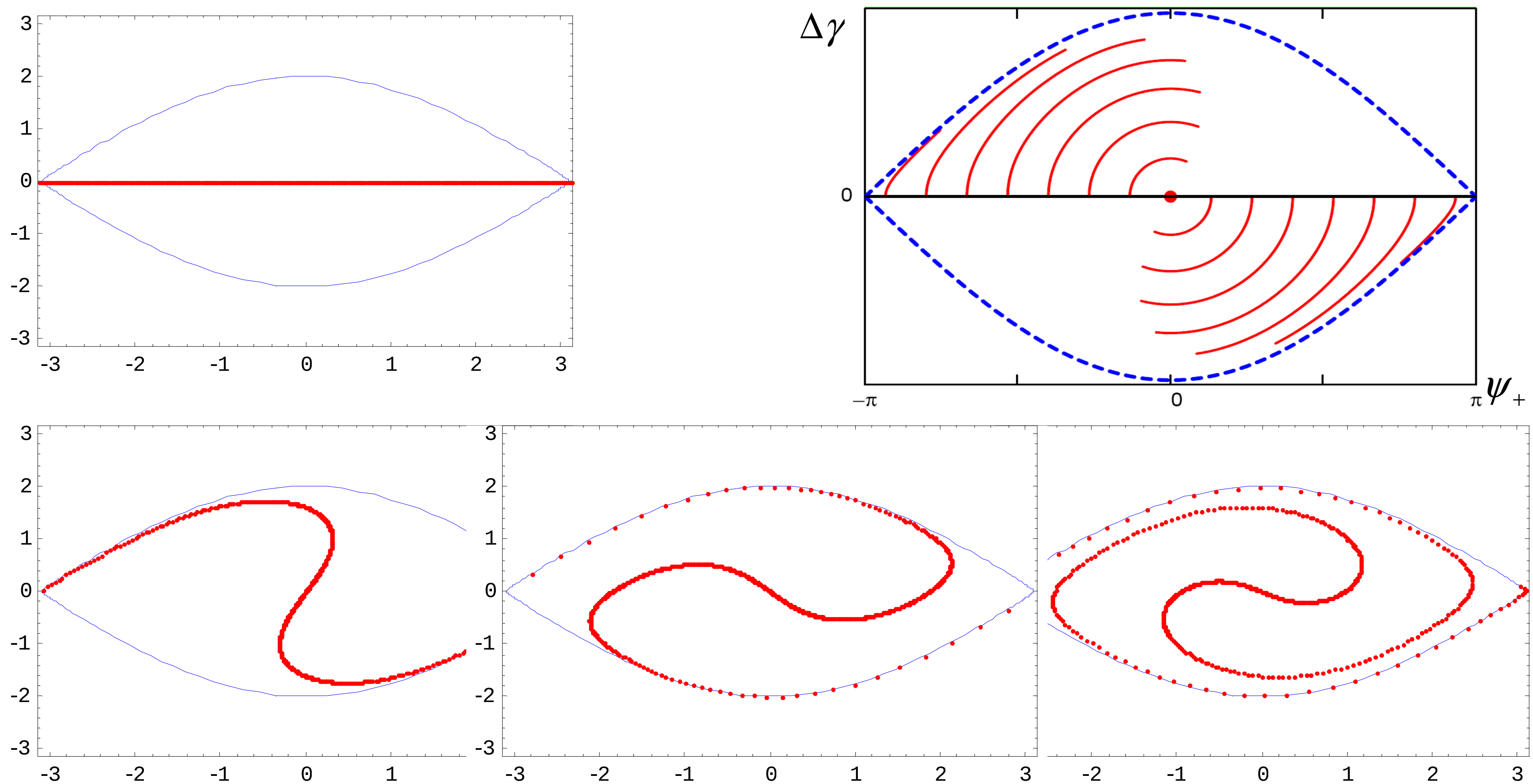
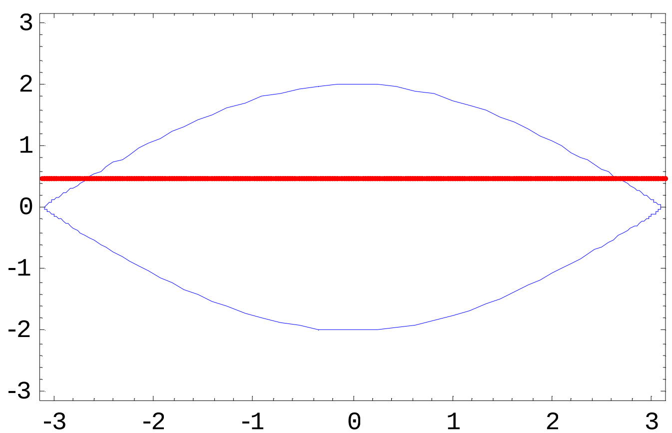
Energy Loss during Phase Space Motion

CHESS & LEPP

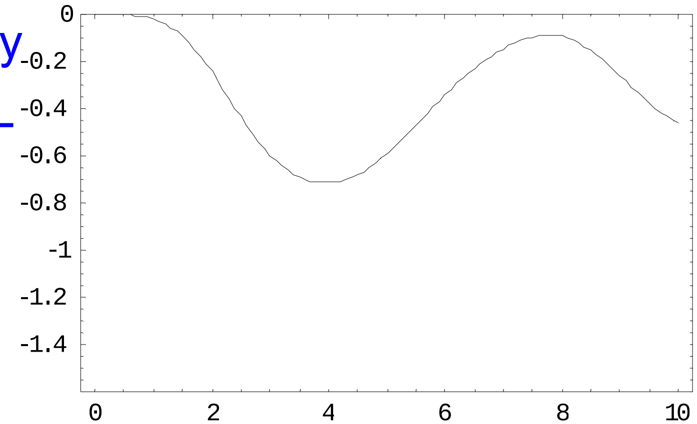


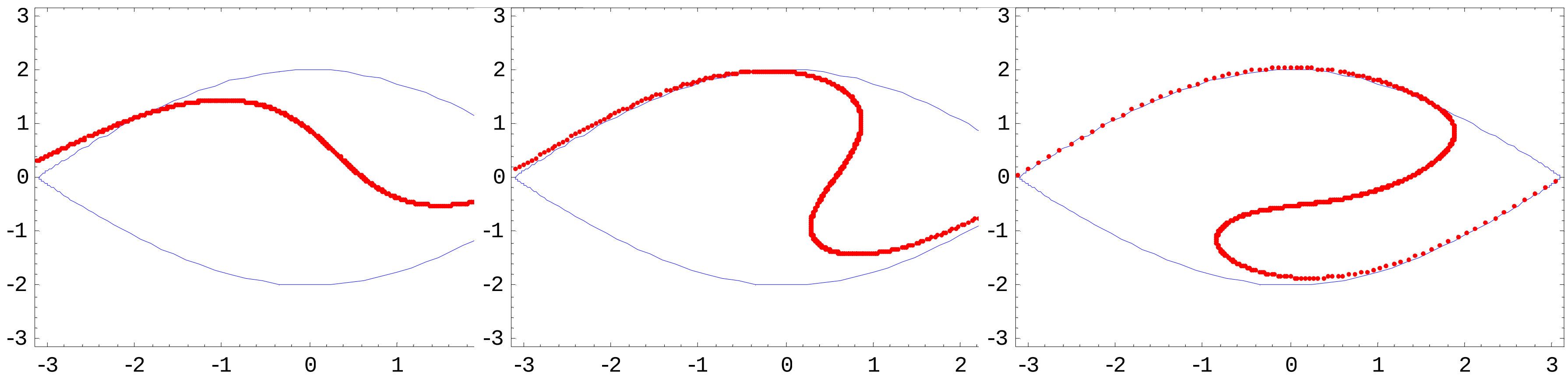
For a mono-energetic beam with $\Delta\gamma$=0, no net energy loss and beam filaments within the phase space separatrix.

Energy Loss during Phase Space Motion



Average energy loss along FEL





For a mono-energetic beam with $\Delta\gamma>0$, net energy loss and beam filaments within the phase space separatrix.

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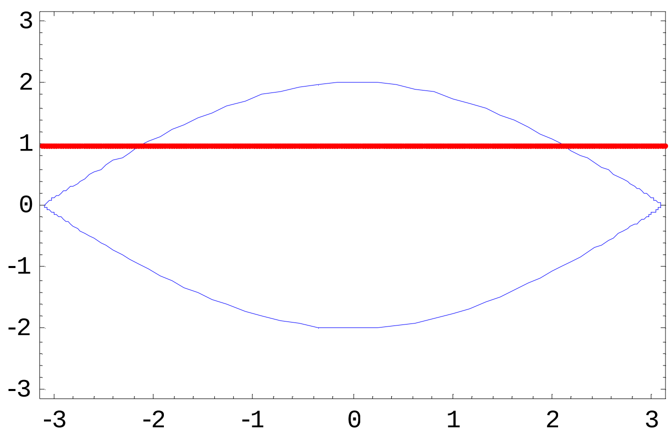
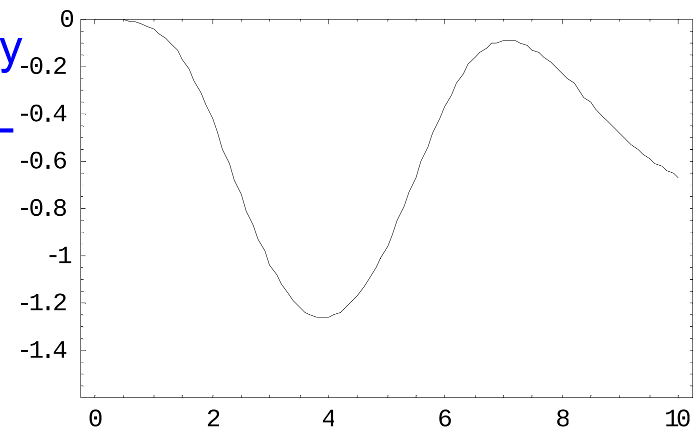
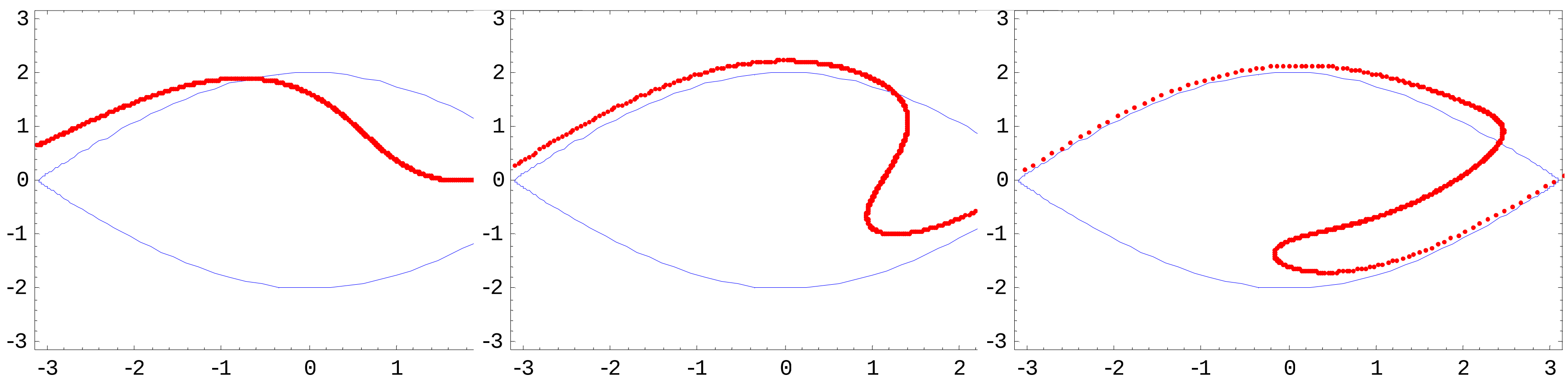


Average energy loss along FEL





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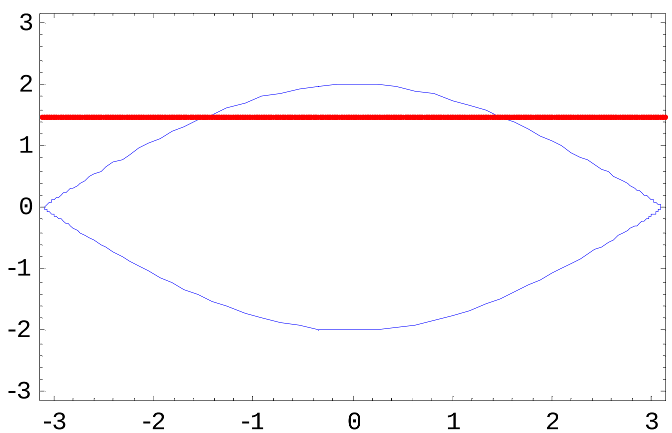
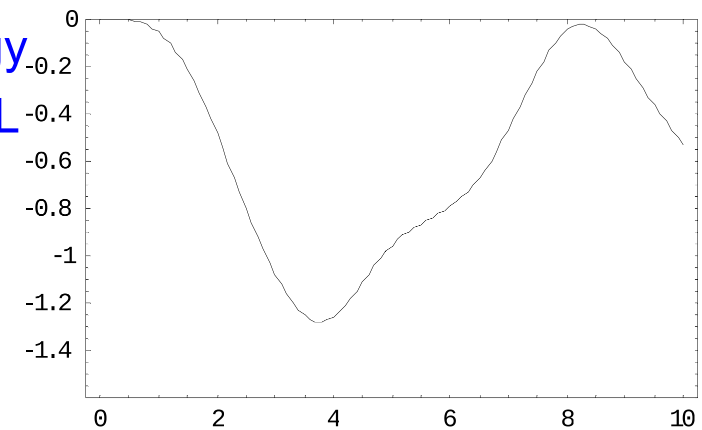
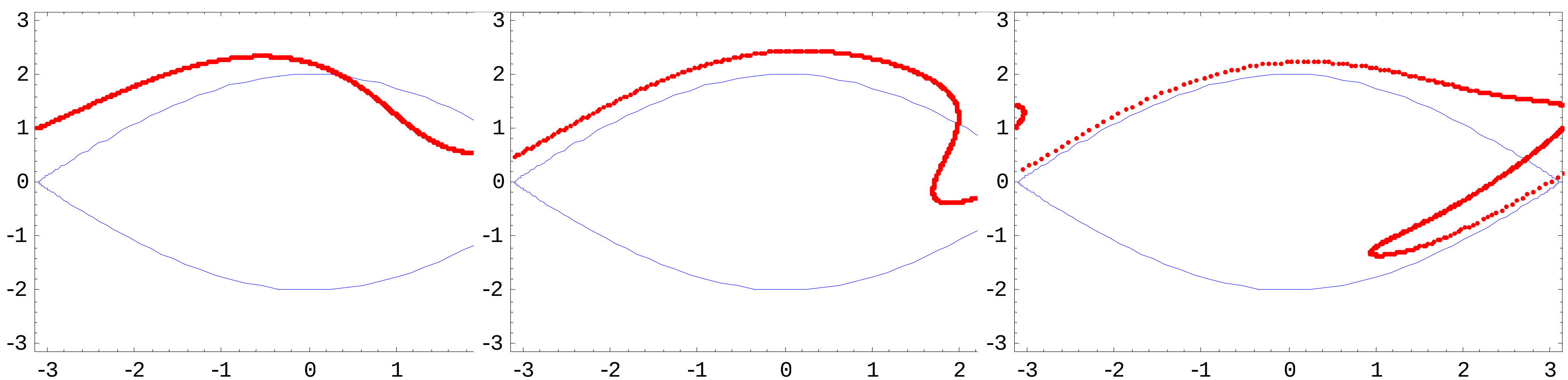
Energy Loss during Phase Space Motion



Average energy loss along FEL





For a mono-energetic beam with $\Delta\gamma>0$, net energy loss and beam filaments within the phase space separatrix.

Change in Average Energy

Wave number for small amplitudes: $\Omega = \frac{k_u}{\gamma}\sqrt{K_L K}$

$$\frac{d}{dz}\psi_+ = \frac{2k_u}{\gamma}\Delta\gamma + O^5(\tfrac{1}{\gamma})\,, \quad \frac{d}{dz}\Delta\gamma = -\frac{K_L k_u K}{2\gamma}\sin\psi_+ + O^3(\tfrac{1}{\gamma})$$

$$\frac{d^2}{dz^2}\Delta\gamma = -\Omega^2\Delta\gamma\cos\psi_+ + O^3(\tfrac{1}{\gamma})$$

$$\frac{d^3}{dz^3}\Delta\gamma = \Omega^2(\frac{2k_u}{\gamma}\Delta\gamma^2\sin\psi_+ + \frac{K_L k_u K}{2\gamma}\sin\psi_+\cos\psi_+) + O^3(\tfrac{1}{\gamma})$$

$$\left\langle \frac{d^4}{dz^4}\Delta\gamma \right\rangle_{\psi_+} = -\Omega^4\Delta\gamma + O^3(\tfrac{1}{\gamma})$$

Energy initially changes very slowly, only with z^4.

How much energy can maximally be lost is determined by higher derivatives, i.e. by nonlinear terms in $\Delta\gamma$.

The saturation length of the FEL, i.e. when the maximal energy loss occurs, is also determined by nonlinear terms.

Gain of an FEL

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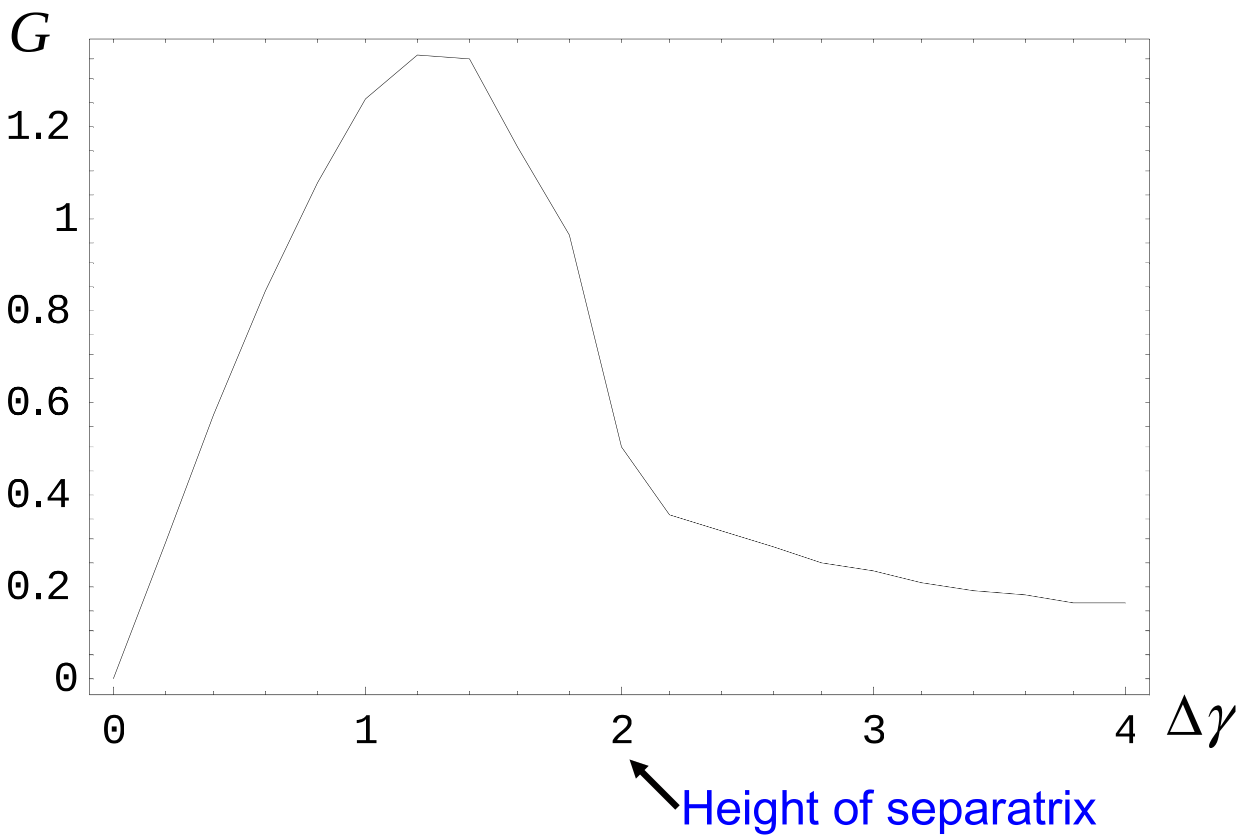

The Gain describes how much the field amplitude is amplified during one pass. It is a function of $\Delta\gamma$.

Microbunching

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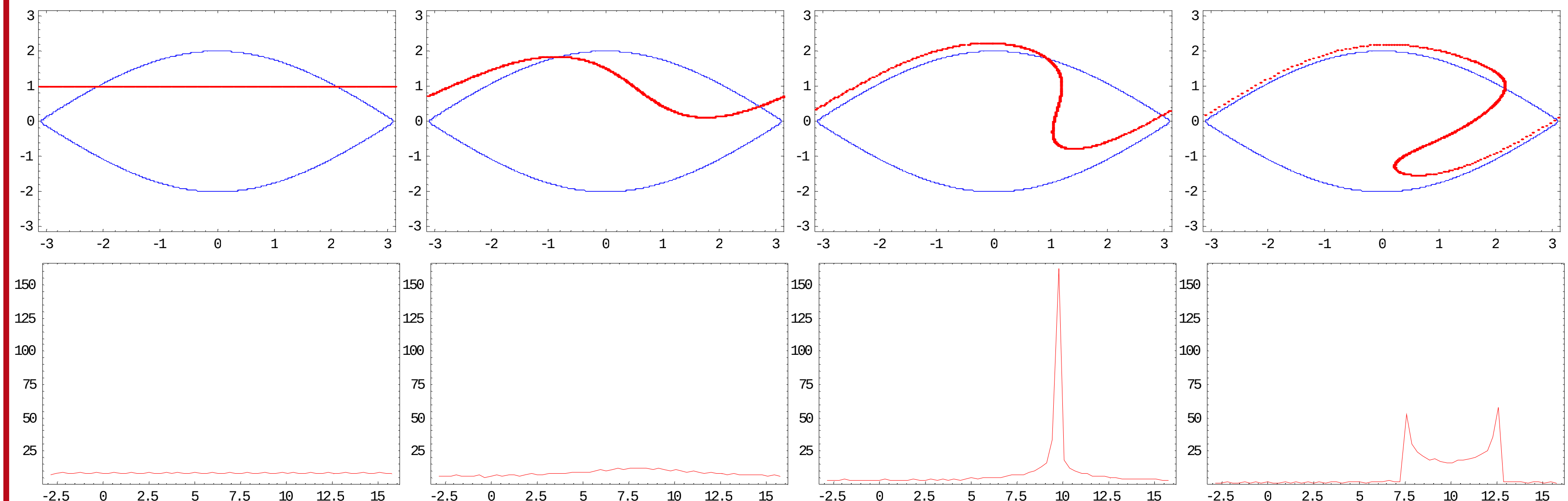
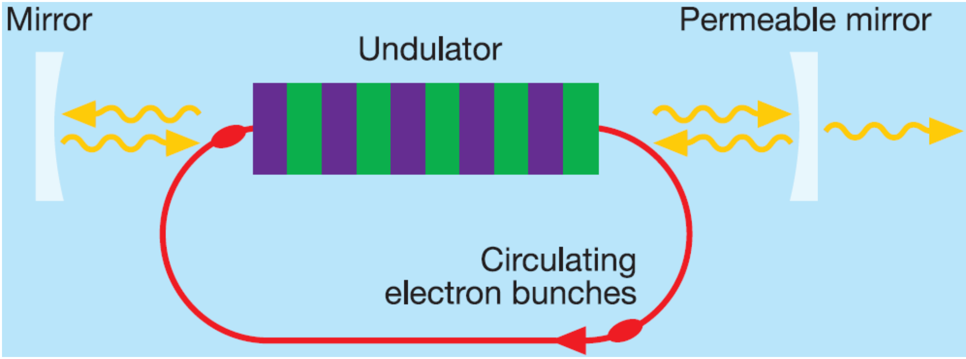
The FEL theory so far was for weak amplification. It has been considered how the field changes the electron distribution, but not how the electron distribution subsequently changes the field by radiation. This is the domain of strong amplification and needs a combined theory of radiation field and electron density.



1) Electron density becomes microbunched on the light wavelength! (Here by 20)
2) The microbunches radiate very strongly, as if they were one particle with N charges, radiating coherently N times the incoherent power !
3) The initial energy spread has to be very small to produce strong bunching.

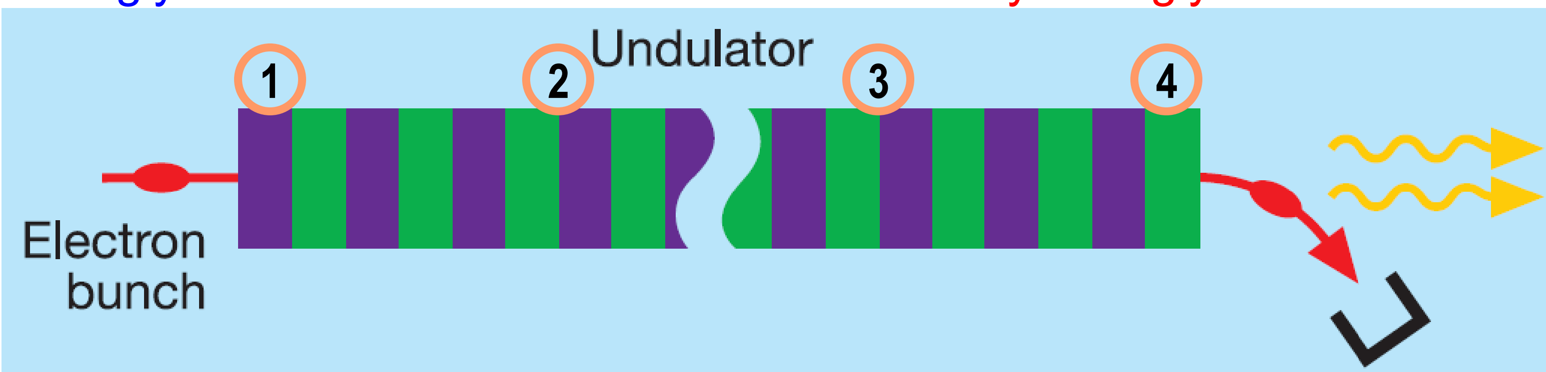
SASE FELs

Oscillator FEL: can be described well by the weak amplification theory.



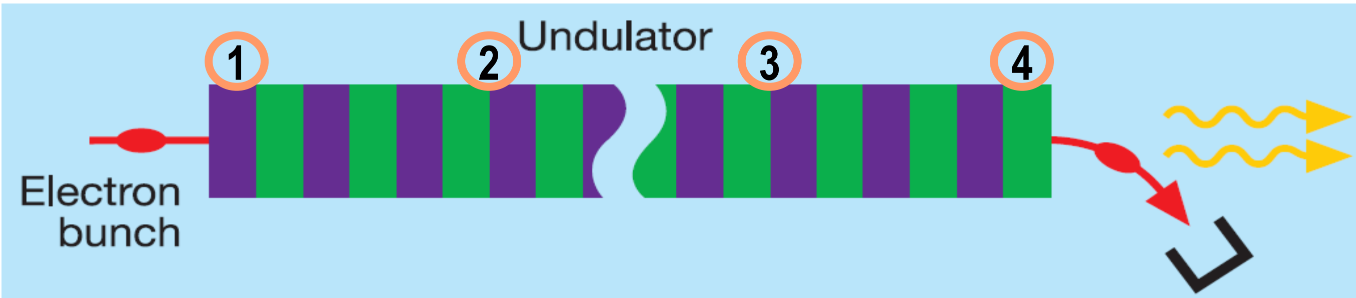
SASE FEL: Self Amplification of Spontaneous Emission

1) Incoherent undulator radiation from each electron is produced
2) This radiation leads to weak microbunching
3) Microbunches radiate strongly and produce strong microbunching
4) Strongly microbunched beam radiates extremely strongly !

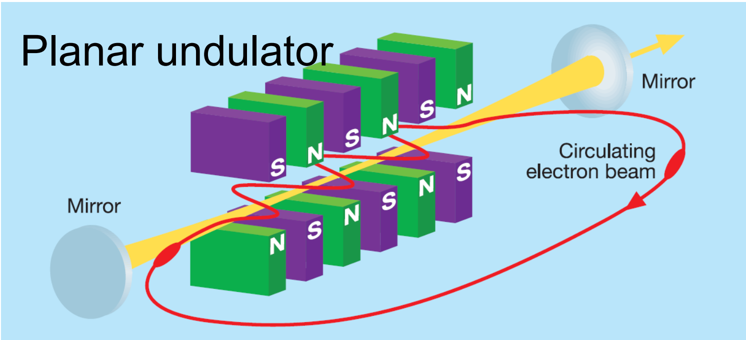


SASE FELs

1) Undulators have to be very long (order 100m).
2) Current within an electron bunch has to be very large to produce enough field for bunching from initial incoherent radiation.
3) The phase of the initial incoherent radiation from (1) is determined by a statistical fluctuation of the density in the electron bunch. (A DC current would not radiate !) The radiation process therefore start from noise.
4) The length has to be matched to saturation of the energy loss for maximum power.
5) The radiation power growth exponentially with length until saturation.
6) The start from noise lets the intensity fluctuate strongly, except at saturation.
7) The undulator has to have saturation length, where the power gets very large, destroying sample by the radiation from a single electron bunch.
8) SPRING8 / Japan, SLAC / USA, and DESY / Germany are building SASE FELs



Higher Harmonics in an FEL



Only the fundamental wavelength $\lambda_L = \lambda_u(\frac{1}{\beta_z} - 1)$ was discussed for an FEL.
The undulator radiate higher harmonics; can these
Also be amplified by an E&M wave?

Change of particle energy due to the E&M wave (stimulated emission):

$$\frac{dE}{dt} = -qc\frac{E_{L0}K}{2\gamma}(\sin\Psi_+ + \sin\Psi_-)\,,\quad \Psi_\pm = k_L[z-ct] + \phi_0 \pm k_u z$$

The energy transfer is large when $\frac{d}{dt}\Psi_+ = 0$ or $\frac{d}{dt}\Psi_- = 0 \quad \Rightarrow \quad \lambda_L = \lambda_u(\frac{1}{\beta_z} - 1)$

But $z(t) = \bar{\beta}_z ct + \left(\frac{K}{2\gamma}\right)^2 \frac{1}{2k_u}\sin(2k_u\bar{\beta}_z ct) + O^4(\frac{1}{\gamma})$

$$\frac{dE}{dt} = -qc\frac{E_{L0}K}{2\gamma}\{\sin[\Psi_{1+} + (k_L + k_u)\hat{z}\sin(2k_u\bar{\beta}_z ct)] + \sin\Psi_-\}$$

$$= -qc\frac{E_{L0}K}{2\gamma}\{\sin[\Psi_{1+}]\cos[(k_L + k_u)\hat{z}\sin(2k_u\bar{\beta}_z ct)] + \cos[\Psi_{1+}]\sin[\ldots] + \sin\Psi_-\}$$

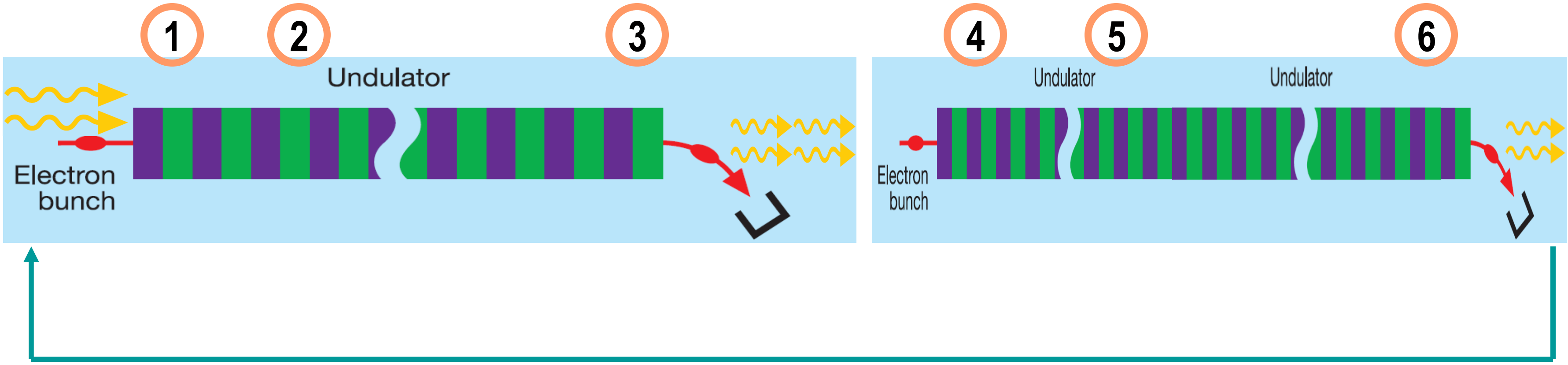
$$= -qc\frac{E_{L0}K}{2\gamma}\{\sum_n A e^{\pm i\Psi_{1+}} e^{in2k_u\bar{\beta}_z ct} + \sum_n A e^{\pm i\Psi_{1-}} e^{in2k_u\bar{\beta}_z ct}\}$$

Energy transfer can also be
Large when one phase is constant: $k_L c(\bar{\beta}_z - 1) \pm k_u\bar{\beta}_z(1+2n) = 0 \Rightarrow \lambda_L = \frac{1}{n_{odd}}\lambda_u(\frac{1}{\bar{\beta}_z} - 1)$

High Gain Harmonic Generation (HGHG)

CHESS & LEPP

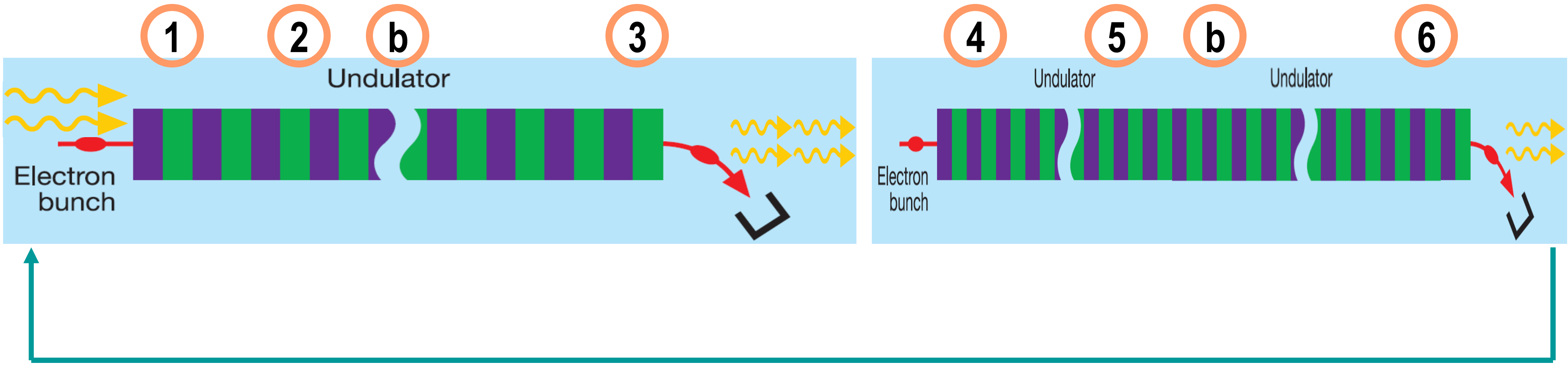
HGHG FELs avoid starting a SASE FEL from noise by seeding with a laser beam.



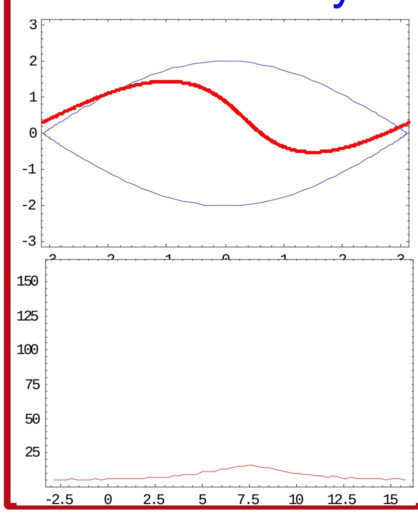
1) A beam from a quantum laser, often frequency multiplied by nonlinear media is send into an undulator matched to the fundamental frequency of the e-beam.
2) Bunching of the e-beam in phase with the laser
3) Strong radiation of the bunches, including in higher harmonics, e.g. 3
4) This radiation is sent into an undulator with the 3rd harmonic as its fundamental
5) Bunching
6) Radiating

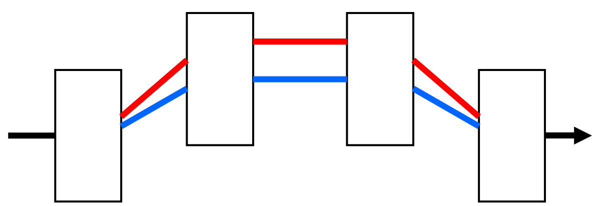
HGHG Modulator and Radiator

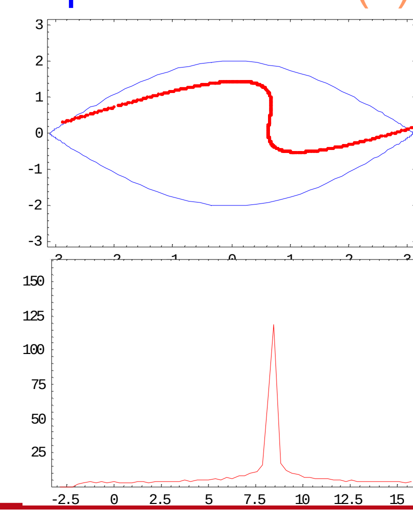
HGHG FELs avoid starting a SASE FEL from noise by seeding with a laser beam.



Note: In real projects, the microbunching would require too long undulators. Each undulator is therefore split in 2, one modulating the energy distribution (2), followed by a buncher section (b), the bunches then radiate, esp. harmonics (3).







Buncher: A chicane of bending magnets through which higher energetic particles can pass faster.

HGHG FELs

CHESS & LEPP

1) HGHG FELs have undulators with a total length significantly less than SASE FELs
2) Very small energy spread is needed.
3) So far only one stage of Modulator and Radiator has been tested.
4) BESSY / Germany will test a second stage.
5) Several Labs are proposing HGHG FELs for the 1nm soft x-ray regime with an approximately 2GeV e-beam with approximately 4 stages of HGHG, e.g. LBNL / USA, Madison / USA, BESSY / Germany, INFN / Italy, possibly STFC / UK.