Case Study 2 Design a normal conducting X-ray FEL at 1 Angstrom		
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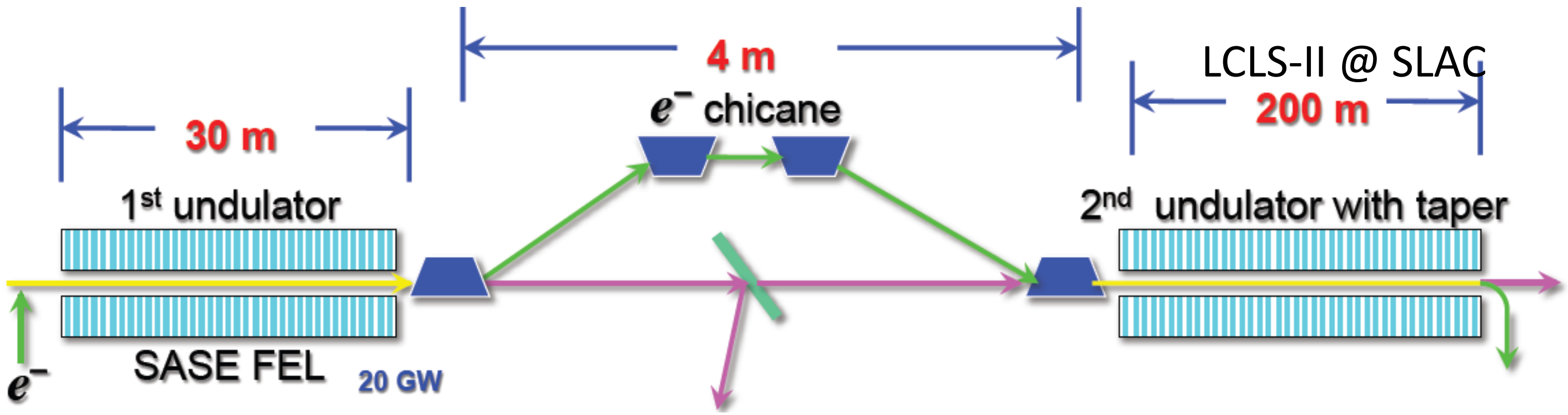
Case 2 – High Peak Power X-Ray FEL

- Goal: ***Design an FEL, operating at 1 Angstrom, with a saturation power of more than 20 GW with a possible enhancement by tapering to up to 1 TW.***

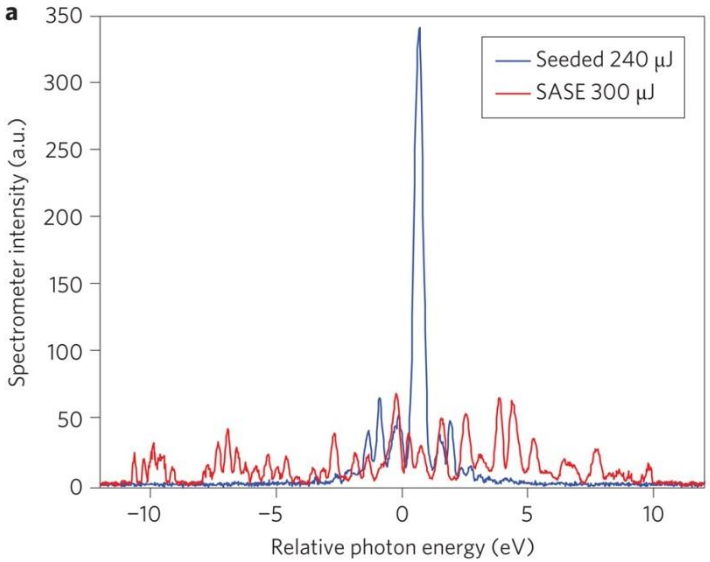
- Background: The holy grail of FEL application is the single molecule imaging by coherent diffraction. Large angle scattering of photons have a low probability and therefore must be compensated by a high photon flux. They are needed to allow for the determination of the orientation of the molecule, which changes from shot to shot of proteins in liquid solutions. Also the FEL pulse has to be shorter than 10 fs, otherwise the molecule is damaged and a significant rearrangement of the atoms can occur

- Approach: Saturation power scales with the FEL parameter and the beam energy. It is beneficial to improve both quantities till other effects degrades the performance (e.g. quantum fluctuation). The remaining power can be extracted by tapering – keeping the bunching phase constant with respect to the radiation phase

Self-Seeding Scheme



The radiation produced in first undulator is used to seed the radiation



SASE Radiation Power(1D)

$$P_{sat} = \rho \cdot P_{beam}$$

1) $P_{beam} = I_b E_b$ ⇦ Beam Power

2) $\lambda_r = \frac{\lambda_u}{2\gamma^2}(1 + K^2/2)$ ⇦ Resonant Condition

3) $\rho = [\frac{1}{16}\frac{I_b}{I_A}\frac{K^2[JJ]^2}{\gamma^3 \sigma_x^2 k_u^2}]^{1/3}$ ⇦ Pierce Parameter

- Beam Power
- Undulator Period assuming K = 1.96
- Pierce Parameter -> Saturation Power

Pre-tapering conditions

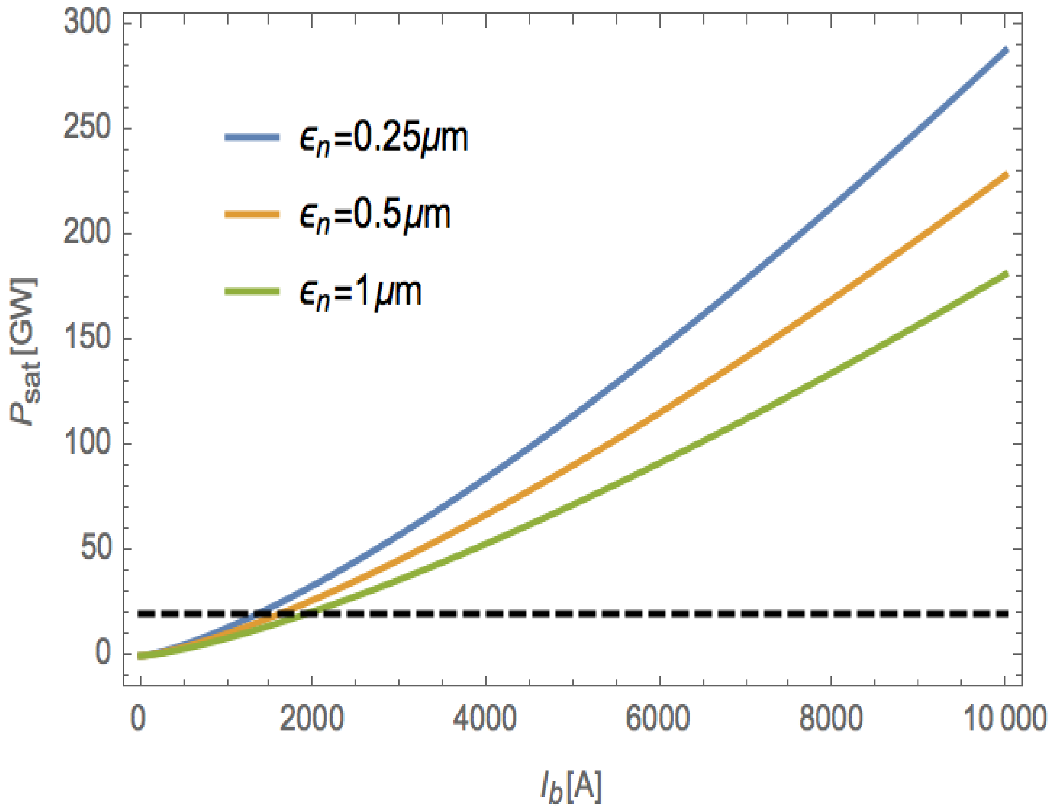
Required parameters

P_{sat} > 20 GW
λ_{rad} = 0.1 nm

Our Beam Parameters

E_{beam} = 19.5 GeV
I_{peak} = 10 kA
$\varepsilon_{nor.}$ = 0.5 μm

λ_u = 100 mm
P_{sat} = 195 GW



L_{sat}=100 m

Quantum fluctuations limit

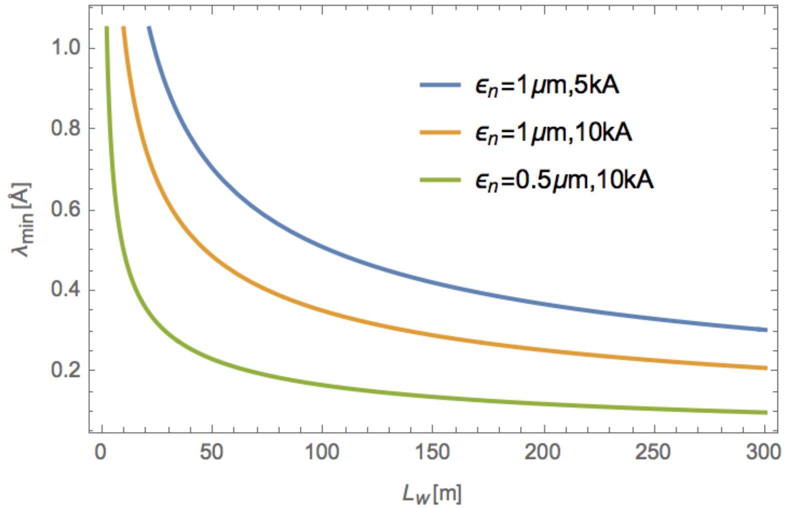
- Particles moving along undulators emit **coherent** and **uncoherent** radiation
- Energy losses are associated with these processes:

$$\mathrm{d}\mathscr{E}_0/\mathrm{d}z = 2r_e^2\gamma^2 H_w^2(z)/3,$$

$$\langle \mathrm{d}(\delta\mathscr{E})^2_{\mathrm{qf}}/\mathrm{d}z\rangle = 55e\hbar\gamma^4 r_e^2 H_w^3/24\sqrt{3}m_e c.$$

- Strong dependence on the energy (increasing for increasing energies)
- If the total energy spread > ρ the FEL process is drastically reduced or completely inhibited
- The minimum *„permitted“* wavelength is given by:

$$\lambda_{\min} \simeq 45\pi\,[\lambda\!\!\!^{-}_c r_e]^{1/5}\, L_w^{-7/15}\left[\varepsilon_n^2 \frac{I_A}{I}\right]^{8/15}$$



In the following we assume:

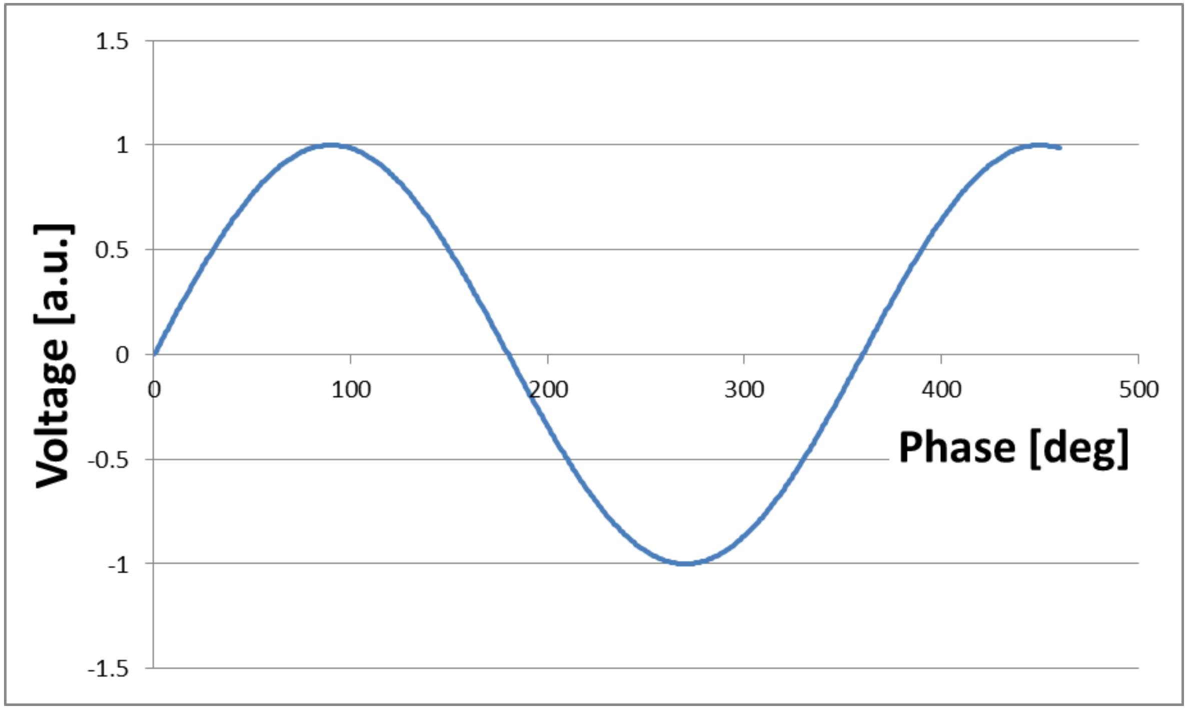
I (kA)	εn (m)
10	0.5e-6

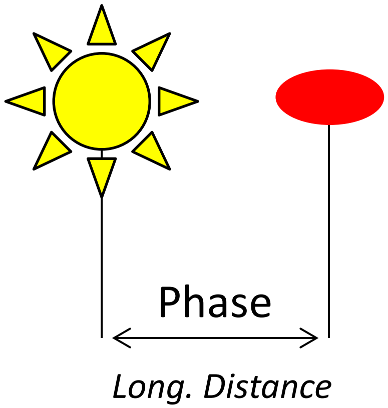
Reference: *Fundamental limitations of an X-ray FEL operation due to quantum fluctuations of undulator radiation*, J. Rossbach et al., NIM A **393** (1997) 152- 56

Tapering – Simple Picture

What happens in a cavity/Light?

<u>Ponderomotive Bucket = RF-Bucket</u>





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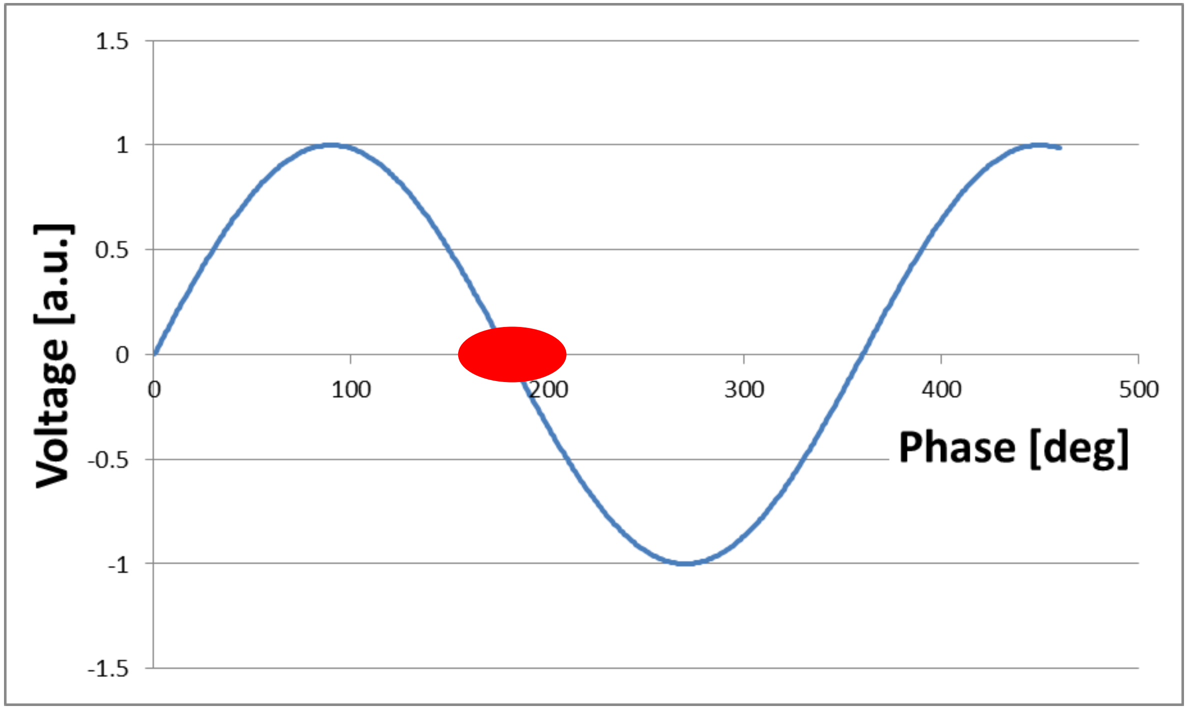

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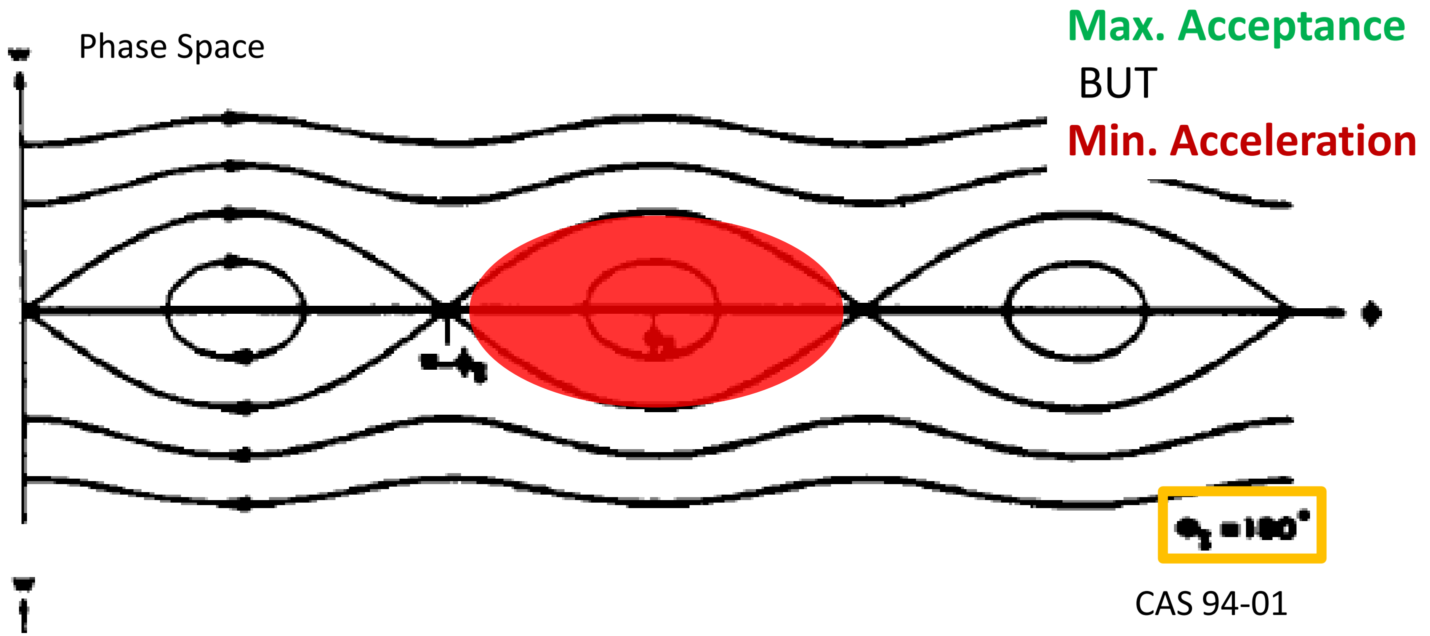

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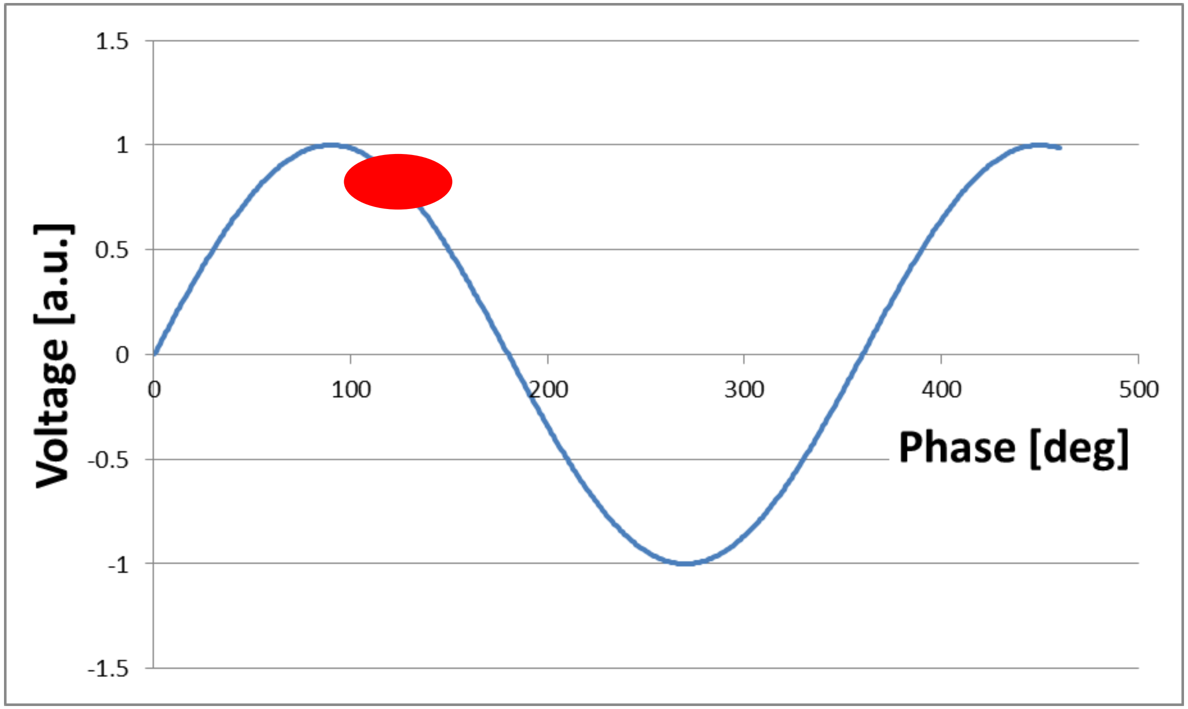

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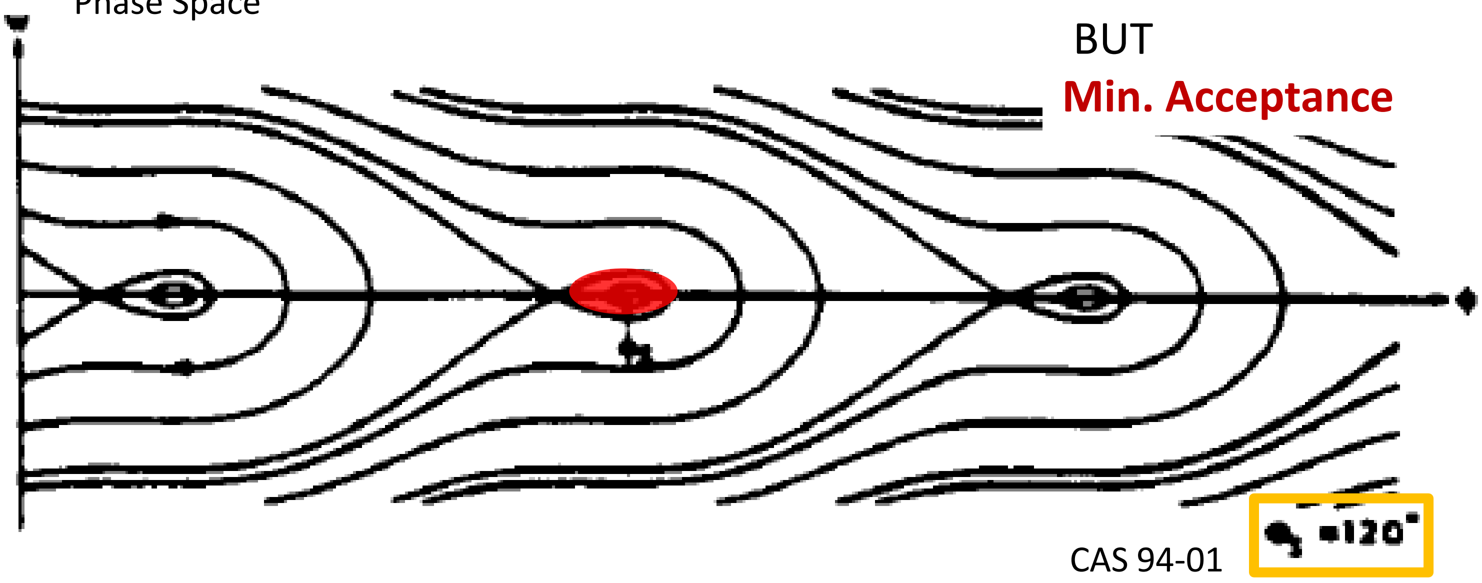


Max. Acceleration
BUT
Min. Acceptance

Tapering results

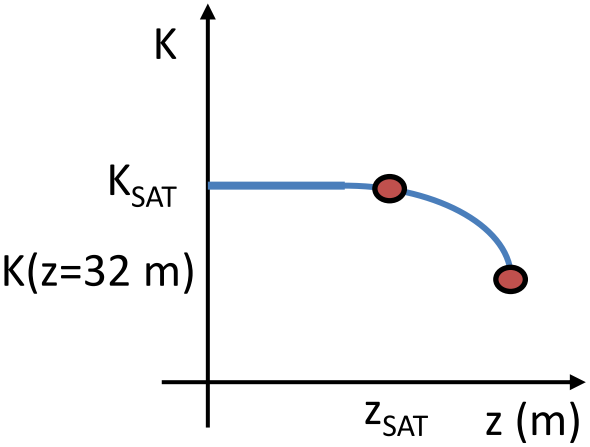
- Energy exchange between electrons and radiation described by:

$$\frac{d\gamma_R}{dz} = -\frac{e}{2m_e c^2}\frac{a_w(z) f_B(z) E_0(z)}{\gamma_R(z)}\sin[\psi_R(z)]$$

- Constant ponderomotive phase assumed (0.4 rad)§
- Bunching factor of 0.83

Rate (1/m)	Δ γ	Length (m)
4.9	158	32

From $K(z) = K_{SAT}(1 - bz^2)$ with the condition $K(z = 32\ m) = K_{\gamma+\Delta\gamma}(1 - b \cdot 32^2)$ the coefficient b is computed

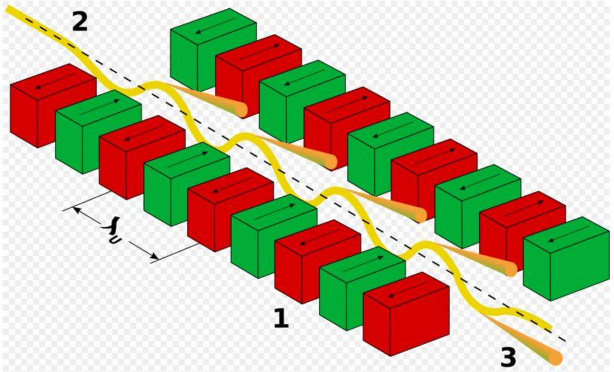


§ W. Fawley et al., „Tapered Undulator for SASE FELs“,2001

Summary parameters

A possible set of parameters to satisfy the request is summarized:

Beam energy (GeV)	19.5
Beam normalized emittance (m)	0.5e-6
Current (kA)	10
Undulator field (T)	0.2
Undulator period (m)	0.1
Undulators length (m)	100 + 32
K value	1.96
Radiation wavelength (nm)	0.1
Saturation power (GW)	230
Final power with tapering (TW)	1



Thank you

Superradiance

- Electrons radiate as N^2 (N: number of electrons)
- Can occur for prebunched and unbunched beam
- Based on „*opening*“ and „*closing*“ of bucket
- Kinetic energy is transfered to radiation field
- Requires small energy spread
- Beam quality and energy spread reduced during procedure

→ Superradiance limited by deterioration of energy spread

Radiation Basics

E_{kin}=19.5 GeV γ=38160

K=1.96 (Undulator – B_0=0.21T)

$$\lambda_r = \frac{\lambda_u}{2\gamma^2}(1 + K^2/2)$$

λ_u = 100 mm

$\rho = 8.9 \cdot 10^{-4}$

$P_{sat.}$ = 195 GW @ $\lambda_{res.}$= 0.1nm

Tapering – Simple Picture

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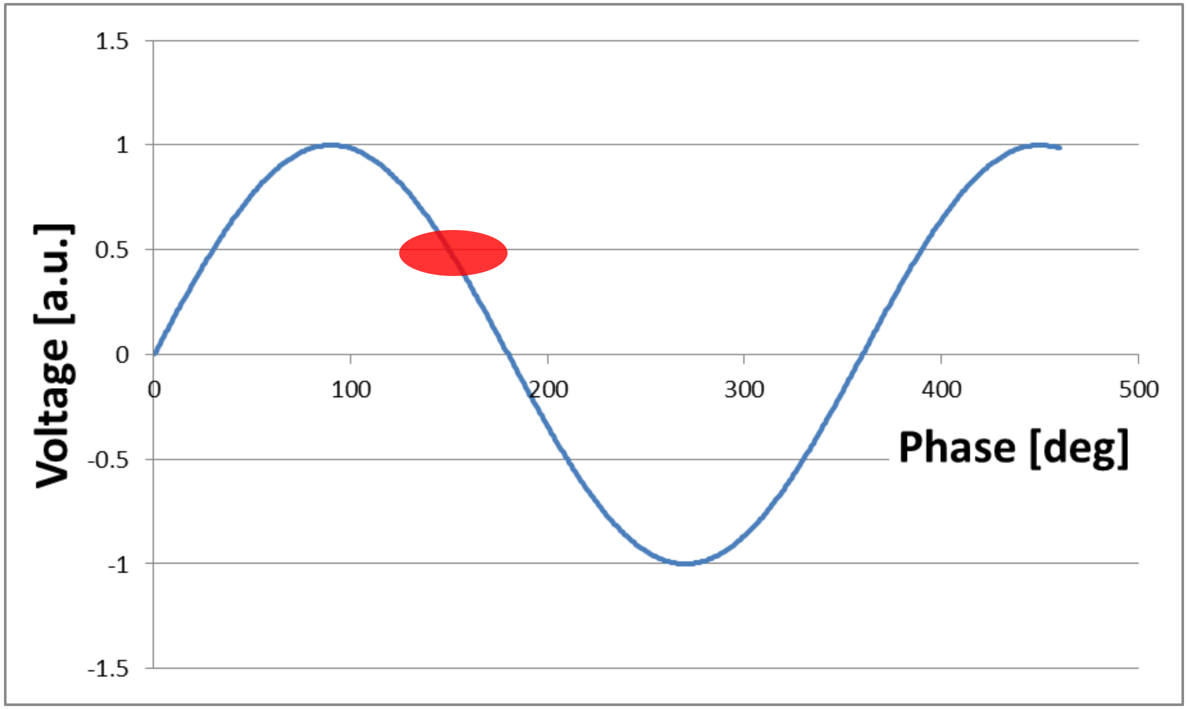
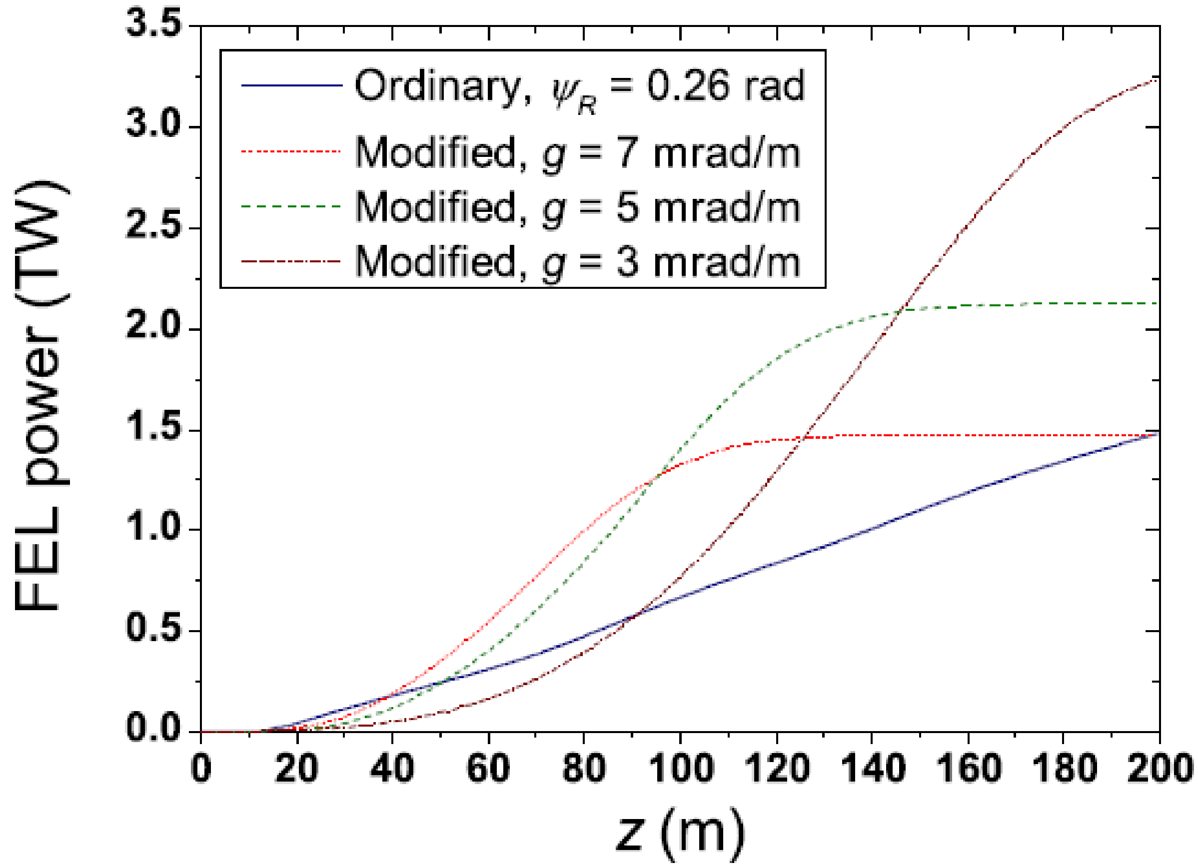


Maintaining Resonance Condition + Play with the Ponderomotive Phase

Ponderomotive Phase

Example: MAX IV FEL



Max IV FEL
Beam Parameters

E = 4 GeV
I = 4kA
ε_t = 0.2μm
λ_u = 20 mm
$\lambda_{res} = 0.4\ nm$

Optimising the Output

Beam Parameters

$$\rho = [\frac{1}{16}\frac{I_b}{I_A}\frac{K^2[JJ]^2}{\gamma^3\sigma_x^2 k_u^2}]^{1/3}$$

I_b … Beam Peak Current

σ_x^2 … Beam Size
-> transverse Emittance