Synchrotron radiation

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Storage ring light sources

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- radiation damping and radiation excitation
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- Short introduction to Free Electron Lasers (FELs)

FEL basic concepts (I)

In a storage ring the phase relationship between the radiation emitted by each electron is random and the spatial and temporal coherence of the radiation is limited.

The electrons emit radiation in an undulator **incoherently**

In a FEL the electron interact back with the radiation emitted in the undulator.

Under certain conditions this process can generate a **microbunching** of the beam.

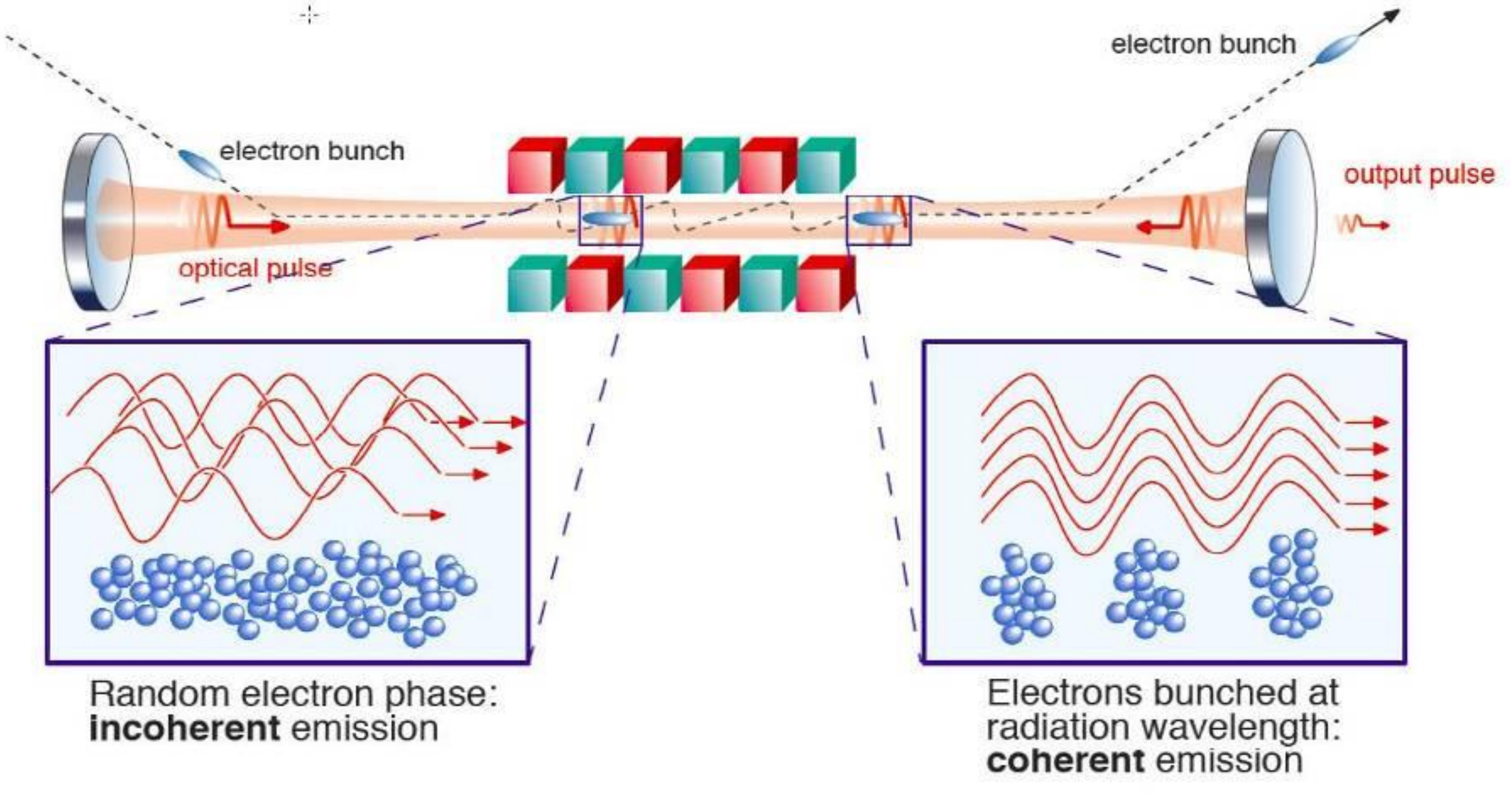
Microbunching happens mostly at the undulator resonant wavelength.

The electrons will now emit in phase with each other, **coherently**

The radiation power (and brilliance) will scale as N_e^2 not as N_e

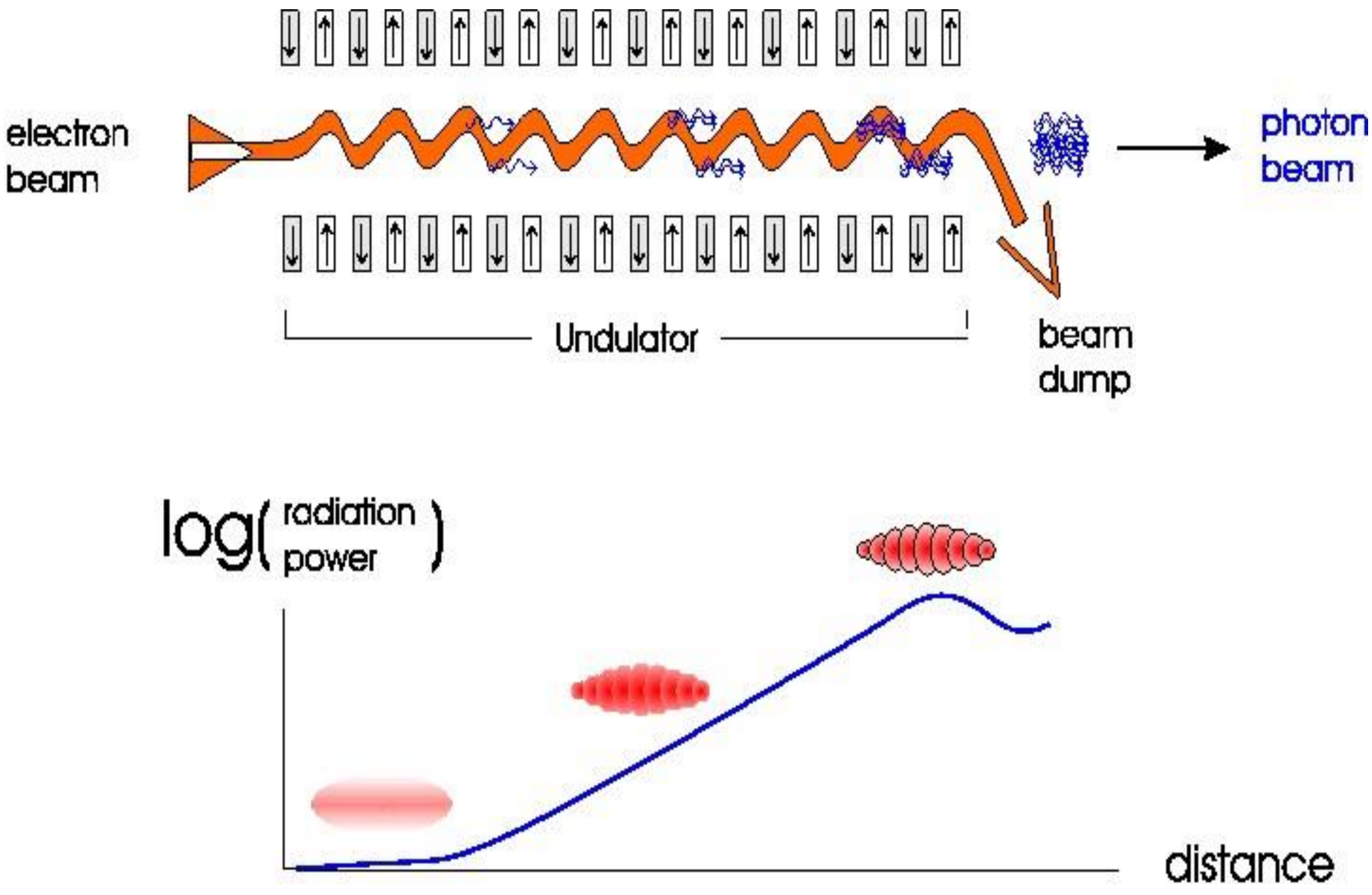
FEL oscillators

The FEL are of two types oscillators and amplifiers. In oscillators the radiation is stored in a cavity. The growth of radiation occurs over many bounces (low gain)



FEL amplifiers

The FEL are of two types oscillators and amplifiers. In amplifiers the radiation grows within a single pass in the undulator



FEL basic concepts (II)

How is the microbunching happening?

In certain conditions the interaction of the radiation emitted in an undulator, with the electron bunch itself, can be strong and generates a strong modulation of the energy of the electrons in the bunch. The equations of motion are

$$\frac{d\bar{p}}{dt} = e\bar{E} + \frac{e}{c}\bar{v}\times\bar{B} \qquad \bar{p} = m_e\gamma\bar{v}$$

$$\frac{dE}{dt} = e\bar{E}\cdot\bar{v} \qquad E = m_e c^2\gamma$$

N.B. It is called laser but it can be explained entirely with classical electromagnetism

E and B are the magnetic field of the undulator and the undulator radiation

$$\bar{B} = B_0\left(0, \quad \cos(k_u z), \quad 0\right)$$

$$\bar{E} = E_0\left(\cos\alpha, \quad 0, \quad 0\right) \qquad \bar{B} = E_0\left(0, \quad \cos\alpha, \quad 0\right) \qquad \alpha = kz - \omega t + \phi \qquad \omega = kc$$

Having simplified the undulator radiation with a plane wave, we can integrate them

FEL basic concepts (II)

The energy change of the electron occurs because of the coupling between

transverse (horizontal) oscillation of the electron in the undulator
and
transverse (horizontal) component of the electric field of the plane wave

$$\frac{dE}{dt} = e\overline{E} \cdot \overline{v} = eE_x v_x$$

unlike the RF cavities where the energy change occur because of the coupling between

longitudinal velocity of the electron in the undulator
and
longitudinal component of the electric field in the RF cavity

$$\frac{dE}{dt} = e\overline{E} \cdot \overline{v} = eE_z v_z$$

FEL basic concepts (III)

Changing the independent variable form t to z, and integrating, the transverse velocity reads

$$\beta_x = -\frac{K}{\gamma}\sin k_u z - \frac{eE_0}{m_e \omega c \gamma}\sin\alpha$$

→ new term from the radiation (plane wave)

The energy change reads

$$\dot{\gamma} = -\frac{eE_0}{m_e c \gamma}\cos\alpha \cdot \left[\frac{eE_0}{m_e \omega c}\sin\alpha + K\sin k_u z\right]$$

These two equations make a system of first order differential equation for (z, γ)

We make the following assumptions

- small signal (keep first order only in E_0)
- small gain ($\Delta\gamma << \gamma$)
- radiation wavelength close to the fundamental undulator radiation wavelength
- averaging all quantities over one undulator period (to remove fast oscillations)

FEL basic concepts (IV)

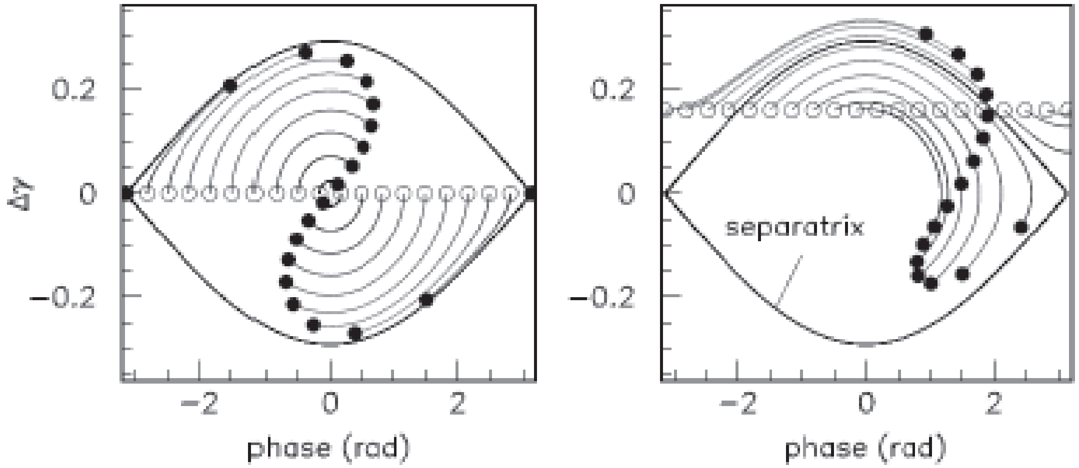
Introducing the variable

$$\zeta = k_u z + \alpha = (k + k_u)z - \omega t + \phi$$

the system of first order differential equations can be transformed in a second order differential equation

$$\ddot{\zeta} = -\frac{eE_0(k_u + k)[J_0(\xi) - J_1(\xi)](1 + K^2/2)K}{2m_e\gamma^4}\sin\zeta = \Omega^2 \sin\zeta$$

This is the so-called FEL-pendulum equation and describes the FEL interaction



FEL basic concepts (IV)

Each electron gain or loses energy depending on the relative phase $\zeta(0)$ between the transverse oscillation in the undulator and the phase of the radiation plane wave

$$\Delta\gamma = -\frac{eE_0 K\left[J_0(\xi) - J_1(\xi)\right]L}{2m_e c^2 \beta_{z0}\gamma_0}\frac{\sin(\nu/2)}{\nu/2}\sin\left(\zeta(0) + \nu/2\right) + O(\Omega^2)$$

$$\nu = \left(k + k_u - \frac{\omega}{c\beta_0}\right)L$$

The average energy variation (over the initial phases $\zeta(0)$ of the electrons)

$$<\Delta\gamma>_\phi = \frac{eE_0 K\left[J_0(\xi) - J_1(\xi)\right]\Omega^2}{8m_e c\gamma_0}\left(\frac{L}{c\beta_{z0}}\right)^3 \frac{d}{d\nu}\left(\frac{\sin\nu/2}{\nu/2}\right)^2$$

The variation of the energy of the electrons correspond to a variation of the energy of the em wave.

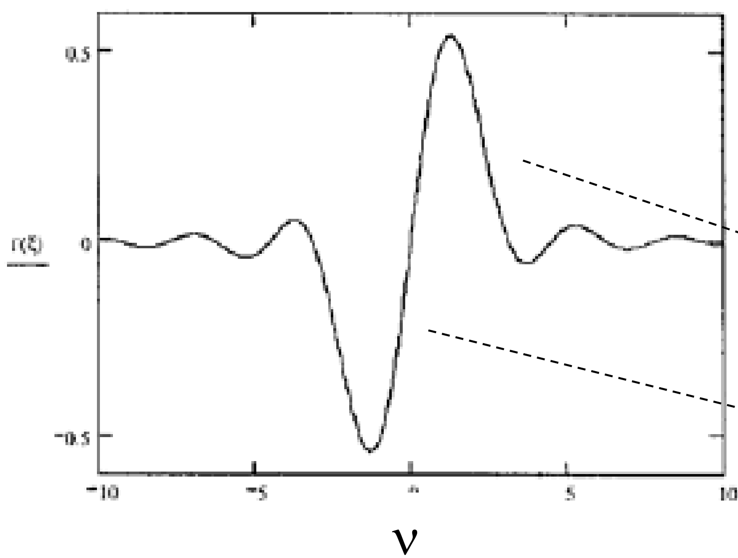
FEL small-signal small-gain curve

We can define a gain as a relative change of the energy of the wave

$$G = \frac{\Delta E_{tot}}{W_0^L} = -m_e c^2 \frac{N}{W_0^L} < \Delta\gamma >_\phi$$

For a bunch with peak current I and transverse area $\Sigma_b = F\Sigma_L$

$$G = -\frac{\pi K^2 \left[J_0(\xi) - J_1(\xi)\right]^2 k_u L^3 (1+\beta_{z0})}{2\gamma^3 \beta_{z0}^3} \frac{F}{\Sigma_L} \frac{I}{I_0} \frac{d}{d\nu} \left(\frac{\sin \nu/2}{\nu/2}\right)^2$$



FEL small signal, small gain curve

Positive gain, the wave is amplified

Negative gain, the beam is accelerated (Inverse FEL)

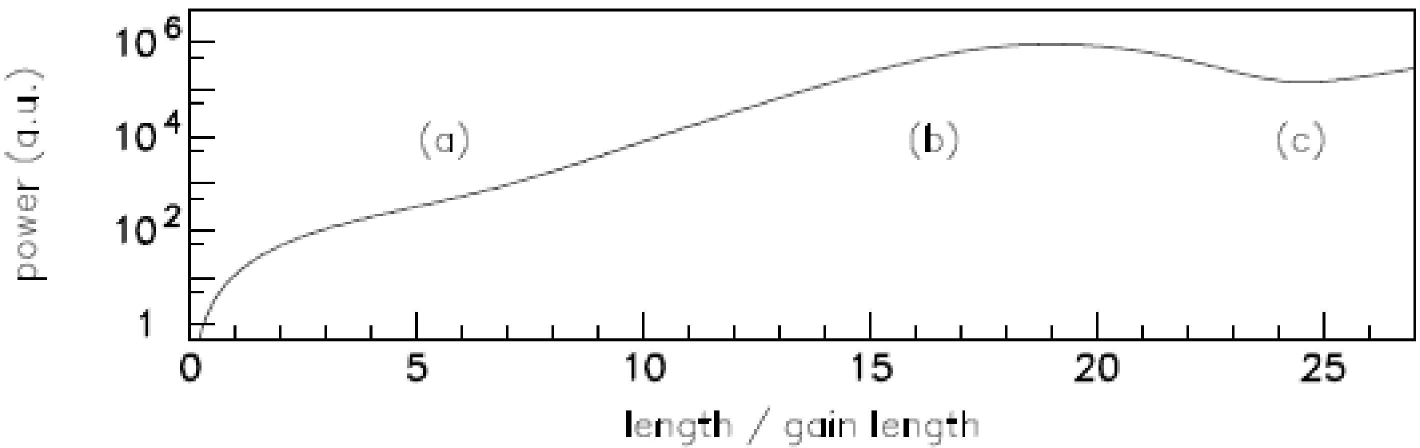
high-gain FELs

When the gain is so large that the wave amplitude changes within a single pass in the undulator, the previous approximations have to be revisited.

The wave amplitude must be described properly with the wave equation driven by the current density of the beam.

The result is an exponential growth of the radiation power until saturation is reached

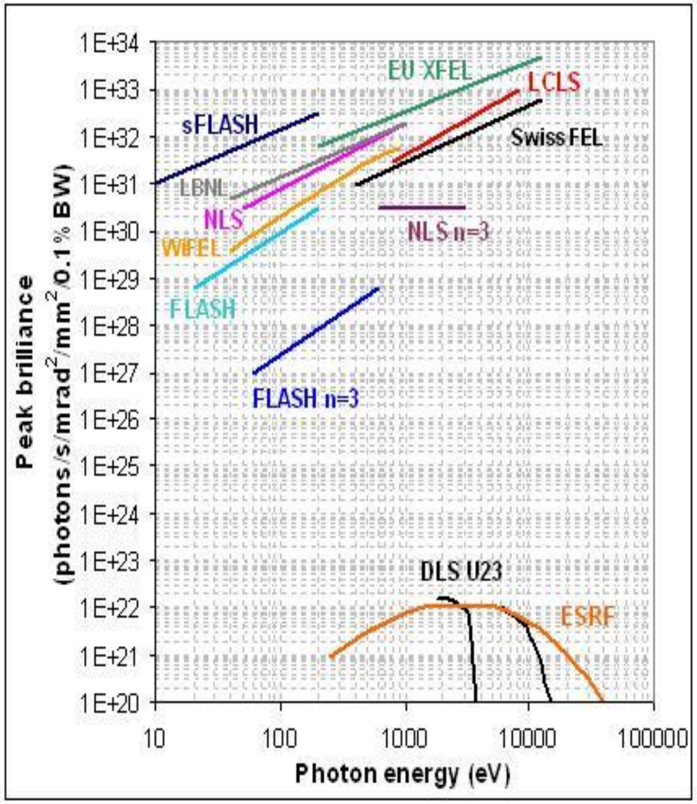
$$P(s) \sim e^{s/L_g} \qquad \text{with} \qquad L_g = \frac{1}{\sqrt{3}} \left(\frac{4\gamma^3 m_e}{\mu_0 K^2 e^2 k_u n_e} \right)^{1/3}$$

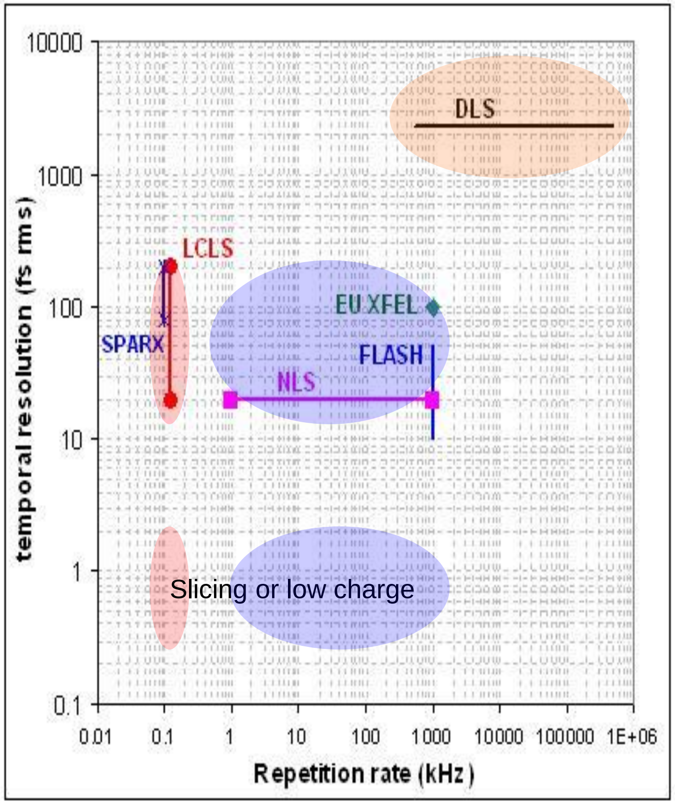


FEL radiation properties

FELs provide peak brilliance 8 order of magnitudes larger than storage ring light sources

Average brilliance is 2-4 order of magnitude larger and radiation pulse lengths are of the order of 100s fs or less



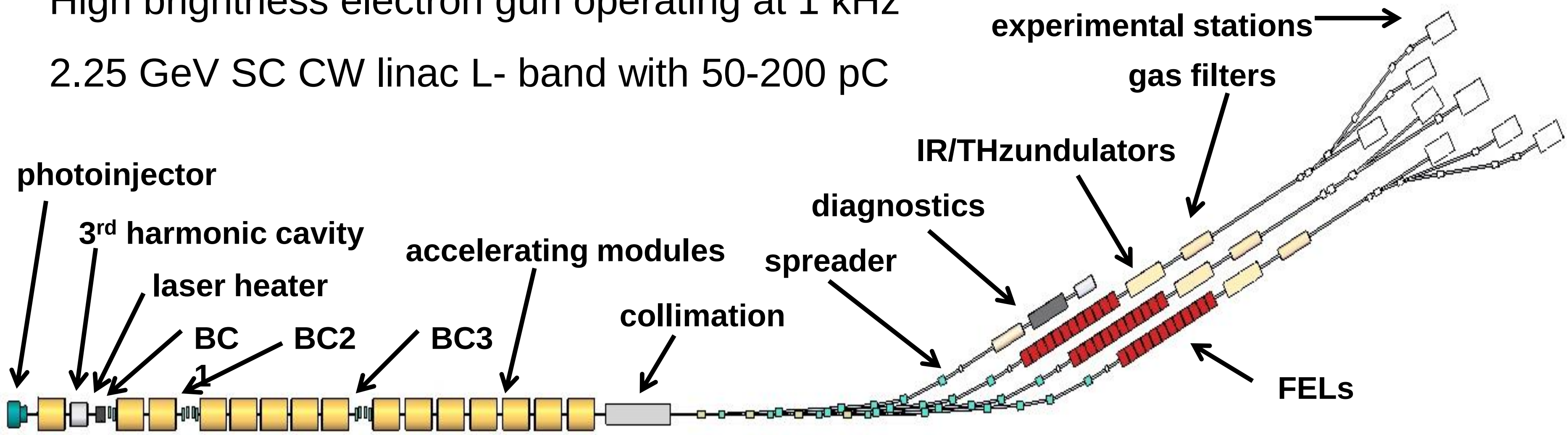


FEL amplifiers main components

An example taken from the UK New Light Source project (defunct)

High brightness electron gun operating at 1 kHz

2.25 GeV SC CW linac L- band with 50-200 pC



3 FELS covering the photon energy range 50 eV – 1 keV (50-300; 250-800; 430-1000)

- GW power level in 20 fs pulses
- laser HHG seeded for temporal coherence
- cascade harmonic FEL
- synchronised to conventional lasers and IR/THz sources for pump probe experiments

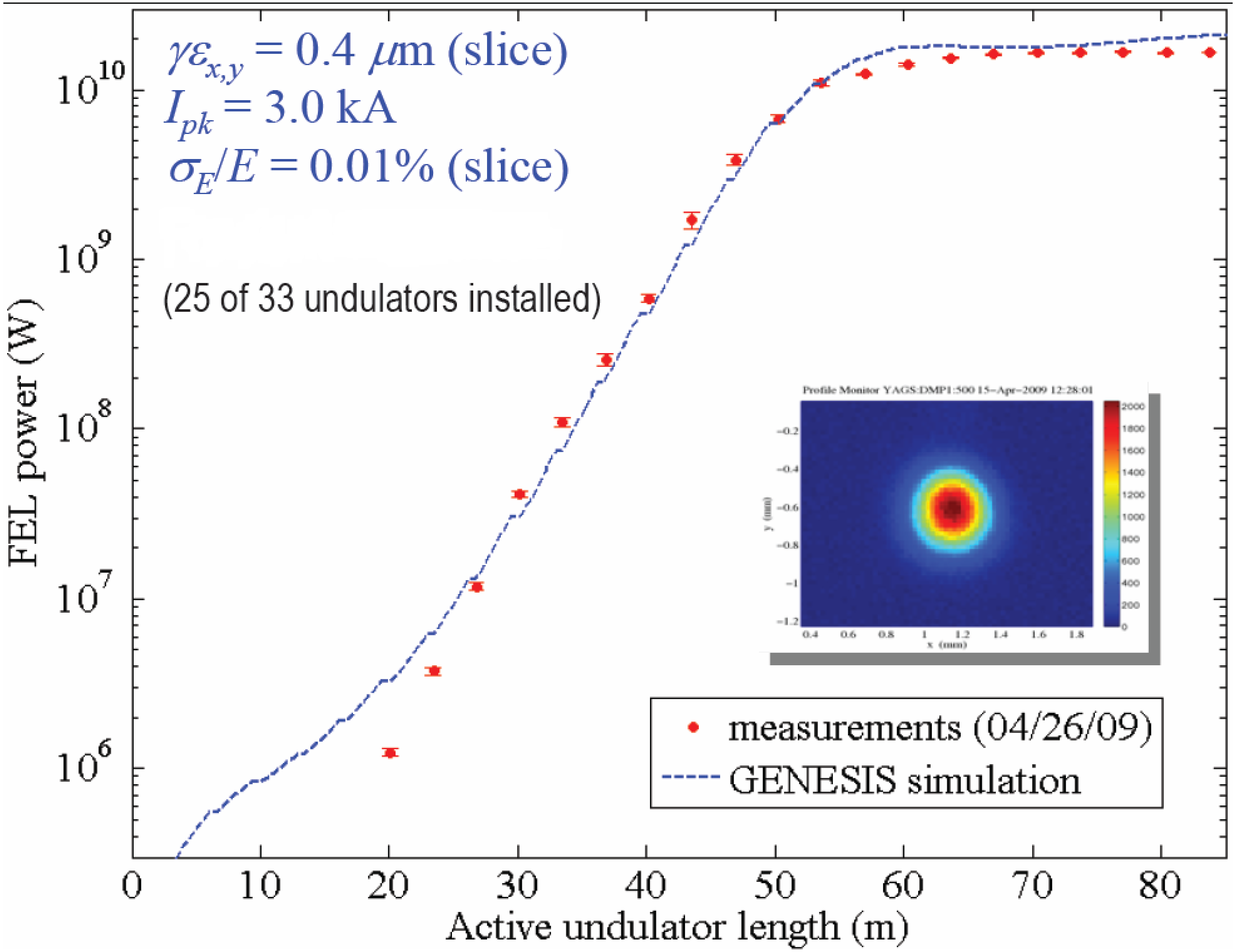
X-rays FELs

LCLS	0.15 nm	14 GeV	S-band	120 Hz	SASE
SACLA	0.1 nm	8 GeV	C-band	60 Hz	SASE
XFEL	**0.1 nm**	**17.5 GeV**	**SC L-band**	**CW (10 Hz)**	**SASE**
Swiss-FEL	**0.1 nm**	**5.8 GeV**	**C-band**	**120 Hz**	**SASE**

FLASH	47-6.5 nm	1 GeV	SC L-band	1MHz (5Hz)	SASE
FERMI	40-4 nm	1.2 GeV	NC S-band	50 Hz	seeded HGHG
SPARX	**40-3 nm**	**1.5 GeV**	**NC S-band**	**100 Hz**	**SASE/seeded**
Wisconsin	**1 nm**	**2.2 GeV**	**SC/CW L-band**	**1 MHz**	**seeded HHG**
LBNL	**100-1 nm**	**2.5 GeV**	**SC/CW L-band**	**1 MHz**	**seeded**
MAX-LAB	**5-1 nm**	**3.0 GeV**	**NC S-band**	**200 Hz**	**SASE/seeded**
Shanghai	**10 nm**	**0.8-1.3 GeV**	**NC S-band**	**10 Hz**	**seeded HGHG**
NLS	**20-1 nm**	**2.2 GeV**	**SC/CW L-band**	**1-1000 kHz**	**seeded HHG**

Swiss-FEL	**10 nm**	**2.1 GeV**	**NC S-band**	**120 Hz**	**SASE/seeded**
LCLS-II	**4 nm**	**4 GeV**	**NC S-band**	**120 Hz**	**seeded**

LCLS lasing at 1.5 Å (April 2009)



Accelerator Physics challenges

Soft X-ray are driven by high brightness electron beam

1 – 3 GeV $\varepsilon_n \leq 1\ \mu m$

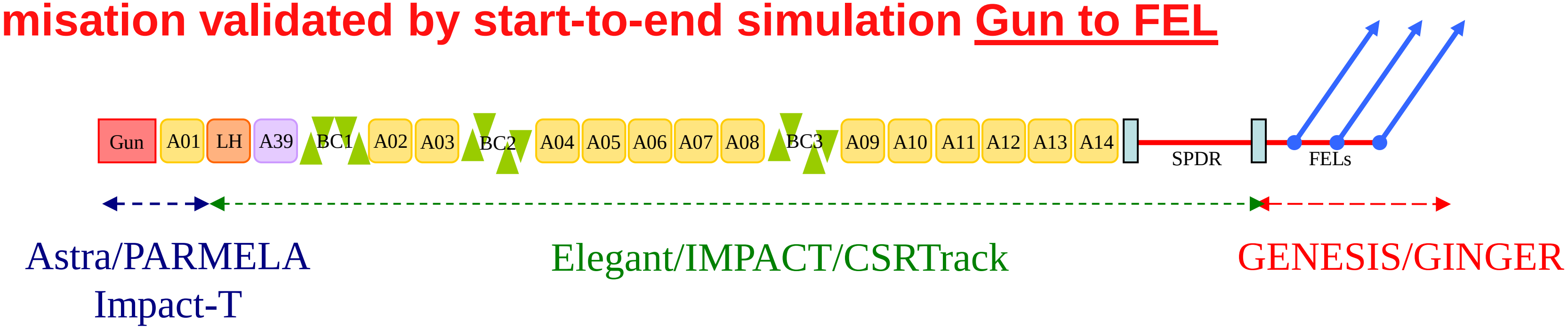
~ 1 kA $\sigma_\gamma / \gamma \leq 10^{-4}$

This requires:

a low emittance gun (norm. emittance cannot be improved in the linac)

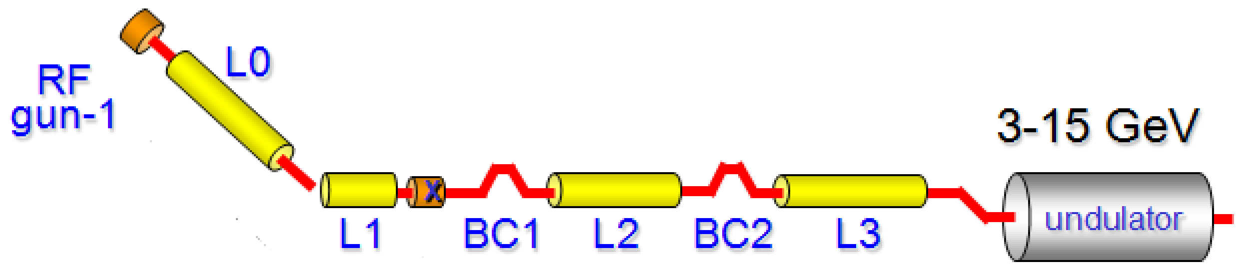
acceleration and compression through the linac keeping the low emittance

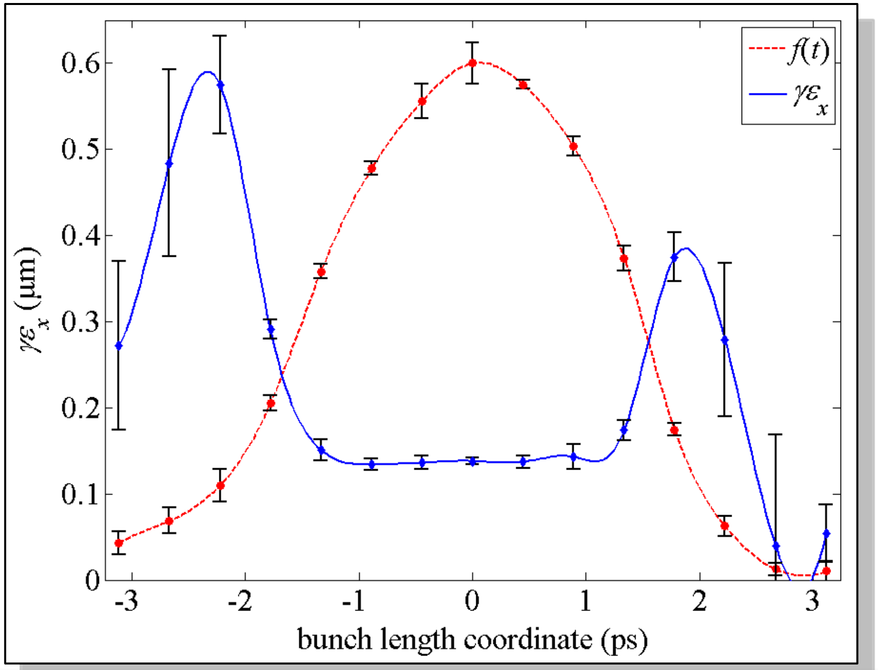
Optimisation validated by start-to-end simulation <u>Gun to FEL</u>



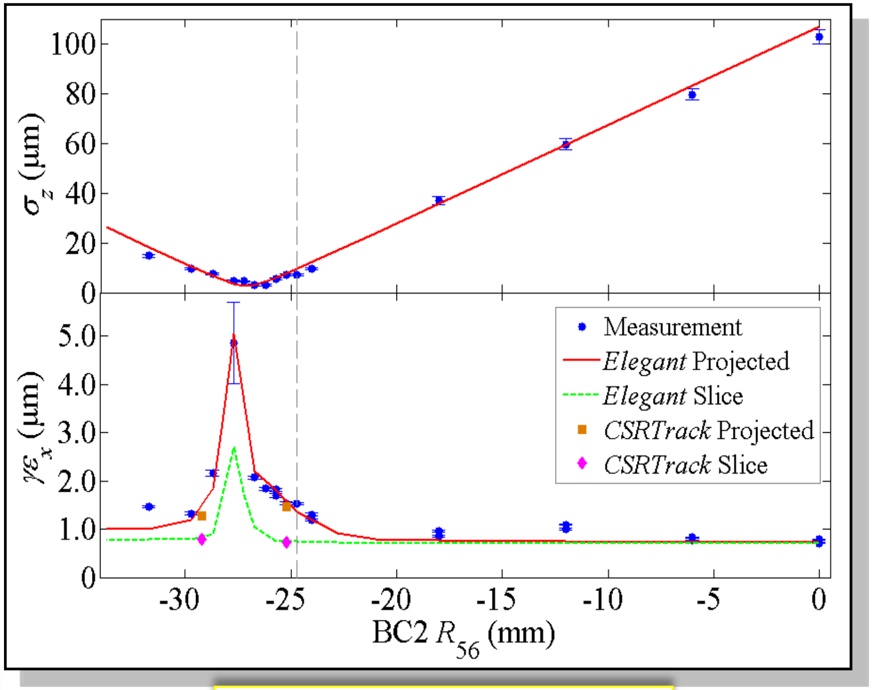
High brightness beam at LCLS

Managing collective effects with high brightness beams is a non trivial AP task





MEASURED SLICE EMITTANCE at 20 pC



CSR effects at BC2

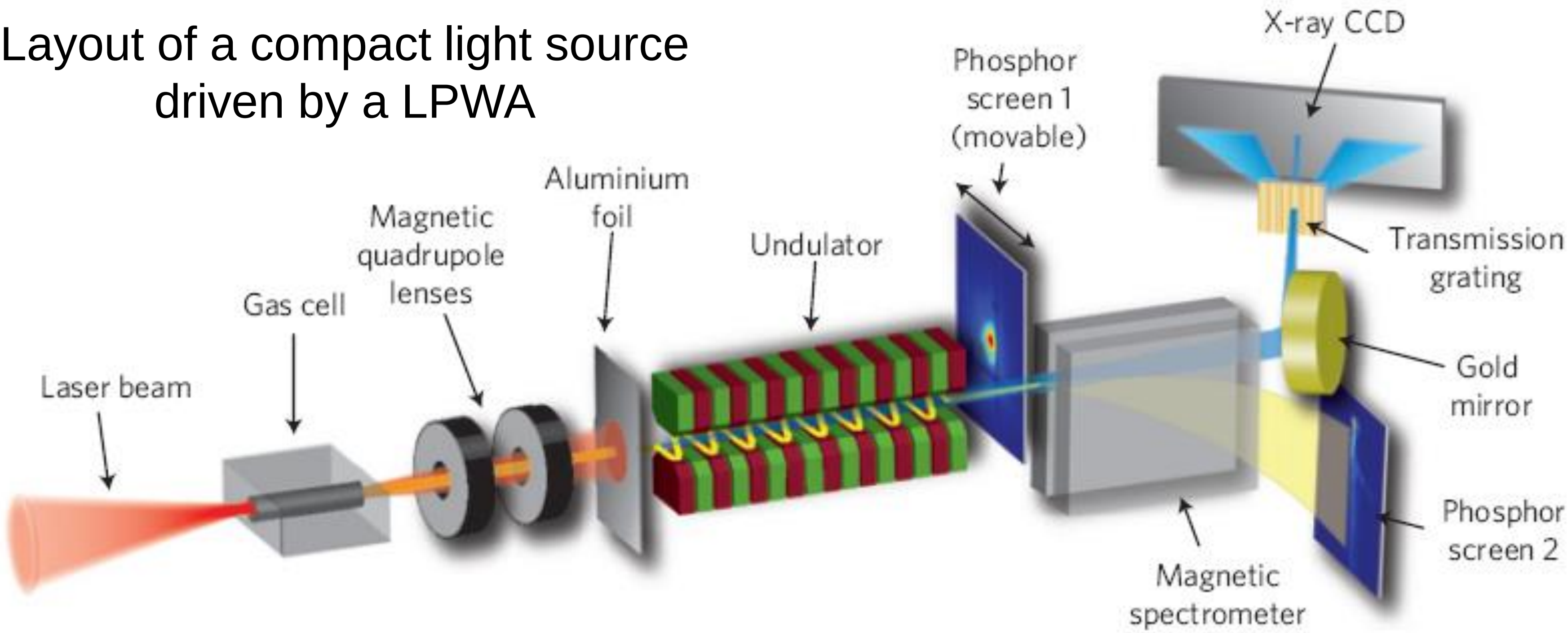
Beyond fourth generation light sources

The progress with laser plasma accelerators in the last years have open the possibility if using them for the generation for synchrotron radiation and even to drive a FELs

First observation of undulator radiation achieved in Soft X-ray

FEL type beam can be achieved with relatively modest improvements on what presently achieved and significant improvement on the stability of these beams

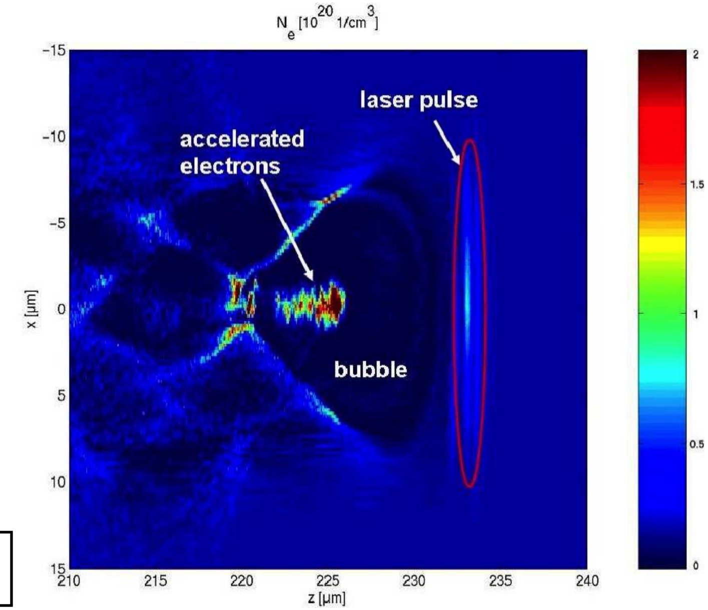
Layout of a compact light source driven by a LPWA



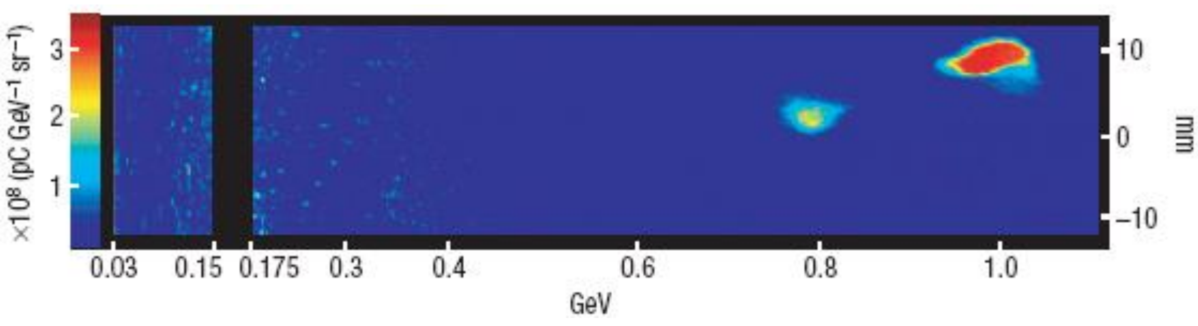
LBNL-Oxford experiment (2006)

Laser plasma wakefield accelerators demonstrated the possibility of generating GeV beam with promising electron beam qualities

Very large peak current makes up for poor energy spread in a possible FEL application



W. P. Leemans et al. *Nature Physics* **2** 696 (2006)



E = 1.0 +/-0.06 GeV
ΔE = 2.5% r.m.s
$\Delta\theta$ = 1.6 mrad r.m.s.
Q = 30 pC charge

Capillary: 310 µm
Laser: 40 TW
Density: 4.3 ×10^{18} cm^{-3}

Density 4.3 10^{18} cm^{-3}
Laser Power > 38 TW (73 fs) to 18 TW (40 fs)

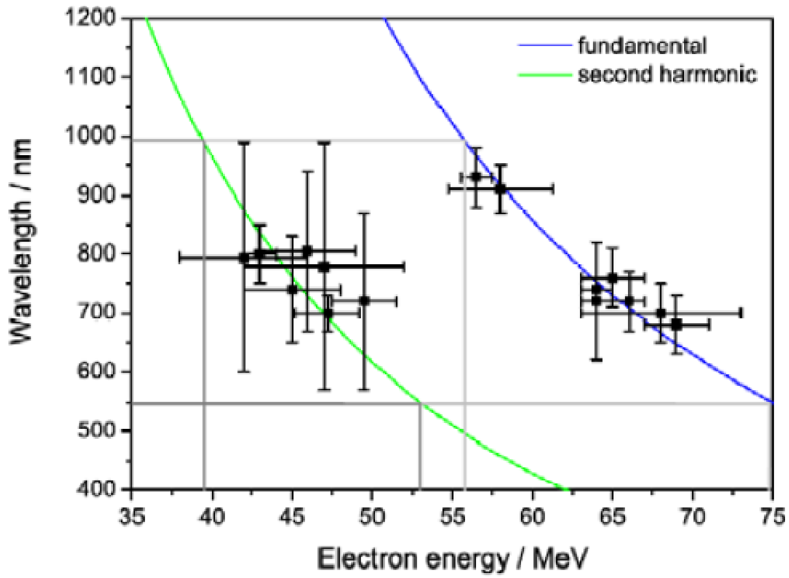
Undulator radiation from LPWA

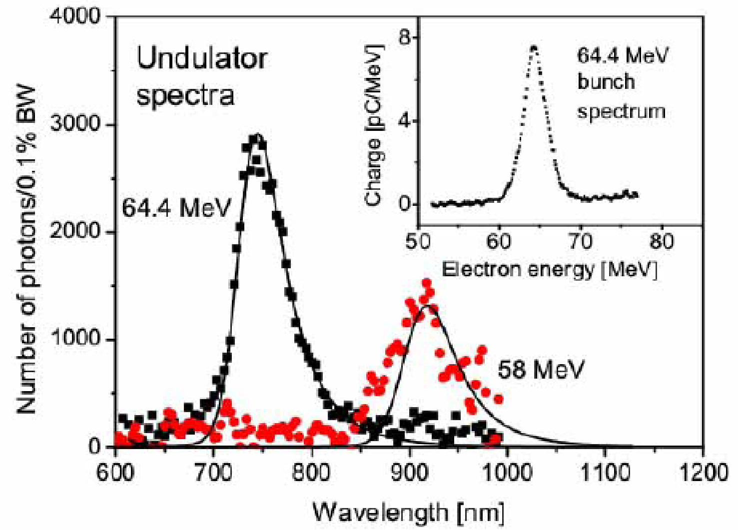
First combination of a laser-plasma wakefield accelerator, producing 55–75MeV electron bunches, with an undulator to generate visible synchrotron radiation

- Jena / Strathclyde / Stellenbosch experiment
- 55-70 MeV electrons
- VIS/IR synchrotron radiation

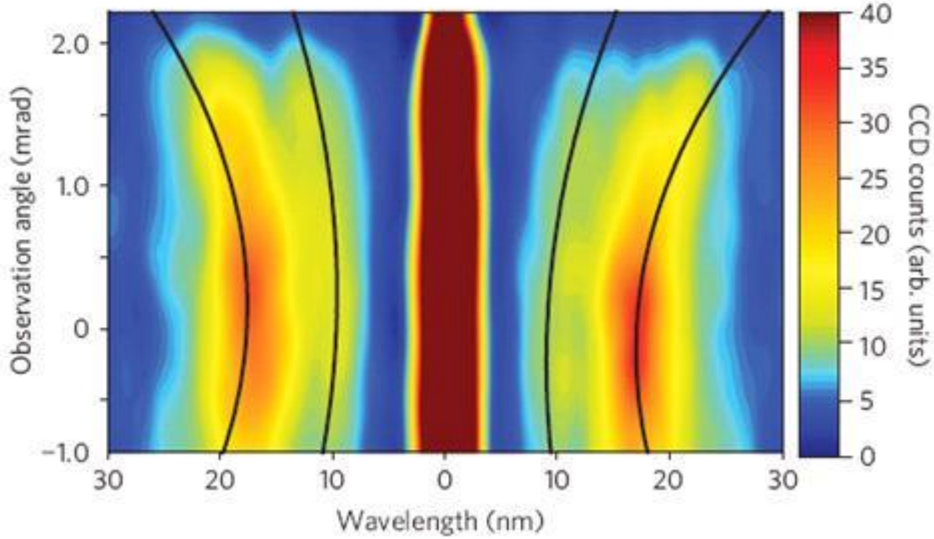
Schlenvoigt et al., Nature Phys. **4**, 130 (2008)

Gallacher et al., Phys. Plasmas **16**, 093102 (2009)

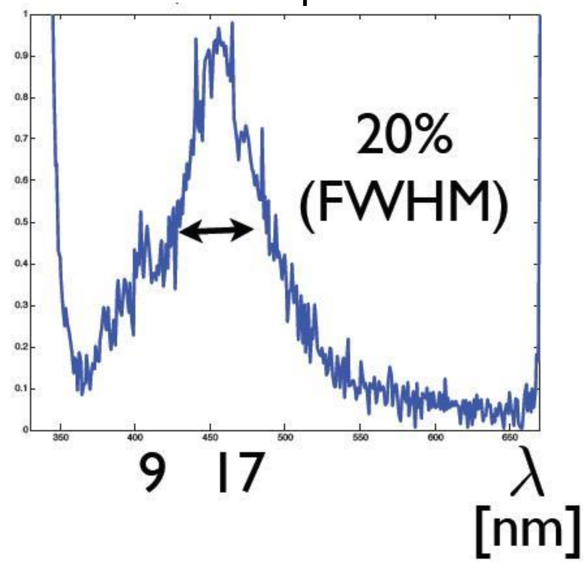




Undulator radiation Soft Xrays
MPQ experiment

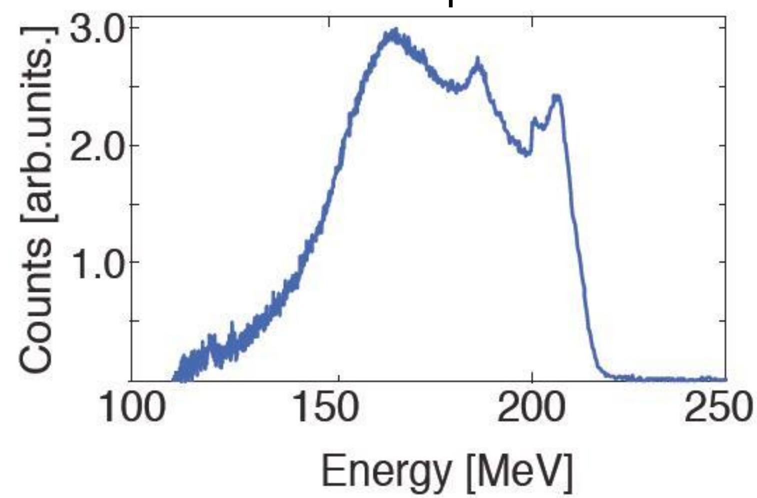


radiation spectrum



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

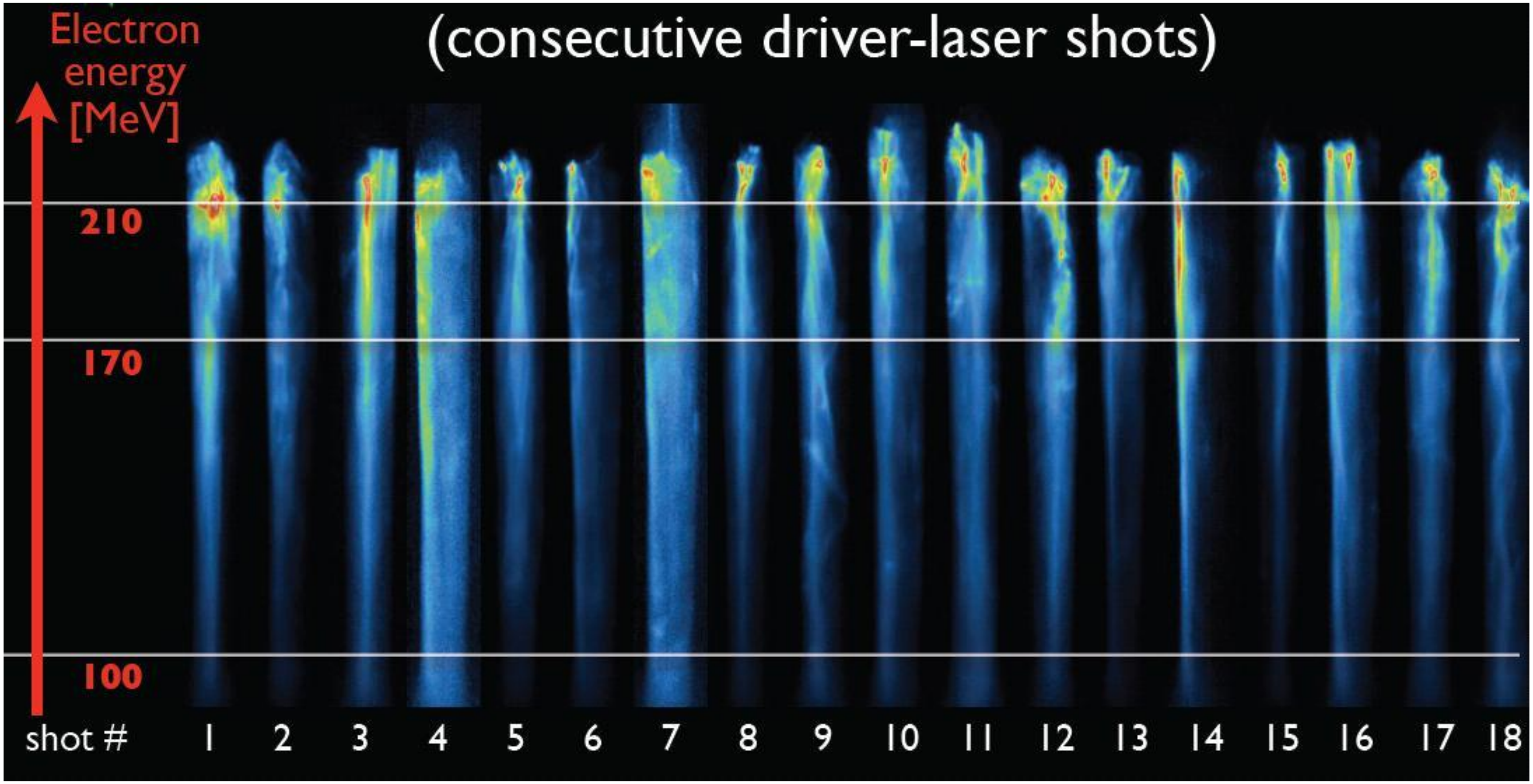
Electron spectrum



Spontaneous undulator radiation and off-axis dependence

M. Fuchs et al, Nature Physics (2009)

Undulator radiation Soft Xrays – MPQ experiment



Stability of the electron beam quality is crucial for a successful FEL operation

Conclusions

Third generation (storage rings) and FEL have complementary properties which make them both valuable tools.

SR are stable, serve many beamlines, approaching full transverse coherence with diffraction limited rings

FEL have high brightness, short pulses, full transverse cohehrence but can serve a few beamlines at a time and very expensive.

New solutions are required to build more economic and compact radiation sources (table-top). Laser plasma accelerators are an interesting candidates, but they still require improvement in their beam quality – notably the nenergy spread from the actual few % to few 0.01 %