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High-brightness Electron Radiation

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Outline

1. Relativistic Electron Radiation

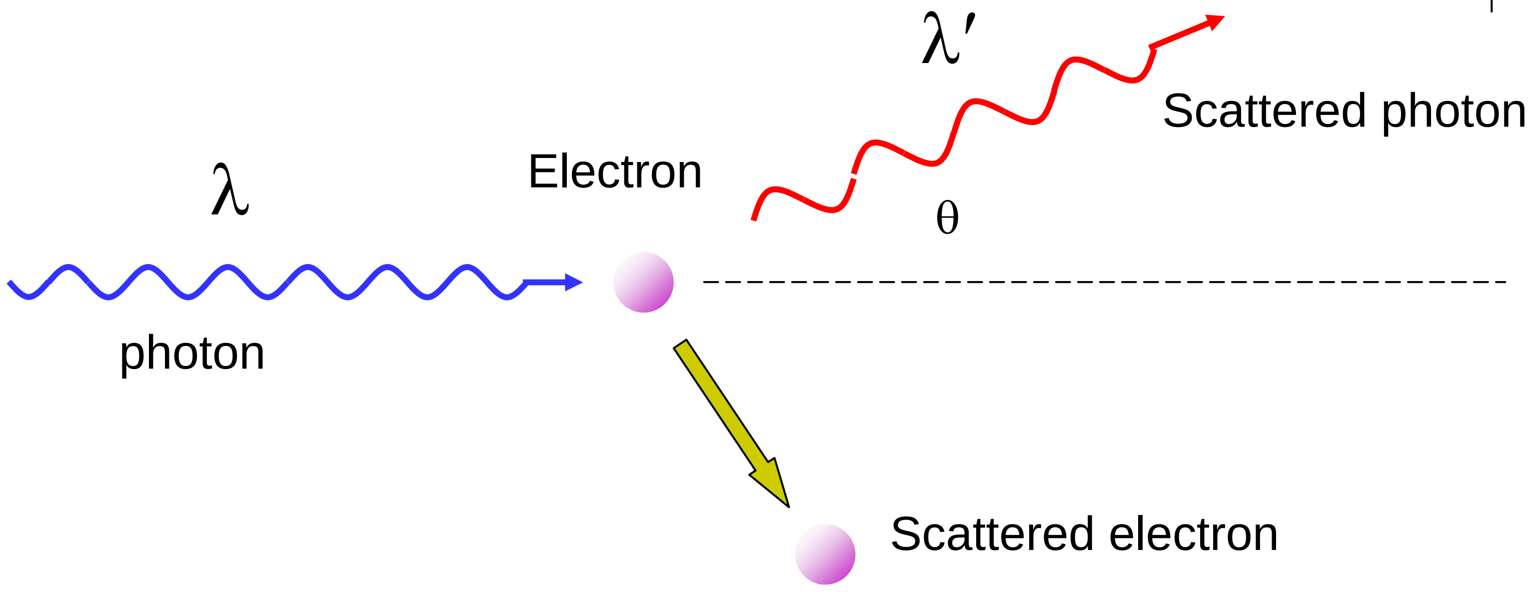
   - Laser Synchrotron
   - Undulator Radiation
   - Smith-Purcell Radiation

2. Superradiance: Radiation from Bunched Electron Beam

3. High-brightness Radiation from x-ray to THz

4. Summary

Compton Scattering

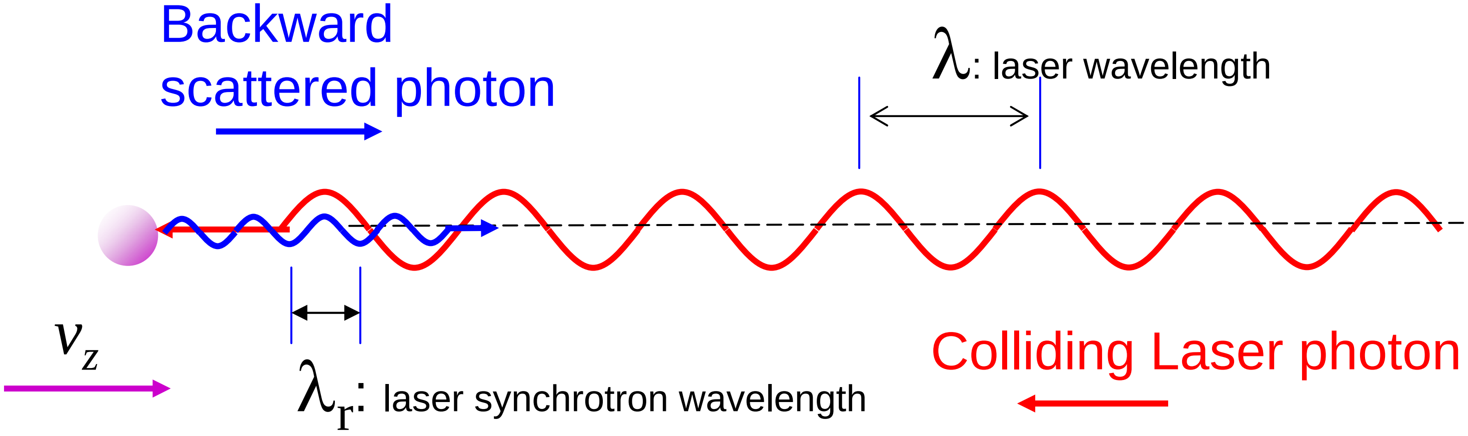


λ: wavelength
h: Planck’s constant
m_0: electron rest mass
c: vacuum wave speed
p: momentum

Compton Effect

$$\lambda' - \lambda = \frac{h}{m_0 c}(1 - \cos\theta)$$

Thomson Scattering ⇒ laser synchrotron



Backward scattered photon

λ: laser wavelength

v_z

λ$_r$: laser synchrotron wavelength

Colliding Laser photon

c

Colliding electron

$$f = f_0\sqrt{\frac{1+\beta_z}{1-\beta_z}}$$

Double Doppler shifted wavelength $\lambda_r = \dfrac{\lambda}{4\gamma_z^2}$

Given λ = 800 nm (Ti:sapphire laser), $\gamma \sim \gamma_z$ = 45 (23 MeV beam), λ´ = 1 Å (hard x-ray!)

Lorentz factor $\gamma \equiv \dfrac{1}{\sqrt{1-\beta^2}}$

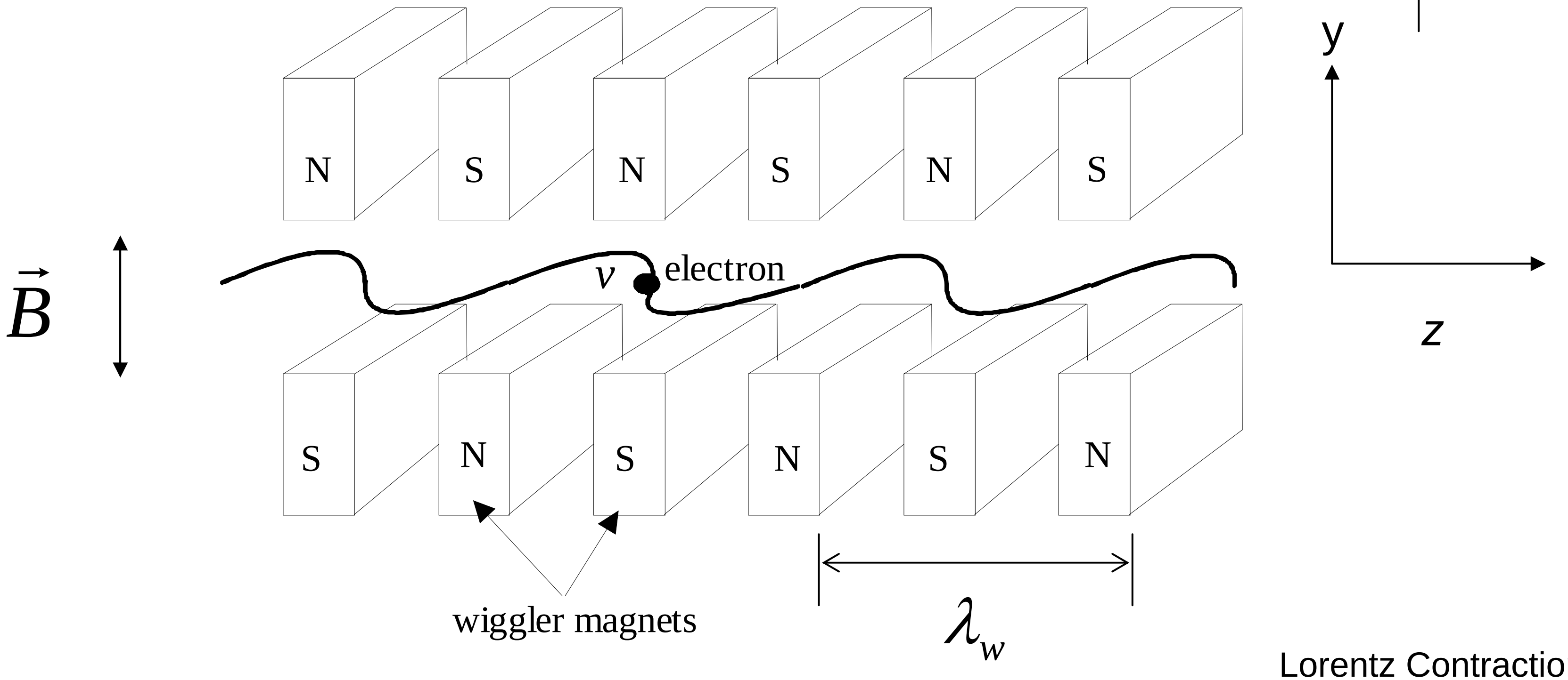
where $\vec{\beta} \equiv \vec{v}/c$

Longitudinal Lorentz factor $\gamma_z \equiv \dfrac{1}{\sqrt{1-\beta_z^2}}$

where $\beta_z \equiv v_z / c$

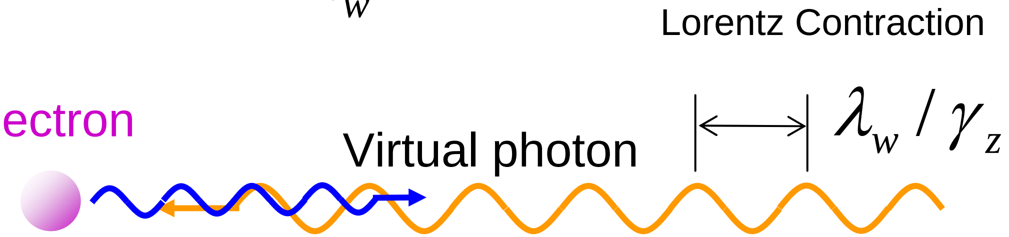
Undulator/Wiggler Radiation

In laboratory frame



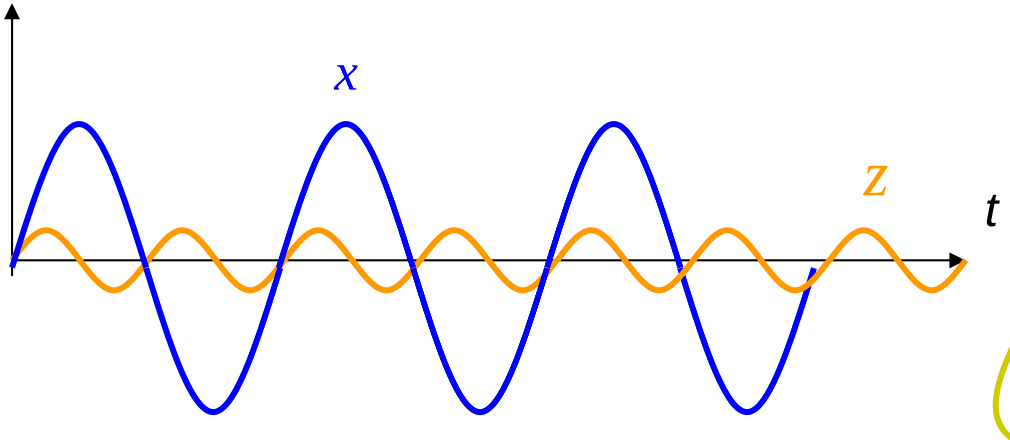
In electron rest frame

$$\vec{E}' = \gamma\vec{\beta}\times\vec{B}, \vec{B}' = \gamma\vec{B}$$



(Sec. 11.10 in J. D. Jackson’s text)

In the Electron Rest Frame



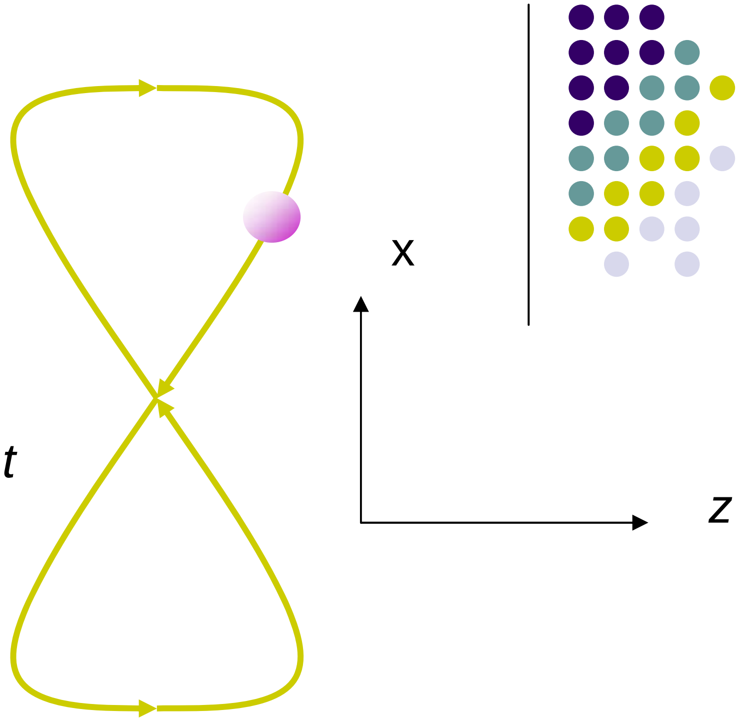
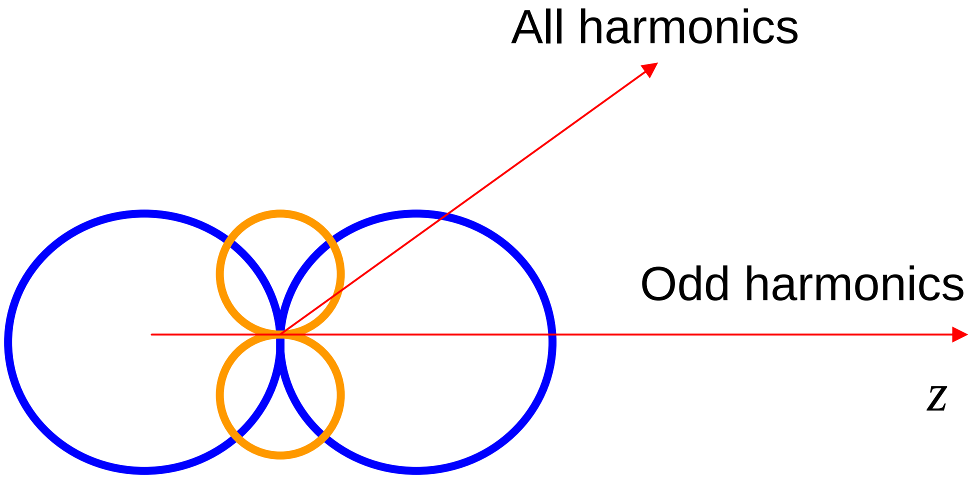


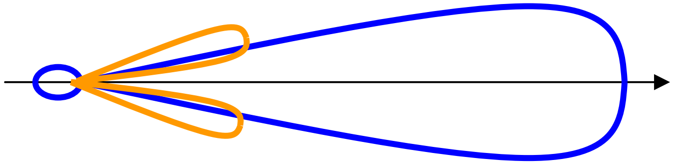
Figure-8 motion



Dipole radiation pattern

In the laboratory frame

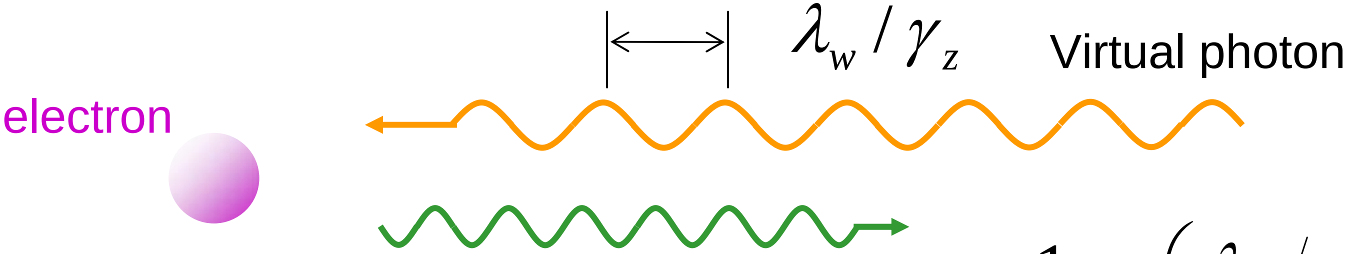
($\gamma >> 1$)



Dipole radiation pattern[6]

Spontaneous Compton Radiation

Electron Rest Frame



Electron oscillation frequency

$$f' = \frac{1}{T'} = \left(\frac{\lambda_w / \gamma_z}{v_z} \right)^{-1}$$

Laboratory Frame

Doppler Shift

$$f = f' \sqrt{\frac{1+\beta_z}{1-\beta_z}} \Rightarrow \boxed{\lambda = \lambda_w \left(\frac{1}{\beta_z} - 1 \right) \approx \frac{\lambda_w}{2\gamma_z^2}}$$

For $\lambda_w \sim 1$ cm, $\gamma_z \sim 200$ (100 MeV), $\Rightarrow \lambda = 125$ nm (deep UV)

- Relativistic undulator radiation is an effective means for producing expensive short-wavelength photons from economic long-wavelength virtual photons

Wavelength Tuning

In a magnetic field, γ is a constant and γ_z is a function of *B* field

$$\gamma_z \equiv \frac{1}{\sqrt{1-\beta_z^2}} = \frac{1}{\sqrt{1-v_z^2/c^2}}, \text{ and } \quad \lambda \approx \frac{\lambda_w}{2\gamma_z^2}$$

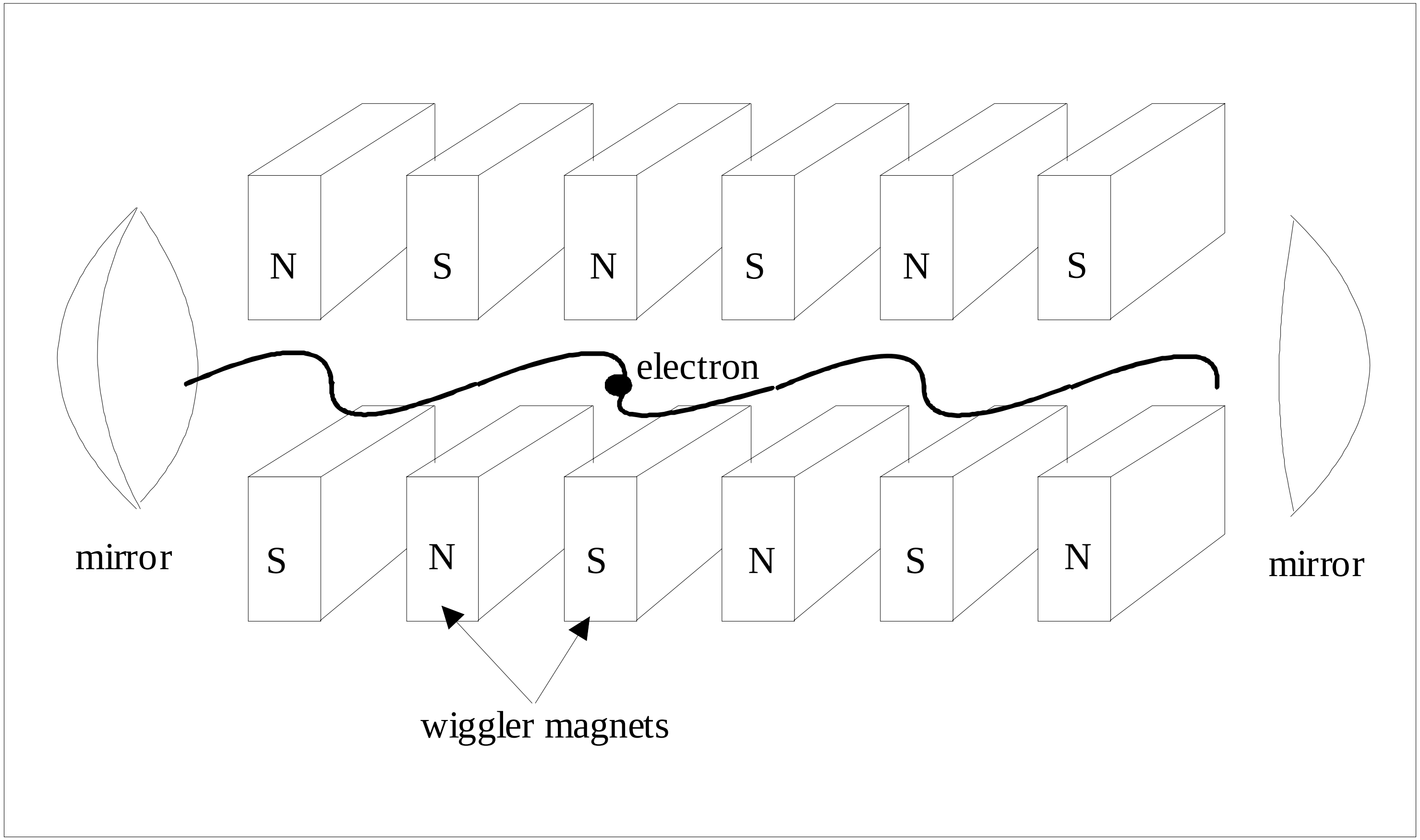
⇒ $$\frac{1}{\gamma_z^2} = \frac{1+a_w^2}{\gamma^2} \quad \text{where} \quad a_w = 0.093 B_{rms}(\text{kgauss}) \times \lambda_w(\text{cm})$$

is called the *wiggler parameter*

⇒ $$\boxed{\lambda = \frac{1+a_w^2}{2\gamma^2}\lambda_w \quad \text{: FEL synchronism condition}}$$

Radiation wavelength can be tuned by magnetic field *B*, wiggler period λ_w, and electron energy γ

Free-electron Laser (Stimulated Compton Scattering)



Courtesy of 王逸群

China Times, Apr. 11, 2006

中國時報 http://news.chinatimes.com CHINA TIMES
中華民國九十五年四月十一日／星期二

雷射光束加熱熔脂 革命性

FEL 嚴重粉刺、橘皮的剋星

楊明暐／綜合報導

只要輕輕按下一個開關，就能消除粉刺、橘皮（脂肪團）或身體過多的脂肪。這聽起來像是科幻小說情節，不過，美國科學家已研發出一種雷射技術，能穿透皮膚表層底下的脂肪，利用高強度雷射光束將它們熔化。

自由電子雷射比傳統更具威力

治療特殊粉刺 還可預防

消除脂肪

洛克斯·安德森（右）正與自由電子科學家史蒂夫·班森（左）討論雷射光束的影響。

雷射

雷射光

科學家發現，只要將自由電子雷射調到非常準確的頻率（波長1210奈米），雷射光束能穿透皮膚且不傷及皮膚。

毛細

汗孔

表皮

自由電子雷射

循環利用的電子

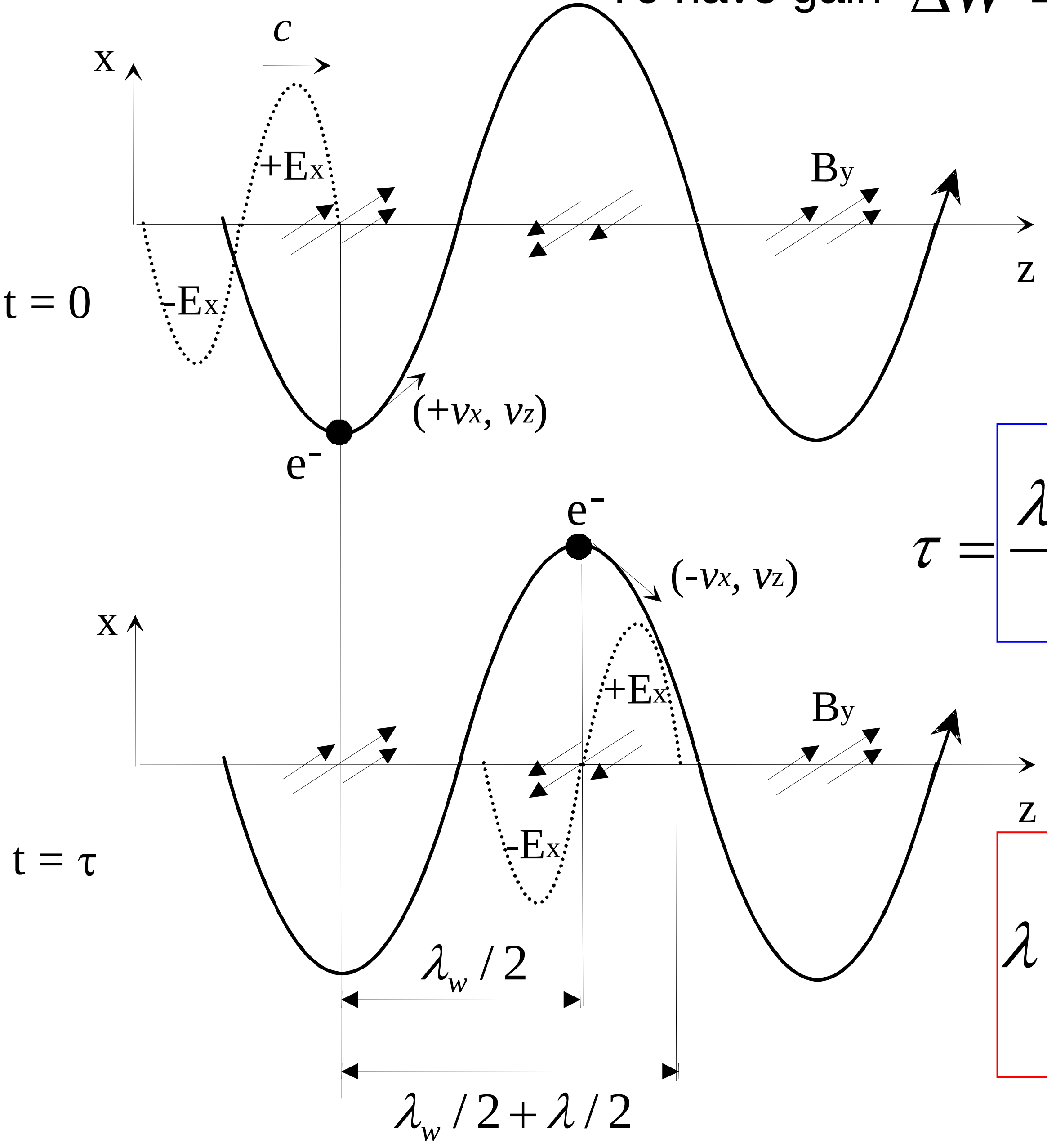
光在兩片光學鏡片間彈跳

電子光束

雷射光

Free-electron Laser

To have gain $\Delta W = e\int_{\tau=L_w/v_z} \vec{E}\cdot\vec{v}\,dt < 0$



amplification

$$\boxed{\vec{v}\cdot\vec{E} > 0}$$

$$\tau = \frac{\lambda_w/2+\lambda_z/2}{c} = \frac{\lambda_w/2}{v_z}$$

⇩

$$\lambda = \lambda_w\left(\frac{1}{\beta_z}-1\right) \approx \frac{\lambda_w}{2\gamma_z^2}$$

Electron-Wave Energy Exchange

Wave Amplification

$$\Delta W = e\int_{\tau=L/v_{//}} \vec{E}\cdot\vec{v}dt < 0$$

Particle Acceleration

$$\Delta W = e\int_{\tau=L/v_{//}} \vec{E}\cdot\vec{v}dt > 0$$

Transverse Coupling

(Eg. Compton/Thompson/undulator radiation etc.)

$$\Delta W = e\int_{\tau=L/v_{//}} \vec{E}_{\perp}\cdot\vec{v}_{\perp}dt$$

Longitudinal Coupling

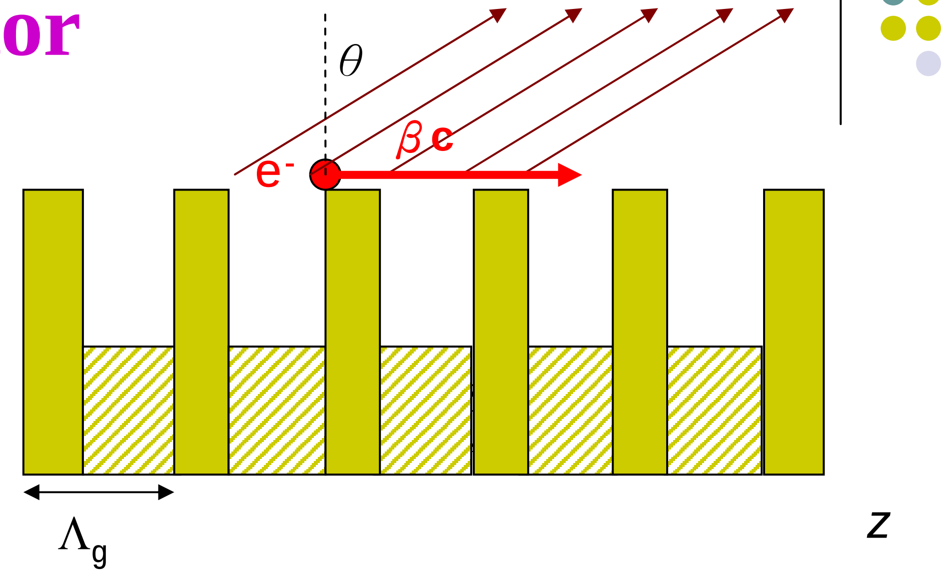
(Eg. Smith-Purcell radiator, backward-wave oscillator etc.)

$$\Delta W = e\int_{\tau=L/v_{//}} \vec{E}_{//}\cdot\vec{v}_{//}dt$$

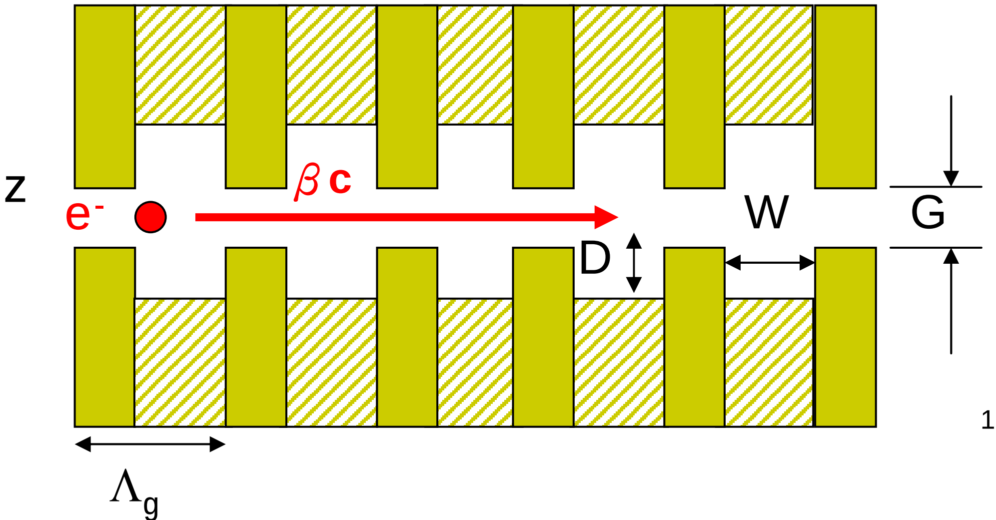
$$\Delta W = e\int_{\tau=L/v_z} \vec{E}_z \cdot \vec{v}_z dt < 0$$

Smith-Purcell Radiator

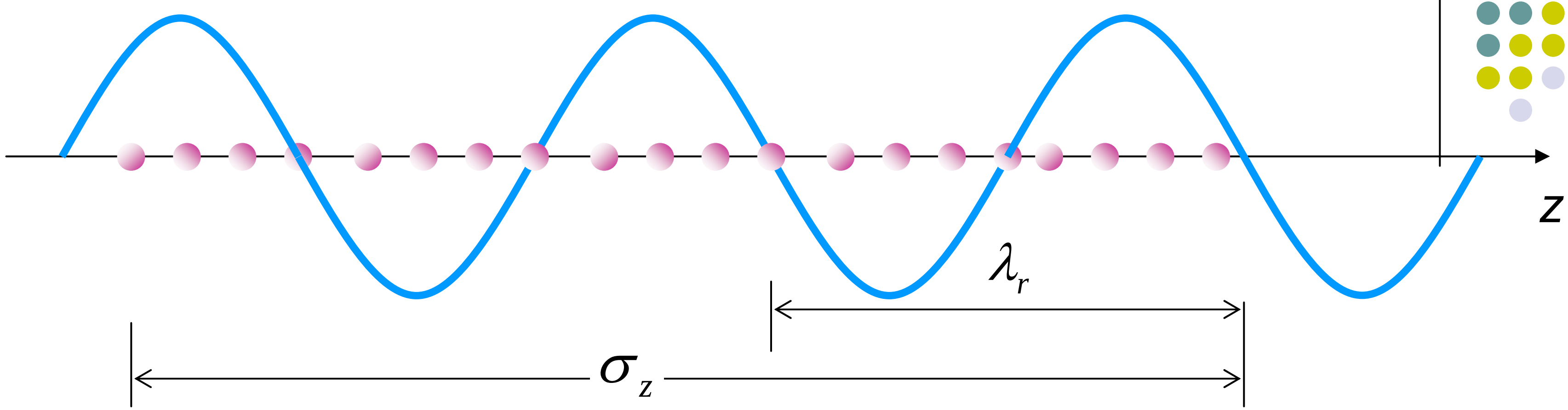
$$\lambda = \Lambda_g \left(\frac{1}{\beta} - \sin\theta\right)$$

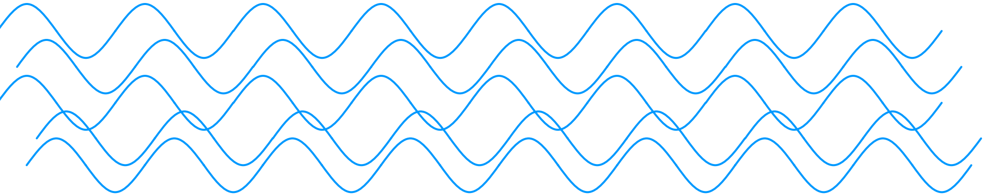


Backward-wave Oscillator



Incoherence Radiation $\sigma_z >> \lambda_r$

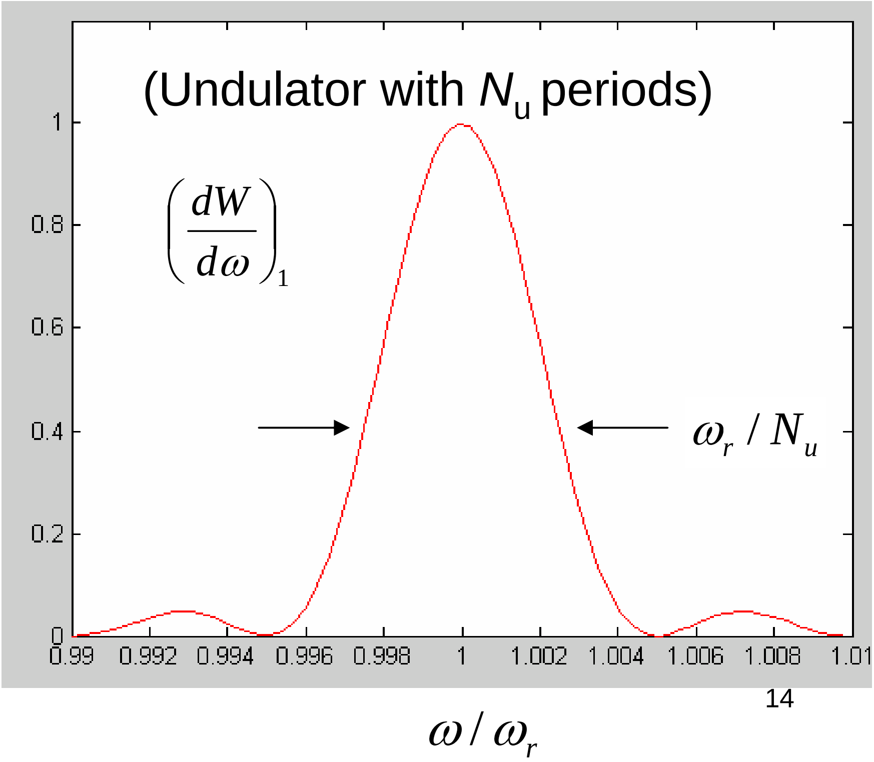




$$\left(\frac{dW}{d\omega}\right)_{inc,N} = \left(\frac{dW}{d\omega}\right)_1 \left|\sum_{j=1}^{N} e^{i\omega_j t}\right|^2$$

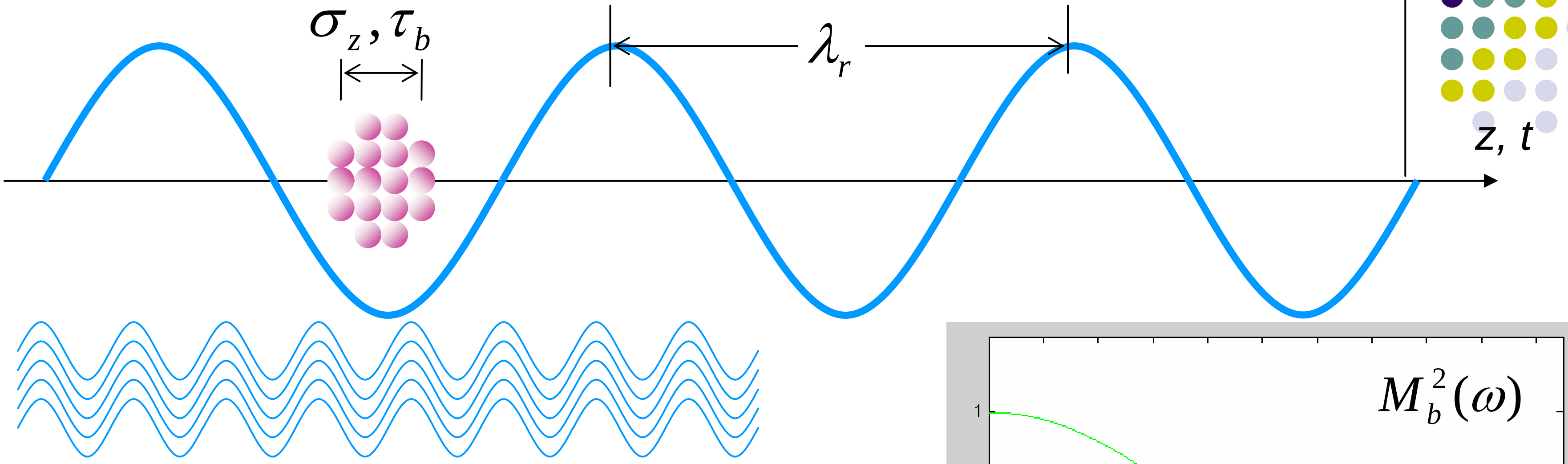
Spectral Energy $$\left(\frac{dW}{d\omega}\right)_{inc,N} = N\left(\frac{dW}{d\omega}\right)_1$$

N: number of electrons

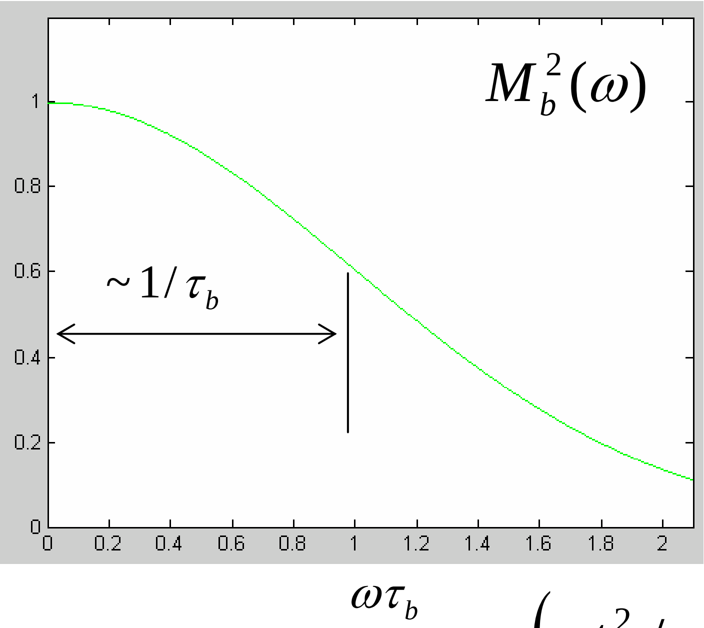


Superradiance: coherent radiation

$$\sigma_z \ll \lambda_r$$



Spectral Energy $\left(\frac{dW}{d\omega}\right)_{SR,N_b} = \boxed{N_b^2}\left(\frac{dW}{d\omega}\right)_1 \boxed{M_b^2(\omega)}$



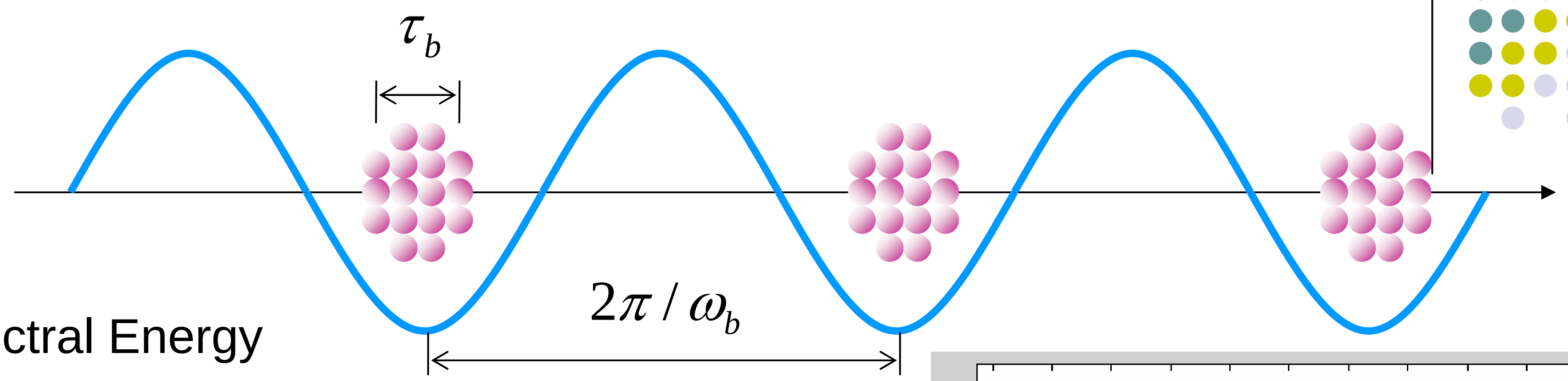
$M_b(\omega)$:Fourier transform of bunch shape

N_b: number of bunched electrons

* For 1 nC in 10 ps and λ_r = 1 μm, $N_b = 2 \times 10^6$!

$M_b(\omega) = \exp\left(-\frac{\omega^2\tau_b^2}{4}\right)$ **for Gaussian bunch shape function** $f(t) = \frac{\exp\left(-t^2/\tau_b^2\right)}{\sqrt{\pi}\tau_b}$

Superradiance from a Periodically Bunched Beam

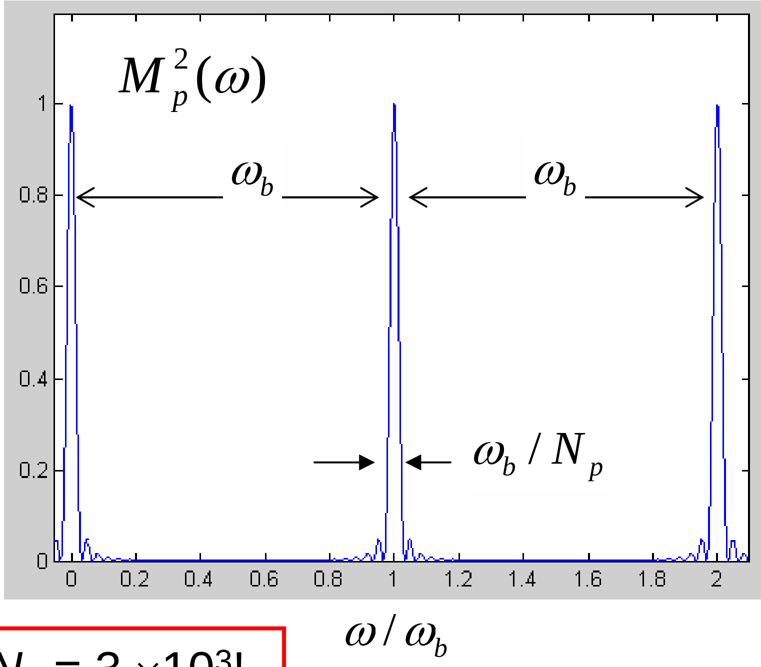


Spectral Energy

$$\left(\frac{dW}{d\omega}\right)_{SR,N_p\times N_b} = (\boxed{N_p} N_b)^2 \left(\frac{dW}{d\omega}\right)_1 M_b^2(\omega)\boxed{M_p^2(\omega)}$$

$$M_p(\omega) = \frac{\sin(N_p \pi\omega / \omega_b)}{N_p \sin(\pi\omega / \omega_b)}$$

Coherent sum of N_p bunches with bunching freq. ω_b



* For 10-ps macro-bunch length and λ_r = 1 μm, N_p = 3 ×10^3!

Reference: A. Gover, “Superradiance and stimulated-superradiance emission in prebunched electron-beam radiators. I. formulation, Phys. Rev. ST AB **8**, 030701 (2005)

Spectral narrowing from periodic bunched beam

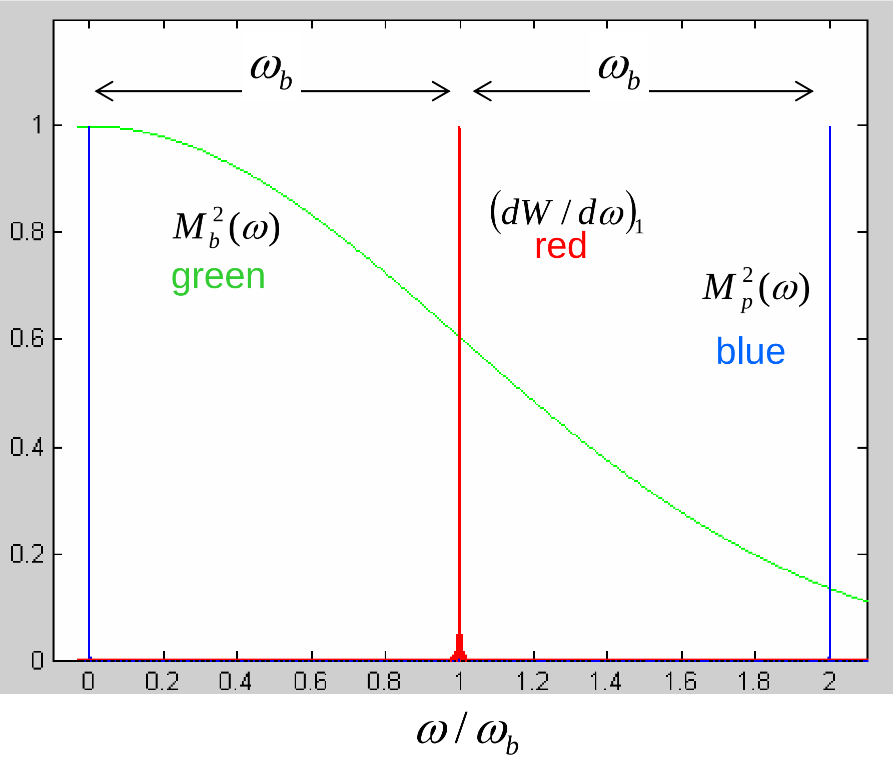
$$\left(dW/d\omega\right)_{SR,N_p\times N_b} = (N_p N_b)^2 \boxed{\left(dW/d\omega\right)_1 M_b^2(\omega) M_p^2(\omega)}$$

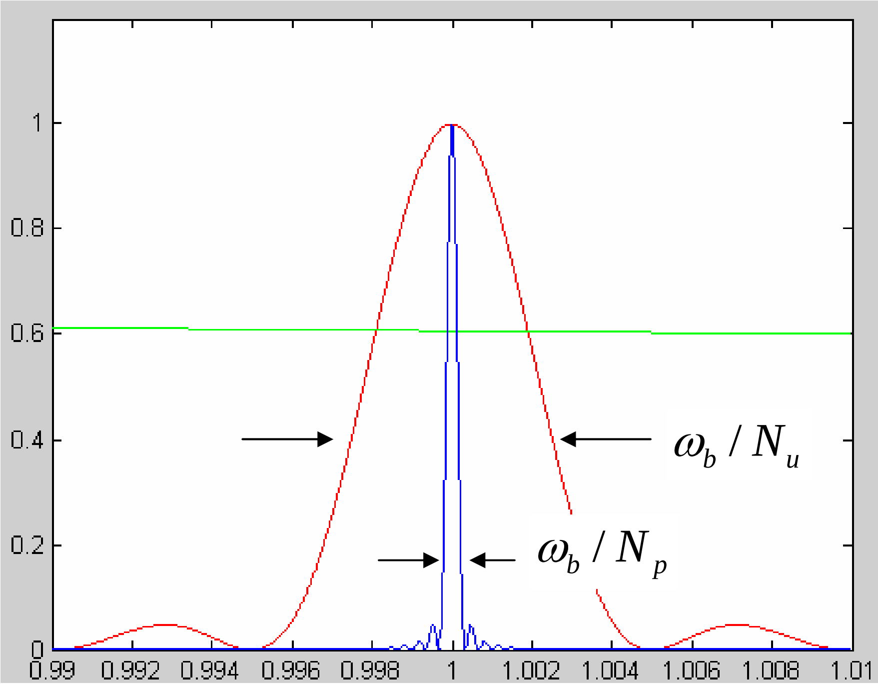
where $M_p(\omega) = \sin(N_p\pi\omega/\omega_b)/\sin(\pi\omega/\omega_b)/N_p$

Assume undulator radiation $\Rightarrow \left(dW/d\omega\right)_1 \propto \mathrm{sinc}^2[2N_u(\omega/\omega_r - 1)]$

for undulator with period N_u

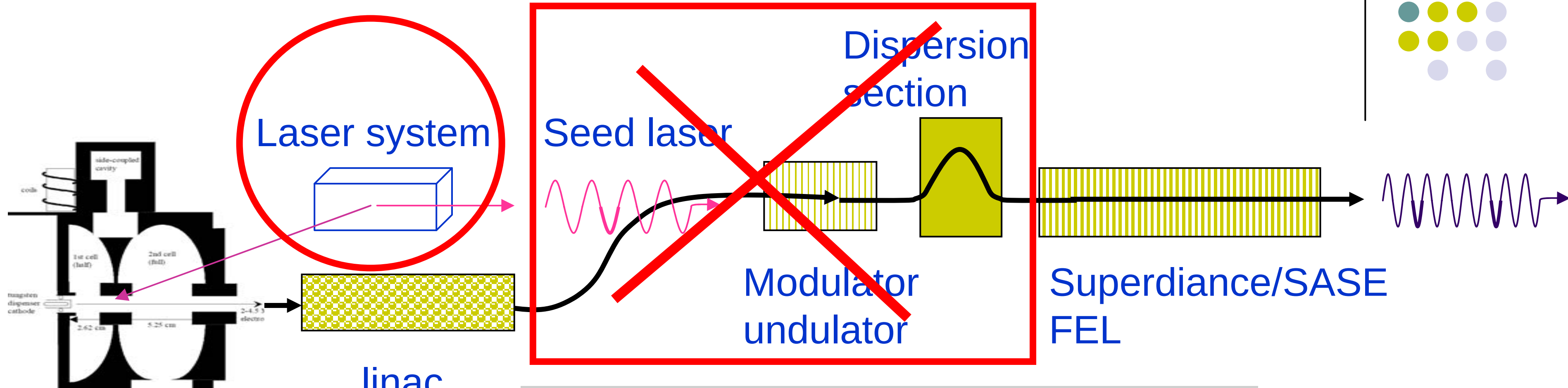
Assume $\omega_b = 1/\tau_b \Rightarrow M_b(\omega) = \exp\left(-\omega^2/(4\omega_b^2)\right)$ (3) $\omega_r = \omega_b$





Example: High Gain Harmonic Generation

(HGHG, L. H. Yu et. @ BNL)



Laser system

Seed laser

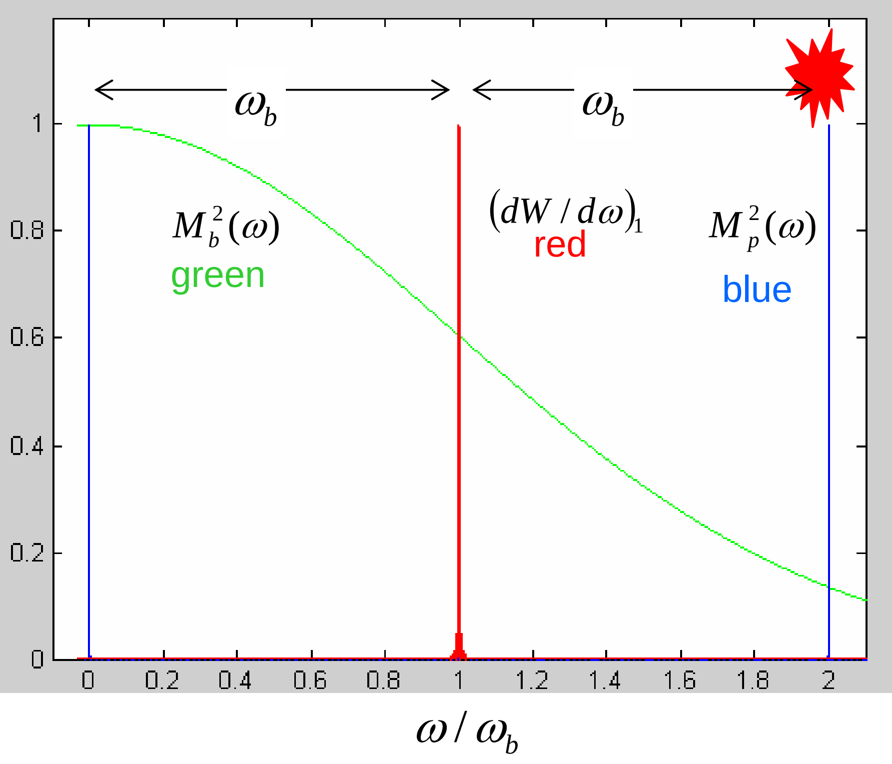
Dispersion section

Modulator undulator

Superdiance/SASE FEL

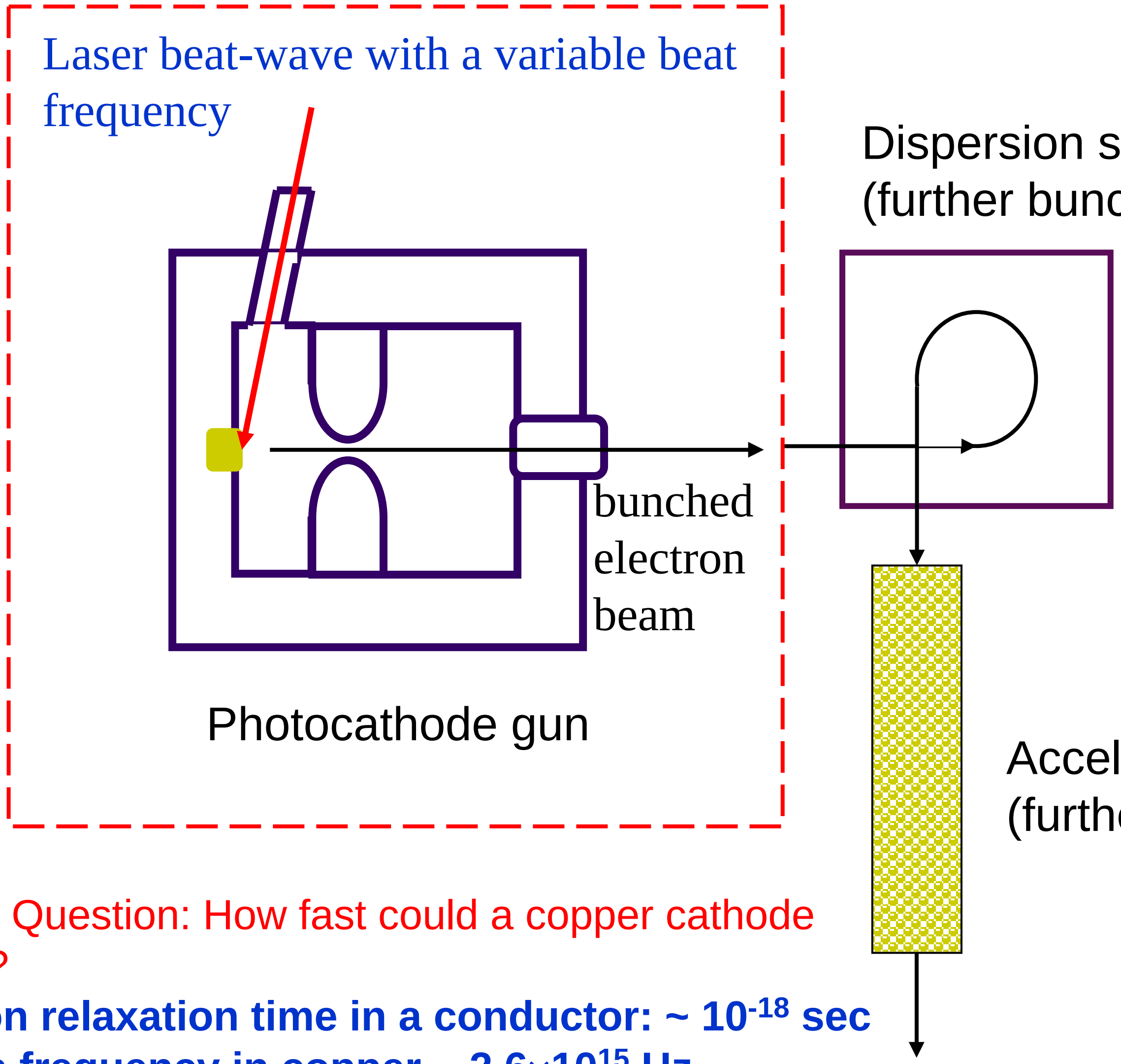
linac

RF Photocathode gun



Idea: Laser-beat-wave Bunched-beam Accelerator

(B^3 technique)



Laser beat-wave with a variable beat frequency

bunched electron beam

Photocathode gun

Dispersion section
(further bunch compression)

For an alpha magnet, compression ratio
50 ~ 100

Accelerator
(further particle acceleration)

Bunched beam to
radiation insertion device

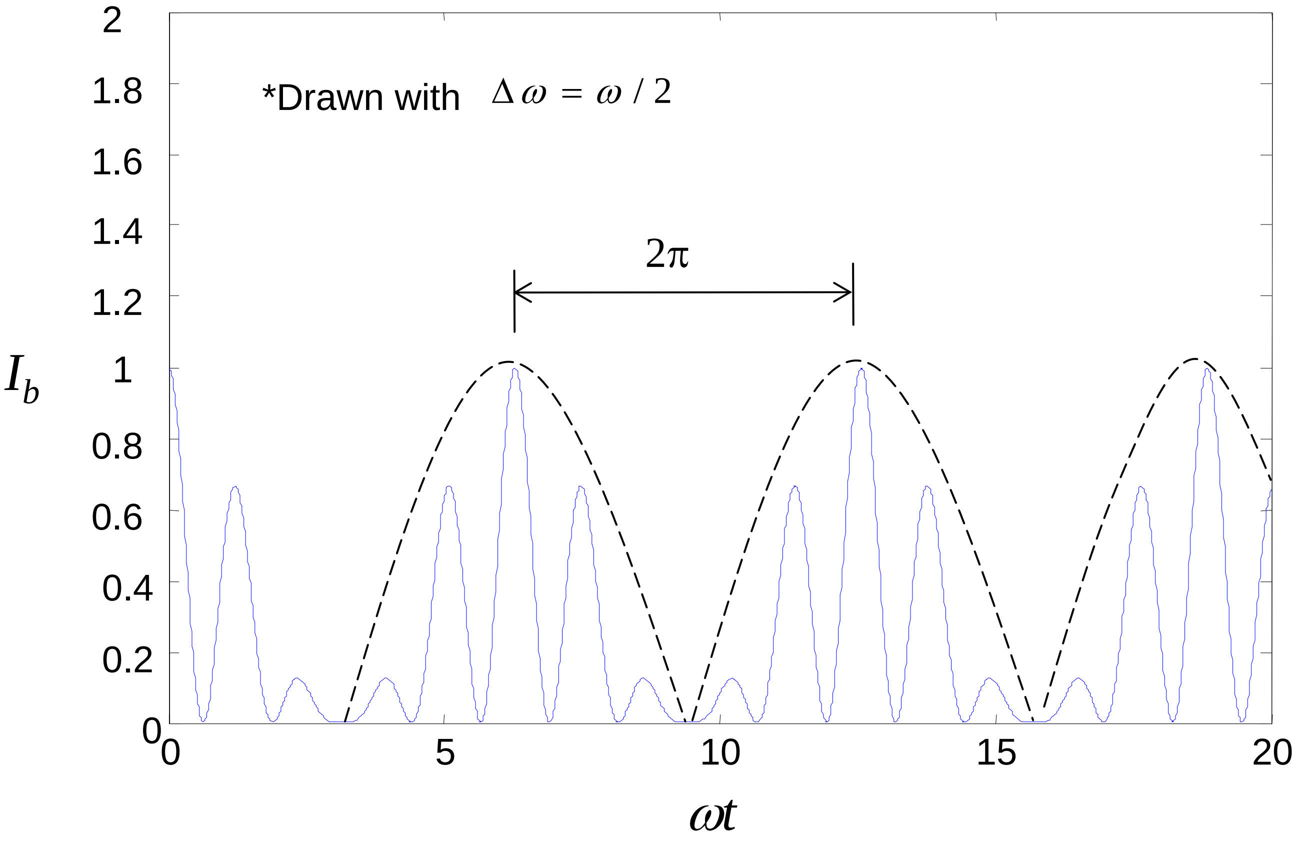
An Open Question: How fast could a copper cathode respond?

- **Electron relaxation time in a conductor: ~ 10^{-18} sec**
- **Plasma frequency in copper ~ 2.6×10^{15} Hz**

Laser Beat Wave: beating of two waves

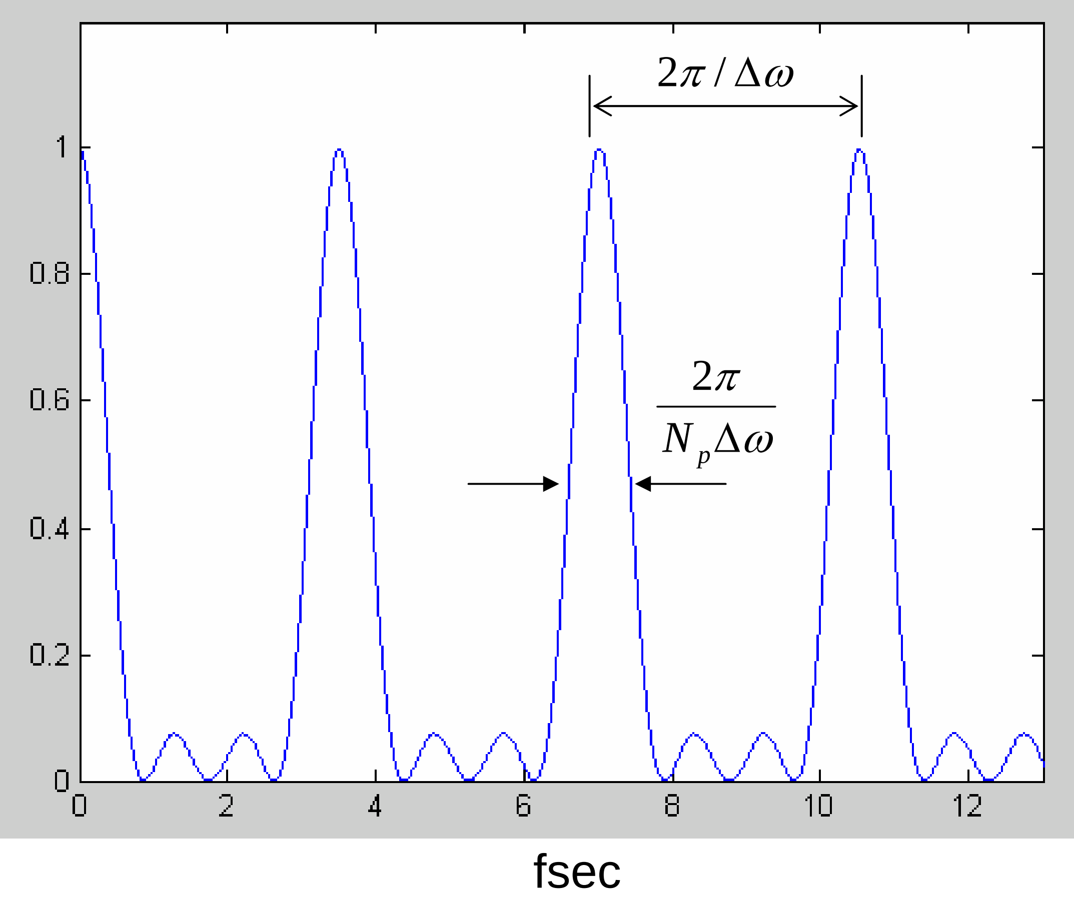
Superposition of two fields with $\Delta\omega$ $E = E_0 \cos\omega t + E_0 \cos(\omega - \Delta\omega)t$

Instantaneous intensity $I = I_0 \cos^2[(\omega - \frac{\Delta\omega}{2})t] \times \cos^2(\frac{\Delta\omega}{2}t)$ beating at frequency $\Delta\omega$



Laser Beat Wave: multi-wave beating

$$I = I_0 \left| \exp(j\omega_0 t)\{1 + \exp(-j\Delta\omega t) + \ldots + \exp[-j(N-1)\Delta\omega t]\} \right|^2 = I_0 \frac{\sin^2(N_p \Delta\omega t/2)}{\sin^2(\Delta\omega t/2)}$$



(1 fs ⇔ 300 nm)

Pump laser

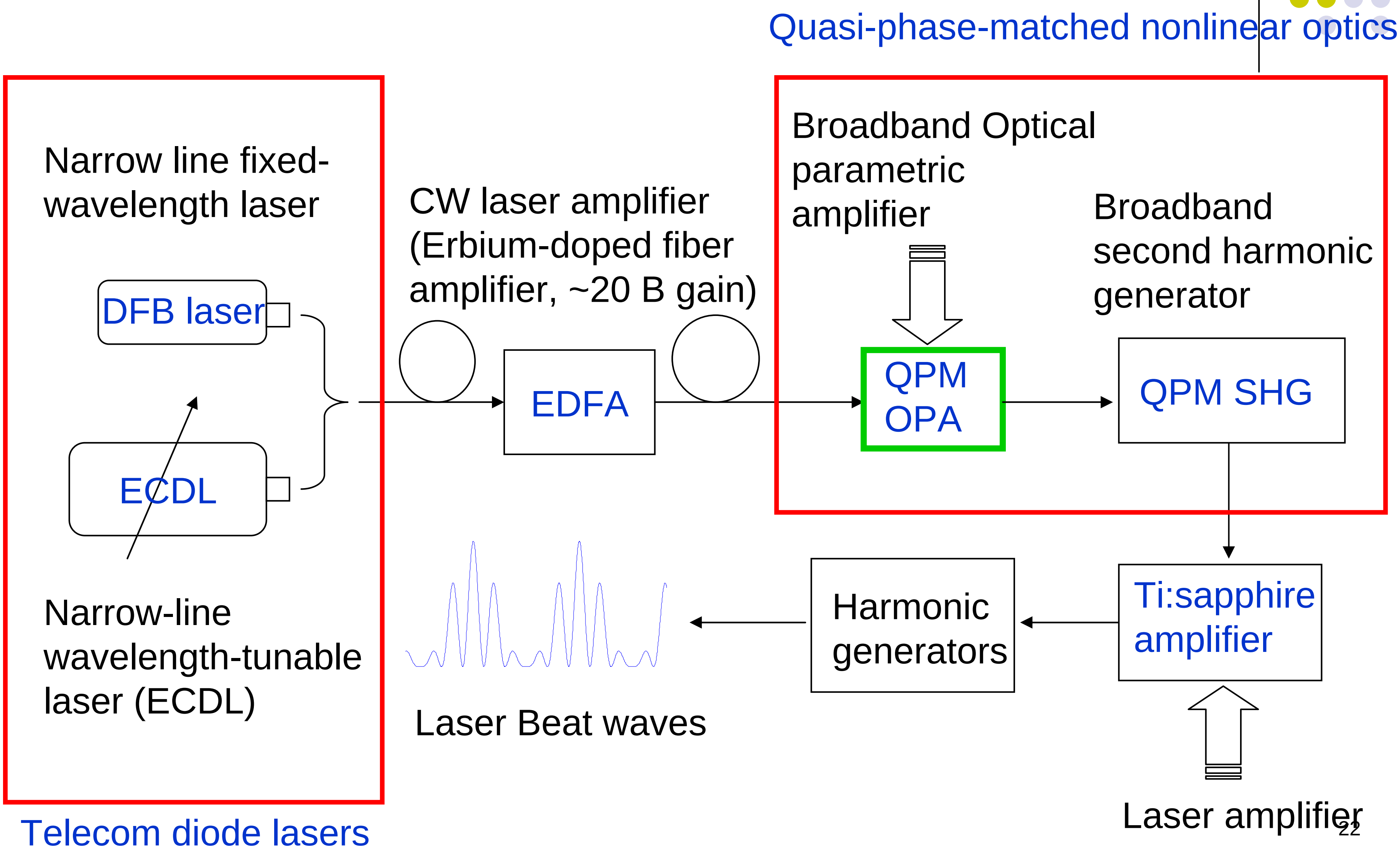
↓

Eg. Raman material with Stokes shift $\Delta\omega$

↓

Coherent Stokes and anti-Stokes

Frequency Tunable Beat-wave Laser System



Quasi-phase-matched nonlinear optics

Narrow line fixed-wavelength laser

DFB laser

ECDL

Narrow-line wavelength-tunable laser (ECDL)

Telecom diode lasers

CW laser amplifier (Erbium-doped fiber amplifier, ~20 B gain)

EDFA

Broadband Optical parametric amplifier

QPM OPA

Broadband second harmonic generator

QPM SHG

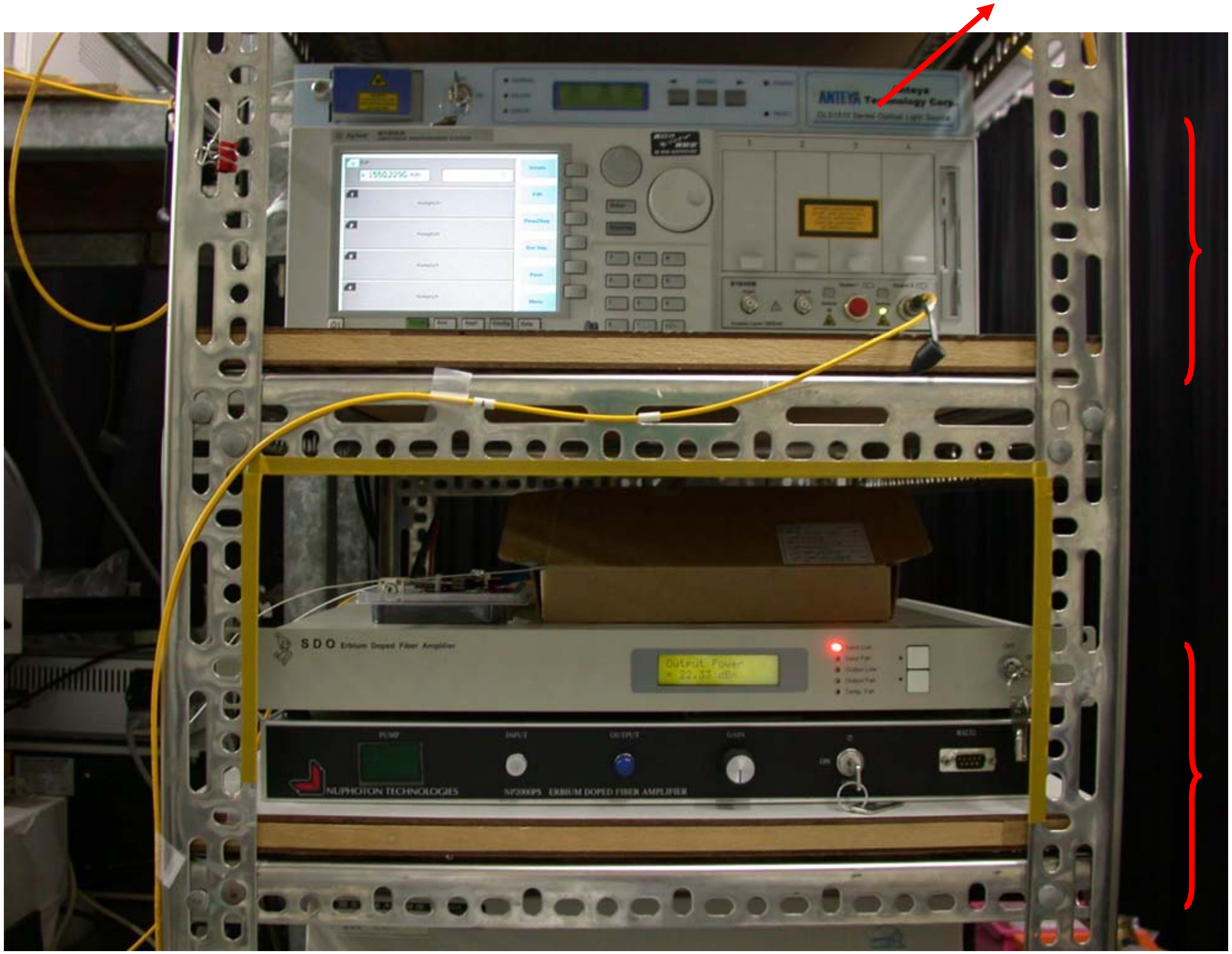
Ti:sapphire amplifier

Laser amplifier

Harmonic generators

Laser Beat waves

Seed Laser System

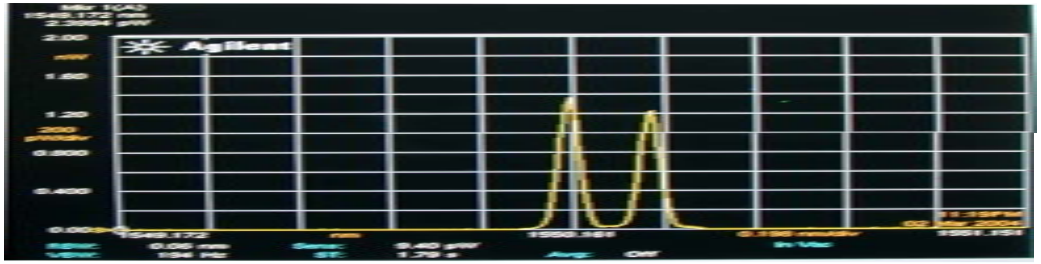


Distributed-feedback diode laser with kHz linewidth

External-cavity tunable diode laser 1.4-1.6 μm with MHz linewidth

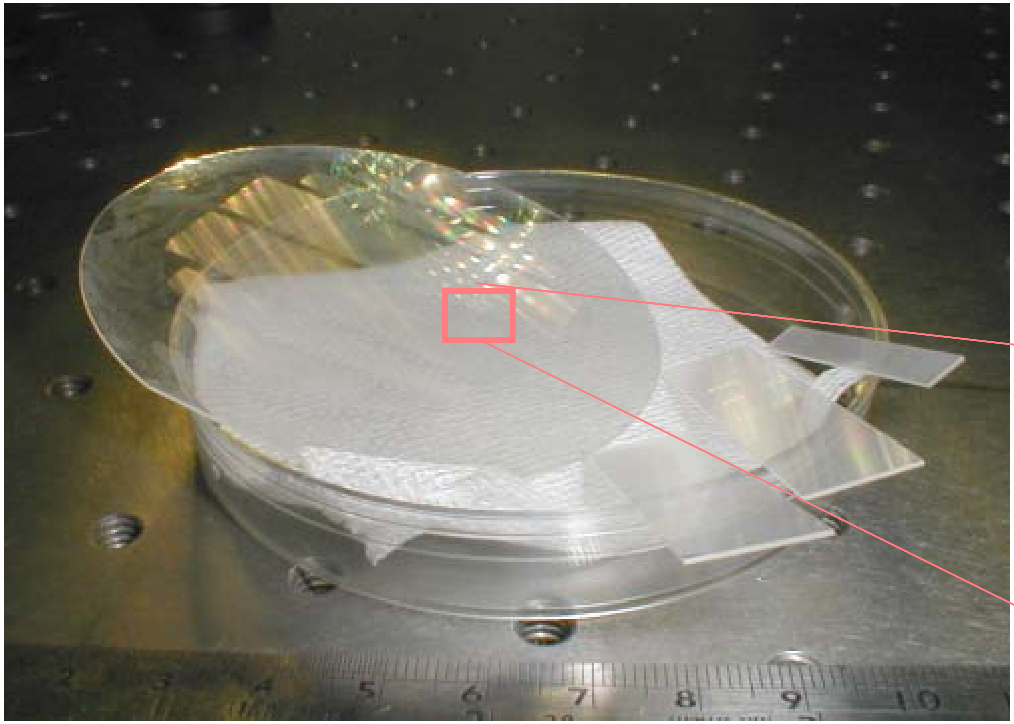
Erbium doped fiber amplifier 1.48 ~1.62 μm (20 THz bandwidth)

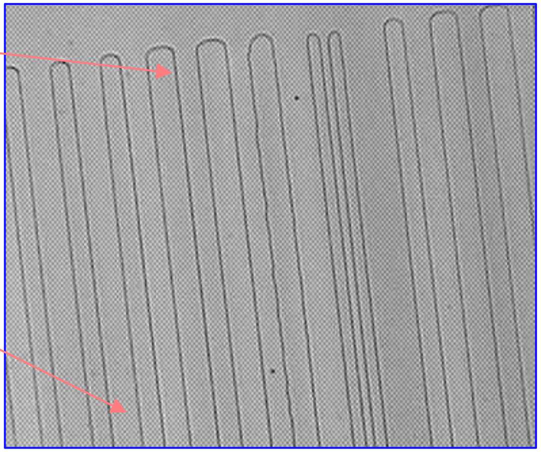
Seed laser spectrum

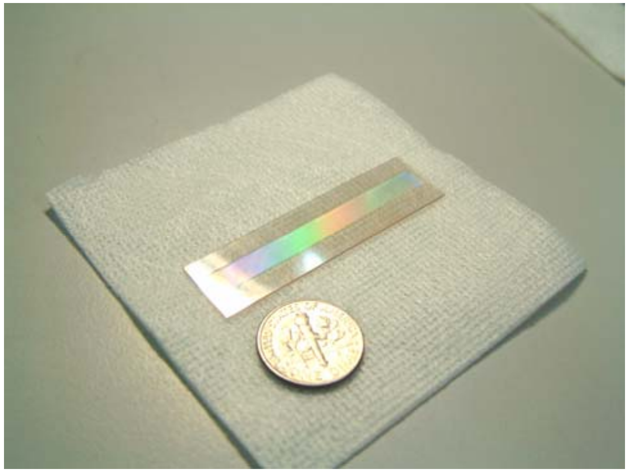


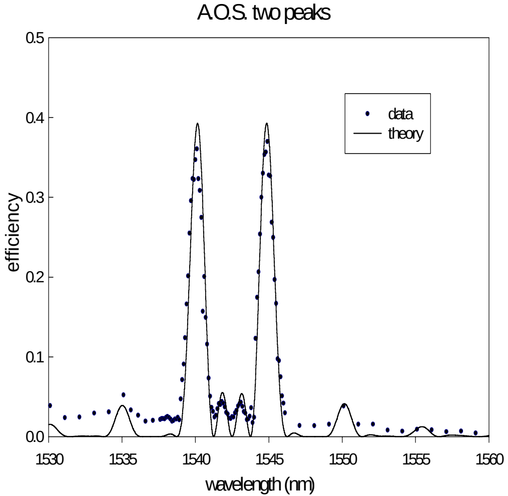
Quasi-phase-matched (QPM) Nonlinear Optical Crystals:

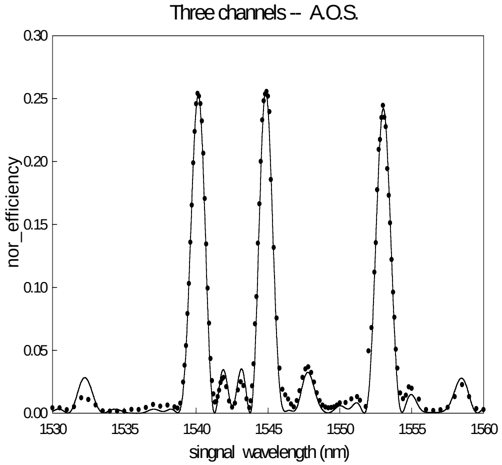
Phase-matching wavelengths can be engineered by using lithographic technology





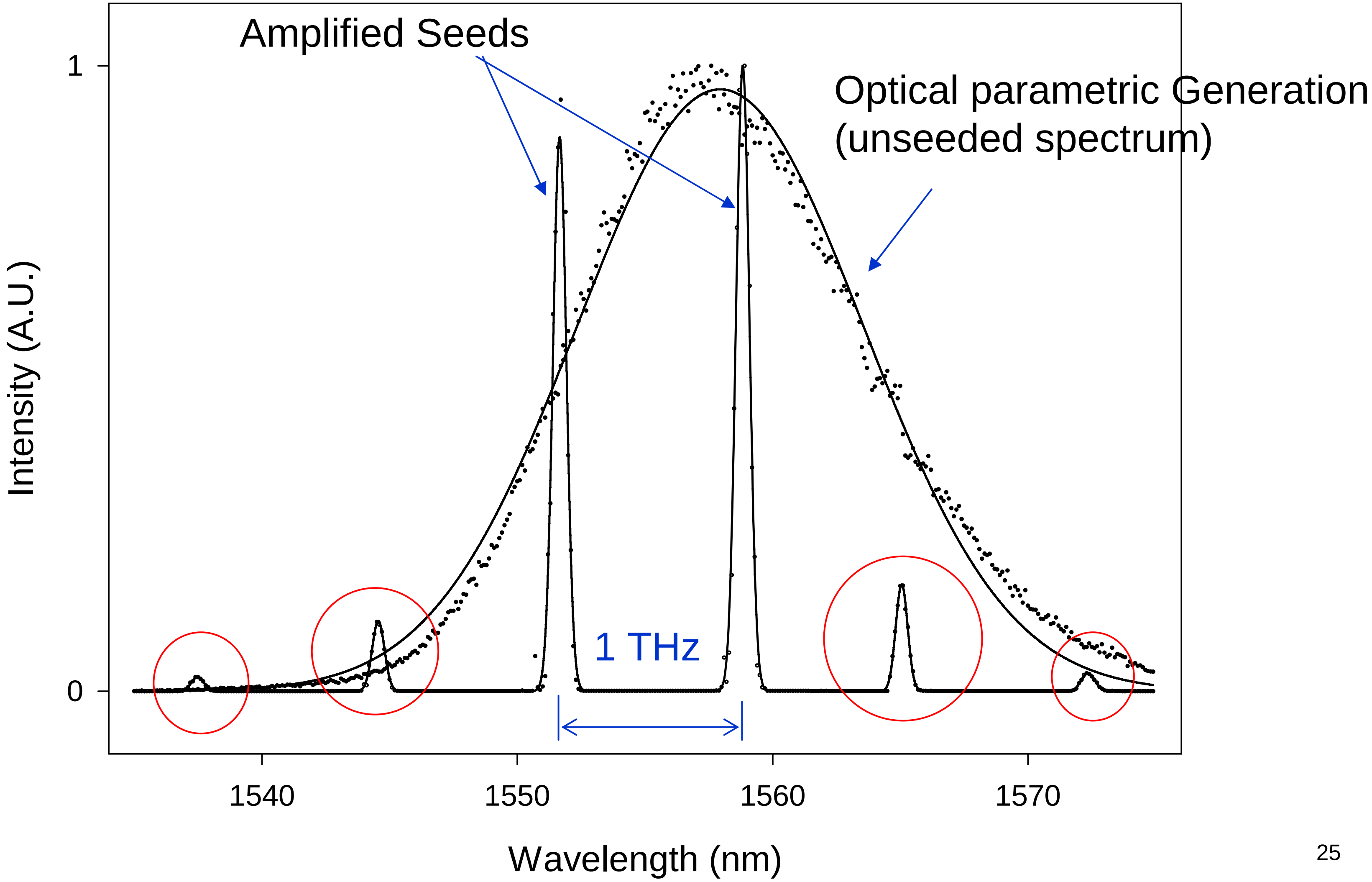






Broadband Optical Parametric Amplification: Amplified Beat-wave Spectrum

Input: 60 μJ/pulse at 1064-nm
Output: 11 μJ/pulse at 1.55-6 μm

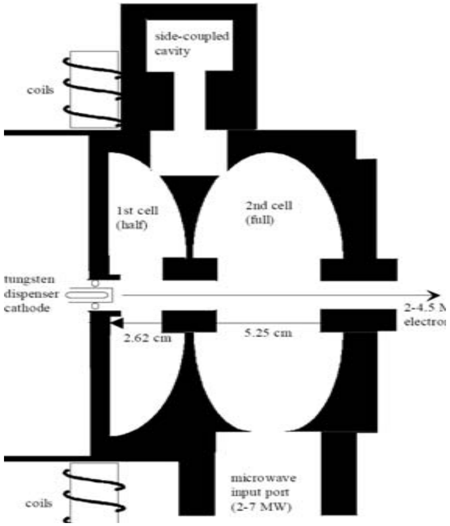


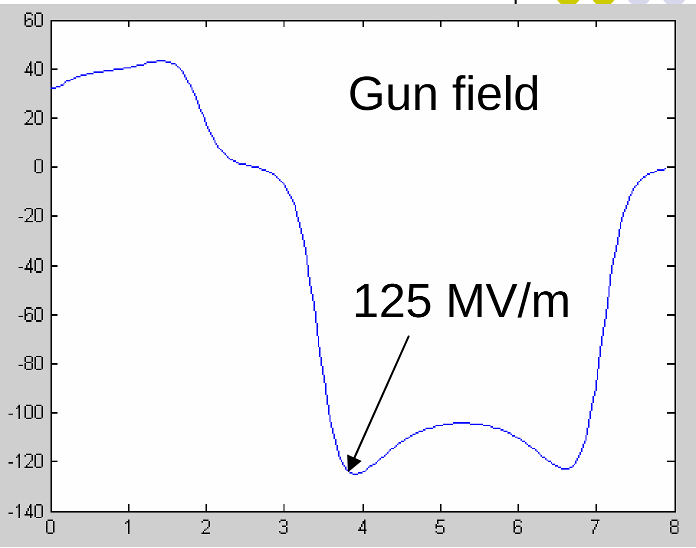
Question: Would particle acceleration smear out particle distribution?

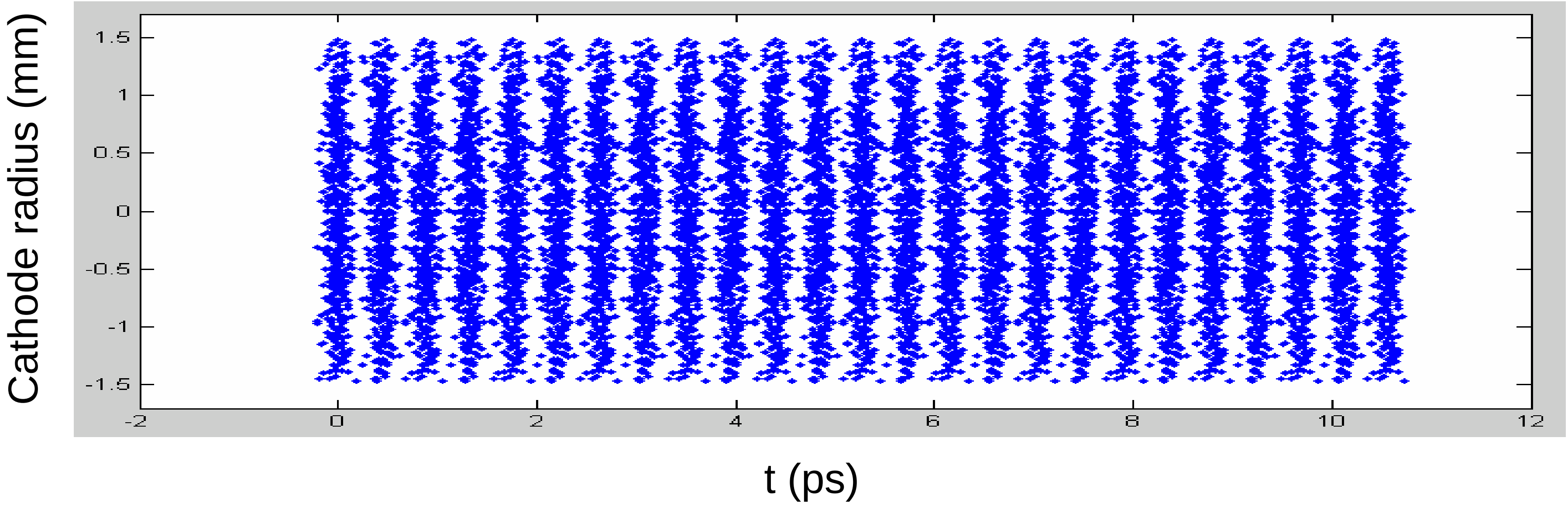
Simulation (ASTRA) 1: 1-1/2 Cell S-band SSRL RF gun (input)

Input

- 25 periodic bunches over 11 ps or 0.44 ps/bunch
- Gaussian bunch with rms bunch length = 72 fsec
- rms radius = 0.75 mm at cathode with radial distribution
- Total charge 0.1 nC or 4 pC/bunch
- Space charge force was considered.



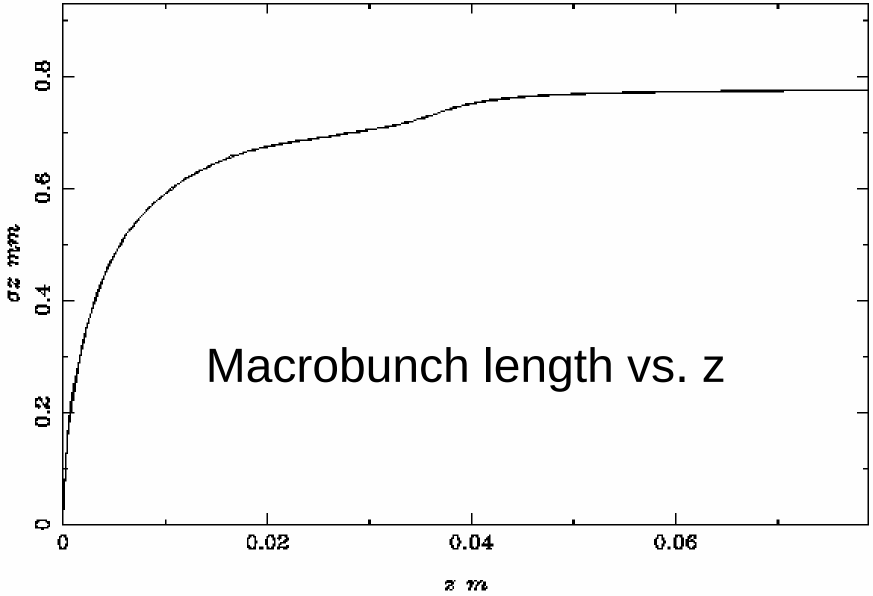


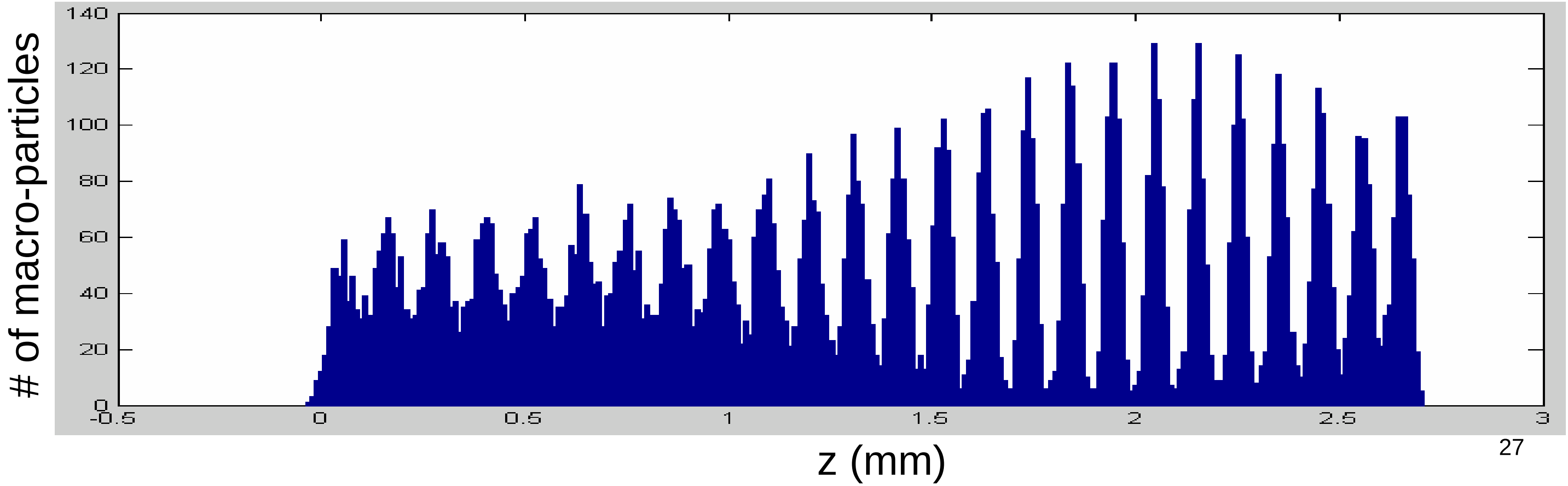


Simulation (ASTRA) 1: 1-1/2 Cell S-band SSRL RF gun (output)

Output

1. 11 A over 9 ps
2. Average energy: 3.994 MeV
3. Rms energy spread = 0.37%
4. normalized emittance = 1.19 π-mm-mra
5. Micro-bunch length ~ 108 μm

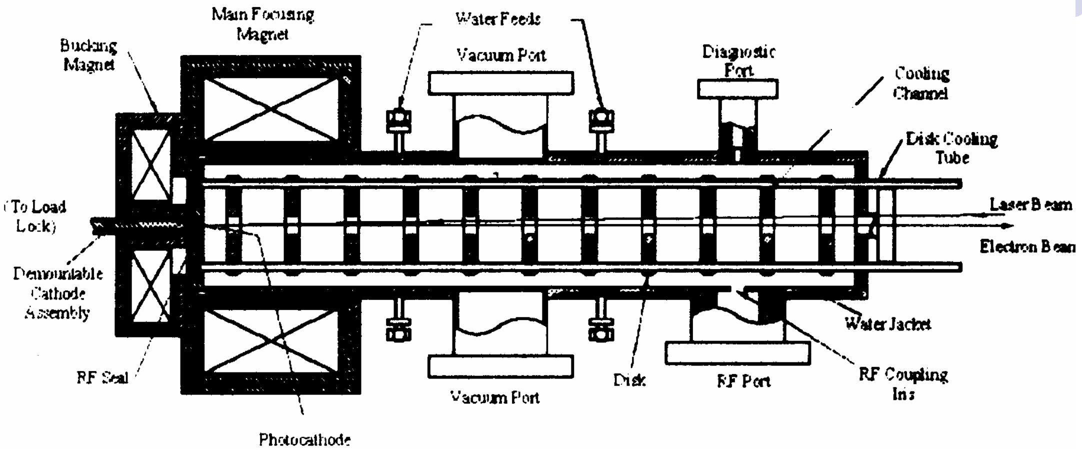




Simulation (ASTRA) 2: UCLA/DULY Planewave Transformer Accelerator

Input

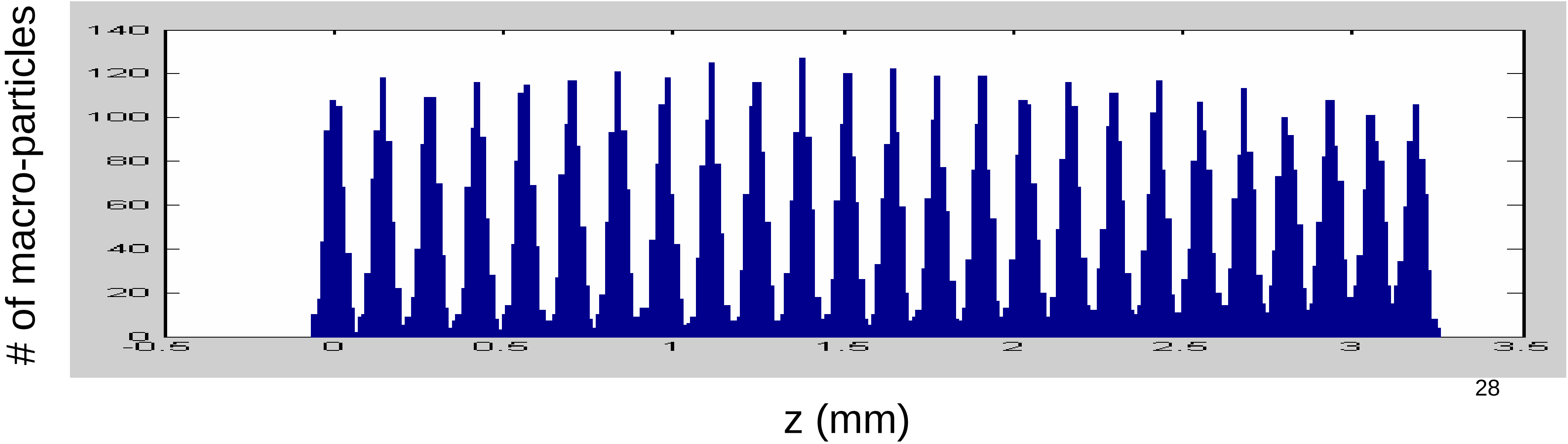
Same as in simulation 1



Output

1. 9 A over 10.8 ps
2. Average energy: 19.15 MeV
3. Rms energy spread = 0.7%
4. normalized emittance = 5.24 π-mm-mrad
5. Micro-bunch length ~ 130 μm

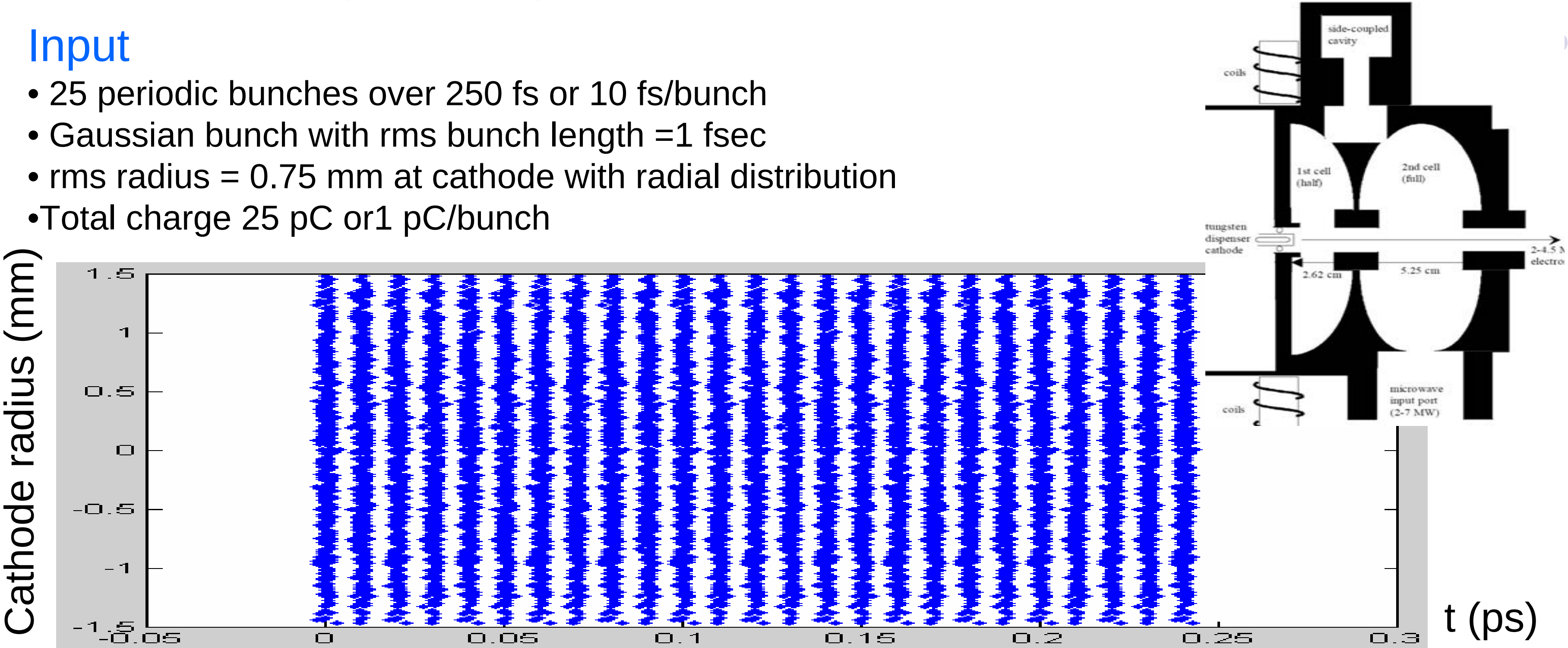
10+2x1/2 cell S-band RF gun
with Peak accelerator gradient = 60 MV/m

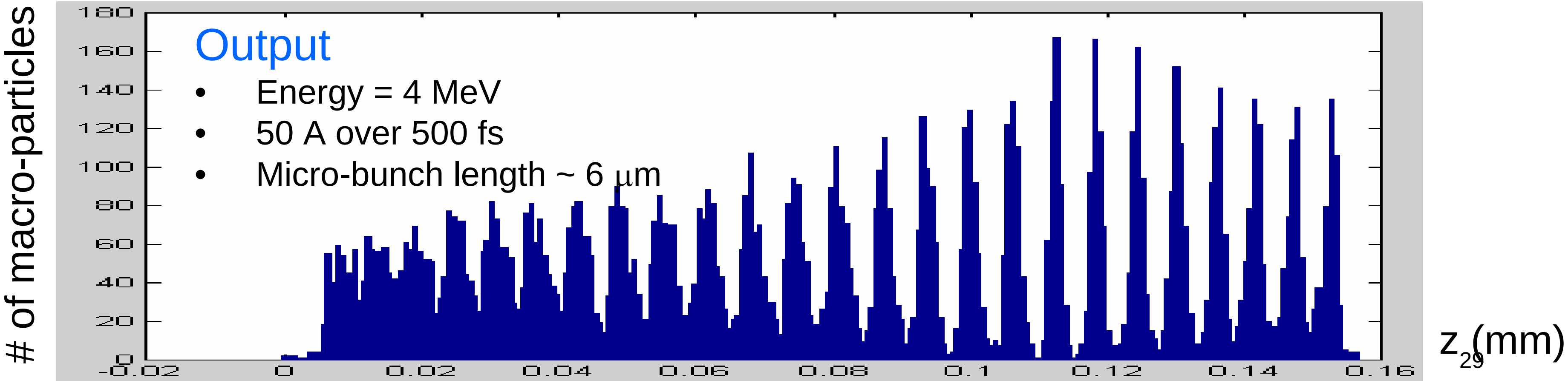


Simulation (ASTRA) 3: Generation for 6μm bunch length

Input

- 25 periodic bunches over 250 fs or 10 fs/bunch
- Gaussian bunch with rms bunch length =1 fsec
- rms radius = 0.75 mm at cathode with radial distribution
- Total charge 25 pC or1 pC/bunch



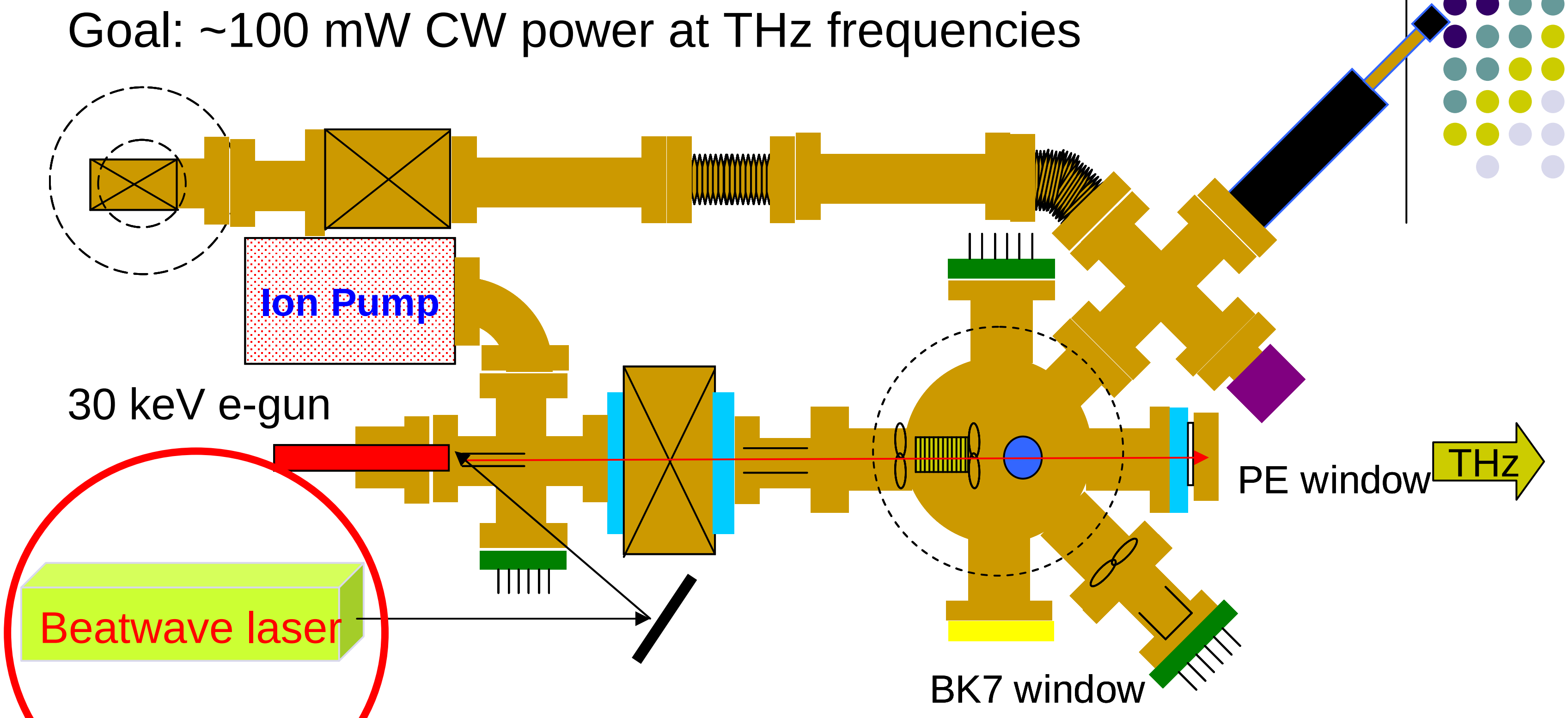


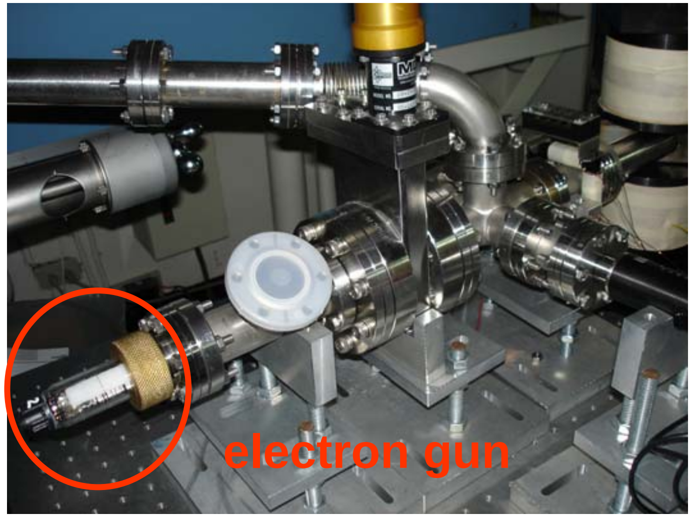
Output

- Energy = 4 MeV
- 50 A over 500 fs
- Micro-bunch length ~ 6 μm

Superradiance Smith-Purcell FEL: beam line

Goal: ~100 mW CW power at THz frequencies



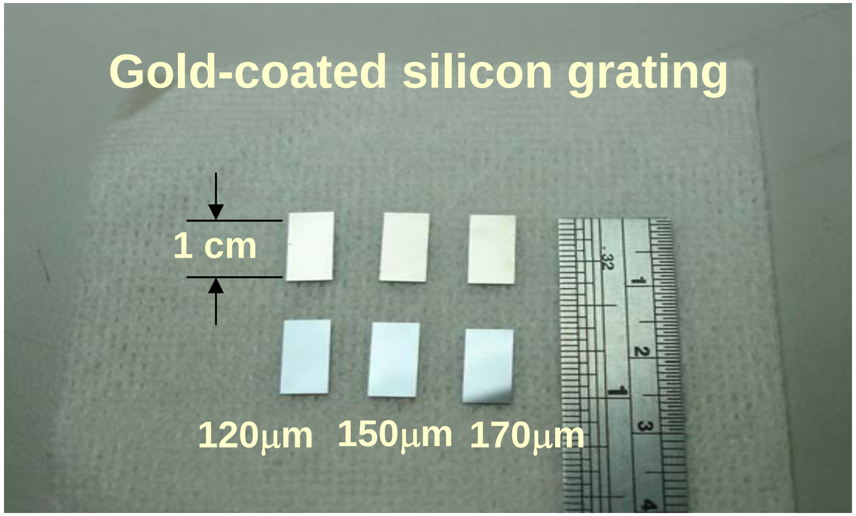


Power enhancement factor 2×10^4 (!)using B^3 technique

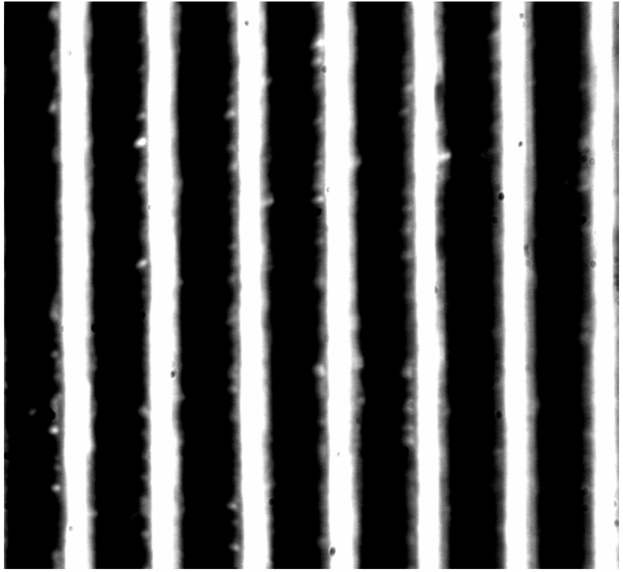
Y. Y. Lin et al., Proceedings 2005 FEL Conference, Stanford U., Aug. 22-26, 2005.

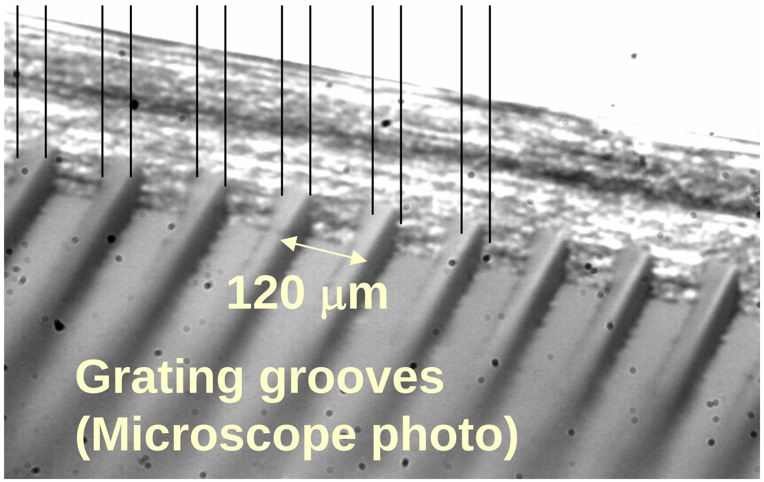
Superradiance Smith-Purcell FEL: components

Y. Y. Lin et al., Proceedings 2005 FEL Conference, Stanford, Aug. 22-26, 2005.



Gold-coated silicon grating

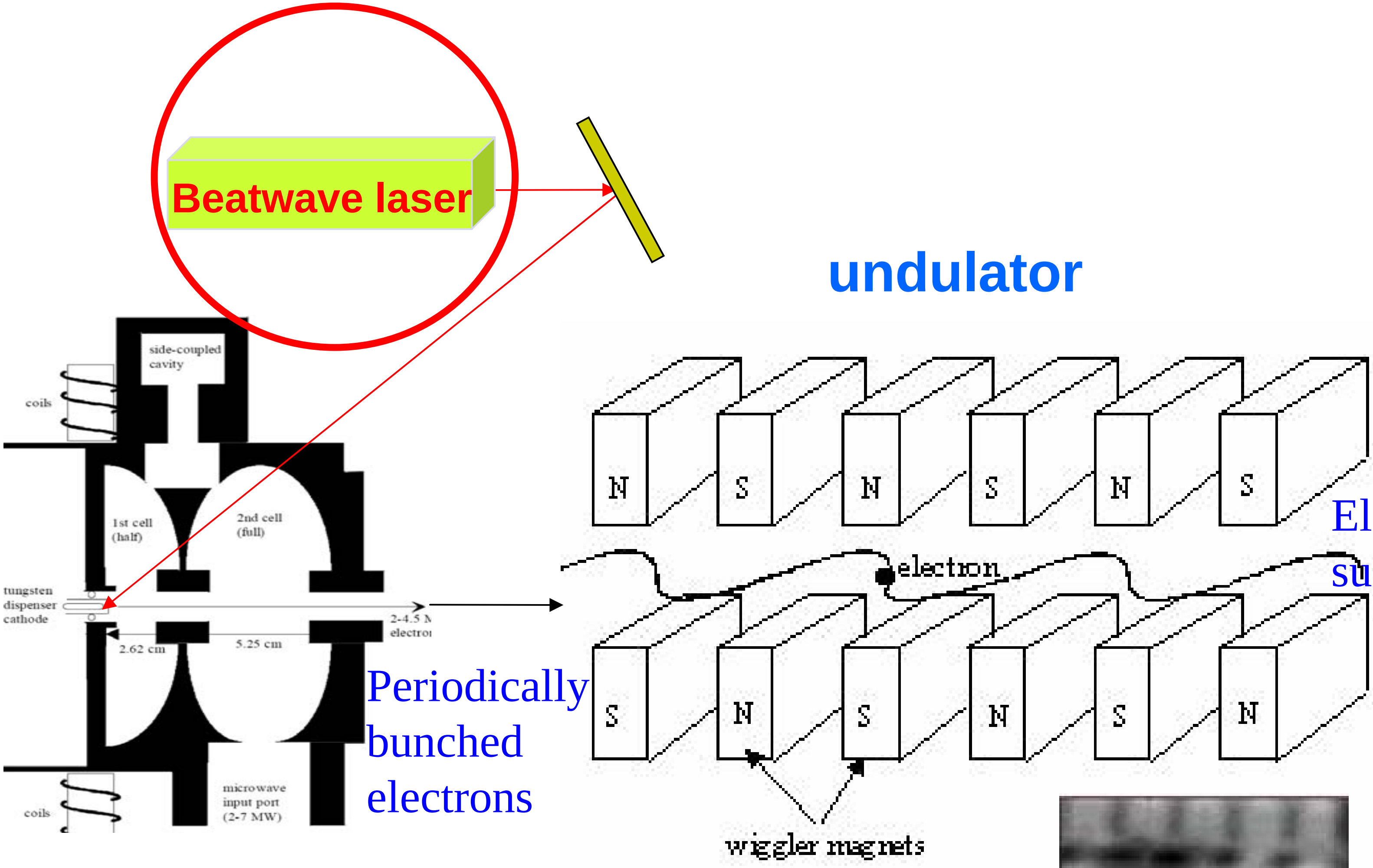




Grating grooves
(Microscope photo)

Electron gun:
30-50 keV with 2-3 mA

10-100 kW, THz Superradiance Free-electron Laser



Beatwave laser

undulator

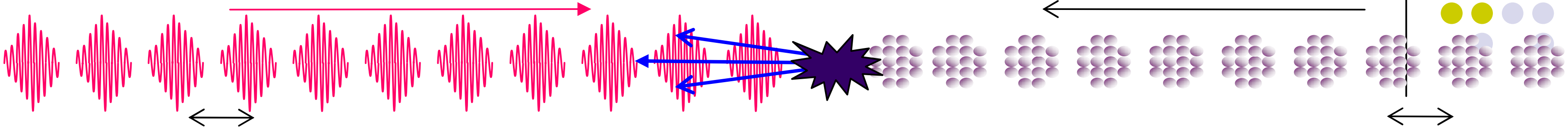
Electron superradiance

Periodically bunched electrons

2-4 MeV RF Photocathode Gun

THz medical imaging (NTHU，馬偕醫院)

Hard *x*-ray Laser Synchrotron



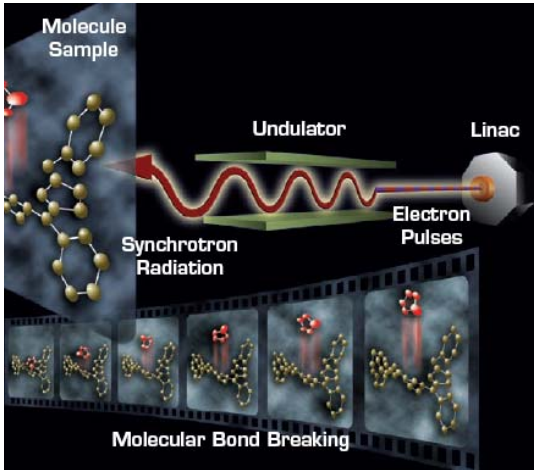
TW laser

x-ray radiation

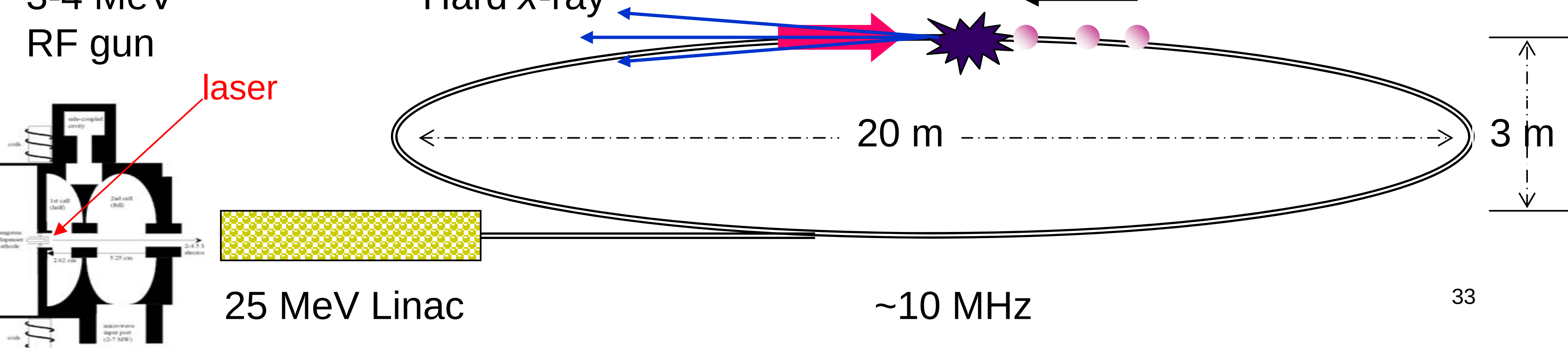
25 MeV beam

350 ps

350 ps



X-ray wavelength **1 Å**
10^{10} photons/collision
10^{17} photons/sec



3-4 MeV
RF gun

laser

Hard *x*-ray

TW laser

25 MeV beam

20 m

3 m

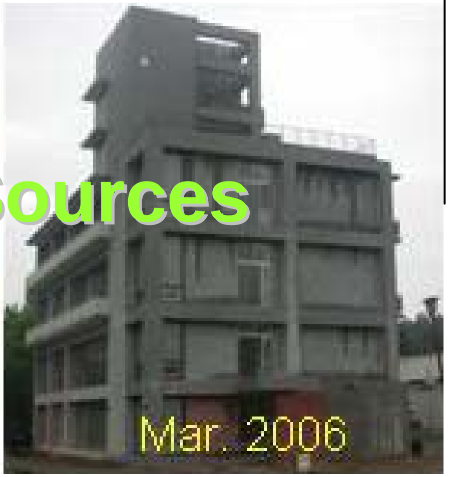
25 MeV Linac

~10 MHz

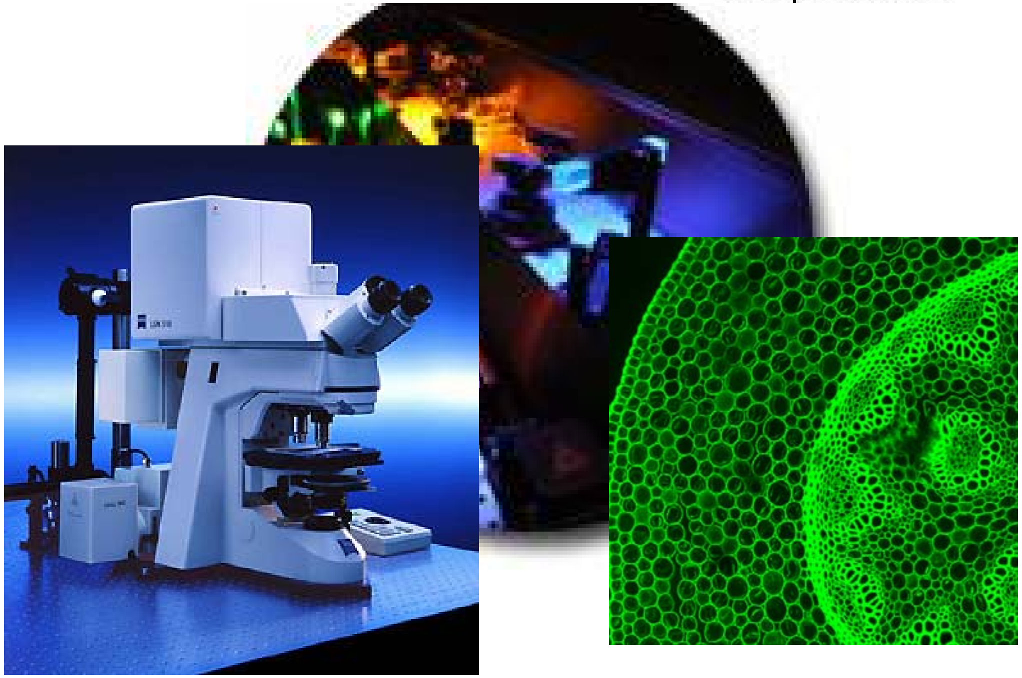
NTHU Relativistic Photonics Research Laboratory

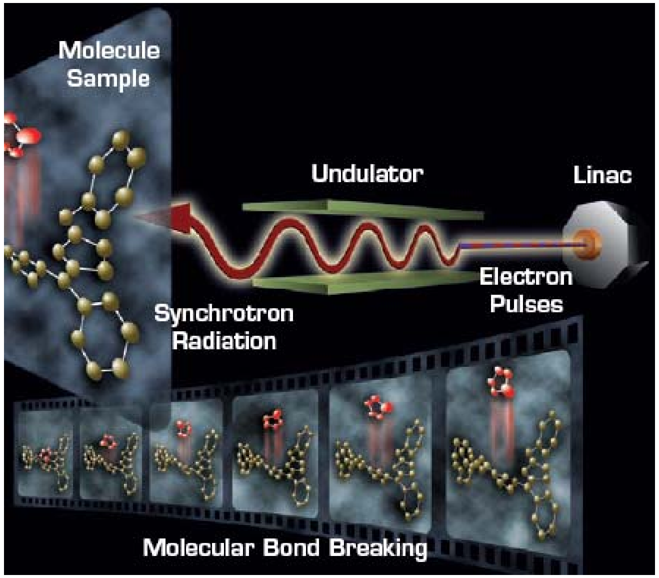

Jan. 2005


Sep. 2005


Mar. 2006

X-ray, UV, Visible, IR, THz Sources





Bio-molecular and Bio-medical Imaging Core Facility

(Courtesy of 奈米中心 齊正中主任) 楊尙達、楊士禮、林凡異、江安世、高甫仁

Thank you for your attention

歡迎加入跨領域研究

雷射光電、加速器物理、相對論電子輻射、
生物醫學影像