Lecture 2 : Main features of a 3rd GLS Storage Ring

- Brilliance
- Emittance
- Current
- Lifetime

Brilliance

The main figure of merit for the 3rd Generation Light Sources is the **Brilliance** (or spectral brightness), which describes the photon density:

Number of photons
- per second
- per unit source size
- per unit solid angle
- per 0.1 % bandwidth of Xray energy

$$B = \frac{dN_{ph}}{dt} \frac{1}{dA\, d\Omega\, d\lambda / \lambda}$$

$$\frac{photons\ \ per\ \sec ond}{mm^2\, mrad^2\, 0.1\% b.w}$$

SOLEIL SYNCHROTRON

Brilliance and Emittance

The **brilliance** of the source indicates the coherent flux of the photon beam emittance, at a given Xray energy.
The photon beam emittance (size x divergence) is the convolution of :

- ❑ the photon emittance from a single electron $\varepsilon_r \quad \left(\sigma_r . \sigma_r^{'}\right)$

with

- ❑ the electron beam emittance $\varepsilon_x \ , \ \varepsilon_z$

$$\text{brilliance} = \frac{\text{flux}}{4\pi^2 \Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'}}$$

$$\Sigma_{x,z} = \sqrt{\sigma_{x,z}^2 + \sigma_r^2} \qquad \sigma_x = \sqrt{\varepsilon_x \beta_x + (D_x \sigma_E)^2} \qquad \sigma_z = \sqrt{\varepsilon_z \beta_z + (D_z \sigma_E)^2}$$

$$\Sigma_{x',z'} = \sqrt{\sigma_{x',z'}^2 + \sigma'^2_r} \qquad \sigma_{x'} = \sqrt{\varepsilon_x / \beta_x} \qquad \sigma_{z'} = \sqrt{\varepsilon_z / \beta_z}$$

Brilliance and Emittance

The brilliance from undulator may be expressed as

$$B(E_{xray}) = \frac{I}{\varepsilon_x \varepsilon_z} f(E, ID, E_{xray}, \ldots)$$

I	:	electron beam intensity
ε_x	:	horizontal emittance
ε_z	:	vertical emittance $\varepsilon_z = \varepsilon_x$. coupling
E	:	electron beam energy
E_{xray}	:	Xray energy
ID	:	Insertion device parameters : Bmax, period, length, gap

Brilliance and Emittance

Reducing the emittances is a way to further increase the Brilliance

However, there is no interest in reducing the emittances below the diffraction limit (single electron emission):

The minimum photon beam emittance from a single electron is

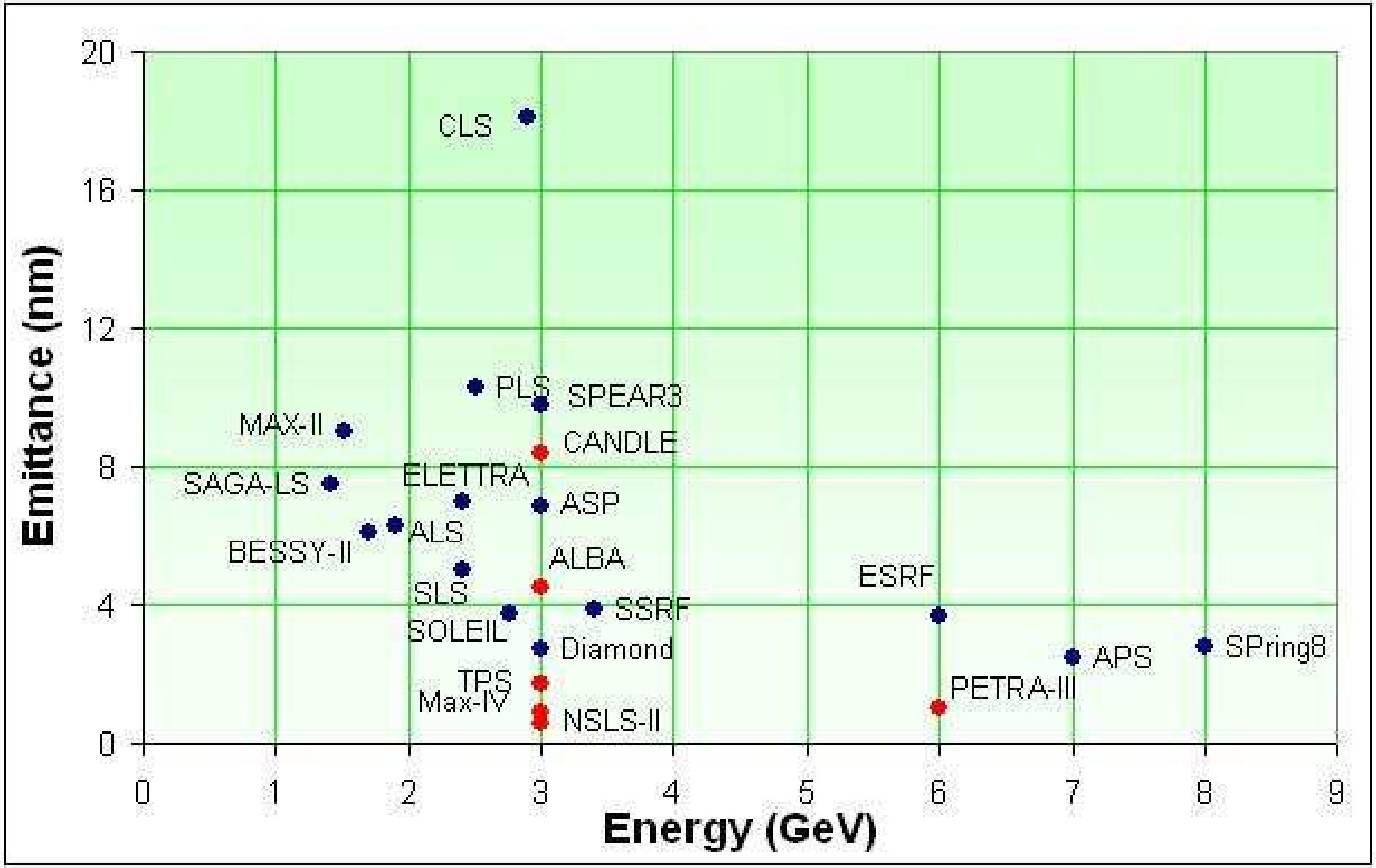
$$\varepsilon_r \approx \frac{\lambda}{4\pi} \approx \frac{10^{-10}}{E_{Xray}[keV]}$$

which gives	**100**	**pm.rad**	**at**	**1**	**keV**
	10	**pm.rad**	**at**	**10**	**keV**.

All 3rd GLS are close to the diffraction limit in the vertical plane.

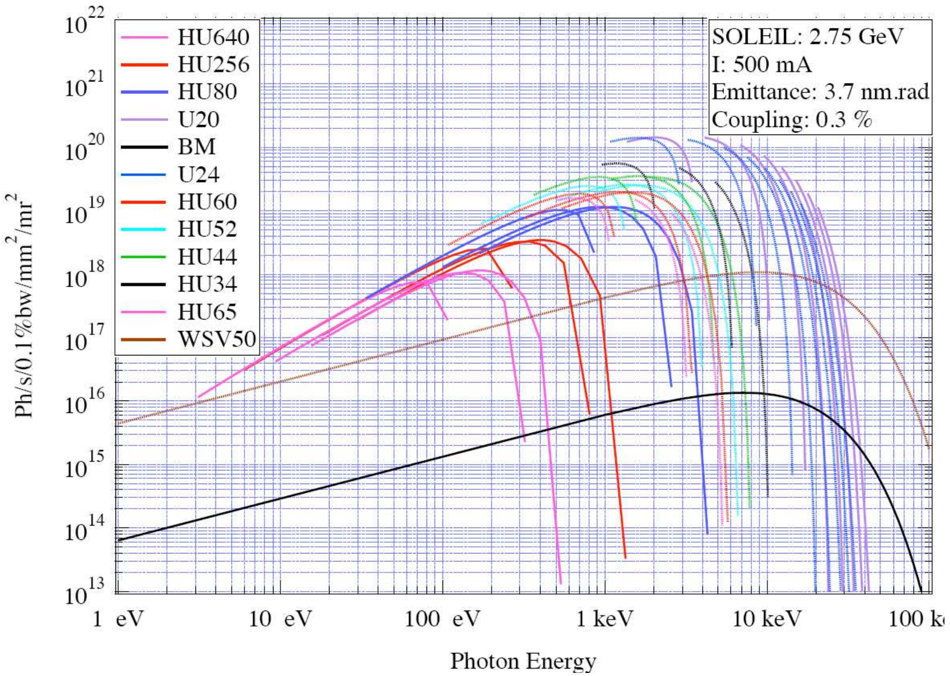
=> Action on the horizontal emittance

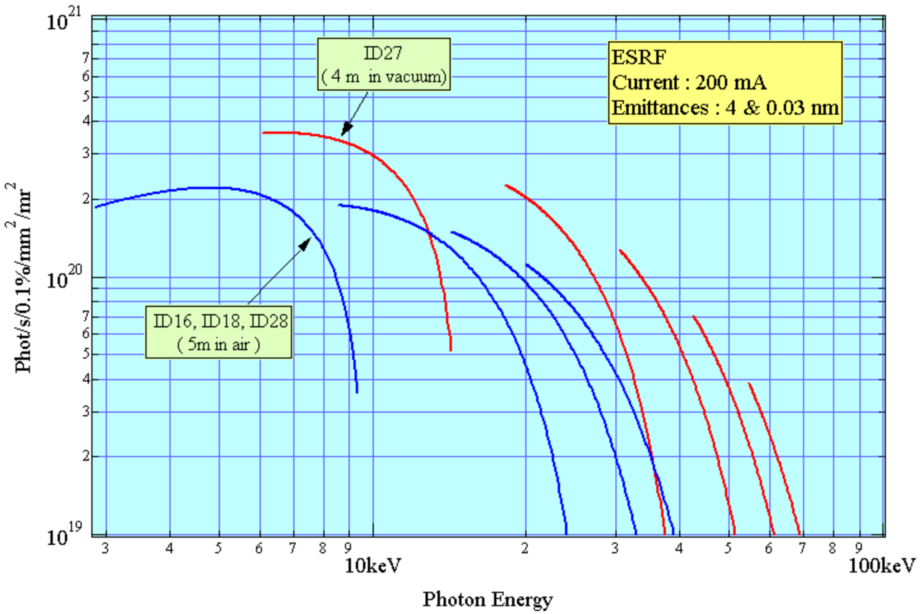
Brilliance and Emittance



Brilliance with IDs

Thanks to the progress with IDs technology storage ring light sources can cover a photon range from few tens of eV to tens 10 keV or more with high brilliance





Medium energy storage rings with In-vacuum undulators operated at low gaps (e.g. 5-7 mm) can reach 10 keV with a brilliance of 10^{20} ph/s/0.1%BW/mm²/mrad²

Brilliance and low Emittance

When the electron vertical emittance is of the order of the radiation emittance, **matching the electron emittance to the radiation emittance** (single electron emission) is required to fully benefit of the increased brilliance.

Example at the ESRF : moving from high βz to low βz

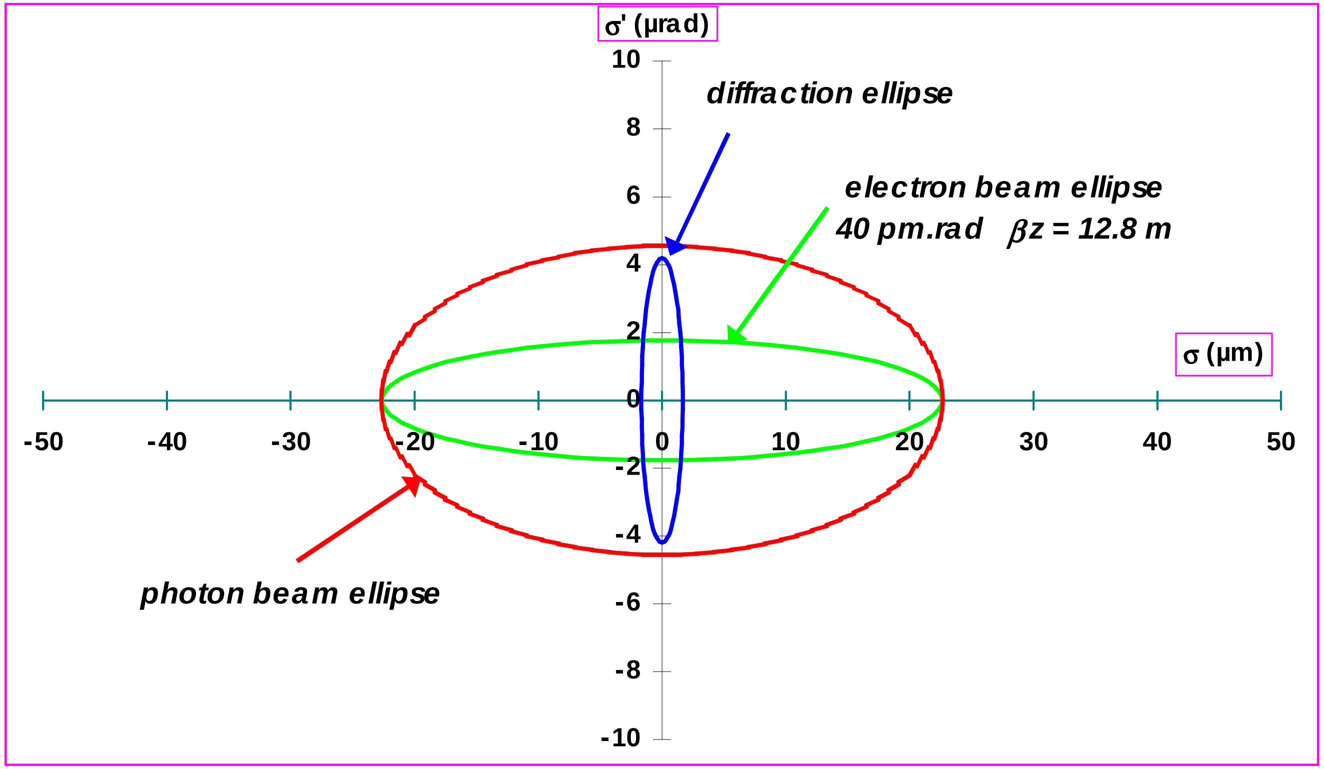
For 14 keV X-ray (λ=0.88 Å), the minimum photon emittance is defined by the diffraction limit : $\varepsilon r \sim \lambda / 4\pi = 7.2$ pm.rad

For an undulator of length L the radiation beam size is $\sigma_r = \frac{\sqrt{\lambda L}}{4\pi}$

and the radiation beam divergence is $\sigma_r' = \sqrt{\frac{\lambda}{L}}$

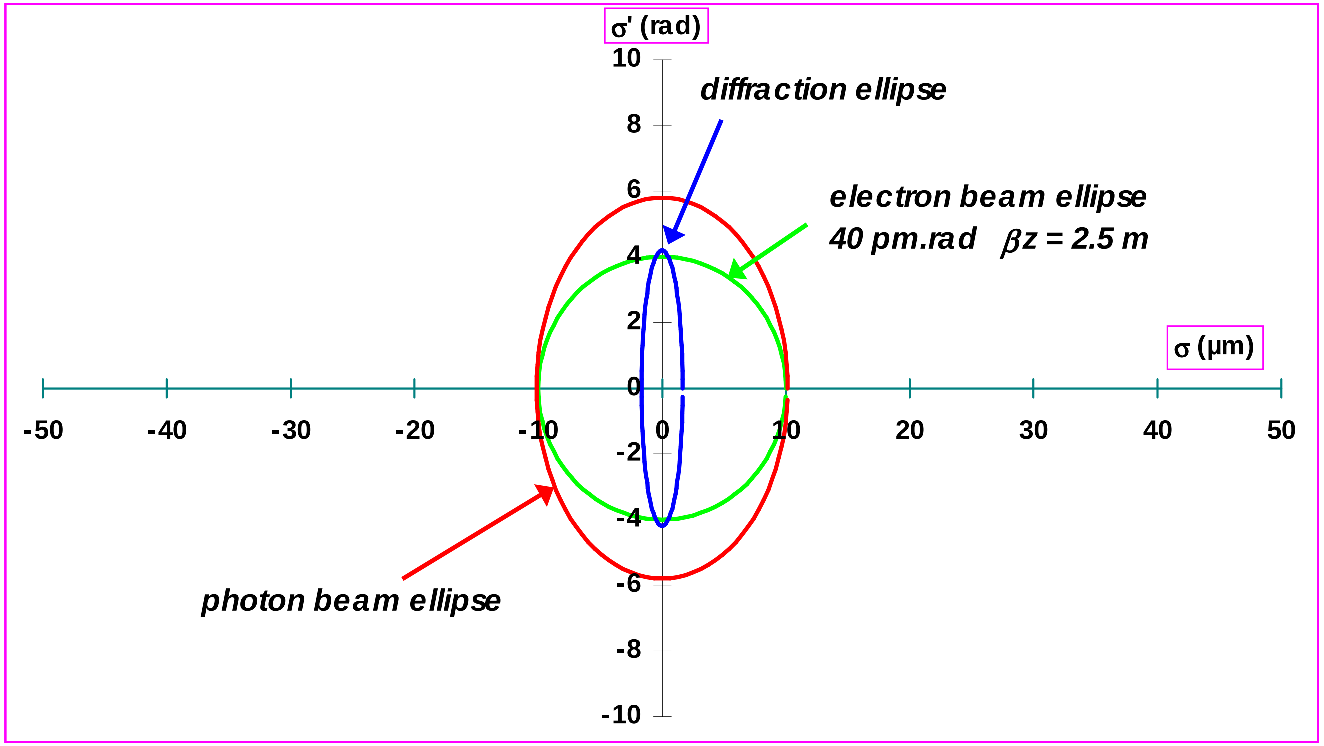
Brilliance and low Emittance

Initially ε_Z = 40 pm.rad and βz = 12.8 m in middle of SS
$\Rightarrow$Photon emittance = 104 pm.rad



Brilliance and low Emittance

With ε_Z = 40 pm.rad and **βz = 2.5 m** in middle of SS
⇒Photon emittance = **59 pm.rad**



Horizontal Emittance

The Horizontal emittance results from 2 adverse effects :

- ❑ The heating of the beam due to the emission of photons
- ❑ The damping provided by the compensation of energy loss by the RF system

The 2 adverse effects (heating + damping) lead to an equilibrium emittance value and gaussian distributions in X and X'.

Horizontal Emittance

Generation of emittance by radiation

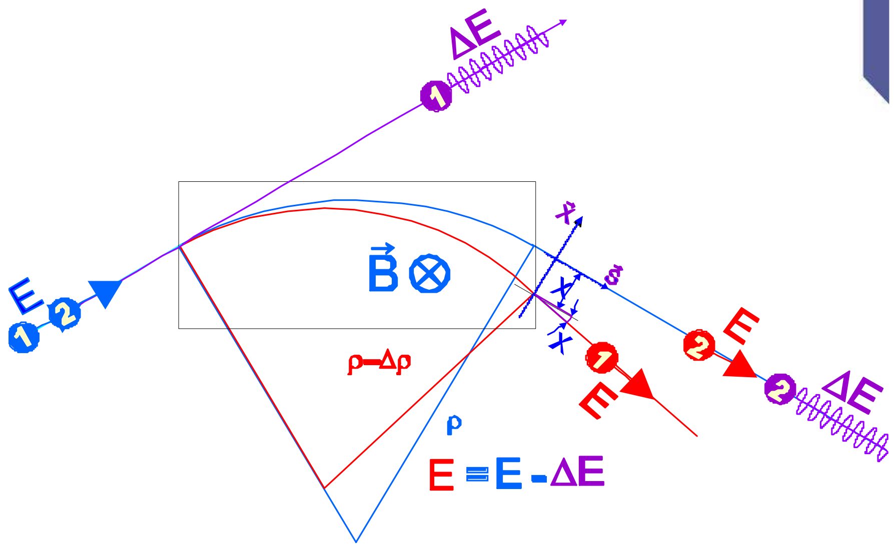
Two e⁻ with same E and same trajectory at the entrance of the bending magnet (they cannot be distinguished : no e- beam size)

They both radiate ΔE and exit with E-ΔE

1 emits ΔE at the origin, smaller ρ

2 emits ΔE but at the end

They follow different trajectories



$$dx(s) = \eta(s)\frac{\Delta E}{E} \qquad dx'(s) = \eta'(s)\frac{\Delta E}{E}$$

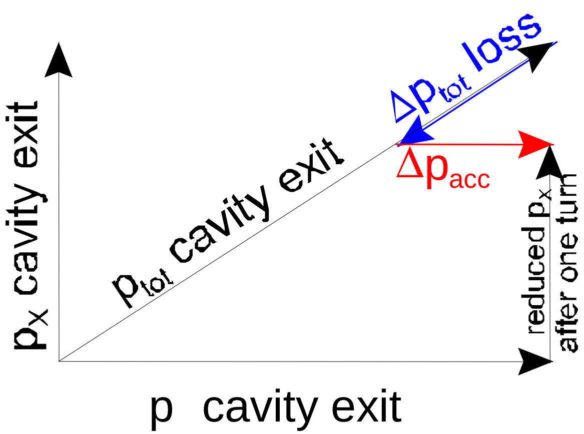
With η(s) and η’(s) the dispersion function and its derivative

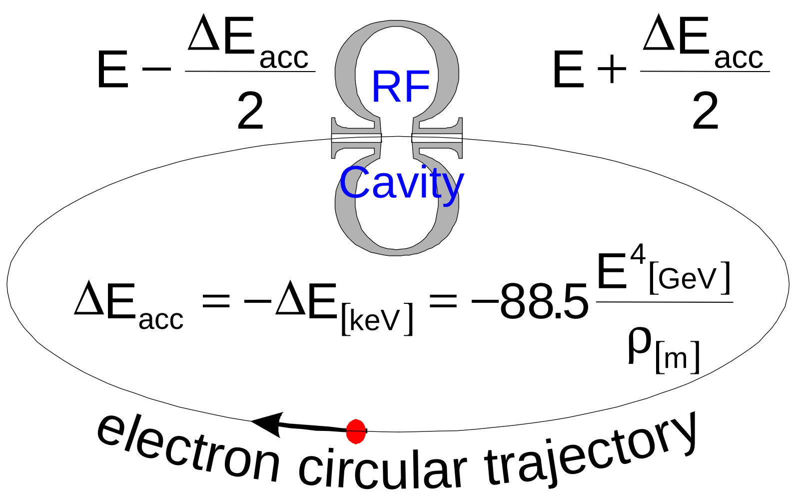
Due to the random aspects of the emission (location, energy), the different electrons exit the bending magnet with different trajectories and different energies. The beam is heated up by the radiation :

⇒ **increase of H beam size, H beam divergence and energy spread.**

Horizontal Emittance

Damping by the RF





The heating in the H plane induced by radiation in every bending magnets would lead to a continuous blow up of the H emittance.

However, the restoring of the lost energy by the RF cavity cool down the transverse oscillations in the H plane

The damping time is about the time it would require for the electron to lose its full energy.

$\tau \sim E/U_0$. **Memory of initial conditions is totally lost when the RF has restored the total energy of the electron. =>Emittance independent of injection conditions**

Vertical emittance

The vertical emittance in a storage ring originates from the coupling to the horizontal emittance, and to a lesser extent from the residual vertical dispersion.
Low coupling in the % range (or less) is now achieved on all machines resulting in vertical emittance between below **10 pm.rad**.

	Model emittance	Measured emittance	β-beating (rms)	Coupling* ($\varepsilon_y / \varepsilon_x$)	Vertical emittance
ALS	**6.7 nm**	**6.7 nm**	**0.5 %**	**0.1%**	**4-7 pm**
APS	**2.5 nm**	**2.5 nm**	**1 %**	**0.8%**	**20 pm**
CLS	**18 nm**	**17-19 nm**	**4.2%**	**0.2%**	**36 pm**
Diamond	**2.74 nm**	**2.6-2.9 nm**	**0.4 %**	**0.15%**	**4 pm**
ESRF	**4 nm**	**4 nm**	**1%**	**0.25%**	**10 pm**
SLS	**5.6 nm**	**5.4-7 nm**	**4.5% H; 1.3% V**	**0.05%**	**3.2 pm**
SOLEIL	**3.73 nm**	**3.70-3.75 nm**	**0.3 %**	**0.1%**	**4 pm**
SPEAR3	**9.8 nm**	**9.8 nm**	**< 1%**	**0.05%**	**5 pm**
SPring8	**3.4 nm**	**3.2-3.6 nm**	**1.9% H; 1.5% V**	**0.2%**	**6.4 pm**

Vertical Beam sizes

$$\sigma_z = \sqrt{\varepsilon_z \beta_z + (D_z \sigma_E)^2} \qquad \sigma_{z'} = \sqrt{\varepsilon_z / \beta_z}$$

	BetaZ m		V Size SigmaZ µm	V Divergence SigmaZP µrad
Short straight	1,75		**8,1**	**4,6**
Medium straight	1,77		**8,1**	**4,6**
Long straight	8,01		**17,3**	**2,2**
Dipole 4°	16,01		**24,5**	**2,1**

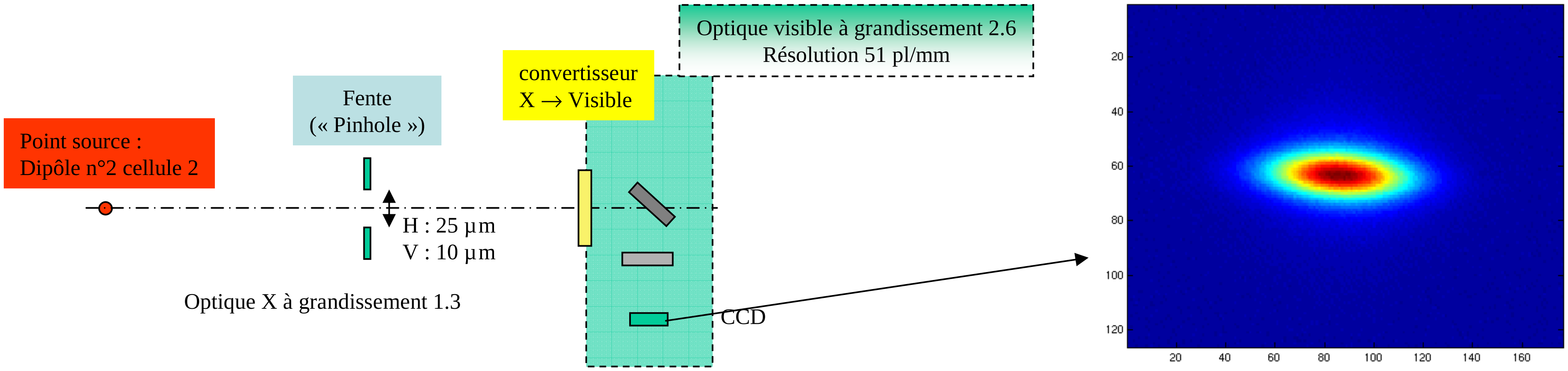
SOLEIL

V emit= 37 pm.rad,

dE/E = 1.016 E-03

Beam emittance measurements at SOLEIL

Pinhole camera inside the tunnel



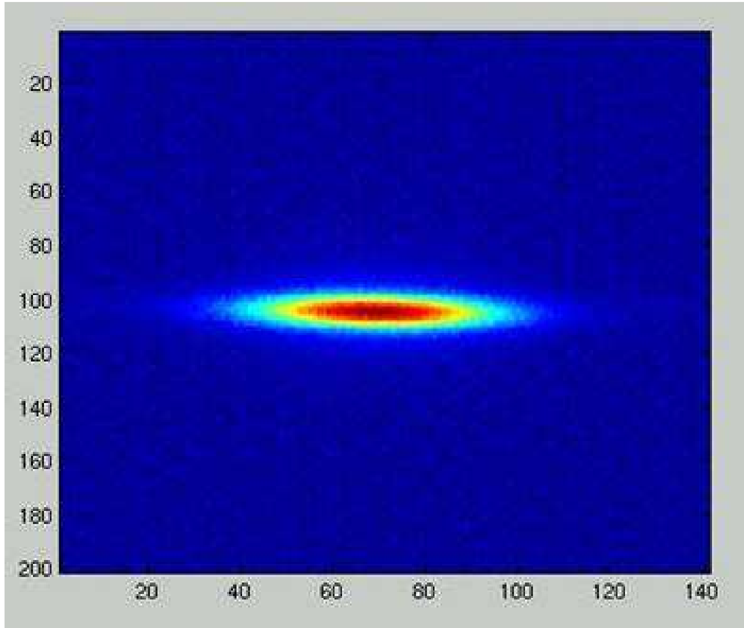
ε_x = 3.9 ± 0.25 nm.rad
(design 3.75 @ 2.75 GeV)

ε_z = 0.011 ± 0.002 nm.rad
Natural Coupling ≲ 0.3 % without correction

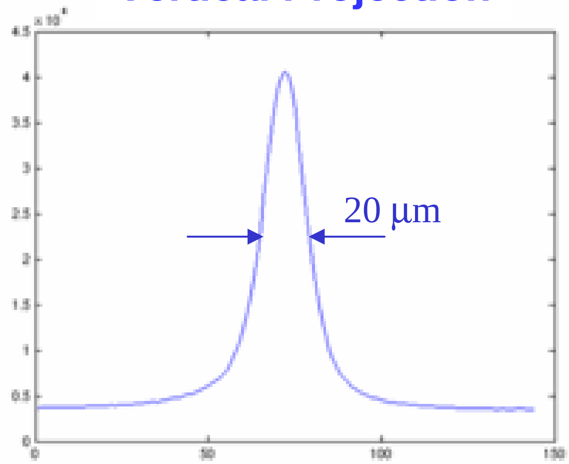
=> Excellent magnet alignment

Vertical Emittance (SOLEIL)

Pinhole Camera

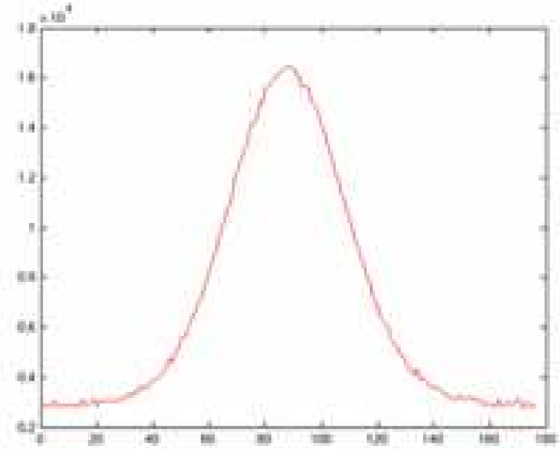


Vertical Projection



σ_z =9 µm (including 5 µm instrument resolution)

Horizontal Projection



with coupling correction (skew Qpoles) => ε^*_z ~ 4 pm.rad (κ ~ 0.1 %)

Vertical emittance can also be increased to provide better lifetime:
In 8 bunch mode, SOLEIL operates with 6% coupling (from Vertical dispersion)

*: after correction. Before correction, κ is around 0.3%

Current

To reach a high brilliance you need to operate with a high current.
There are 3 main limitations to overcome :

First limitation : the coupled bunch instabilities, which are excited by **H**igher **O**rder **M**odes in the RF cavities (**HOM**).

$\Rightarrow$ increase of the energy spread and bunch length => brilliance reduction

$\Rightarrow$ transverse beam oscillations => beam losses

Solutions to push the instability thresholds have been experienced and successfully implemented :

- Shifting the mode frequencies to avoid interaction with the bunch spectrum (**temperature control of the cavities**)
- Landau damping : **partial filling or harmonic cavity**
- Reducing the number and impedances of parasitic modes (**superconducting cavities, parasitic mode dampers**)
- **Feedback systems**

Current

Second limitation : the transverse instabilities, resistive wall, ions trapping in multibunch / mode detuning and TMCI in single bunch

⇒ Beam blow-up => brilliance reduction

⇒ transverse beam oscillations => beam losses

Resistive wall is enhanced by the presence of low gap ID vessels

Solutions to push the instability thresholds have been experienced and successfully implemented :

- Shifting the mode spectrum with positive chromaticities
- Landau damping : **partial filling (mainly against ions)**
- Reducing machine impedance (**smooth tapers, no gaps, RF fingers..**)=> at design stage
- **Bunch by bunch transverse Feedback systems (required to achieve high current)**

Current

Third limitation : the thermal load on the vacuum system and front-end
⇒ High heat load with high power density on beam absorbers
⇒ Heating due to RF losses in transitions

Solutions :
- Distributed lump absorbers
- Geometry and material of the absorbers (Glidcop, cooling circuits,..)
- Reduce trapping mode geometry (**smooth tapers, no gaps, RF fingers..**)=> at design stage
- **Require efficient and reliable Machine protection system (thermocouples, flowswitches, Beam position interlocks, instability interlock,..)**

Note : the danger is not coming from the power in the electron beam (Thousands of Joules lost in few microsec) but from the photons beam
⇒ **In case of electron beam mis-steering (without losing it) the photons may reach a part which is not able to sustain the power.**

Current

Few figures :

APS,	**100 mA**
SPRING8	**100 mA**
ESRF	**200 mA**
SLS	**400 mA**
DIAMOND	**300 mA**
SOLEIL	**300 mA => 500 mA**

Lifetime

The **lifetime** should be as long as possible to :

- optimize the integrated photon intensity between refills
- reduce the heat load variations on both machine and beamlines
- reduce the radiation dose in case of top-up

2 main processes limits the lifetime :

- Interaction with the residual gas :

elastic scattering, Bremsstrahlung

⇒the vacuum system should provide as low a pressure as possible (10^{-9} mbar with beam)

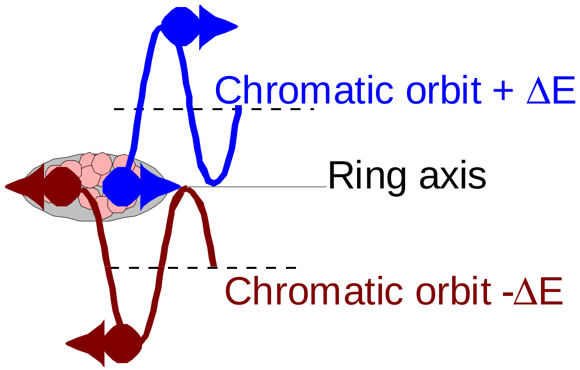
$$\frac{1}{\tau_{vacuum}} \propto \frac{f(p)}{E^2 g^2} \beta_{z(ID)}$$

Transverse deflexion and subsequent loss in regions of low aperture, which are usually the narrow vertical gaps in undulators (g).

Lifetime

❑ Interaction between electrons within the bunch :

Touschek effect (inelastic collisions)



The Touschek lifetime is proportional to $\tau_t \propto \dfrac{E^2 \cdot \left(\dfrac{\delta p}{p}\right)^3 \cdot \sigma_x \sigma_z \sigma_s}{I_b}$

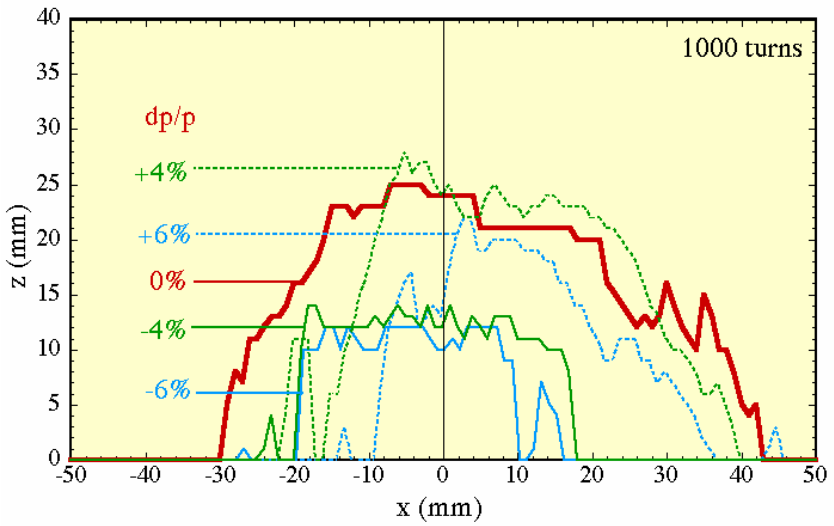
E	:	beam energy
I_b	:	bunch intensity
σ_x , σ_z , σ_s	:	bunch dimensions
$(\delta p/p)$	:	energy acceptance of the ring

Lifetime

⇒The Touschek lifetime is predominant for low energy rings (τ < 10 h)

⇒The Touschek lifetime affects also the high energy rings when operated in single or few bunch modes

In all cases, **machine design and tuning** should be optimized to provide a large dynamic aperture and a large energy acceptance (RF and transverse)

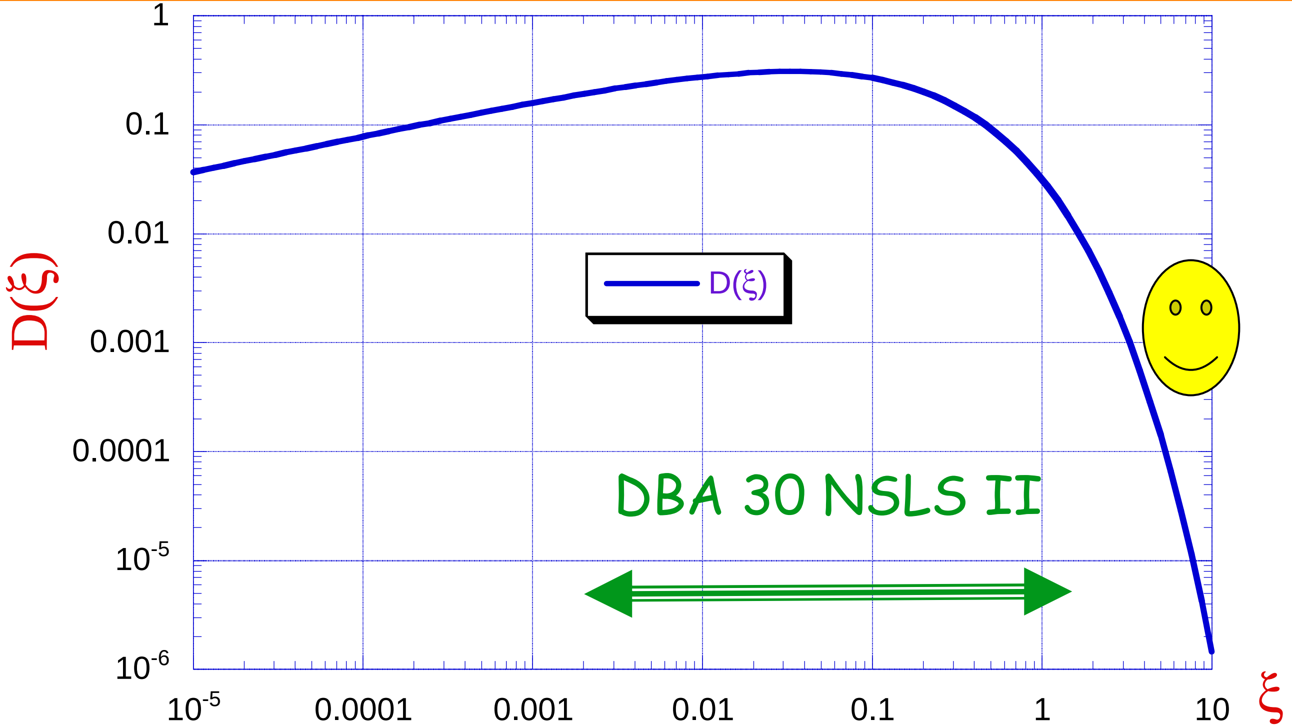


(SOLEIL: ε_{acc} = 4 to 6%)

Touschek Life-time (more)

$$\frac{1}{\tau_{Touschek}} = \frac{N_e r_e^2 c}{8\pi \cdot \sigma_x \sigma_y \sigma_s \cdot \gamma^2 \cdot \delta_{acc}^3} D(\xi); \qquad \xi = \left(\frac{\delta_{acc}}{\gamma \sigma_\theta}\right)^2;$$

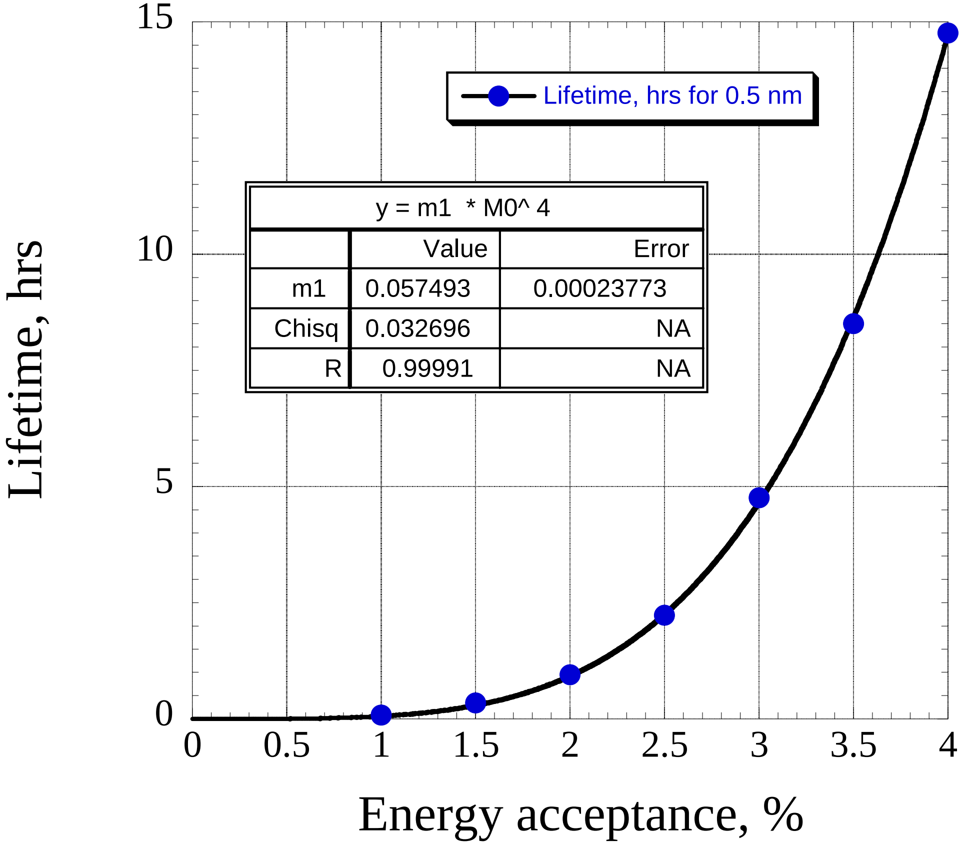
$$D(\xi) = \sqrt{\xi}\left\{-\frac{3}{2}e^{-\xi} + \frac{\xi}{2}\int_\xi^\infty \frac{\ln u \cdot e^{-u}}{u} du + \frac{1}{2}(3\xi - \xi \ln \xi + 2)\int_\xi^\infty \frac{e^{-u}}{u} du\right\}$$



NSLS II
Litvinenko

Touschek Life-time (more)

For 0.5 nm emittance the dependence
on the energy acceptance is about power of 4 !



Energy acceptance >2.5% is the must

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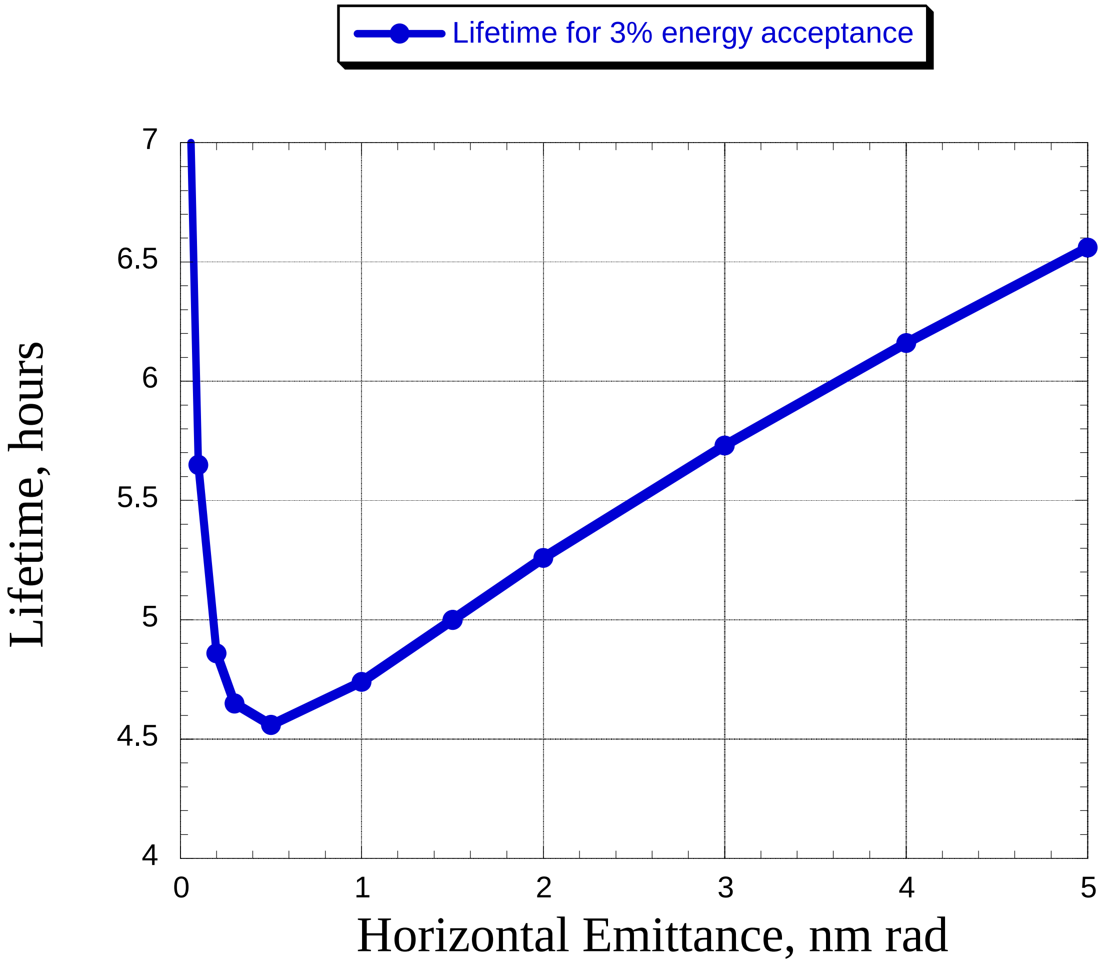
Touschek Life-time (more)



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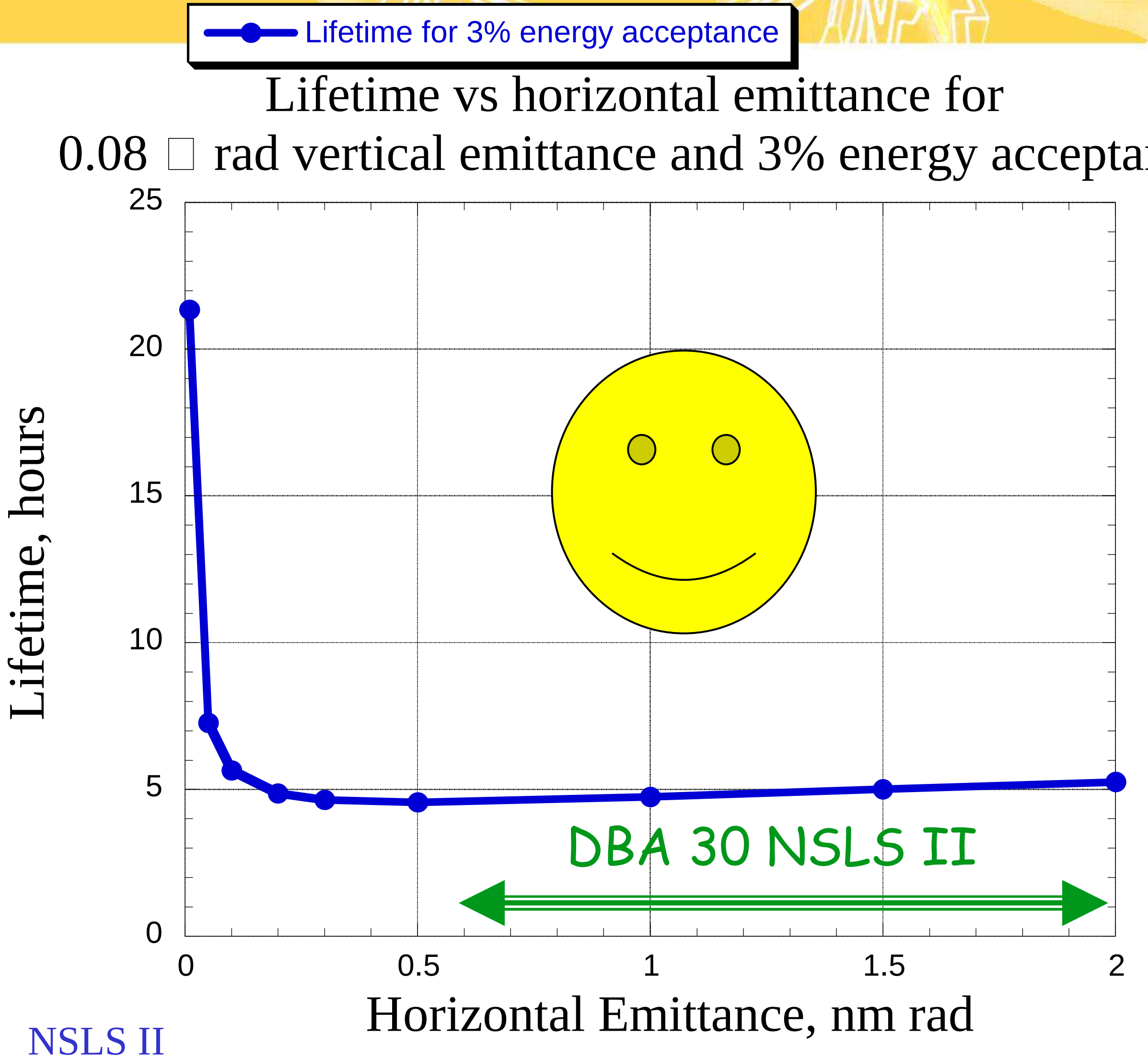
Touschek Life-time (more)



NSLS II will not reach lifetime heaven.

But MAX IV should !

NSLS II
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