Shaping FEL radiation: from multipulse/multicolor emission to generation of twisted light

PRIMOŽ REBERNIK RIBIČ

Elettra Sincrotrone Trieste

School on Synchrotron and Free-Electron-Laser Based Methods, ICTP, April 2016

SOME OF THE PROPERTIES USERS EXPECT FROM A LIGHT SOURCE

- High peak brilliance and full tunability in the spectral region of interest
- Possibility of controlling pulse duration
- Full transverse and longitudinal coherence (diffraction imaging, coherent control)
- Variable polarization (circular dichroism, surface science)
- Ultimate feature: the ability to arbitrarily shape the radiation pulse in the temporal and spatial (longitudinal and transverse) domains

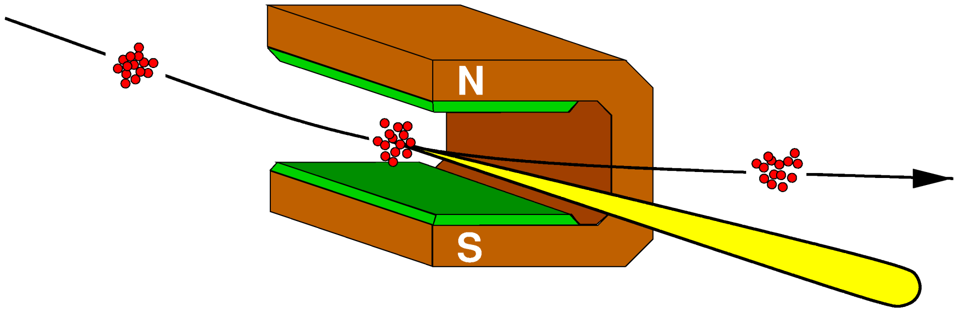
YOU CAN'T ALWAYS GET WHAT YOU WANT?

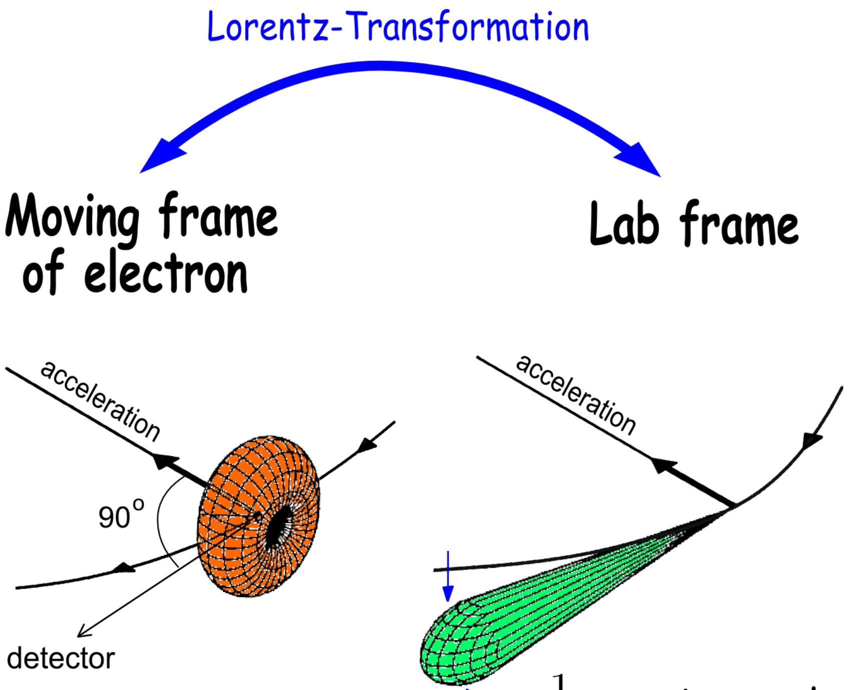
- In the IR to UV spectral region, the majority of previously mentioned requirements are met by conventional table-top lasers.
- In the VUV to X-ray spectral domain, different approaches must be used in order to achieve laser-like properties of light. Seeded FELs are currently the most promising candidates for reaching this goal.

OUTLINE

- quick recap of bending magnet and undulator radiation
- basic principles of FEL operation
- self-amplified spontaneous emission (SASE) vs. seeded FELs
- advanced FEL concepts: longitudinal (temporal) and transverse (spatial) shaping of FEL pulses

BENDING MAGNET RADIATION

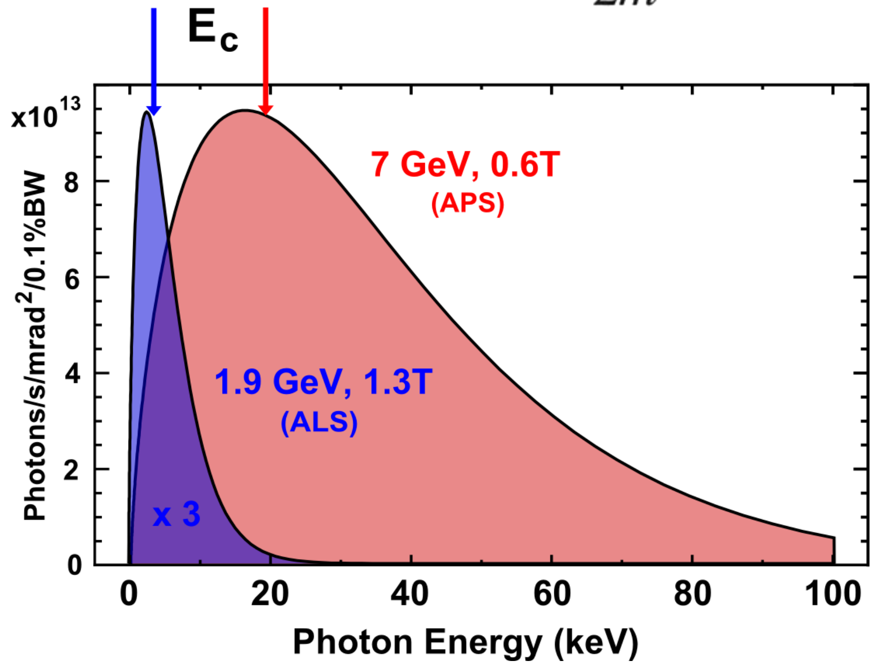




$$\pm\frac{1}{\gamma} \text{ opening angle}$$

$$\frac{1}{\gamma} = \frac{m_o c^2}{E} = \sqrt{1 - (\frac{v}{c})^2}$$

$$E_c = \hbar\omega_c = \frac{3e\hbar B\gamma^2}{2m}$$



http://photon-science.desy.de

UNDULATOR RADIATION

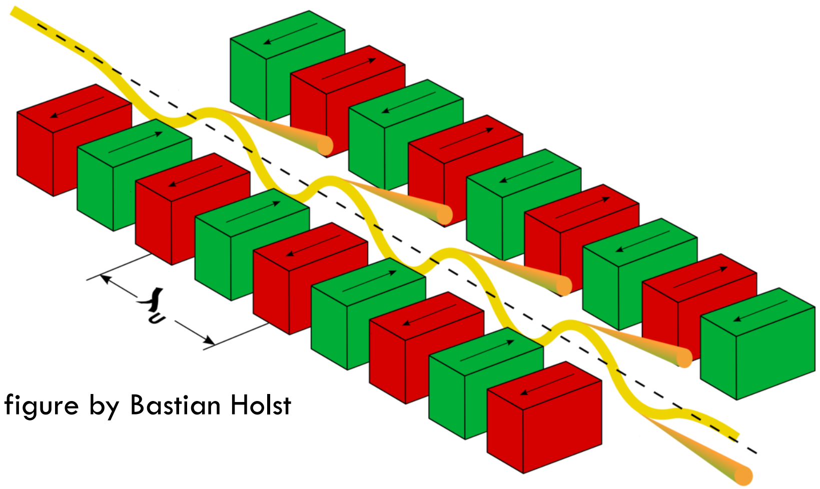
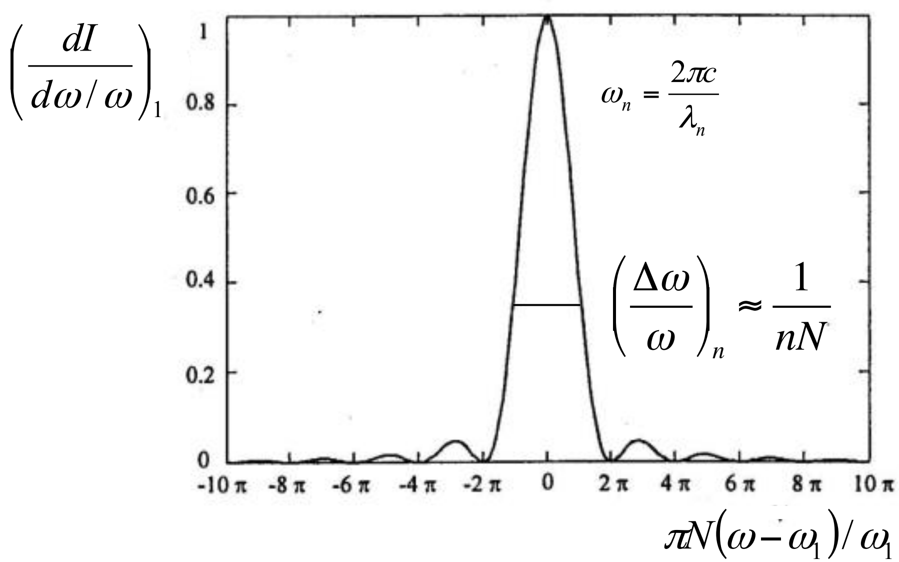


figure by Bastian Holst



N = number of undulator periods

Resonant wavelength:

$$\lambda_n = \frac{\lambda_u}{2n\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right),$$

(only odd harmonics on-axis, i.e., $\theta = 0$)

λ_u = undulator period

γ = electron energy

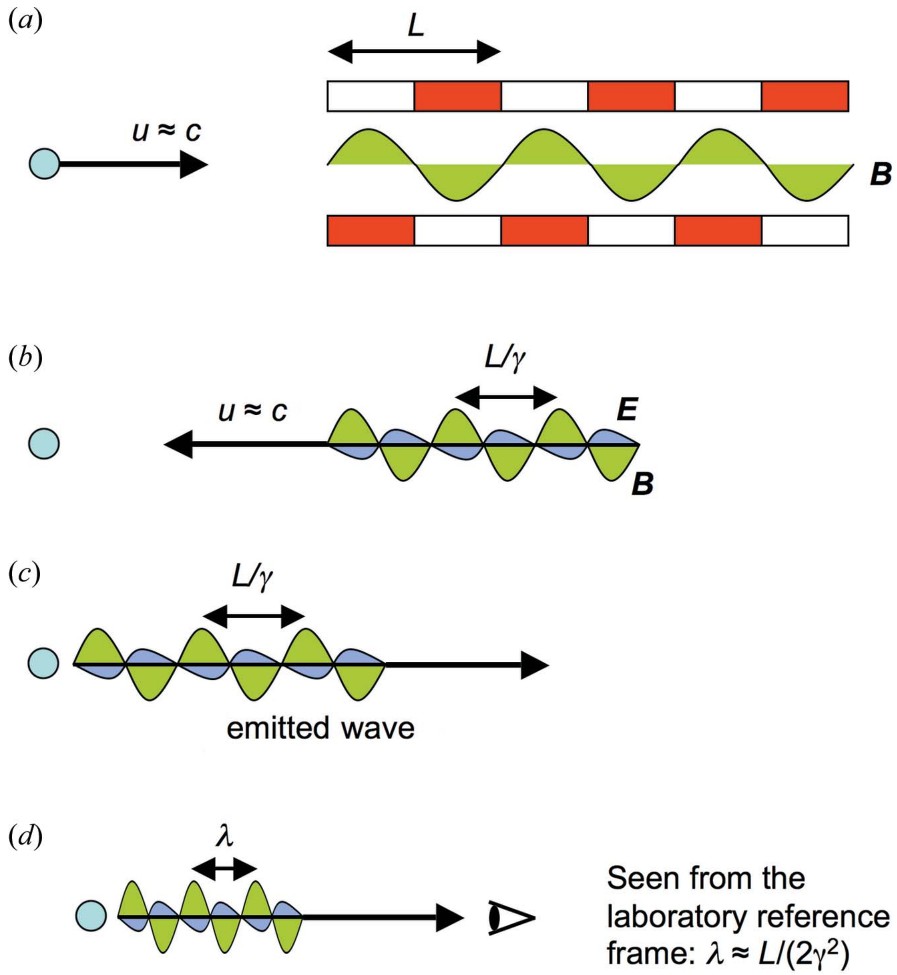
$K \propto \lambda_u B_0$ = undulator parameter

B_0 = peak undulator field

n = harmonic number

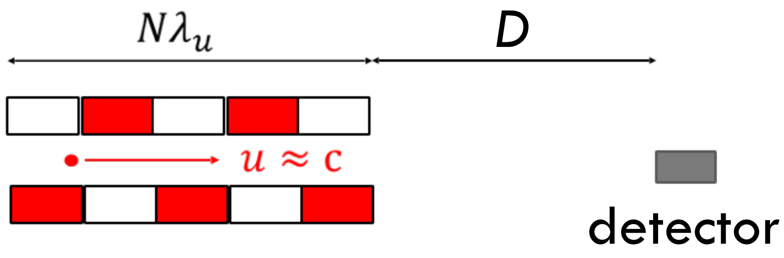
UNDULATOR RADIATION „EXPLAINED“

Resonant wavelength:



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

Pulse properties:



Frist photons detected at $t_1 = \frac{N\lambda_u + D}{c}$

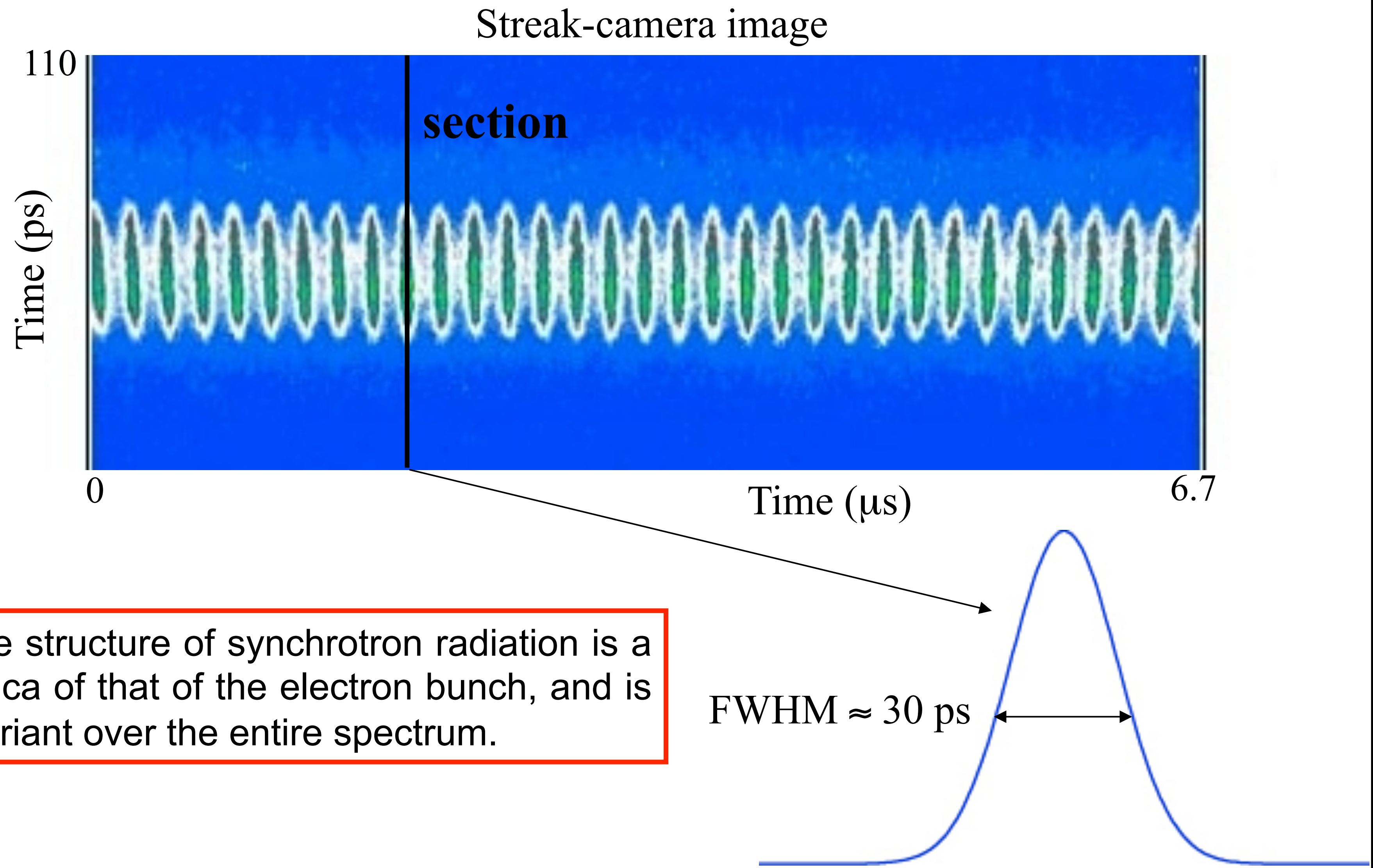
Detection ends at $t_2 = \frac{N\lambda_u}{u} + \frac{D}{c}$

Pulse duration $= t_2 - t_1 \approx \frac{N\lambda_u}{2c\gamma^2} \approx \frac{N\lambda}{c}$

Characteristic frequency $\propto 1/\Delta t \propto \frac{c}{N\lambda}$

Bandwidth $\frac{\Delta\omega}{\omega} \propto \frac{1}{N}$

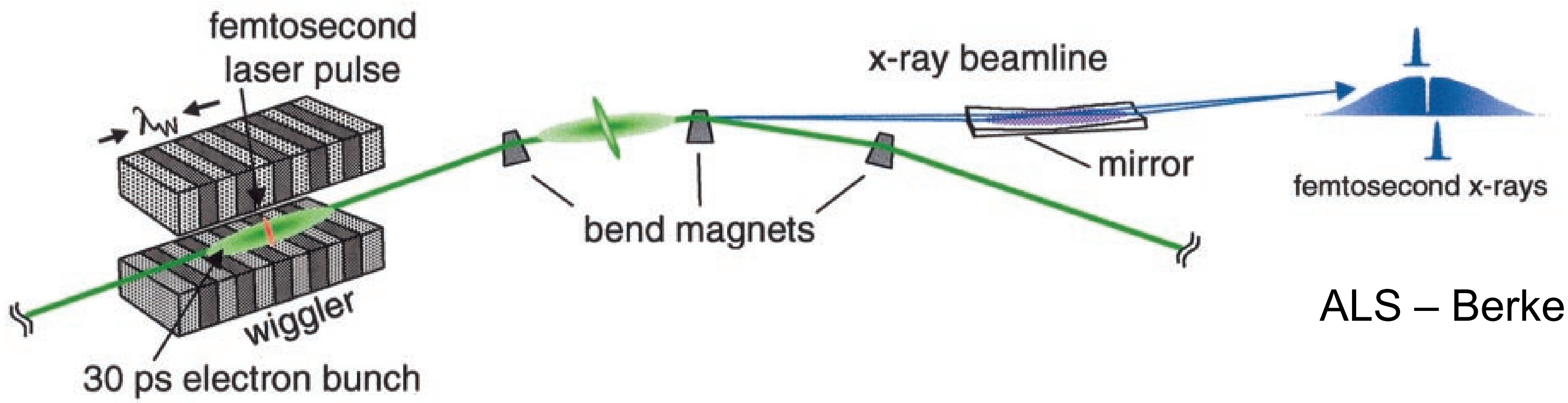
TIME STRUCTURE OF SYNCHROTRON RADIATION



Time structure of synchrotron radiation is a replica of that of the electron bunch, and is invariant over the entire spectrum.

DECREASING THE PULSE DURATION

A femtosecond laser is used to imprint an energy modulation onto a long electron bunch (femtoslicing).



ALS – Berkeley

Drawback: strong reduction of photon flux (by a factor of 1000).

R. W. Schoenlien et al., Science, 2000

SYNCHROTRON RADIATION: TYPICAL PERFORMANCE

Tunability: Full (between IR and X-rays)

Shot-to-shot reproducibility: Very good

Polarization: Fully adjustable

Repetition rate: hundreds of MHz

Peak brilliance: $\approx 10^{21}$ ph/s/0.1%BW/mm^2/mrad^2 (at 10 keV)

Pulse duration: tens of picoseconds

Natural spectral resolution: $\approx$ few percent

Coherence: good transverse, poor longitudinal

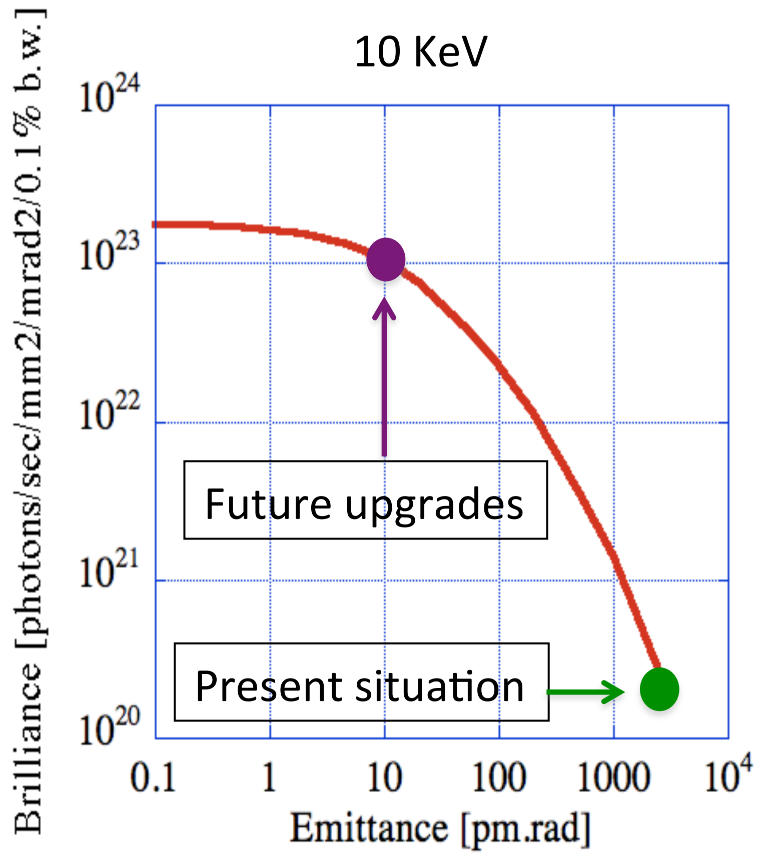
INCREASING THE BRILLIANCE

$$\text{brilliance (or brightness)} \propto \frac{\text{photon flux}}{\text{unit area} \times \text{unit solid angle}}$$

Limited by *wake field instabilities*

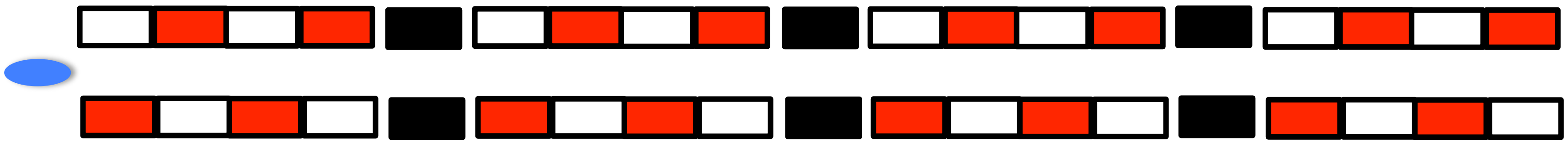
$$\text{brilliance} \propto \frac{I_{\text{beam}}}{\varepsilon_x \varepsilon_y}$$

Limited by diffraction



Low Emittance Rings Workshop, Crete, 2011

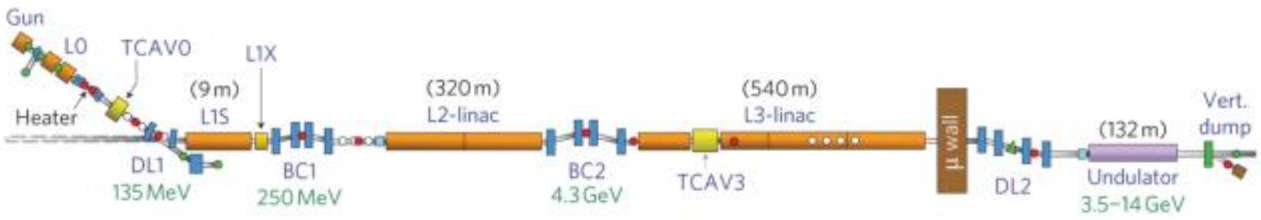
INCREASING THE BRILLIANCE, TRY NO. 2



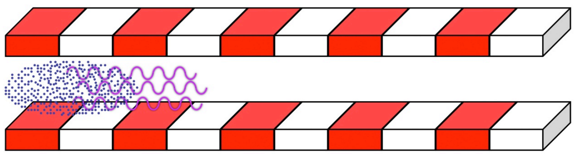
Is this a brute force approach? Yes and no…

WHAT IS A FEL ?

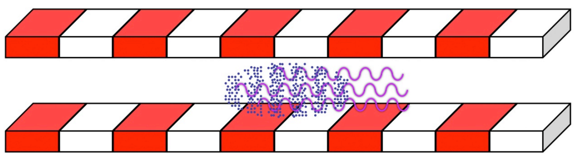
- electrons are accelerated in a high-energy linear accelerator to a speed close to c (speed of light)



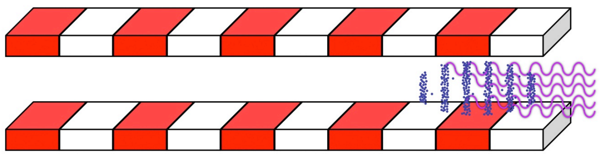
P. Emma *et al.*, *Nat. Photonics* (2010) **4**, 641



- electron bunch enters the undulator → (uncorrelated) emission of radiation by individual electrons

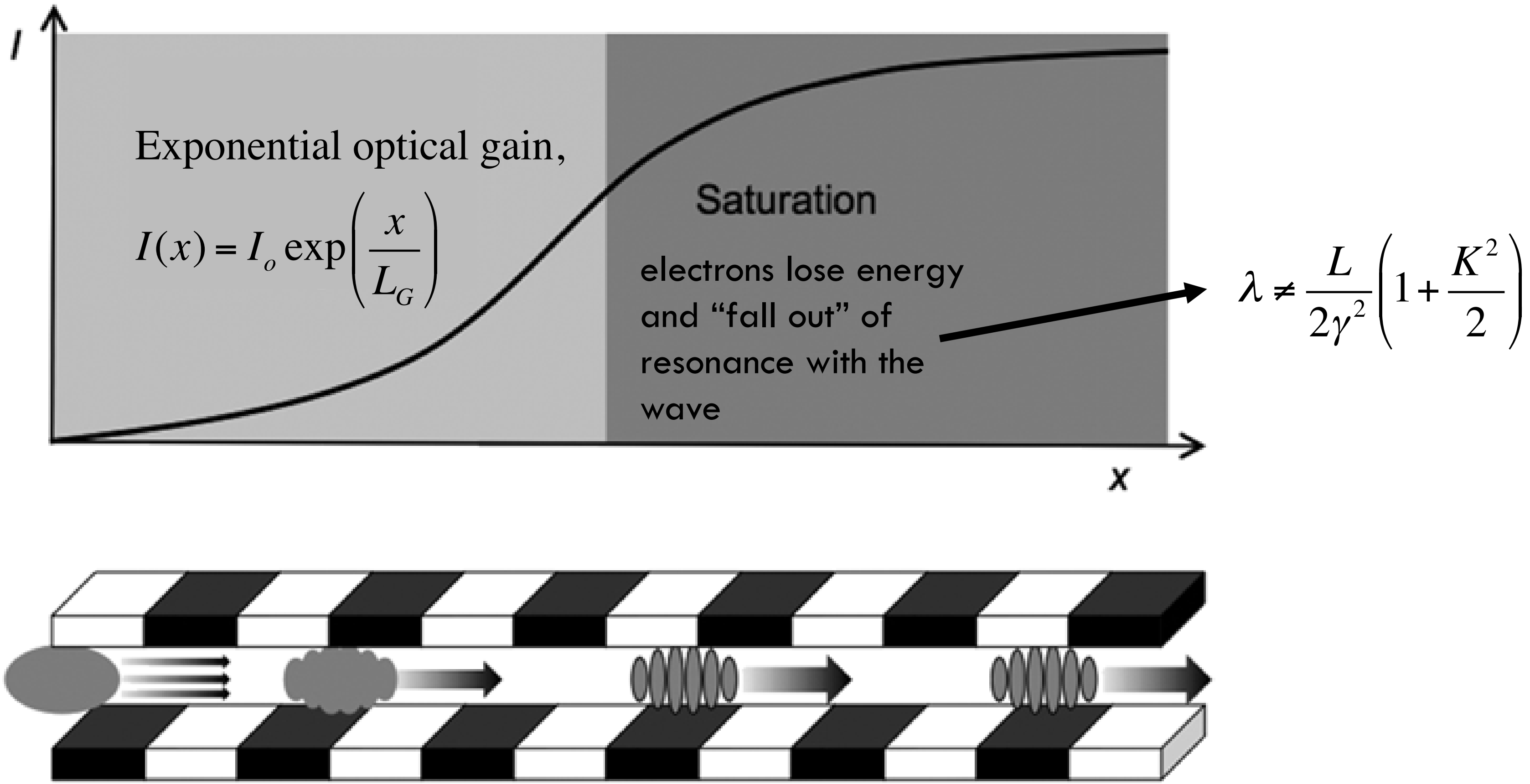


- interaction of electrons with previously emitted waves leads to microbunching → partly correlated emission



- complete microbunching → the emission is fully correlated

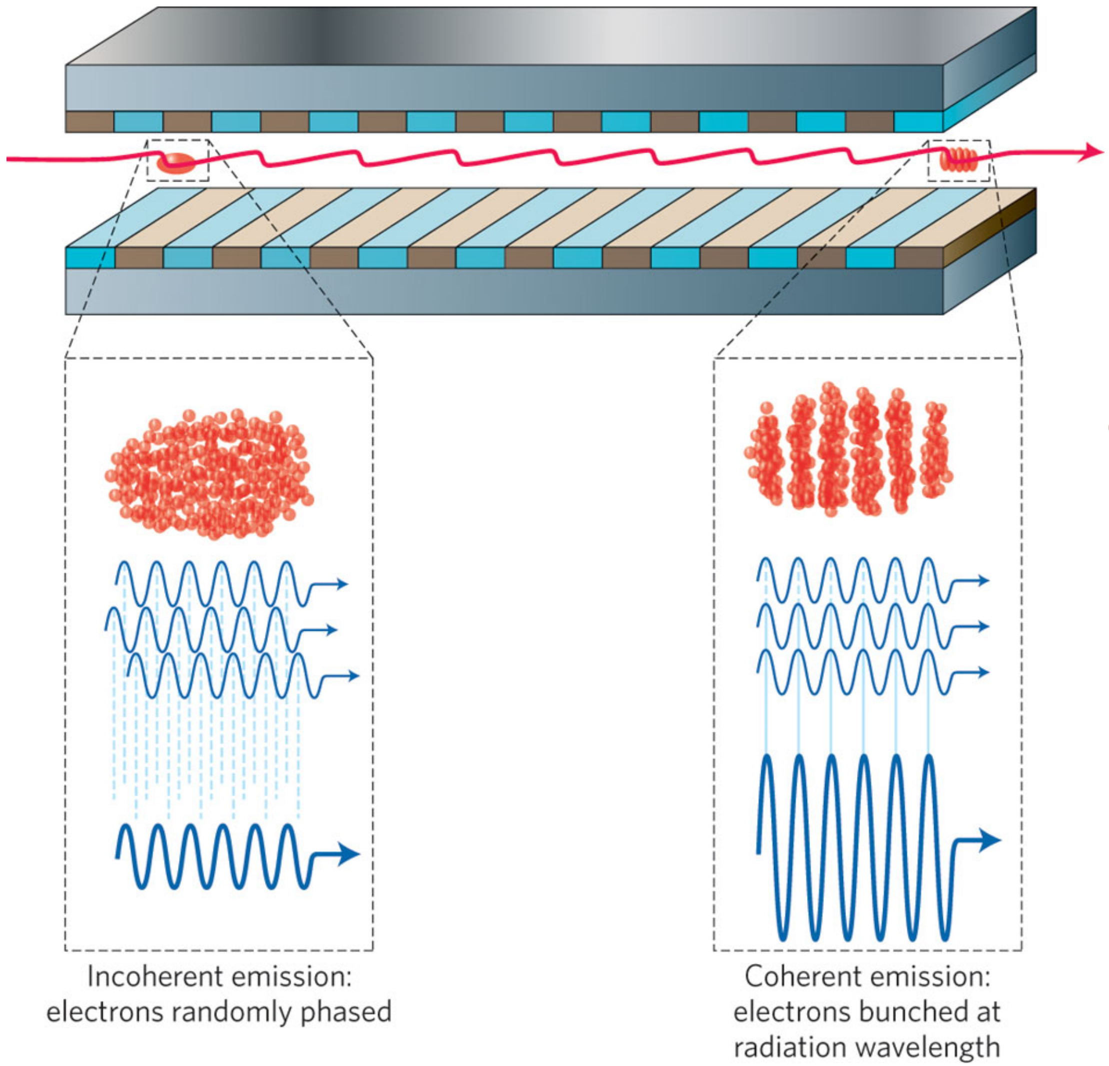
FEL GAIN



The electron beam and the emitted electromagnetic wave co-propagate in a long undulator. Electrons couple with spontaneous emission, resulting in exponential amplification (gain) of the intensity until saturation is reached.

A QUESTION OF COHERENCE

Incoherent synchrotron emission



Coherent FEL emission

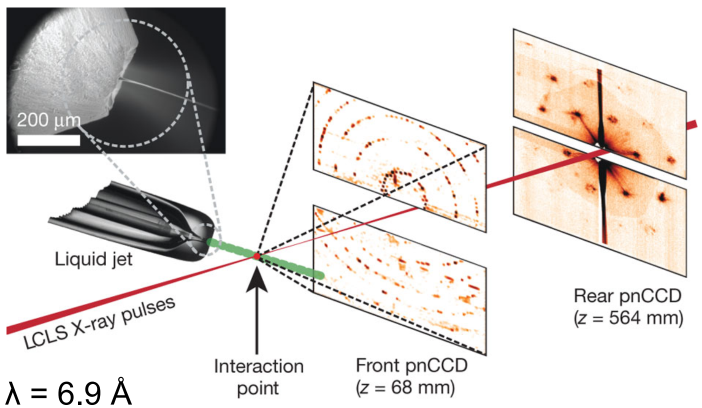
$$\text{brilliance} \propto I_{\text{beam}}$$

$$\text{brilliance} \propto I^2_{\text{beam}}$$

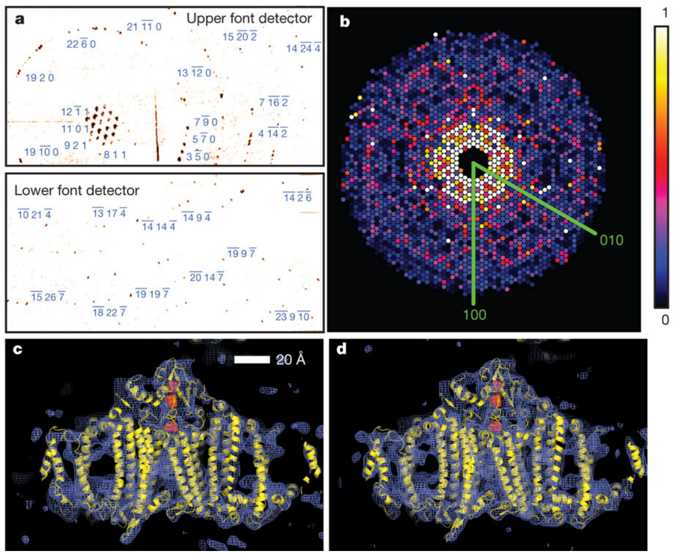
B.W.J. McNeil, N. R. Thompson, *Nature Photonics*, 2010

WHY MORE BRILLIANCE? AREN'T SYNCHROTRONS POWERFUL ENOUGH?

protein nanocrystallography



measurements on photosystem I

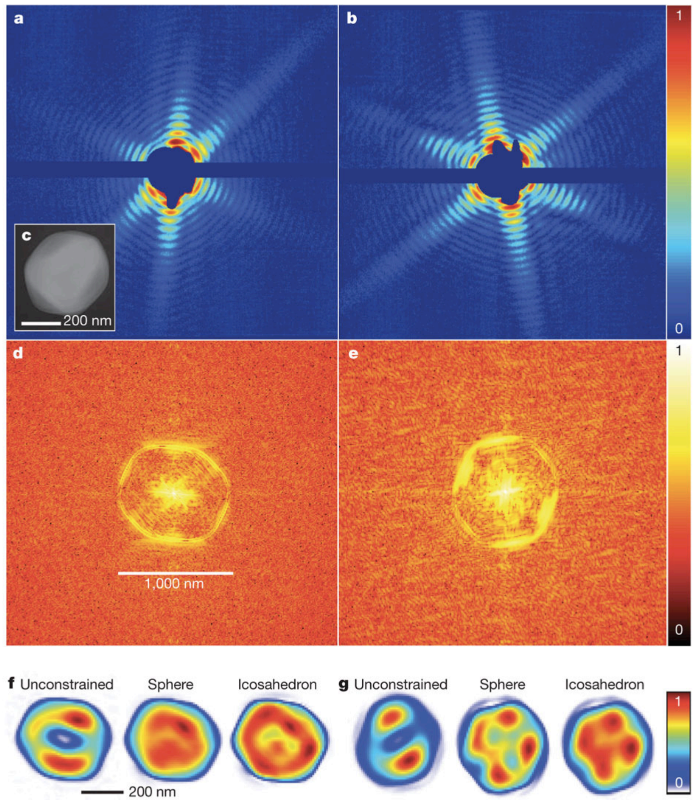


H. N. Chapman *et al.*, *Nature,* 2011

coherent X-ray diffraction imaging (CXDI)

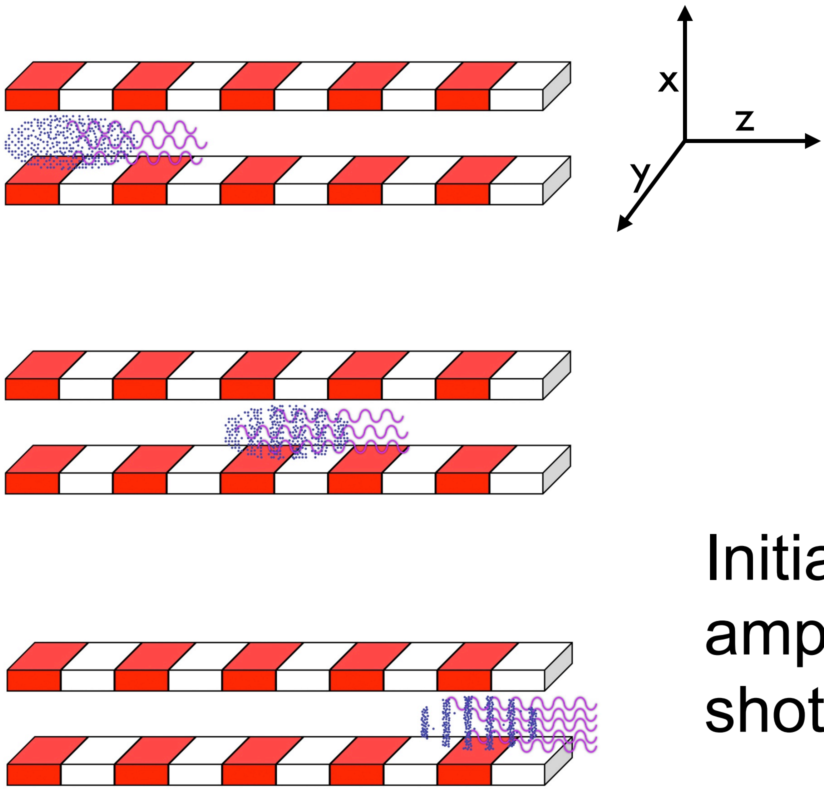
non-periodic objects ➝ continuous diffraction pattern ➝ oversampling ➝ phase retrieval ➝ image reconstruction

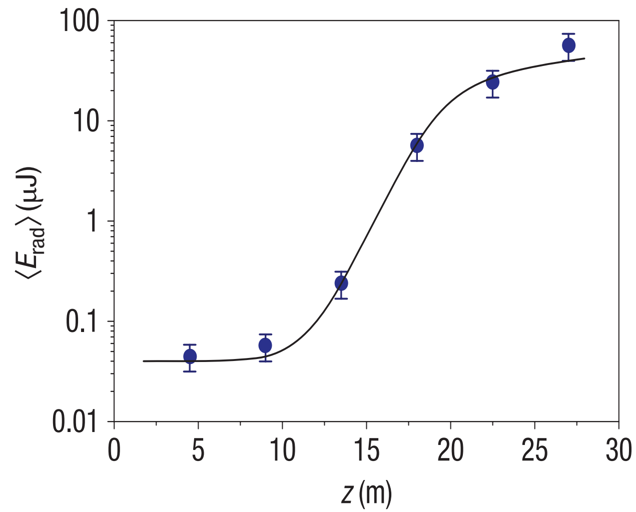
CXDI of single mimivirus particles



M. M. Seibert *et al.*, *Nature*, 2011

SELF-AMPLIFIED SPONTANEOUS EMISSION (SASE) FEL



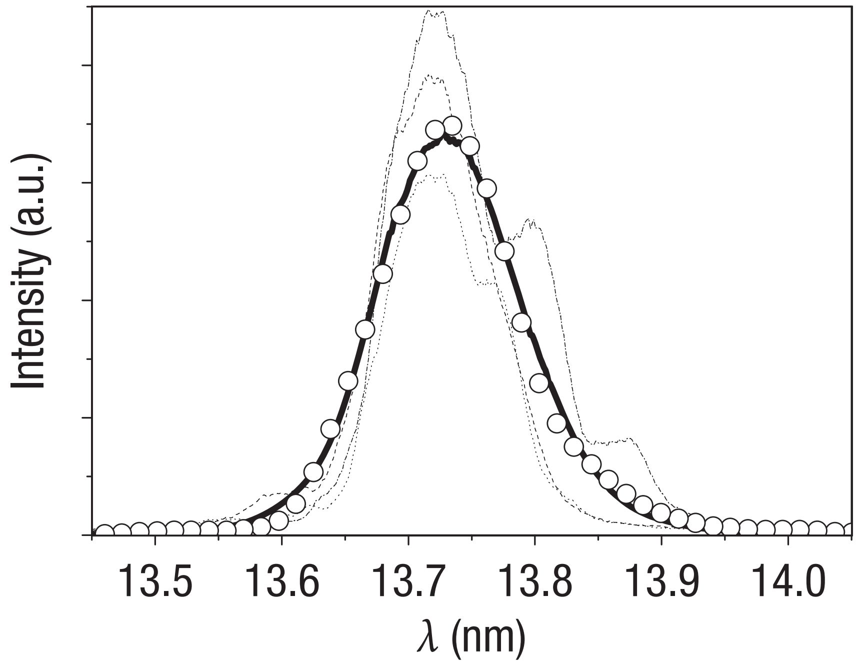


Initial emission that is being amplified originates from electron shot-noise:

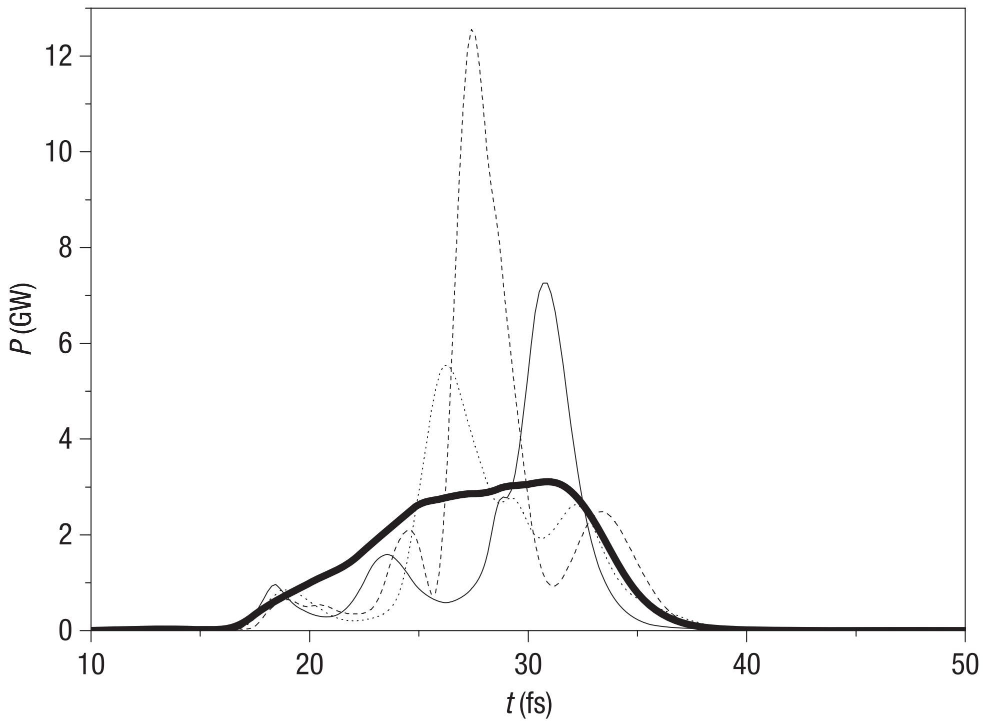
$$j_e = eK\cos\left(\frac{2\pi}{L}z\right)\sum_{j=1}^{N}\frac{1}{\gamma_j}\delta[\vec{x}-\vec{x}_j(z)]\delta[t-t_j(z)]$$

SASE SPECTRAL AND TEMPORAL CHARACTERISTICS (FLASH)

Spectral profile



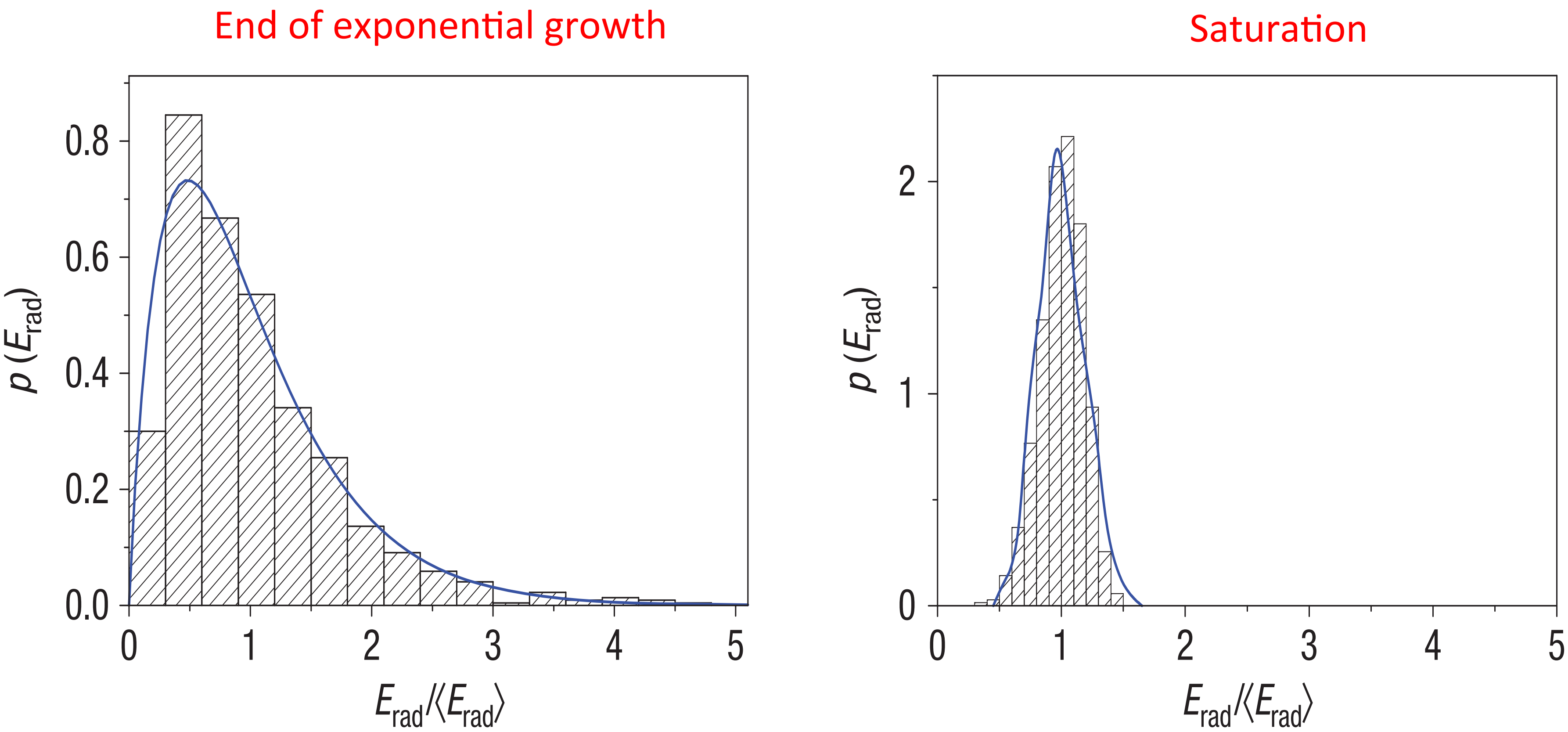
Temporal profile (simulation)



W. Ackermann *et al., Nature, 2007*

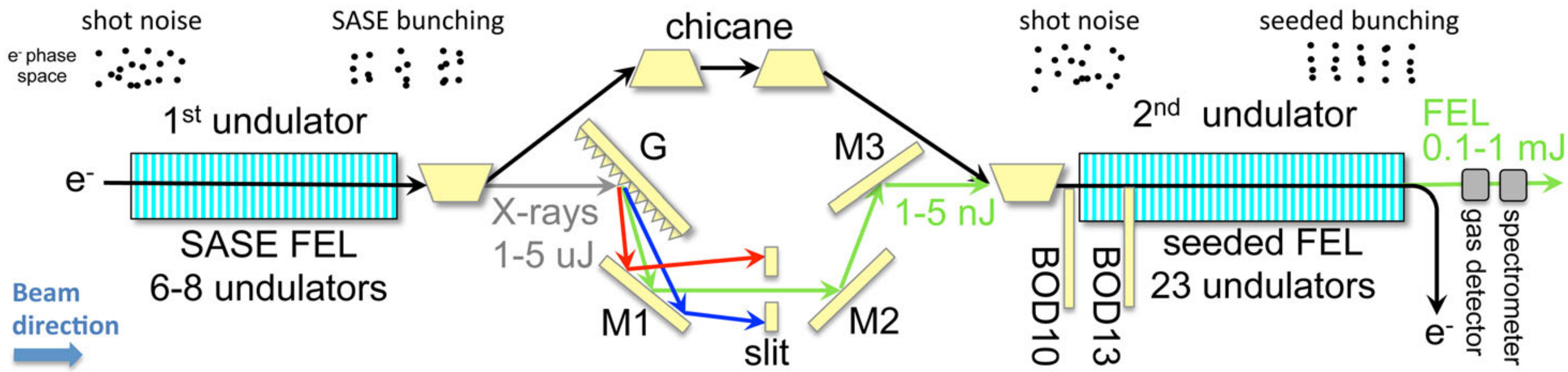
SASE PULSE ENERGY STABILITY (FLASH)

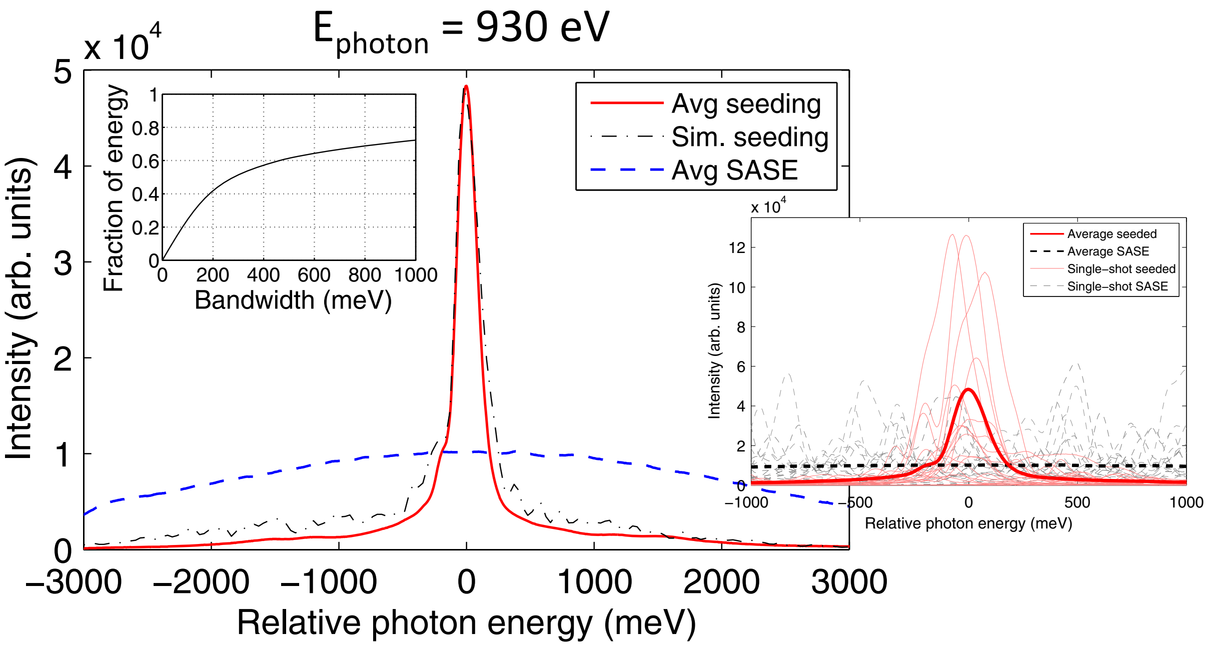
Probability distribution for the energy of FLASH radiation pulses



W. Ackermann *et al., Nature, 2007*

OVERCOMING SASE LIMITS 1 – SELF SEEDING

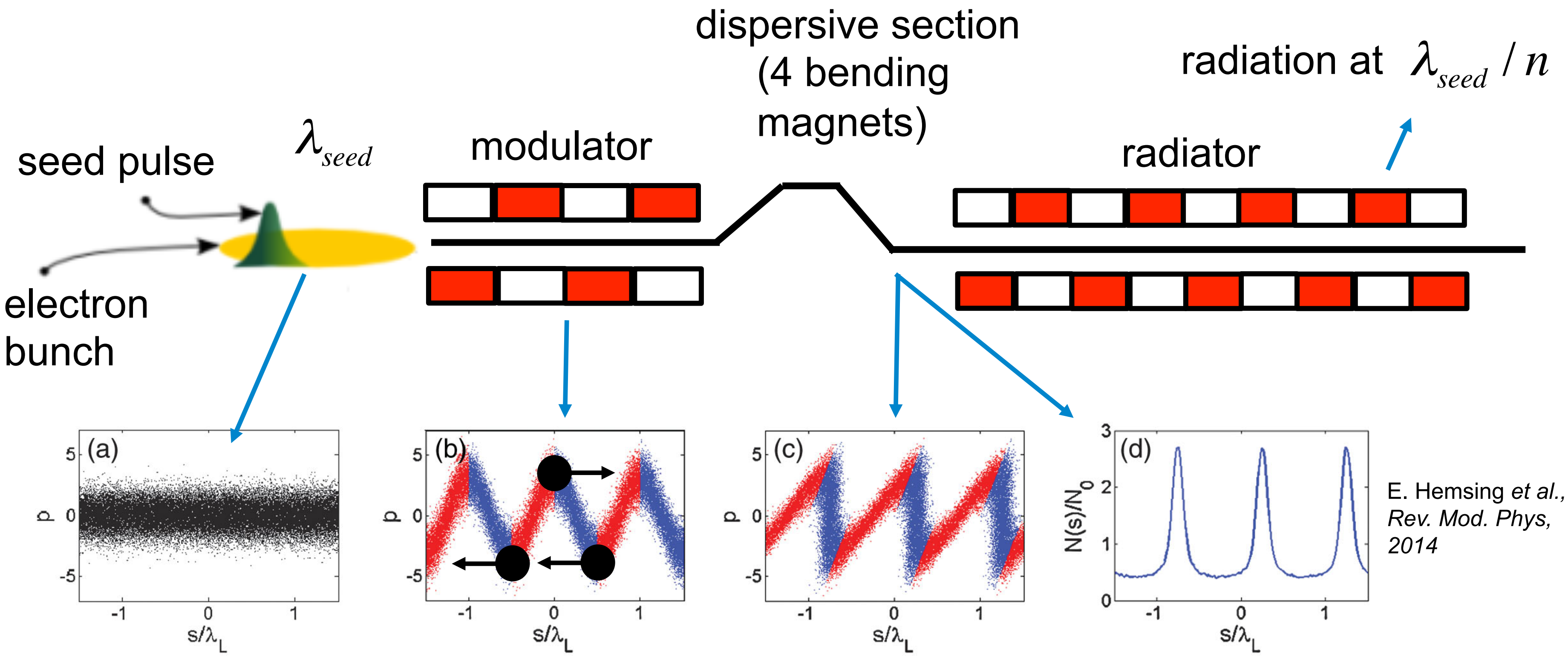




- improved central wavelength stability
- narrower bandwidth (increased brightness)
- limited ability to shape the radiation pulse

D. Ratner *et al.*, PRL, 2015

OVERCOMING SASE LIMITS 2 – SEEDING BY AN EXTERNAL COHERENT SIGNAL (HIGH GAIN HARMONIC GENERATION - HGHG)



E. Hemsing *et al.*, *Rev. Mod. Phys,* *2014*

$$b_n \sim \exp[-n^2 B^2 / 2] \mathrm{J}_n[-nAB]$$

$$\max : AB \approx 1 \Rightarrow b_n \sim \exp[-n^2 / 2A^2]$$

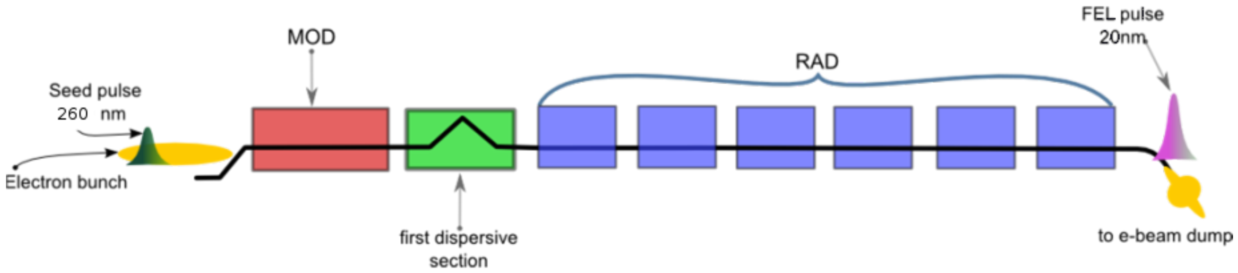
A = energy modulation normalized to the initial energy spread

B = (dimensionless) dispersive strength

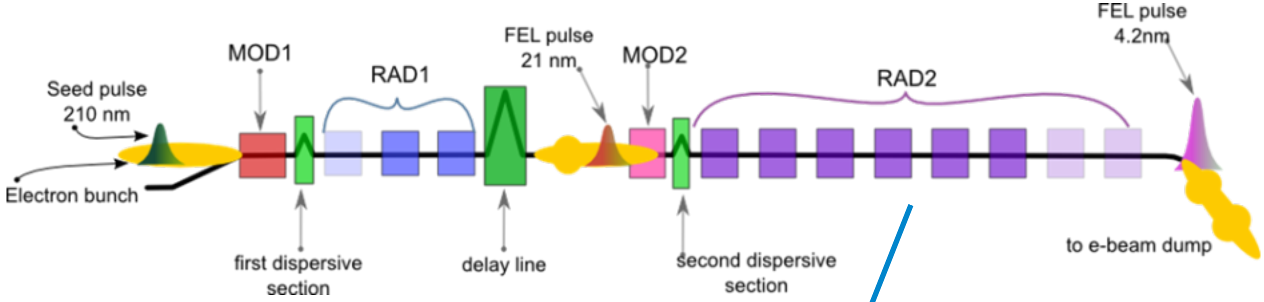
FEL radiation properties are governed by the seed laser => PULSE SHAPING!

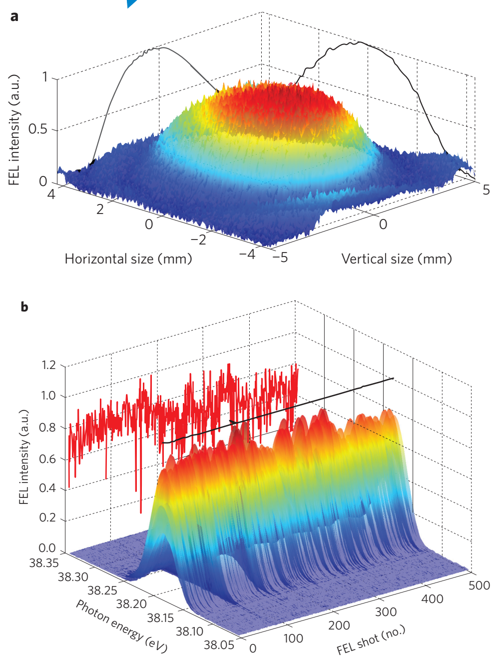
FERMI SEEDED FEL

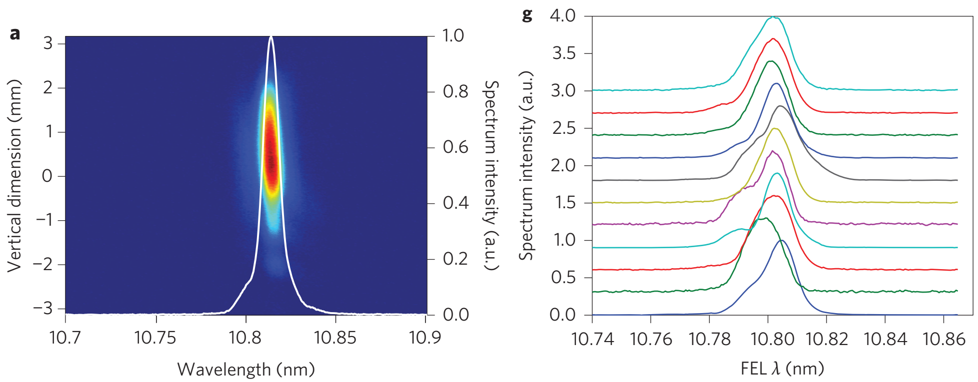
FEL1:
100 nm – 20 nm



FEL2:
20 nm – 4 nm

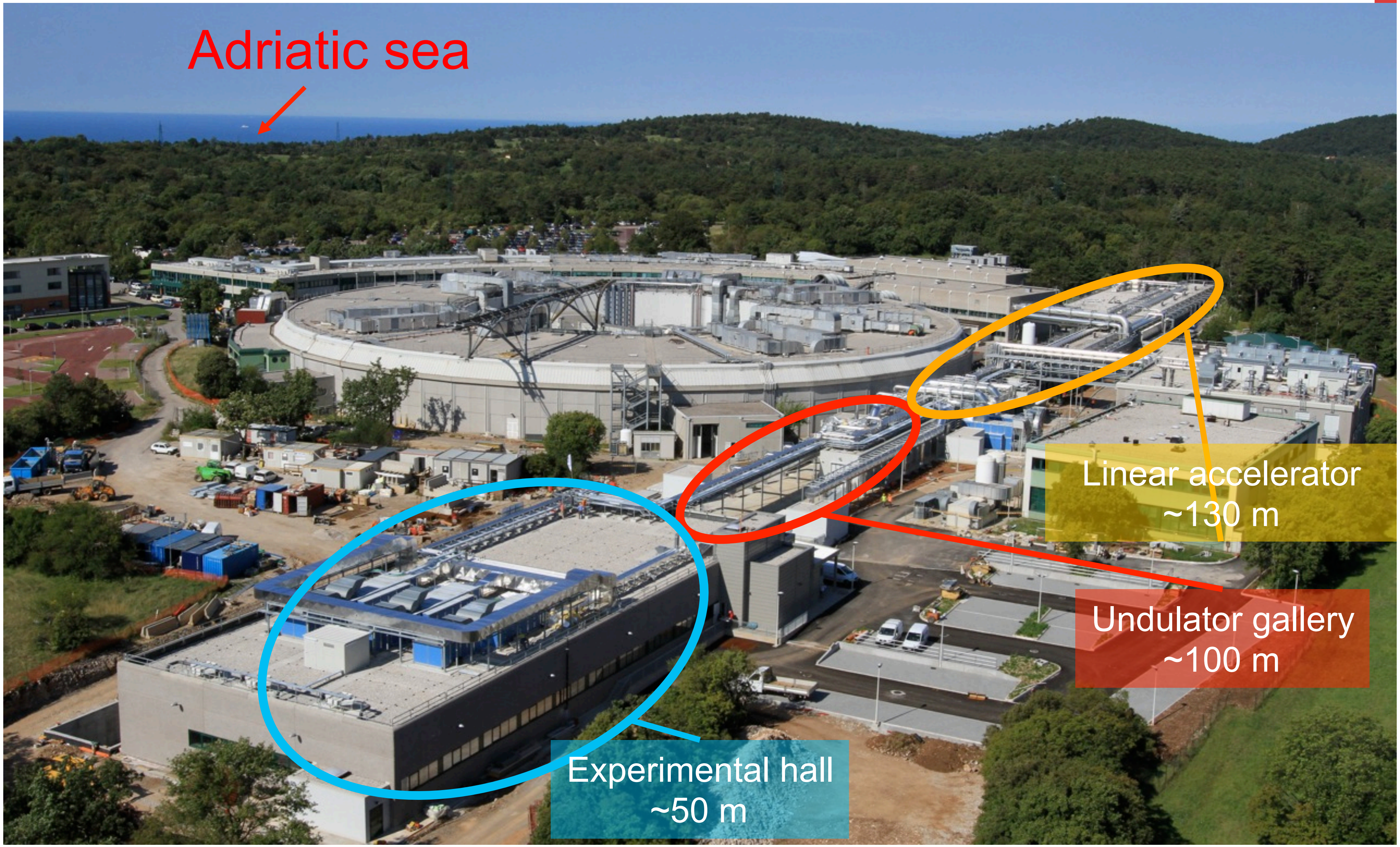






Allaria *et al.*, *Nature Photonics*, 2012 and 2013

FERMI SEEDED FEL



SHAPING FEL LIGHT:
TWO COLOR FEL SCHEMES
(FOR X-RAY PUMP-X-RAY PROBE EXPERIMENTS)

TWO COLOR FEL SCHEMES

How can we generate two FEL pulses with different wavelengths?

$$\lambda = \lambda_u \frac{1+K^2}{2\gamma^2}$$

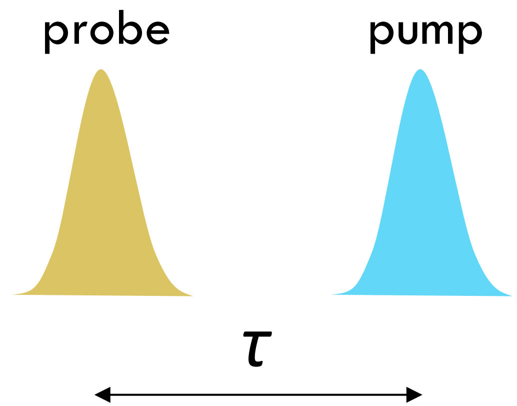
$$\lambda_{1,2} = \lambda_u \frac{1+K_{1,2}^2}{2\gamma^2}$$

split undulator scheme

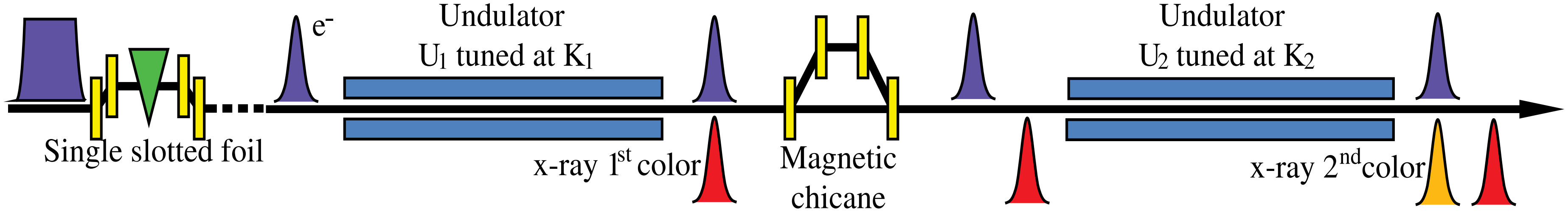
$$\lambda_{1,2} = \lambda_u \frac{1+K^2}{2\gamma_{1,2}^2}$$

twin-bunch scheme

two colors + delay =

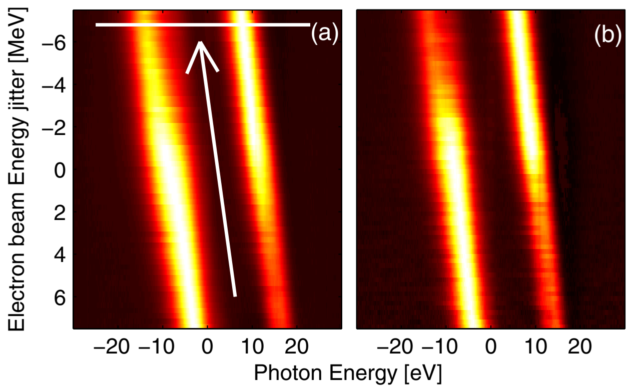


TWO COLOR SASE FEL: SPLIT UNDULATOR SCHEME

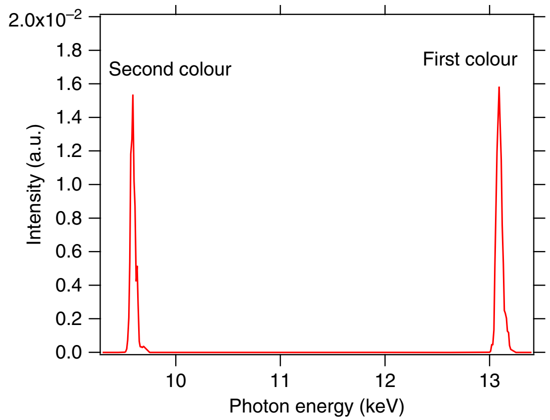


- Advantage: easy to tune
- Drawback: reduced power due shorter undulator length available for one color (1/20 to 1/5 of one color SASE power)

- Max delay limited by chicane magnets: typically from ~50 fs to hundreds of fs
- Min delay: below 1 fs
- Time delay jitter: ~ 0.1%
- Energy separation of two colors: 0 to several 10%

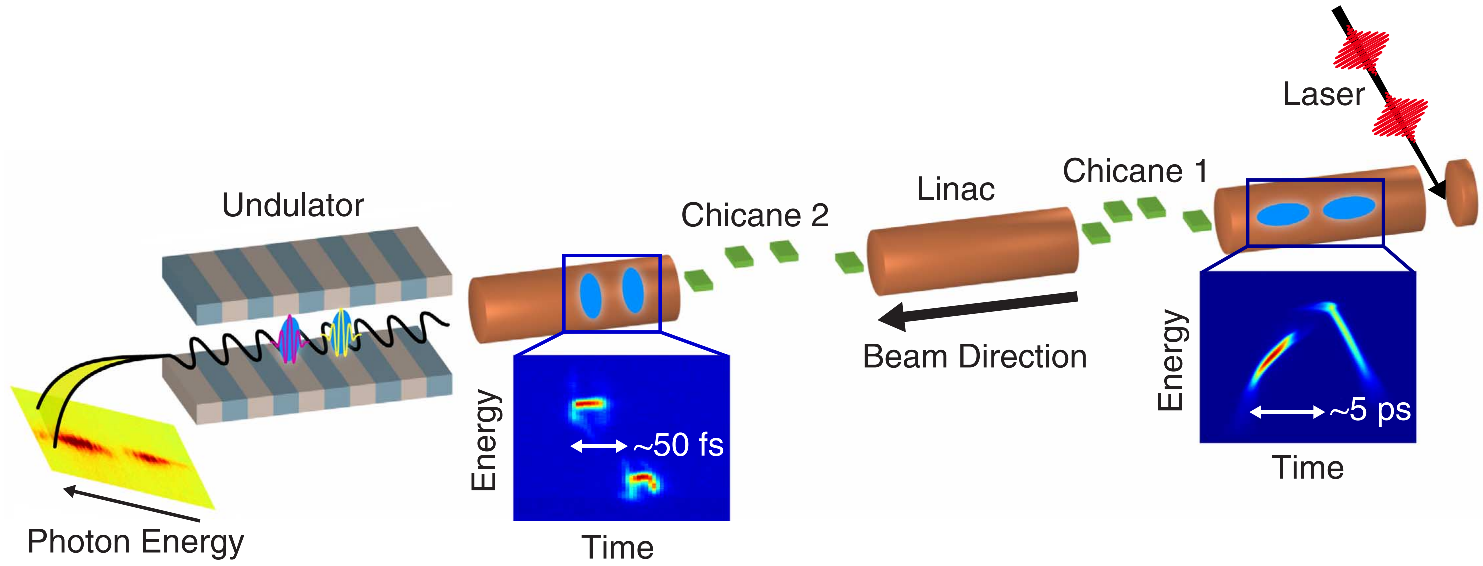


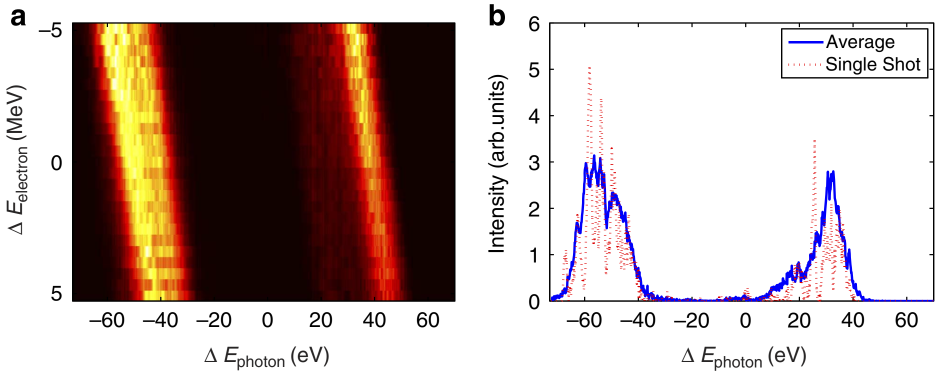
A. A. Lutman *et al.*, PRL, 2013



T. Hara *et al., Nat. Commun.*, 2013

TWO COLOR SASE FEL: TWIN-BUNCH SCHEME





A. Marinelli *et al., Nat. Commun.,* 2015

- Advantage: full undulator available for both colors -> more power
- Maximum energy separation: ~1%, tuned by compression in Chicane 1
- Maximum delay: ~100 fs, tuned by cathode delay and compression in Chicane 2
- Time delay jitter: ~5 fs