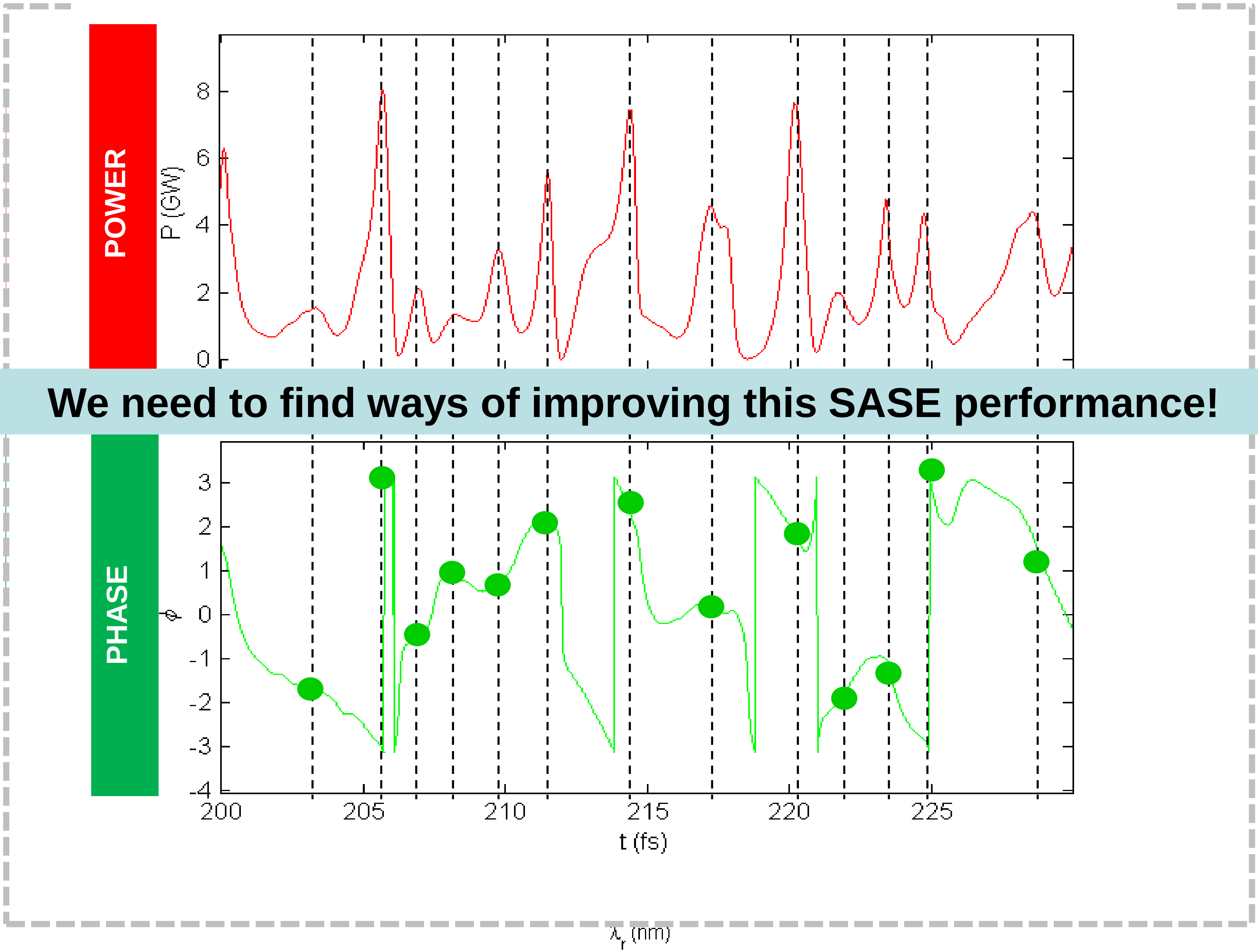
Far from FT limited $\Delta\nu.\Delta t >> 1$



SIMULATED XFEL OUTPUT*

*Taken from DESY report

SASE Coherence



We need to find ways of improving this SASE performance!

These considerations have recently led to a proposal for an FEL test facility in the UK.

CLARA: The UK FEL Test Facility

ASTeC

diamond

The Cockcroft Institute of Accelerator Science and Technology

JAI John Adams Institute for Accelerator Science

University of Strathclyde

Royal Holloway University of London

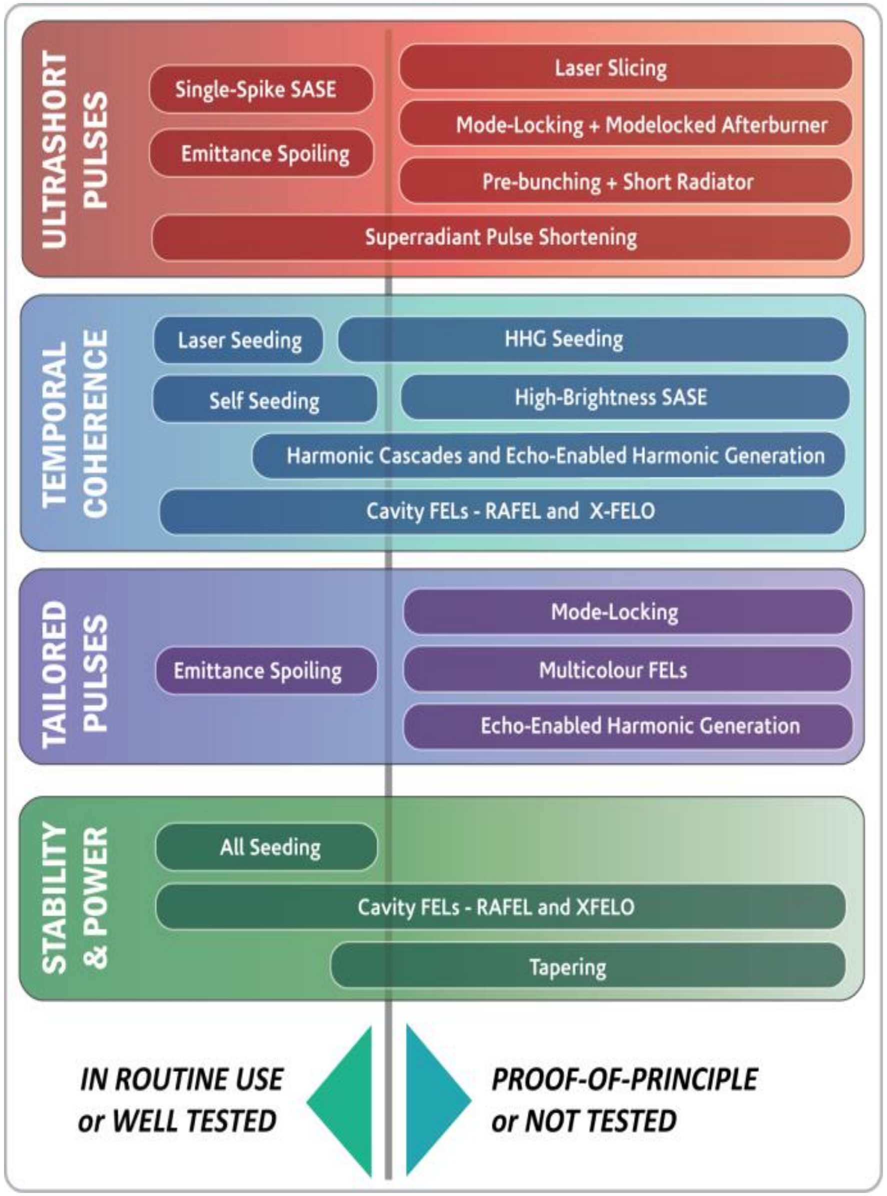
LANCASTER UNIVERSITY

UNIVERSITY OF LIVERPOOL

University of HUDDERSFIELD

MANCHESTER 1824 The University of Manchester

The ‘FEL Case’ for an FEL Test Facility



ULTRASHORT PULSES

Single-Spike SASE

Emittance Spoiling

Laser Slicing

Mode-Locking + Modelocked Afterburner

Pre-bunching + Short Radiator

Superradiant Pulse Shortening

TEMPORAL COHERENCE

Laser Seeding

HHG Seeding

Self Seeding

High-Brightness SASE

Harmonic Cascades and Echo-Enabled Harmonic Generation

Cavity FELs - RAFEL and X-FELO

TAILORED PULSES

Emittance Spoiling

Mode-Locking

Multicolour FELs

Echo-Enabled Harmonic Generation

STABILITY & POWER

All Seeding

Cavity FELs - RAFEL and XFELO

Tapering

IN ROUTINE USE or WELL TESTED

PROOF-OF-PRINCIPLE or NOT TESTED

- Free-Electron Lasers (FELs) are remarkable scientific tools
- Short-wavelength FELs are operating for users around the world, for example LCLS (USA), SACLA (Japan), FLASH (Germany) and FERMI@Elettra (Italy).
- There are still many ways their output could be improved:
  - ***Shorter Pulses***
  - ***Improved Temporal Coherence***
  - ***Tailored Pulse Structures***
  - ***Stability & Power***
- There are many ideas for achieving these aims, ***but many of these ideas are untested***
- Most FELs have users and therefore have little time for detailed R&D

The UK Strategic Case

The UK science community has identified that
X-ray FELs are critical to many science challenges

- Complexity and Emergence
- Novel and Functional Materials
- Device Physics
- Warm Dense Matter
- Laboratory Astrophysics
- Planetary Physics
- Ultrafast Electron Dynamics
- Structural Dynamics
- Fast Biomolecular Dynamics/Structure
- Imaging Nanoscale Cell Function
- Single Molecule Imaging.

- There is thus a high priority to secure access to an X-Ray FEL
- This may be done initially through engagement in the European XFEL project, or looking further ahead, the ***UK may wish to construct its own X-ray FEL facility***
- FEL R&D activities in support of this aim need to be put in place.

The CLARA Concept

There are many ways FELs can be improved, but limited scope with existing facilities

UK Scientists need FELs and we want to develop next generation FEL technology towards a possible UK facility

CLARA

Compact Linear Accelerator for Research and Applications

*An upgrade of the existing VELA Photoinjector Facility at **Daresbury Laboratory** to a 250MeV Free-Electron Laser Test Facility*

Proof-of-principle demonstrations of novel FEL concepts

*Emphasis is on **ULTRA-SHORT PULSE GENERATION***

Other Goals and Benefits of CLARA

- The opportunity for R&D on advanced technologies:
  - New photoinjector technologies
  - Novel undulators (short period, cryogenic, superconducting….)
  - New accelerating structures: X-Band, etc...
  - Single bunch electron & photon diagnostics.
- The enhancement of VELA beam power and repetition rate, enabling additional industrial applications.
- The possibility to ***use the electron beam*** for other scientific research applications:

COMPTON SCATTERING FOR GAMMA BEAMS

PLASMA ACCELERATOR RESEARCH

ULTRAFAST ELECTRON DIFFRACTION

DIELECTRIC WAKEFIELD ACCELERATION

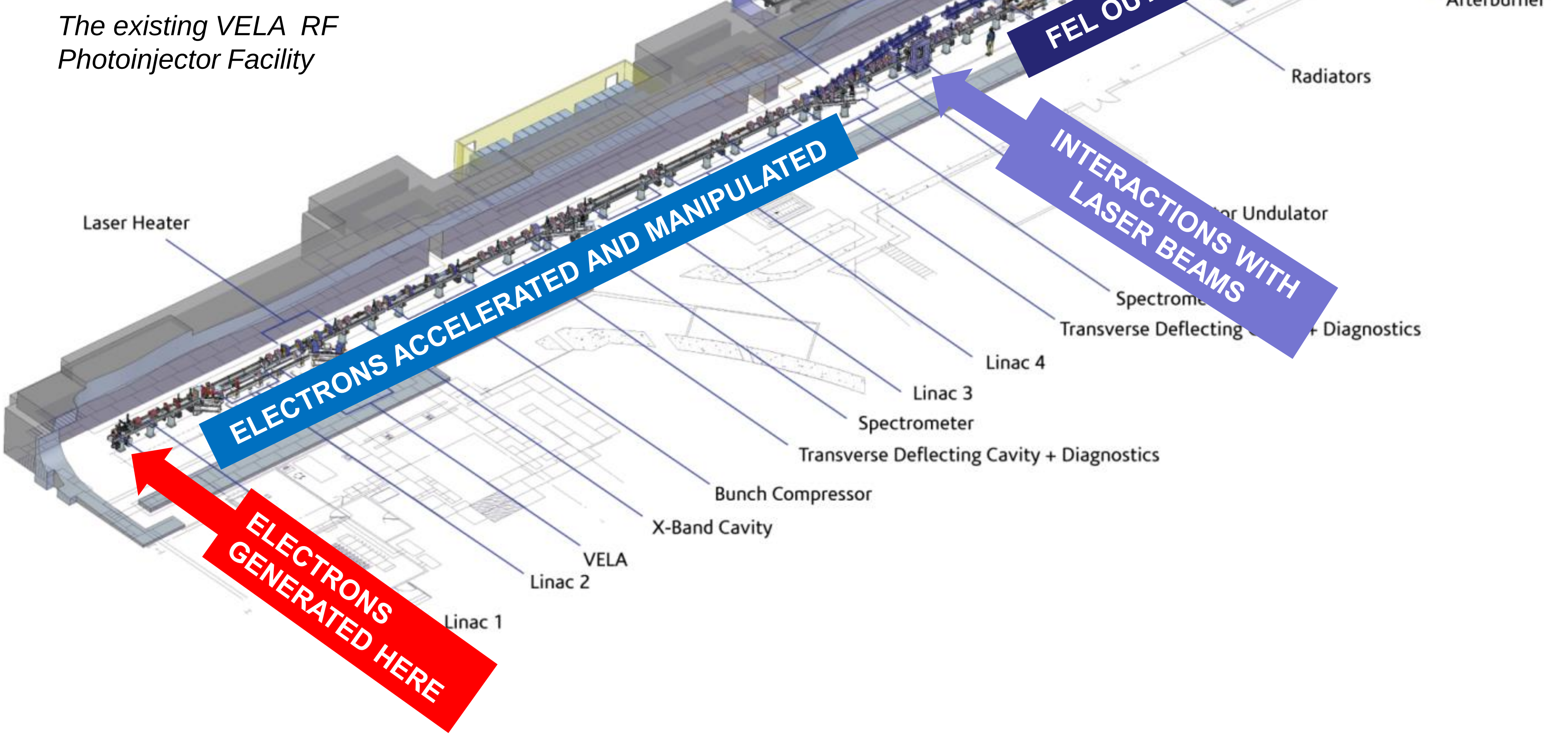
NONEQUILIBRIUM STORAGE RINGS

Design Philosophy and Parameters

- CLARA will be a flexible test facility allowing the broad range of accelerator and FEL R&D necessary to ensure a future UK FEL facility is world leading.
- Many of the FEL research topics are in two main areas which are intended to demonstrate improvement of FEL output beyond that available from SASE
  - ***The generation of ultra-short pulses***
    - Our emphasis for the short pulse schemes ***is to generate pulses with as few optical cycles as possible*** with durations of the order of, or shorter than, the FEL cooperation length.
    - ***For these schemes we will lase at 400–250 nm***, where suitable nonlinear materials for single-shot pulse profile characterisation are available.
    - A suitable wavelength range for seed sources to manipulate the electron beam longitudinal phase space is 30 – 120 μm
  - ***Improvement of temporal coherence.***
    - ***For these schemes we will lase at 266-100nm*** because here only spectral characterisation is required.
    - A suitable seed source for harmonic up-conversion, if required, is an 800 nm Ti:S.
- In all cases, we aim to study the essential physics of the schemes which can often ***be independent of the FEL wavelength.***
- Using a hybrid planar undulator, with minimum gap 6mm, and gap tuning wavelength range from 400 –100 nm, the required electron beam energy is ~230 MeV.

CLARA Layout

The existing VELA RF Photoinjector Facility



FEL OUTPUT STUDIED

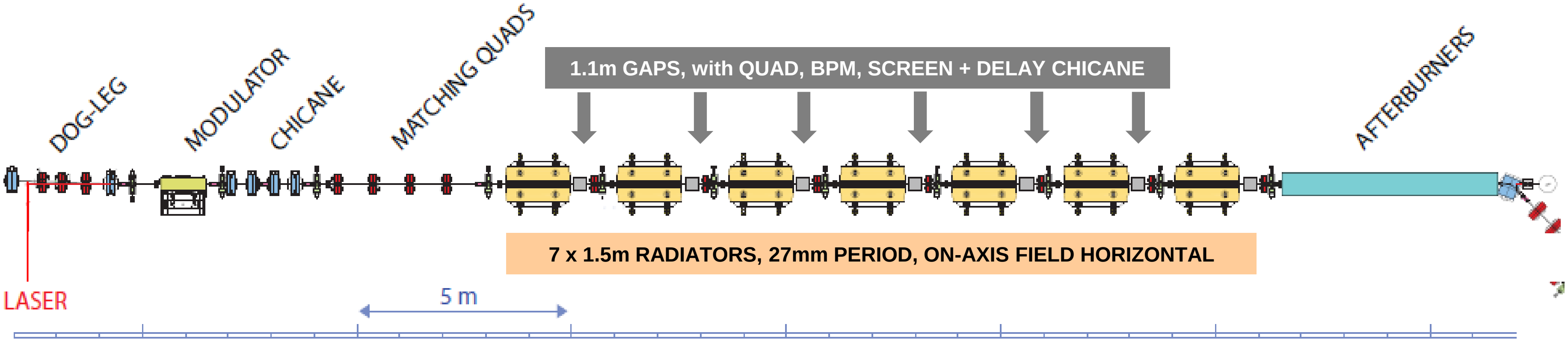
FEL OUTPUT GENERATED

INTERACTIONS WITH LASER BEAMS

ELECTRONS ACCELERATED AND MANIPULATED

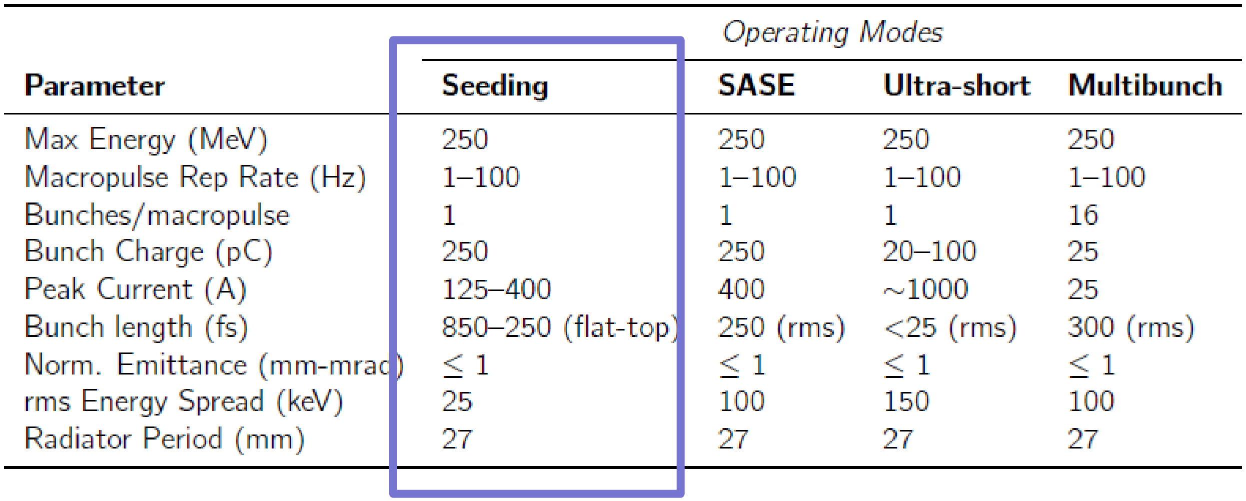
ELECTRONS GENERATED HERE

CLARA FEL Layout + Operating Modes: CDR



1.1m GAPS, with QUAD, BPM, SCREEN + DELAY CHICANE

7 x 1.5m RADIATORS, 27mm PERIOD, ON-AXIS FIELD HORIZONTAL



Parameter	Operating Modes Seeding	SASE	Ultra-short	Multibunch
Max Energy (MeV)	250	250	250	250
Macropulse Rep Rate (Hz)	1–100	1–100	1–100	1–100
Bunches/macropulse	1	1	1	16
Bunch Charge (pC)	250	250	20–100	25
Peak Current (A)	125–400	400	∼1000	25
Bunch length (fs)	850–250 (flat-top)	250 (rms)	<25 (rms)	300 (rms)
Norm. Emittance (mm-mrad)	≤ 1	≤ 1	≤ 1	≤ 1
rms Energy Spread (keV)	25	100	150	100
Radiator Period (mm)	27	27	27	27

Table 3.1: Main parameters for CLARA operating modes.

Seeding Mode is for

Short Pulse Schemes

FEL lasing: 400-250nm

(Seed: 30-120µm)

+

Temporal Coherence Schemes

FEL lasing: 266-100nm

(Seed: 800nm)

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

… and some examples based on CLARA and X-FEL parameters

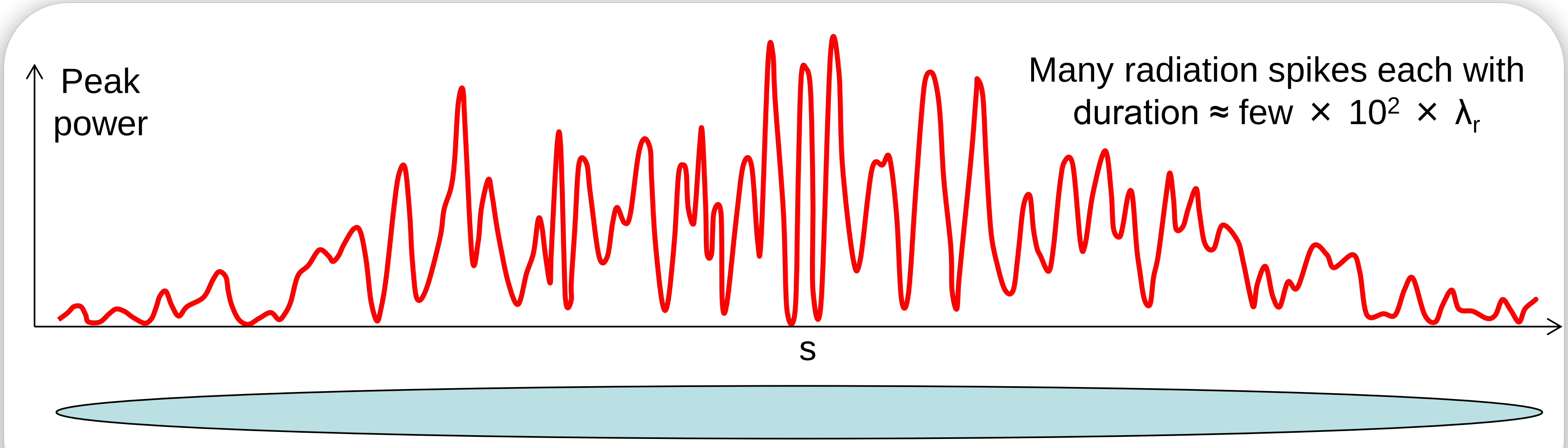
Introduction - SASE

- First consider self-amplified spontaneous emission (SASE) at x-ray wavelengths.
- 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 ~$10^4 \times \lambda_r/c$ at $\lambda_r = 0.1$nm.
- In the undulator a resonant radiation wave-front propagates ahead of the electrons (due to "slippage") at a rate of one radiation wavelength (λ_r) per undulator period (λ_u).
- 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 $\times \lambda_r$ in x-ray FELs.

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

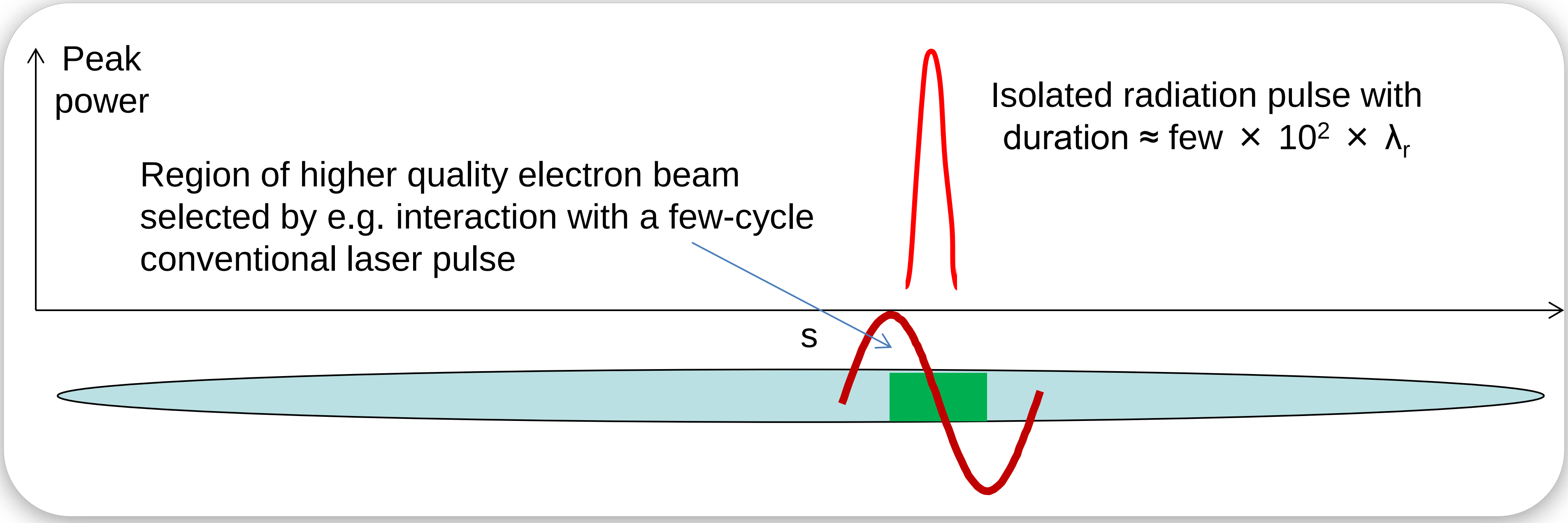


Many radiation spikes each with duration ≈ few $\times 10^2 \times \lambda_r$

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

Slicing a single SASE spike

- Each SASE spike acts independently – we 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 this corresponds to a few hundred cycles or ~100 as – close to record from HHG, but at shorter wavelength & higher photon flux. Fantastic potential for experiments.
- Potential for a further two orders of magnitude reduction with fewer cycles per pulse.

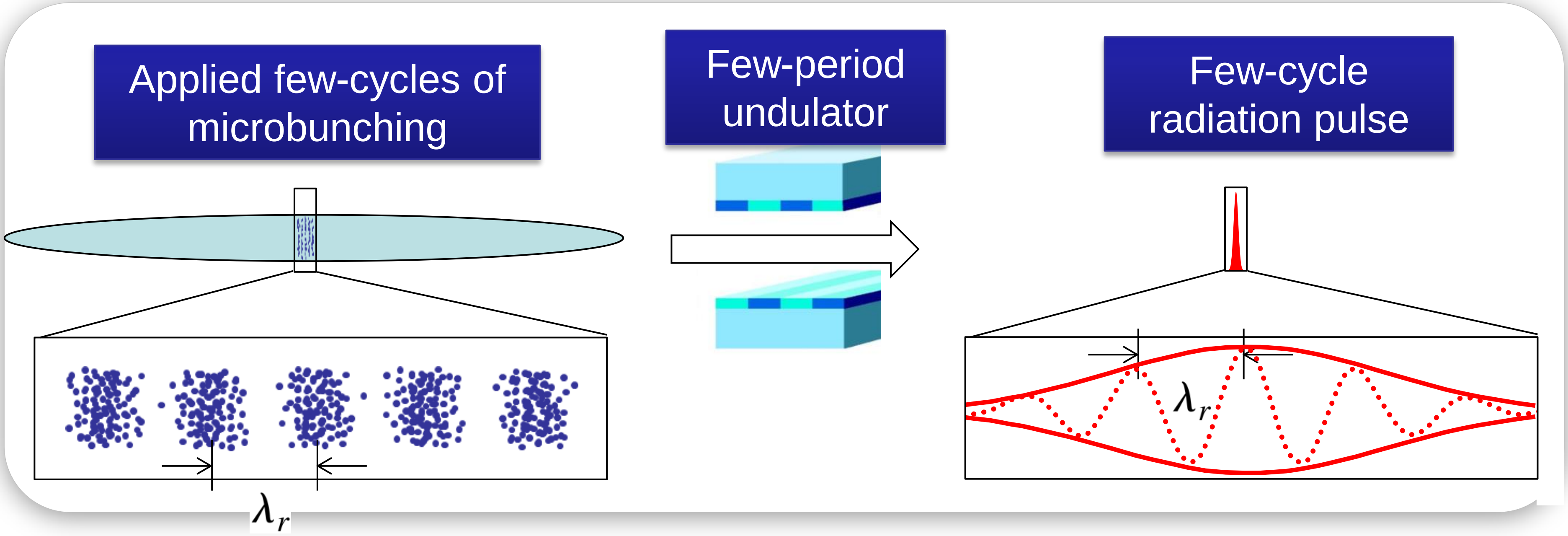


Isolated radiation pulse with duration ≈ few × 10^2 × λ_r

Region of higher quality electron beam selected by e.g. interaction with a few-cycle conventional laser 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)



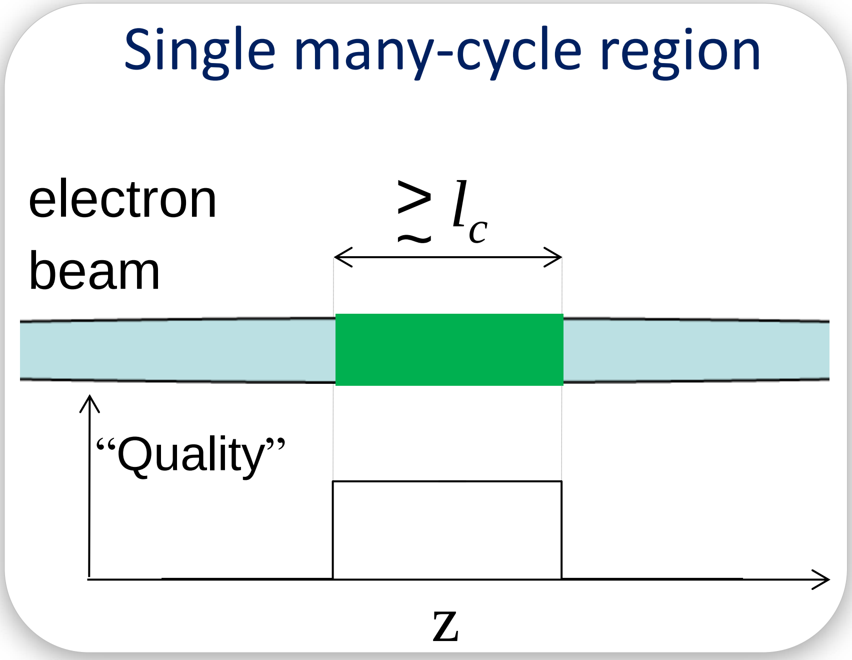
Applied few-cycles of microbunching

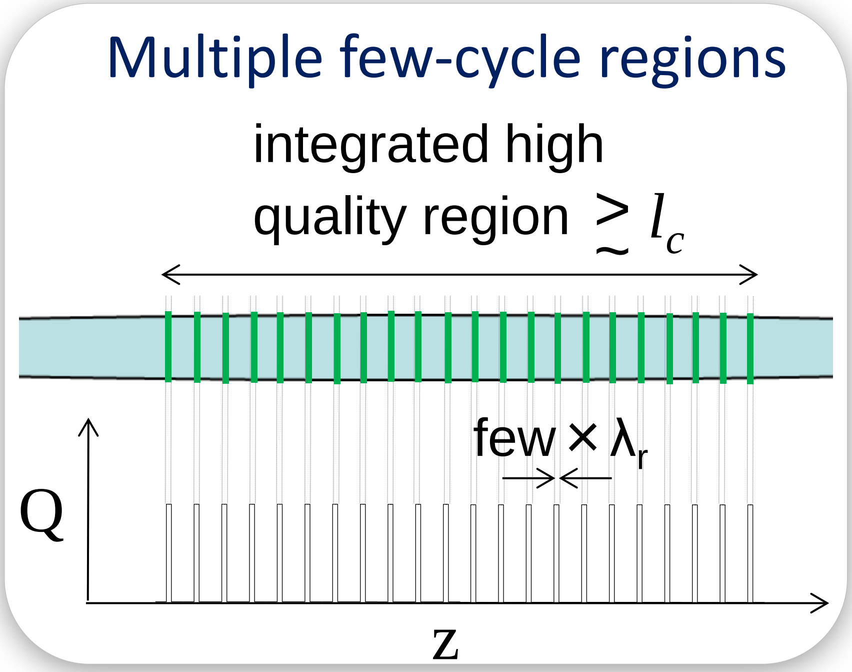
Few-period undulator

Few-cycle radiation pulse

Introduction to new method

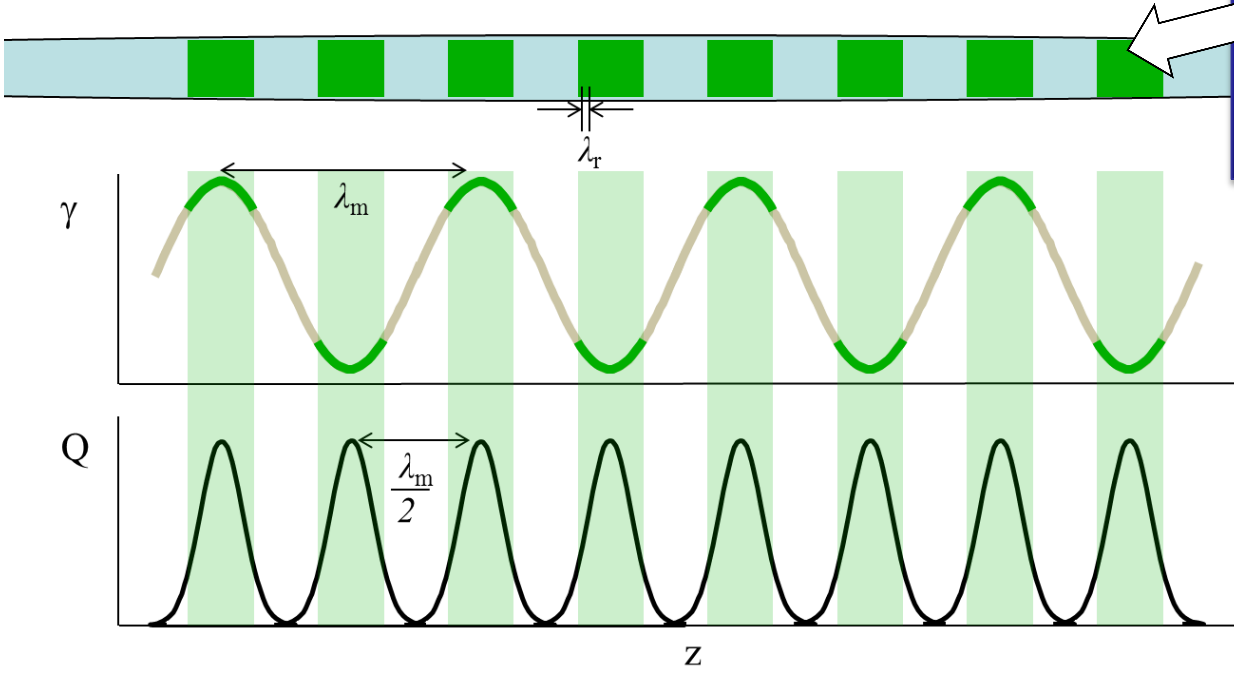
- Our proposal is to use FEL amplification but to do so in such a way that we beat the limit imposed by the co-operation length.
- We *still* need a region of high quality electron beam with a length on the scale of the co-operation length – *but* the key point is that it *does not need to be continuous.*
- 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 together, they can interact via the radiation slipping between them and amplification can occur.
- Effectively trading an isolated many-cycle pulse for multiple few-cycle pulses


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 + a short modulator undulator, already present at several facilities.
- The expectation was that this sinusoidal energy modulation would correspond to a variation in electron beam quality in some way, e.g. higher quality beam (low energy chirp) and lower quality beam (high energy chirp).



Few-cycle slices of high quality

Electron energy

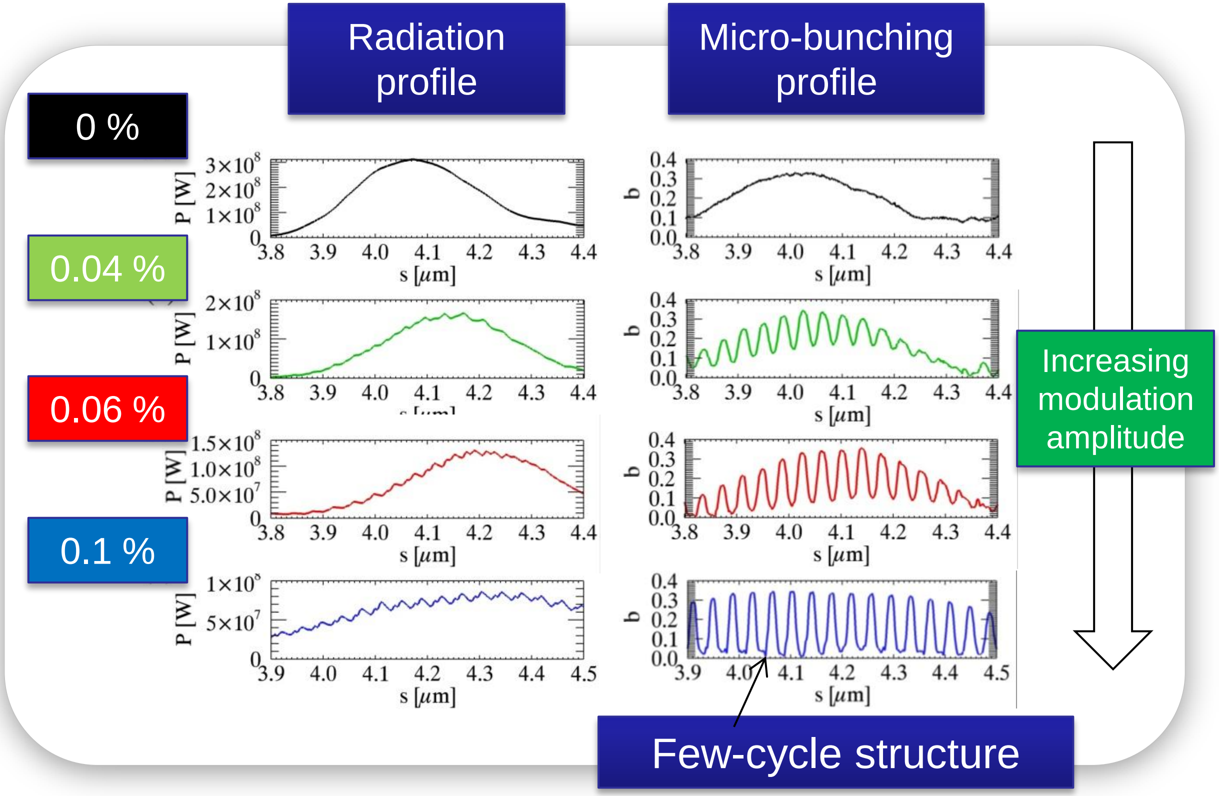
Electron “quality”?

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 l_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



Radiation profile

Micro-bunching profile

0 %

0.04 %

0.06 %

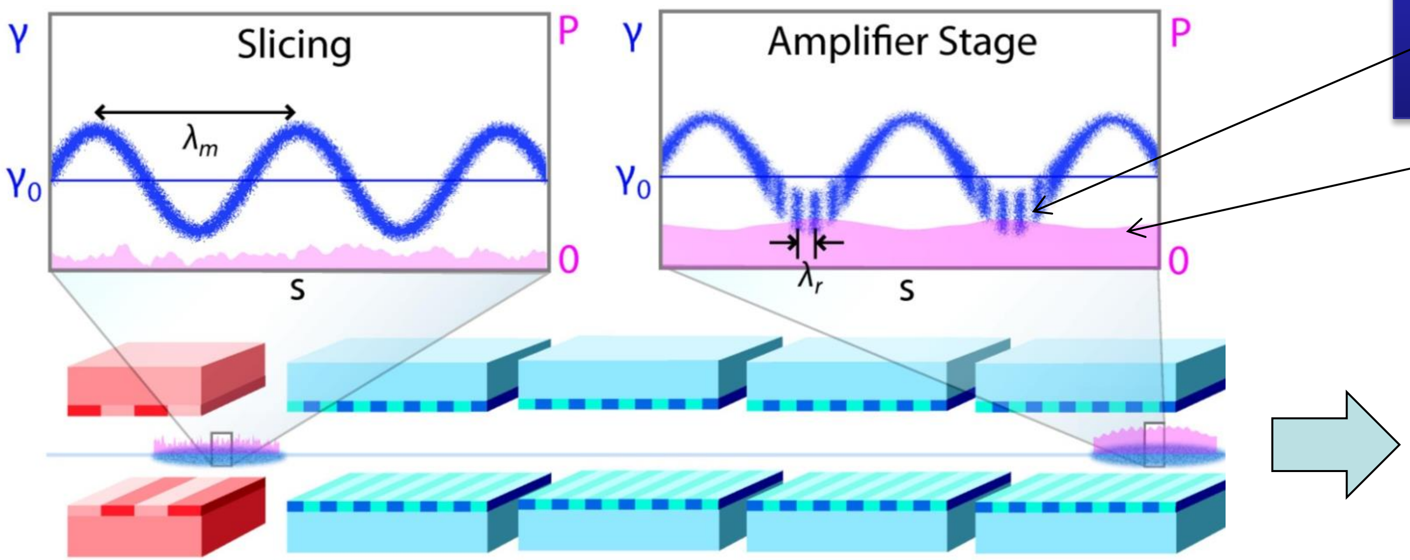
0.1 %

Increasing modulation amplitude

Few-cycle structure

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.



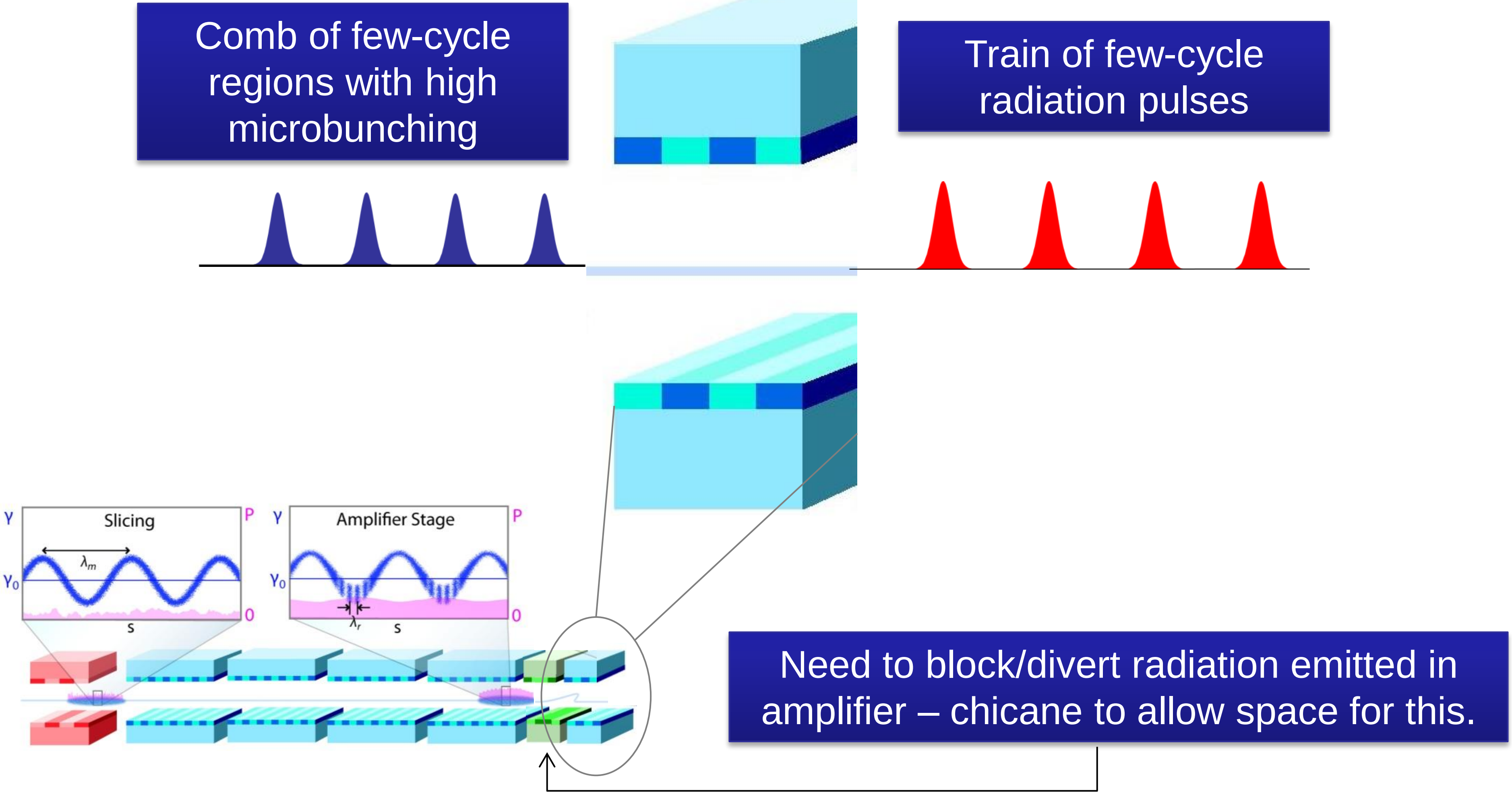
Comb-structure in micro-bunching, but not in radiation

Few-cycle radiation pulses?

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 electron 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

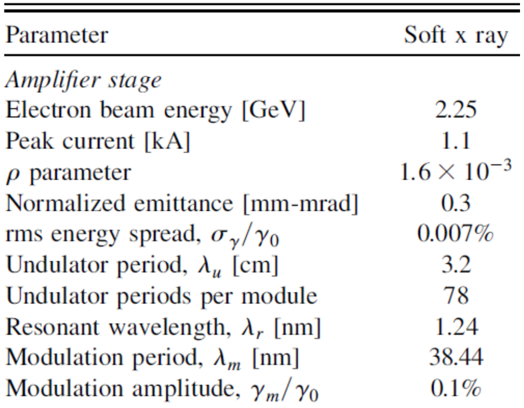
Train of few-cycle radiation pulses

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

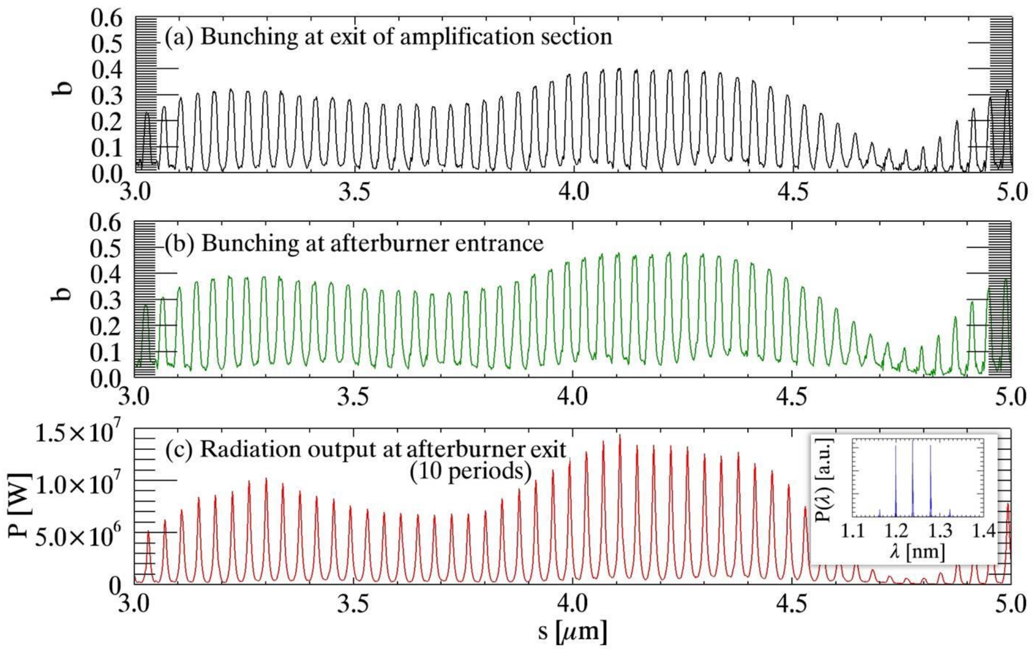
Single few-period undulator – simulations

- 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 extracted the electron beam slightly before saturation and put it through a chicane (blocking amplifier radiation) which slightly enhanced the micro-bunching.
- We then used a 10-period undulator to get a train of radiation pulses. Pulse duration ~10as rms and peak power ~10MW.
- Relatively low power but a promising option for a proof-of-principle experiment.

Soft x-ray 1.24 nm example



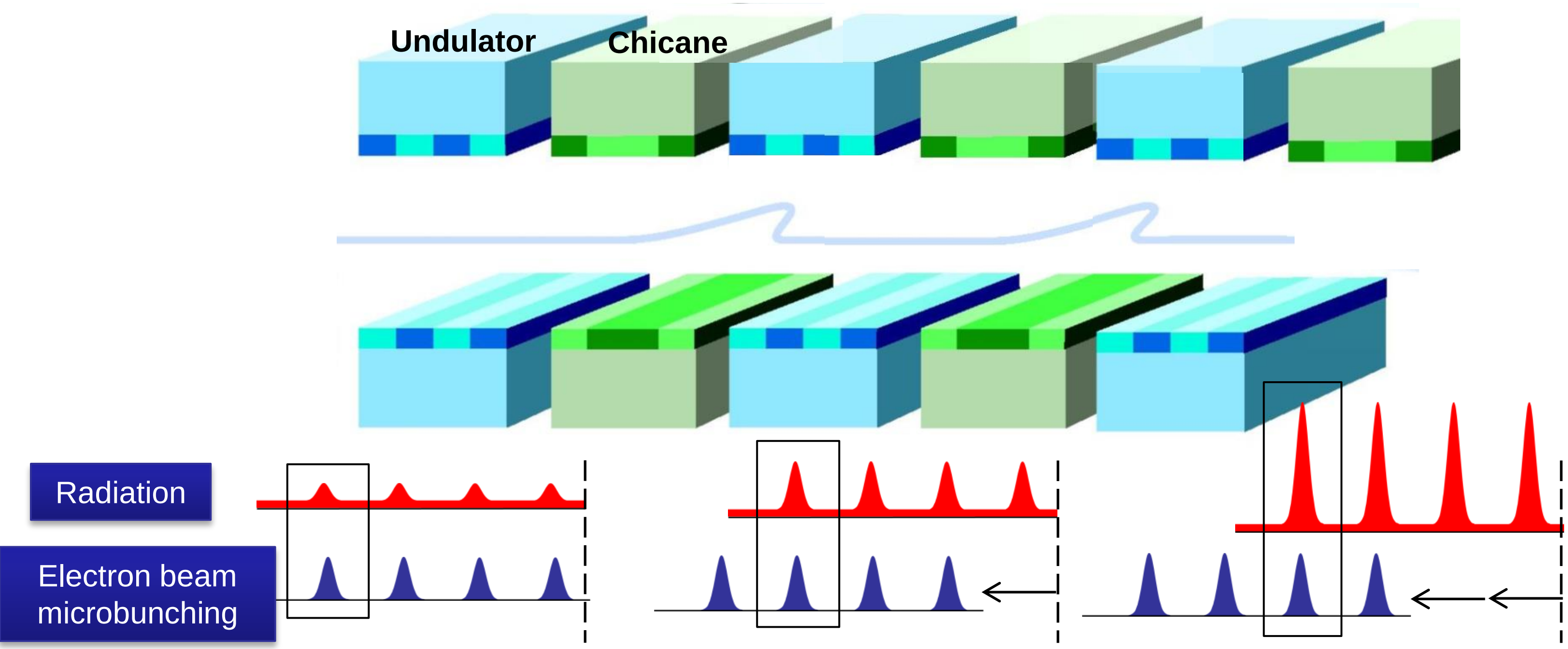
Parameter	Soft x ray
Amplifier stage	
Electron beam energy [GeV]	2.25
Peak current [kA]	1.1
ρ parameter	1.6×10^{-3}
Normalized emittance [mm-mrad]	0.3
rms energy spread, σ_γ/γ_0	0.007%
Undulator period, λ_u [cm]	3.2
Undulator periods per module	78
Resonant wavelength, λ_r [nm]	1.24
Modulation period,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

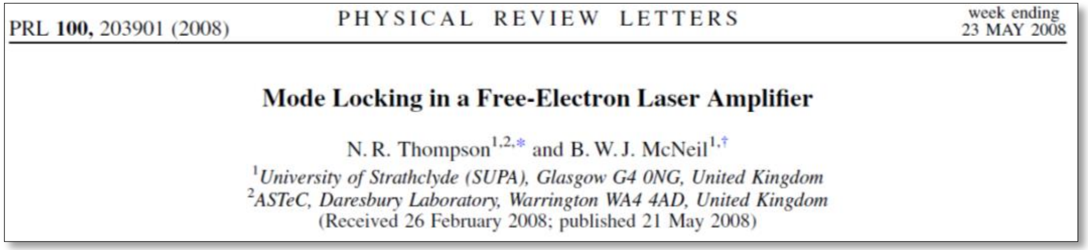


~10 as rms pulses

Method for generating 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 the short-scale structure.
- Use concept from laser mode-locking in an FEL amplifier – use a series of short undulator sections with magnetic chicanes inserted between them to periodically delay the electrons.
- A train of radiation pulses can then be amplified. The 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

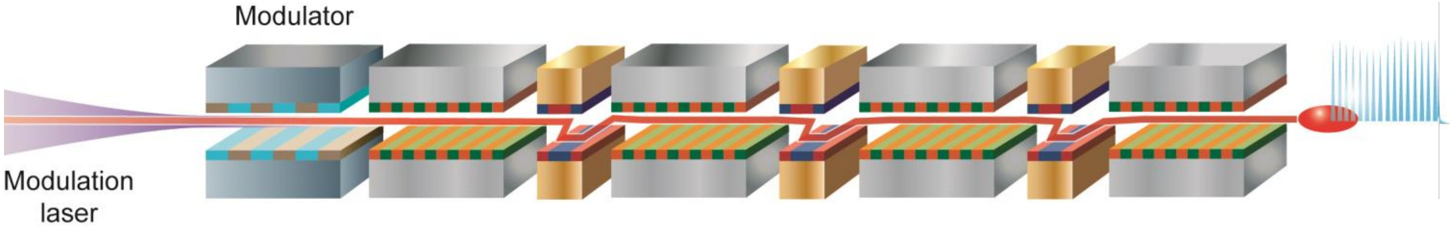
N. R. Thompson[1,2,*] and B. W. J. McNeil[1,†]
[1]*University of Strathclyde (SUPA), Glasgow G4 0NG, United Kingdom*
[2]*ASTeC, Daresbury Laboratory, Warrington WA4 4AD, United Kingdom*
(Received 26 February 2008; published 21 May 2008)

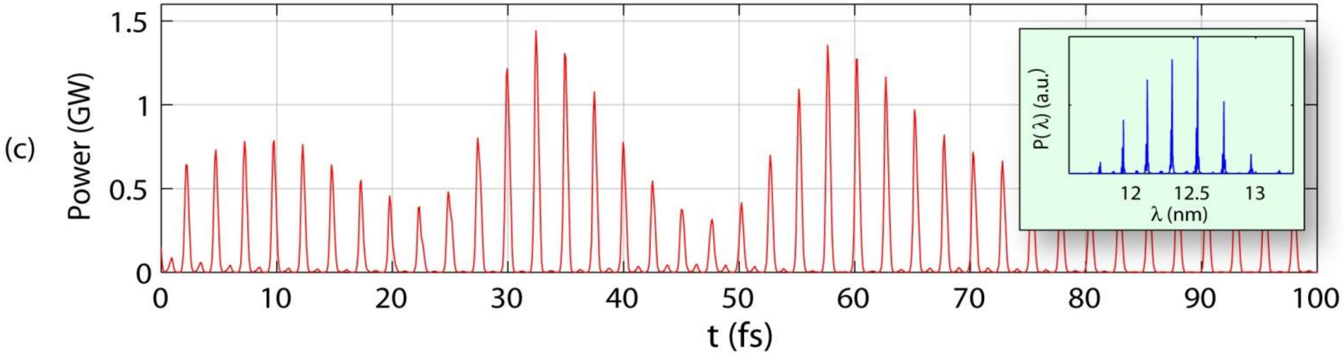
A Recipe for Mode-Locking…

1. Take a NORMAL SASE FEL with a long sectional undulator

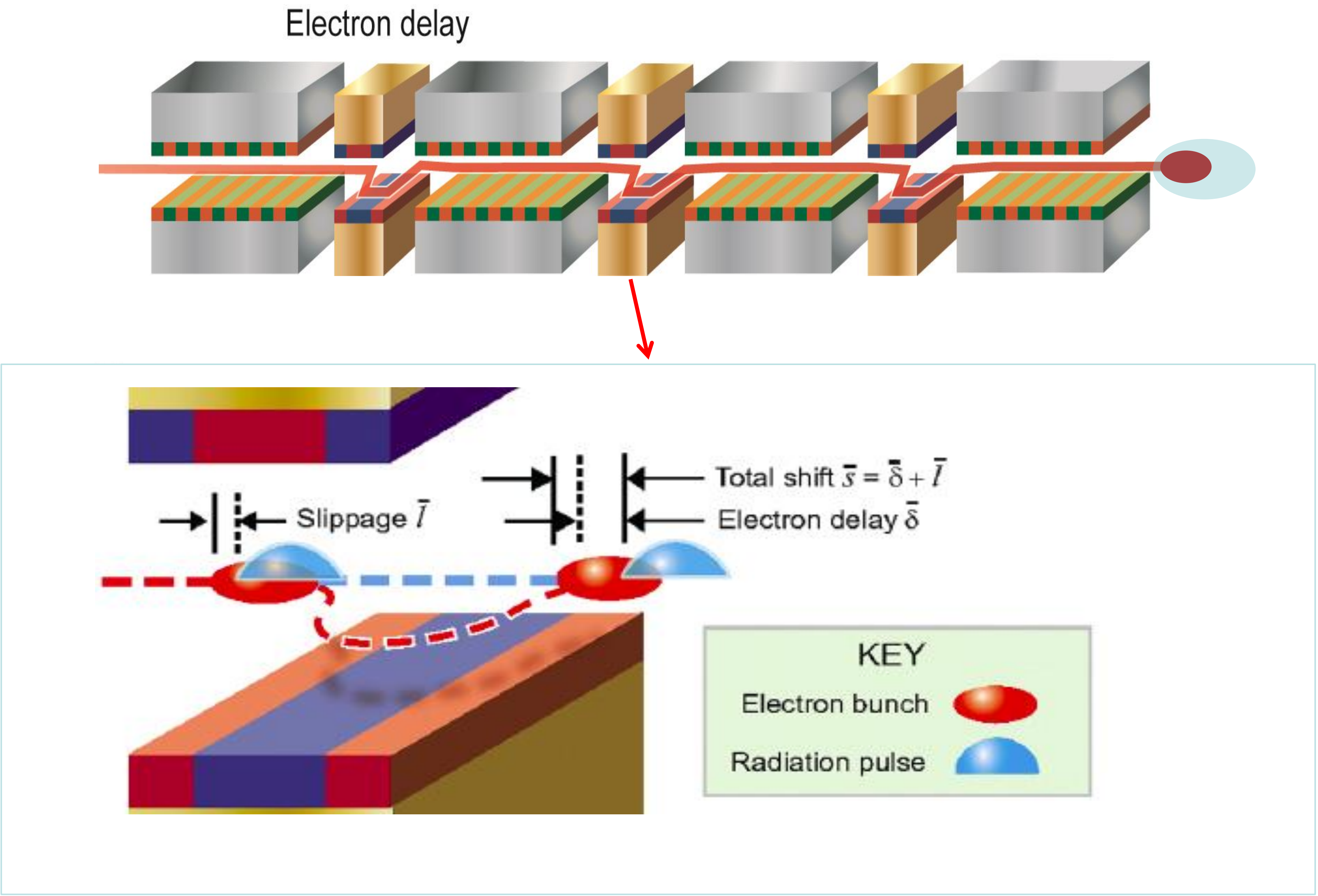
2. Add electron beam delays to produce axial mode structure: ***Mode Coupling***

3. Add a periodic electron bunch modulation giving each mode sidebands which then overlap with neighbouring modes, causing phases to lock: ***Mode Locking!***

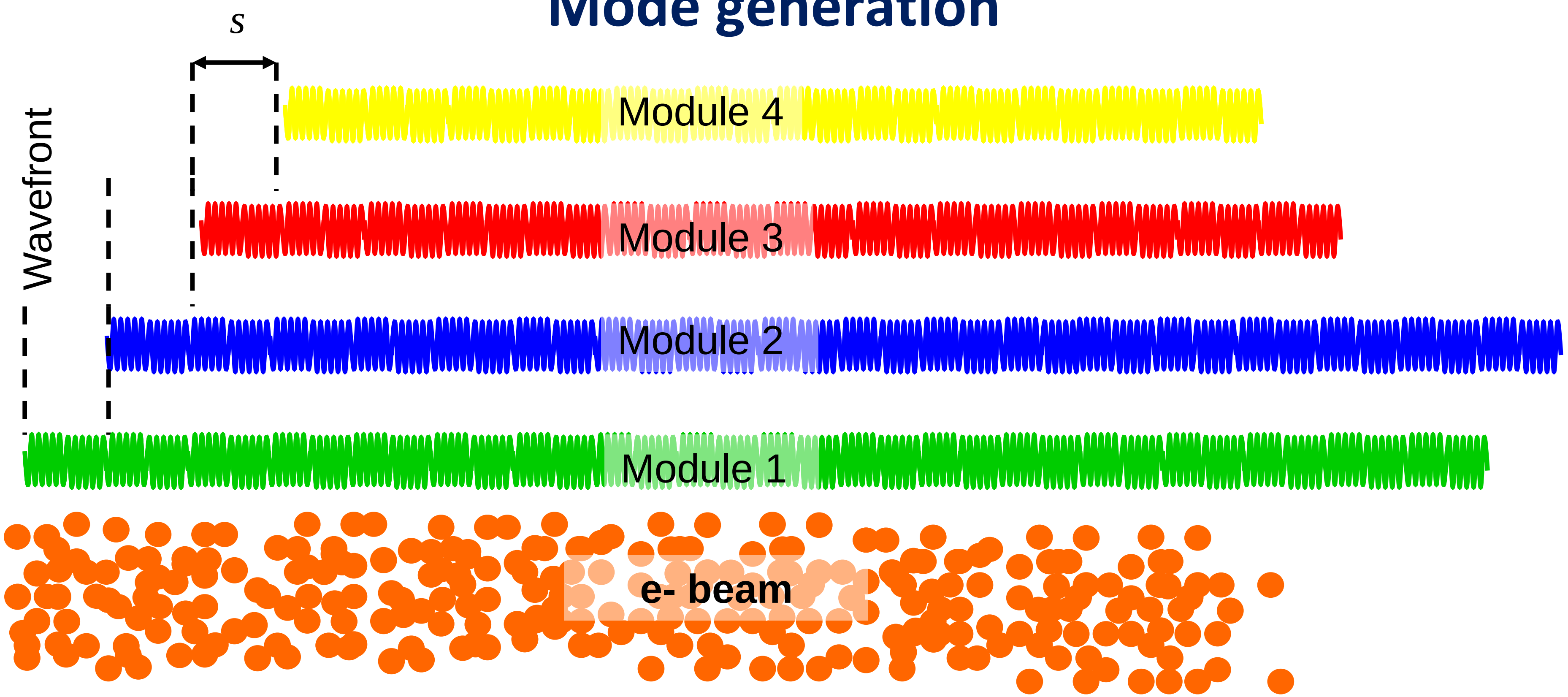


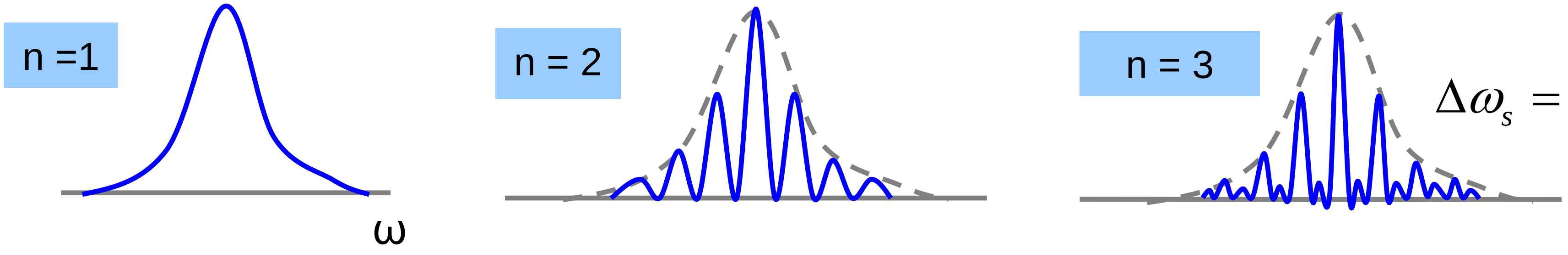


Phase shifting



Mode generation



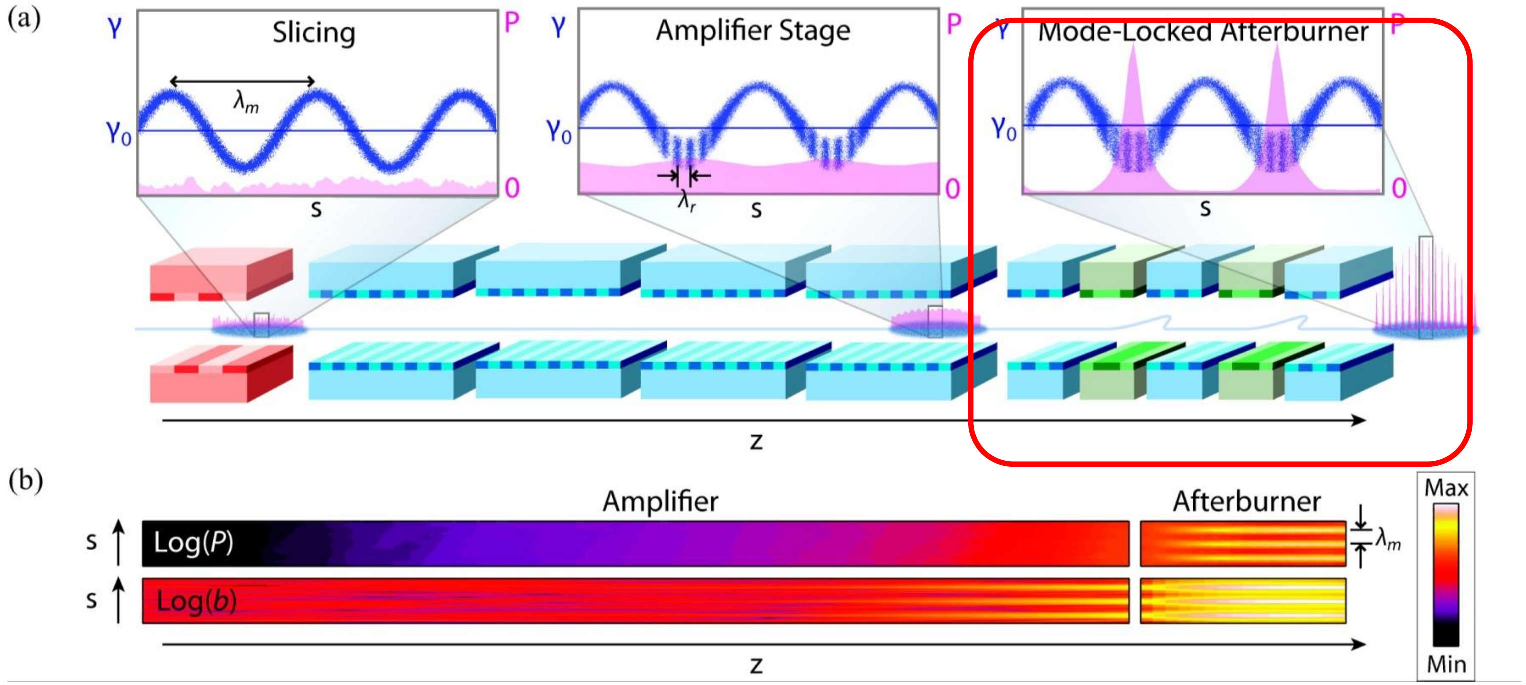


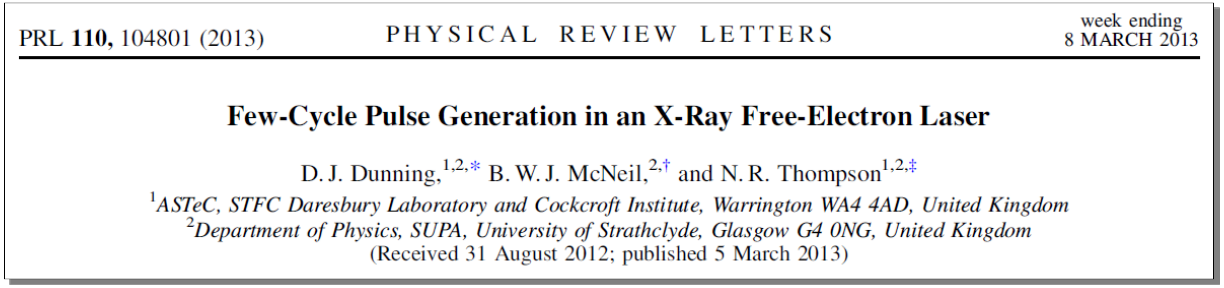
$$\Delta\omega_s = \frac{2\pi c}{s}$$

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

“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.



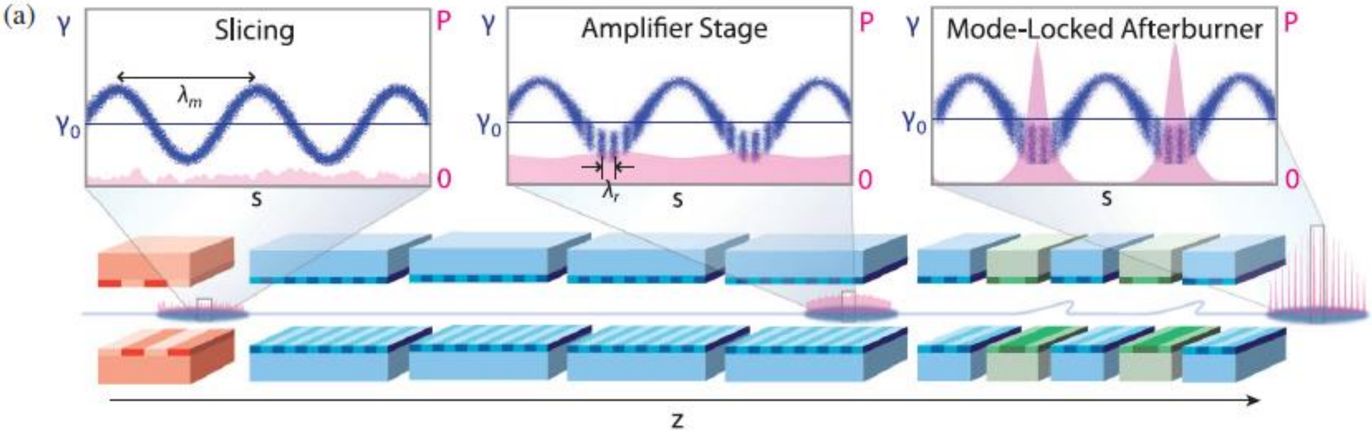


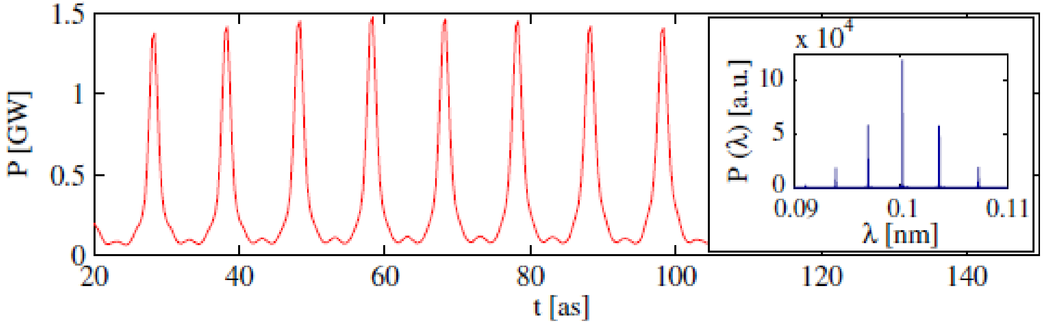
PRL **110,** 104801 (2013) PHYSICAL REVIEW LETTERS week ending 8 MARCH 2013

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

D. J. Dunning,[1,2,*] B. W. J. McNeil,[2,†] and N. R. Thompson[1,2,‡]
[1]*ASTeC, STFC Daresbury Laboratory and Cockcroft Institute, Warrington WA4 4AD, United Kingdom*
[2]*Department of Physics, SUPA, University of Strathclyde, Glasgow G4 0NG, United Kingdom*
(Received 31 August 2012; published 5 March 2013)

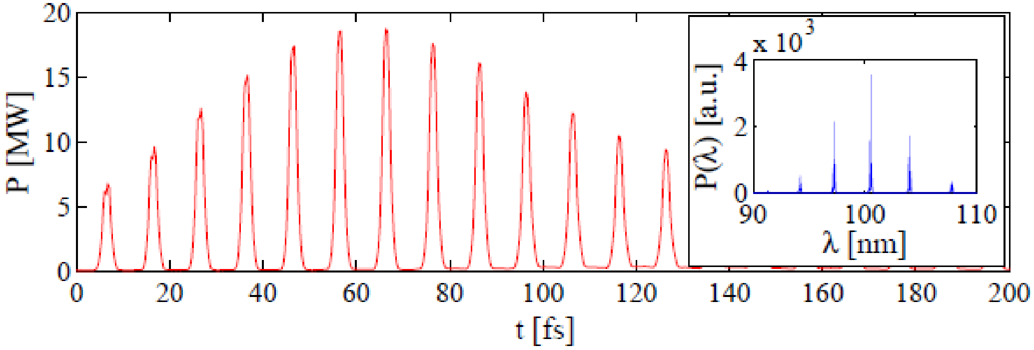
Short Pulse Schemes: Mode-Locked Afterburner





Hard X-Ray @ 0.1nm
700zs Pulse Duration (rms)

(see below)



CLARA Parameters @ 100nm
700as Pulse Duration (rms)

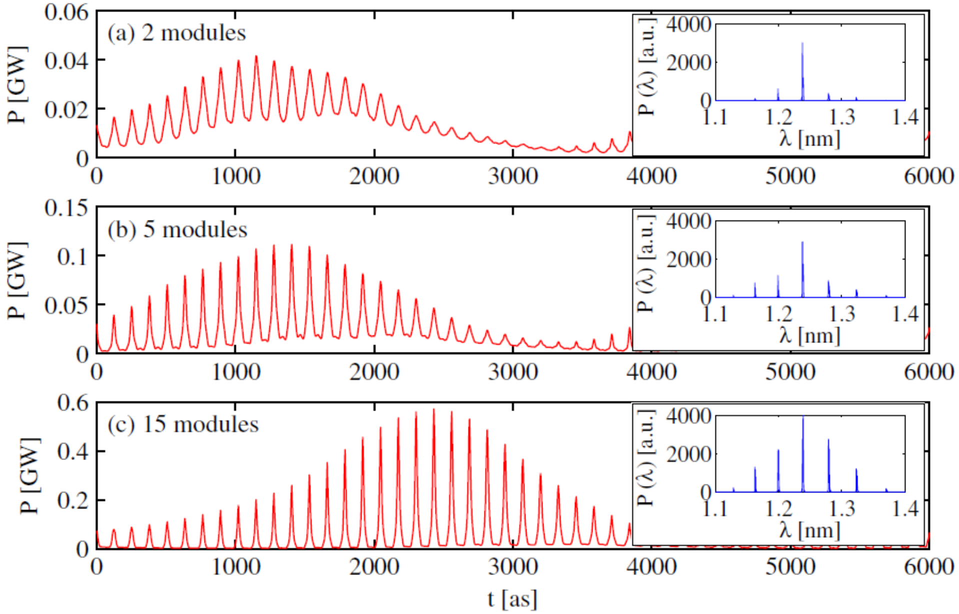
Mode-locked afterburner soft x-ray simulation

- 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 ~9as rms pulses separated by 124as, at ~0.6GW.

[c.f. ~10as rms and peak power ~10MW from few-period undulator]

Soft x-ray 1.24 nm example

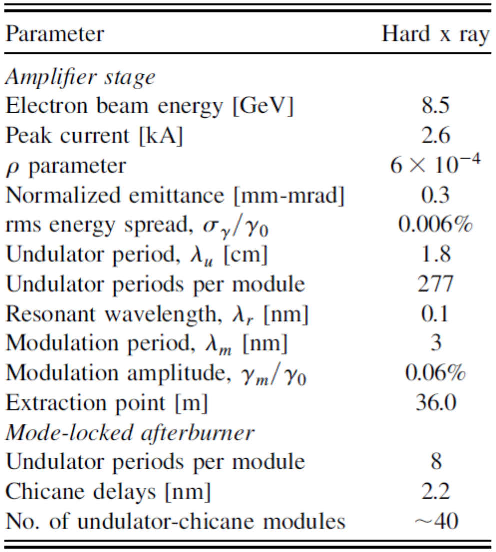
Parameter	Soft x ray
Amplifier stage	
Electron beam energy [GeV]	2.25
Peak current [kA]	1.1
ρ parameter	1.6×10^{-3}
Normalized emittance [mm-mrad]	0.3
rms energy spread, σ_γ/γ_0	0.007%
Undulator period, λ_u [cm]	3.2
Undulator periods per module	78
Resonant wavelength, λ_r [nm]	1.24
Modulation period,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



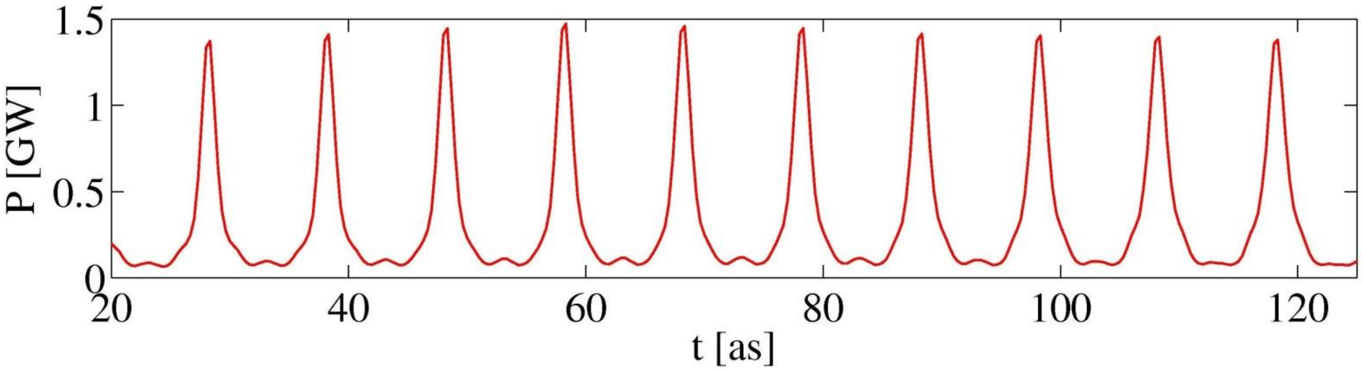
Mode-locked afterburner hard x-ray simulation

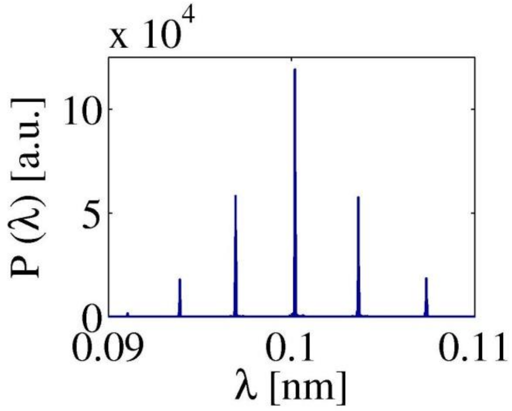
- A hard x-ray case with resonant FEL wavelength 0.1 nm was also simulated, with the aim of demonstrating shorter pulse generation.
- Used parameters similar to the SACLA facility.
- Aiming for shortest pulses, so used 8-period undulator modules in afterburner and a 3 nm modulation period (30 x λ_r).
- 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



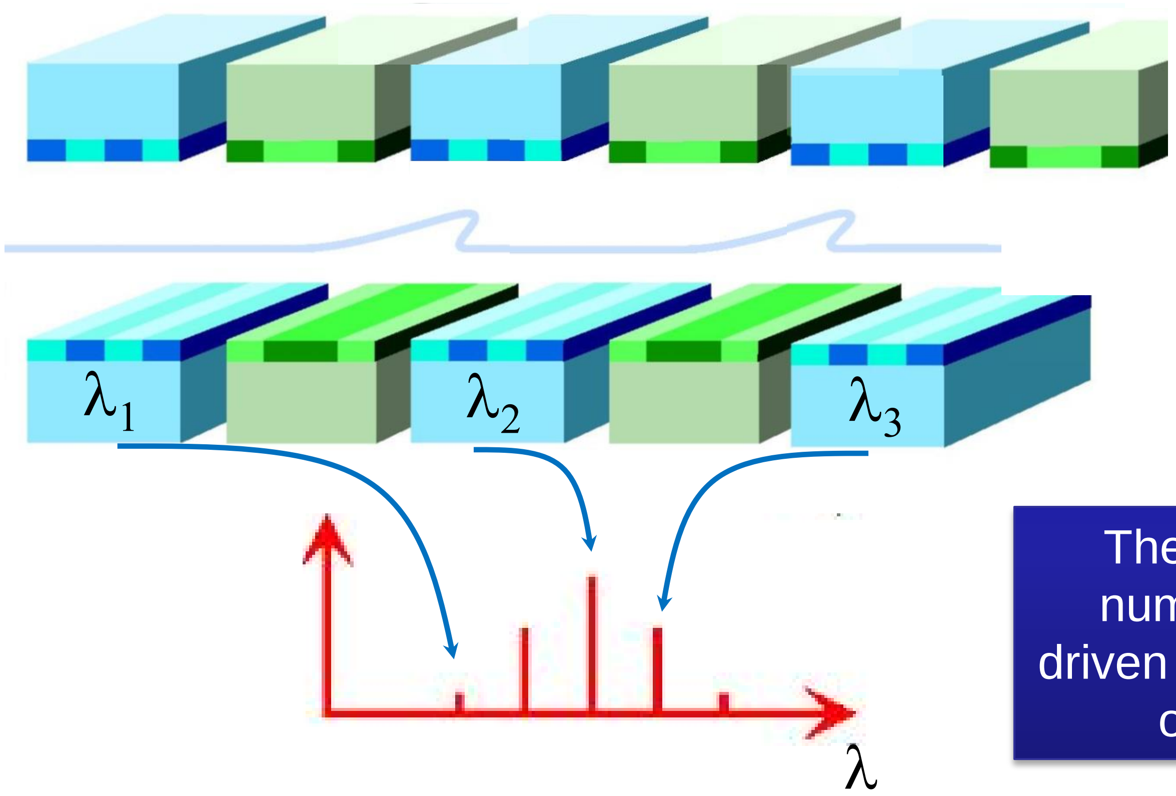


~700 zs rms pulses

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 Schemes: Sliced Chirped Beam + Taper*

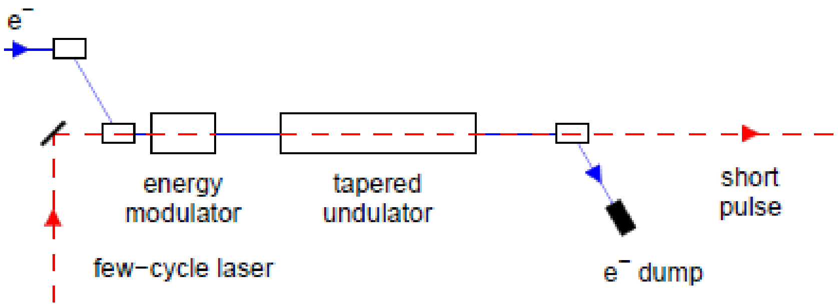
[Good example of Slide 23 →]

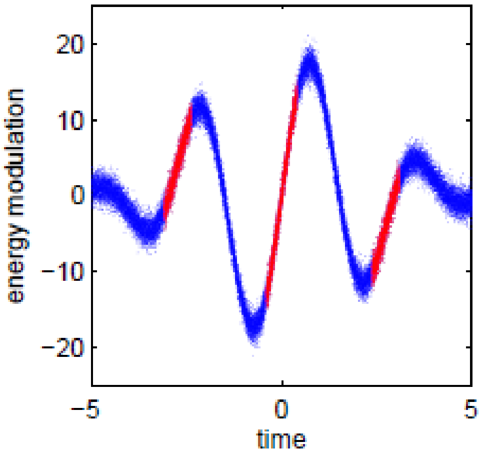
Principle of scheme

- Few-cycle laser interacts with electron beam to generate strong energy chirp in short region of bunch
- Radiator taper is matched to the energy chirp to maintain resonance as the FEL pulse slips forwards to electrons with different energies
- FEL gain strongly suppressed in remainder of bunch

Constraints

- Length of chirp needs to match cooperation length for single SASE spike to grow
- Amplitude of chirp needs to be greater than natural bandwidth of the FEL



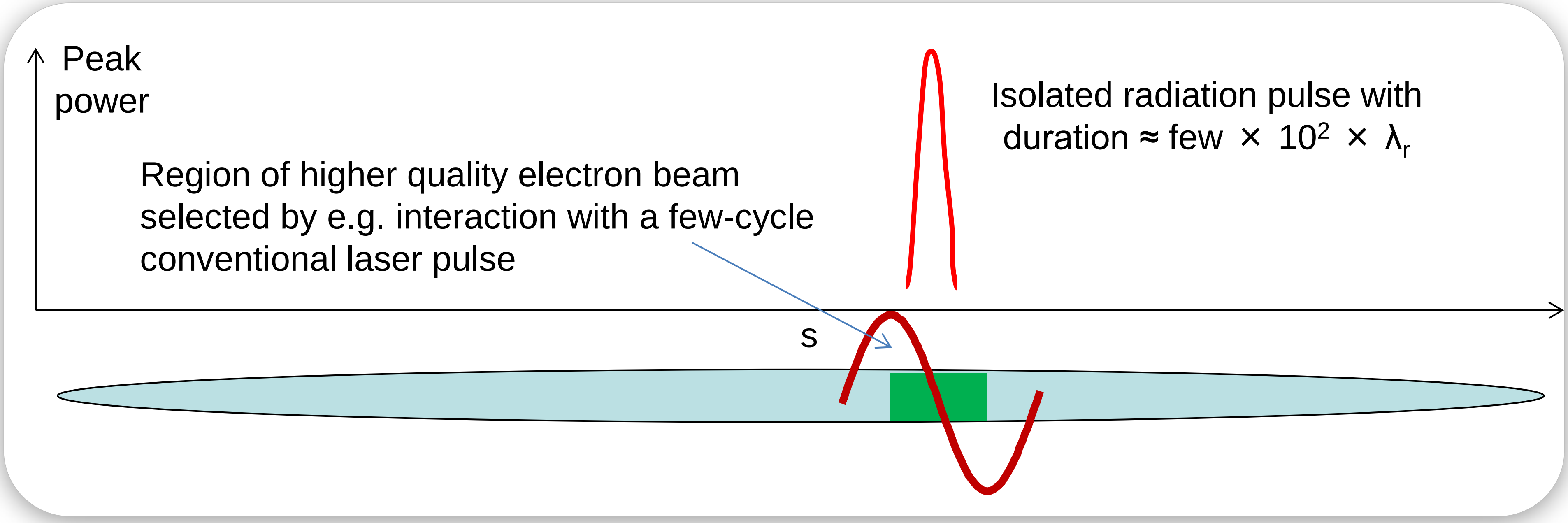


* E. Saldin et al., **PRST-AB**. 9, 050702, (2006)

Slide courtesy Ian Martin, DLS

Slicing a single SASE spike

- Each SASE spike acts independently – we 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 this corresponds to a few hundred cycles or ~100 as – close to record from HHG, but at shorter wavelength & higher photon flux. Fantastic potential for experiments.
- Potential for a further two orders of magnitude reduction with fewer cycles per pulse.

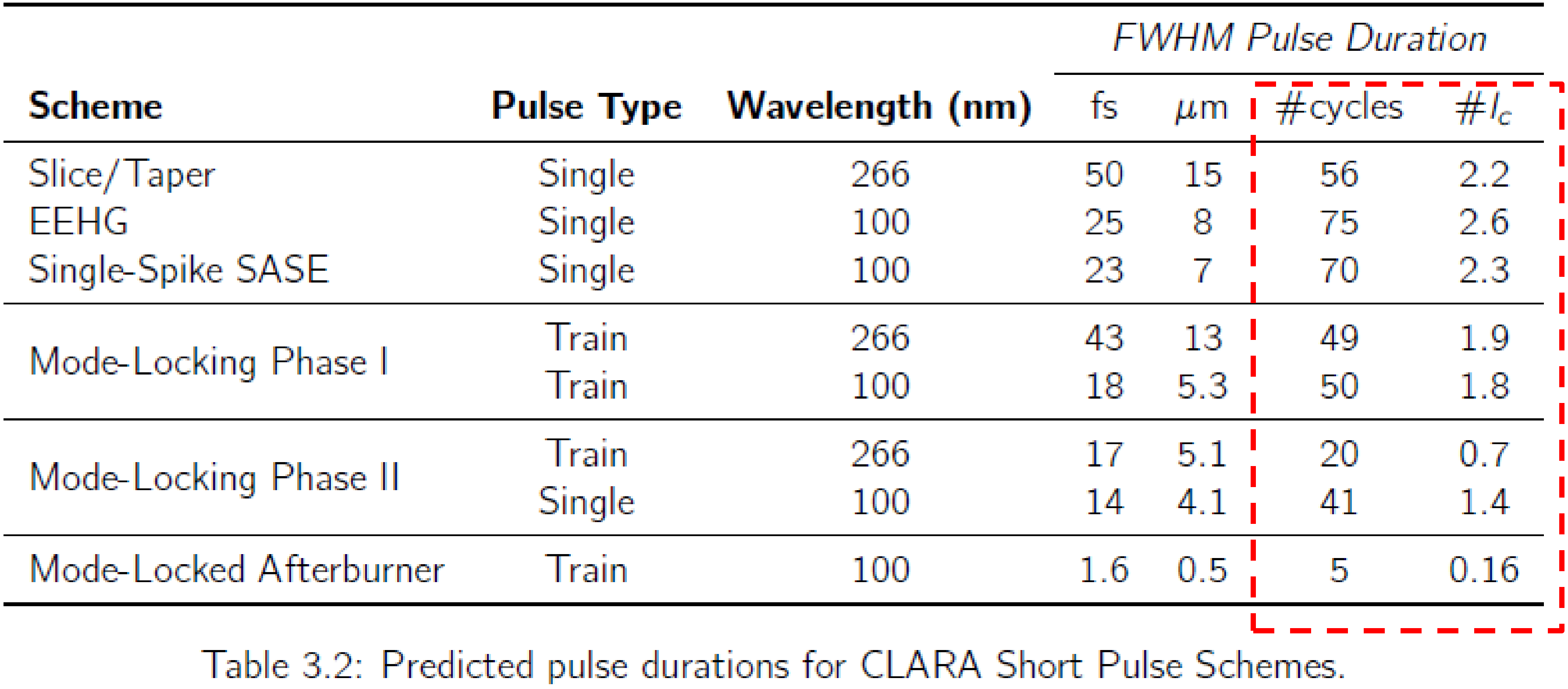


Isolated radiation pulse with duration ≈ few × 10^2 × λ_r

Region of higher quality electron beam selected by e.g. interaction with a few-cycle conventional laser pulse

CLARA Short Pulse Schemes:

Predicted Pulse Durations

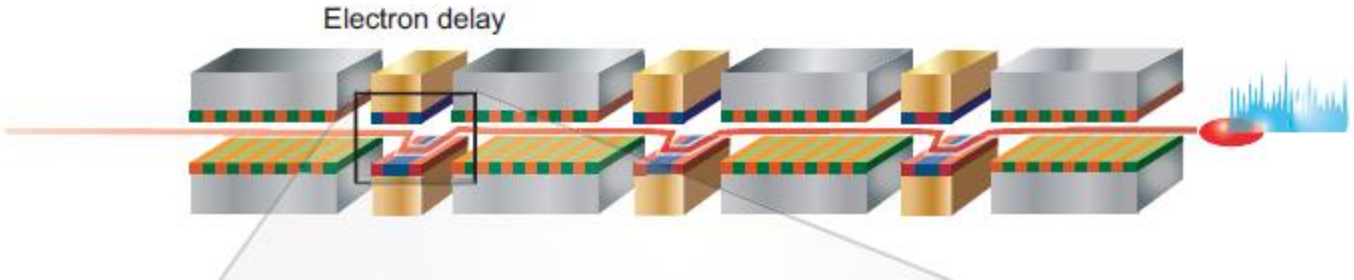


			FWHM Pulse Duration			
Scheme	**Pulse Type**	**Wavelength (nm)**	fs	μm	#cycles	$\#l_c$
Slice/Taper	Single	266	50	15	56	2.2
EEHG	Single	100	25	8	75	2.6
Single-Spike SASE	Single	100	23	7	70	2.3
Mode-Locking Phase I	Train	266	43	13	49	1.9
	Train	100	18	5.3	50	1.8
Mode-Locking Phase II	Train	266	17	5.1	20	0.7
	Single	100	14	4.1	41	1.4
Mode-Locked Afterburner	Train	100	1.6	0.5	5	0.16

Table 3.2: Predicted pulse durations for CLARA Short Pulse Schemes.

Temporal Coherence: High-Brightness (HB) SASE*

- As in the mode-coupled FEL, delays are used between undulator modules

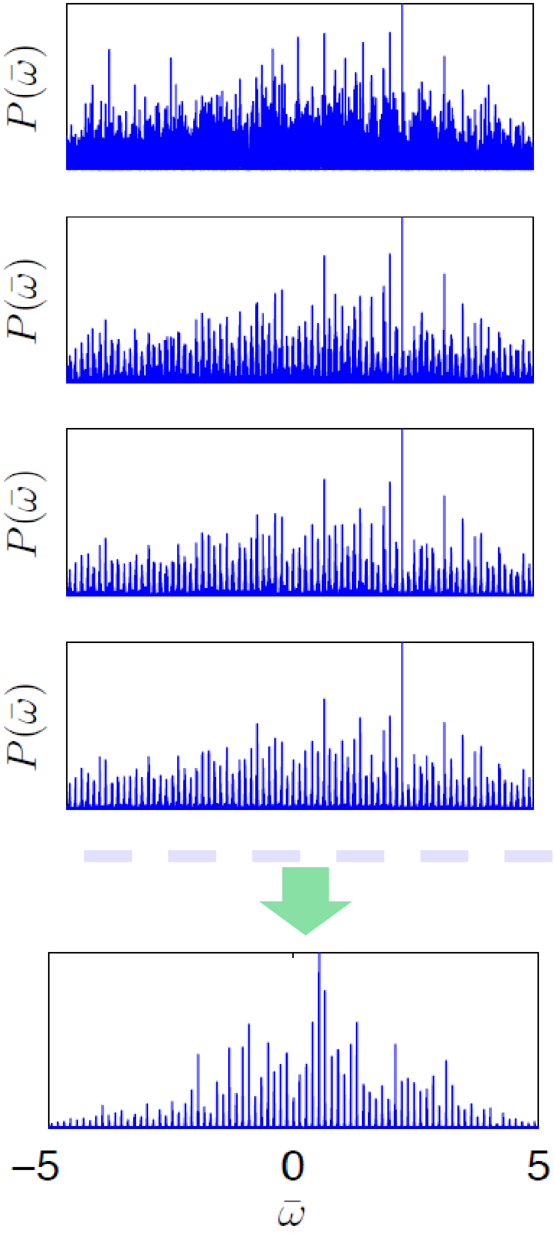


- ***But*** each delay is now ***different*** to ***prohibit*** the growth of modes which limit temporal coherence (and whose spacing depends on the delay)
- Increased slippage gives increased communication length between radiation and electrons, *delocalising* the collective FEL interaction and allowing ***coherence length to grow exponentially*** by up to 2 orders of magnitude (compared to SASE)
- In contrast with other schemes for improving temporal coherence:
  - *There is no requirement for seed laser or photon optics*
  - *It's all done with magnets, and is thus applicable at* ***Any Repetition Rate*** *and* ***Any Wavelength****.*
- Has been demonstrated (over a limited parameter range) on LCLS at SLAC, using detuned undulators as delays, and been shown to reduce linewidth in inverse proportion to the increased slippage. (***NB:*** LCLS name for the scheme is ***iSASE)***

* B. W. J. McNeil, N. R. Thompson & D. J. Dunning, *Transform-Limited X-Ray Pulse Generation from a High-Brightness SASE FEL*, **PRL** 110, 134802 (2013)

Temporal Coherence: HB-SASE

CONSTANT DELAYS



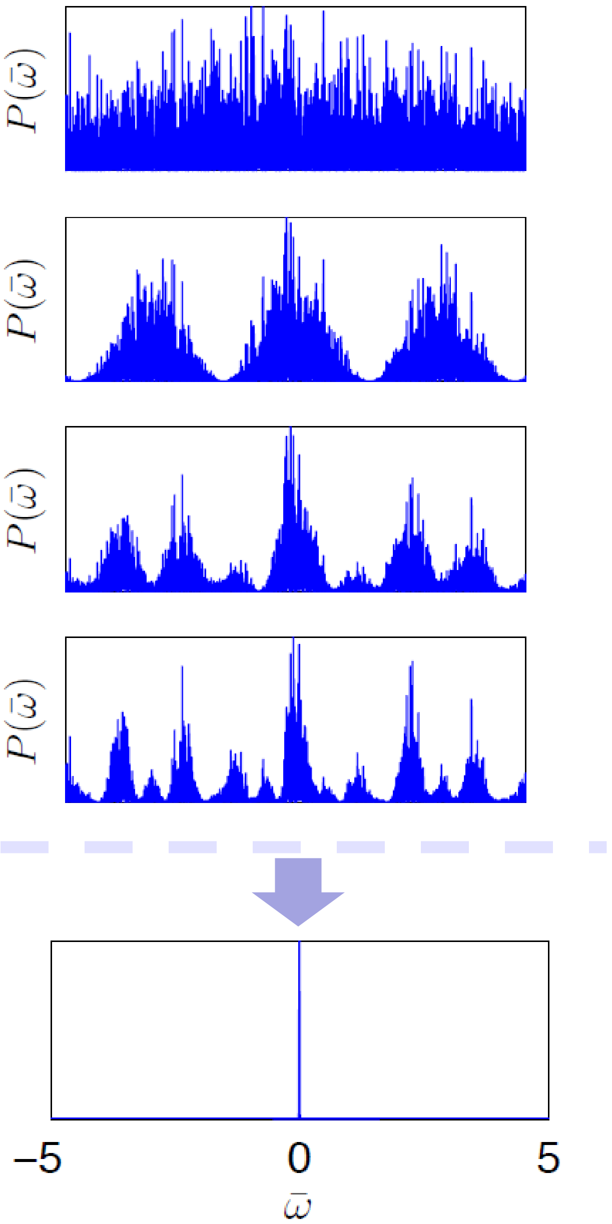
z = 0.5

z = 1.0

z = 1.5

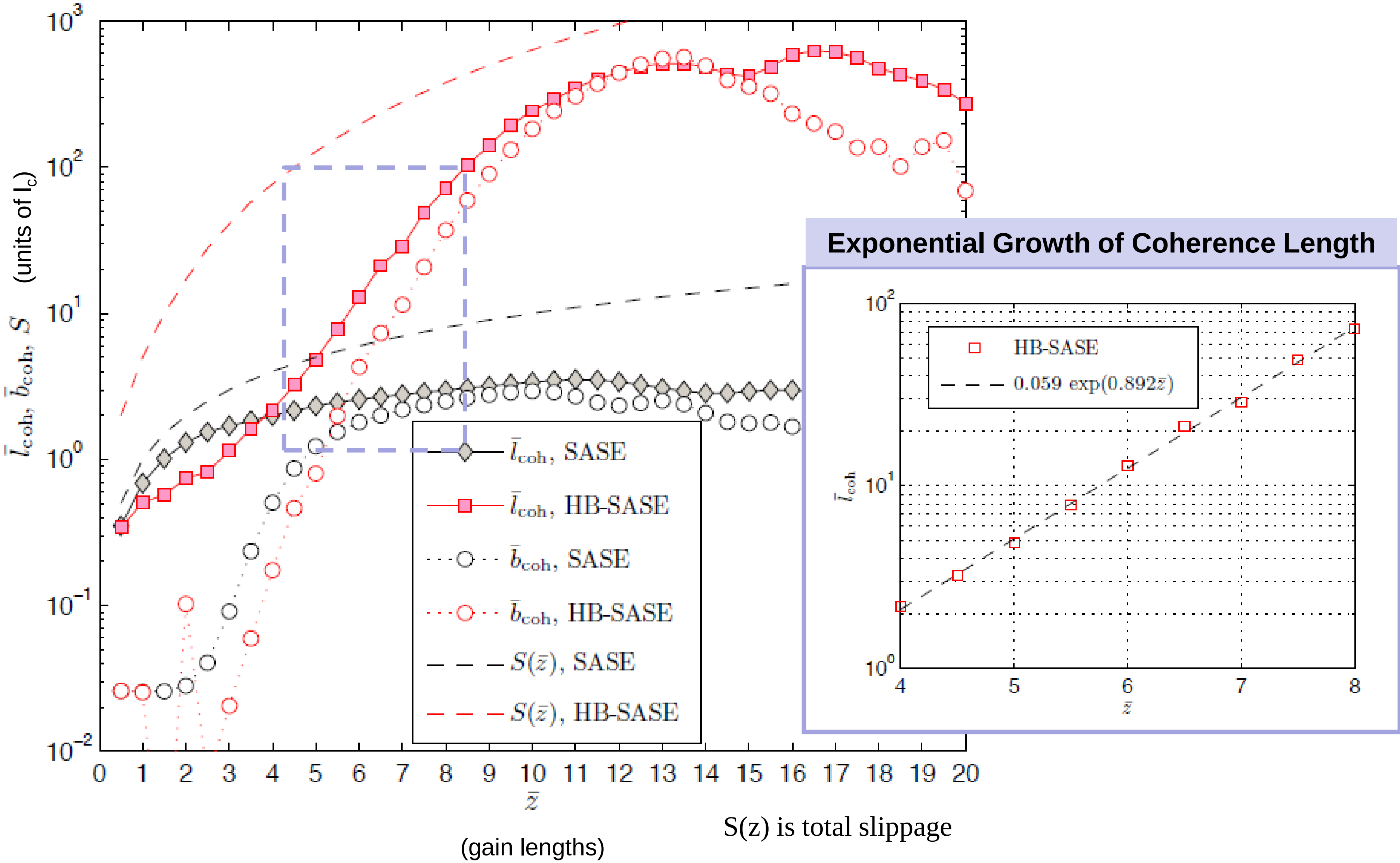
z = 2.0

z = 14



INCREASING DELAYS – PRIME NUMBER SEQUENCE

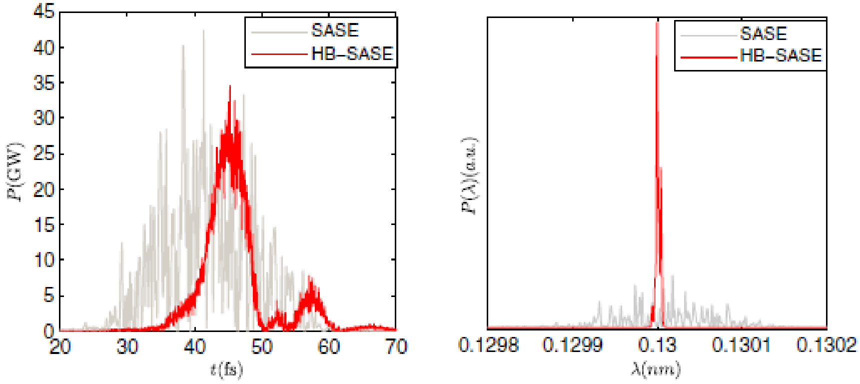
Temporal Coherence: HB-SASE



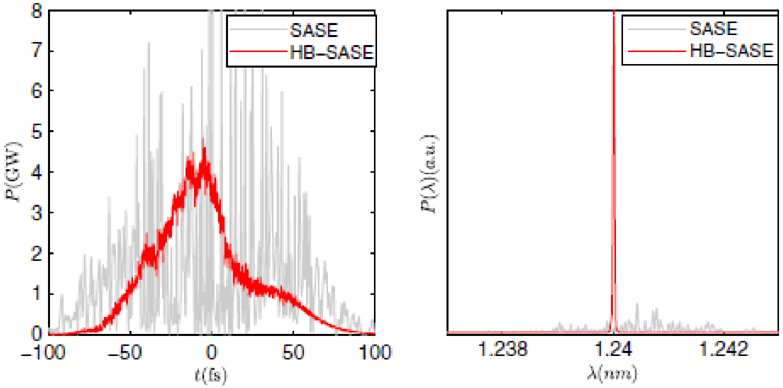
S(z) is total slippage

Temporal Coherence: HB-SASE

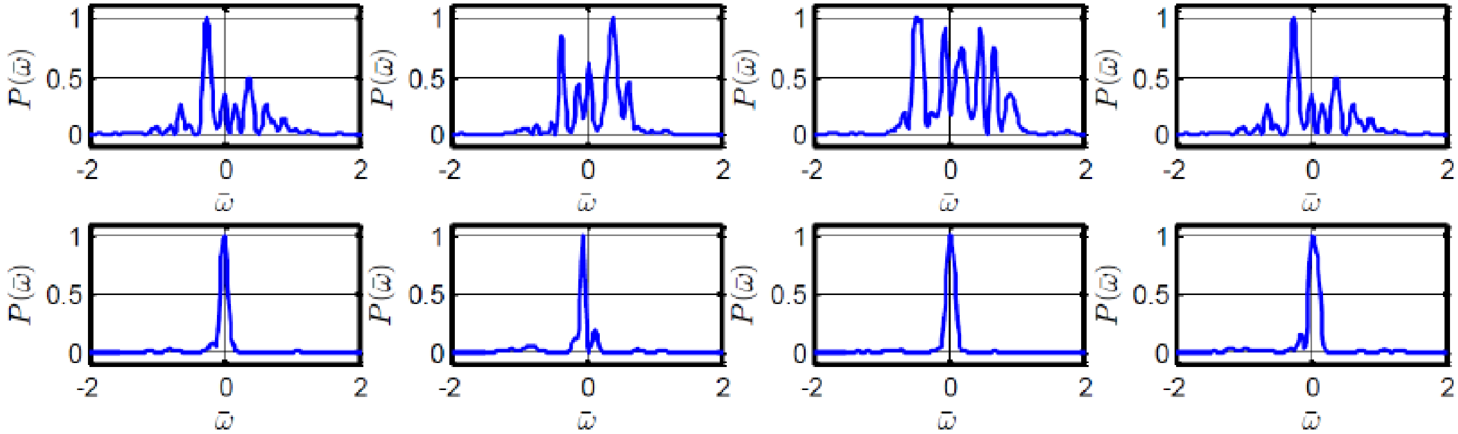
Hard X-Ray (0.13nm) HB-SASE



Soft X-Ray (1.24nm) HB-SASE



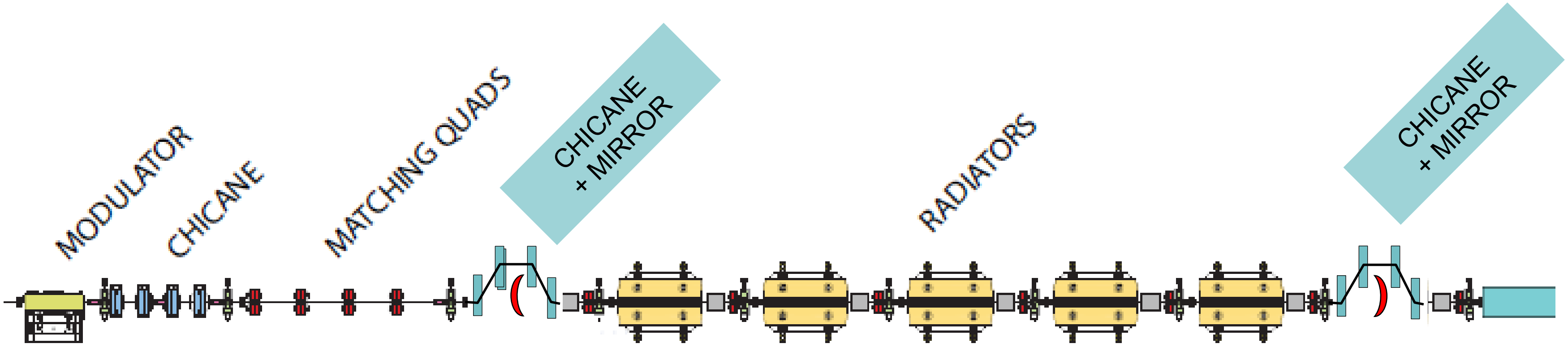
100nm HB-SASE on CLARA, CDR lattice



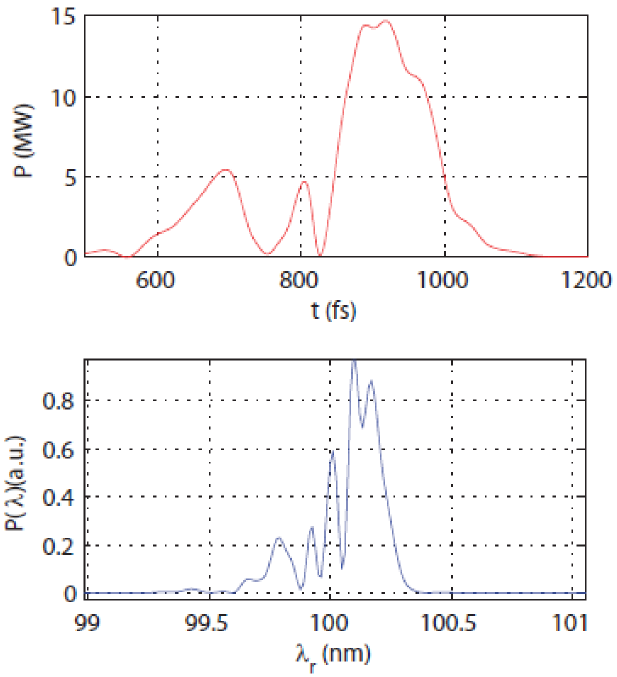
SASE

HB-SASE

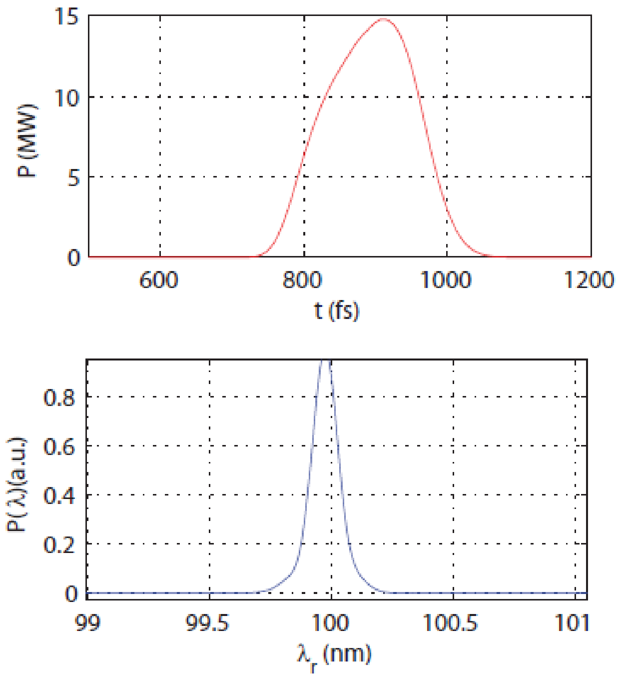
Temporal Coherence: 100nm RAFEL



SASE



RAFEL



Future development

There are many possibilities for future development:

Further development of concept:

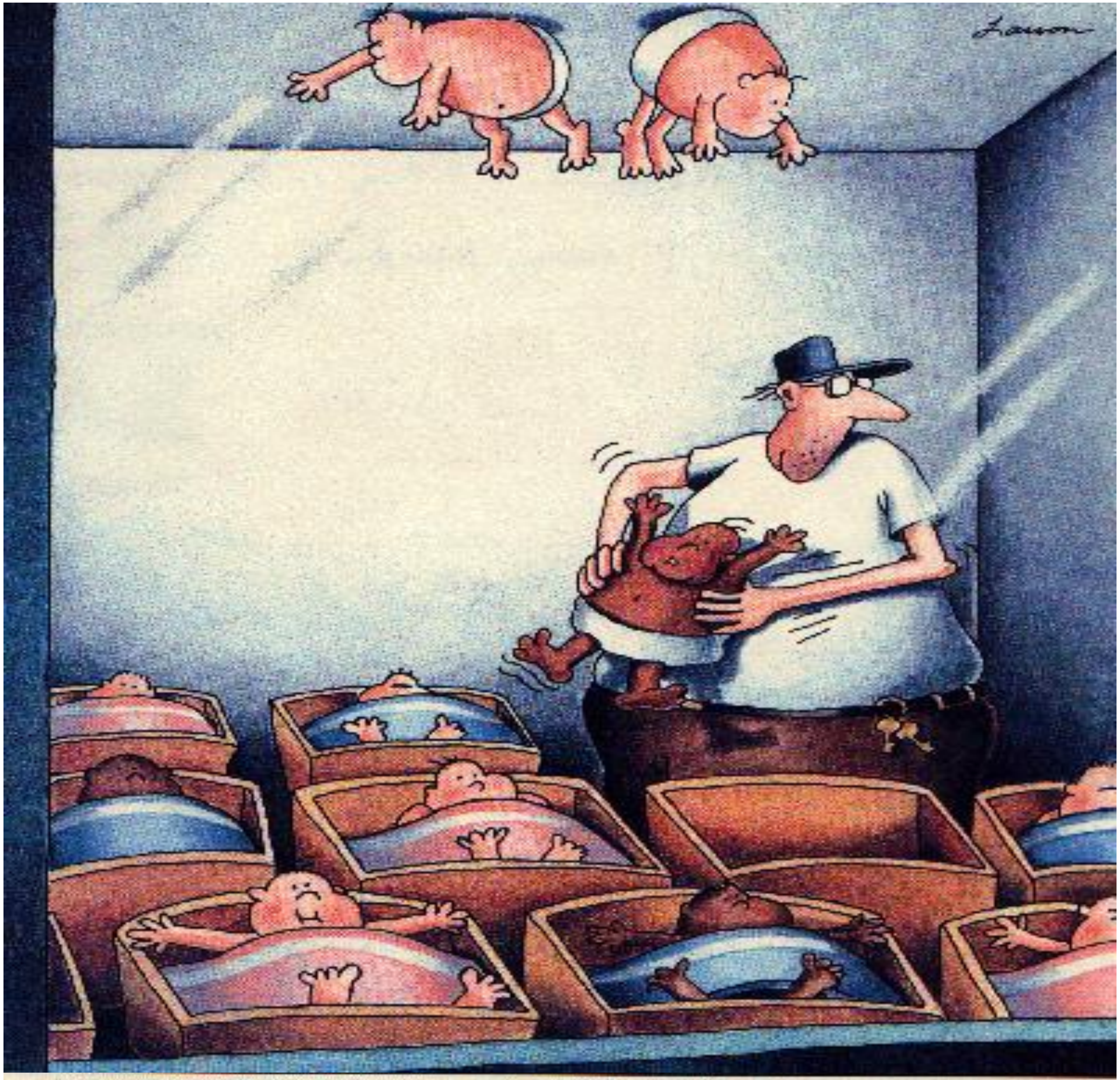
- Investigate flexibility in terms of changing pulse separation, increasing power, etc.
- Combining with other techniques for, e.g., improved temporal coherence / stability. Shorter pulses by tuning different undulator modules to different modes.
- Modelling with non-averaged FEL code such as PUFFIN: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

Further investigation of potential applications:

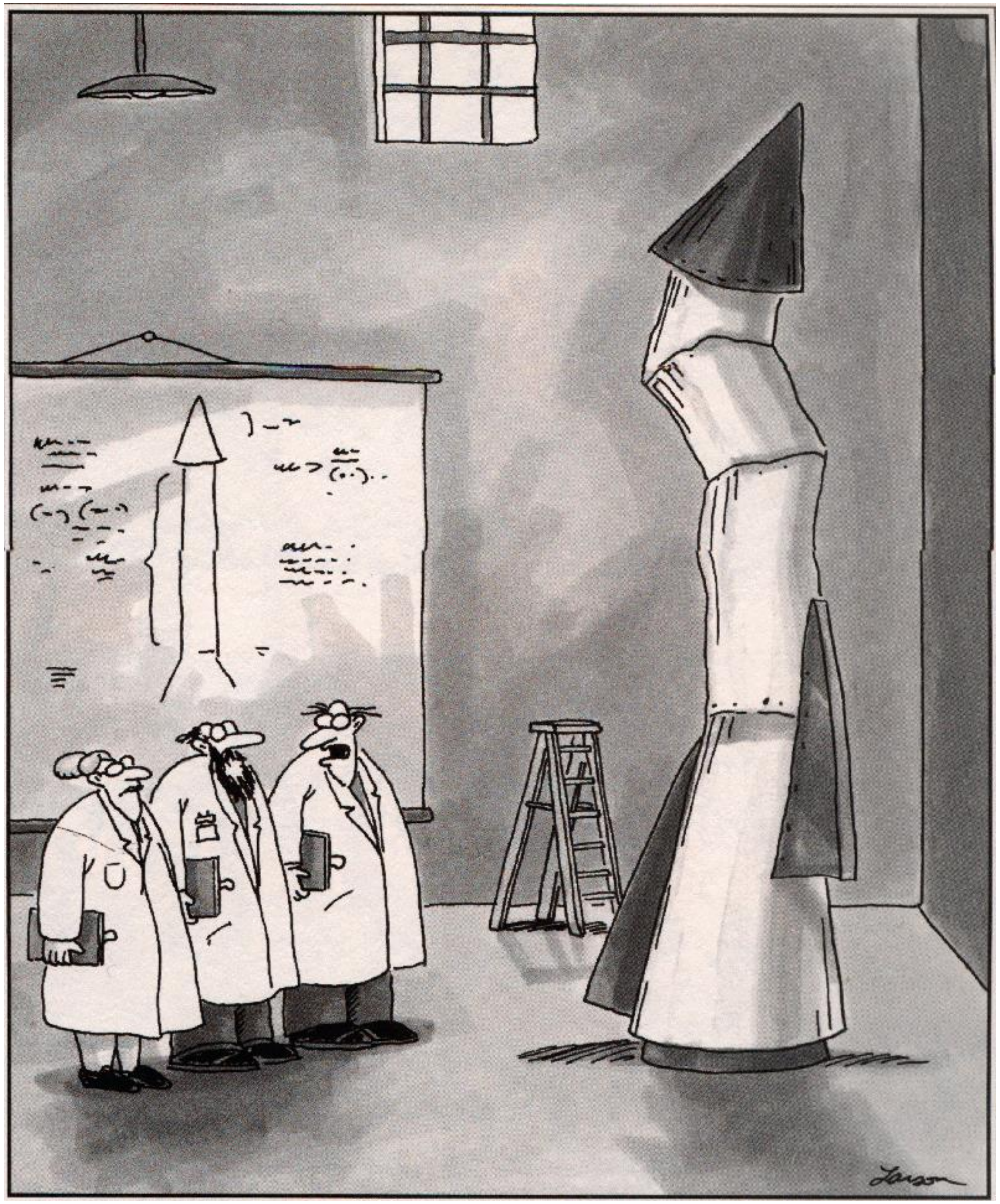
- Ultra-fast dynamics – e.g. stroboscopic measurements as for HHG pulse trains.
- Broad bandwidth / discrete modes could also have applications.

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 experiments. The mode-locked afterburner is also modular and could be tested with a few modules before going to high power.
- How would we measure such short pulses?
  - Spectral measurements could be sufficient for a 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.



Late at night, and without permission, Reuben would often enter the nursery and conduct experiments in static electricity.

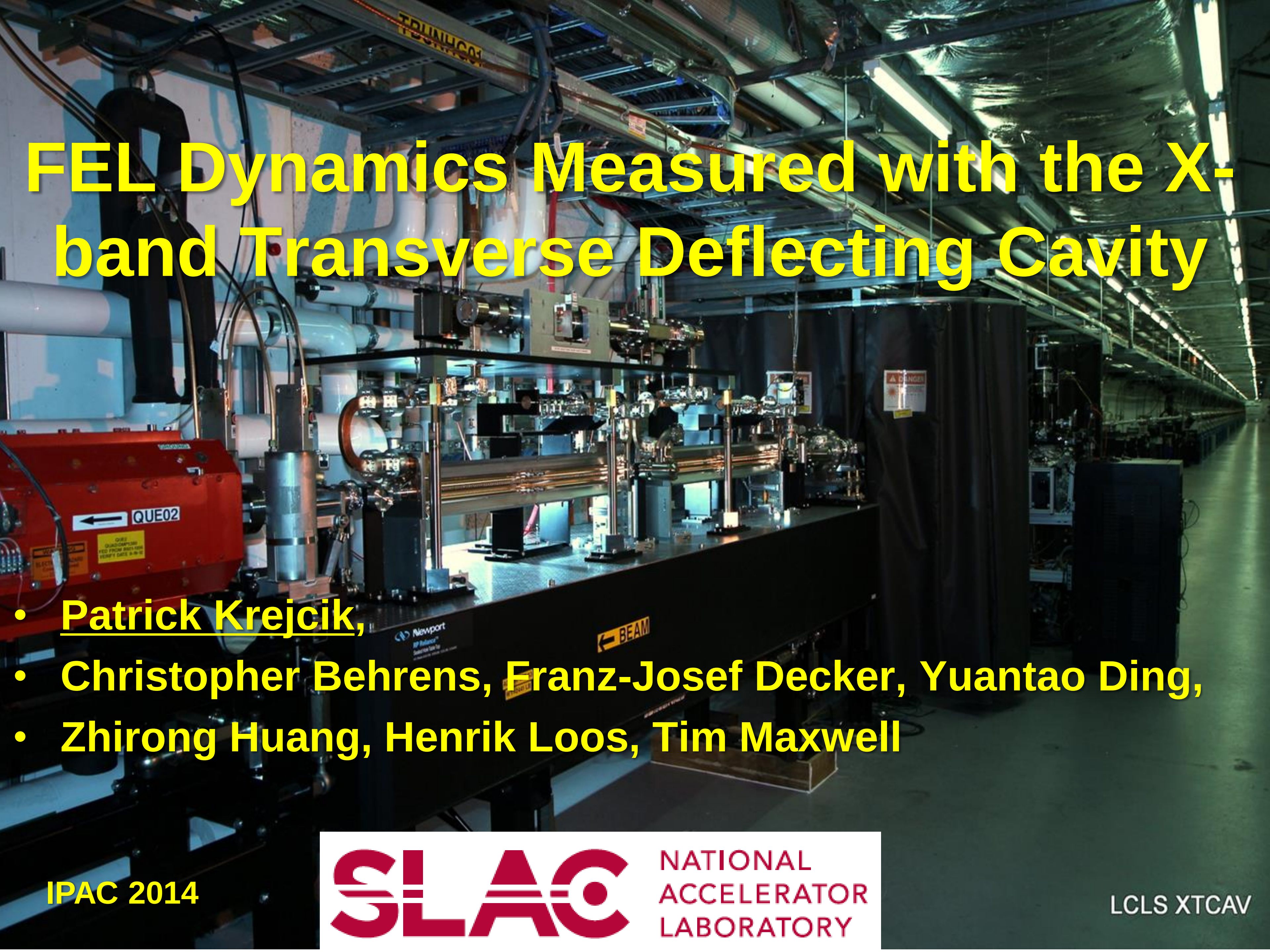


Let’s face it. We are not exactly rocket scientists.

Advanced FEL Diagnostics

What is probably the “ultimate diagnostic” for a free-electron laser has recently been installed on LCLS at SLAC.

[Following slides courtesy of Patrick Krejcik of SLAC]



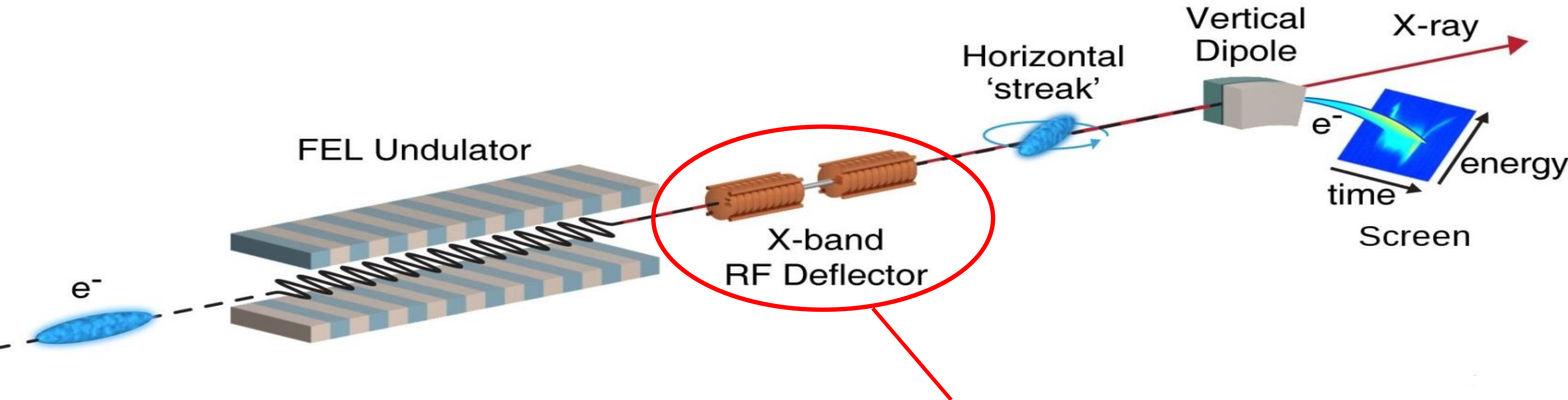
FEL Dynamics Measured with the X-band Transverse Deflecting Cavity

- **Patrick Krejcik**,
- Christopher Behrens, Franz-Josef Decker, Yuantao Ding,
- Zhirong Huang, Henrik Loos, Tim Maxwell

NATIONAL ACCELERATOR LABORATORY

IPAC 2014

LCLS XTCAV



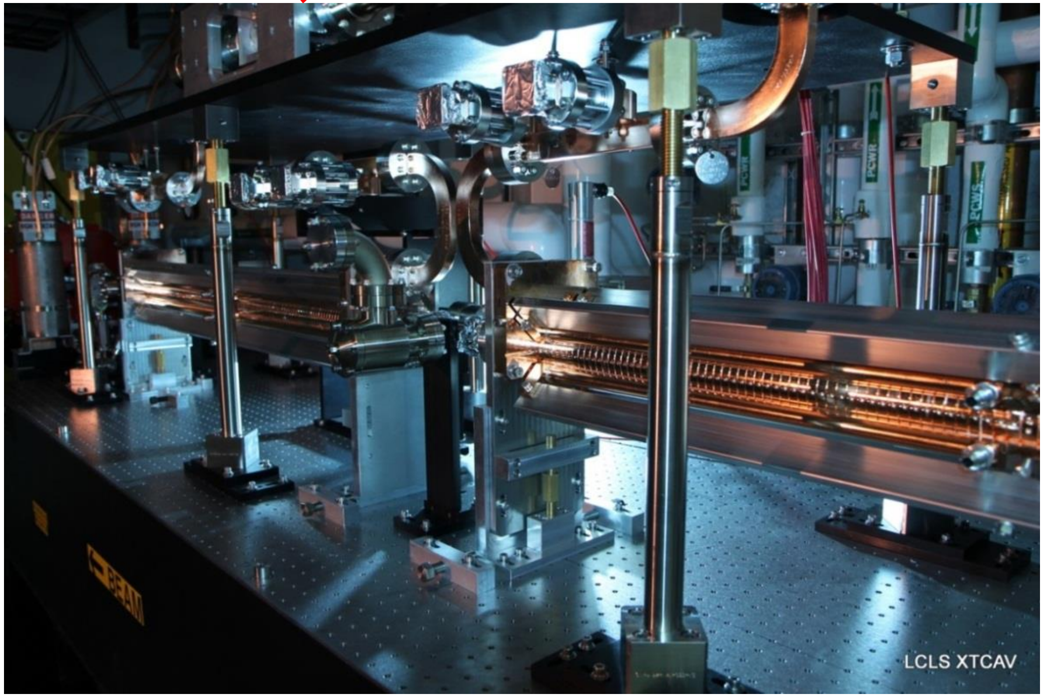
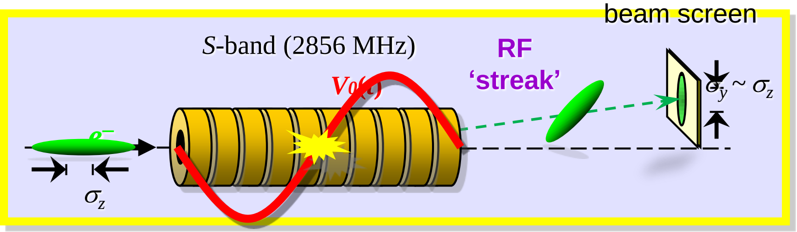
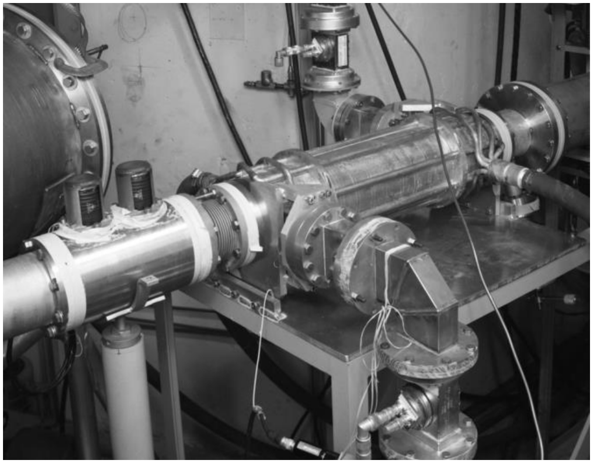


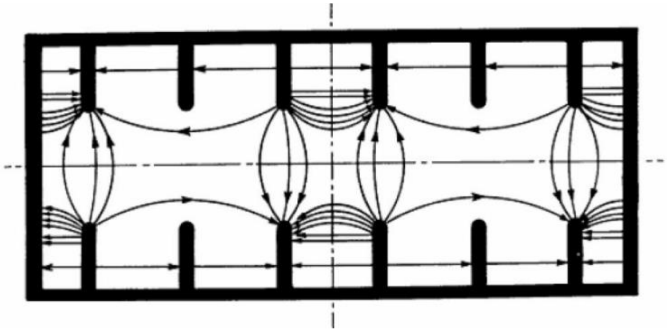
Image the temporal profile of the electron beam by streaking with an RF deflecting cavity and measuring the time-dependent energy

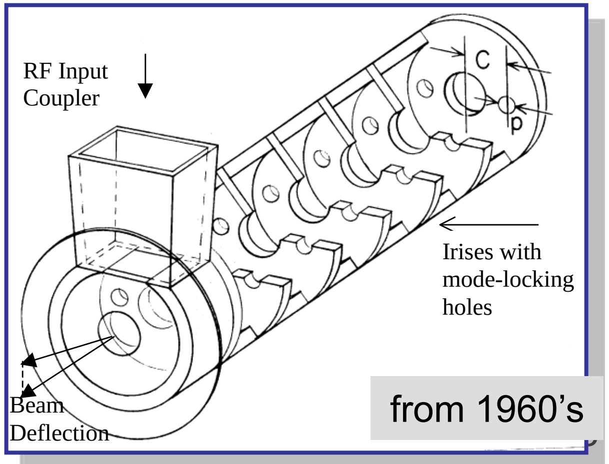
Transverse Deflecting Structures



- **Well-established technique at SLAC to measure bunch length.**
- **Use a time-varying transverse electric field to "streak" the beam across a monitor screen *("e-bunch streak camera").***
- **3 m long S-band 2856 MHz ('LOLA') structures built in the 1960's**
- **Previously installed in the LCLS linac, but were <u>invasive</u> to operation for photon users.**

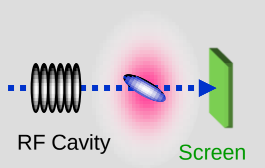


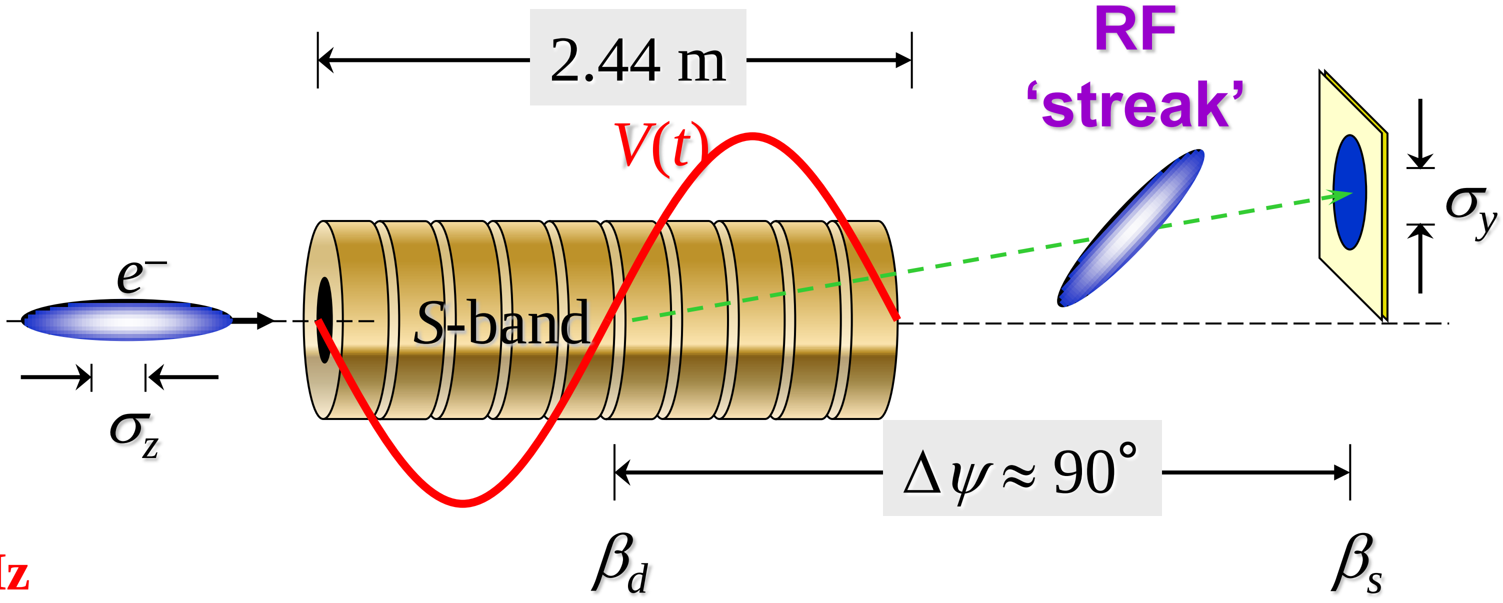




from 1960's

Transverse Deflector Cavity (TDC)





$V_0 > 20$ MV

$f_{RF} = 2856$ MHz

$E_S = 13.6$ GeV

$$\sigma_y^2 = \sigma_{y0}^2 + \beta_d \beta_s \sigma_z^2 \left(\frac{k_{RF} e V_0}{E_s} \sin \Delta\psi \cos\phi \right)^2$$

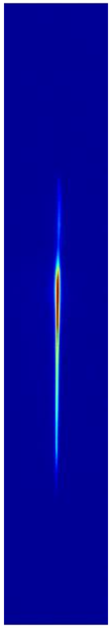
- Map time axis on to transverse coordinate (vertical here)
- Simple calibration by scan of cavity phase

XTCAV offers 3 new Important Features

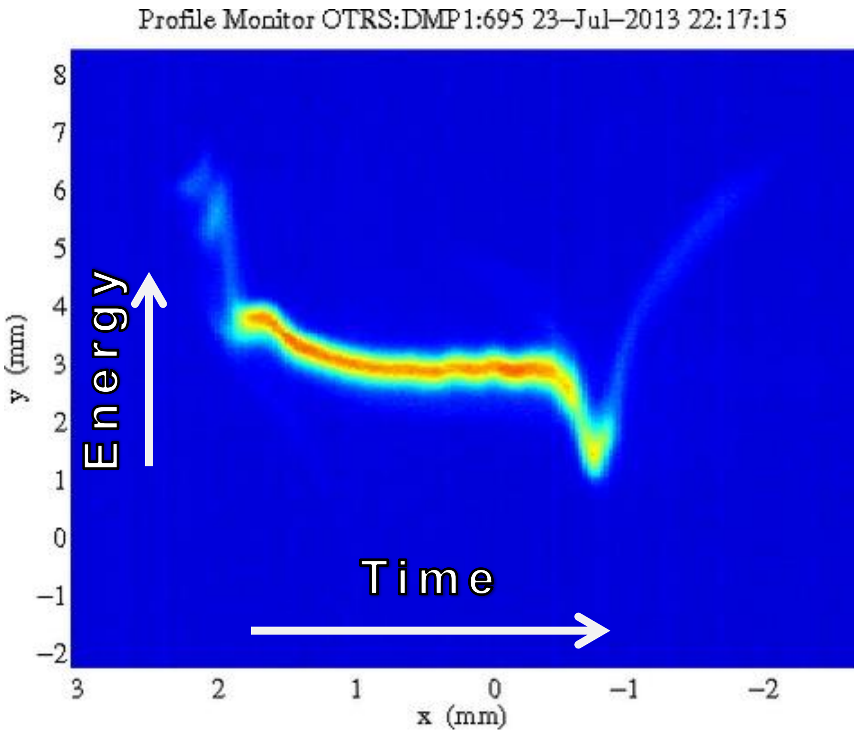
- Operates at 11.424 GHz and gives 8 times better temporal resolution
  - Factor of 4 from shorter wavelength and twice the voltage gradient
- Located downstream of the undulator and cannot interfere with photon operation
  - Continuous non-invasive operation at 120 Hz
- Reconstructs the temporal profile of the x-ray beam from the energy loss profile of the electrons
  - Compares the “FEL-off” and “FEL-on” images

Measurement examples: 4.7GeV, 150pC (1keV)

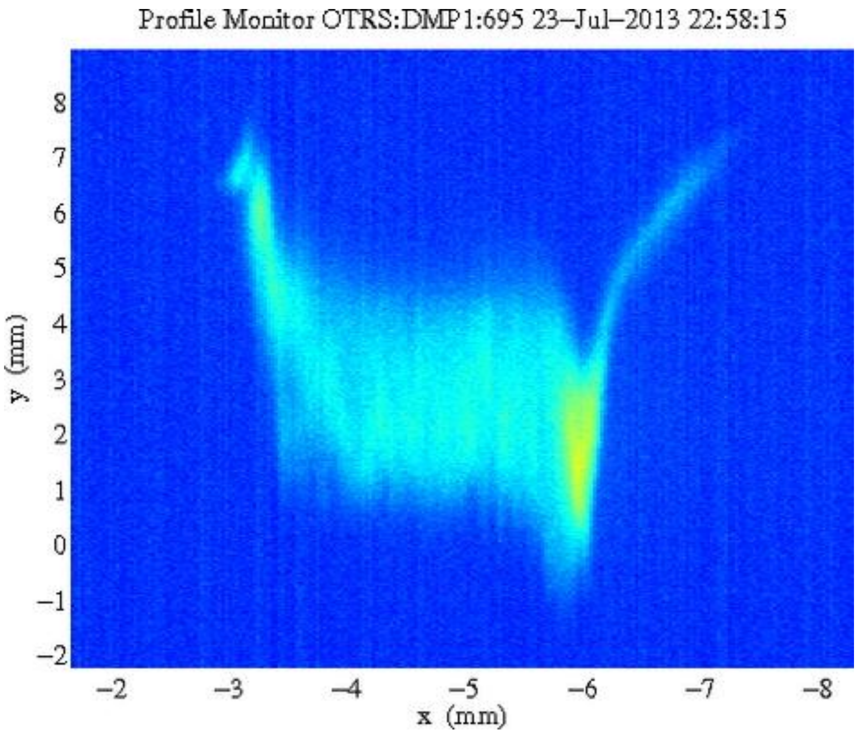
Three Images at the e-dump spectrometer screen



XTCAV Off



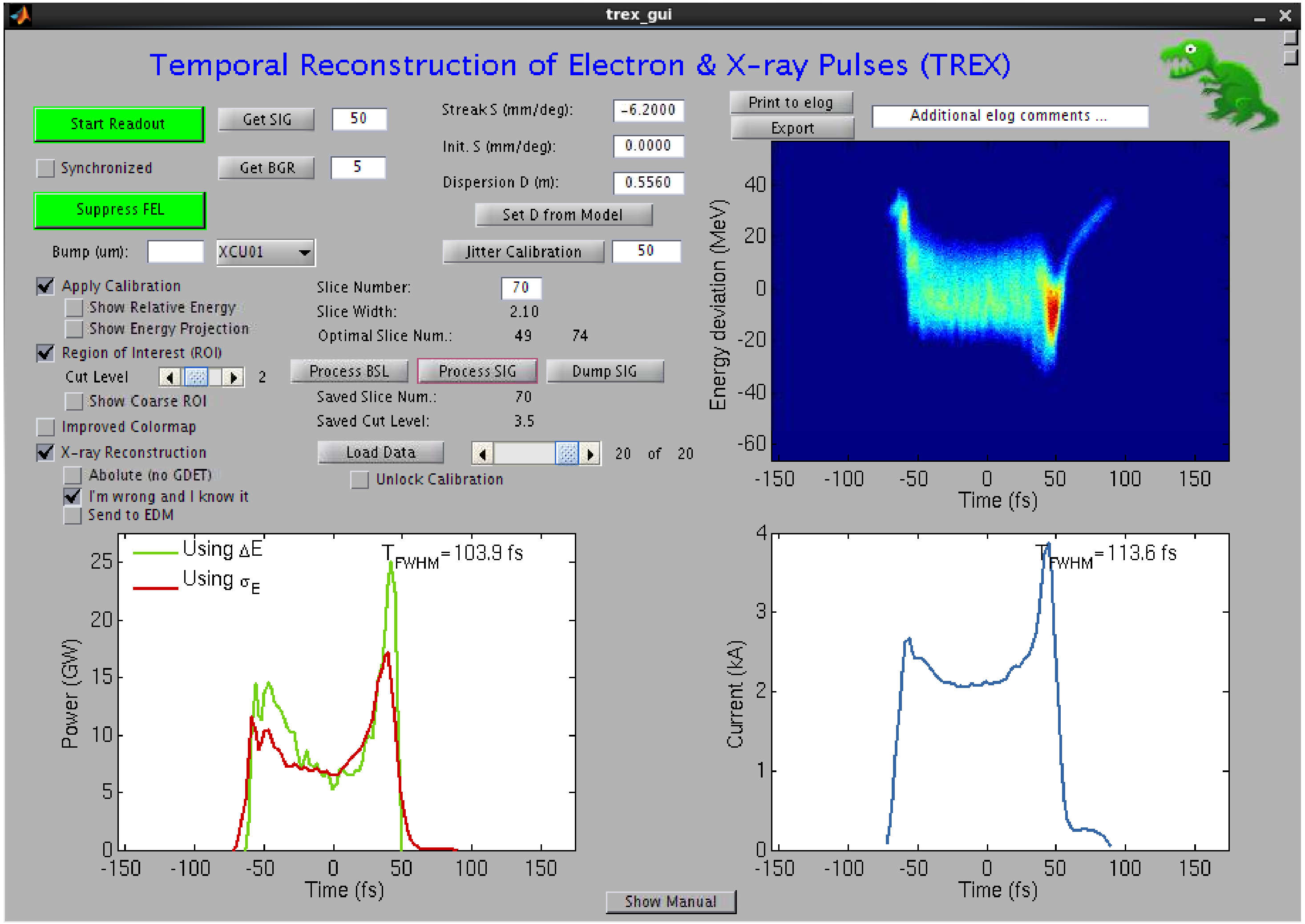
XTCAV On
FEL Suppressed
(baseline)



XTCAV On
FEL On
~1mJ FEL pulse energy

Transfer of energy to photons causes e^- energy loss and spread

Single-shot data processing


trex_gui

Temporal Reconstruction of Electron & X-ray Pulses (TREX)

Get SIG 50

Get BGR 5

Streak S (mm/deg): -6.2000

Init. S (mm/deg): 0.0000

Dispersion D (m): 0.5560

Additional elog comments ...

☐ Synchronized

Bump (um): XCU01

Jitter Calibration 50

☑ Apply Calibration
  ☐ Show Relative Energy
  ☐ Show Energy Projection
☑ Region of Interest (ROI)
  Cut Level 2
  ☐ Show Coarse ROI
☐ Improved Colormap
☑ X-ray Reconstruction
  ☐ Abolute (no GDET)
  ☑ I'm wrong and I know it
  ☐ Send to EDM

Slice Number: 70

Slice Width: 2.10

Optimal Slice Num.: 49 74

Saved Slice Num.: 70

Saved Cut Level: 3.5

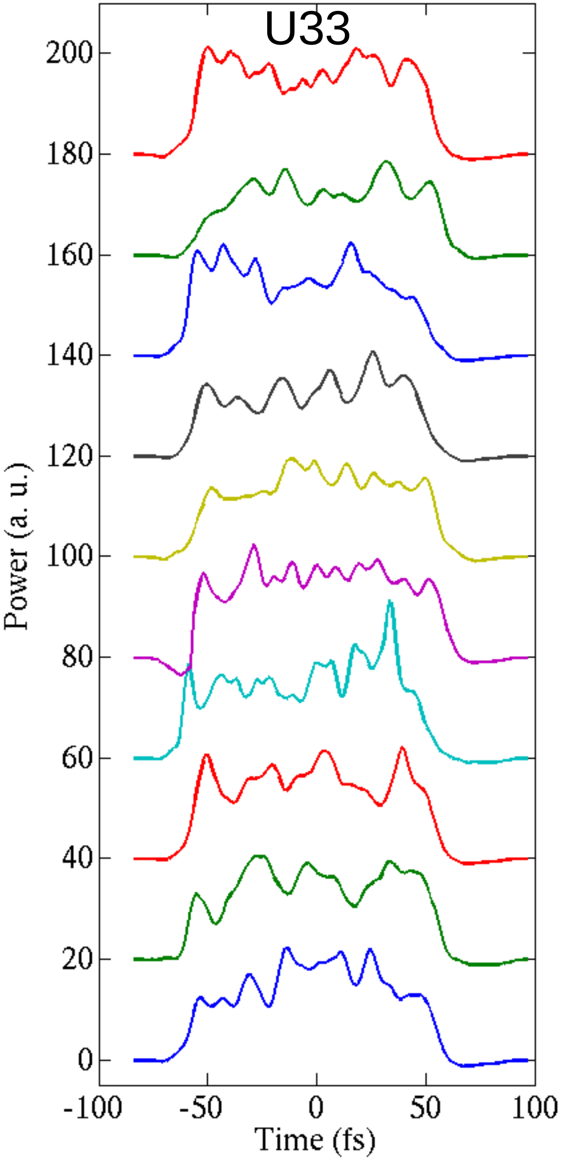
20 of 20

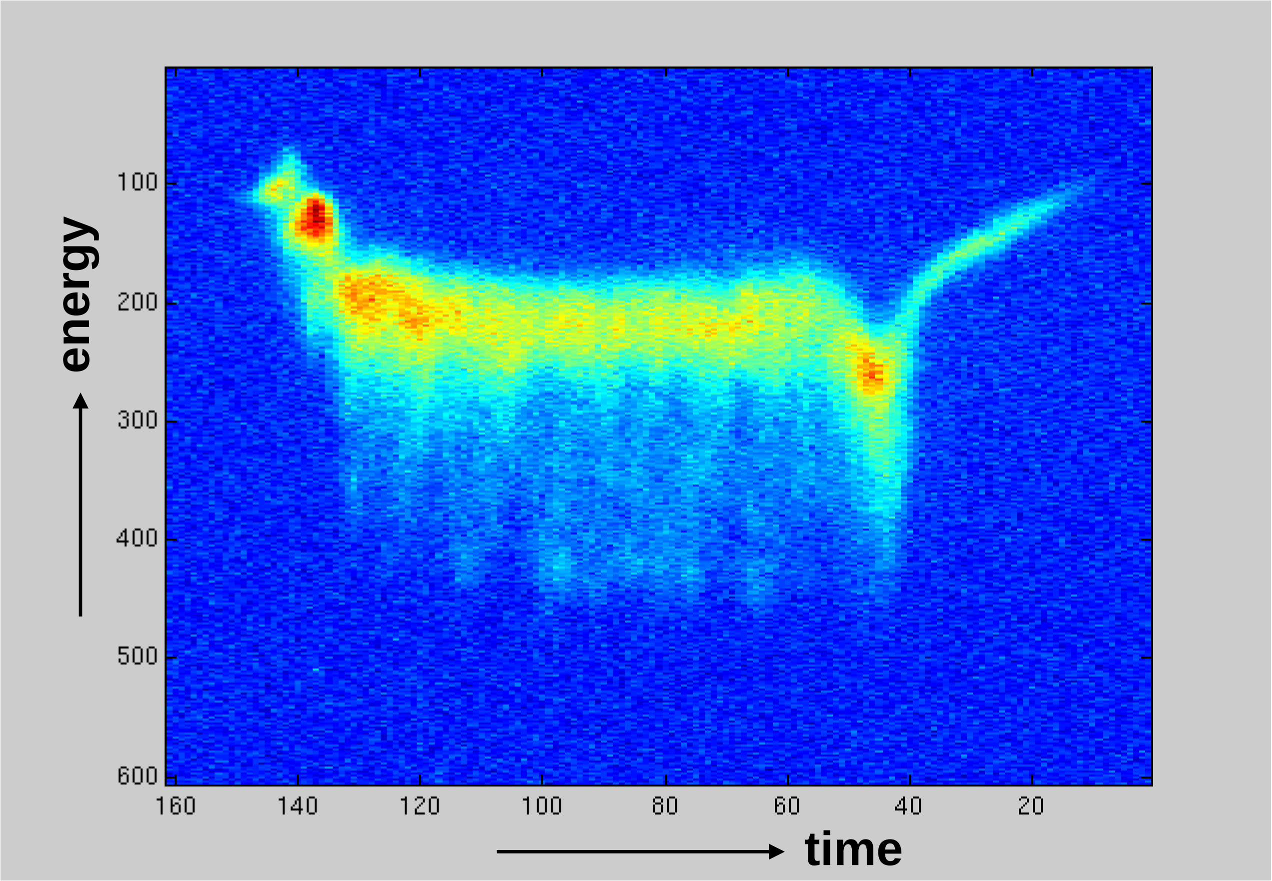
☐ Unlock Calibration

successful DESY collaboration: C. Behrens

- Calibration;
  - Record baseline images (FEL-off);
  - Image processing, slicing and averaging baseline data;
- Take single-short image (FEL-on) and other beam parameters;
  - Reconstruct electron and x-ray temporal profile from peak current in each slice and energy change in each slice.

10 consecutive shots (1keV, 150pC)

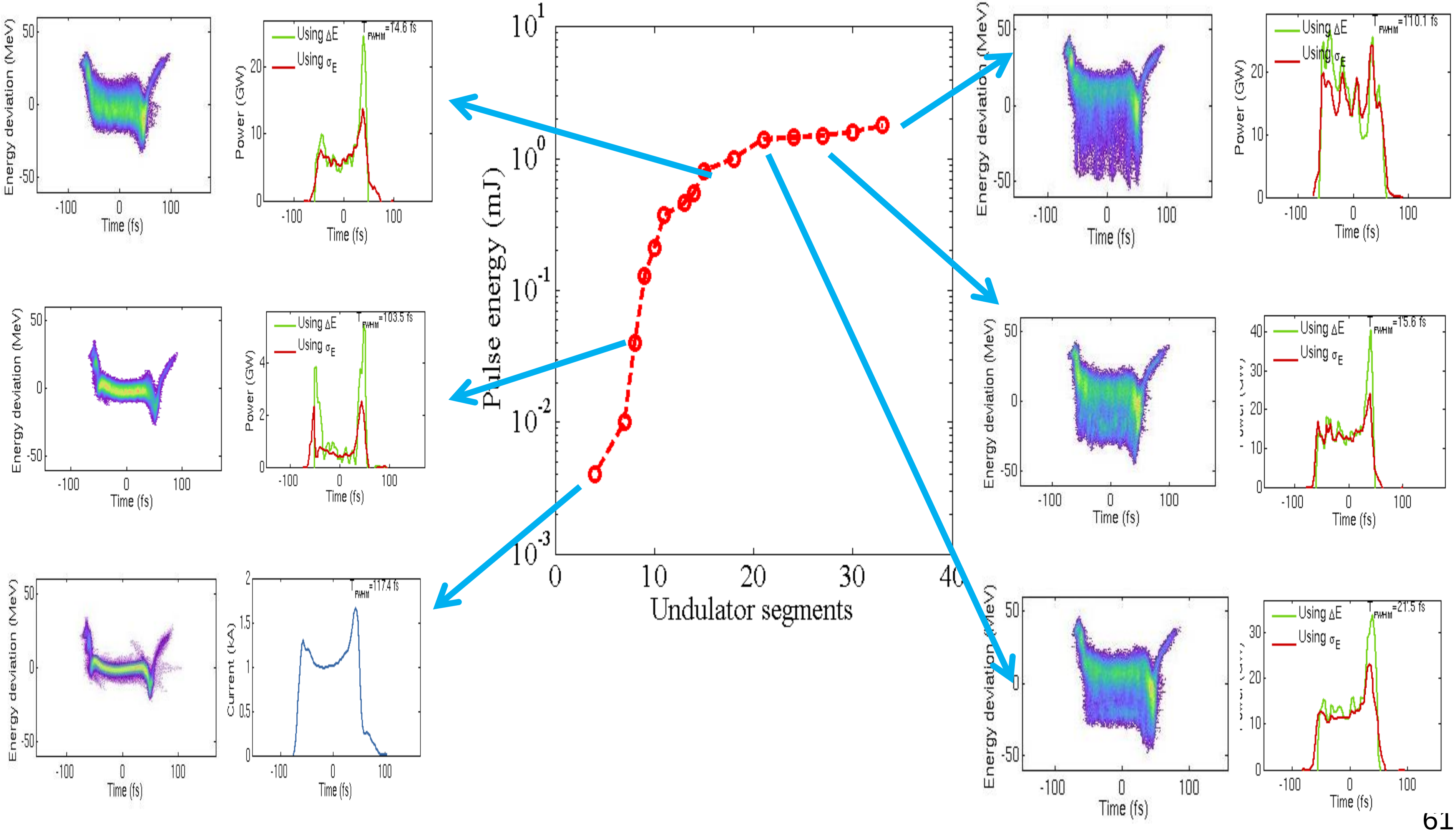




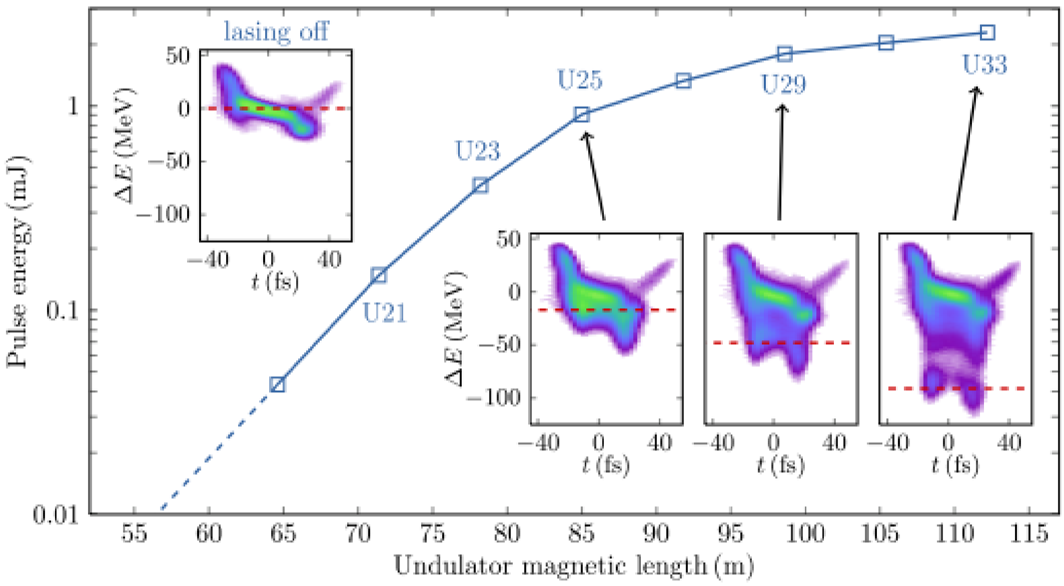
It is important to analyze every shot at 120 Hz.

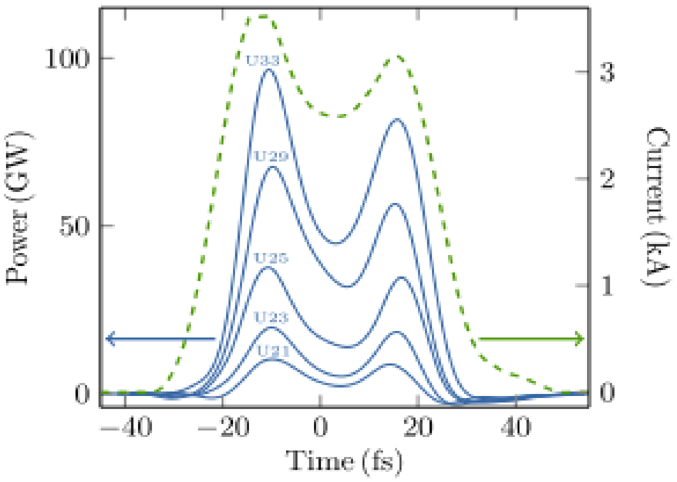
Evolution of SASE along the Gain Curve at 4.7GeV, 150pC (1keV)

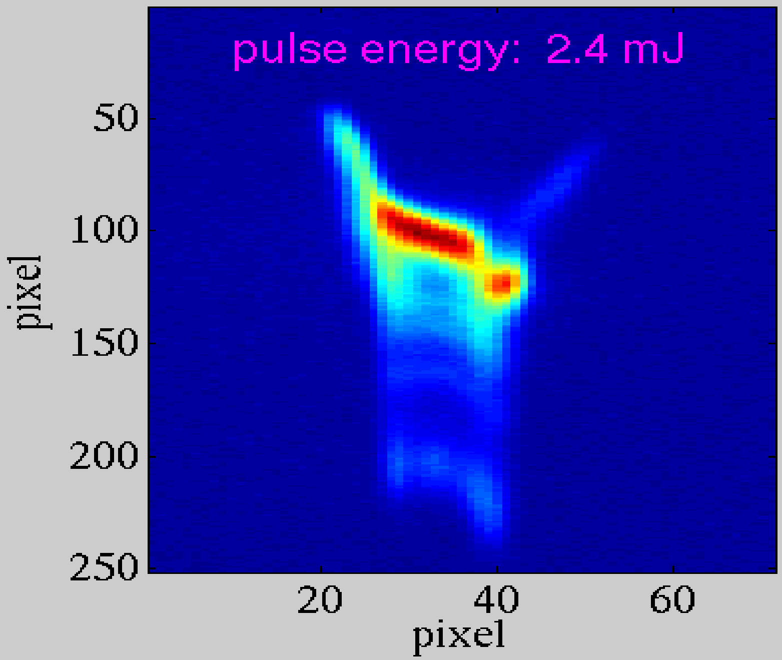
FEL power gain curve

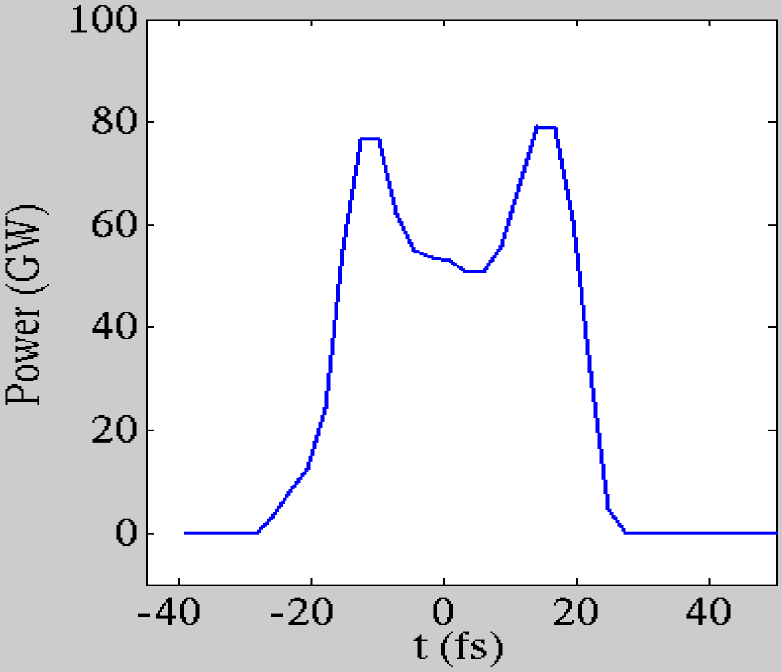


Taper optimization and resonant trapping at 15.2GeV, 150pC, 10.2keV

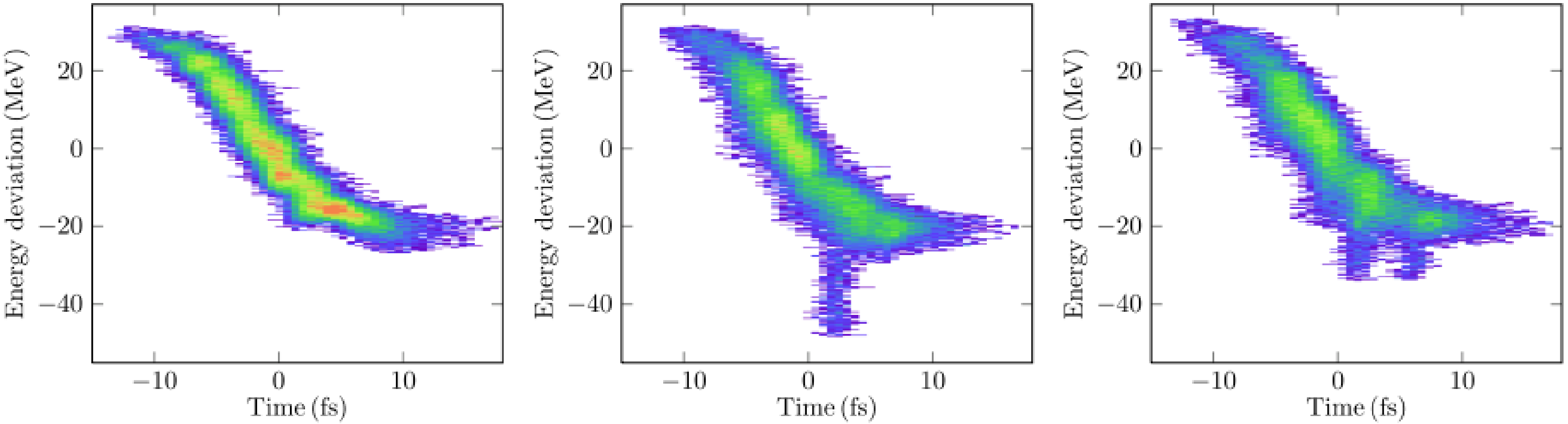








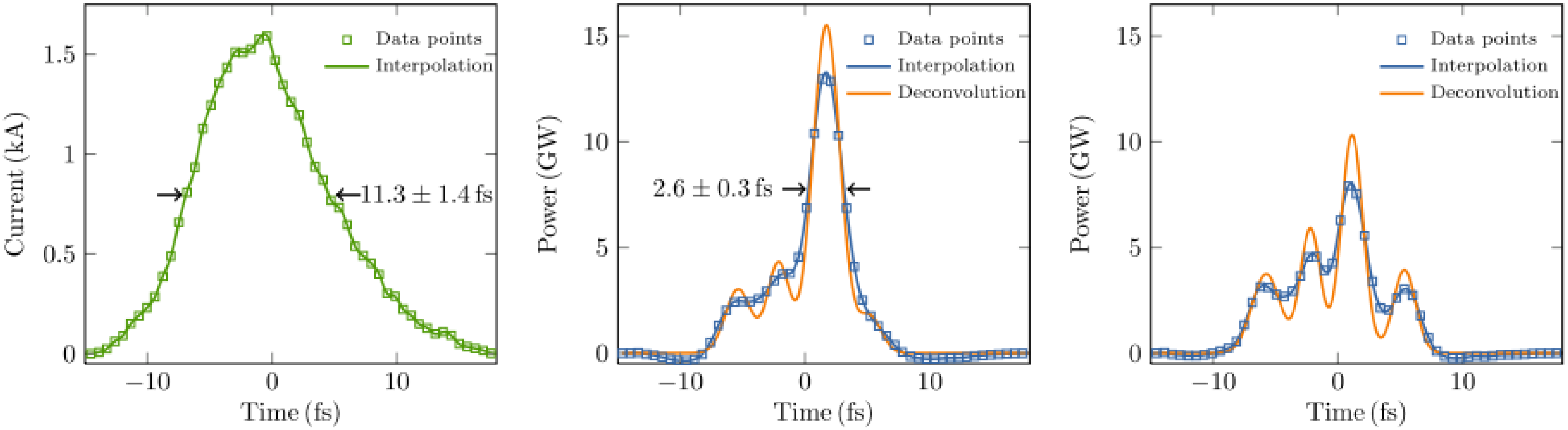
Short pulse -- 20pC, 1keV examples



(a) Lasing off

(b) Lasing on, shot 1

(c) Lasing on, shot 2



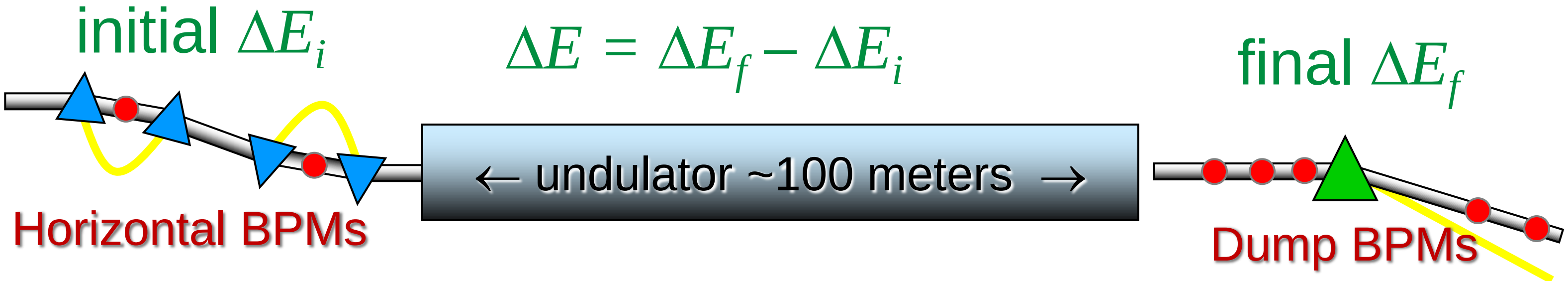
(d) Electron current

(e) X-ray power, shot 1

(f) X-ray power, shot 2

How to retrieve the x-ray temporal profile?

- The E-loss scan for measuring x-ray pulse energy:



initial ΔE_i

$\Delta E = \Delta E_f - \Delta E_i$

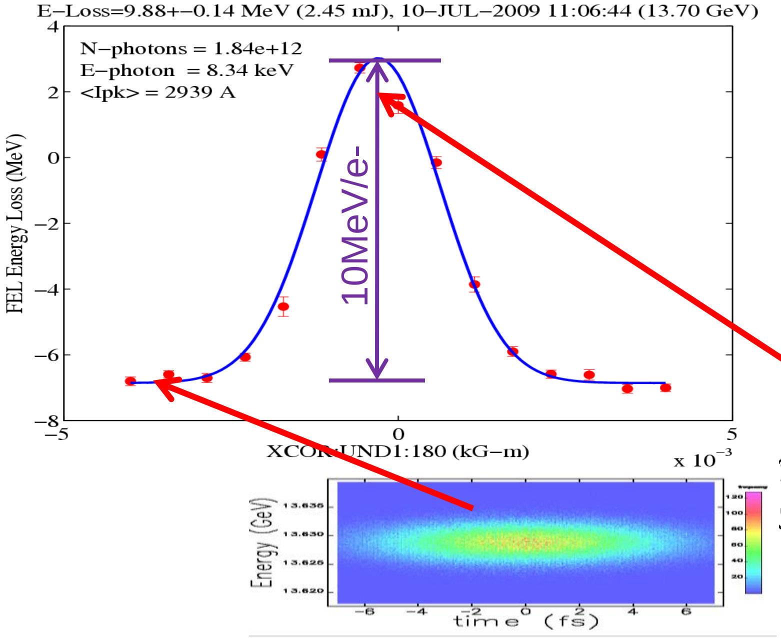
final ΔE_f

← undulator ~100 meters →

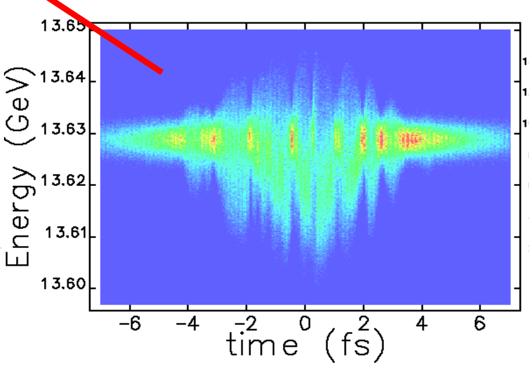
Horizontal BPMs

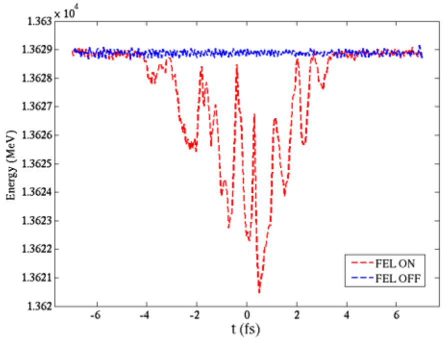
Dump BPMs

vary FEL power with oscillations & record e^- energy loss

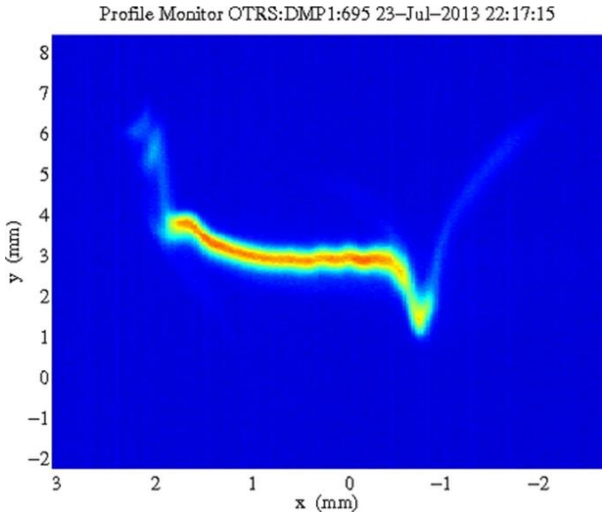


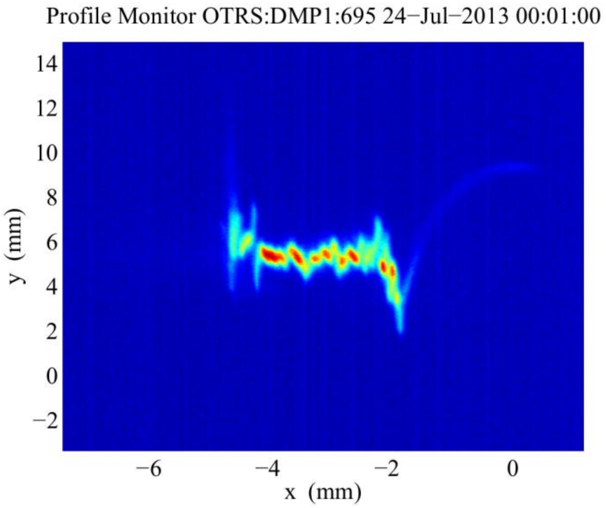
→ to measure the ***time-resolved*** lasing effect ("footprint") left on the electron bunch.
(**Ding et al., PRSTAB2011**)

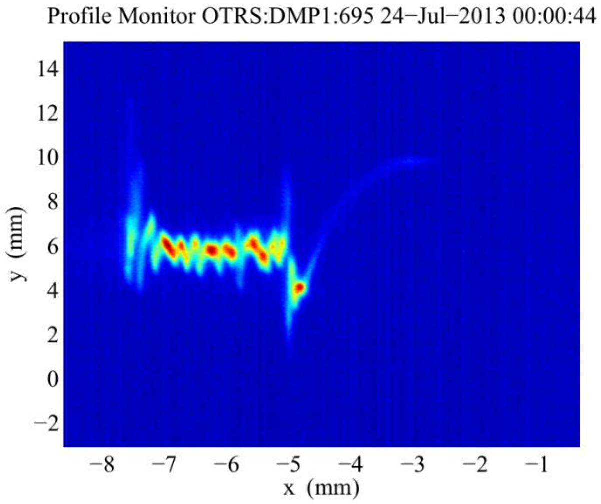




Direct Observation of Microbunching Instability







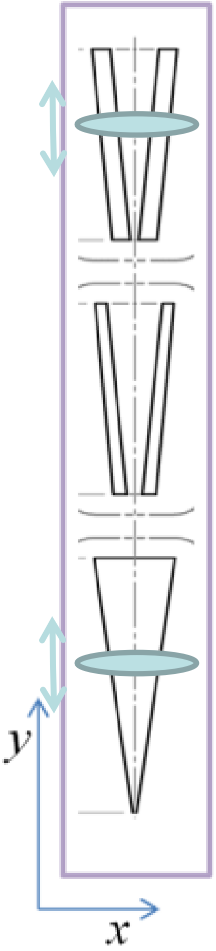
instability becomes dominant

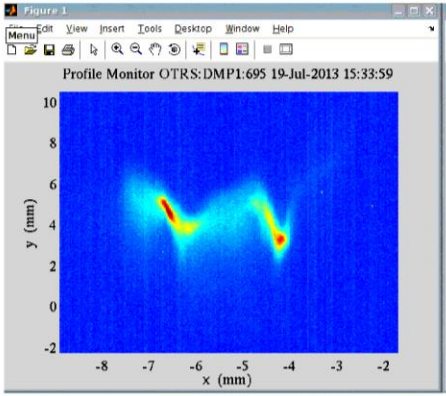
Decreasing gain on the Laser Heater

Slotted-foil examples (lasing off) show clearly the unspoiled beam region

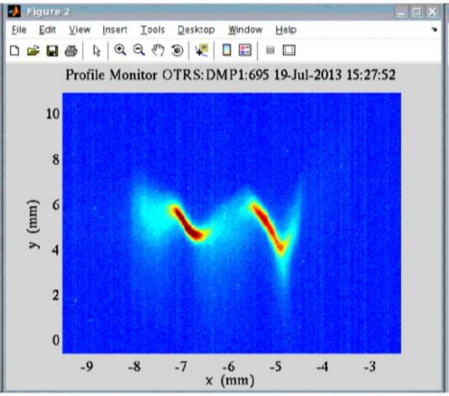
Double Slit

Single Slit

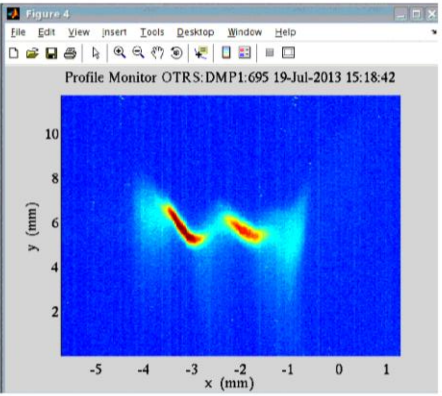




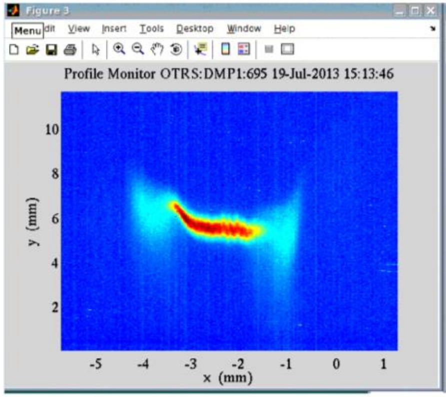
Profile Monitor OTRS:DMP1:695 19-Jul-2013 15:33:59



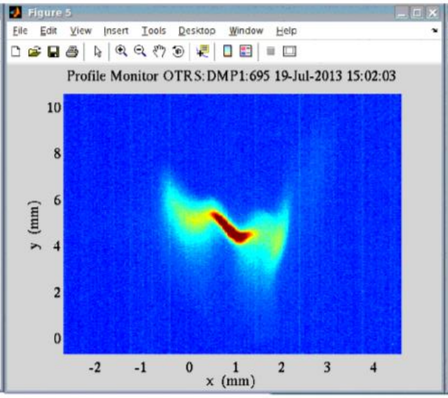
Profile Monitor OTRS:DMP1:695 19-Jul-2013 15:27:52



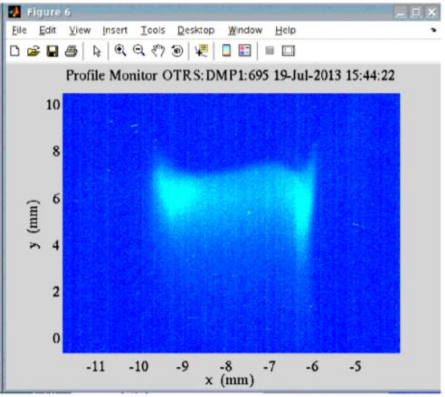
Profile Monitor OTRS:DMP1:695 19-Jul-2013 15:18:42



Profile Monitor OTRS:DMP1:695 19-Jul-2013 15:13:46



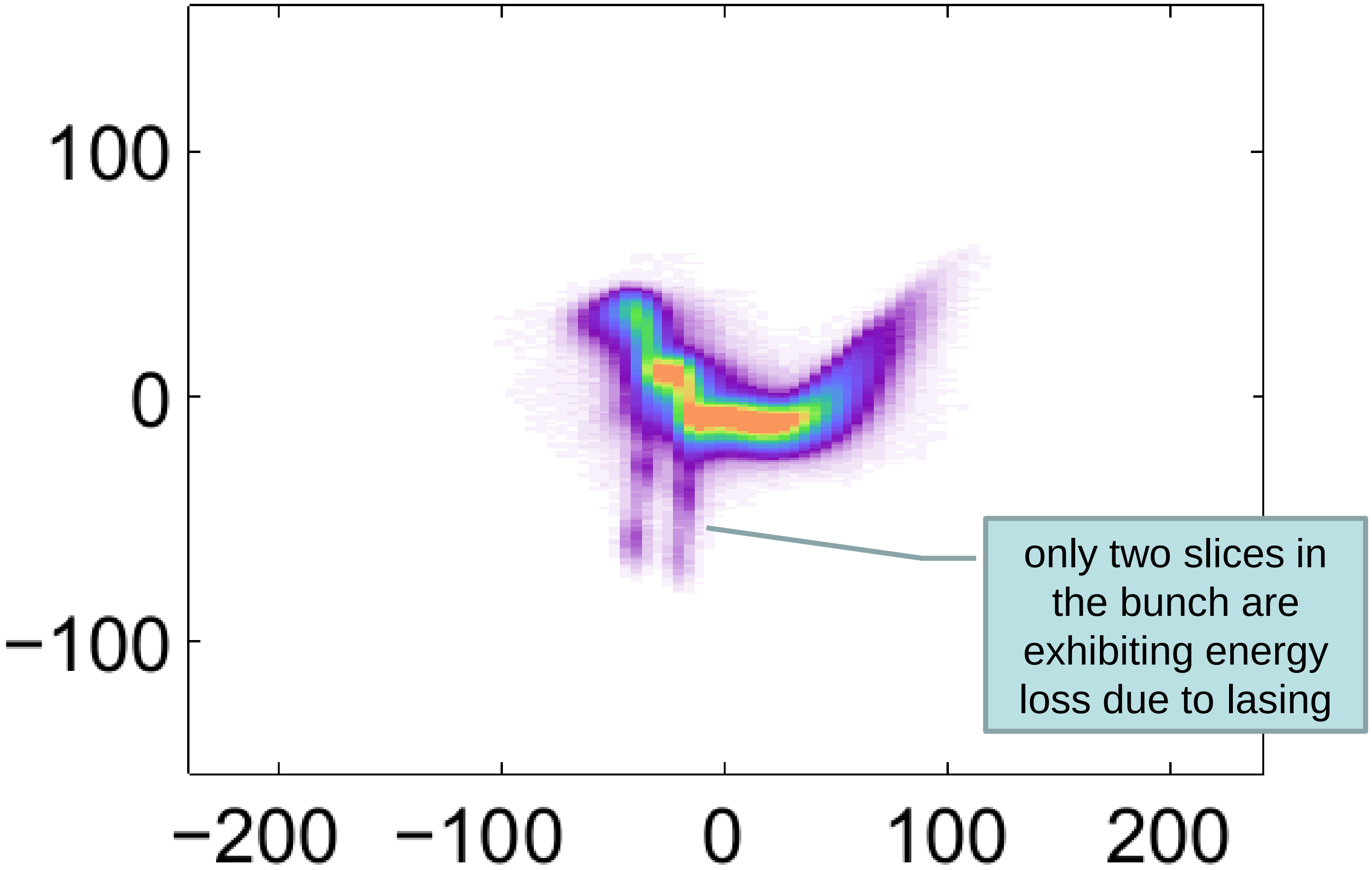
Profile Monitor OTRS:DMP1:695 19-Jul-2013 15:02:03



Profile Monitor OTRS:DMP1:695 19-Jul-2013 15:44:22

4.7GeV, 150 pC

Lasing with double-slotted foil

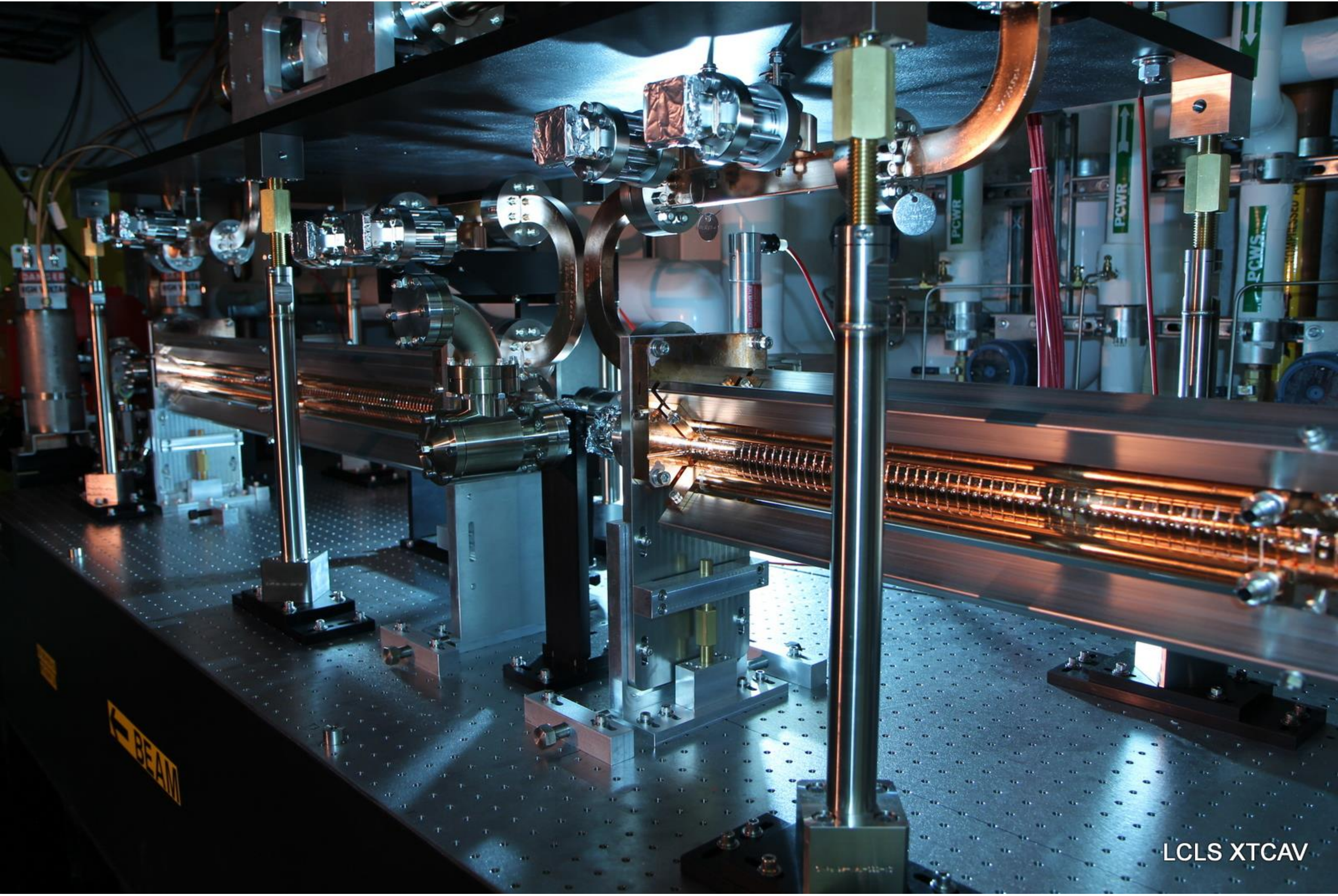


only two slices in the bunch are exhibiting energy loss due to lasing

XTCAV System Improvements

- **120 Hz camera** installed so that images can be captured at full beam rate
  - Raw images are written to photon experiment DAQ in real-time
  - Real time processing of x-ray slice profiles (TREX) is underway

- **Doubling the temporal resolution** by raising the RF power by a factor 4 is being proposed

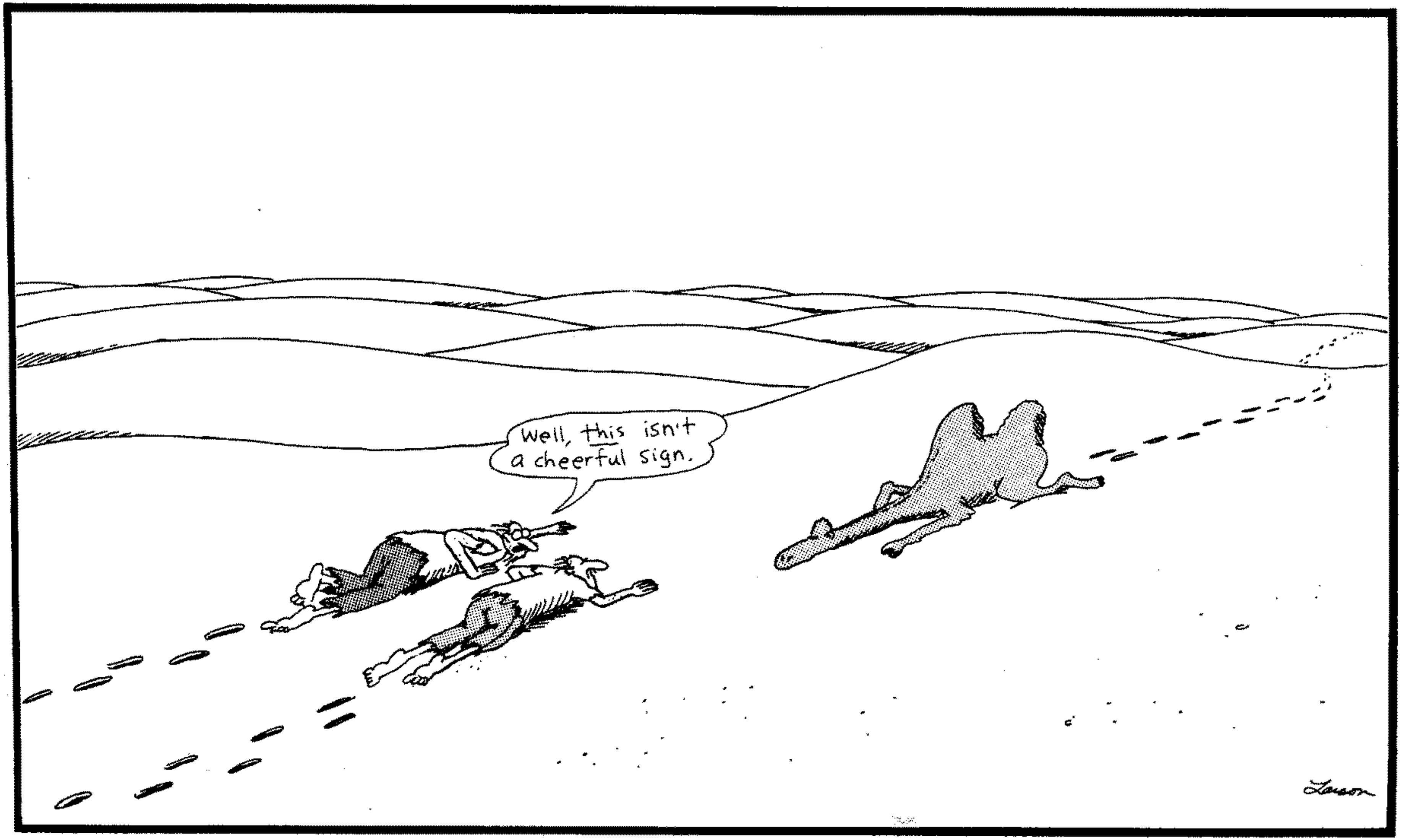


Thanks to the many engineers and physicists at SLAC !

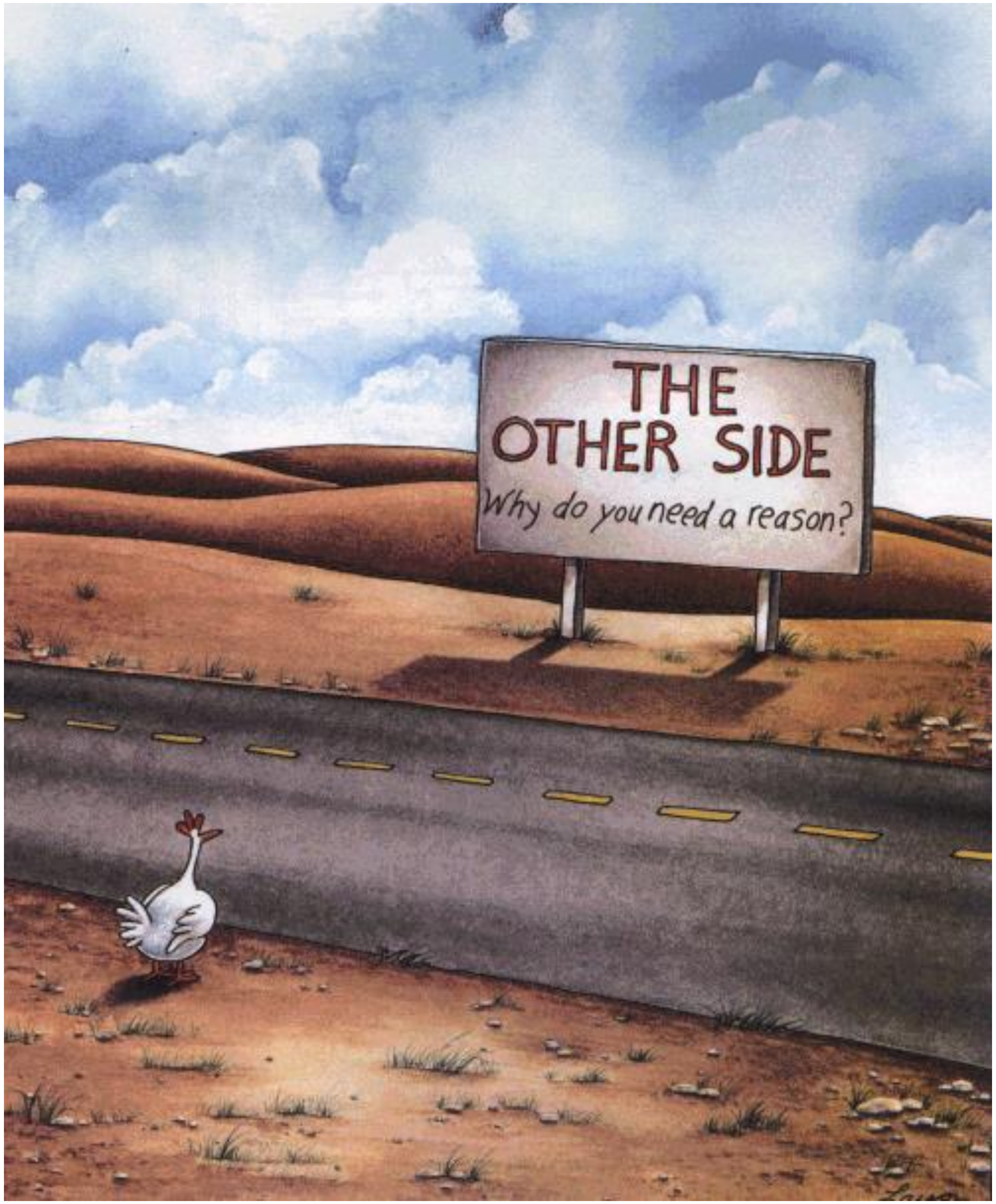
Summary and Outlook

- Demonstrated resolution of **0.8 ±0.2 fs**
- XTCAV provides non-invasive monitoring of longitudinal phase space at 120 Hz
  - quantitative measurement,
  - absolute calibration
- Directly observed
  - SASE evolution
  - Chirp and bunch compression dynamics
  - Microbunching
  - Slotted foil
  - Multi-bunch, Two-colour, Self-seeding …
- Upgrade data acquisition to stream 120 Hz measurements to photon users
- Upgrade RF power for enhanced resolution

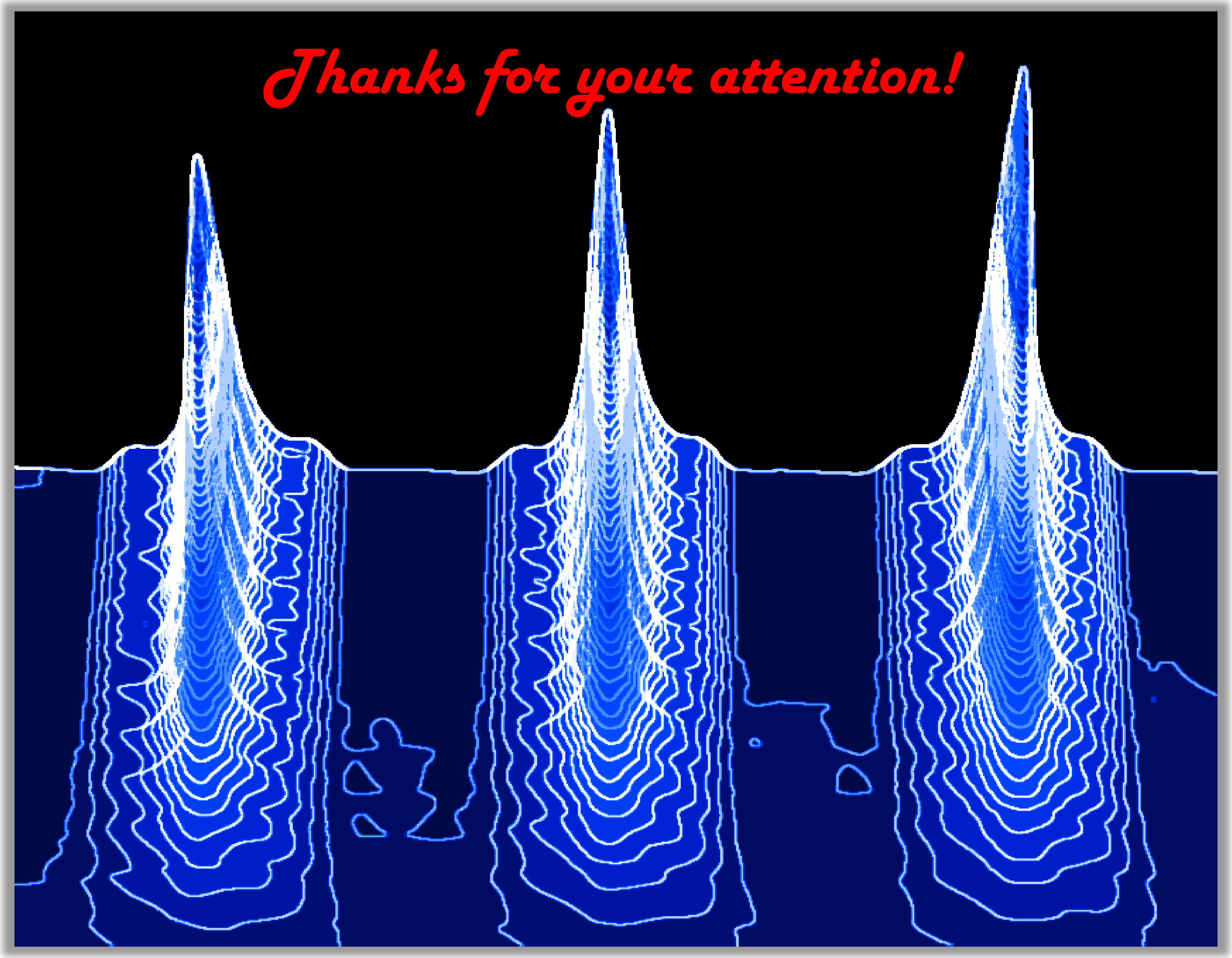
This is pretty close to the “ultimate FEL diagnostic” !



Don't give up!

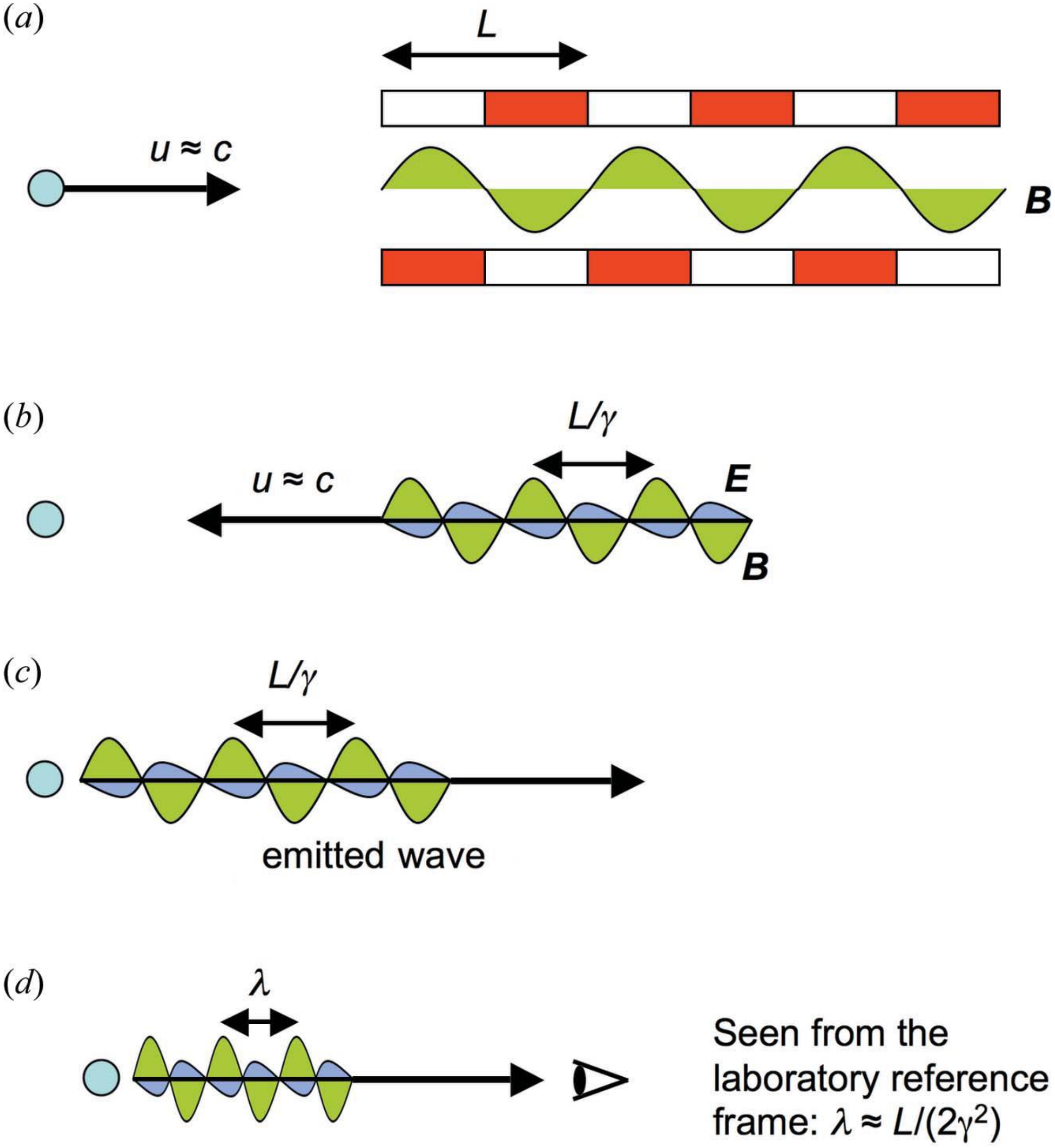


Always try new things!

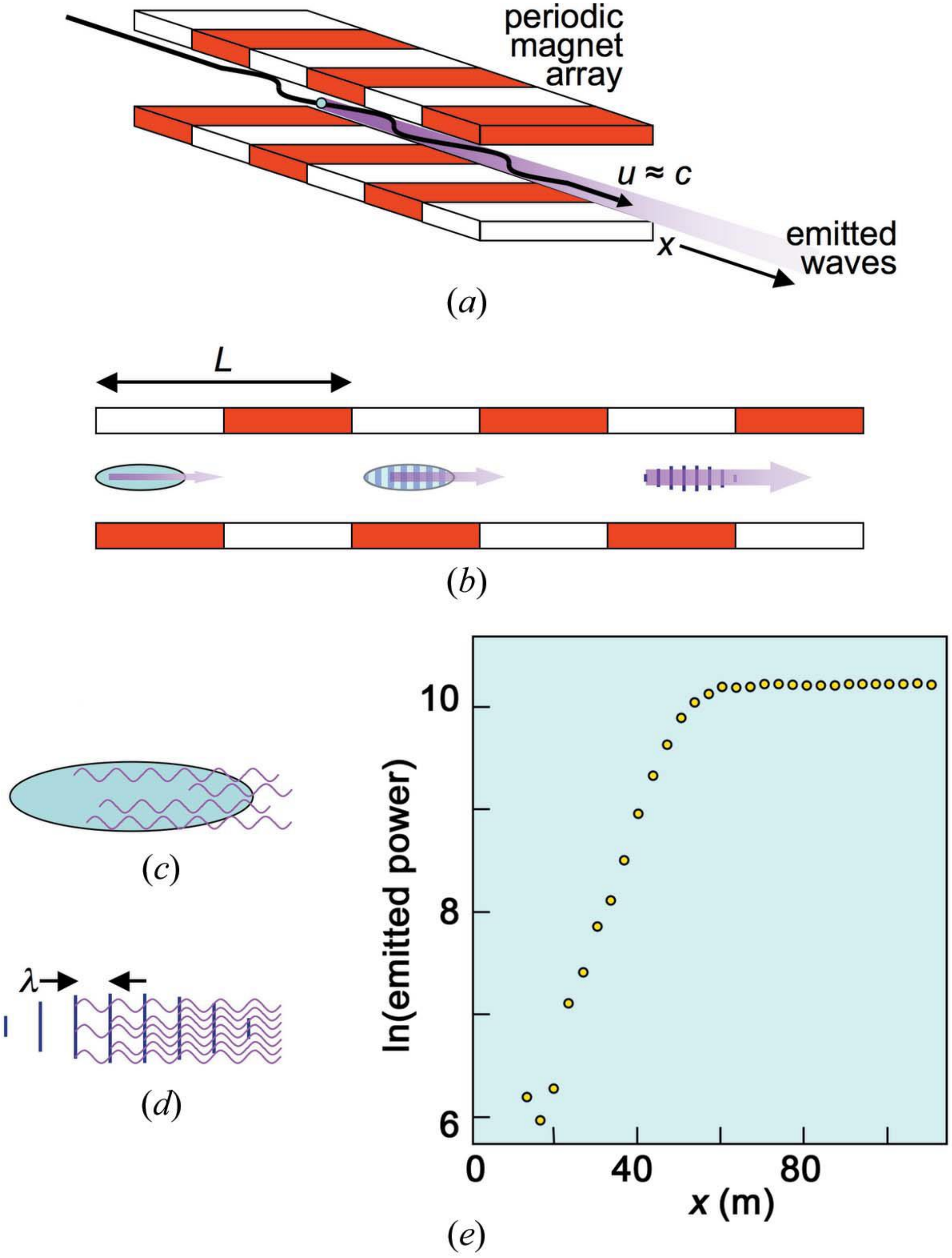


Thanks for your attention!

END

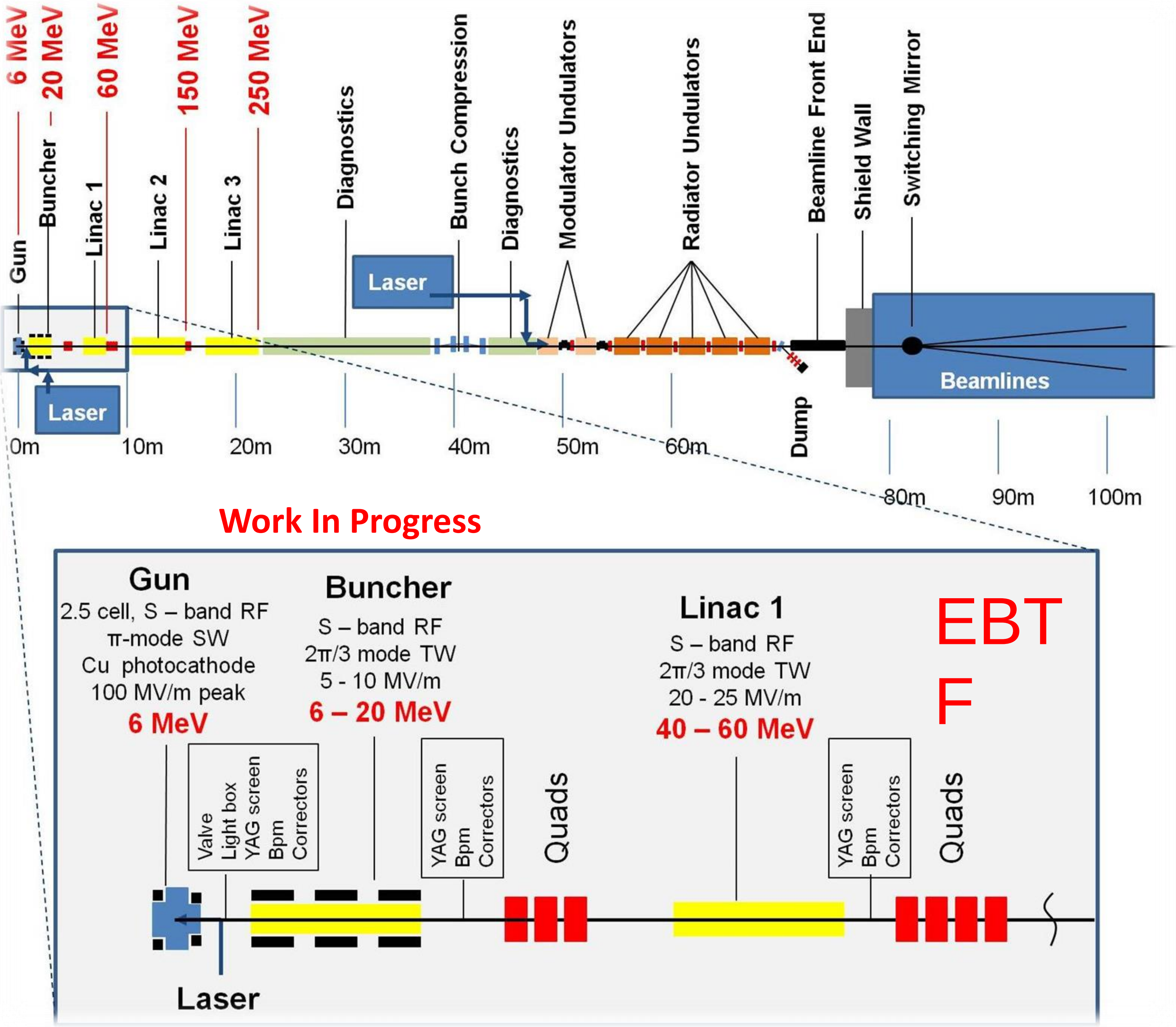


Why are the emitted wavelengths in the X-ray range? Relativity provides the answer. (a) The relativistic electron approaches the periodic B-field of the undulator. (b) In the electron reference frame the undulator period L is Lorentz-contracted to L/γ and the B-field is accompanied by a transverse E-field perpendicular to it: the two fields resemble an electromagnetic wave. (c) This wave stimulates the electron to oscillate and emit waves of equal wavelength. (d) The (relativistic) Doppler effect further reduces the wavelength in the laboratory frame, bringing it to the X-ray range.
Margaritondo (2010)



Mechanism of a free-electron laser for X-rays. (a) The optical amplification is produced by relativistic electrons in an accelerator and is activated by a periodic array of magnets (undulator). (b) The first waves emitted by the electrons trigger the formation of microbunches. (c) and (d) Contrary to non-microbunched electrons (c), the emission of electrons in microbunches (d) separated from each other by one wavelength is correlated. (e) This causes an exponential intensity increase with the distance that continues until saturation is reached. [experimental data from Emma et al. (2010)]

Margaritondo, 2010.



Work In Progress

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

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

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

EBT
F

extra material
on SLAC XTCAV

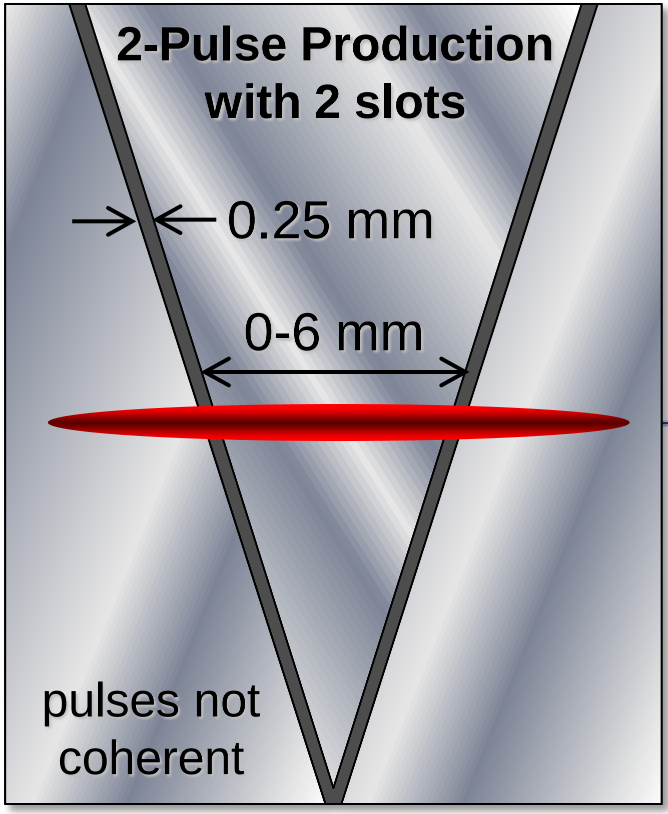
Pre-Assembly and Alignment on an Optical Bench

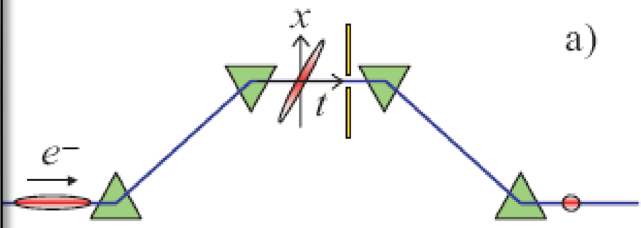
SLAC X-Band Klystron

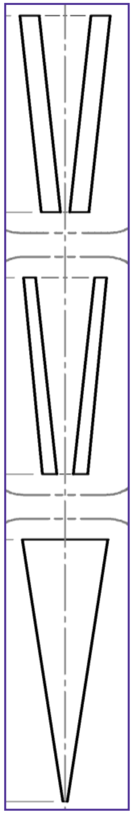
- 50 MW XL4 tube
- 120 Hz, 0.2 us pulse length

Short pulse--

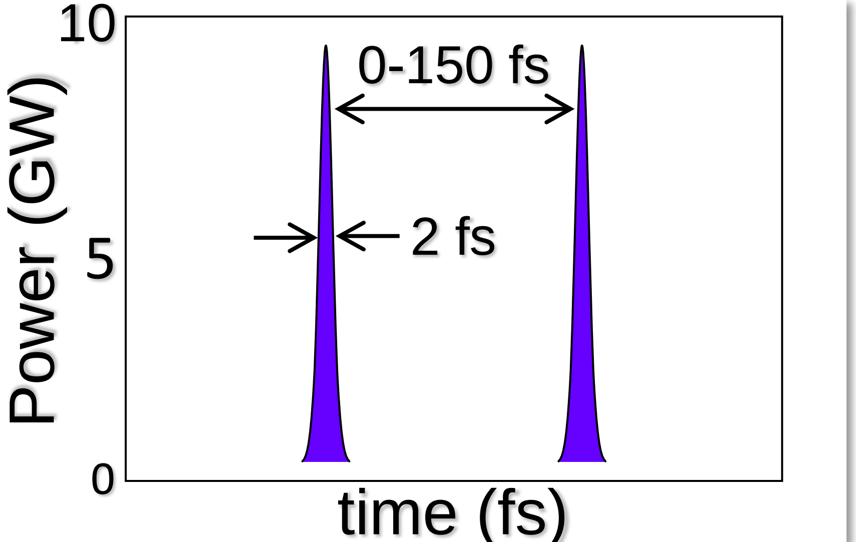
Double X-Ray Pulses from a **Double-Slotted Foil**





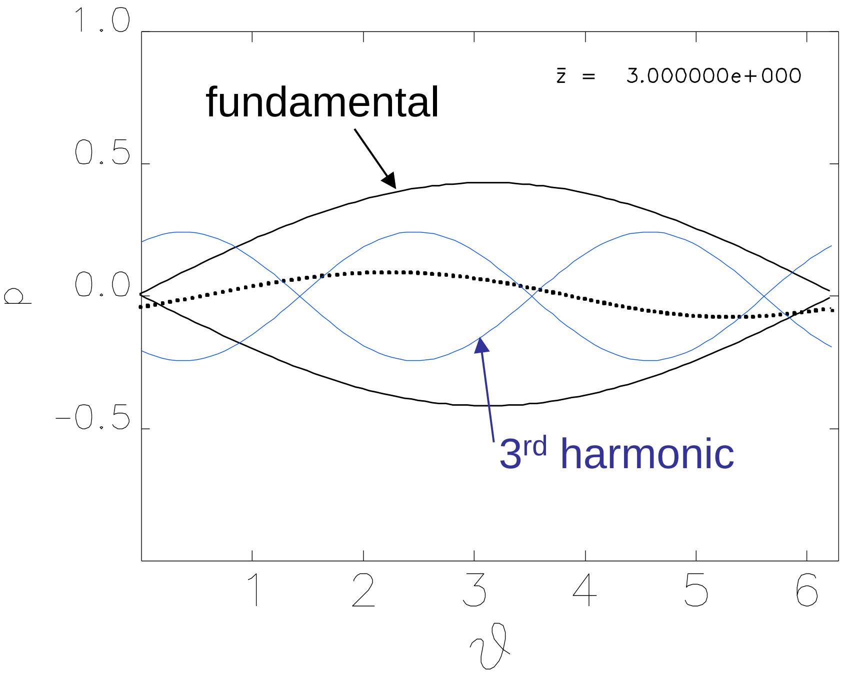


Emma et al., PRL 92, 074801;
Ding et al., PRL 109, 254802.



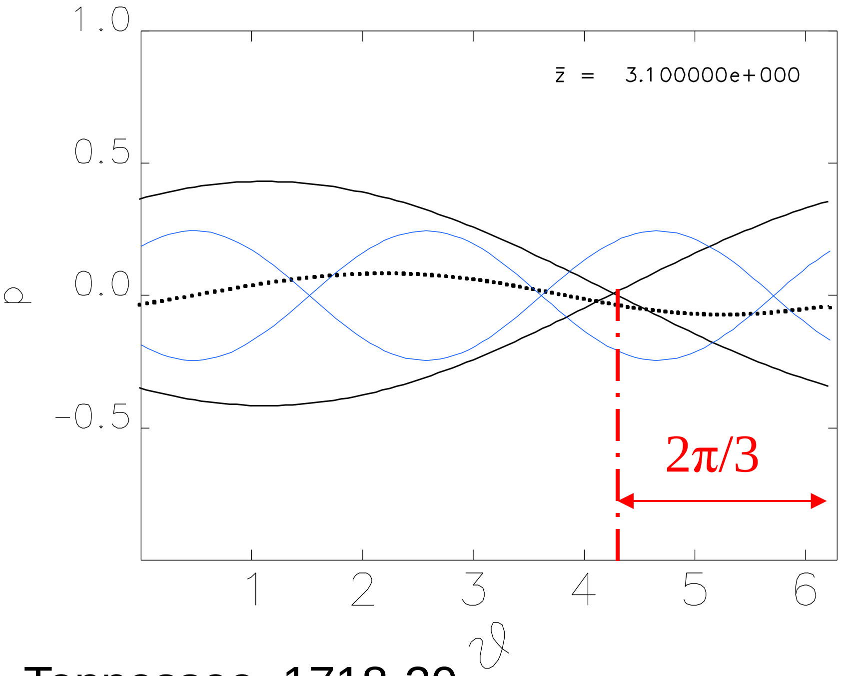
Courtesy P. Emma

Can also get Harmonic Amplifier FEL*



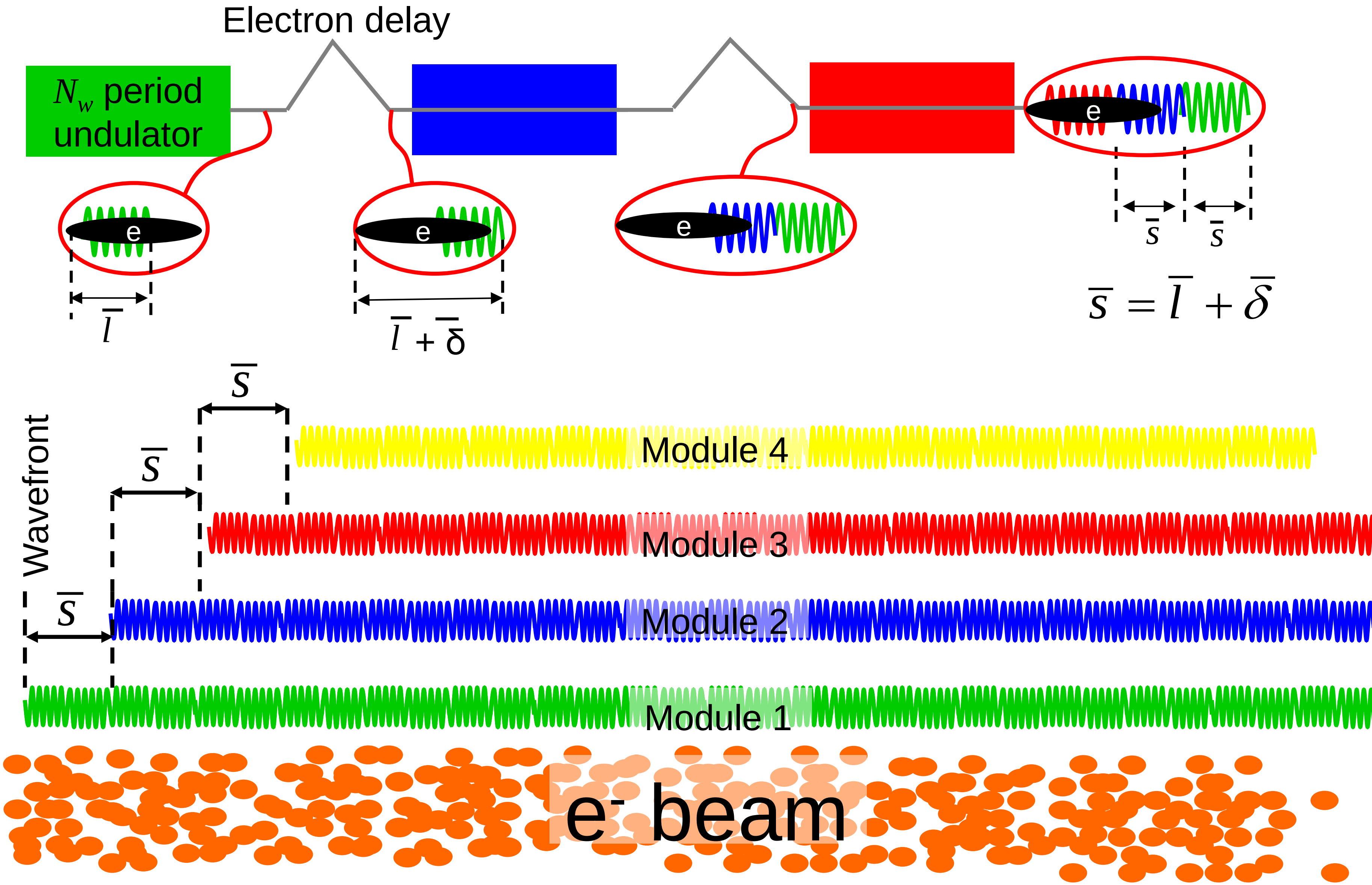
A relative phase change between electrons and fundamental radiation of $n2\pi/3$ (n - integer) will disrupt the fundamental-electron coupling and so the fundamental's growth.

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**.

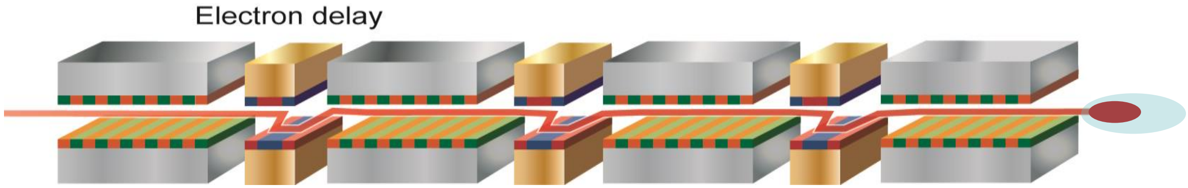


*McNeil, Robb & Poole, PAC 2005, Knoxville, Tennessee, 1718-20

Large shifts >> λ_r,



Chicanes with equal electron delays >> λ_r



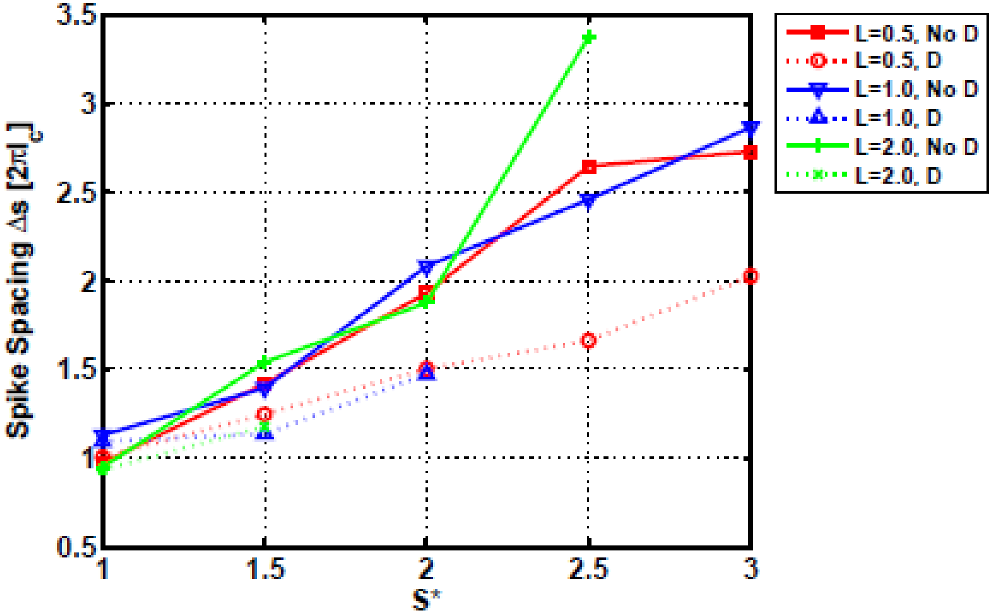


Figure 2: The mean spacing between spikes in units of $2\pi l_c$ for rectangular electron bunch current profile, as a function of the slippage enhancement factor S^*.

Increased cooperation length:

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

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

Undulator slippage

Chicane slippage

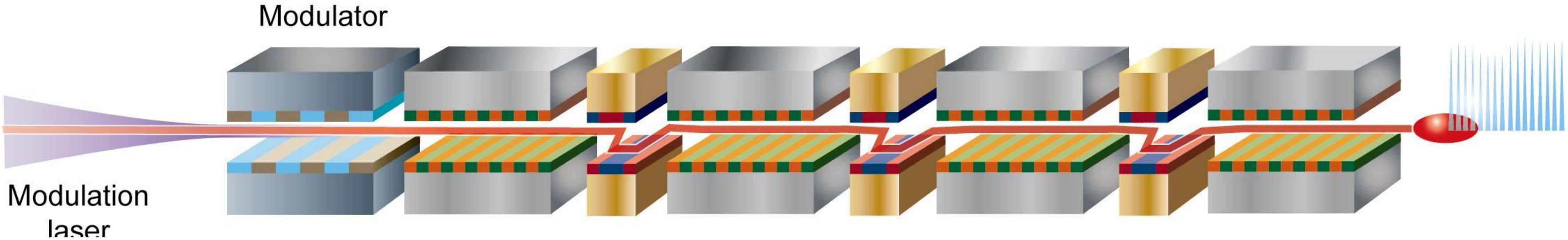
Summarising:

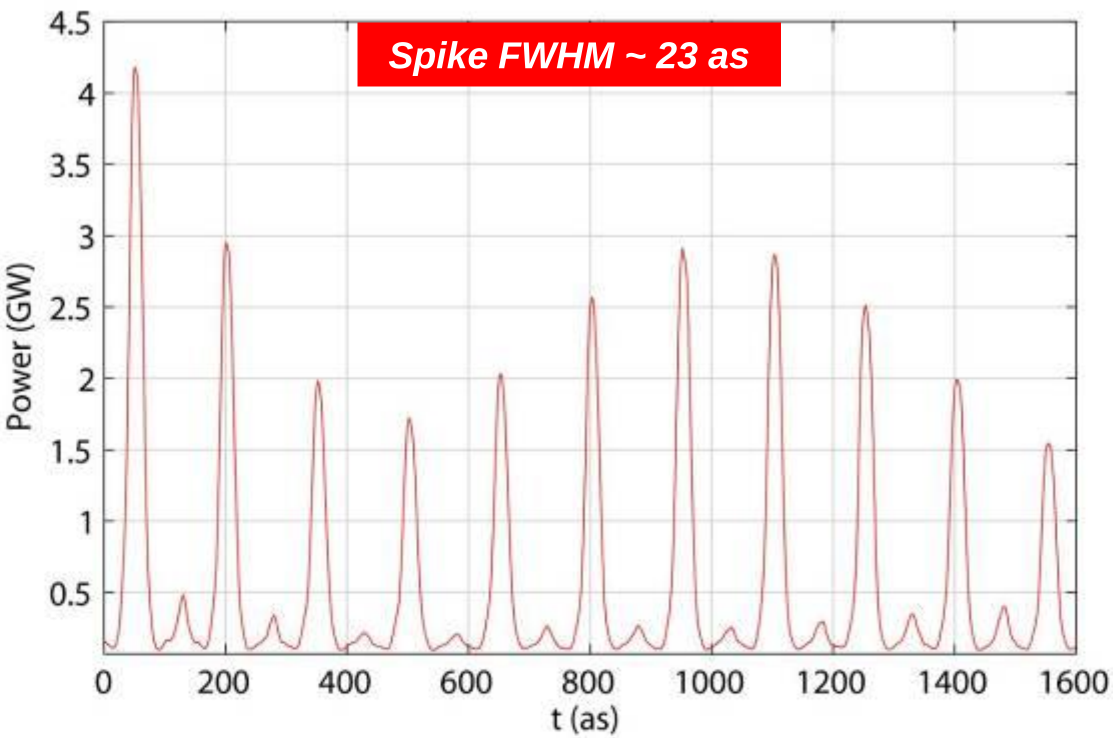
Increasing spike separation => Increasing cooperation length

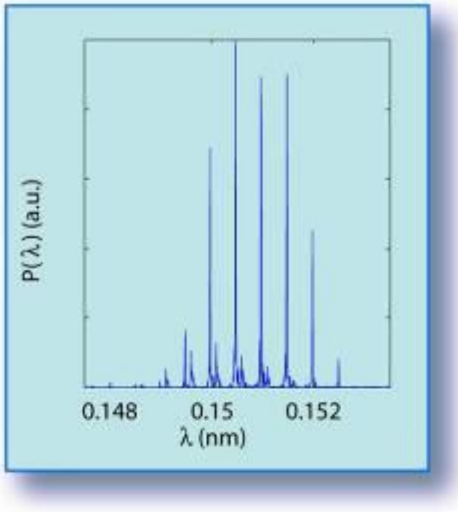
=> Improved temporal coherence

X-ray FEL amplifier with mode-locking*

Electron energy modulation at mode spacing




Spike FWHM ~ 23 as



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