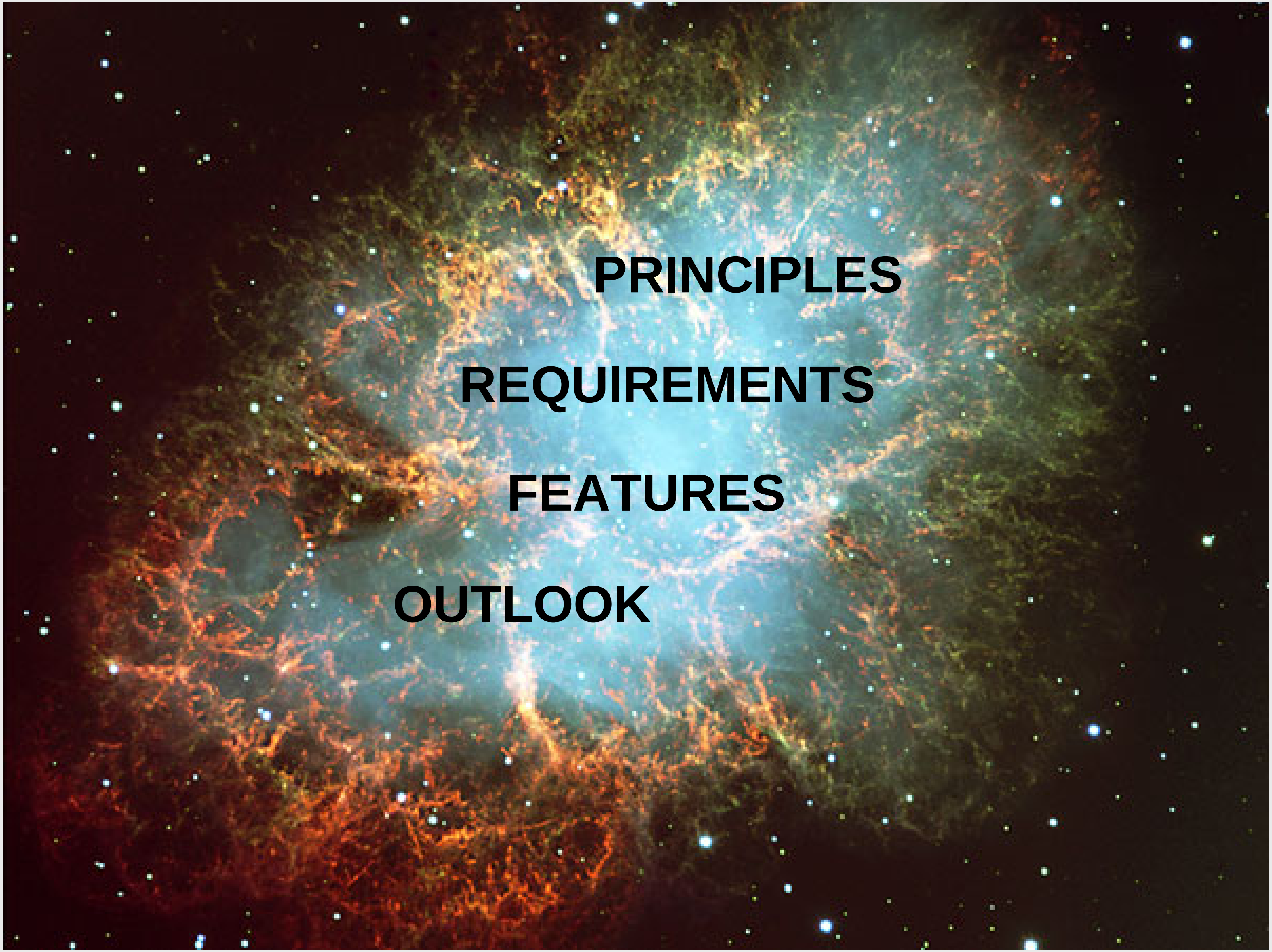
CERN ACCELERATOR SCHOOL / ACCELERATOR PHYSICS COURSE
Baden, Austria, 12-24 September 2004

SYNCHROTRON LIGHT SOURCES

Albin F. Wrulich

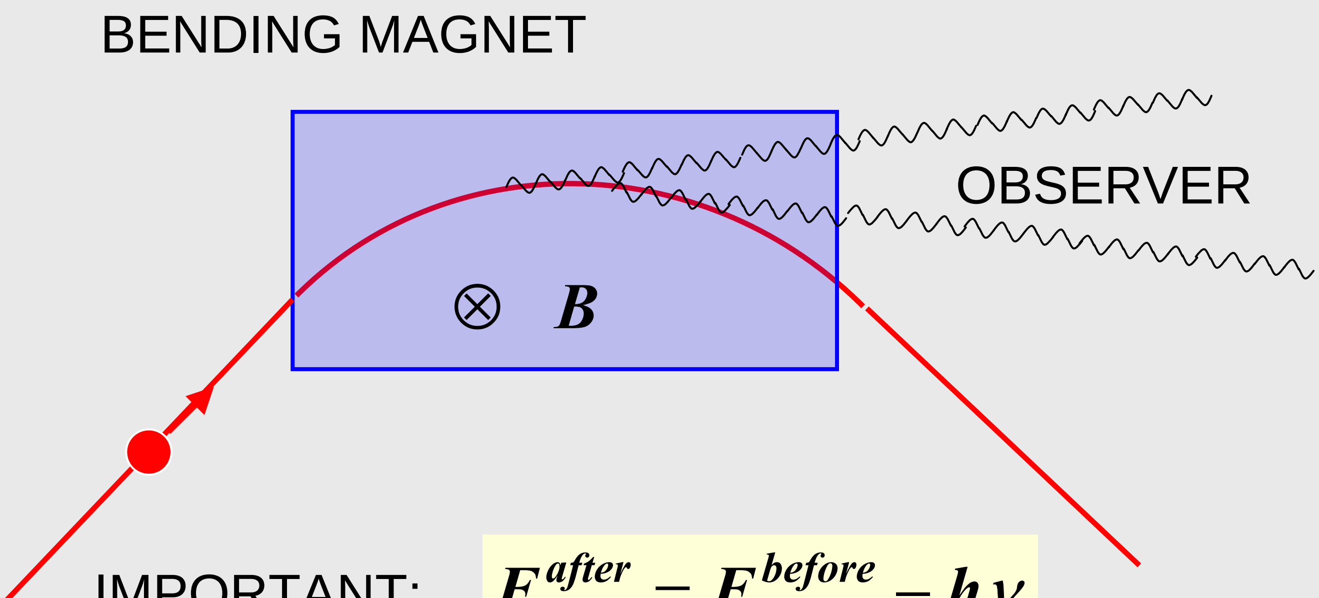
- SYNCHROTRON **LIGHT-SOURCES**
- **SYNCHROTRON-LIGHT** SOURCES

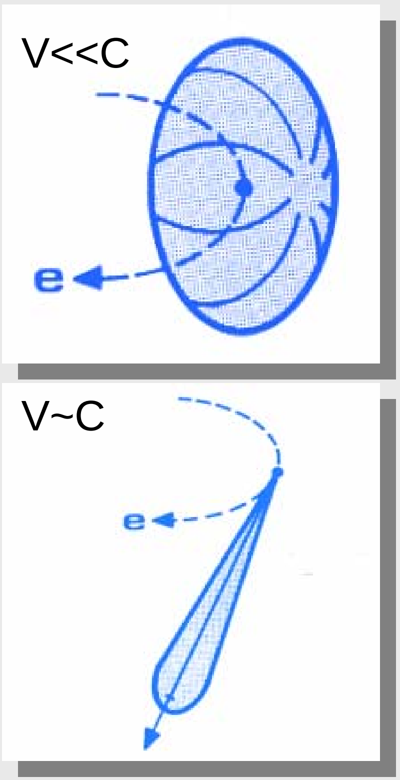
SYNCHROTRON RADIATION FROM CRAB NEBULA



PRINCIPLE OF ACCELERATOR BASED LIGHT PRODUCTION

Accelerated charged particles are emitting electromagnetic radiation. The dominant effect comes from transverse acceleration, as the deflection of a charged particle in a bending magnet of a circular accelerator:



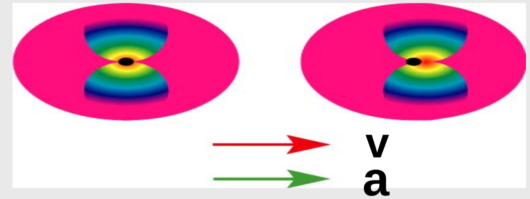


IMPORTANT: $$E_e^{after} = E_e^{before} - h\nu$$

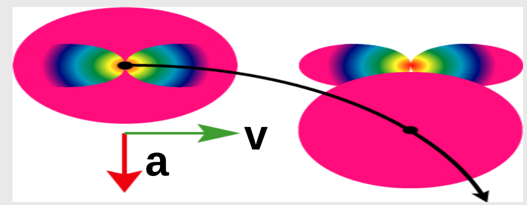
Due to the emission the energy of the particle is changed !

1898 Liénard:

$$P = \frac{2}{3}\frac{e^2\gamma^6}{4\pi\varepsilon_o c}\left[\dot{\vec{\beta}}^2 - \left(\vec{\beta}\times\dot{\vec{\beta}}\right)\right]$$



LONGITUDINAL:
Radiation field cannot separate itself from the Coulomb field



TRANSVERSE:
Radiation field quickly separates itself from the Coulomb field

$$\boxed{P \sim \frac{\gamma^4}{\rho^2}}$$

POWER emitted:

$$\boxed{E = \int_0^{T_o} P dt \sim \frac{\gamma^4}{\rho}}$$

ENERGY lost per turn:

The POWER of the emitted radiation is increasing with the 4th power of the Lorentz factor!

$$P \sim \frac{\gamma^4}{\rho^2}$$

Since: $$\gamma = 1 + \frac{E_k}{E_o} \approx \frac{E_k}{E_o} = \frac{eU}{E_o}$$

E_o Rest energy

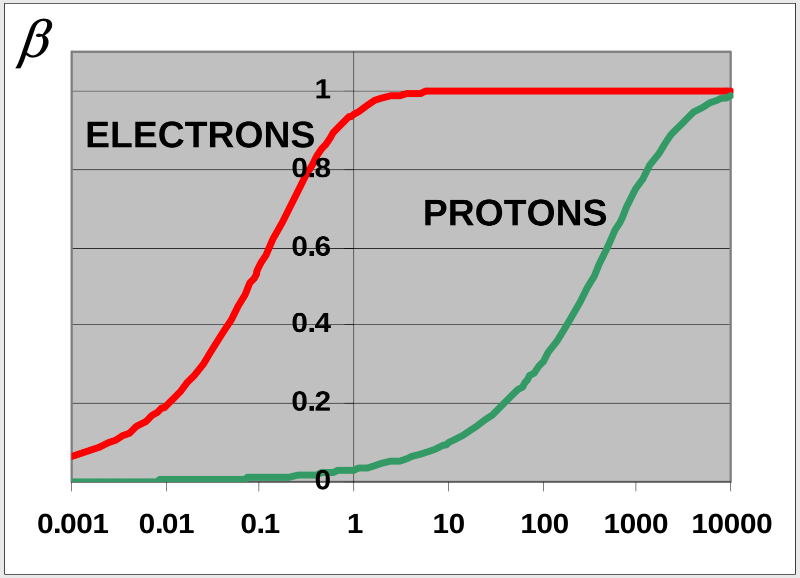
E_k Kinetic energy

U Accelerating voltage

Predominately particles with low masses are suitable for the use in light sources.

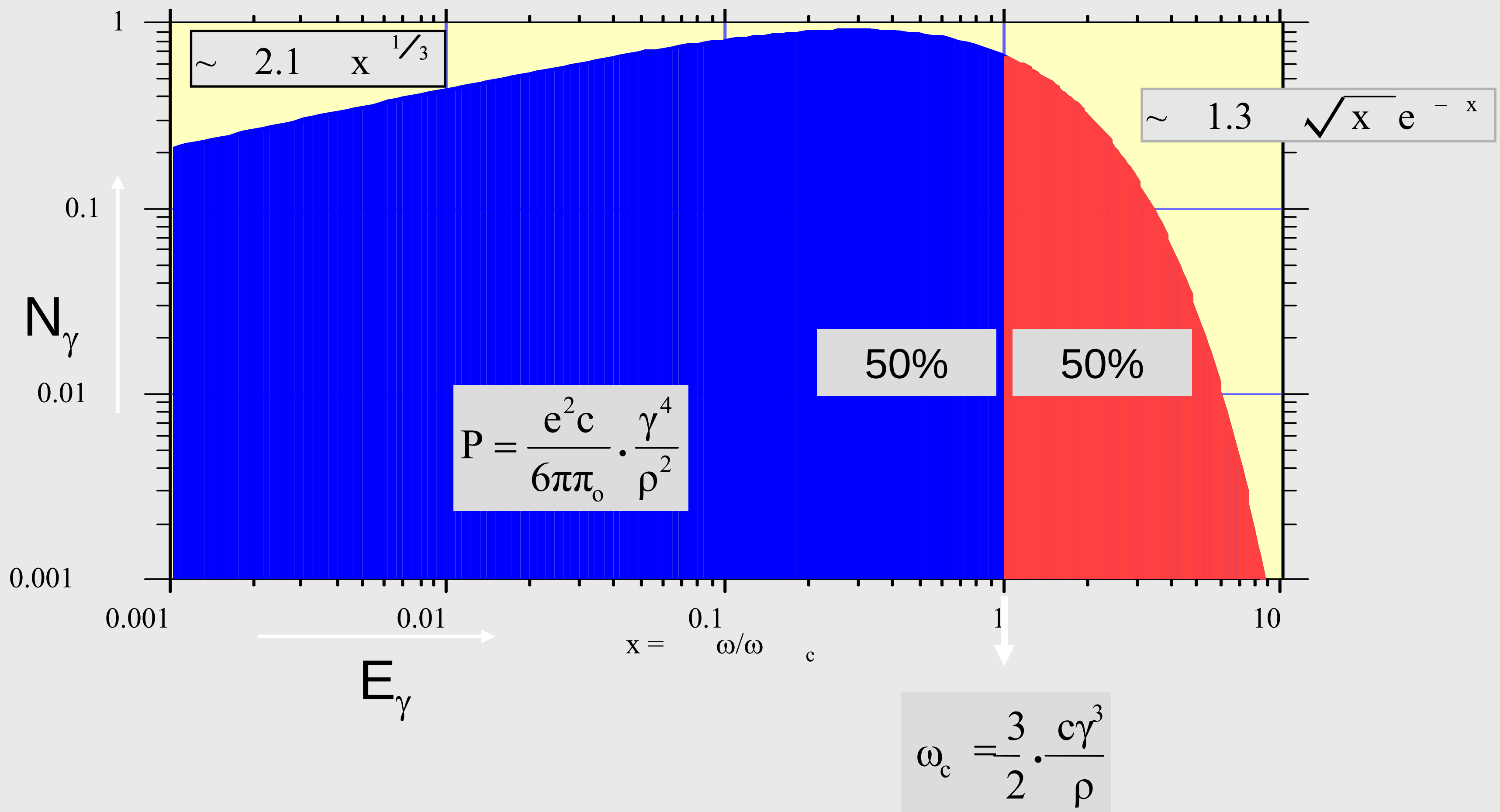
ELECTRONS, POSITRONS

$$\beta = \frac{v}{c} = \sqrt{1 - \frac{1}{\gamma^2}} \quad \rightarrow$$



$eU\left[MeV\right]$

SYNCHROTRON RADIATION FROM A BENDING MAGNET



1949 - On the classical radiation of accelerated electrons / J.S. Schwinger

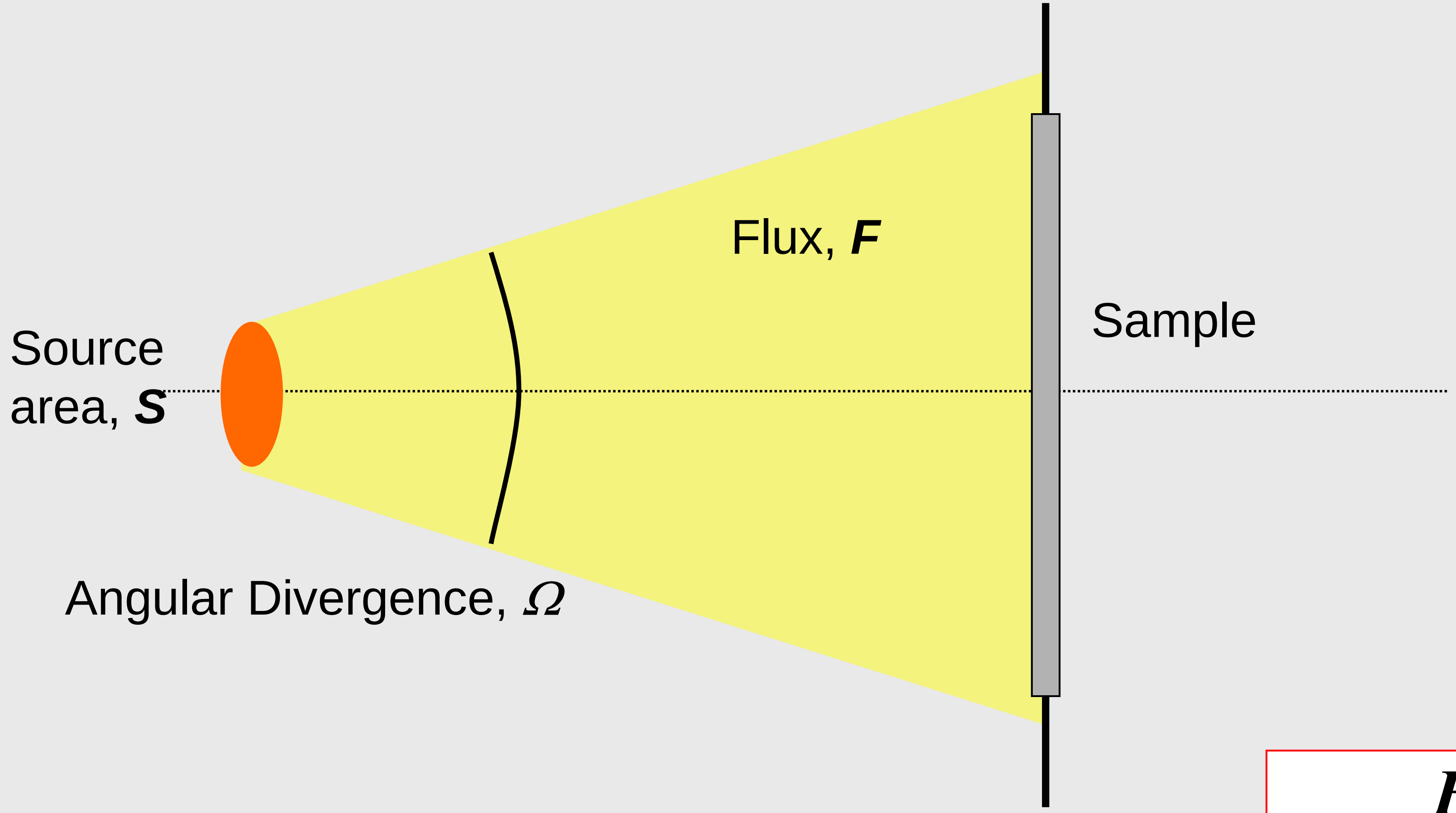
WHAT LIGHT CHRACTERISTIC IS REQUESTED FOR EXPERIMENTS

- HIGH BRILLIANCE
- COHERENCE
  - Transverse coherence
  - Longitudinal coherence
- POLARISATION
- SHORT PULSES

LOTS OF OTHER REQUIREMENTS
as stability, tunability, wide spectral range, higher photon energies (shorter wavelengths)

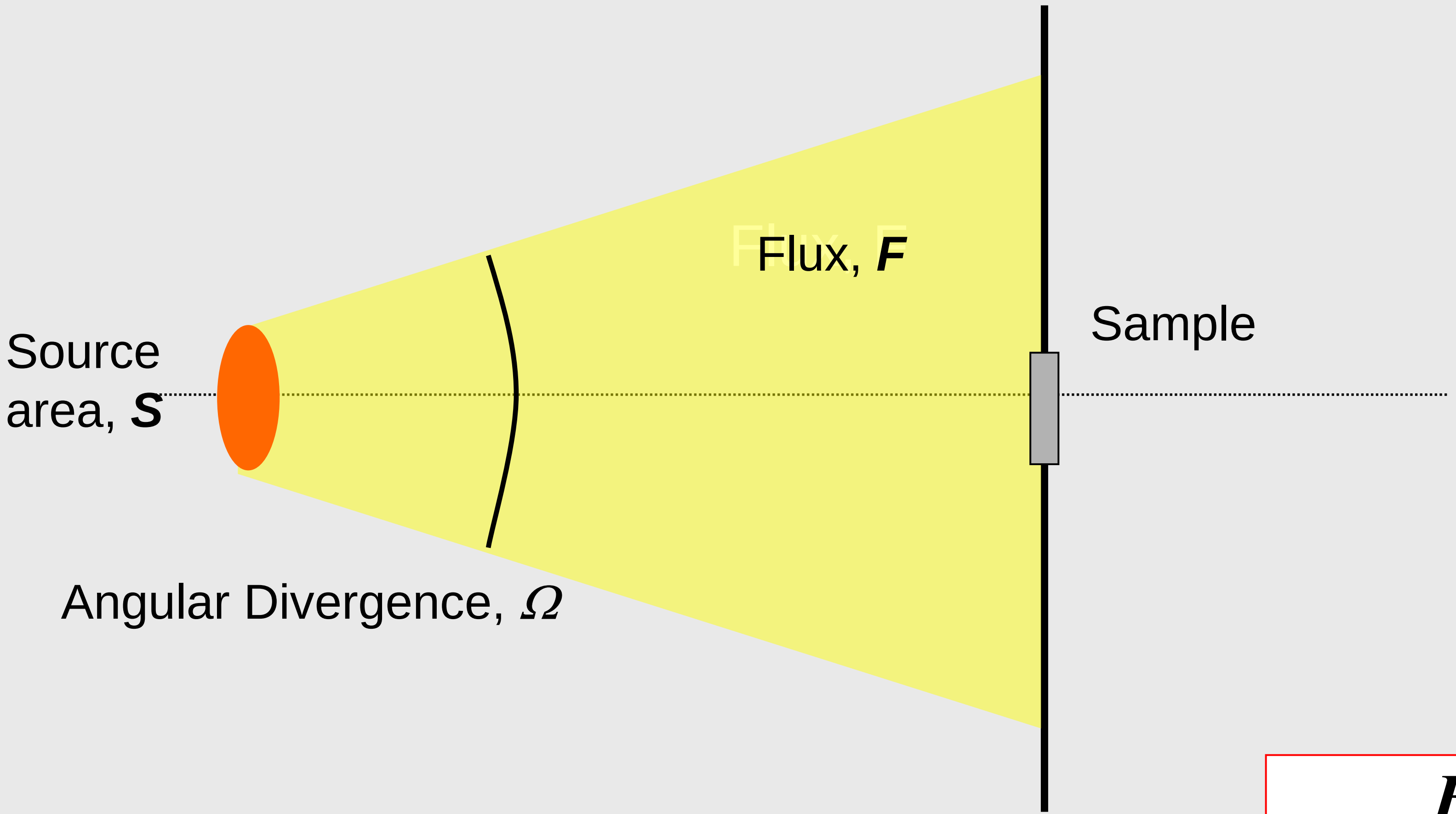
HIGH BRILLIANCE

Users want a MANY PHOTONS on the sample!



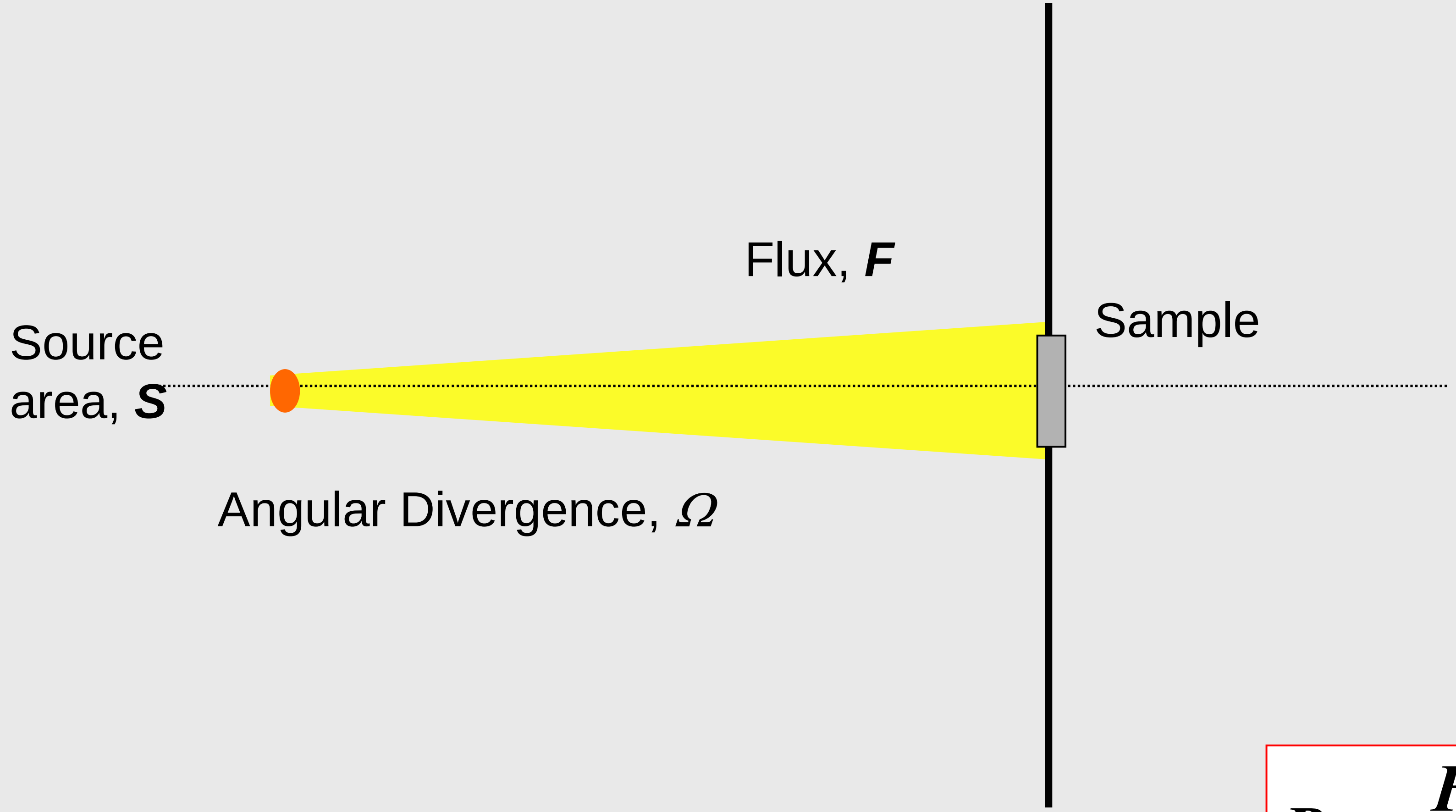
$$B \sim \frac{F}{S\Omega}$$

For smaller sample size most of the photons are wasted.
They generate an unwanted heating of the optical elements !

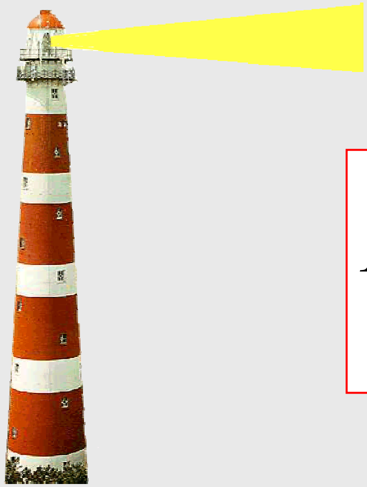


$$B \sim \frac{F}{S\Omega}$$

To overcome this problem: decrease source size and divergence, i.e. increase the brilliance



$$B \sim \frac{F}{S\Omega}$$



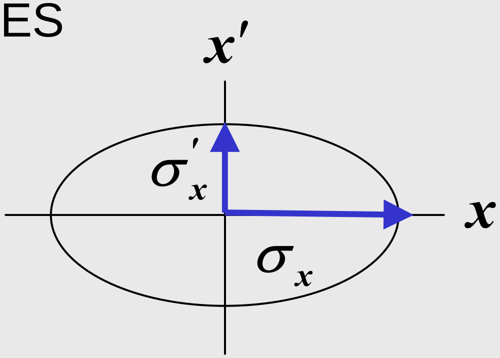
BRILLIANCE = FIGURE OF MERIT

$$\boxed{B = \frac{F}{(4\pi)^2 (\Sigma_x \Sigma_y)(\Sigma_x{}' \Sigma_y{}')}} \qquad \Sigma^2 = \sigma_e^2 + \sigma_\gamma^2$$

$$\sigma_e \gg \sigma_\gamma \quad \rightarrow \quad \Sigma_x \Sigma_x{}' \approx \sigma_x \sigma_x{}' = \varepsilon_x$$

→ TRUE FOR MOST PRACTICAL CASES

Here we assumed: $\sigma_x = \sqrt{\varepsilon_x \beta_x} \quad \sigma_x' = \sqrt{\dfrac{\varepsilon_x}{\beta_x}}$

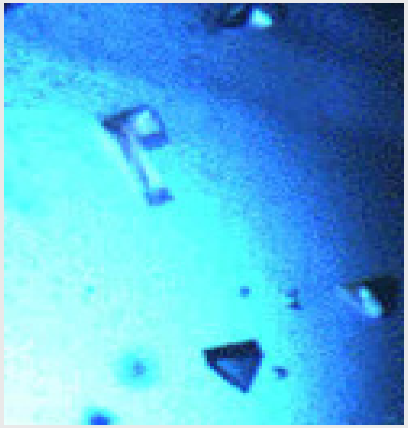
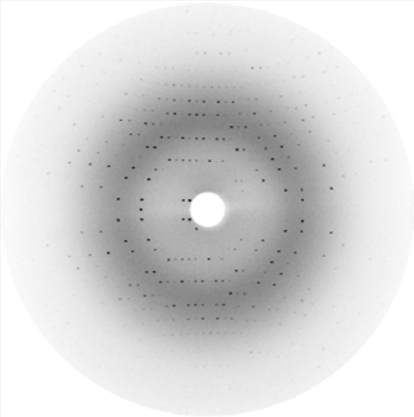
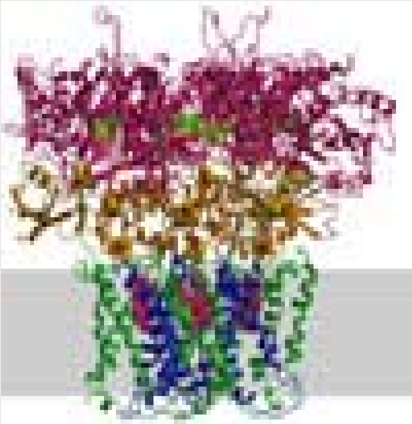


$$\sigma_\gamma = \frac{\sqrt{\lambda L}}{4\pi} \quad \sigma_\gamma{}' = \sqrt{\frac{\lambda}{L}} \quad IF: \quad \sigma_\gamma \sigma_\gamma{}' = \frac{\lambda}{4\pi} = \sigma_x \sigma_x{}' = \varepsilon_x$$

DIFFRACTION LIMIT

HIGH BRILLIANCE is needed for: ***CRYSTALLOGRAPHY***

....

CRYSTAL	DIFFRACTION PATTERN	RECONSTRUCTION
	→  →	

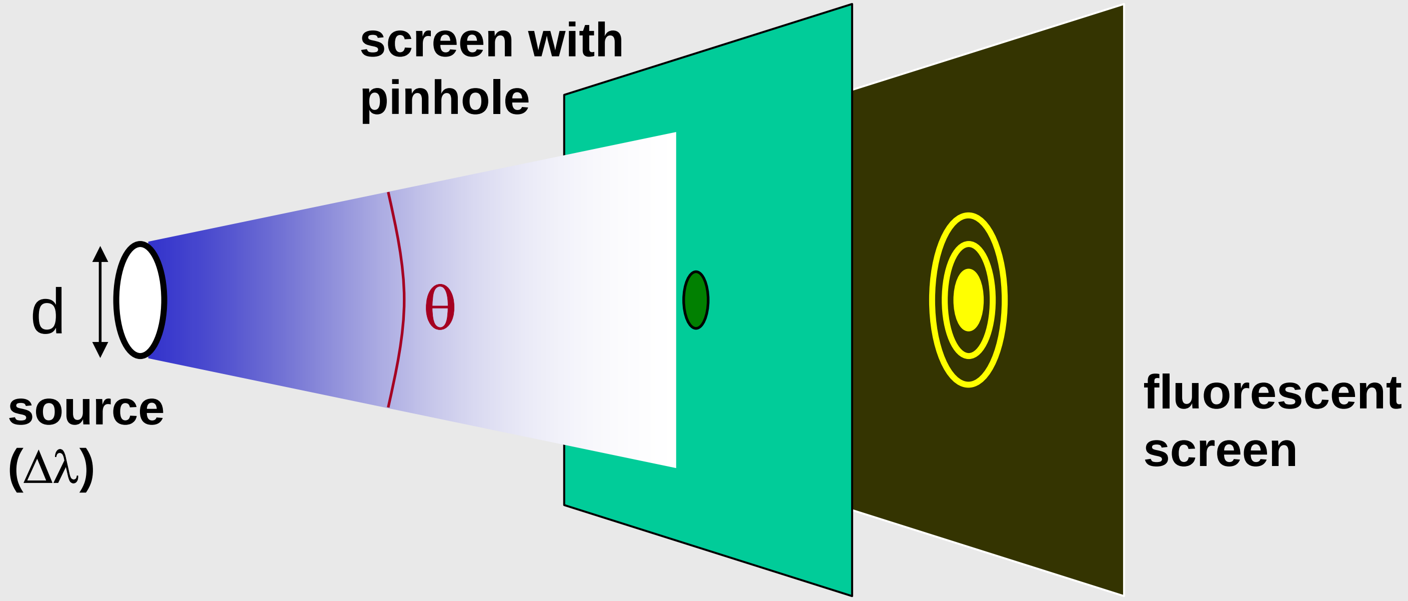
N. Ban, S. Iwata, U. Baumnan et al.

Siccinat-Dehydrogenase

… to get the maximum flux into the sample acceptance phase space !

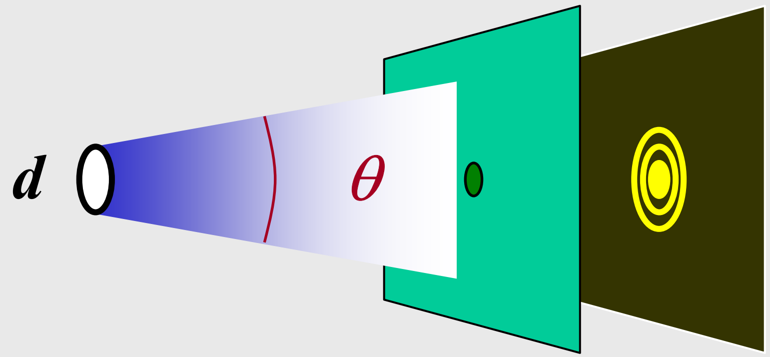
COHERENCE

→ is the property that enables a wave to produce visible diffraction and interference effects



A point-like monochromatic source always creates diffraction patterns

LATERAL COHERENCE - is increasing with brilliance



Extended monochromatic source

$$F_c = \left(\frac{\lambda}{2}\right)^2 \frac{1}{(4\pi)^2} \frac{F}{S\Omega} \sim \left(\frac{\lambda}{2}\right)^2 B$$

$$S = \left(\frac{d}{2}\right)\pi$$

$$\Omega = 4\pi \sin^2 \frac{\theta}{4} \approx \frac{\theta^2 \pi}{4}$$

Full lateral coherence exists if → $d\,\theta = 2\lambda$

LONGITUDINAL COHERENCE

- needs light emitted in a small bandwidth

UNDULATOR: $\dfrac{\Delta\lambda}{\lambda} = \dfrac{1}{2N}$ $\quad N$ … number of magnet poles

→ long undulators can be used to increase the longitudinal coherence (suggested for some RECIRCULATOR projects)

Coherent length of a point-like source with $\Delta\lambda$ bandwidth

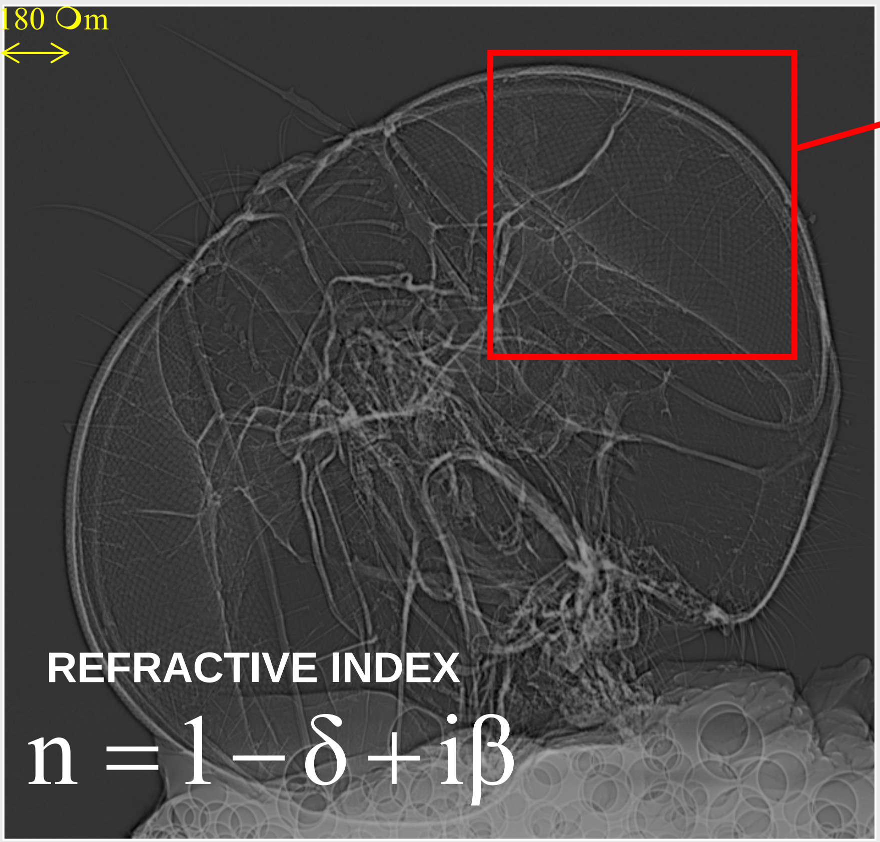
$$\boxed{L_c = \frac{\lambda}{\Delta\lambda/\lambda}}$$

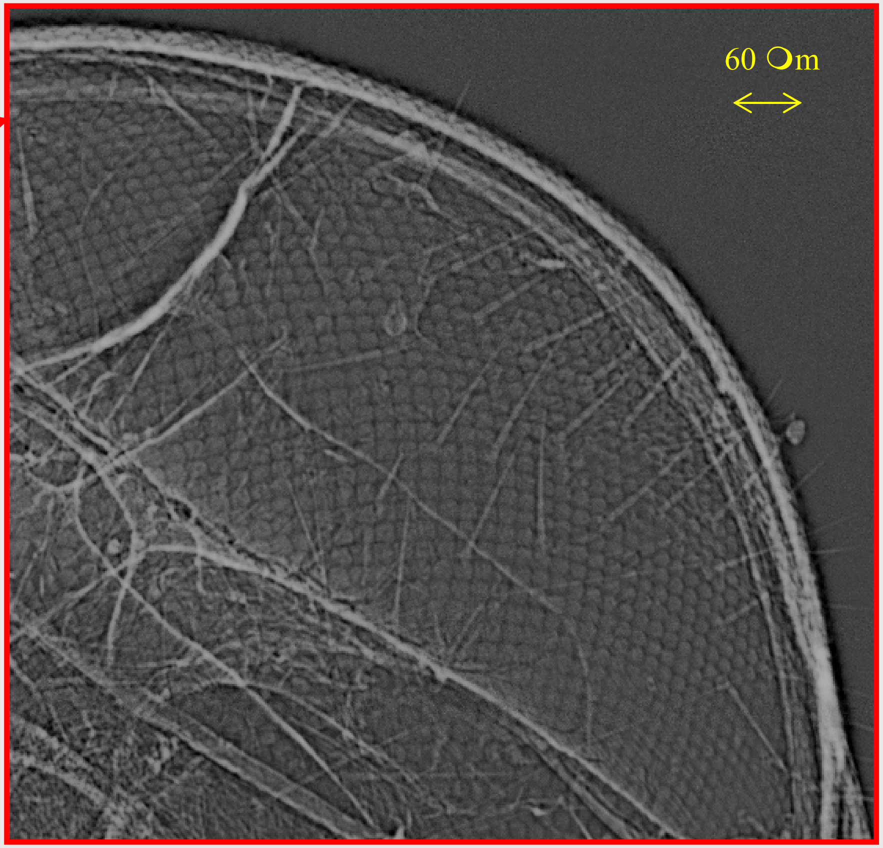
→ is the length over which 2 waves with $\Delta\lambda$ wavelength difference run 180 deg out of phase !

COHERENCE is needed for ….

PHASE COMTRAST IMAGING
HOLOGRAPHY
SPECKLE INTERFEROMETRY
….

EYE OF A FLY

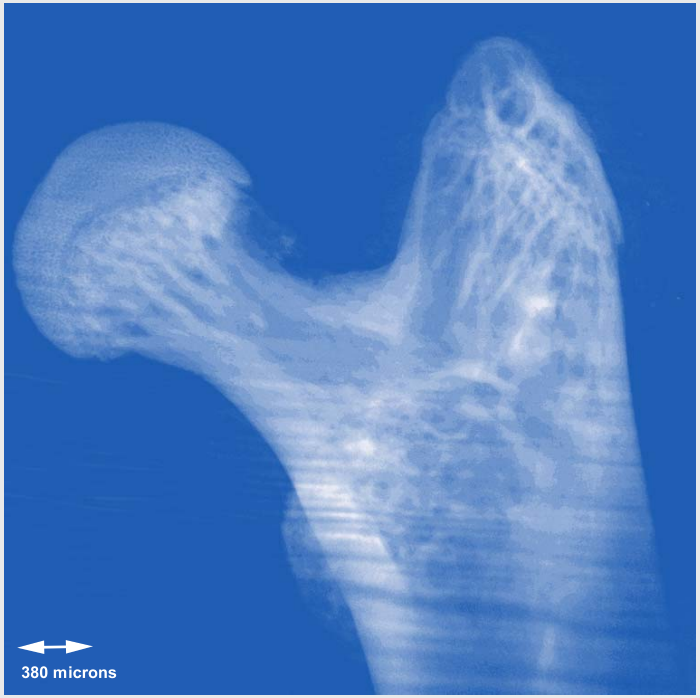




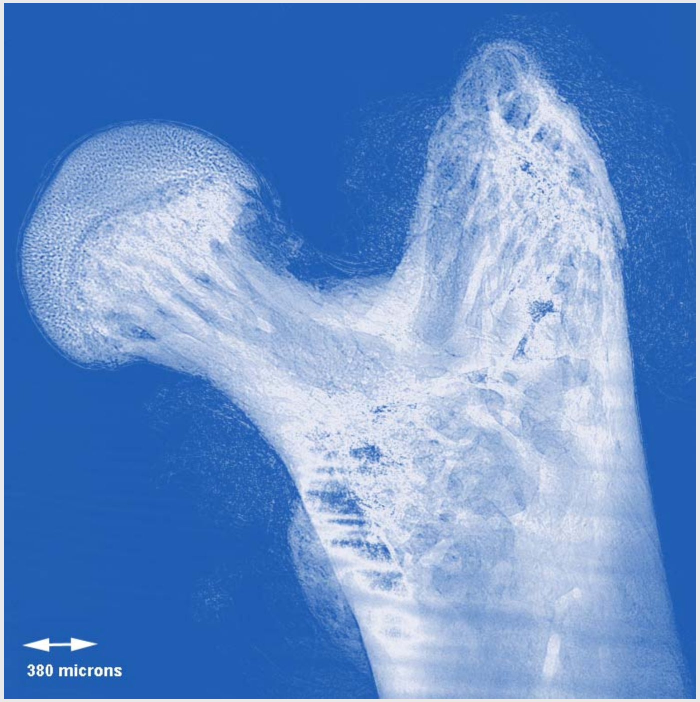
MATERIAL SCIENCE BEAMLINE: Marco Stampanoni, Rafael Abela

M. Stampanoni et al

$$\lambda = 0.08 \text{ nm}$$



Contact: only *absorption* contrast



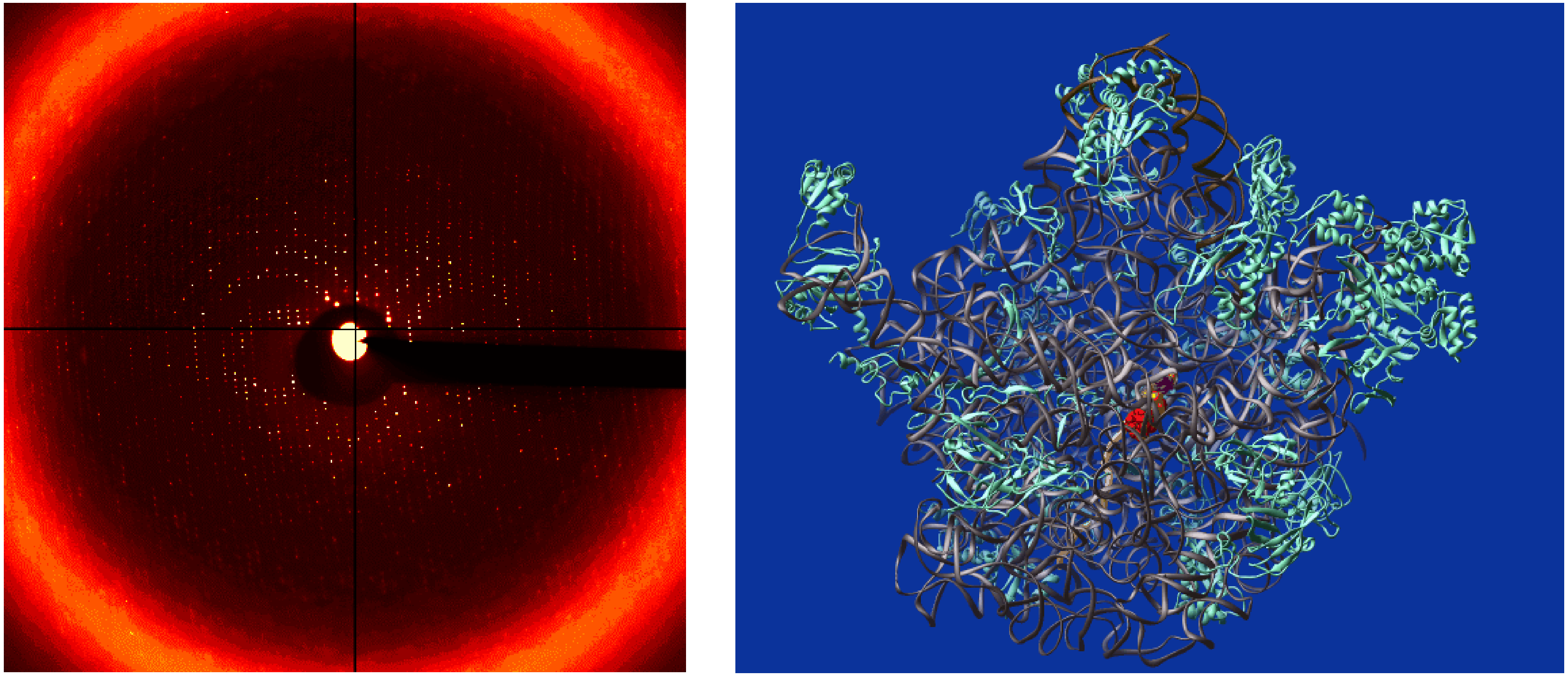
R=100 mm: features of size ζ~3 μm appear in enhanced *phase* contrast

$\Downarrow$

''edge-enhanced contrast''

RELEVANCE OF COHERENCE for *CRYSTALLOGRAPHY*

⇝ Structure of a molecule (Ribosome)



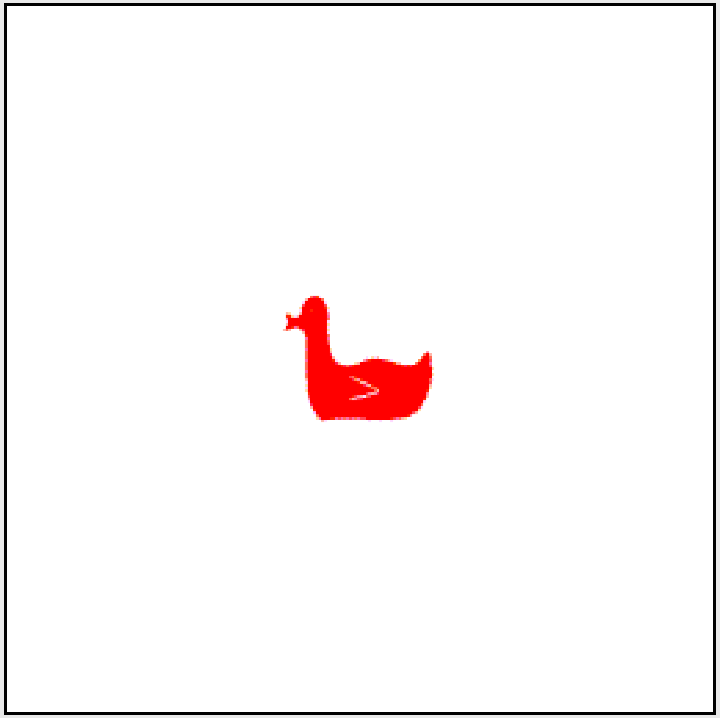
Pictures: Jörg Harms, Arbeitsgruppe für Ribosomenstruktur, Max-Planck-Gesellschaft

Diffraction pattern

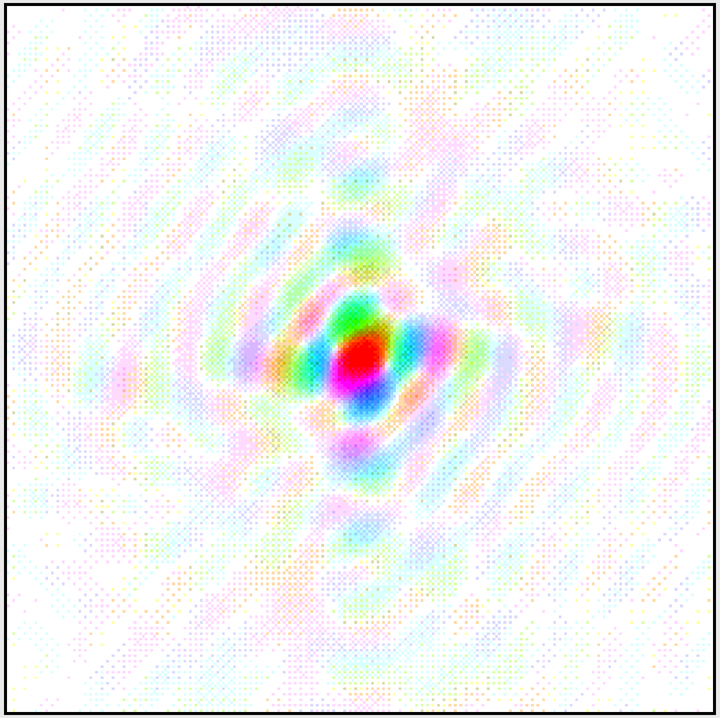
<u>Problem</u>: phase of the diffraction pattern is unknown !

RELEVANCE OF COHERENCE - *DIFFRACTION PATTERN OF A DUCK*

A (2-dimensional) DUCK



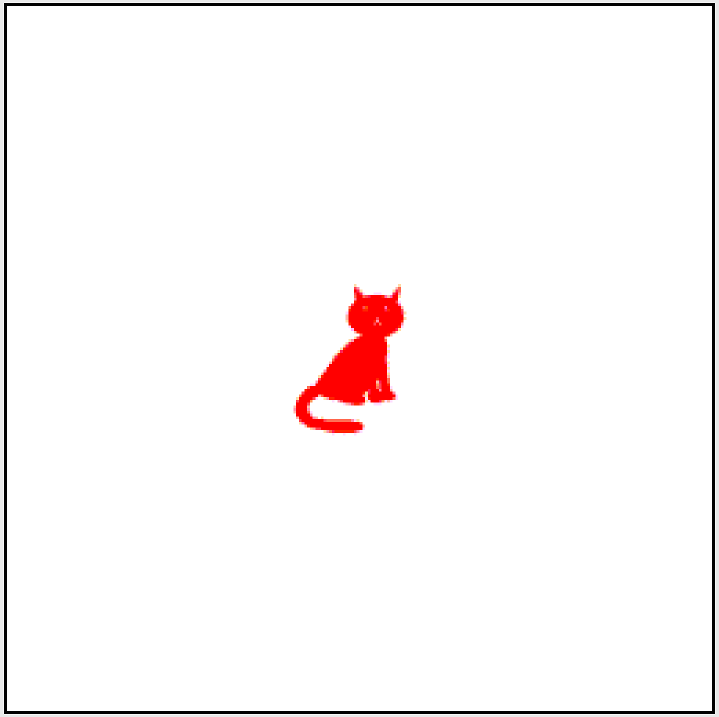
Creates this diffraction pattern
(the colors encode the phase)



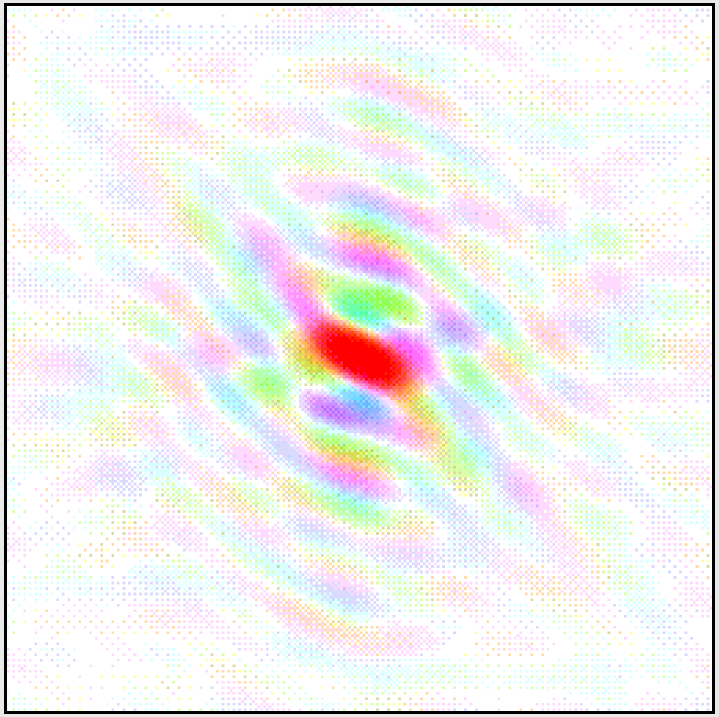
Curtesy Ischebeck
Images by Kevin Cowtan, Structural Biology Laboratory, University of York

RELEVANCE OF COHERENCE - *DIFFRACTION PATTERN OF A CAT*

A CAT



… and its diffraction pattern

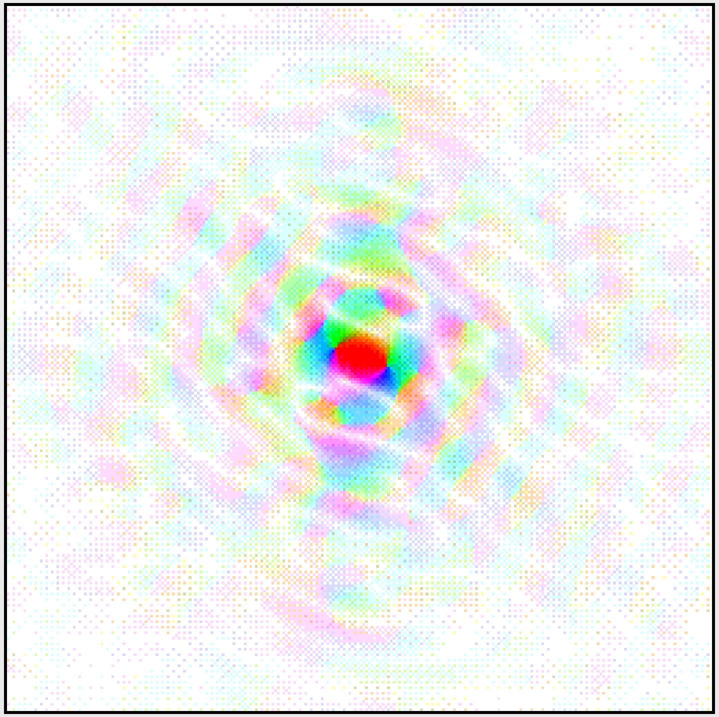


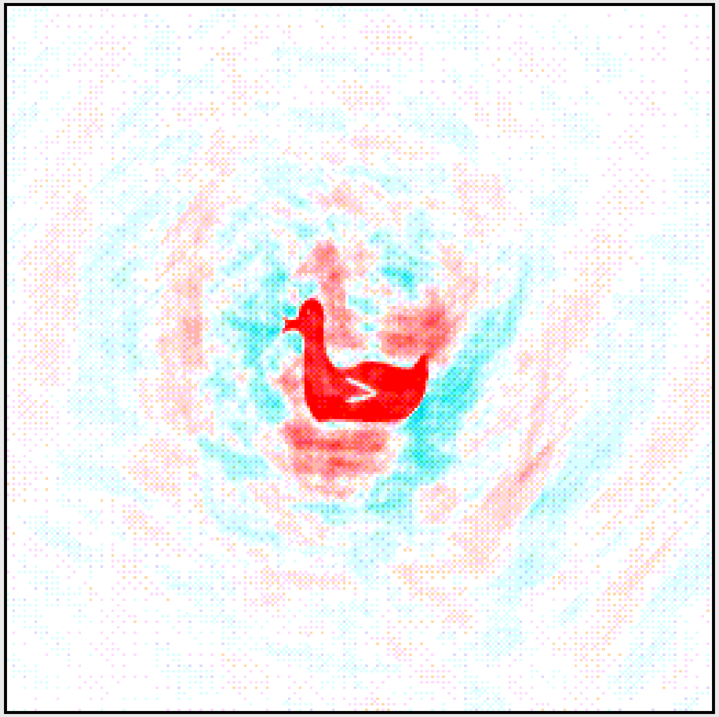
Curtesy Ischebeck

Images by Kevin Cowtan, Structural Biology Laboratory, University of York

RELEVANCE OF COHERENCE - *RECONSTRUCTION*

Combine the AMPLITUDE of the diffraction pattern OF THE CAT with the PHASE of the diffraction pattern OF THE DUCK →





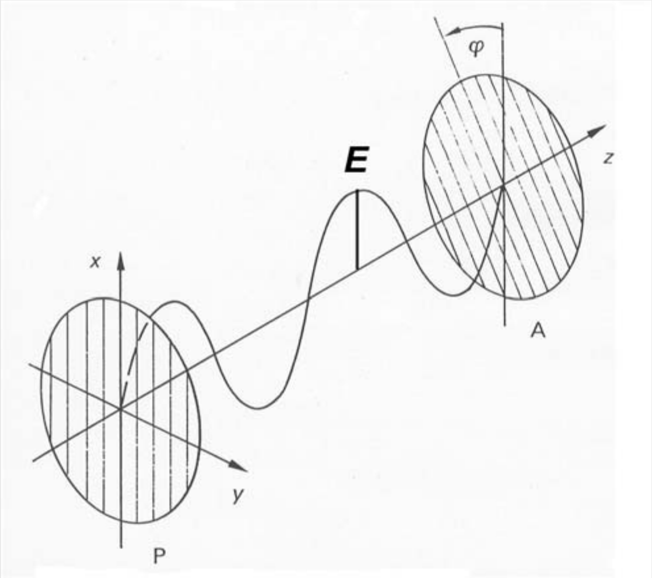
The result: A DUCK !!

Curtesy Ischebeck
Images by Kevin Cowtan, Structural Biology Laboratory, University of York

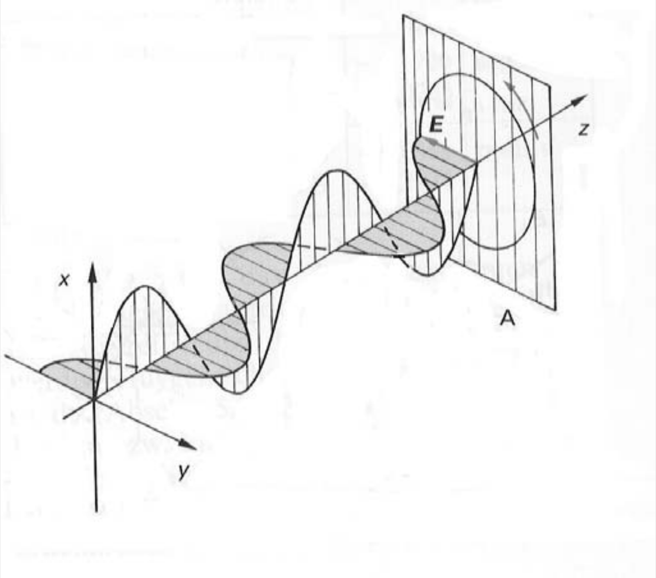
POLARISATION

→ Electric vector oscillates in one plane only or rotates as the wave propagates

LINEAR



CIRCULAR

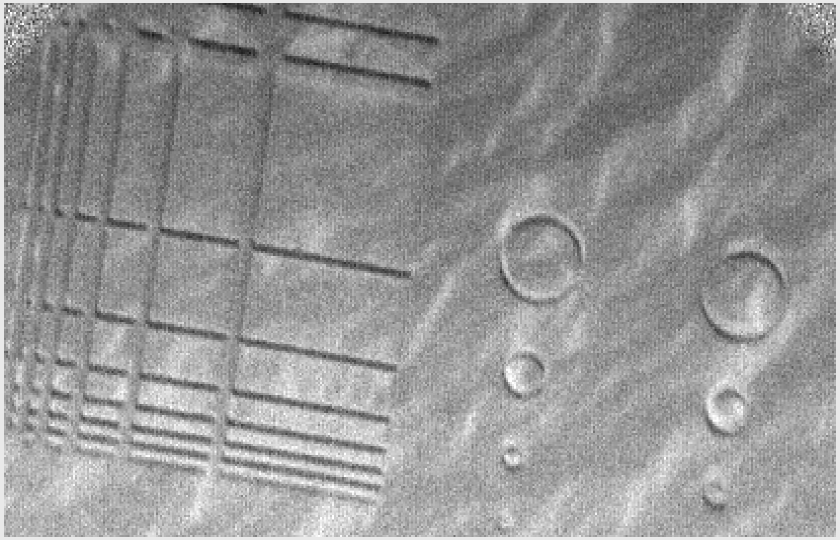


POLARISATION is needed for:

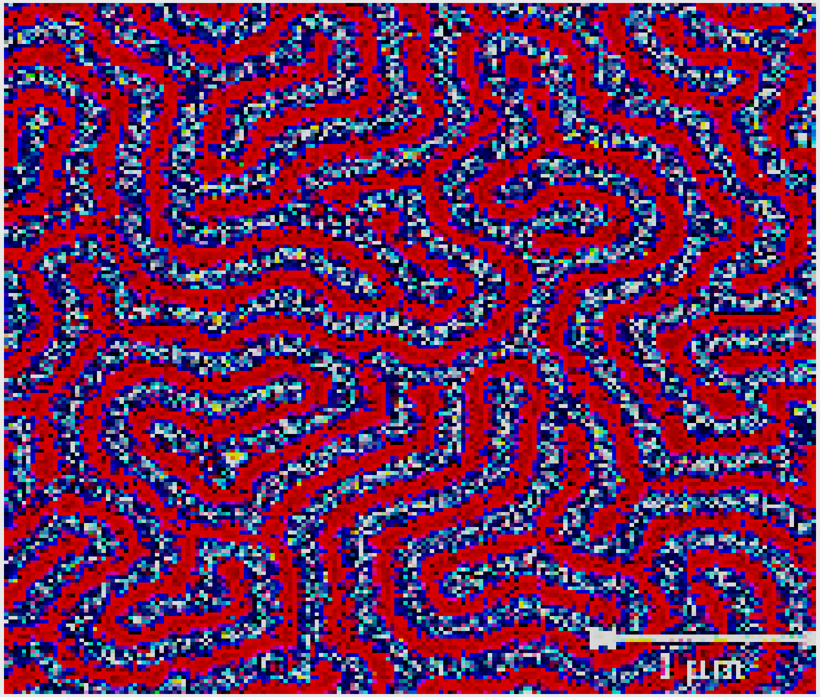
MAGNETIC CIRCULAR DICHROISM
TO FIND OUT THE ORIENTATION OF MOLECULES ….

PEEM INVESTIGATION OF NANOPATTERNED MAGNETOSTRICTIVE SYSTEMS

IMAGING OF MAGNETIC DOMAINS

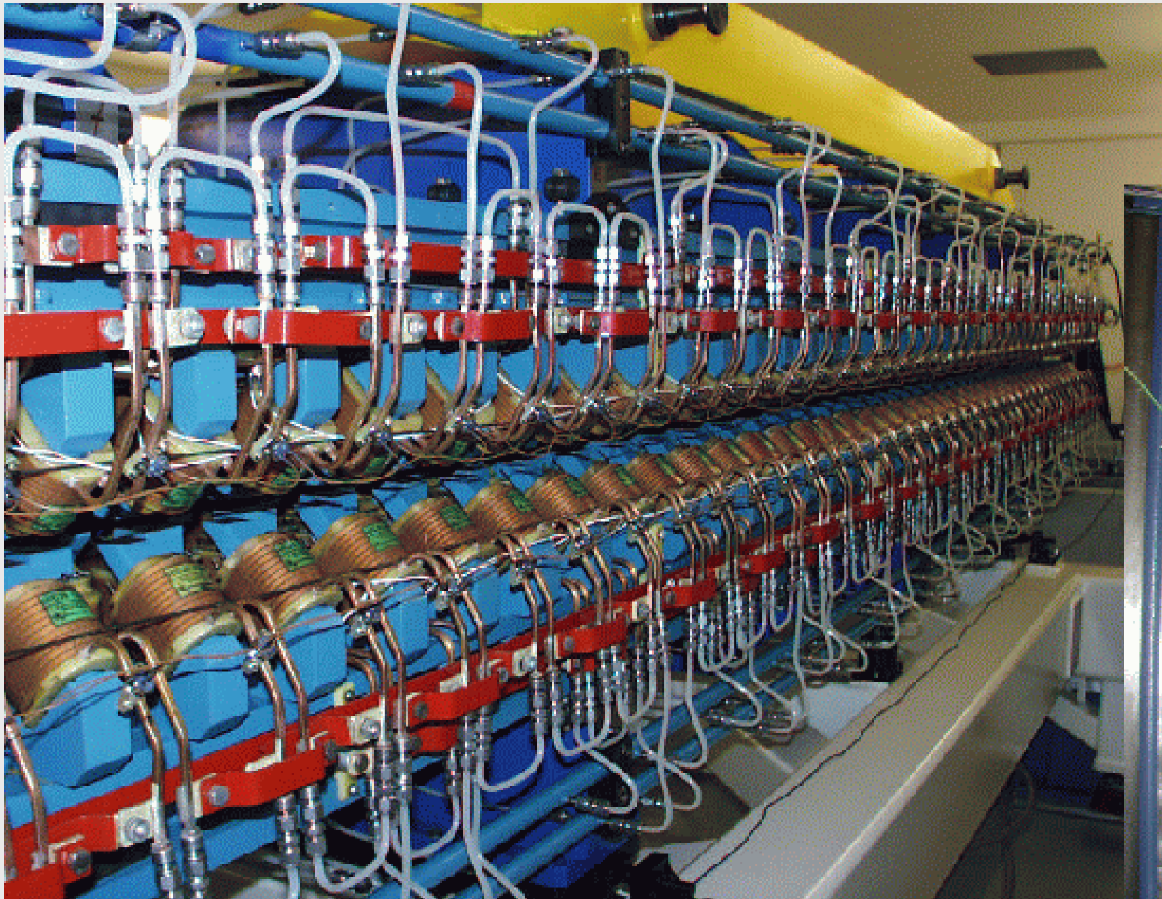


Magnetic ripple in as-grown cobalt-Terfenol sandwich film on pre-patterned Si substrate.



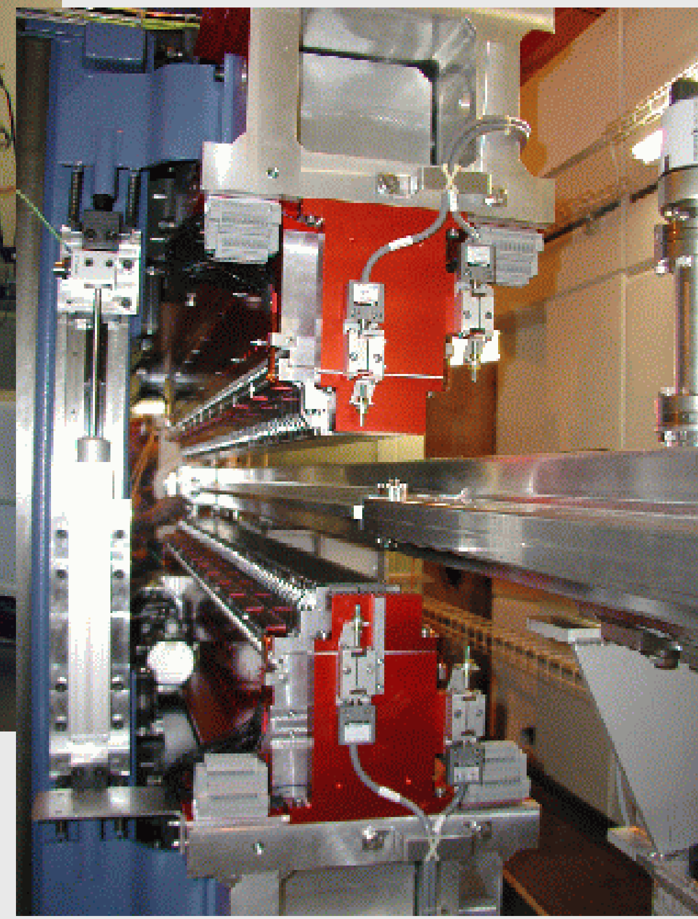
G.Schütz,G.Schmahl, P. Fischer

POLARIZED LIGHT is generated by special undulators:



ELECTROMAGNETIC UE212 (8-800 eV)

APPLE II TYPE UE56
(90 eV–3 keV)



SHORT PULSES

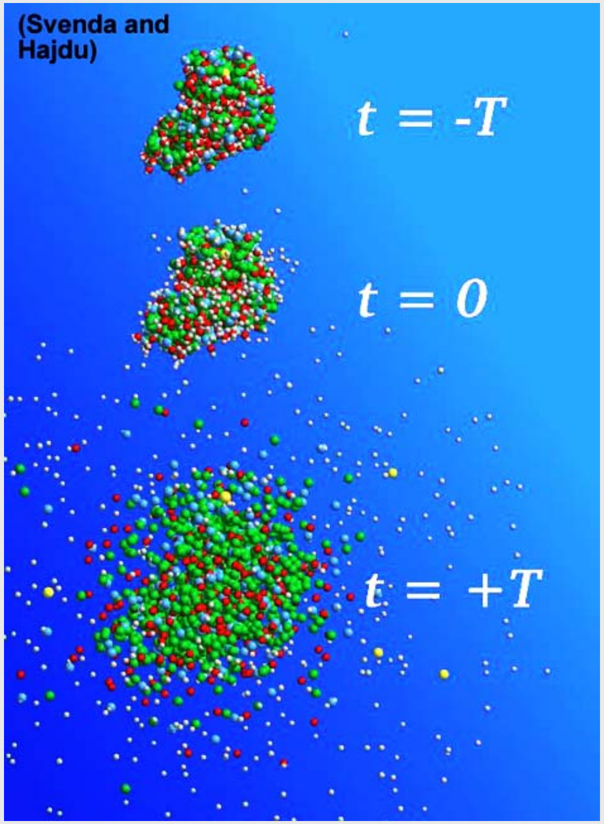
WHY SHORT PULSES ?

On the long time scale the fast motion is averaged out.

On the short time scale the world stands still.

SHORT PULSES in the range of fs are needed in order to study the dynamics on the atomic and molecular level

SHORT PULSES are mandatory to take snap shot before molecule flies apart (takes only 4-20 fs!)



STORAGE RING BASED LIGHT SOURCES:

ARE GOOD FOR →

- diffraction limited light in the VUV range (~ 100 eV)
- high brilliance in the soft- and hard X-ray regime and related Lateral coherence
- any type of polarized light (generated by special insertion devices

HAVE MADE ENORMEOUS PROGRESS →

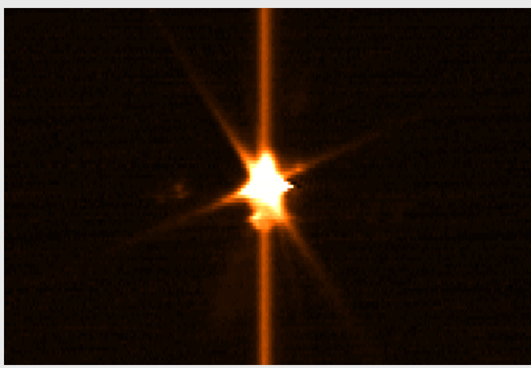
- energy, position and intensity stability
- Achievement of higher photon energies (also from medium energy electrons)

DO NOT COVER THE NEEDS FOR →

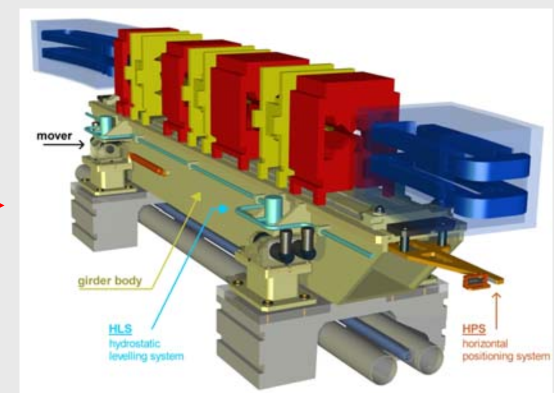
- high temporal coherence
- short pulses

HOW ARE THESE LIGHT FEATURES ACCOMPLISHED BY ACCELERATOR CHARACTERISTICS

FEATURES ***QUALITY*** ***CHARACTERISTICS***



→ **ELECTRON BEAM** →



LIGHT

MAGNET STRUCTURE

PARTICULARITIES OF A LIGHT SOURCE LATTICE

How to get the best performance of the light, i.e. maximum Brilliance

$$B = \frac{F}{(4\pi)^2 \Sigma_x \Sigma_x' \Sigma_y \Sigma_y'} = \frac{F}{(4\pi)^2 \varepsilon_x \varepsilon_y} = \frac{F}{(4\pi)^2 \kappa \varepsilon_x^2}$$

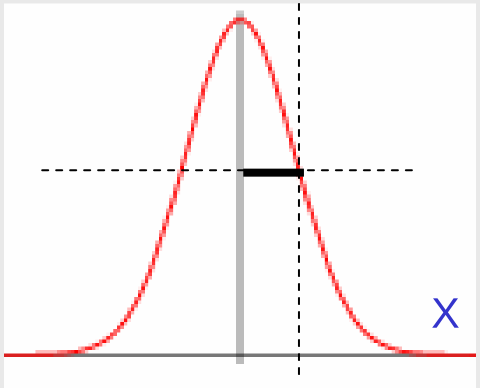
The Flux F is proportional to the stored beam current

κ is the emittance coupling.

In order to get the maximum Brilliance, the emittance must be minimized!

The emittance of an electron storage ring is defined as the phase space area that contains one standard deviation of the gaussian particle distribution

PARTICLE DISTRIBITION



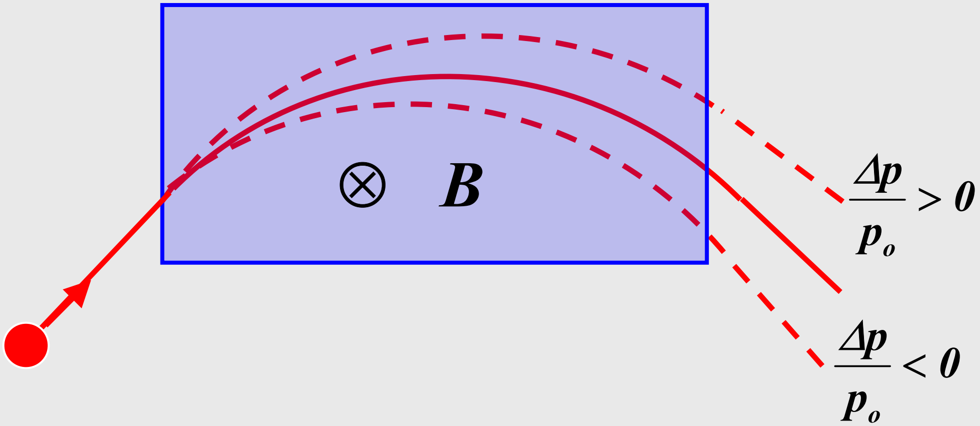
The emittance of an electron storage ring is given by the equilibrium between quantum fluctuation and radiation damping

IN AN ELECTRON STORAGE RING THE EMITTANCE IS A CHARACTERISTIC QUANTITY OF THE MAGNET LATTICE

In order to minimize it we have to understand how it is generated!

BASICS 1:

BENDING MAGNET



Particles with different energies are moving on different orbits in a bending magnet → **DISPERSION** orbit!

Basic equation:

$$\frac{1}{\rho} = \frac{e}{p} B \rightarrow$$

$$\frac{1}{\rho} = \frac{e}{p_o\left(1 + \frac{\Delta p}{p_o}\right)} B$$

$$\frac{1}{\rho} =\approx \frac{e}{p_o} B \left(1 - \frac{\Delta p}{p_o}\right)$$

BASICS 2:

If a particle is not on its closed orbit, it performs betatron oscillations around this closed orbit:

$$x(s) = A\cos[\phi(s) - \phi_o]$$

$$x'(s) = -A\frac{\alpha}{\beta}\cos[\phi - \phi_o] - A\frac{1}{\beta}\sin[\phi - \phi_o]$$

CONSTANT OF THE MOTION

$$A^2 = \varepsilon\beta = x^2 + (x\alpha + x'\beta)^2$$

at position 's'

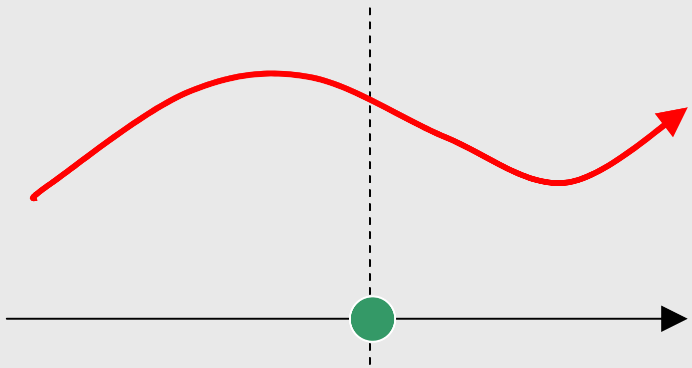
OR

$$\varepsilon = x^2\gamma + 2xx'\alpha + x'^2\beta$$

everywhere in the ring

$$\gamma = \frac{1+\alpha^2}{\beta}$$

An electron emitting a radiation quantum in the bending magnet loses energy and finds itself afterwards not on its closed orbit anymore



$$\frac{\Delta E}{E_o} < 0$$

$$\frac{\Delta E}{E_o} = 0$$

CHANGE IN COORDINATE:

$$\Delta x = -\frac{u}{E_o} D_x$$

$$\Delta x' = -\frac{u}{E_o} D'_x$$

The particle starts to oscillate around the new closed orbit with a betatron amplitude corresponding to the difference in closed orbit before and after the energy jump.

Substitution of these changes into the expression for the constant of motion leads to:

$$A^2 = \left(x - D\frac{u}{E_o} \right)^2 + \left[\left(x' - D'\frac{u}{E_o} \right)\alpha + \left(x' - D'\frac{u}{E_o} \right)\beta \right]^2$$

$$A^2 = A_o^2 - 2\frac{u}{E_o}\left[xD + (x\alpha + x'\beta)(D\alpha + D'\beta \right] + \left(\frac{\Delta u}{E_o} \right)^2 \left[D^2 + (D\alpha + D'\beta)^2 \right]$$

Averaging over many turns makes the mid term vanishing and we get:

$$\Delta(A^2) = A^2 - A_o^2 = \frac{u^2}{E_o^2}\underbrace{\left[D_x^2 + (D_x\alpha_x + D'_x\beta_x)^2\right]}_{H(s)}$$

COURANT SNYDER INVARIANT

In order to get the beam size, respectively the emittance one has to perform:

→ Statistical averaging over all emissions in one turn
→ Averaging over all betatron phases of the particle motion
→ Equilibration to the radiation damping

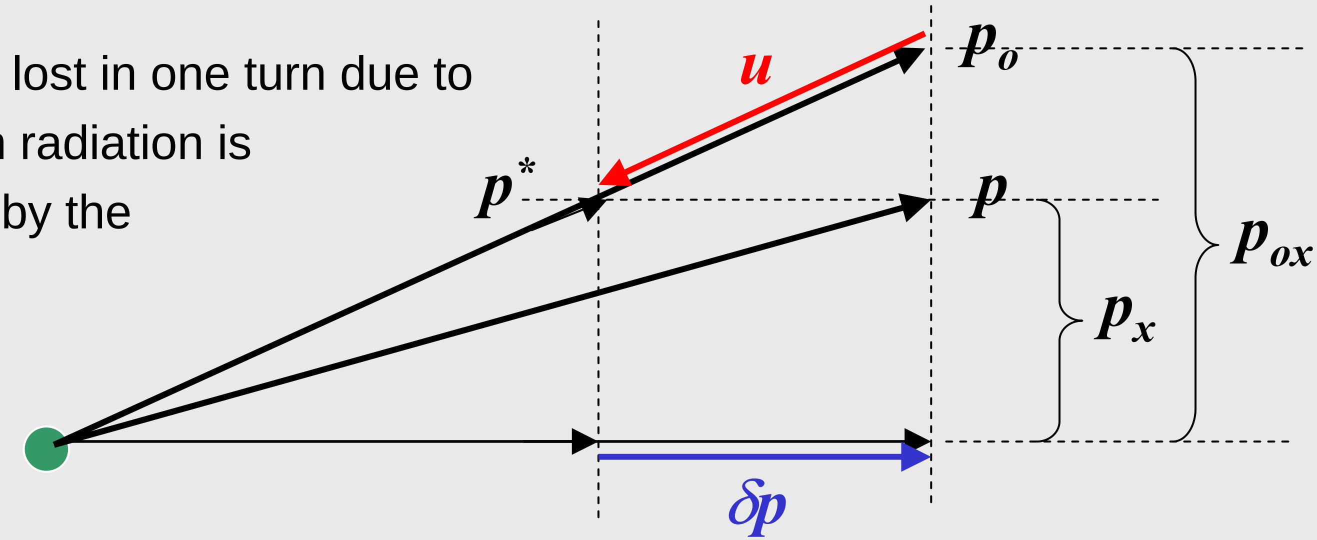
➔ $$\varepsilon_x = C_q \frac{\gamma^2}{J_x} \frac{\left\langle H/\rho^3 \right\rangle}{\left\langle 1/\rho^2 \right\rangle}$$

For constant radius ρ we get:

$$\boxed{\varepsilon_x = C_q \frac{\gamma^2}{J_x} \frac{\langle H \rangle_{BEND}}{\rho}}$$

INSERT: ***RADIATION DAMPING***

The energy lost in one turn due to synchrotron radiation is substituted by the cavities:



Before emission
$$x_o' = \frac{p_{ox}}{p_{os}}$$

After emission
$$x^{*\prime} = \frac{p_x^*}{x_o'} = \frac{p_{ox}}{p_{os}} = x_o'$$

After cavity passage
$$x' = \frac{p_s^*}{p_s} = \frac{p_x^*}{p_s^* + \delta p} \approx x_o'\left(1 - \frac{\delta p}{x_o'}\right)$$

$$\delta x' = -x_o' \frac{u}{E_o}$$

Substituting in the expression for the constant of motion and averaging over all betatron phases leads to (neglecting quadratic terms) →

$$\Delta A^2 = A^2 - A_o^2 = -A^2 \frac{u}{E_o} \quad \rightarrow \quad \frac{\Delta A}{A} = -\frac{1}{2}\frac{u}{E_o}$$

Summation over all energy emissions in one turn:

$$\sum u_i = U_T \quad \rightarrow \quad \left\langle \frac{\Delta A}{A} \right\rangle = -\frac{1}{2}\frac{U_T}{E_o} \quad \rightarrow \quad \frac{1}{A}\frac{dA}{dt} = \frac{1}{T_o}\left\langle \frac{\Delta A}{A} \right\rangle = \frac{1}{\tau_x} = -\frac{1}{2}\frac{U_T}{E_o T_o}$$

INSERT: ***EQUILIBRIUM***

Averaging over all emission processes of one turn leads to →

$$\left\langle \frac{dA^2}{dt} \right\rangle = \frac{\left\langle \dot{N}_{ph} \left\langle u^2 \right\rangle H \right\rangle}{E_o^2}$$

Averaging over all betatron phases for the radiation damping →

$$\frac{1}{A}\frac{dA}{dt} = \frac{1}{T_o}\left\langle \frac{\Delta A}{A} \right\rangle = \frac{1}{\tau_x}$$

Equilibrium between quantum fluctuation and radiation damping:

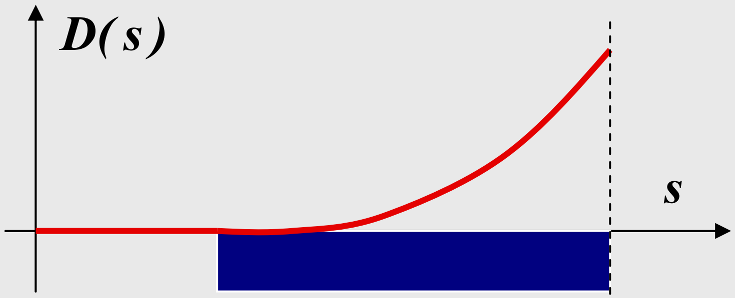
$$\left\langle \frac{dA^2}{dt} \right\rangle = 2\left\langle A\frac{dA}{dt} \right\rangle = 2\left\langle A^2\frac{1}{A}\frac{dA}{dt} \right\rangle = \frac{2}{\tau_x}\left\langle A^2 \right\rangle$$

$$\boxed{\sigma_x^2 = \frac{\left\langle A^2 \right\rangle}{2} = \frac{1}{4}\tau_x \frac{\left\langle \dot{N}_{ph} \left\langle u^2 \right\rangle H \right\rangle}{E_o^2} \quad \Rightarrow \quad \varepsilon_x = C_q \frac{\gamma^2}{J_x} \frac{\left\langle H/\rho^3 \right\rangle}{\left\langle 1/\rho^2 \right\rangle}}$$

To get the minimum emittance the integral over the Courant Snyder invariant ***H*** over the length of the bending magnets has to be minimized:

$$\left\langle H(s)\right\rangle_{BEND} = \frac{1}{L}\int_0^L H(s)ds \rightarrow min.$$

SINGLE MAGNET OPTIMIZATION:



In a bending magnet the dispersion is developing as:

$$D(s) = \rho(1 - \cos\frac{s}{\rho})$$

$$D'(s) = \sin\frac{s}{\rho}$$

A rectangular magnet corresponds to a drift in the horizontal plane and the optical functions α, β, γ inside have a simple relations to the initial values at the entrance of the magnet:

$$\beta(s) = \beta_o - 2\alpha_o s + \gamma_o s^2$$

$$\alpha(s) = \alpha_o - \gamma_o s$$

$$\gamma(s) = \gamma_o$$

Substitution of these relations into the expression for the Courant Snyder Invariant (for D_o=0 and D_o'=0) →

$$D_x^2(s) + \left[D_x(s)\alpha_x(s) + D_x'(s)\beta_x(s)\right]^2$$

We get a functional dependence on s and coefficients that include the initial parameters β_o , α_o and the bending radius ρ.

After performing the integration we get:

$$\langle H(s)\rangle = \frac{L^2}{\rho^2}\left[\frac{1}{3}\beta_o - \frac{1}{4}\alpha_o L + \frac{1}{20}\gamma_o L^2\right]$$

To find the minimum we have to solve:

$$\frac{\partial H}{\partial \beta_o} = 0$$

$$\frac{\partial H}{\partial \alpha_o} = 0$$

→ leads to:

$$\beta_o = 2L\sqrt{\frac{3}{5}}$$

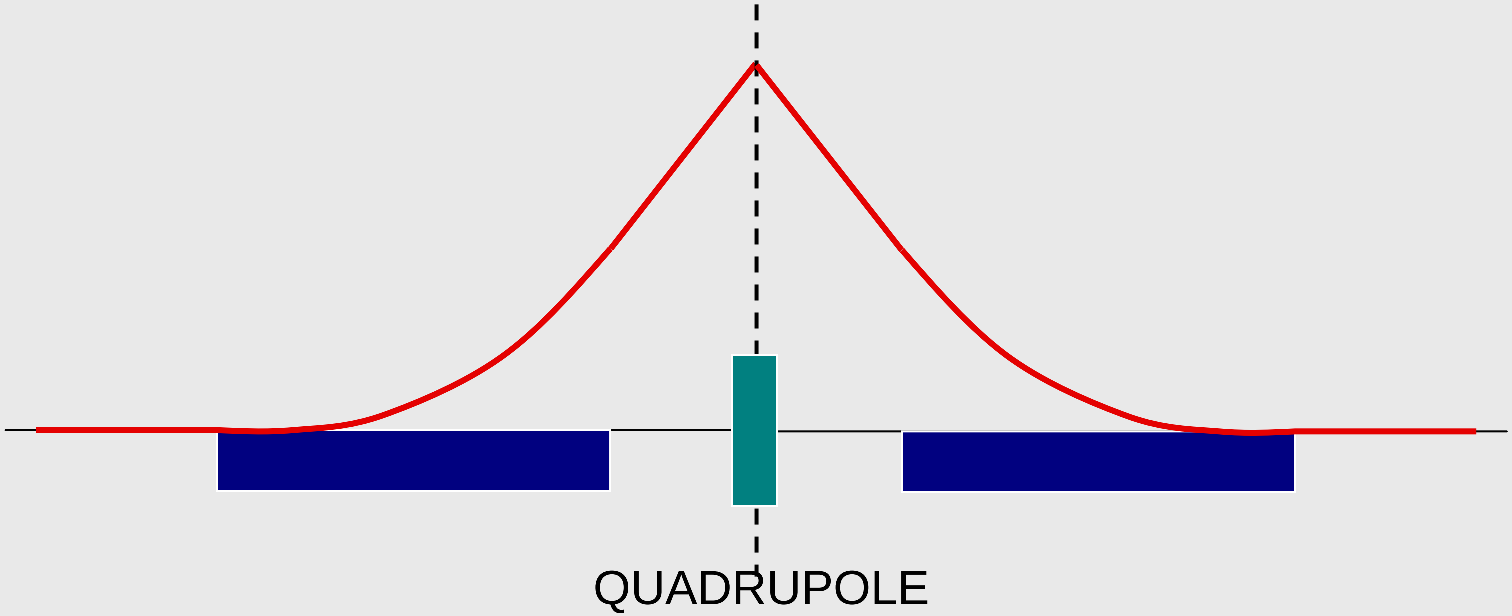
$$\alpha_o = \sqrt{15}$$

Substituting this values in the expression for the emittance we find for the minimum →

MINIMUM EMITTANCE:

$$\varepsilon = \frac{C_q \gamma^2}{J_x} K \left(\frac{L}{\rho}\right)^3 = \frac{C_q \gamma^2}{J_x} K \phi_B^3 \qquad K = \frac{1}{4\sqrt{15}} \approx 6.5 \cdot 10^{-2}$$

We can now construct a simple achromat structure →



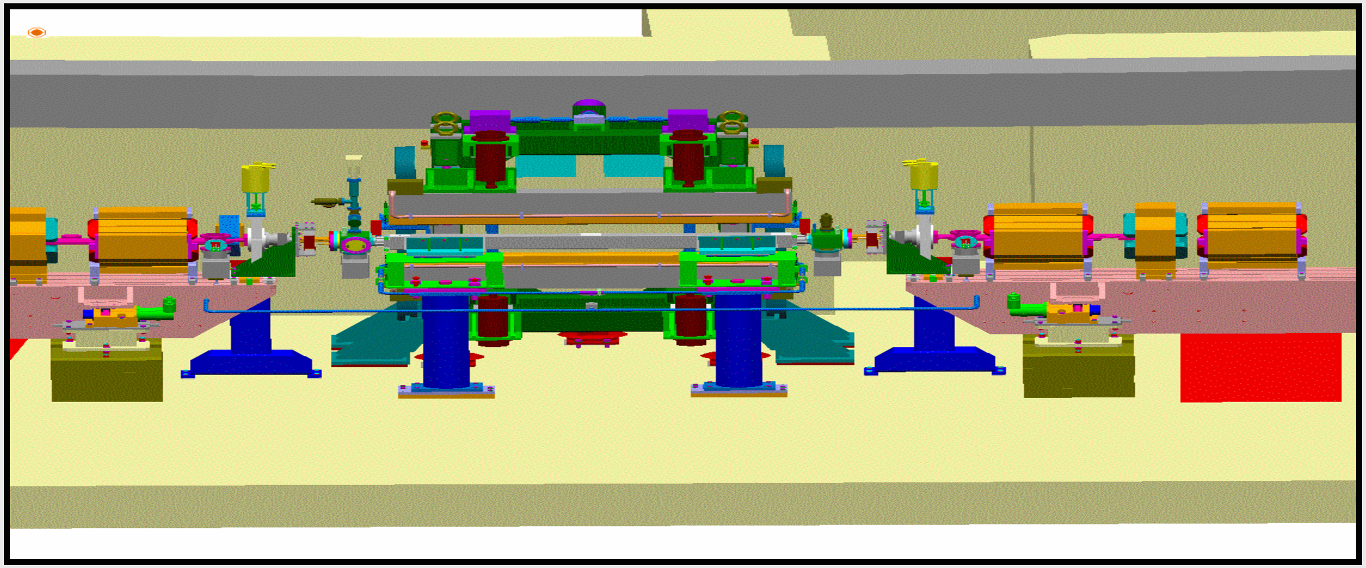
DOUBLE BEND ACHROMAT STRUCTURE
DBA

➔ Light Sources are built up by a large number of identical achromat structures connected by long (empty) dispersion free sections !

The dispersion has to be matched to zero in the straight section in order to get a small beam size and correspondingly high brilliance !

<u>USE of the long straight sections (~ 2 – 12 m):</u>

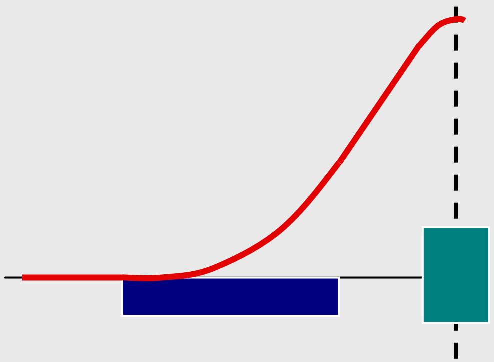
For the implementation of insertion devices – **WIGGLERS** and **UNDULATORS** for enhanced flux and brilliance of the light →



PROBLEM with the DBA

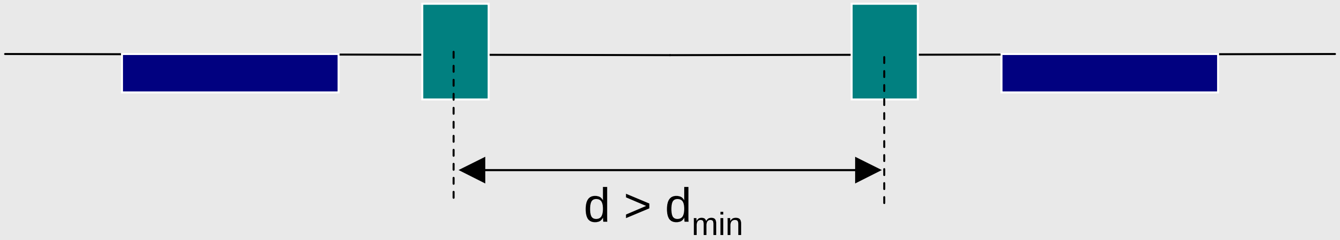
In the center of the achromat we have a symmetry point, i.e. → $\alpha = 0$, $D'_o = 0$

➔ Beta function and dispersion must be matched to zero slope in the center by the quadrupole:

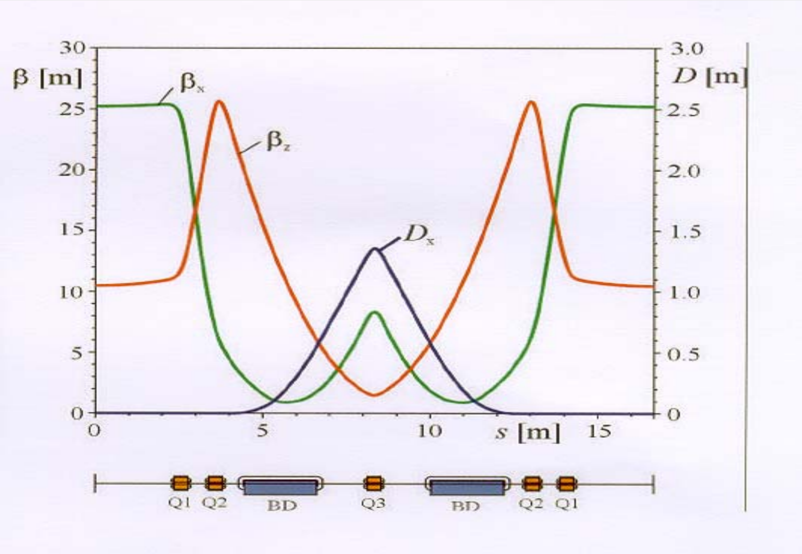


THIS IS NOT POSSIBLE !!
(with a single Quadrupole)

To reach the theoretical minimum for a DBA lattice at least 2 quadrupoles are needed which are seperated by a certain distance:

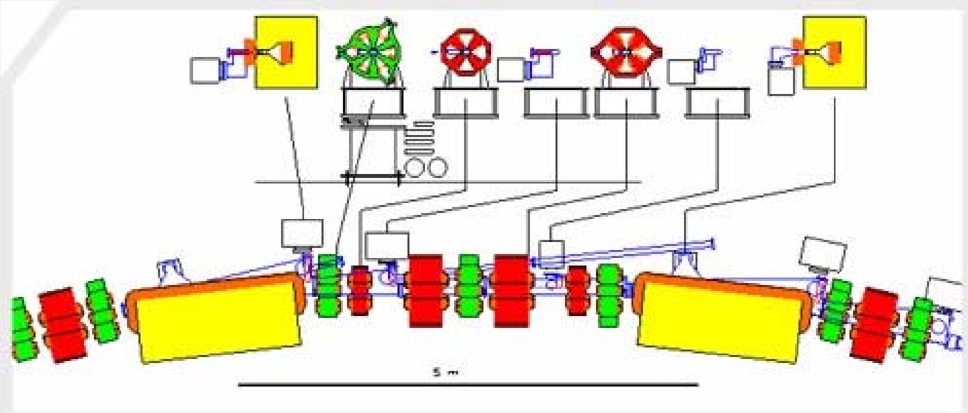


EXAMPLE: ***DBA***



OPTICAL FUNCTIONS

With ONE quadrupole
in the achromat



MAGNET STRUCTURE

With >TWO quadrupoles to approach the theoretical minimum

$$\varepsilon = \frac{C_q \gamma^2}{\boxed{J_x}} K \phi_B^3$$

Horizontal damping partition number !

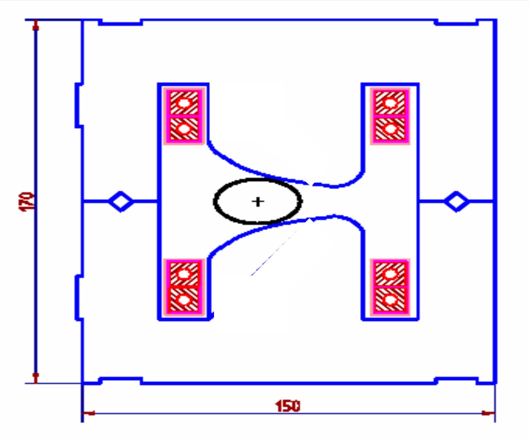
$$\frac{1}{\tau_x} = -\frac{1}{2J_x}\frac{U_T}{E_o T_o}$$

The sum of all 3 damping partition numbers is constant, i.e. damping can be transferred from the longitudinal direction to the horizontal direction for a proper chosen magnet structure.

$$J_x + J_y + J_s = 4$$

If focusing and bending are seperated in amgnet structure – **separate function magnet structure** – we have:

$$J_x = 1, \quad J_y = 1, \quad J_s = 2$$

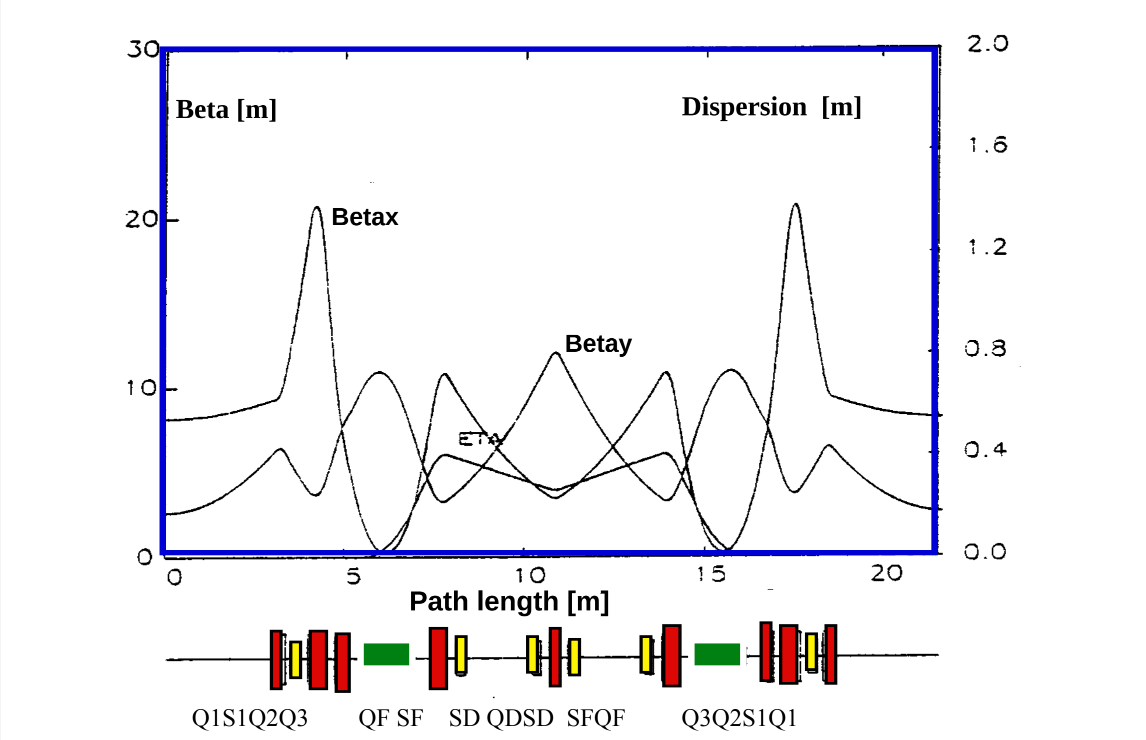


With a **combined function magnet structure** we can have $J_x > 1$ and therefore further reduce the emittance.

EXAMPLE: ***ELETTRA***

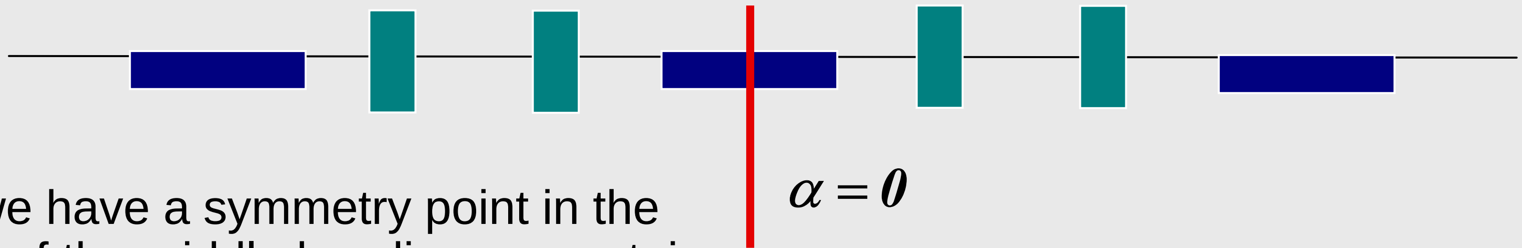
$$\varepsilon = \frac{C_q \gamma^2}{J_x} K \phi_B^3$$

$J_x = 1.3$



→ adds also vertical focusing and keeps β_y low !

The other structure frequently used is the → **TRIPLE BEND ACHROMAT TBA**



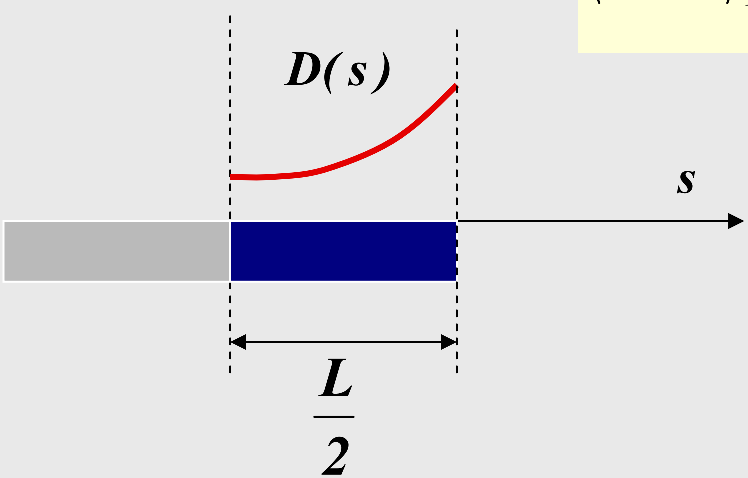
Now we have a symmetry point in the center of the middle bending magnet, i.e.

$$\alpha = 0$$

$$D'_o = 0$$

CENTER MAGNET OPTIMIZATION *(starting from the center):*

$$\langle H(s) \rangle_{BEND} = \frac{1}{L}\int_0^L H(s)ds \quad \rightarrow \quad min.$$



$$D(s) = D_o + \rho(1 - \cos\frac{s}{\rho})$$

$$D'(s) = \sin\frac{s}{\rho}$$

$$\beta(s) = \beta_o + \frac{s^2}{\beta_o}$$

$$\alpha(s) = -\frac{s}{\beta_o}$$

$$\varepsilon_{min} = \frac{C_q \gamma^2}{J_x} K \phi^3_{BEND}$$

$$K = \frac{7}{36\sqrt{15}} \approx 5 \cdot 10^{-2}$$

PROBLEM (1) with the TBA

➔ We have to match now dispersion and beta function from the exit of the optimized outer bending magnet to the center of the optimized inner bending magnet

THIS IS NOT POSSIBLE !! (under no circumstances)

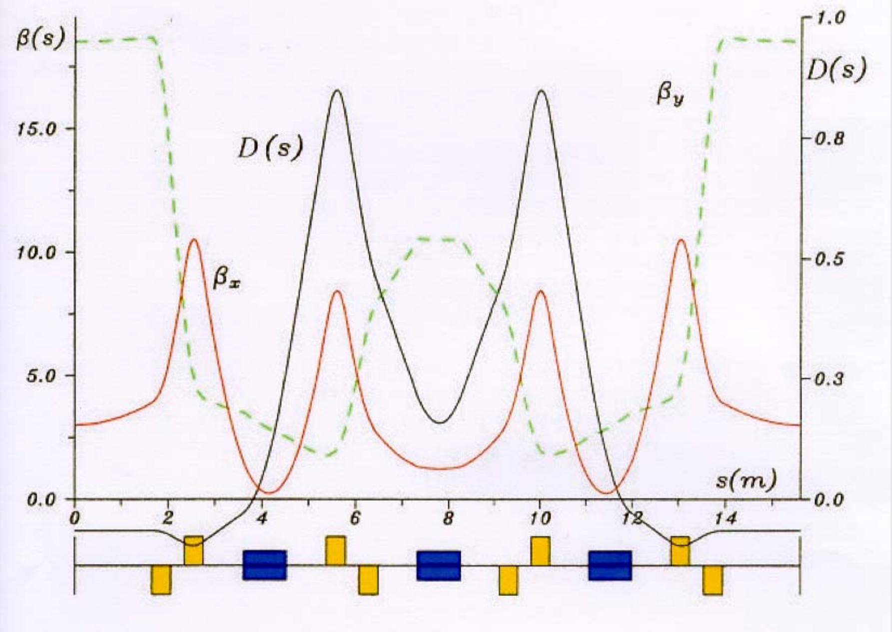
The theoretical minimum of the TBA structure can't be reached but just approached !

But there is nevertheless a big gain due to the reduction of the bending angle →

$$\varepsilon_{min} = \frac{C_q \gamma^2}{J_x} K \phi_{BEND}^3$$

$$\phi_{TBA} = \frac{2}{3} \phi_{DBA}$$

NOTE: if a dispersion in the straight section is permitted the emittance can be further reduced!



PROBLEM (2) with the TBA

$$\frac{\Delta Q}{\Delta p / p_o} = \xi = \frac{1}{4\pi}\oint_C \beta(s)K(s)ds$$

➔ Has to do with the chromaticity correction:

Which is done by introducing sextupoles in the magnet structure.

$$\Delta x' = m(x^2 - y^2) \qquad m = \frac{1}{2}\frac{B''L}{B_o\rho} \qquad x = x_\beta + \delta D_x \qquad \delta = \frac{\Delta p}{p_o}$$

$$\Delta y' = -2mxy \qquad y = y_\beta$$

x_β … betatron oscillations

$$\Delta x' = m\left[(x_\beta + \delta D_x)^2 - {y_\beta}^2\right] = m({x_\beta}^2 - {y_\beta}^2) + \boxed{(\delta 2mD_x)x_\beta} + m(\delta D_x)^2$$

$$\Delta y' = -2m(x_\beta + \delta D_x)y_\beta = -2mx_\beta - \boxed{(\delta 2mD_x)y_\beta}$$

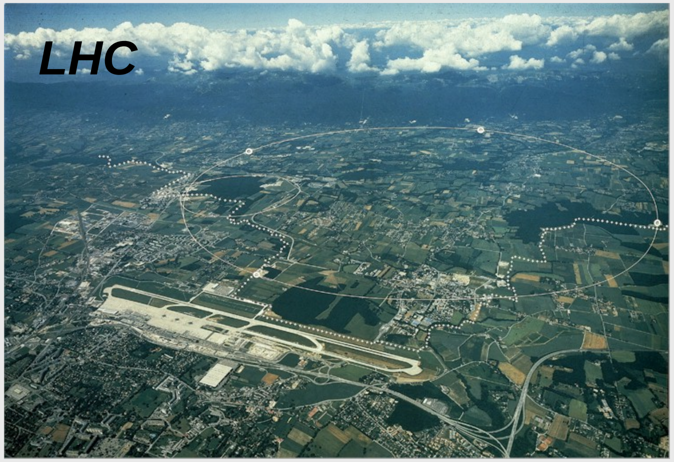
$$\boxed{\xi_x = \frac{1}{4\pi}\left[\sum_{i,j}\beta_{xi}(kl)_i + 2(ml)_j D_{xj}\beta_{xj}\right] \rightarrow 0}$$

Sextupoles are nonlinear elements and reduce the dynamic aperture. In order to keep their strengths low they have to be placed at positions with large dispersion (and large decoupling of the beta function).

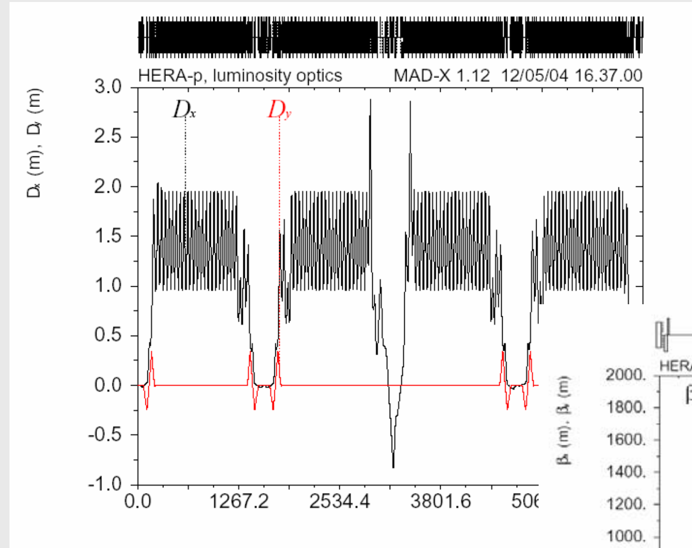
Chromatic corrections are more difficult in TBA lattices !

COMPARISON OF LATTICES FOR LIGHT SOURCES AND HEP COLLIDERS

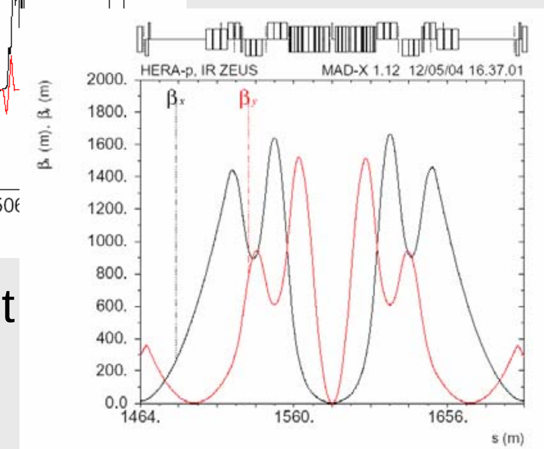
HEP COLLIDER



→ large circumferences



HERA



→Long regular magnet structures with few low beta insertions

HEP colliders are composed by long regular FODO cells in the arcs and a few low beta insertions:

Large circumferences are necessary to reach the highest possible energies

$$\frac{1}{\rho} = \frac{e}{p} B$$

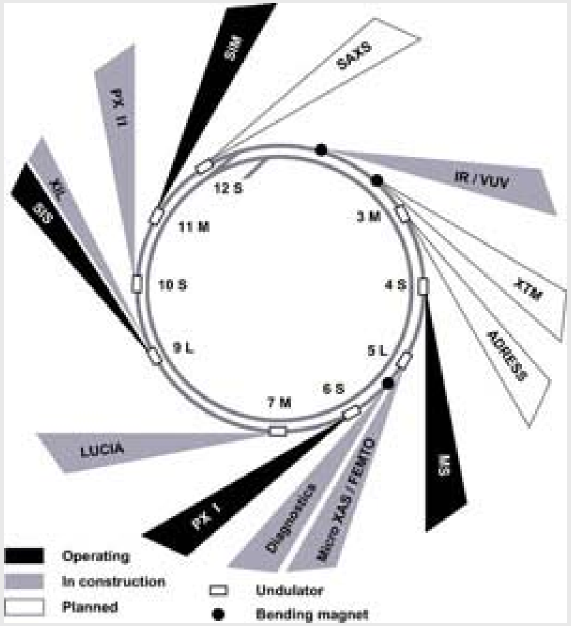
B_{max}
nc: 1.6 T
sc: ~ 9 T

COMPARISON OF LATTICES FOR LIGHT SOURCES AND HEP COLLIDERS

LIGHT SOURCE

Light Sources are built up by a large number of identical achromat structures.

Large circumferences are wanted to increase the BRILLIANCE and to provide many straights for IDs !



SLS

$$B = \frac{F}{(4\pi)^2 \kappa \varepsilon_x^2}$$

$$\varepsilon_{min} = \frac{C_q \gamma^2}{J_x} K \phi_{BEND}^3$$

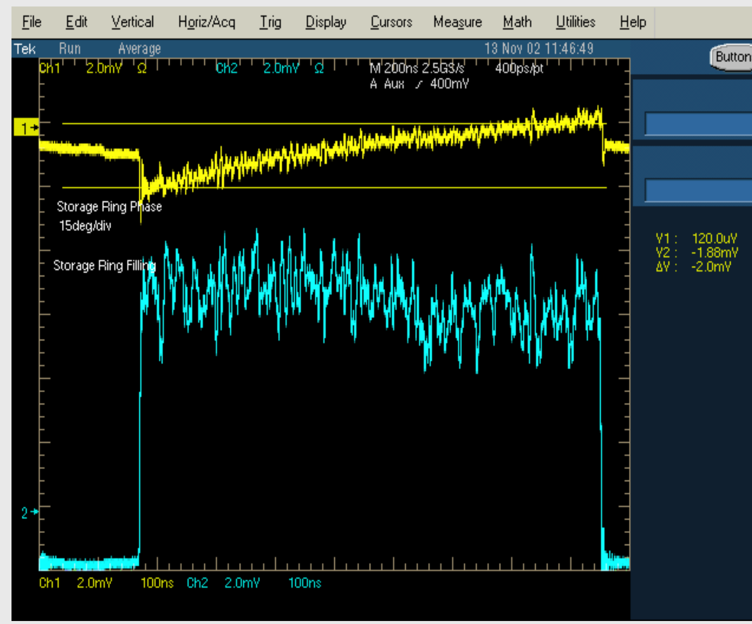
WHAT ELSE IS IMPORTANT FOR A LIGHT SOURCE

- **SUPPRESSION OF ENERGY WIDENING EFFECTS**
  Shift of the radiation harmonics from an undulator → intensity fluctuations, broadning of the lines
- **INTENSITY STABILITY**
  Change in background conditions and thermal load on beamline optics and machine components (→ position stability!)
- **POSITION STABILITY**
  Dilution of the emittance →reduced brilliance, intensity fluctuation
- **ENERGY STABILITY**
  Shift of the radiation harmonics from an undulator → intensity fluctuation
- **TUNABILITY**
- **HIGH PHOTON ENERGIES**

SUPPRESSION OF ENERGY WIDENING EFFECTS

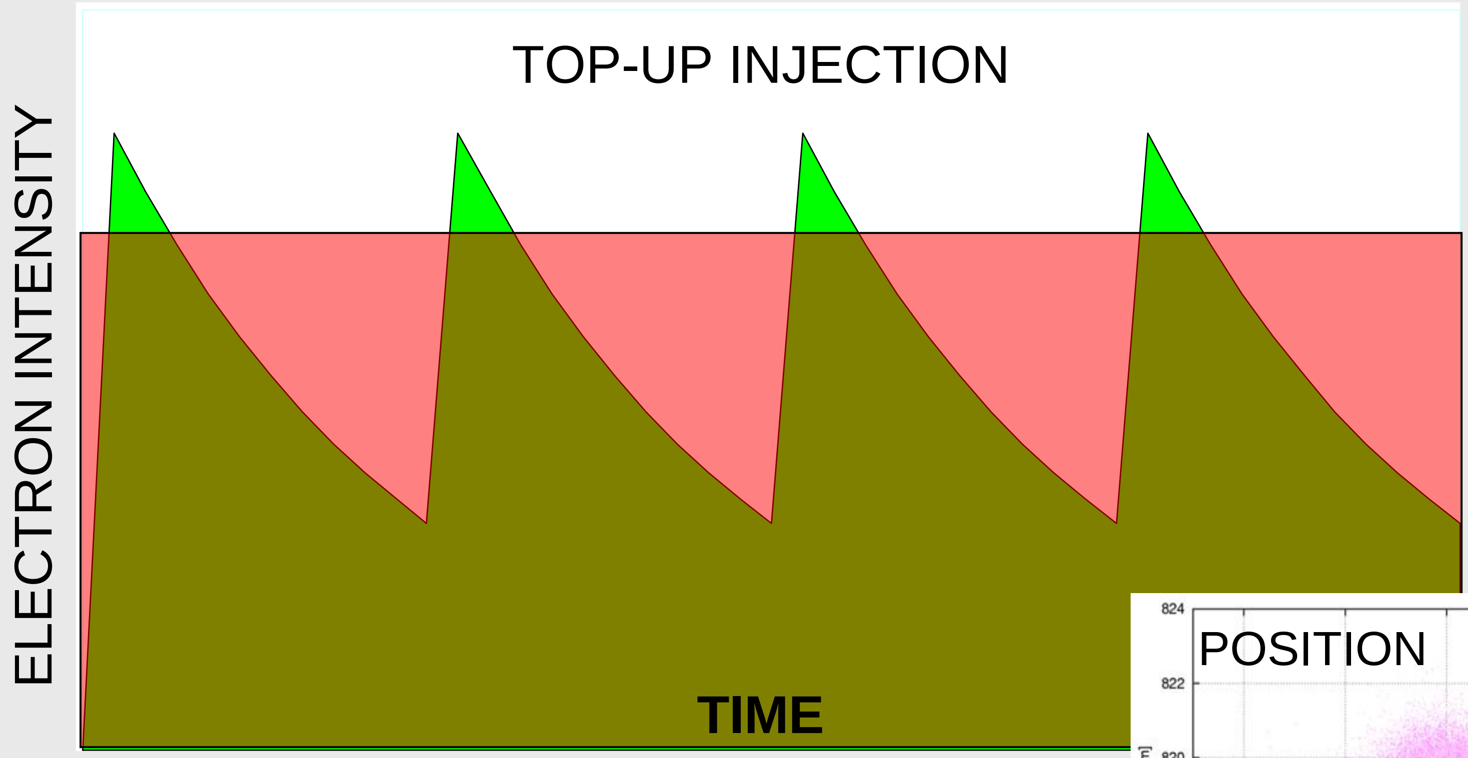
- MULTIBUNCH FEEDBACK SYSTEMS
- PASSIVE SUPERCONDUCTING HIGHER HARMONIC CAVITY

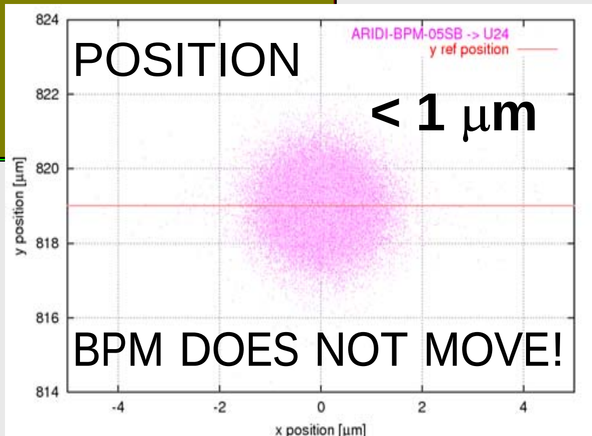
3HC COLLABORATION
CEA (Saclay),CERN,Sincrotrone Trieste, PSI



Phase variation along the bunch train (for a partially filled ring) causes a split in frequency for the individual bunches and therefore a suppression of longitudinal mulit-bunch instabilities

INTENSITY STABILITY





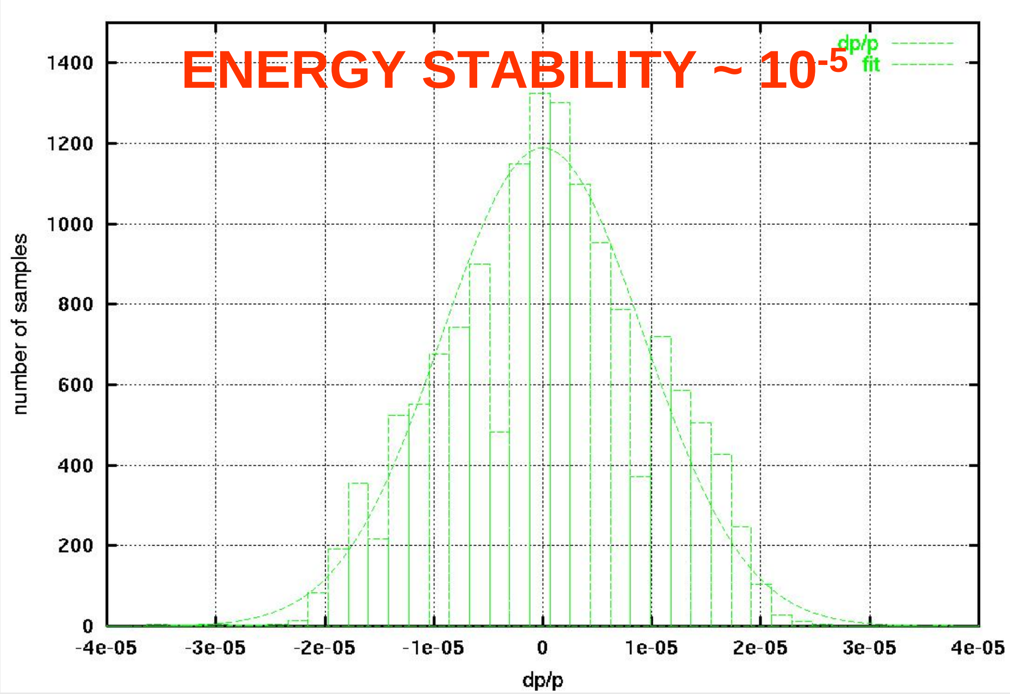
Steady state glow at the SLS

ENERGY STABILITY

CORRECTING THE AVERAGE HORIZONTAL ORBIT BY ADJUSTING THE RF FREQUENCY AND THUS ADJUSTING THE ELECTRON ENERGY

HIGH INTENSITY STABILITY OF MONOCHROMATOR OUTPUT

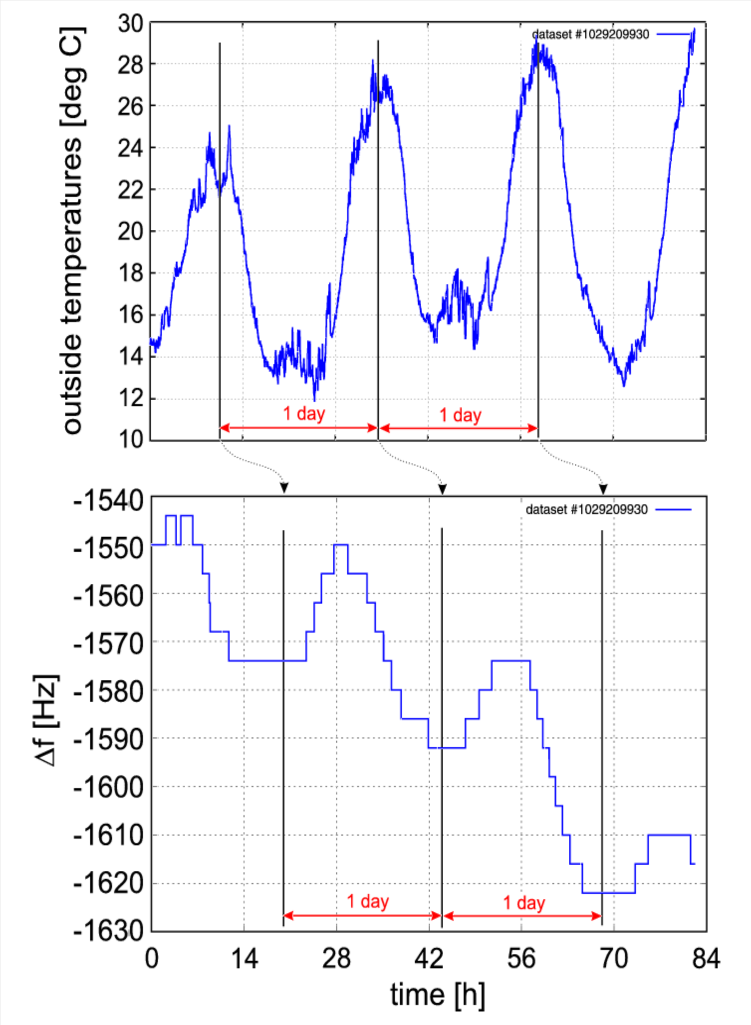
$$\lambda = \frac{\lambda_o}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$



DAY / NIGHT TEMPERATURE VARIATIONS

CIRCUMFERENCE OF THE SLS RING CHANGES WITH OUTSIDE TEMPERATURE

RF FREQUENCY IS ADJUSTED TO COMPENSATE FOR THESE CHANGES

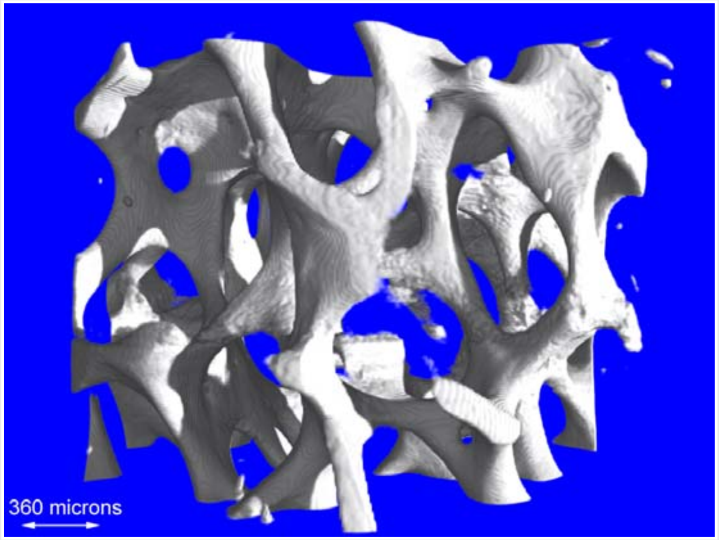


TUNABILITY

→ To adjust the photon energy to the needs of the experiment !

EXAMPLES:

ABSORPTION TOMOGRAPHY
SLS-MATERIAL SCIENCE BEAMLINE
Bone sample damage



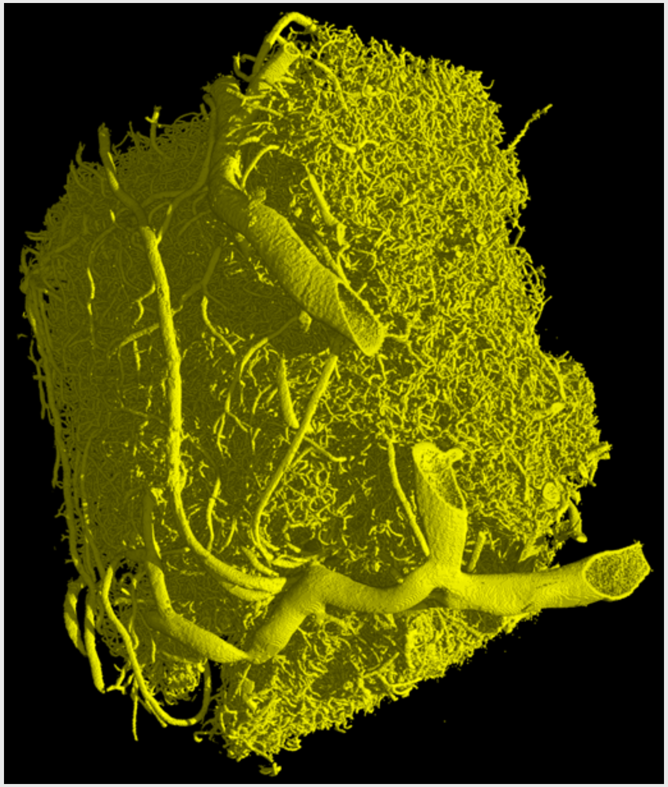
uni | eth | zürich
Institute for Biomedical Engineering

EMPA

Philipp Thurner, EMPA and IBT, Marco Stampanoni, SLS

PHASE CONTRAST TOMOGRAPHY
SLS-MATERIAL SCIENCE BEAMLINE
3-dimensional reconstruction of the vesicular distribution in mouse brains"

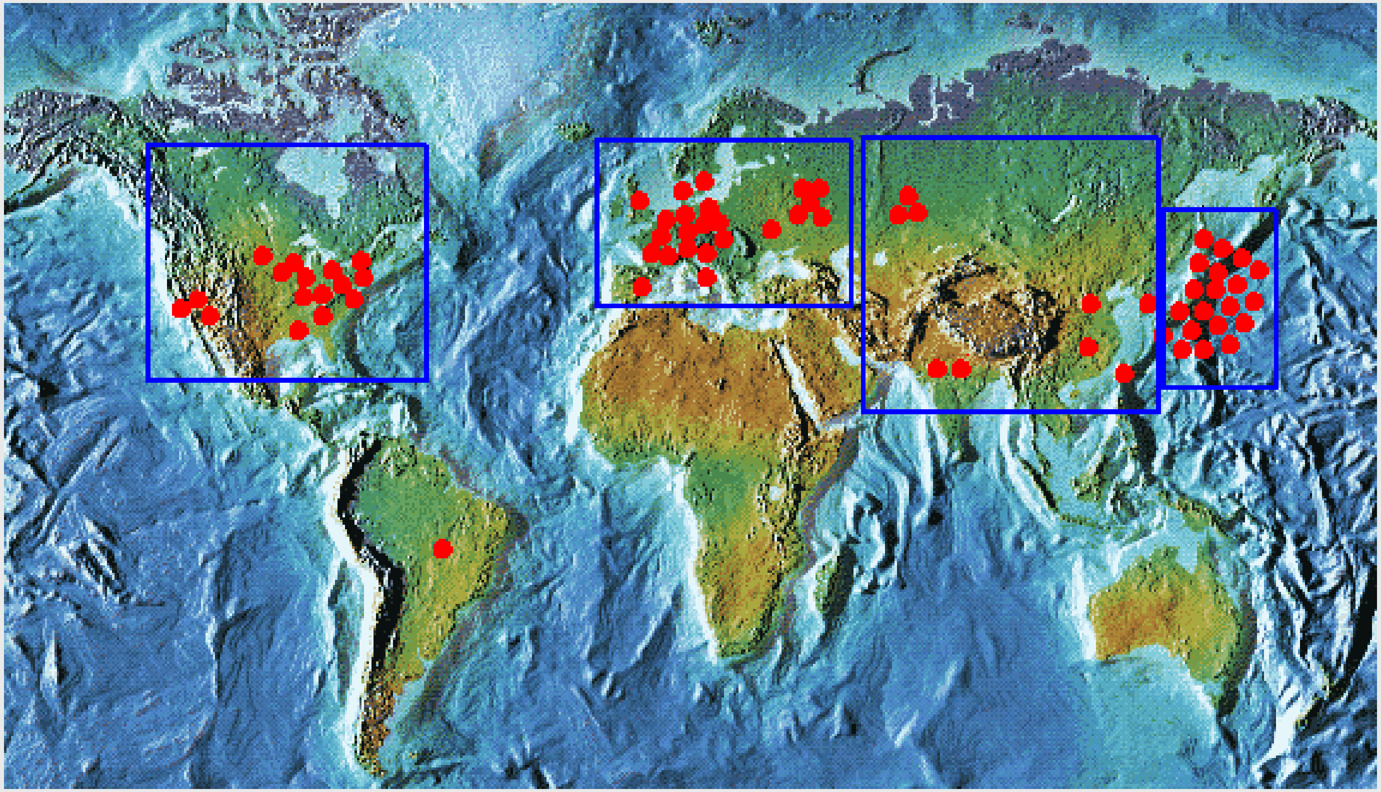
1 mm^3
Resolution
~ 1 μm



- **ALSO IMPORTANT →**

TO REACH HIGH PHOTON ENERGIES WITH A MEDIUM ENERGY MACHINE

SYNCHROTRON RADIATION CENTRES AROUND THE WORLD

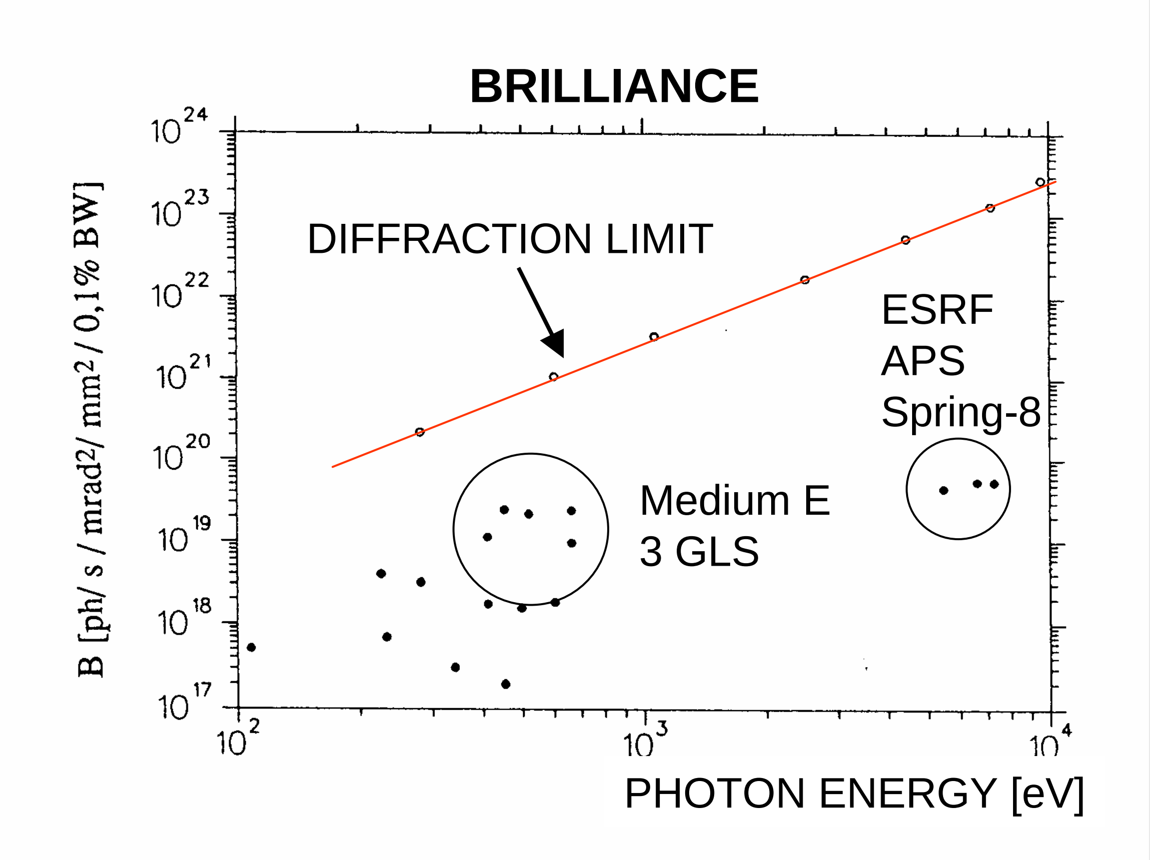


EUROPE → LORD OF THE RINGS

OUTLOOK
NEW GENERATION OF LIGHT SOURCES

Performance of 3rd Generation Light Sources:

Storage ring based light sources are for short wavelengths (high photon energies) far away from the theoretical limits →

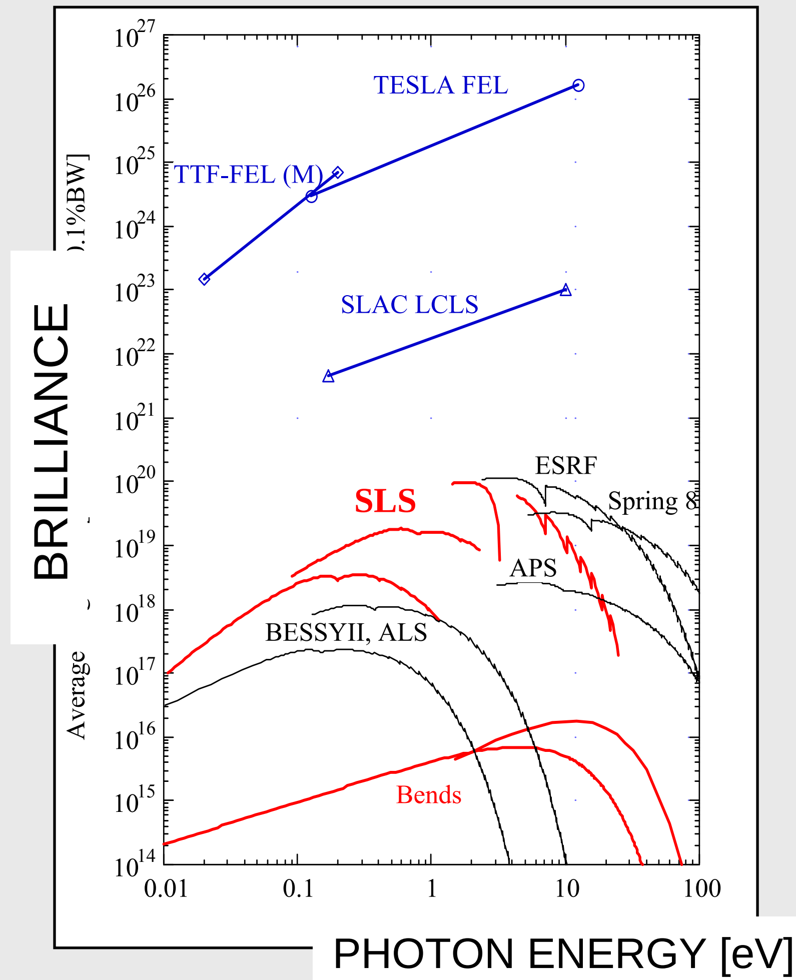


NEW GENERATION LIGHT SOURCE:

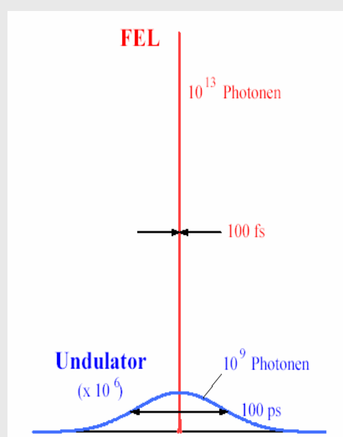
↓

SASE FREE ELECTRON LASERS

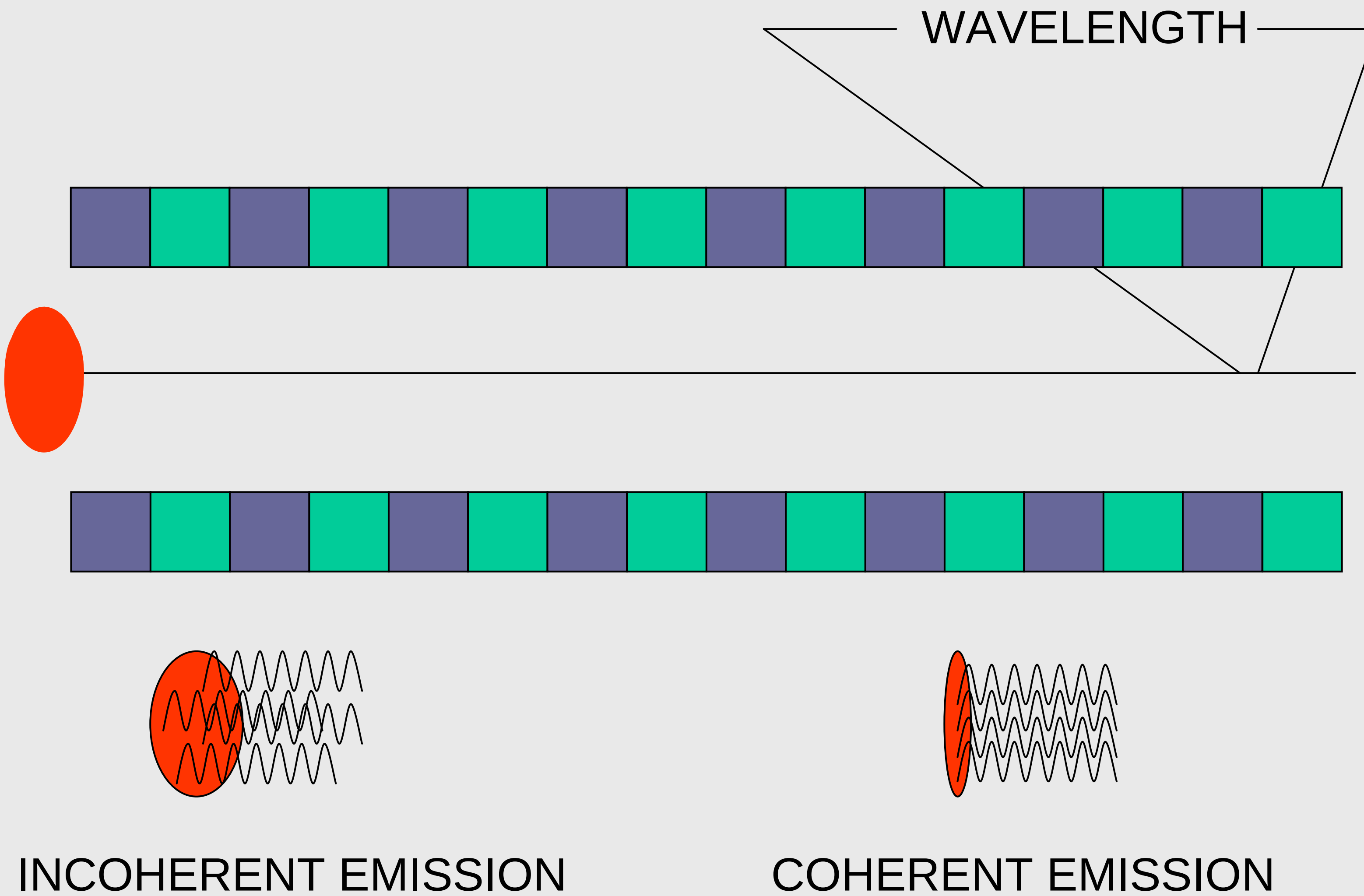
- Unbeatable peak and average BRILLIANCE (10^{30} - 10^{33})
- Short PULSES (1 ps – 50 fs)
- Small BANDWIDTH



BANDWIDTH →



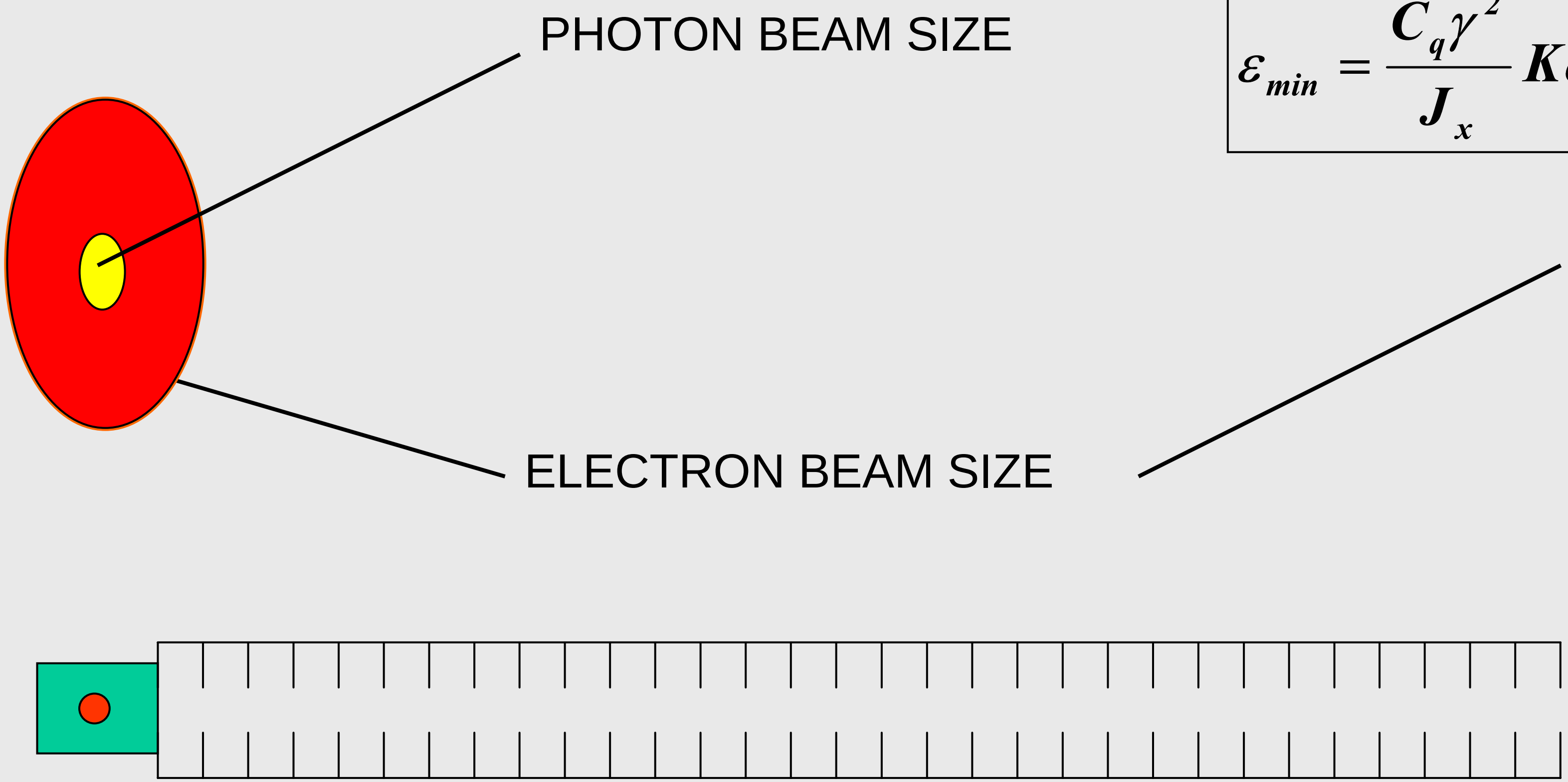
SASE PRINCIPLE:



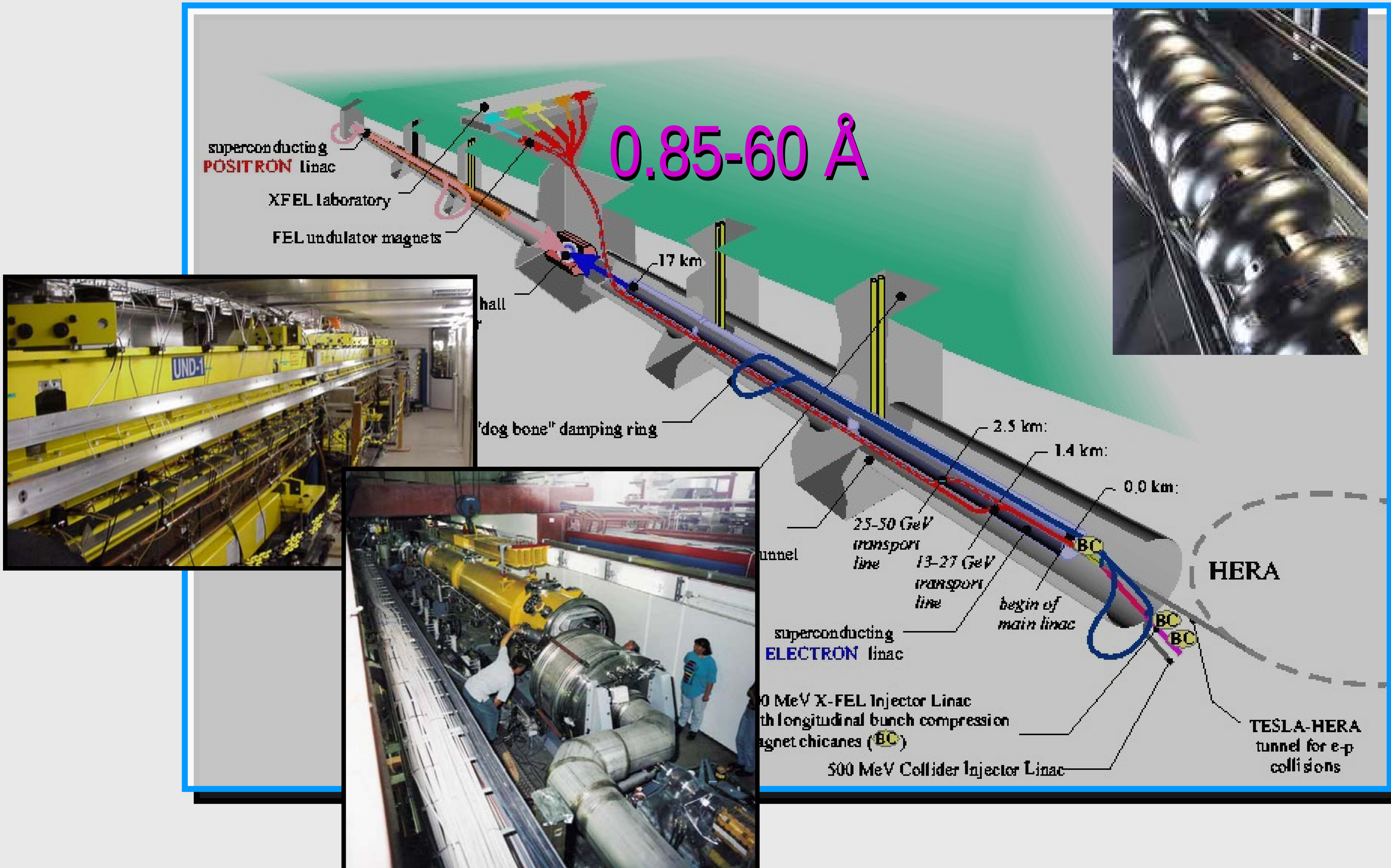
REQUIRES A SMALL ELECTRON BEAM !

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

$$\varepsilon_{min} = \frac{C_q \gamma^2}{J_x} K \phi^3_{BEND}$$



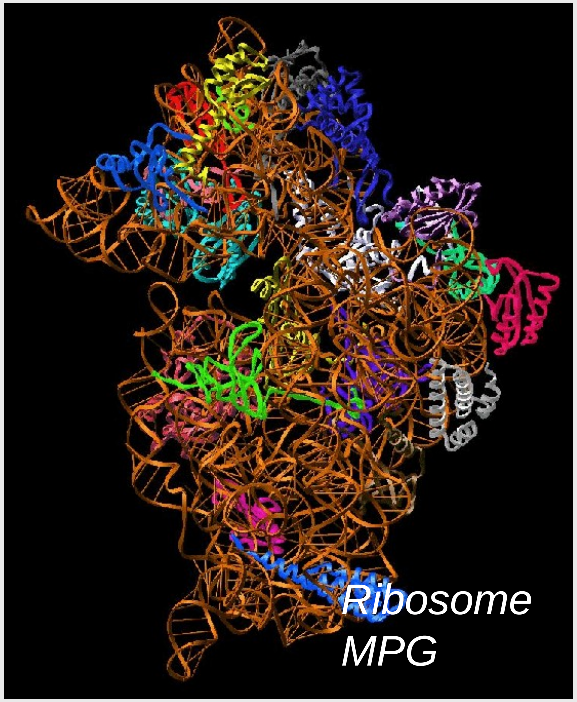
TESLA X - FEL at DESY



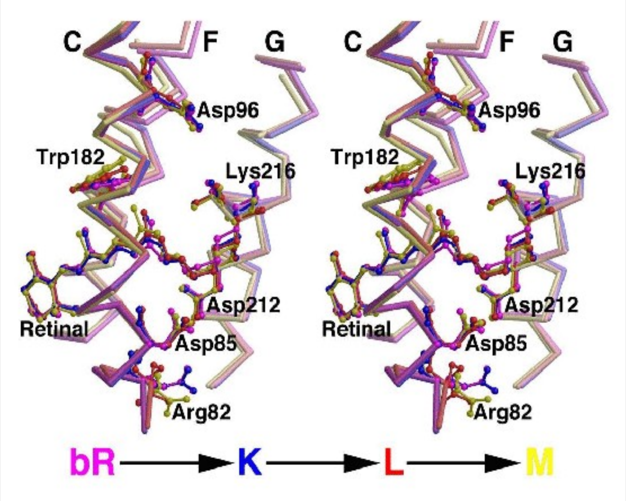
USERS DREAMS WILL THEN BECOME REALITY →

- SINGLE SHOT imaging of single biomolecular complexes

NEEDS MANY PHOTONS ON THE SAMPLE !



***LYSOZYME** MOLEKUEL*



Light induced structural changes during photocycle

- TIME RESOLVED studies of structural processes during chemical and biological reactions

NEEDS VERY SHORT PULSES !

CONCLUSION

- Storage ring based Light Sources need a highly optimized lattice to reach the maximum brilliance (coherence)
- Nonlinear compensation must already be optimized with the linear lattice design
- Large circumferences are wanted to reduce the emittance, i.e. to increase the brilliance and to provide space for many insertion devices
- Not all user requirements can be met with storage ring based light sources (longitudinal coherence, short pulses)
- A new generation of light sources - Free Electron Laser - is needed to meet these requirements
- Stability of intensity, energy and position are crucial issues

THE END