Case 2 – High Peak Power X-Ray FEL

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.

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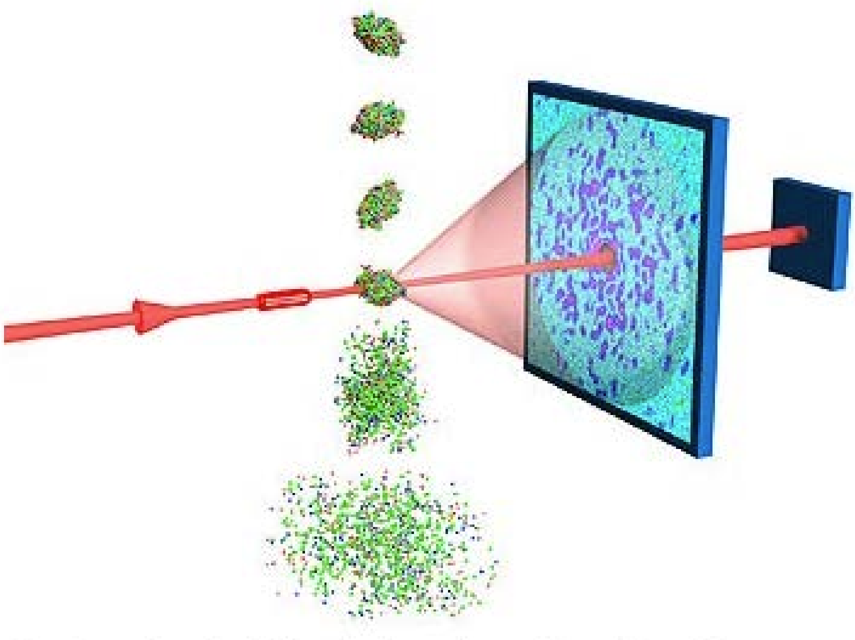
Motivation



The next technological level for macromolecular crystallography will be reached through XFELs:

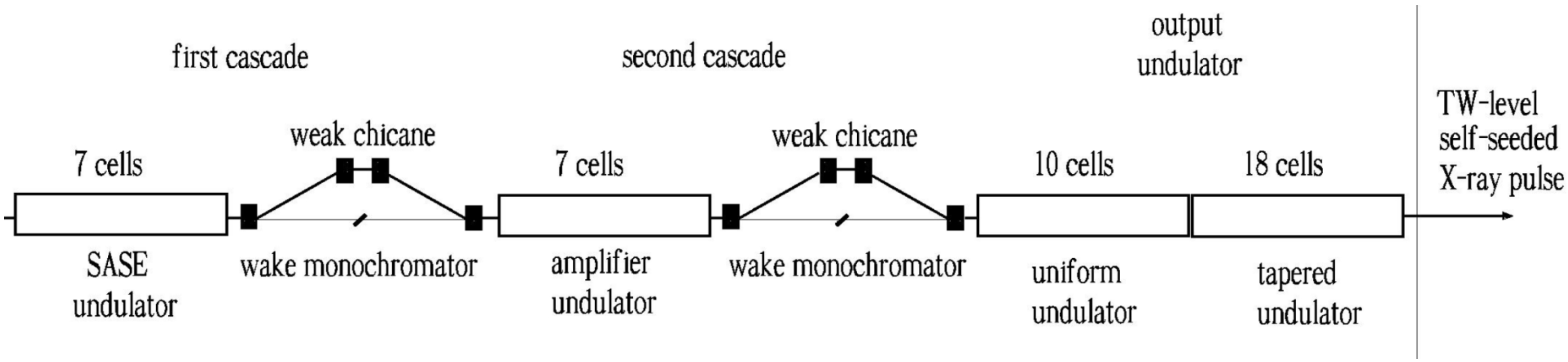
- No sample damage: **very short pulses (<10 fs).**

- Coping with nano-crystals and therefore with molecules hard to crystallize.

- Ultimately enabling single molecule diffraction:
  - Purification and crystallisation are bottlenecks. Some molecules do no crystallize.
  - Phase problem.
  - Requirement of **very high photons flux (>10^15 photon/s/mm^2)**

Machine Layout

1 Å ≙ 12.4 keV
20 GW → e.g. 20 uJ/10 fs
1 TW → e.g. 5 mJ/5 fs ➔ need self-seeding + tapered undulator



G. Geloni, V. Kocharyan, E. Saldin, arXiv:1007.2743v1

GW-level after first undulator
MW-level after monochromator
Tapered undulator: ~100 m

Machnie Parameters	
Electron Energy	20 GeV $\gamma \approx 39000$
Peak Current	5 kA
Bunch charge	25..50 pC (5..10 fs)
Energy Spread	1.3 MeV
Normalized Emittance	0.3 mm mrad

SASE Layout

- Undulator period: λ_u = 40 mm
- Undulator parameter: K = $\sqrt{\frac{2\lambda\gamma^2}{\lambda_u} - 1}$ = 2.57 (helical und.)
  - Gap: d = 11.4 mm
  - Magnetic field: B_{peak} = 1 T
- FEL parameter: $\rho_{1D} \approx 10^{-3}$ (parms)
- Gain length: $L_g \approx \lambda_u/(21.8*\rho_{1D}) \approx$ 1,76 m
- Saturation Length: $L_{sat} \approx$ 38.2 m
- Saturation power: P_{sat} = 107 GW

Tapering

- Compensating the energy loss after saturation is reached by adjusting the undulator strength
- E-field grows linearly and thus radiation power quadratically with z
- Therefore also γ decreases quadratically with z
- $K_{(z)} \approx K_0 \times [1-\alpha(z-z_0)^2]$ $\alpha > 0$: taper rate; z_0: taper start location
- More generalized: $K_{(z)} = K_0 \times [1-\alpha(z-z_0)^b]$ with $b > 1$ (Fawley et al., FEL11)

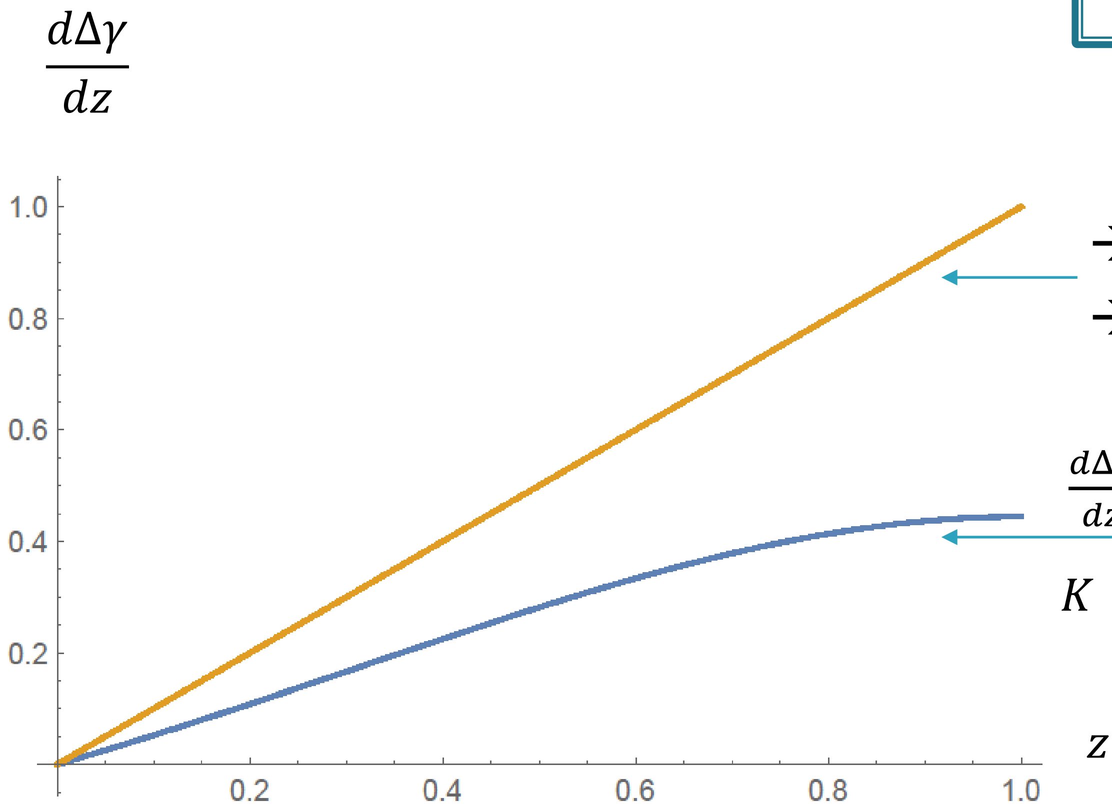
$$\frac{d\Delta\gamma}{dz} = \frac{K}{\gamma_0} E_z \sin(\phi)$$

$$E \sim P^2 \sim \Delta\gamma^2$$

$$\approx const. \sqrt{\Delta\gamma}$$

$$\rightarrow \Delta\gamma \sim z^2$$

$$\rightarrow \frac{d\Delta\gamma}{dz} \sim z$$

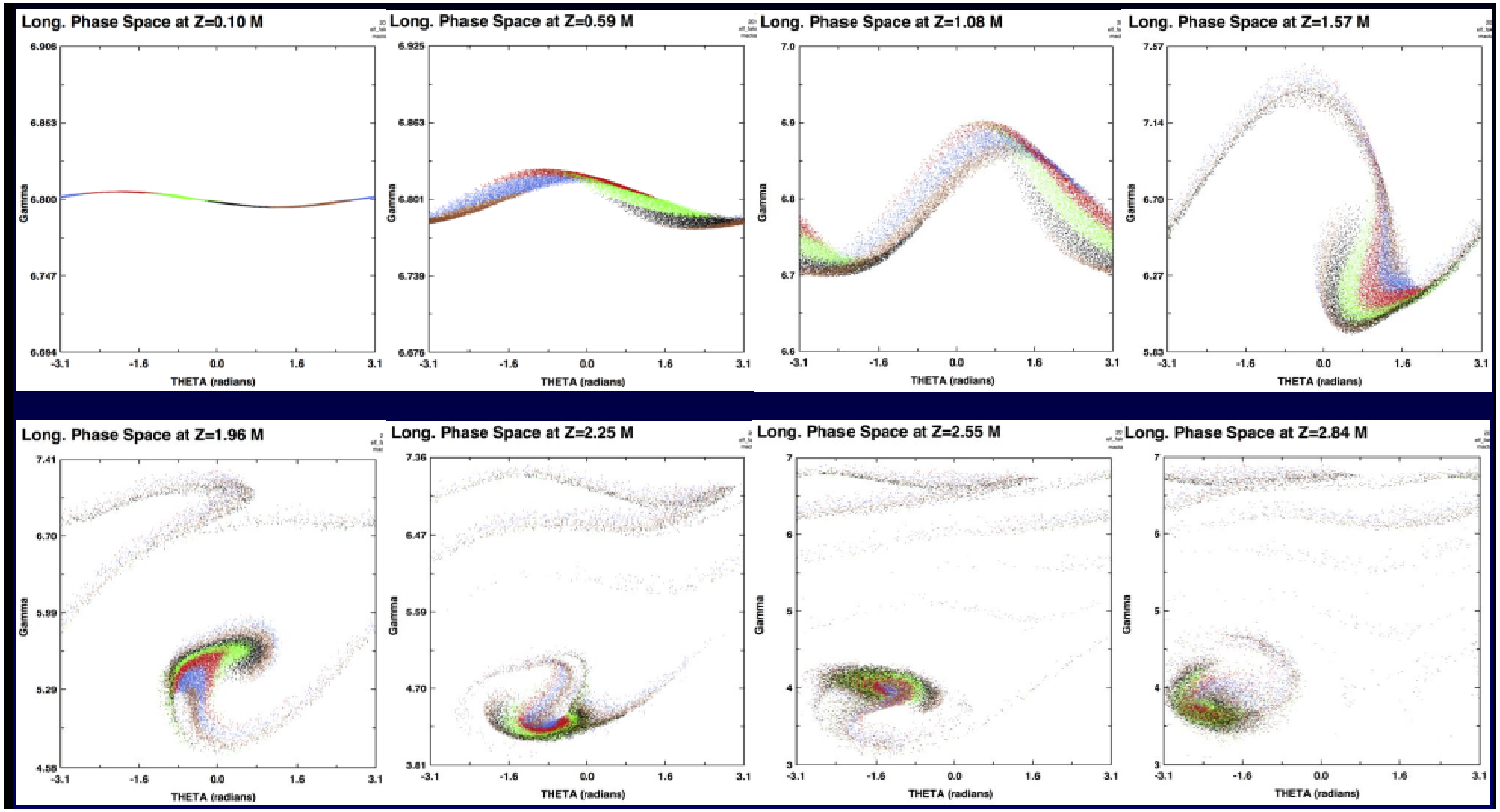


$$\frac{d\Delta\gamma}{dz} = \frac{d\Delta\gamma}{dz}(\mathrm{K(z)})$$

$$K = K(z) = K_0(1 - a(z - z_0)^2)$$

Limitation: Transverse beamsize is growing

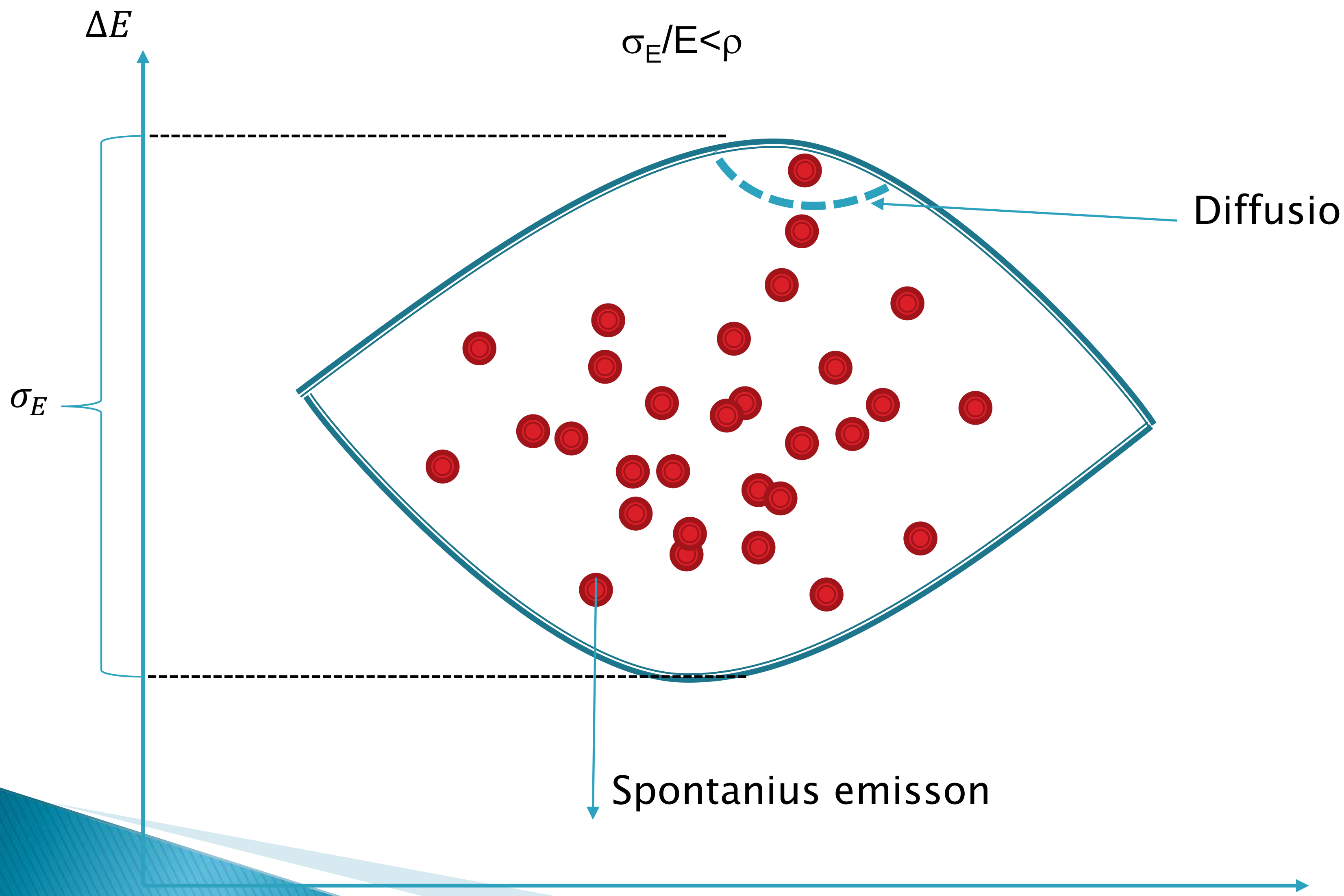
Longitudinal phasespace



→Wait until bunch is compressed

http://accelconf.web.cern.ch/AccelConf/FEL2015/talks/mob01_talk.pdf

Quantum Fluctuation Limit



Quantum Fluctuation Limit

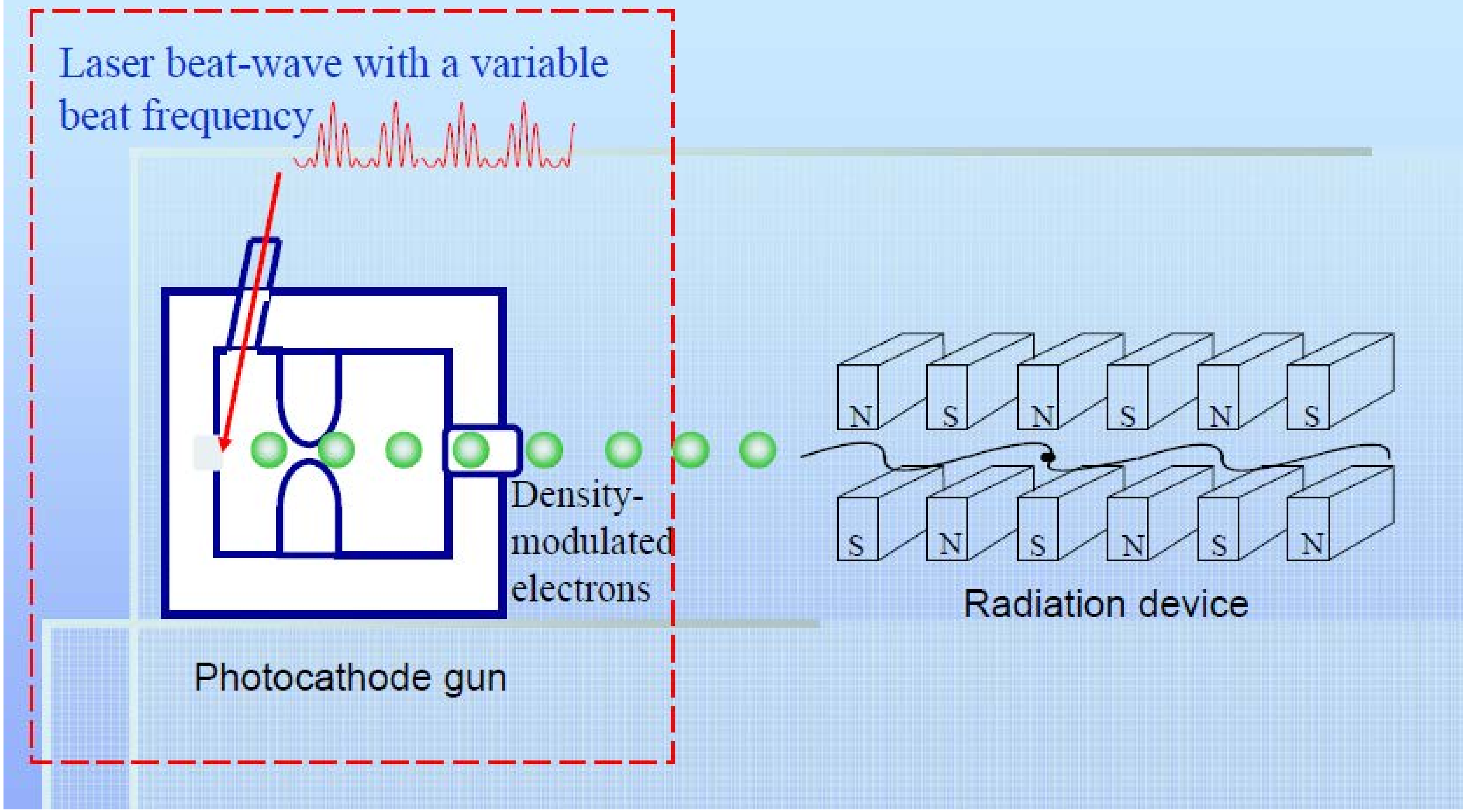
- FEL amplification has finite Energy acceptance: $\sigma_E/E<\rho$
- Effect of quantum fluctuation increase the uncorrelated energy spread by emitting spontaneous photons: $\Delta E_e = h\nu$
- This becomes significant if the photon energy is not negligible compared to the energy spread

$$\lambda_{min} \approx \frac{4\pi\epsilon_n[mm\ mrad]}{\sqrt{I[kA]L_W[m]}} \approx 0{,}5\ \text{Å}$$

Superradiance

- Density modulated electron bunch radiates coherently in a radiator (e.g. undulator)
- Radiation intensity scales with N^2
- Modulation at short wavelength can be achieved by seeding setups (HHG, HGHG, Echo Enabled HG or self-seeding)
- Eg. Long wavelength (THz): modulated cathode laser pulse leads to 'microbunching'

Superradiance FEL driven by Laser-beat-wave Photoinjector



http://www.nsrrc.org.tw/OCPAschool08/lecture/3.8.pdf