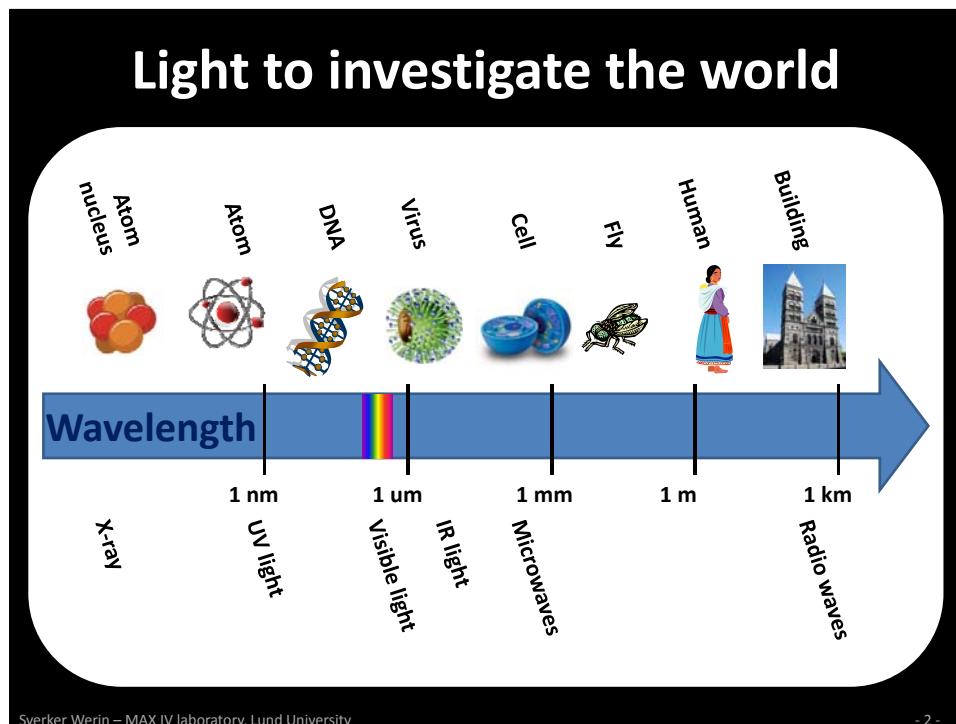


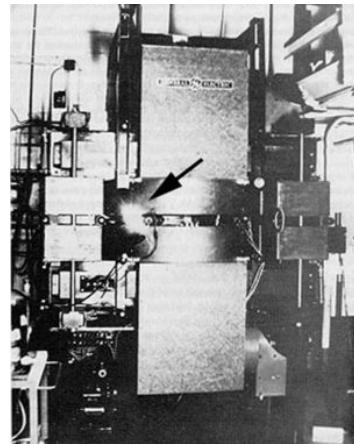
Production of synchrotron radiation

Sverker Werin
MAX IV laboratory,
Lund university

First discovery of SR 1947

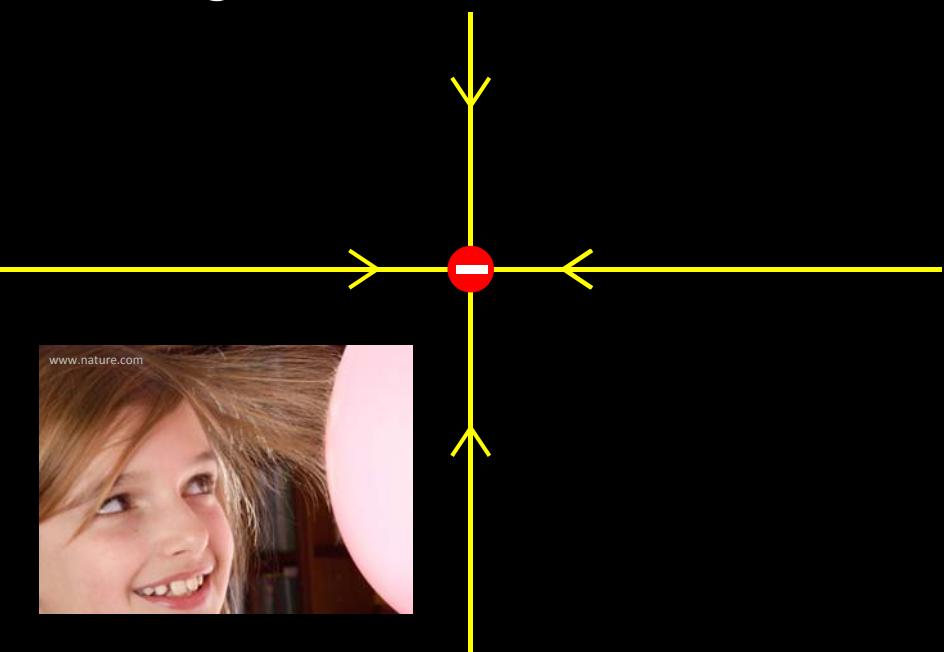
"On April 24, Langmuir and I were running the machine ... we asked the technician to observe with a mirror around the protective concrete wall." (Herb Pollock)

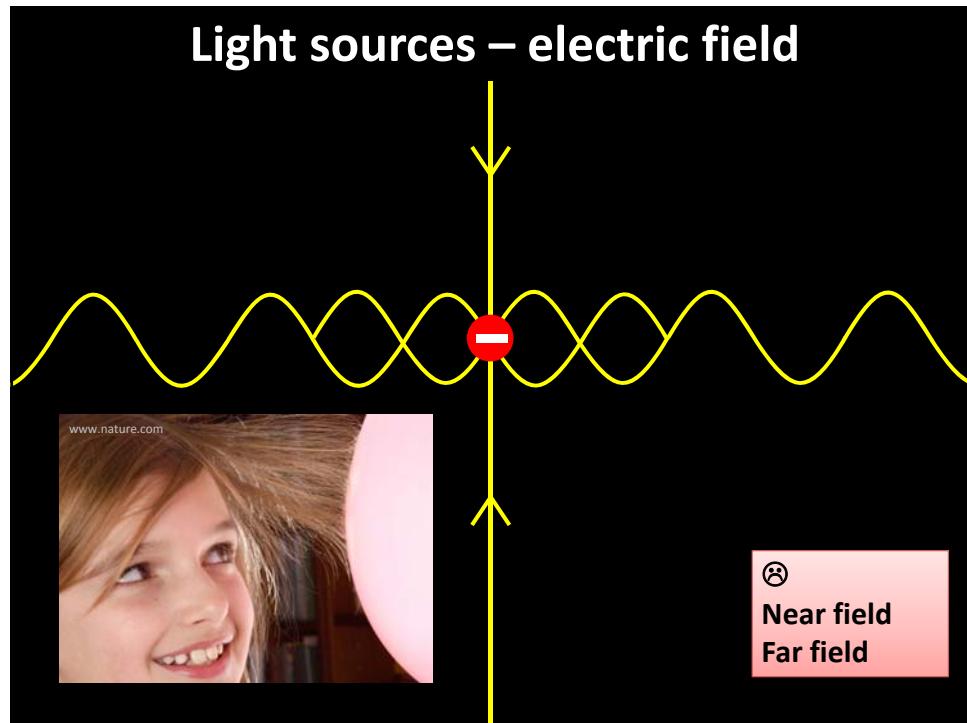


General Electric Research Laboratory,
Schenectady, NY, US

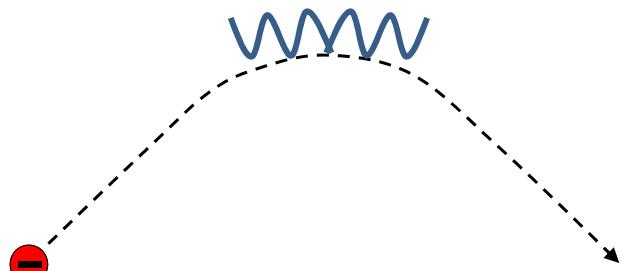
- 3 -

Light sources – electric field

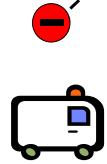




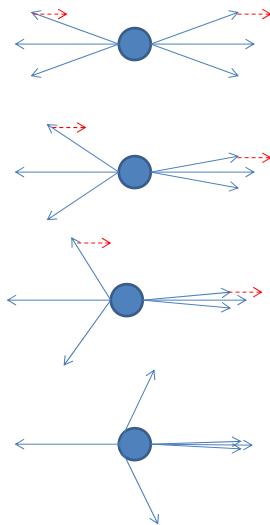
Dipole radiation (antenna)



Dipole radiation (relativistic)



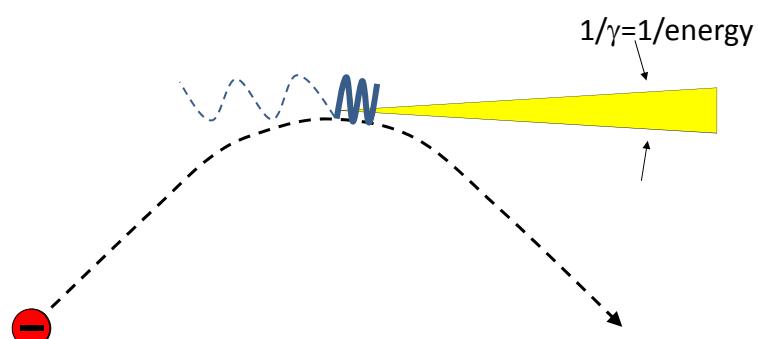
Dipole radiation (relativistic)

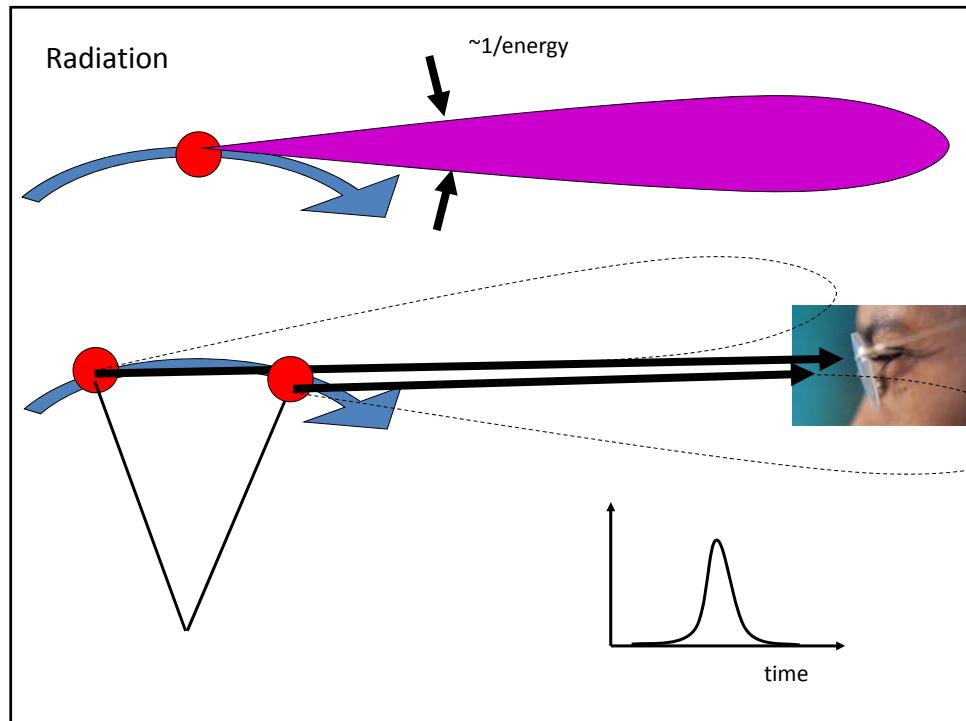
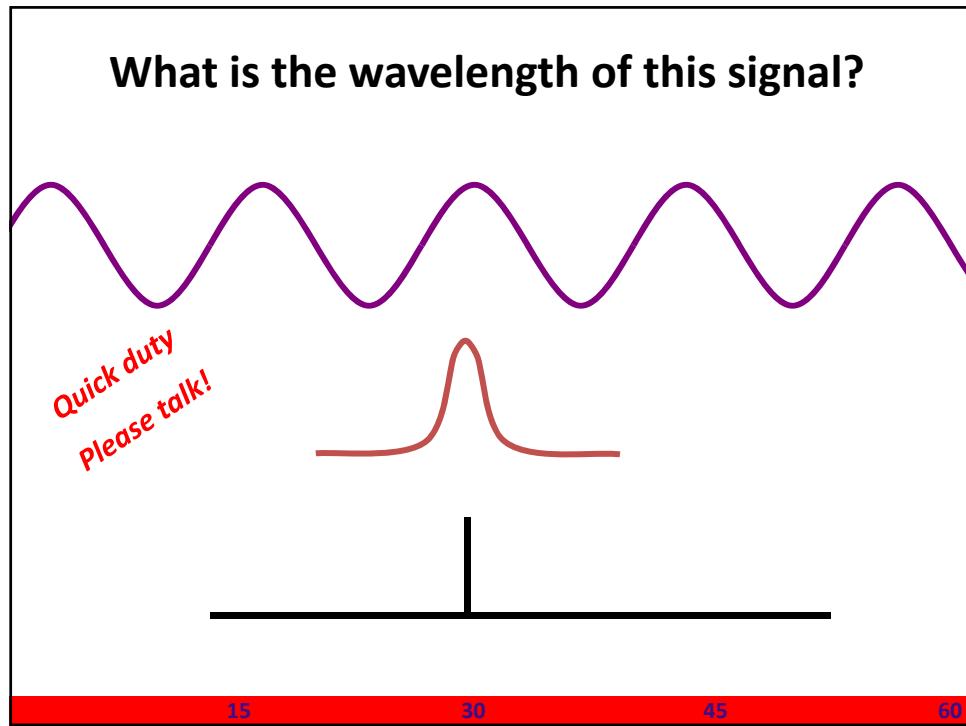


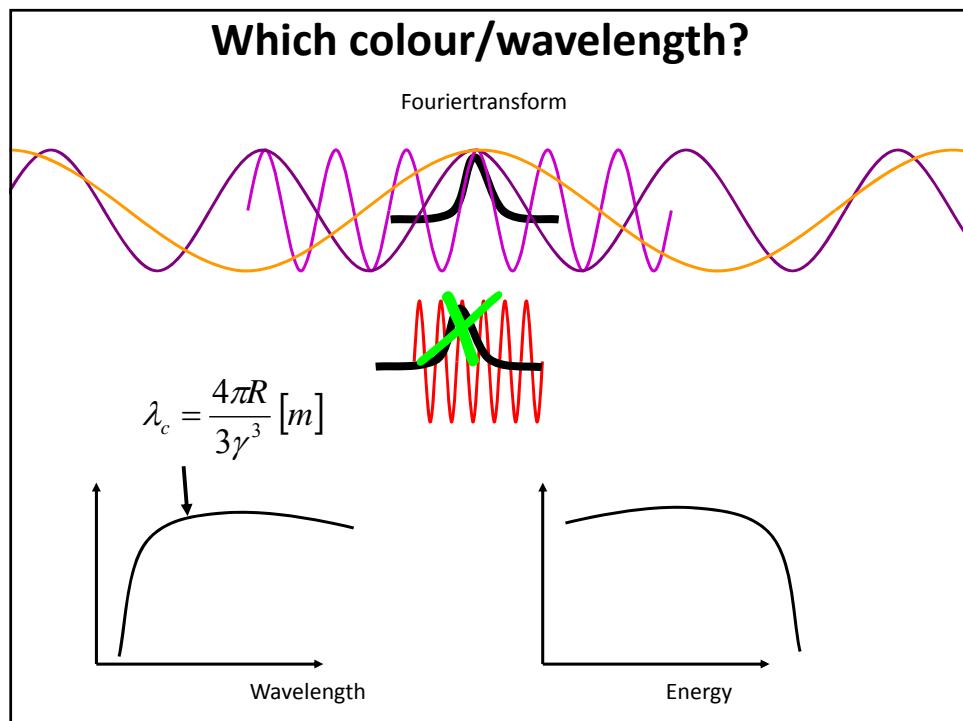
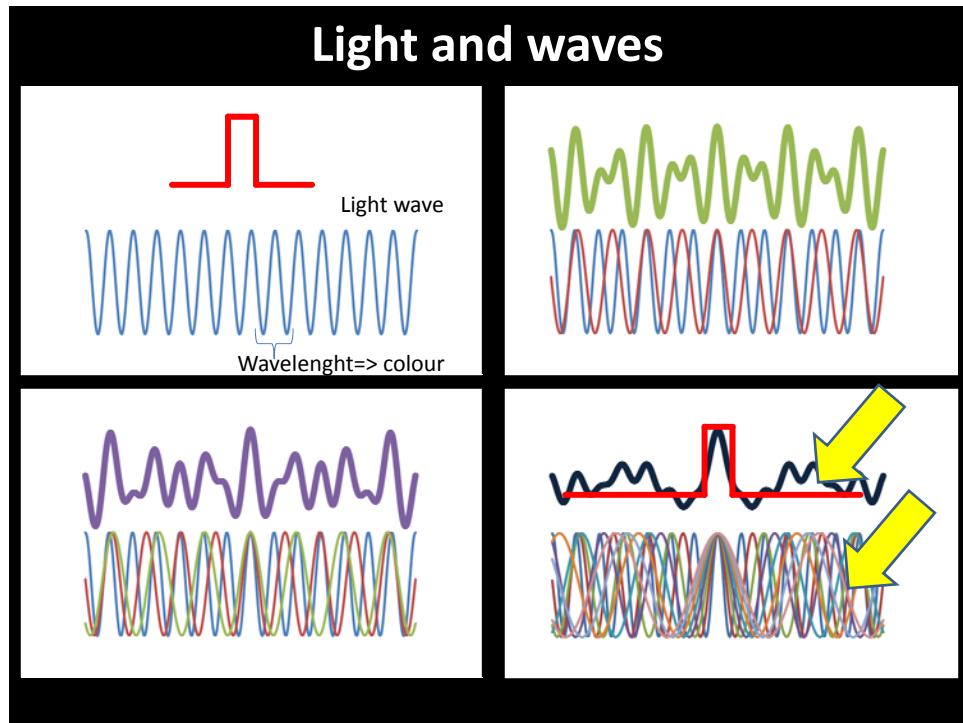
Sverker Weren – MAX IV laboratory, Lund University

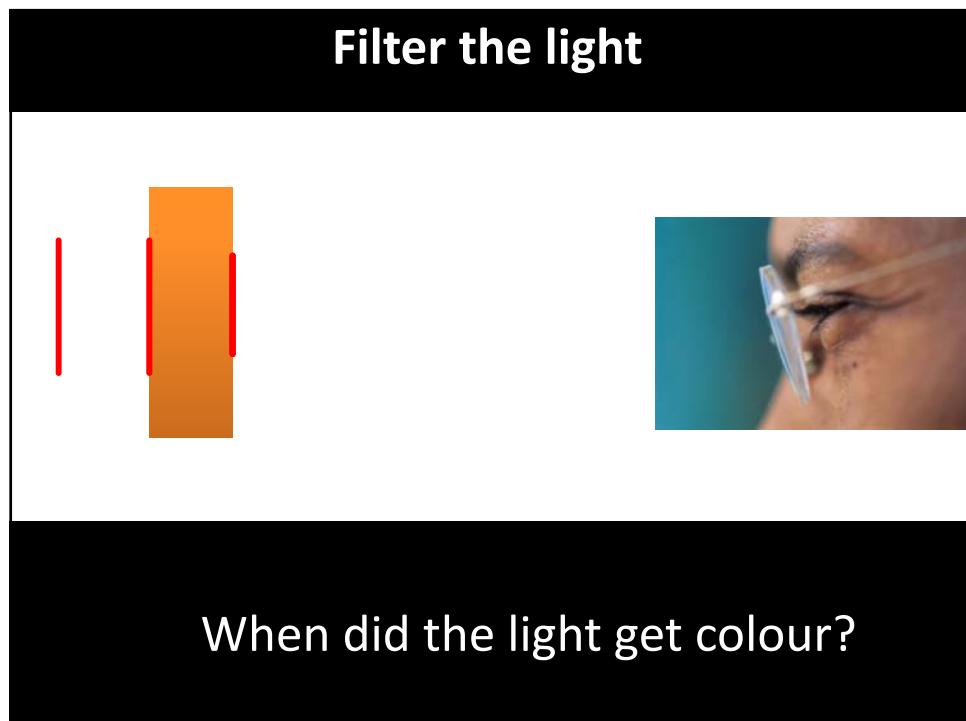
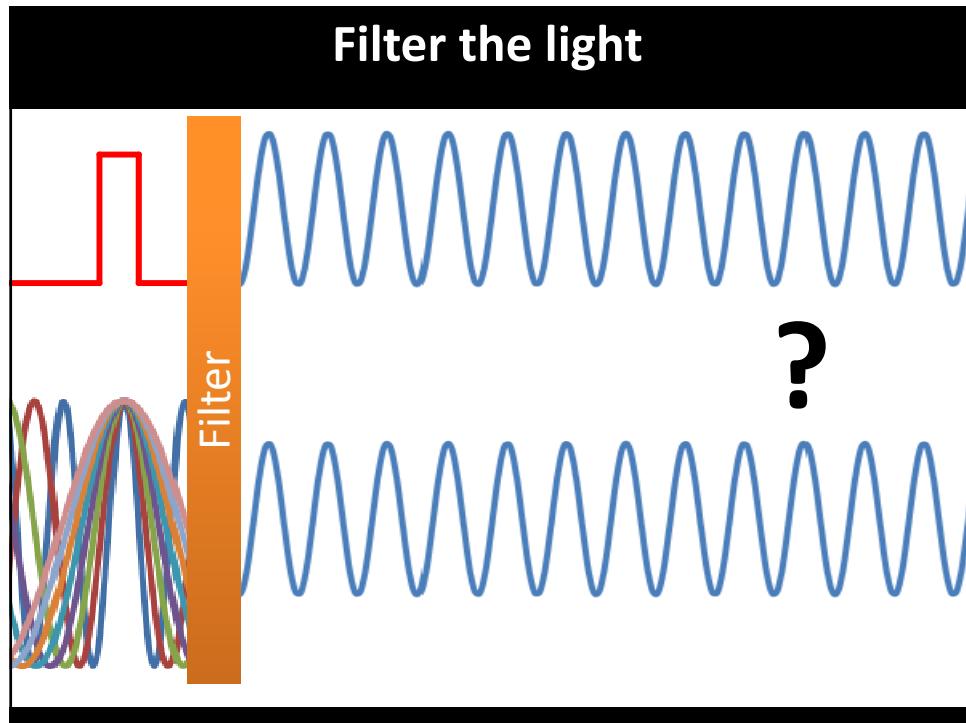
- 9 -

Dipole radiation (relativistic)



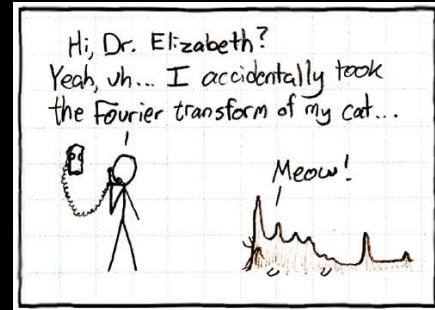






... and in "fancy" language

Heisenberg's uncertainty relation



Fourier transform

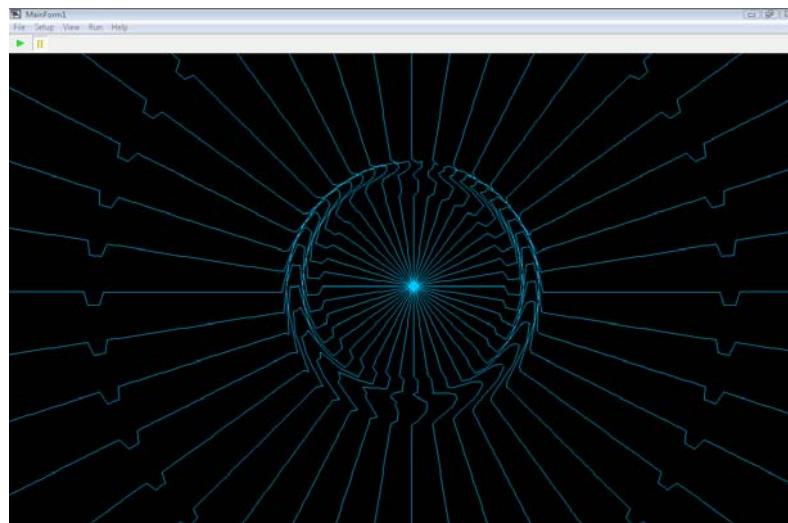
HERE LIES
HEISENBERG



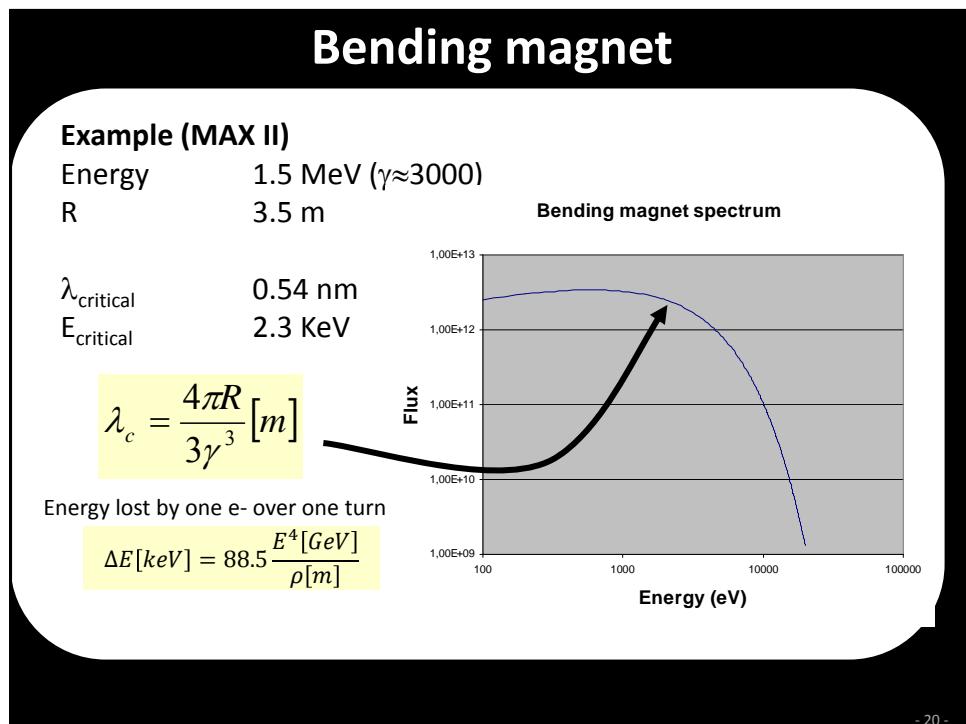
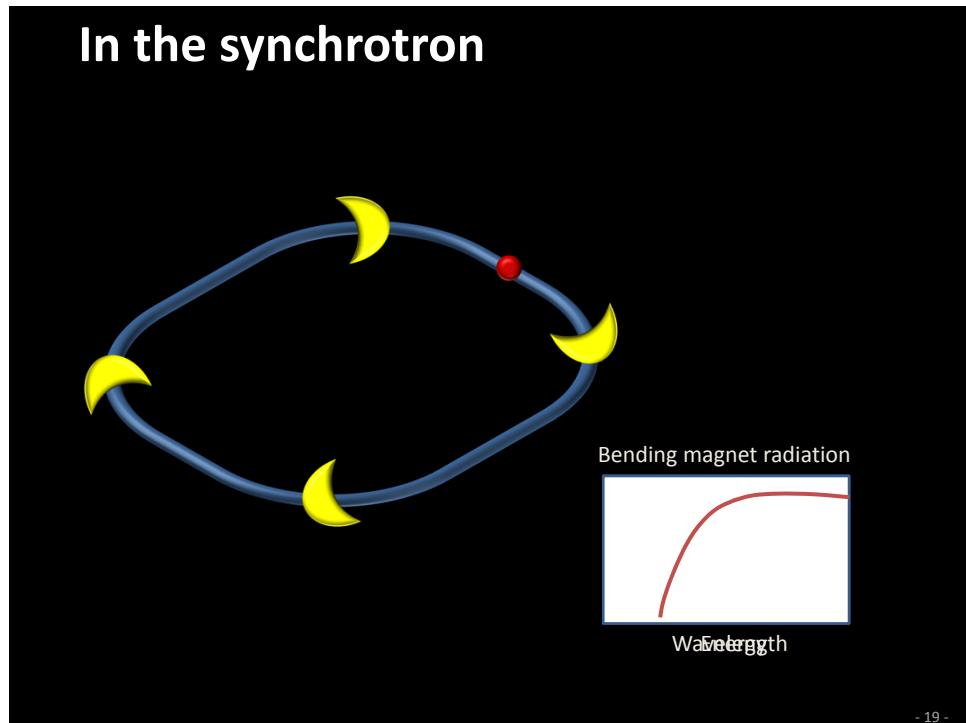
$$\Delta p \Delta x \geq \frac{1}{2} \hbar$$

$$\Delta E \Delta t \geq \frac{1}{2} \hbar$$

Radiation 2D by T. Shintake



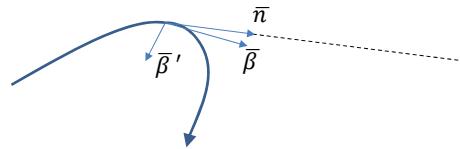
<http://www.shintakelab.com/en/enEducationalSoft.htm>



Liénard-Weichert fields

$$\bar{E}(\bar{r}, t) = \frac{e}{4\pi\epsilon_0} \left[\frac{\hat{n} - \bar{\beta}}{\gamma^2 R^2 (1 - \bar{\beta}\hat{n})^3} + \frac{\hat{n} \times [(\hat{n} - \bar{\beta}) \times \bar{\beta}']}{cR (1 - \bar{\beta}\hat{n})^3} \right]_{ret}$$

near far



- 21 -

No questions?

Polarisation

E field in direction of acceleration → polarisation
Changes with observation plane

$$\begin{cases} \frac{d}{dt}(\gamma m_o \vec{v}) = q (\vec{E} + \vec{v} \times \vec{B}) \\ \frac{d}{dt}(\gamma m_o c^2) = q \vec{v} \cdot \vec{E} \end{cases}$$

$\vec{a} \propto q \vec{E}$

- 23 -

Time structure

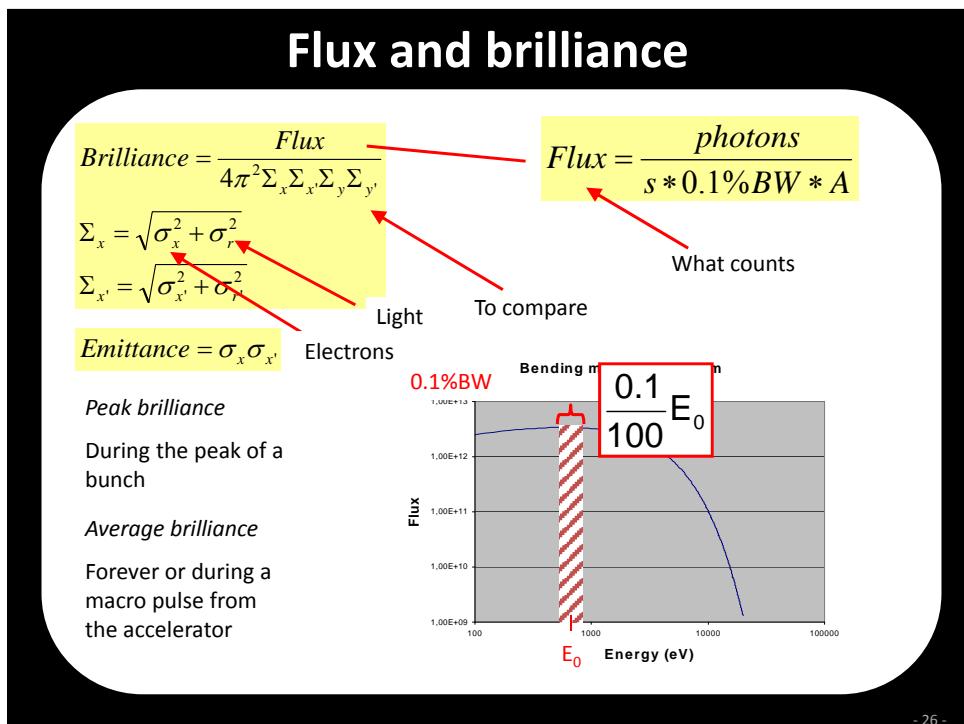
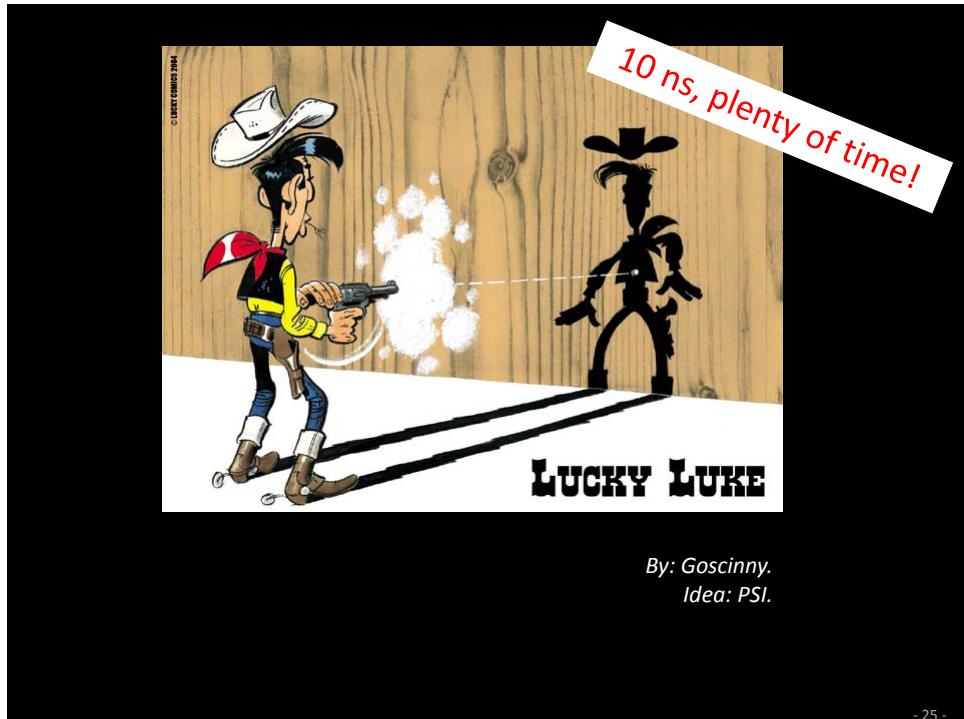
RF system	Storage ring	100-300 ps
500 MHz	MAX IV SPF	100 fs
100 MHz	Slicing	50 fs
	Free Electron Laser	20 fs

Multi bunch

Single bunch

Uneven fill patterns

- 24 -



Think of a gaussian light beam...

$\sigma_\phi = \frac{\lambda}{2\pi w_0} = \sigma_r$

$w_0 = \sigma_r$

Define a quality factor:

$$\sigma_r \sigma_{r'} = \frac{\lambda}{2\pi}$$

Fundamental feature of light!
(=nothing to do about it ;-)

E-field or intensity?
Spherical or cartesian?
(factors of 2 and $\sqrt{2}$)

Today's challenge
for development

...and then of an electron beam.

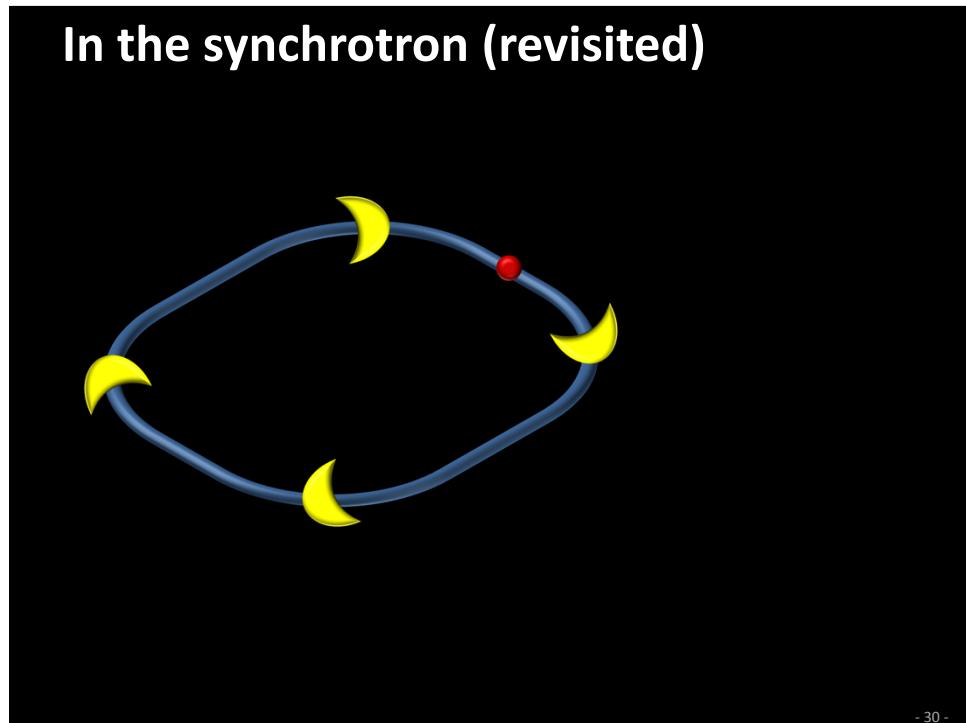
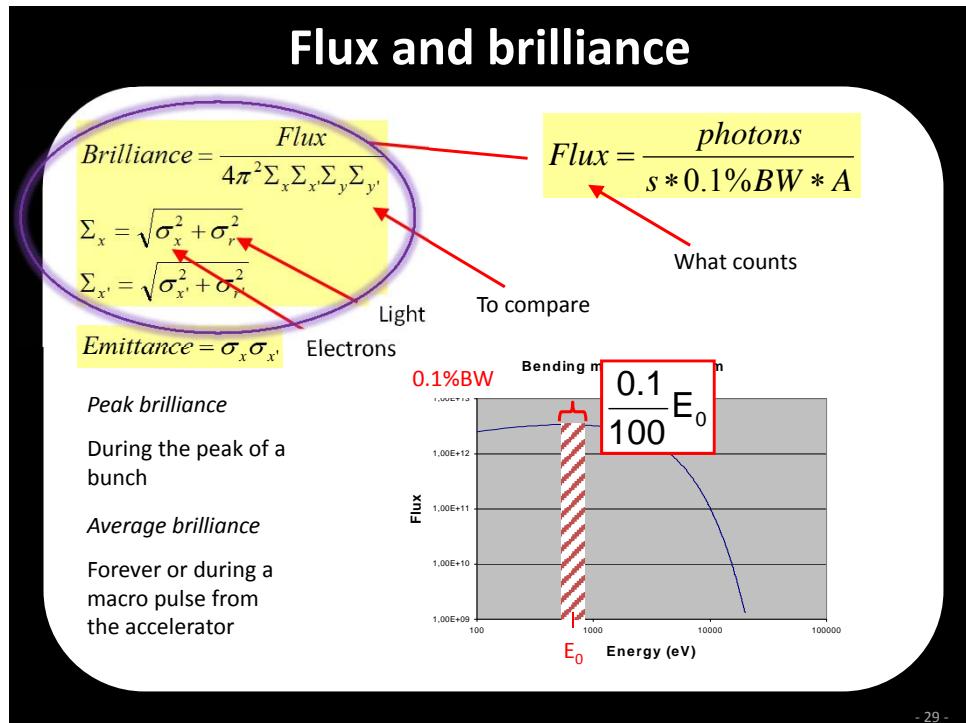
$\sigma_x \sigma_{x'} = \varepsilon$

Emittance

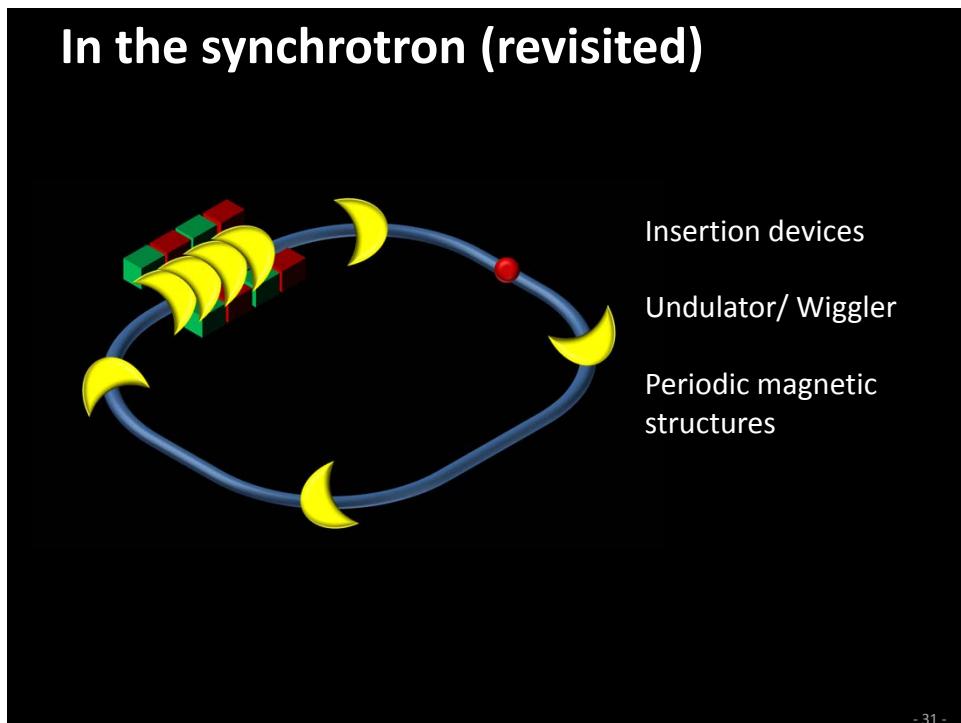
The goal for the accelerator designer is to make the electron beam "smaller" than the light diffraction:

$$\sigma_r \sigma_{r'} = \frac{\lambda}{2\pi} > \varepsilon = \sigma_x \sigma_{x'}$$

But, increasingly difficult for shorter and shorter wavelengths.

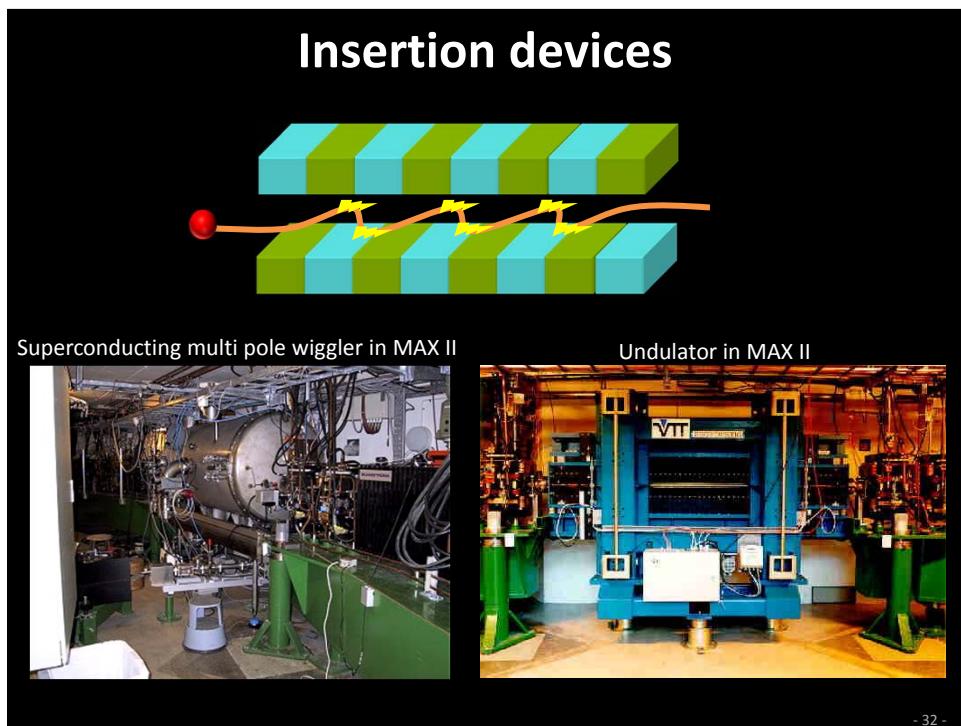


In the synchrotron (revisited)



- 31 -

Insertion devices



- 32 -

A wiggler

$$\lambda_c = \frac{4\pi R}{3\gamma^3} [m]$$

$$R = \frac{mv}{qB} [m]$$

- Shorter wavelength / higher photon energy
- 3 or many strong magnets
- Flux is the **sum** (no interference)

Bending magnet spectrum

- 33 -

Undulator

$$\lambda_{light} = \frac{\lambda_{undulator}}{2\gamma^2} \left(1 + \frac{K^2}{2} + \gamma^2 \theta^2 \right)$$

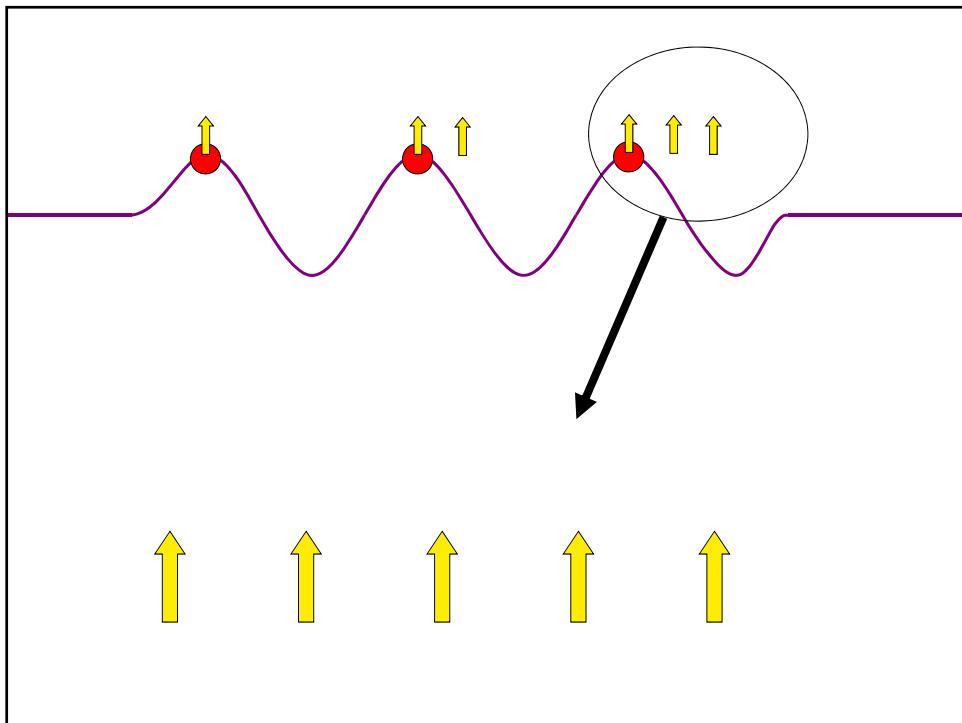
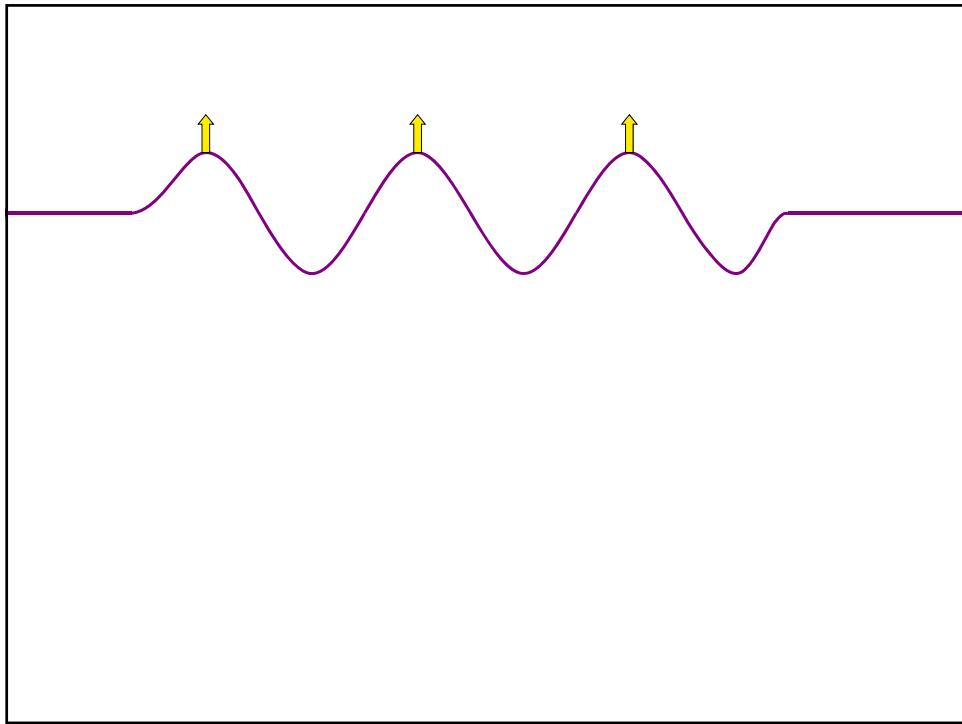
K = undulator parameter, typically between 1 and 4

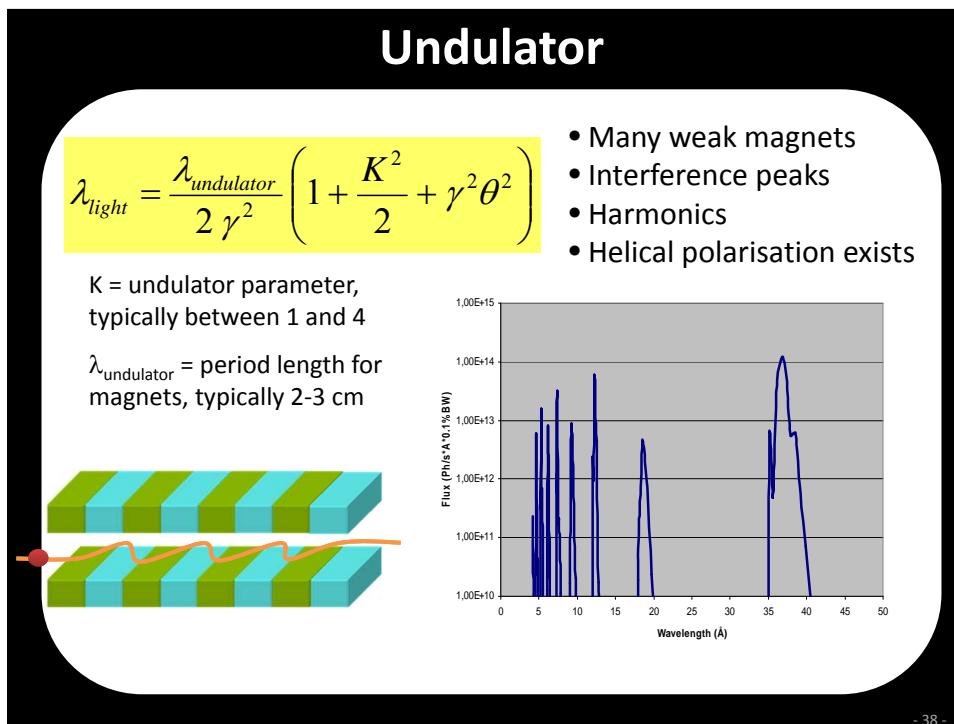
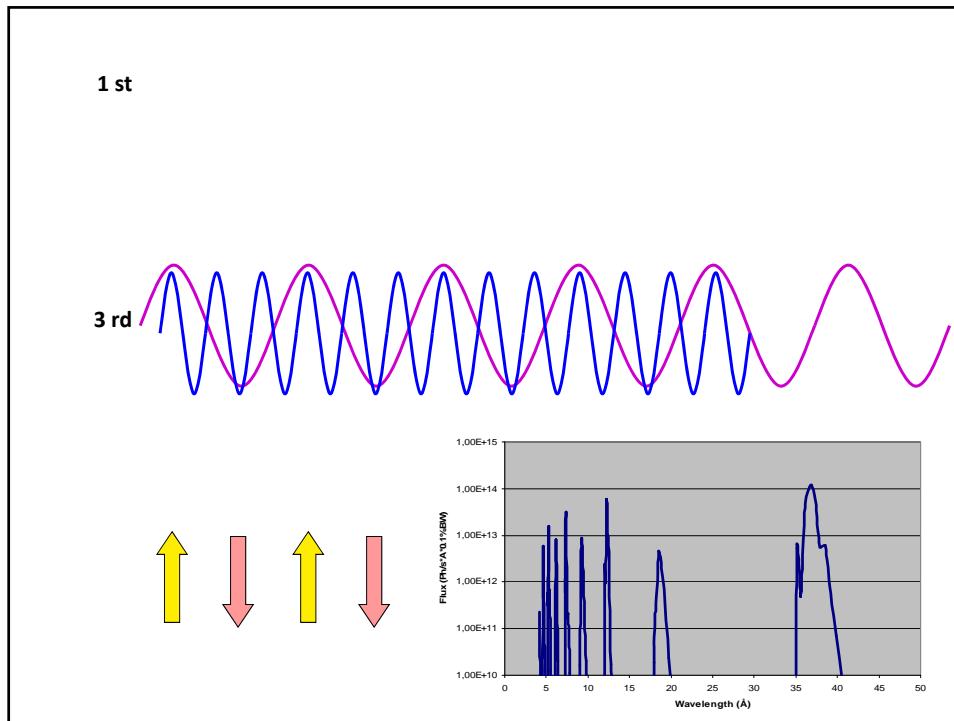
$\lambda_{undulator}$ = period length for magnets, typically 2-3 cm

- Many weak magnets
- Interference peaks
- Harmonics
- Helical polarisation exists

Bending magnet spectrum

- 34 -





Linewidth, energy and angular spread

$$\frac{\Delta\lambda}{\lambda}_{Natural} = \frac{1}{iN}$$

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

$$\frac{\Delta\lambda}{\lambda} = \sqrt{\left(\frac{\Delta\lambda}{\lambda}_{Nat}\right)^2 + \left(\frac{\Delta\lambda}{\lambda}_{Angle}\right)^2 + \left(\frac{\Delta\lambda}{\lambda}_{Energy}\right)^2 + \left(\frac{\Delta\lambda}{\lambda}_{U errors}\right)^2 + \dots}$$

$$\frac{\Delta\lambda}{\lambda}_{Angle} = \frac{d\lambda}{d\theta} \frac{d\theta}{\lambda} = \frac{2\gamma^2}{1+K^2/2} \theta^2$$

$$\frac{\Delta\lambda}{\lambda}_{Energy} = \frac{d\lambda}{d\gamma} \frac{d\gamma}{\lambda} = \frac{2\Delta\gamma}{\gamma}$$

Why wiggler, why undulator?

MAX II SC MPW
(Super Conducting Multi Pole Wiggler)

Period = 0.06 m

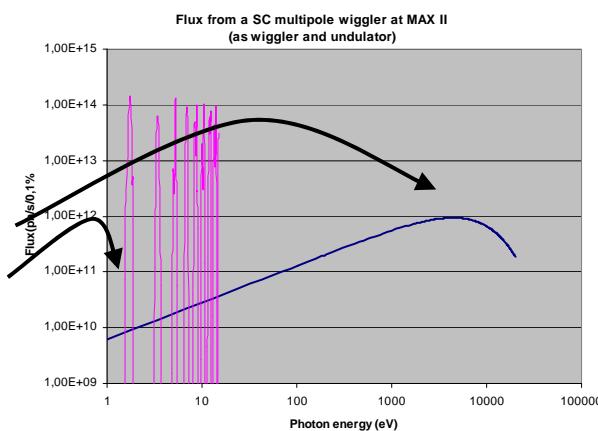
K = 20

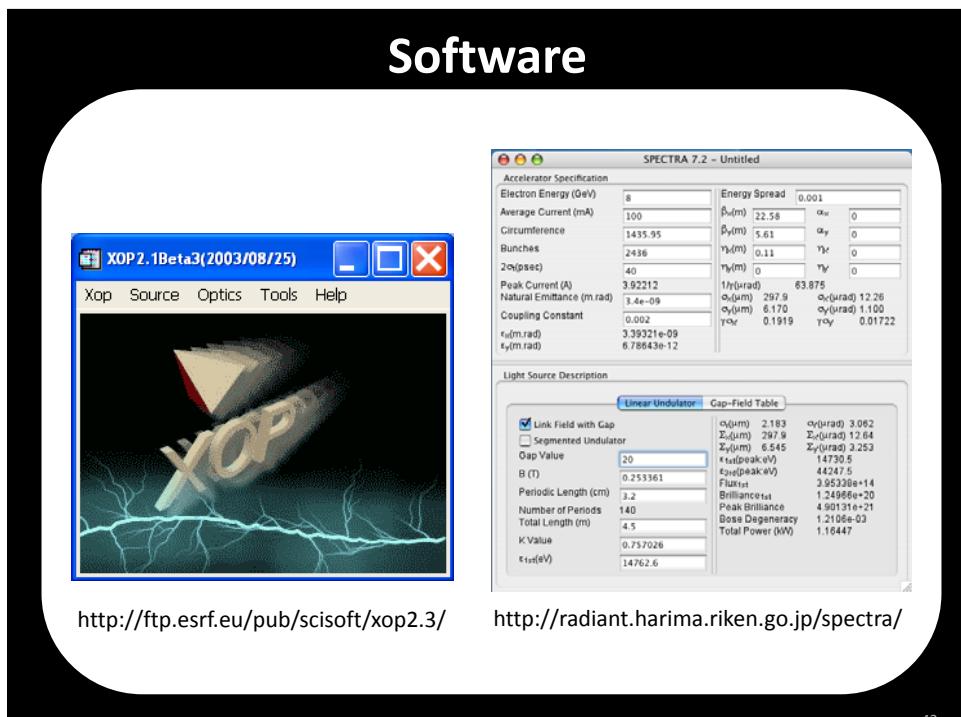
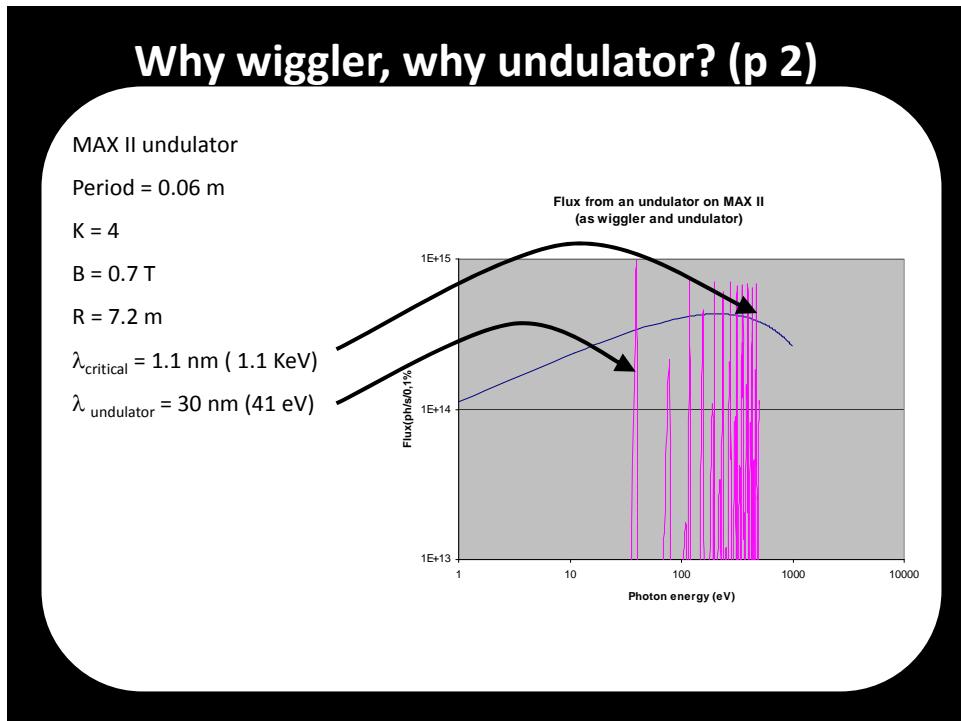
B = 3.5 T

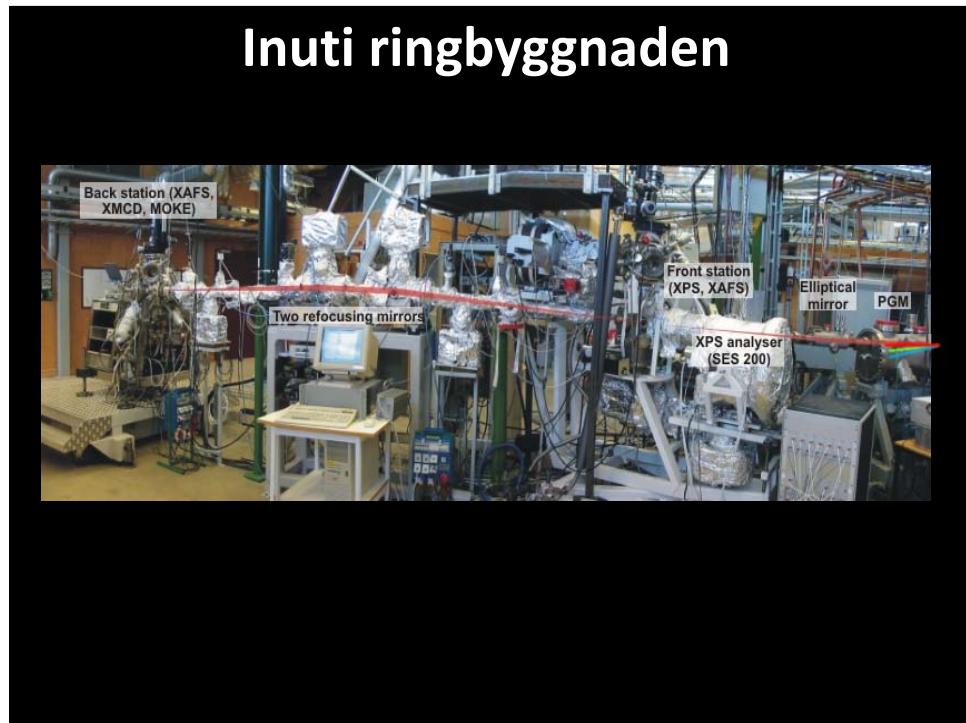
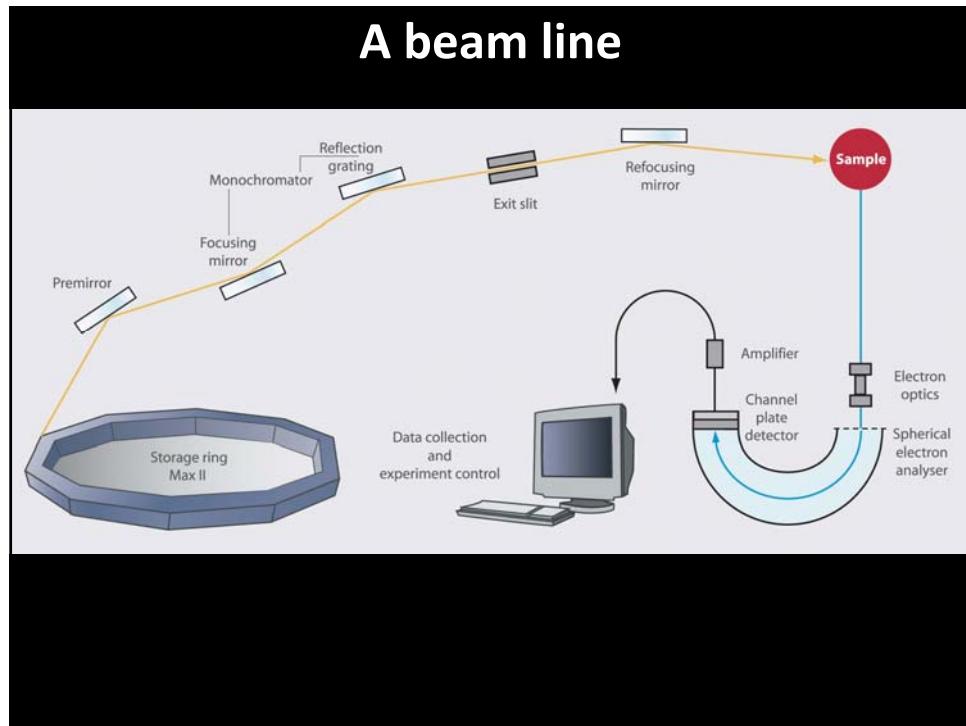
R = 1.4 m

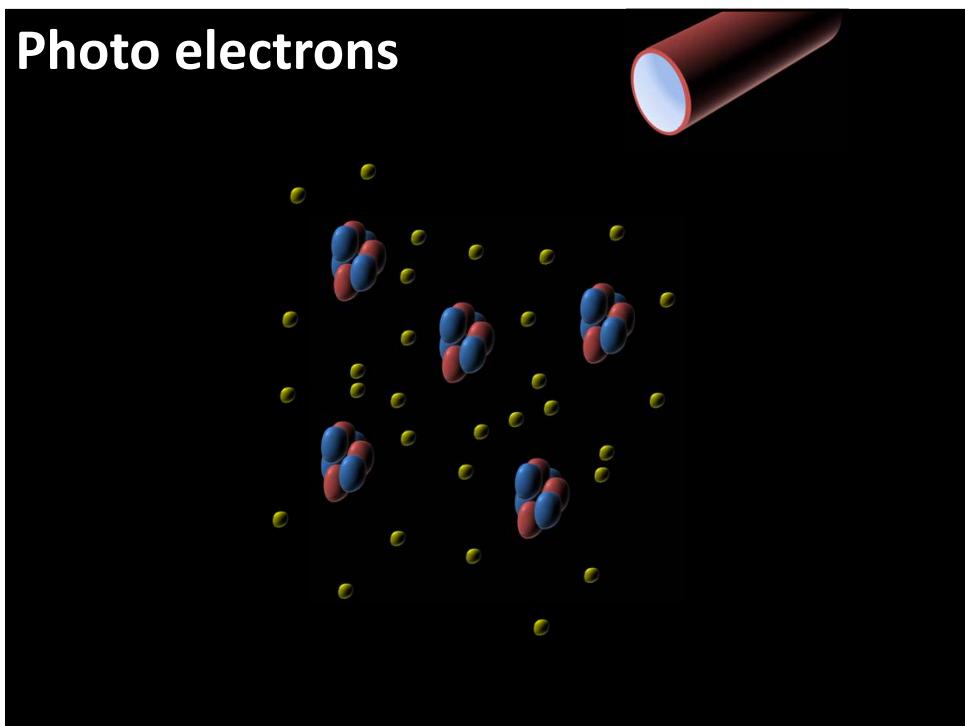
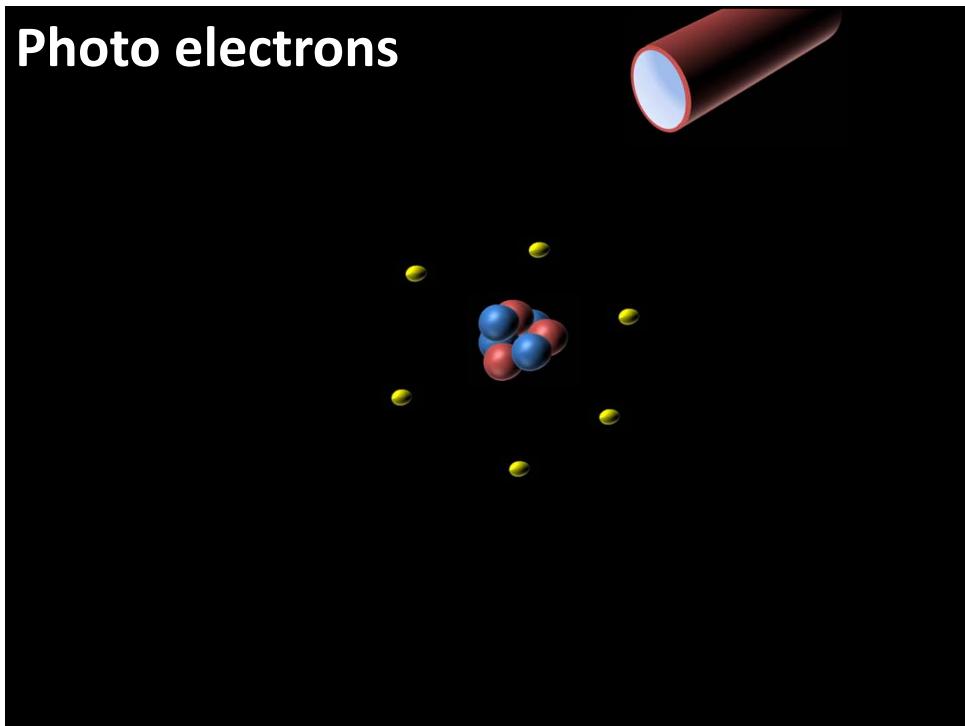
$\lambda_{critical} = 0.22$ nm (5.6 KeV)

$\lambda_{undulator} = 670$ nm (1.8 eV)

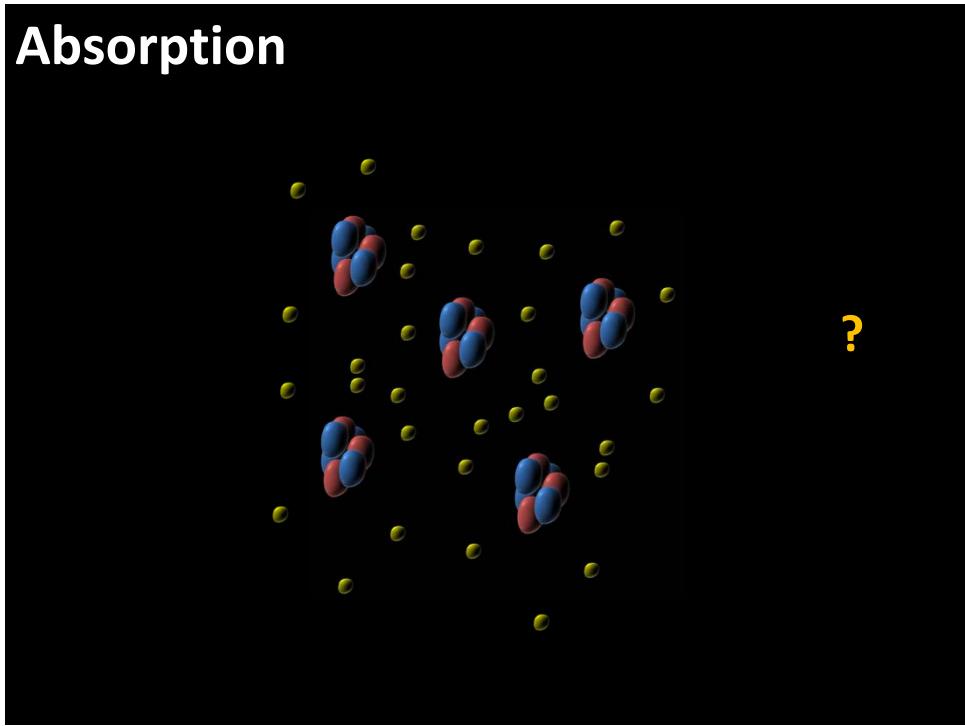




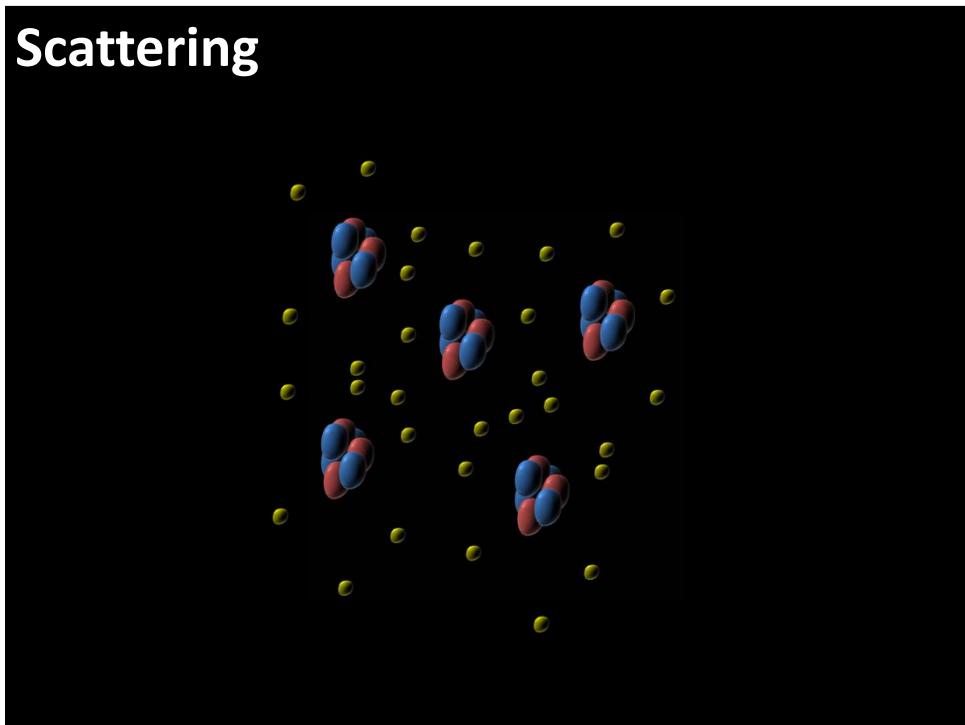




Absorption



Scattering

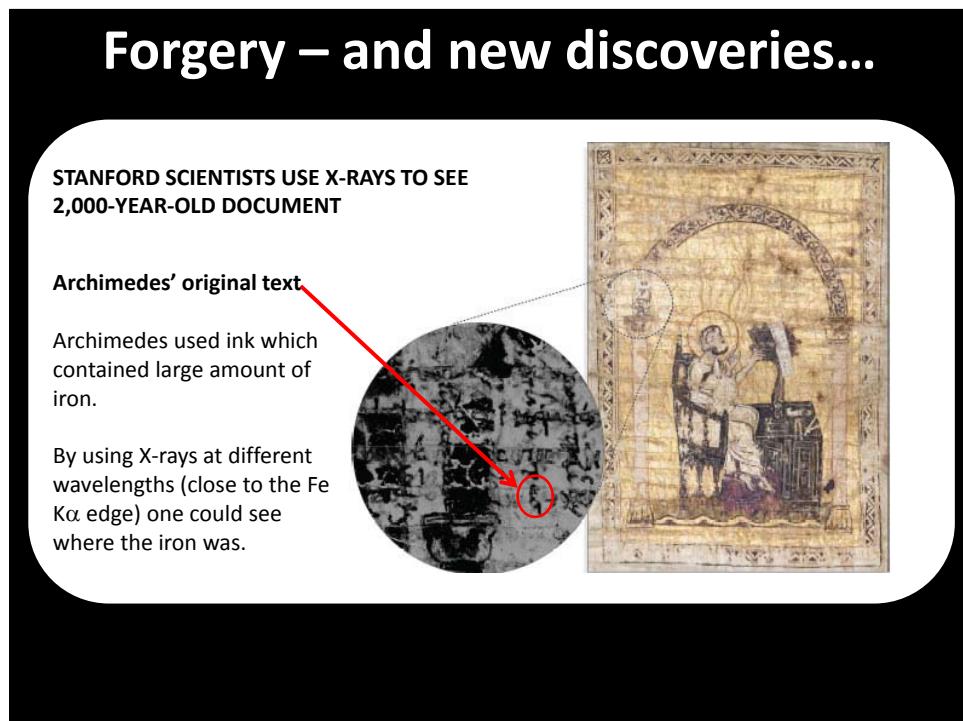
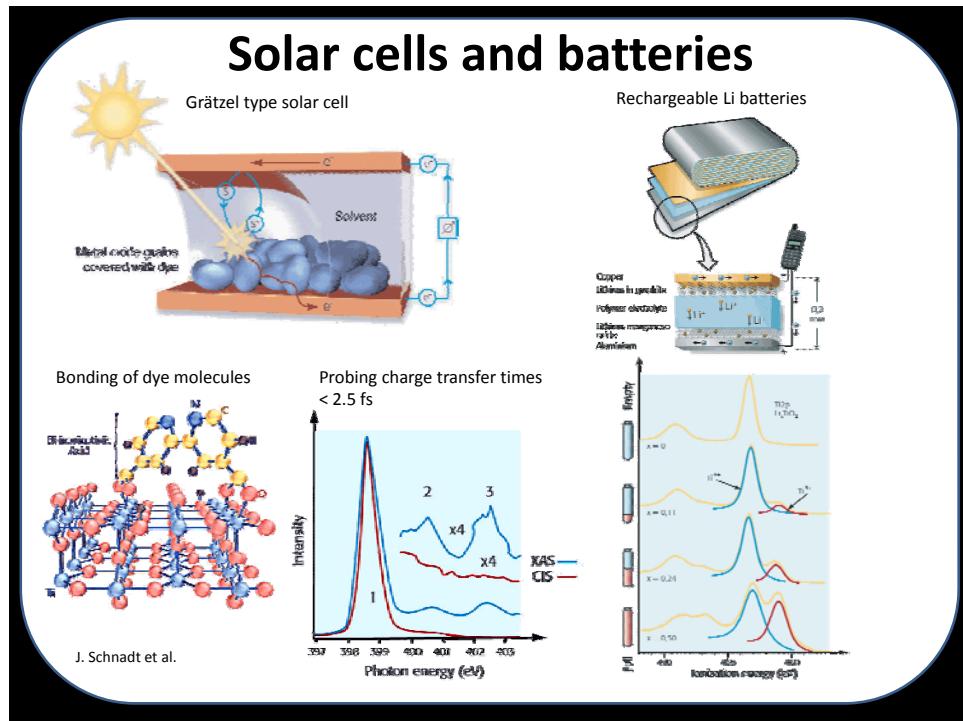


Rhodium

Geometry and chemicals bonds with the help of photon spectroscopy

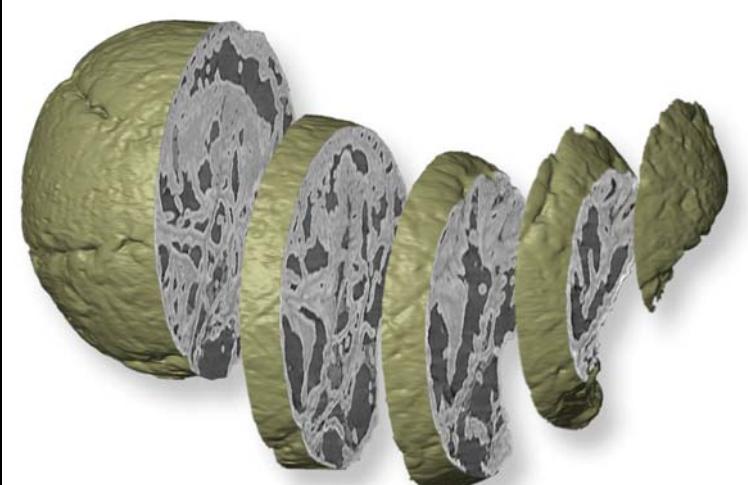
The Ribosome structure and function

2009 years Nobelprice in Chemistry
Venkatraman Ramakrishnan, Thomas A. Steitz och Ada E. Yonath



Petrified embryo of animals

... the greatest invention since sliced bread!!!



Free Electron Laser

What is an FEL?

Why an FEL?

How does it work?

Why an FEL?

Let us start dreaming...

X-ray image 

Hologram, 3D image 

What happens if we combine them?

See atoms and molecules 

Movie of moving objects 

<http://www.mnh.si.edu> <http://earthographics.blogspot.se> <http://www.netanimations.net> <http://dev.nsta.org>

What is an FEL?

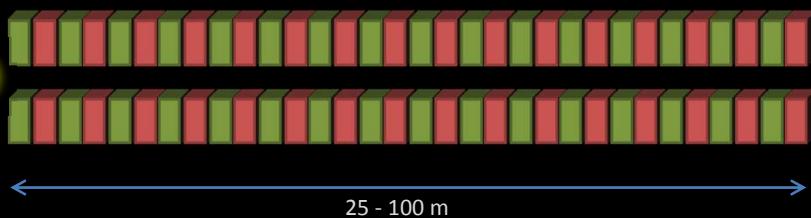
Synchrotron light

- Incoherent
- "Long" pulses (100 ps)
- High average power
- Ring
- Electrons
- Undulators

Free electron laser

- Coherent
- Short pulses (10 fs)
- High peak power (GW)
- Linear accelerator
- Electrons
- Undulators

How does it work? In principle it is fairly simple!



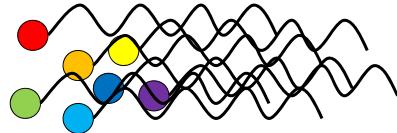
Make the electron beam slightly better:

- Reduce the emittance 50 times
- Reduce the pulse length 1000 times
- Accelerate a little more
- Fix a little higher stability and filter
- ...

Still no questions?

Emission of light and coherence

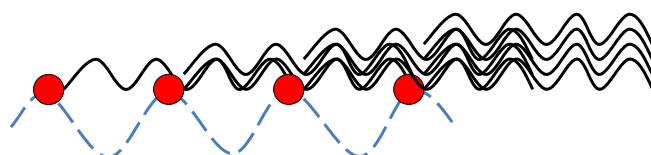
A bunch of electrons



$$E = \cos(\omega t + \phi_1) + \cos(\omega t + \phi_2) + \dots$$

Emission of light and coherence

A single electron in an undulator



$$E = \cos(\omega t + \phi_1) + \cos(\omega t + \phi_1 + 2\pi) + \dots$$

$$I = E^2 = \cos^2(\omega t + \phi_1) + \cos^2(\omega t + \phi_1 + 2\pi) + \dots$$

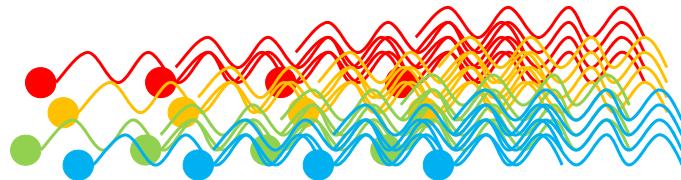
$$\dots + \cos(\omega t + \phi_1) \cos(\omega t + \phi_1 + 2\pi) + \dots =$$

$$= N_{\text{magnets}}^2 \cos^2(\omega t + \phi_1)$$

$$\underline{\underline{N_{\text{magnets}} = 100}}$$

Emission of light and coherence

A bunch of electrons in an undulator



$$E = \cos(\omega t + \phi_1) + \cos(\omega t + \phi_1 + 2\pi) + \dots$$

$$I = E^2 = \cos^2(\omega t + \phi_1) + \cos^2(\omega t + \phi_1 + 2\pi) + \dots$$

$$\dots + \cos(\omega t + \phi_1) \cos(\omega t + \phi_1 + 2\pi) + \dots =$$

$$= N_{\text{magnets}}^2 N_{\text{electrons}} \cos^2(\omega t + \phi_1)$$

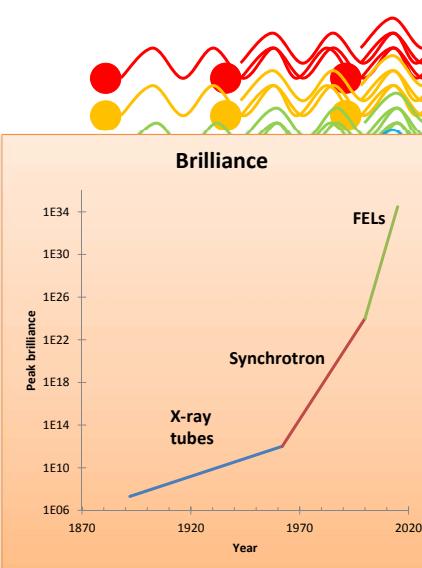
$$N_{\text{magnets, undulator}} = 100$$

$$N_{\text{electrons}} = 10^8$$

MAX II
MAX IV

Emission of light and coherence

A micro bunched beam in an undulator



$$\cos(\omega t + \phi_1) + \cos(\omega t + \phi_1 + 2\pi) + \dots$$

$$\cos^2(\omega t + \phi_1) + \cos^2(\omega t + \phi_1 + 2\pi) + \dots$$

$$(\omega t + \phi_1) \cos(\omega t + \phi_1 + 2\pi) + \dots =$$

It can't be true!

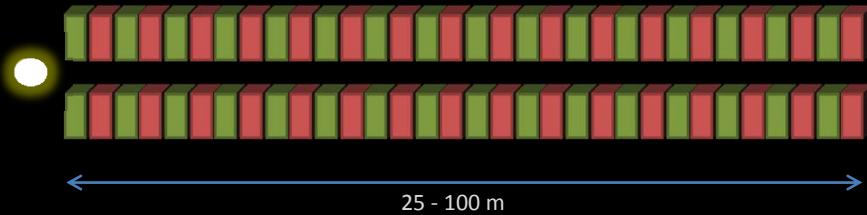
$$N_{\text{magnets}}^2 N_{\text{electrons}} \cos^2(\omega t + \phi_1)$$

$$\times 10^{20}$$

Also valid for harmonics!

How does it work?

In principle it is fairly simple!

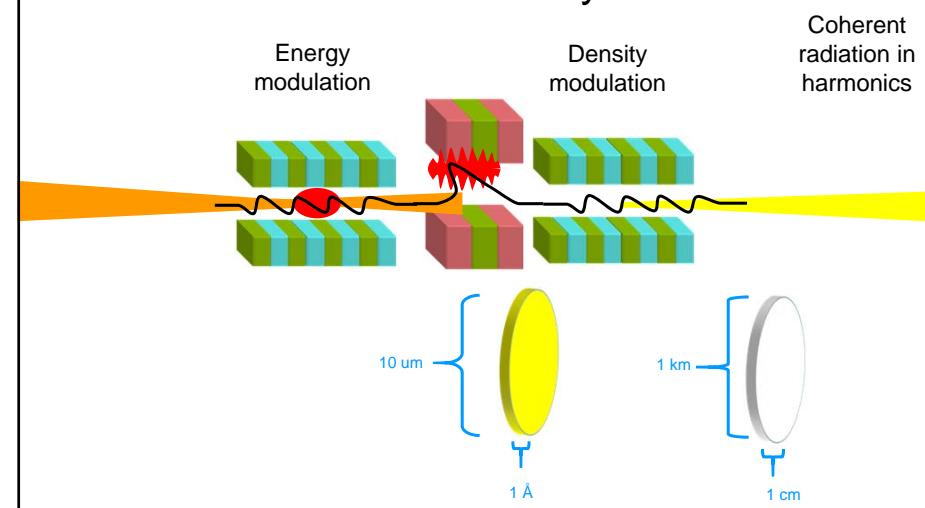


Make the electron beam slightly better:

- Reduce the emittance 50 times
- Reduce the pulse length 1000 times
- Accelerate a little more
- Fix a little higher stability and filter
- ...

How to make the bunching?

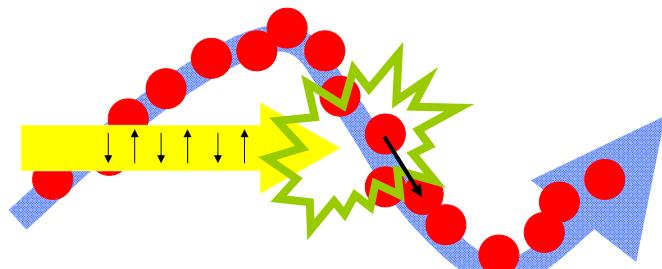
- Make an energy modulation
- Transform it into a density modulation



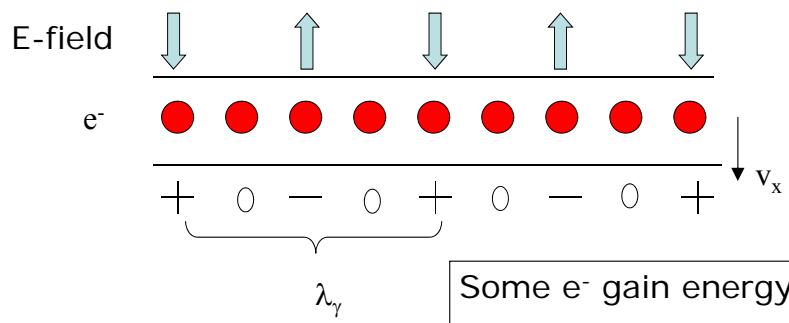
Light interacting with an electron beam

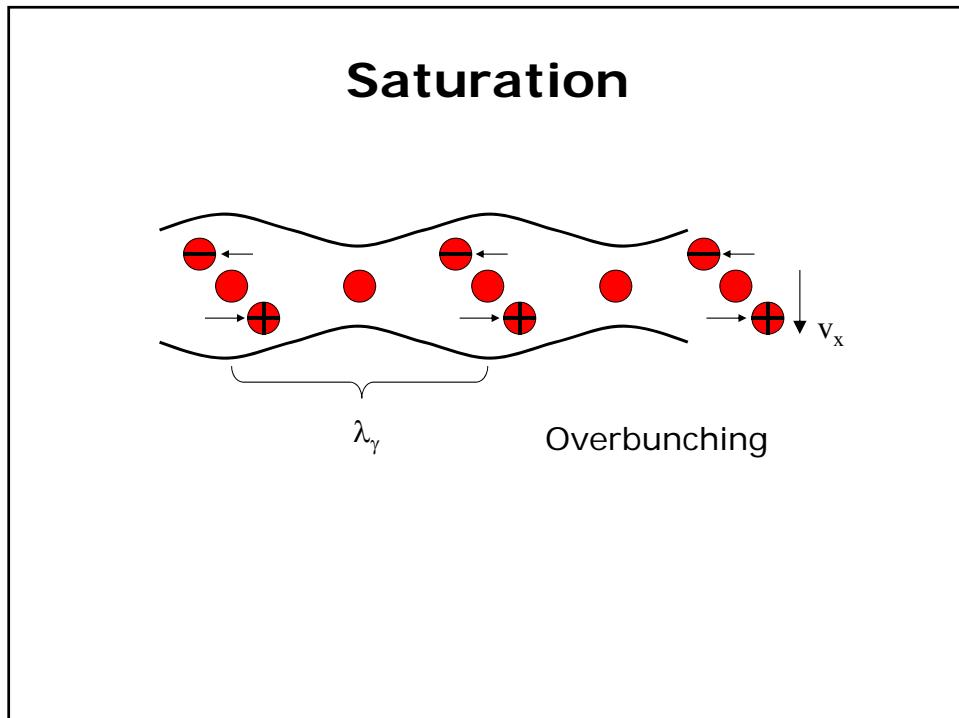
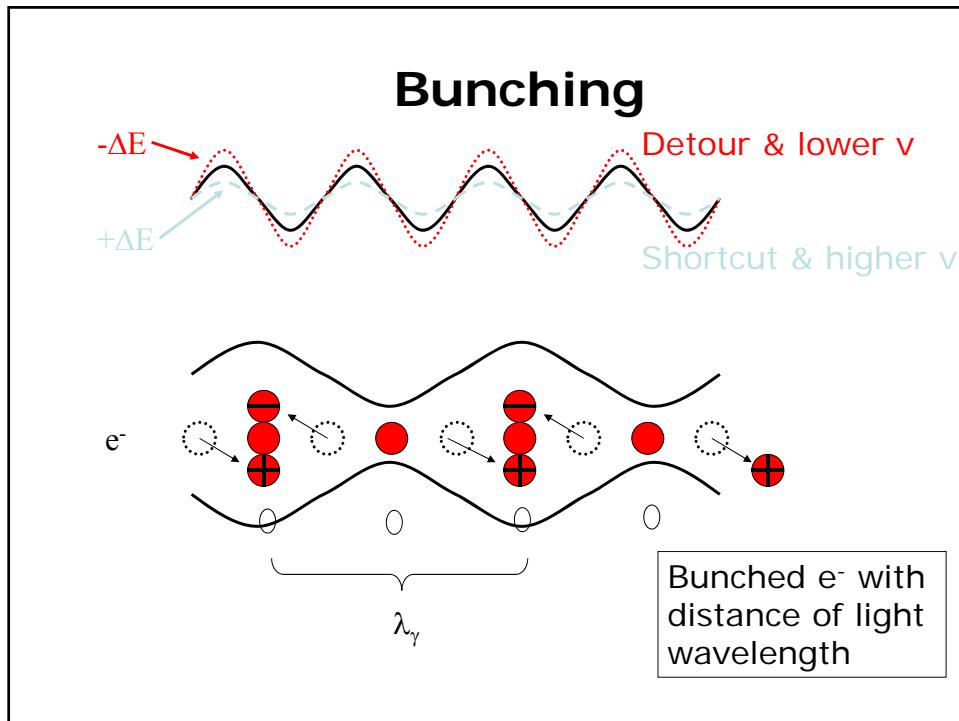
$$\begin{cases} \frac{d}{dt}(m\bar{v}) = q(\bar{E} + \bar{v} \times \bar{B}) \\ \frac{d}{dt}(mc^2) = q\bar{E}\bar{v} \end{cases}$$

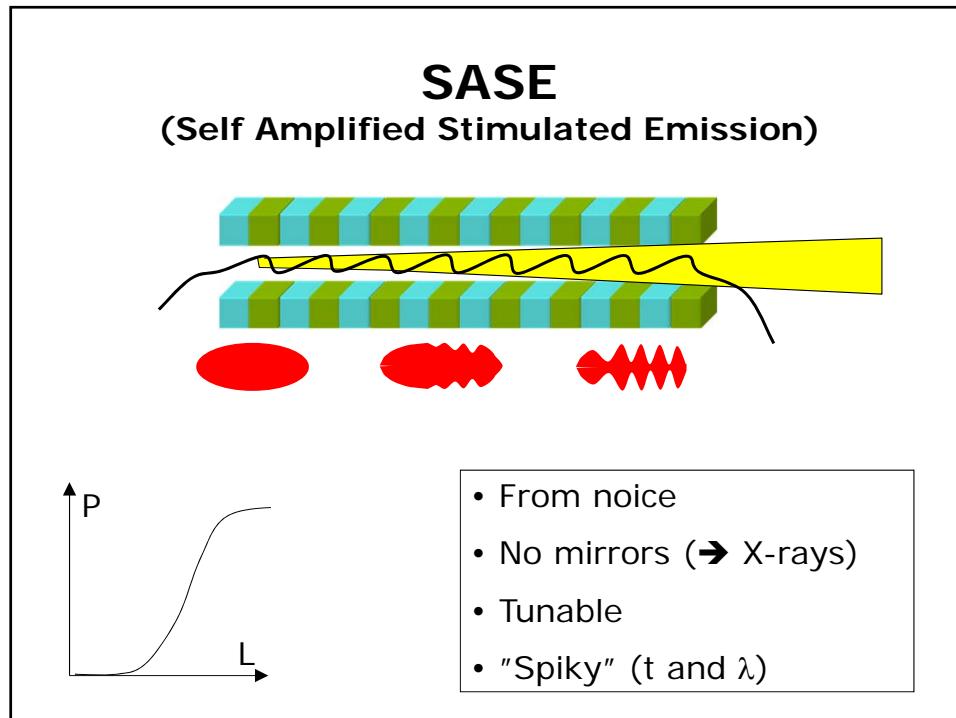
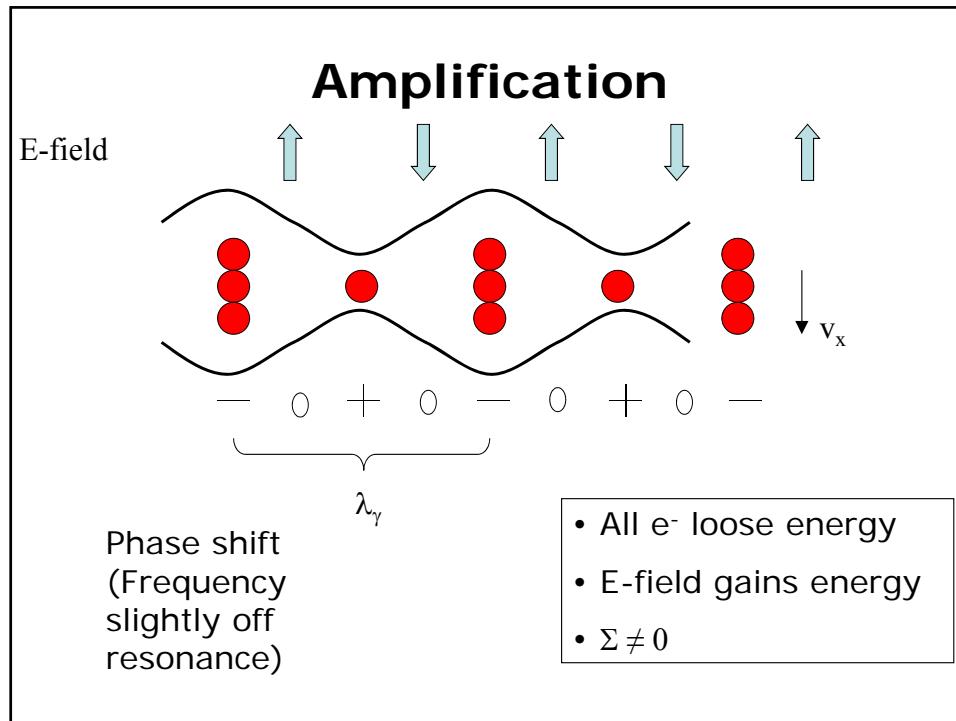
Undulator



Energy exchange







Noise in SASE

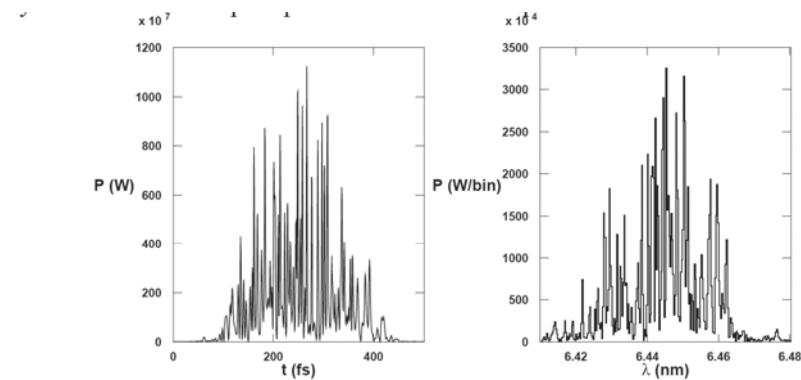
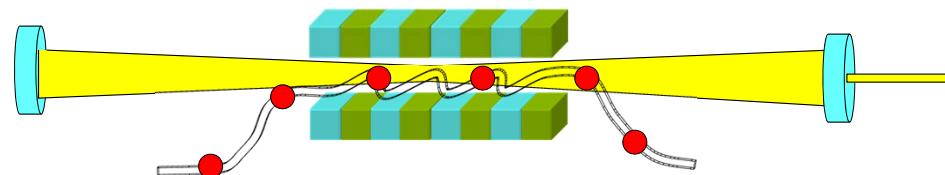


Fig. 2. Temporal structure (left) and spectrum (right) of the output radiation pulse of the TESLA SASE FEL.

Resonator FEL



- IR 5-250 μ m
- UV \approx 200 nm
- Tunable: magnet / e- energy
- Mirrors limit

- **Storage ring:** high rep. Rate, "stable"
- **Linac:** high peak power, "unstable"

