SLS

The Swiss Light Source

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Photons for research

Synchrotron radiation properties

Electron storage rings as light sources

The Swiss Light Source SLS

Summary & outlook

JUAS visit to PSI, February 21, 2019

Photons for research: energy

- Molecular scales
  $\sim 1\text{Å} = 10^{-10}$ m
  (range $10^{-11} \ldots 10^{-7}$ m)
- scale of structure
  ⇕
  size of probe
- typical photon wavelength
  $\lambda \sim 1\text{Å}$
- typical photon energy
  $E = hc/\lambda \sim 10$ keV (X-ray)
- SLS energy range
  [0.003...] **0.25...45 keV**

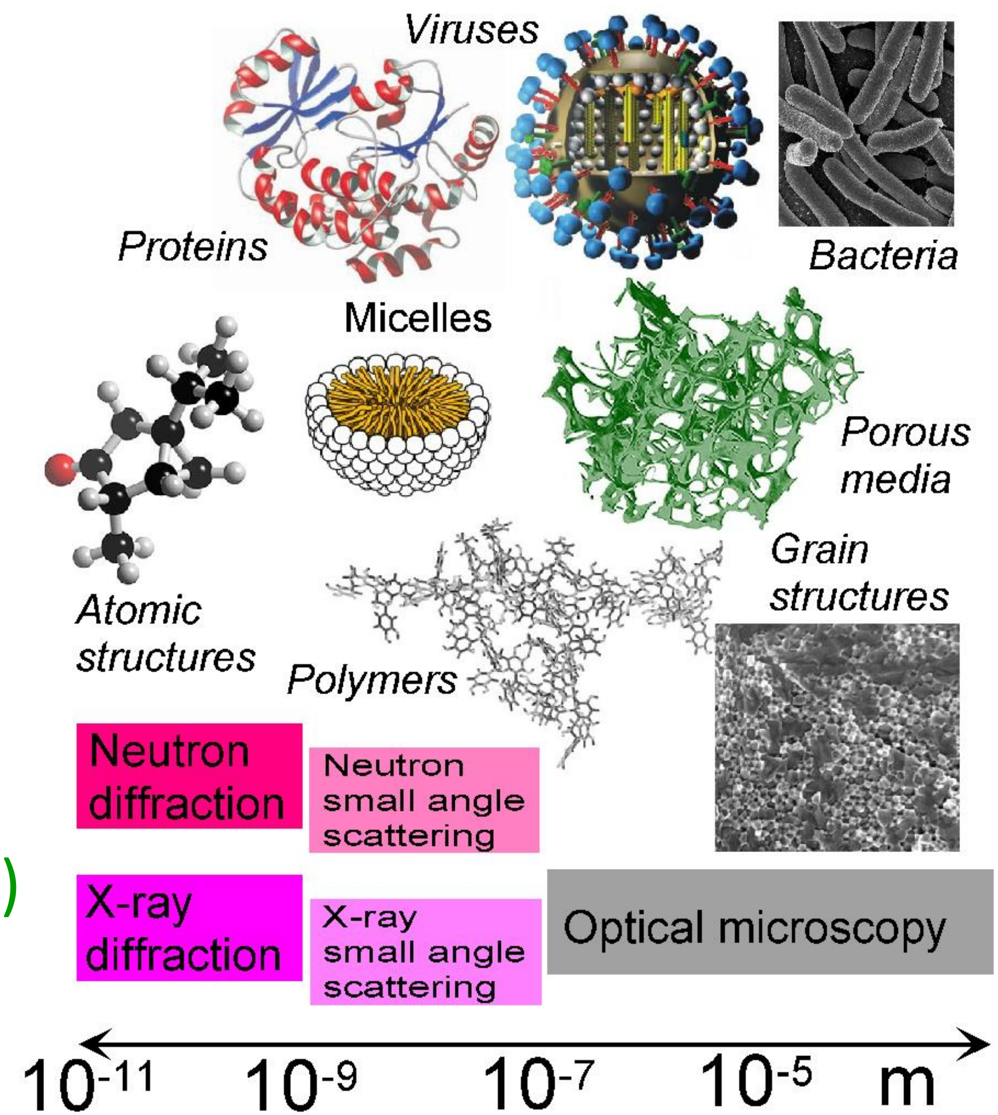


Figure based on Roger Pynn, *Neutron scattering - a primer*, Los Alamos neutron scattering center, 1989

Photons for research: brightness

- small sample size: e.g. protein crystal < 0.1 mm
- high resolution micro- & spectroscopy
- many samples: short measuring time

⇨ high photon density on sample:

  - photons per second
  - photons per band width $\mathrm{BW} = \Delta E/E$ energy interval (usually 0.1%)
  - photons per area on sample: depends on beam line photon optics

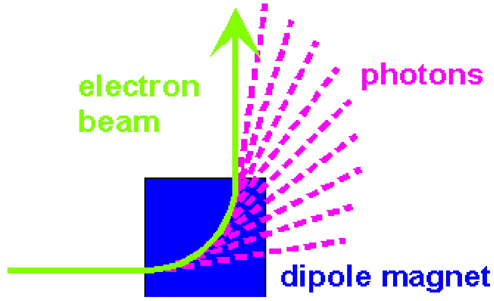
- figure of merit: Brightness

= 6-dimensional *invariant* photon phase space density

$$= \frac{\text{photons}}{(\text{time}) \times (\text{area}) \times (\text{solid angle}) \times (\text{energy interval})} \quad \left[\frac{1}{\mathrm{s\,mm^2 mrad^2 BW}}\right]$$

⇨ *How to get high brightness X-ray photons ?*

Synchrotron radiation: power



- circular acceleration of highly relativistic electrons
- Lorentz factor $\gamma = E / m_o c^2 \approx 10^3 \cdots 10^4$
  - radiated power of accelerated charge $P_{el} \sim (dp/dt`)^2$
  - acceleration in moving system $dp/dt` = \gamma\ dp/dt$
  - acceleration in lab system $dp/dt = E/R$

  = centrifugal acceleration in magnet of of radius R

  ⇨ radiated power of electron, scaling $P_{el} \sim E^{4}$
- Total radiated power of storage ring

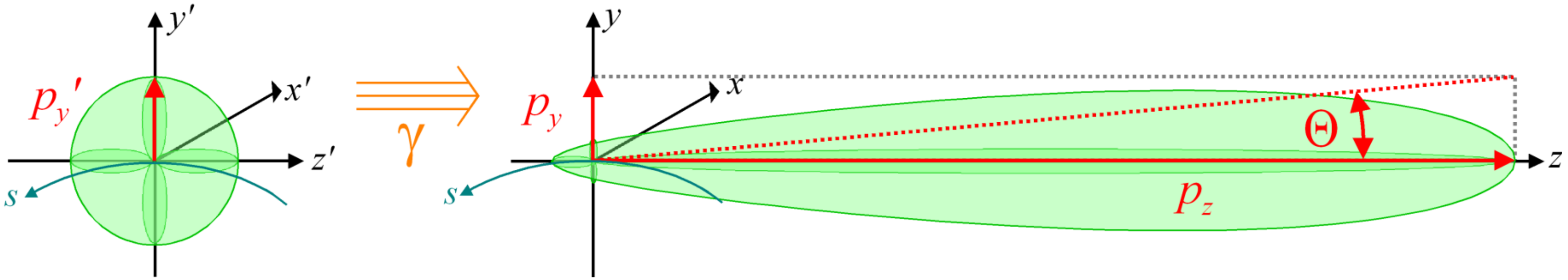
$$P\,[\mathrm{kW}] = 88.5\ \mathrm{kW} \times I_{beam}[\mathrm{A}] \frac{(E\,[\mathrm{GeV}])^4}{R\,[\mathrm{m}]}$$

- **SLS** : **P = 205 kW**

I_{beam}= 0.4 A, E = 2.4 GeV (γ = 4700), R = 5.7 m (B = 1.4 T)

Synchrotron radiation: collimation

- Lorentz transformation to laboratory system

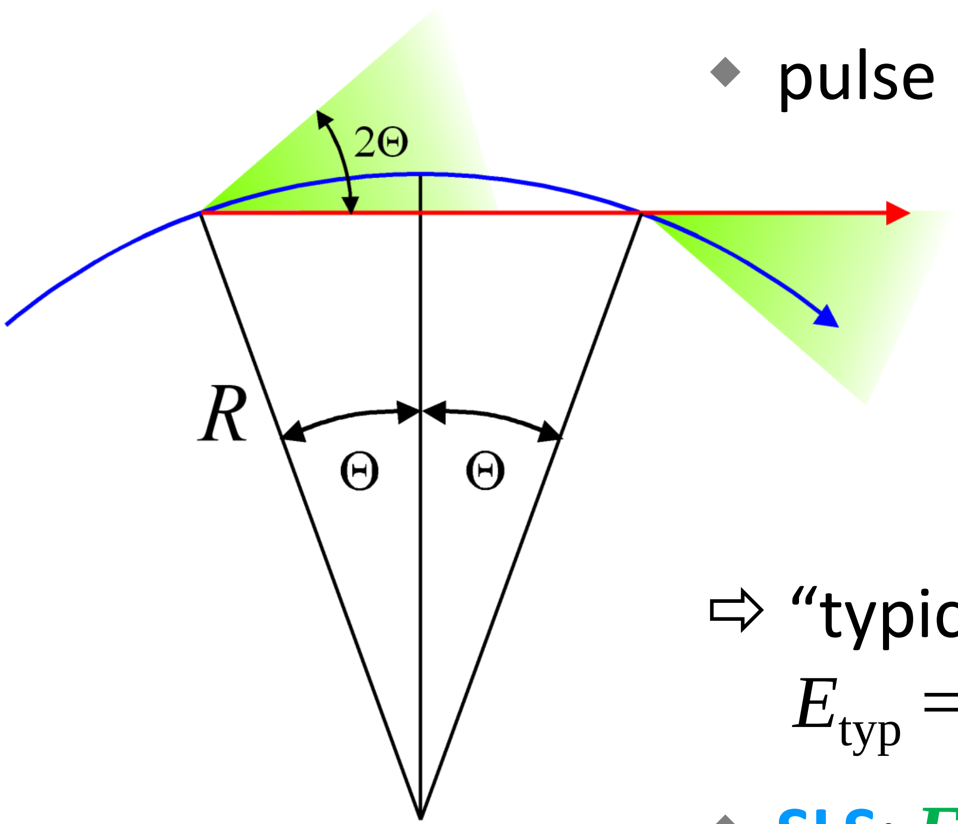


$p_y' = E'/c \quad p_z' = 0$ $\qquad\qquad$ $p_y = p_y' \quad p_z = \gamma E'/c = \gamma p_y$

- Collimation angle: $\Theta = p_y/p_z = 1/\gamma$
- **SLS** : **Θ = 0.2 mrad**

  ⇨ beam spot ∅ 1 cm after 25 m

Synchrotron radiation: photon energy



- Observation from narrow sector ($2\Theta \ll 1$)
- pulse duration = time delay:

electron – photon

$$\Delta t = \frac{2R\Theta}{c\beta} - \frac{2R\sin\Theta}{c}$$

⇨ "typical" energy

$$E_{typ} = h\nu = h/\Delta t \sim 3hc/(4R) \times \gamma^{3}$$

- **SLS**: E_{typ} **=17 keV** ⇨ X-ray !

Synchrotron radiation: spectrum

Radiation spectrum from dipole magnet

$dP/d\omega = P/\omega_c \times S(\omega/\omega_c) \quad E = \hbar\omega$

H. Wiedemann, Accelerator physics 2

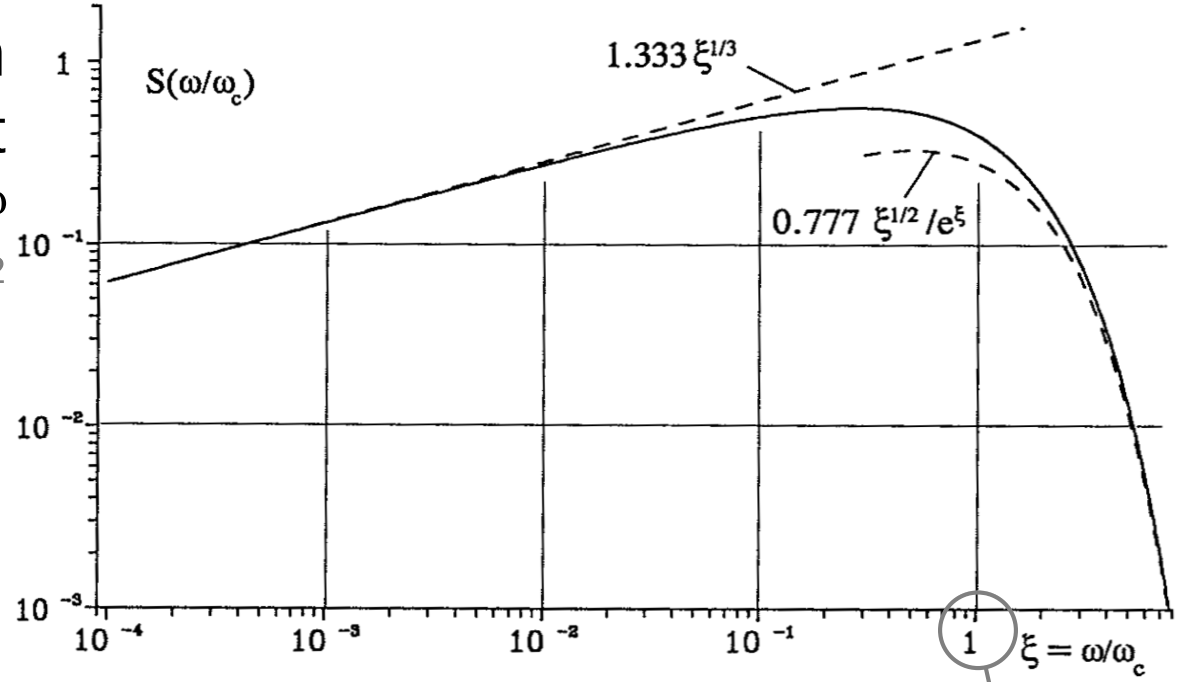
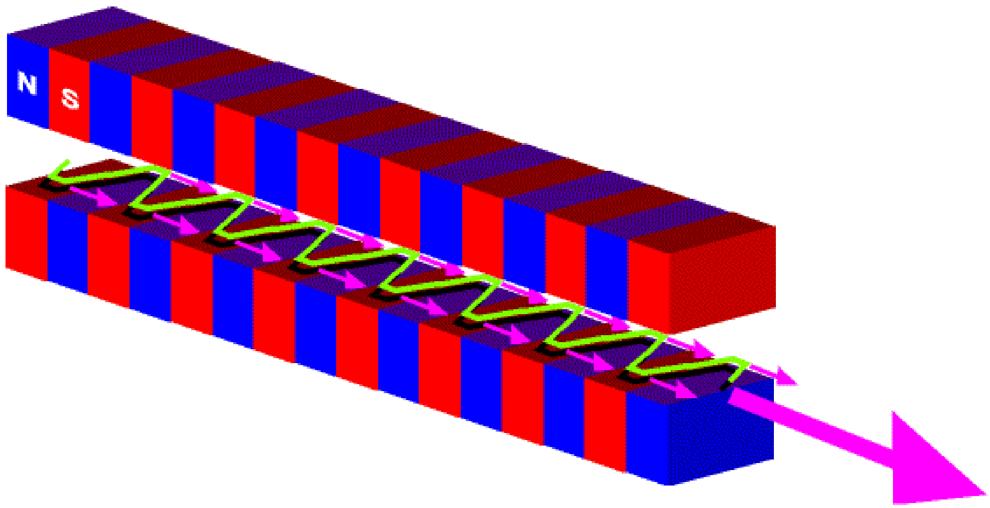


Fig. 7.12. Universal function: $S(\omega/\omega_c) = \frac{9\sqrt{3}}{8\pi} \frac{\omega}{\omega_c} \int_{\omega/\omega_c}^{\infty} K_{5/3}(x)\,dx$

- **Continuous spectrum**
- Critical energy
  $E_c = E_{typ}/\pi$
  $E_c\,[\text{keV}] = 0.665\ B\,[\text{T}] \cdot (E_e\,[\text{GeV}])^2$
- **SLS**: $E_c = 5.3$ keV $(B = 1.4$ T, $E = 2.4$ GeV$)$

Synchrotron radiation: Undulator

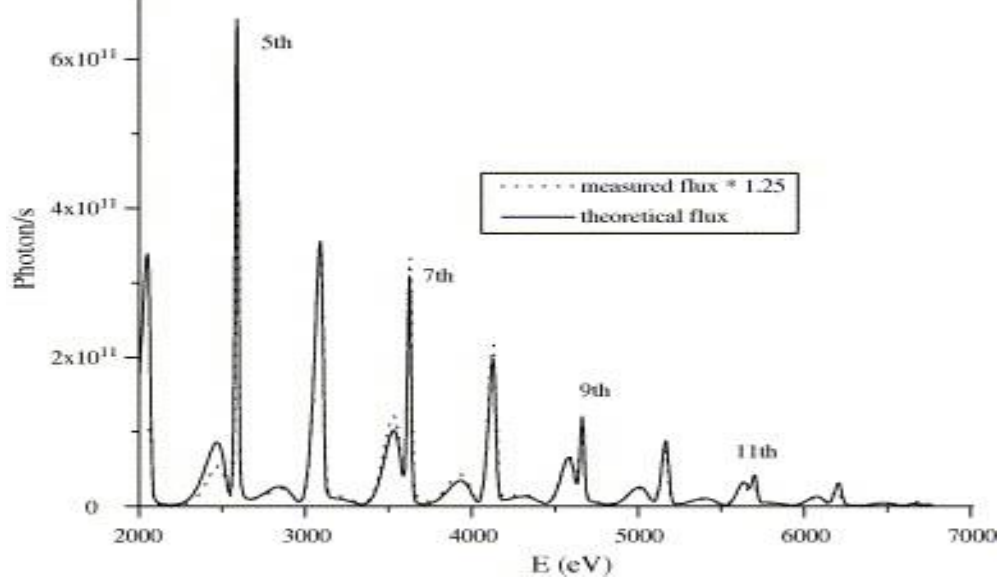


- many small dipoles
  N ~ 20...100 periods
- angle/pole < 1/γ
  (1/γ = radiation opening angle)

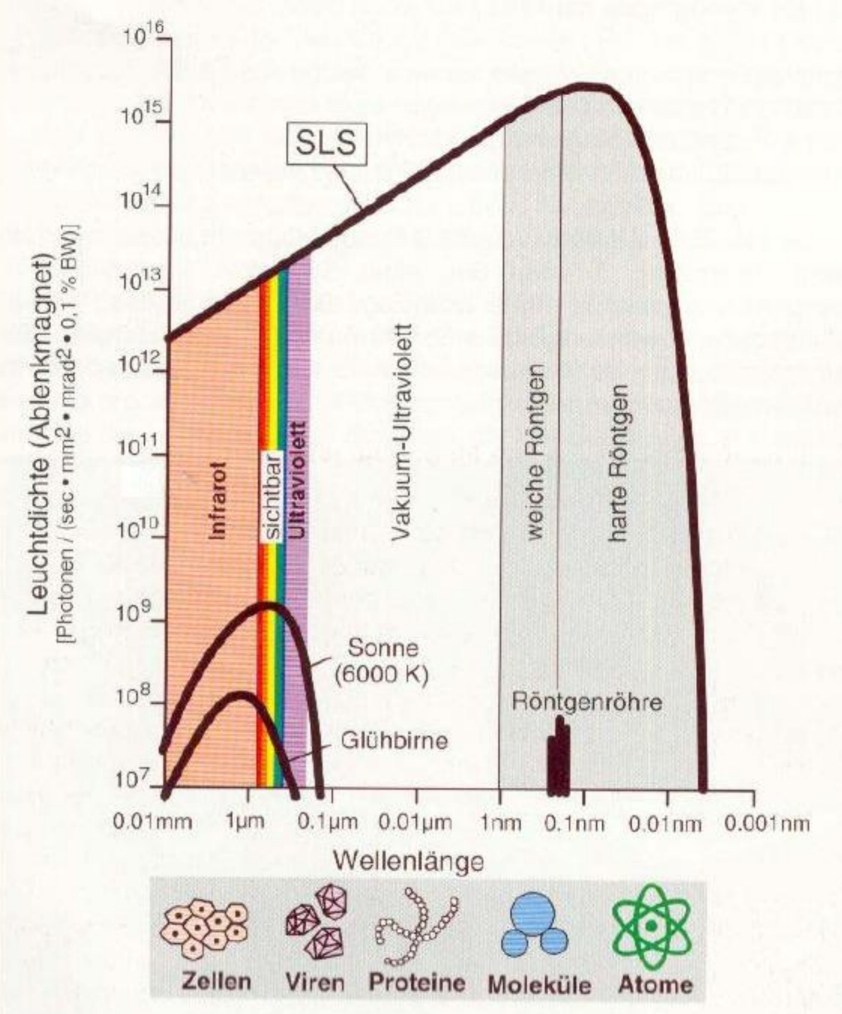
⇨ interference

⇨ **line spectrum**

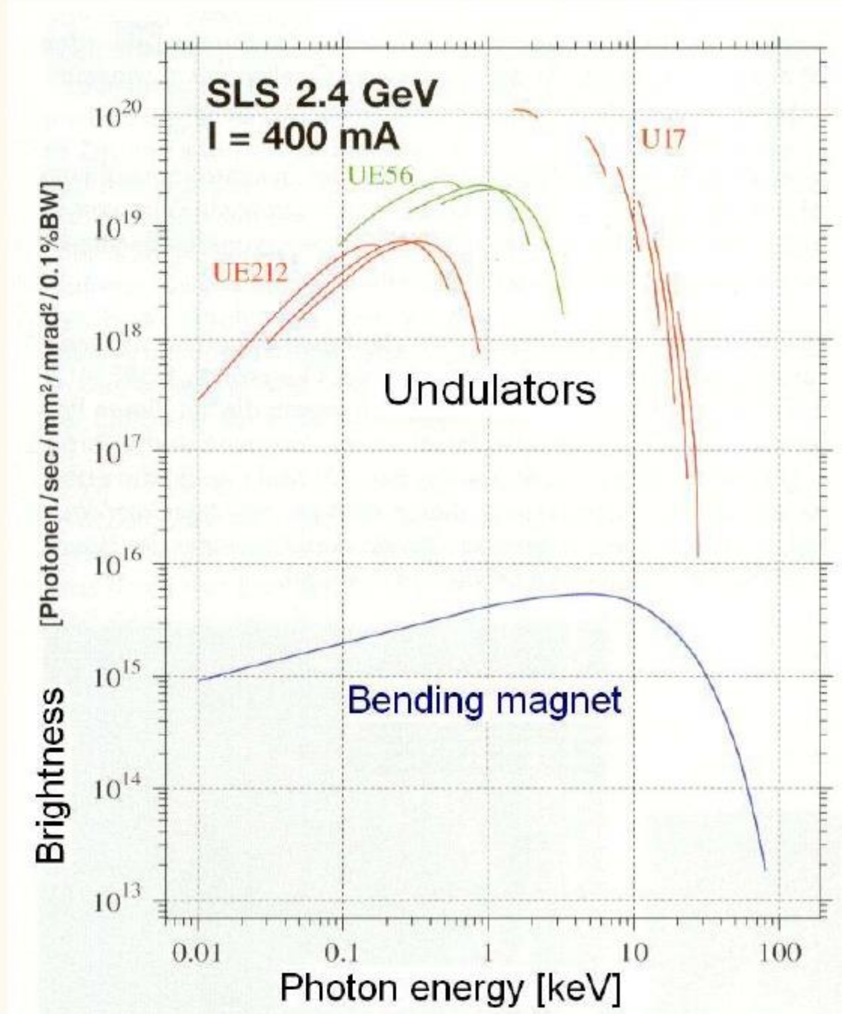
SLS UE54 undulator →



Synchrotron radiation: undulator brightness



Bending magnet brightness in comparison to light bulb, sun and X-ray tube



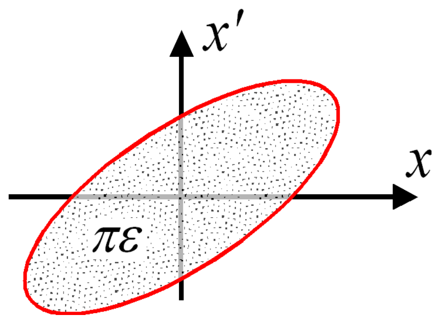
Undulator brightness in comparison to bending magnet brightness

Synchrotron radiation: brightness & emittance

$$B(E)=\frac{\dot{N}(E)}{(\varepsilon_x\otimes\varepsilon_r(E))\times(\varepsilon_y\otimes\varepsilon_r(E))\times\mathrm{BW}}$$

$\dot{N}(E)$ spectral photon flux (dipole or undulator)

ε_x, ε_y electron beam horizontal /vertical emittance:



- 2-d phase space area (position & angle)
- units: mm·mrad, nm·rad, pm·rad
- **SLS** emittances : $\varepsilon_x = 5.5$ nm , $\varepsilon_y \sim 1...10$ pm

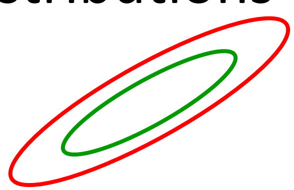
vertically diffraction limited source

$\varepsilon_r(E)$ *diffraction* emittance: $\varepsilon_r \approx \lambda/4\pi$ $(\lambda = hc/E)$

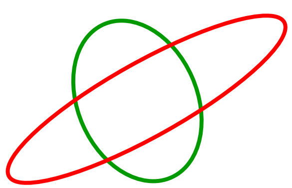
- e.g. protein crystallography: $E \sim 10$ keV ⇨ $\varepsilon_r \sim 10$ pm

$\otimes$ *convolution* of 2-d phase space distributions

- *matched* distributions: $\otimes$ ⇨ $+$
  (same aspect ratio and tilt)



matched: +



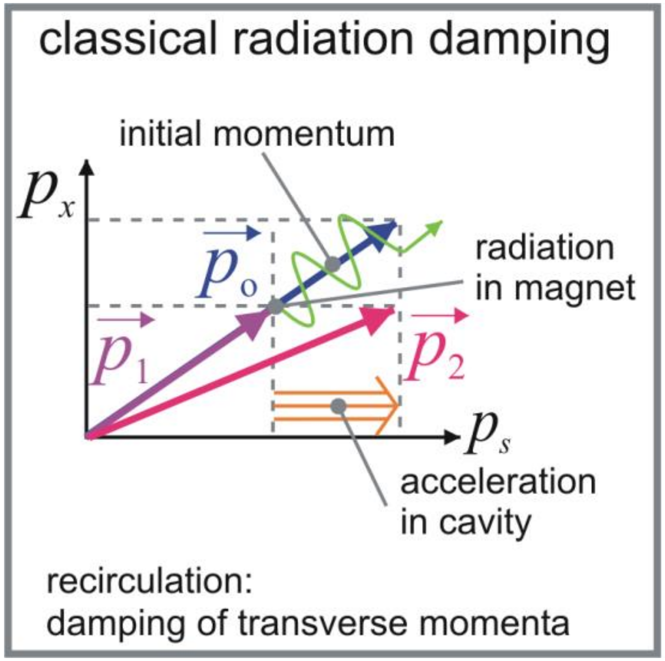
unmatched: ⊗

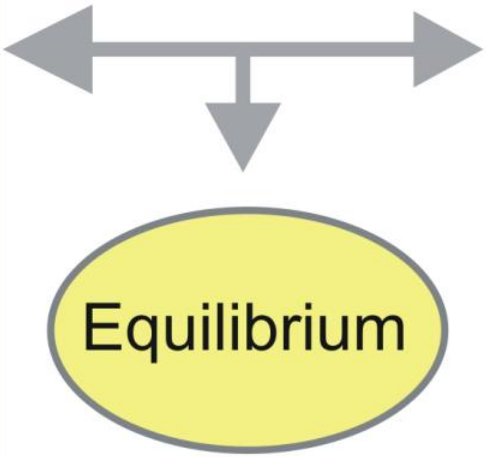
Storage ring: radiation equilibrium

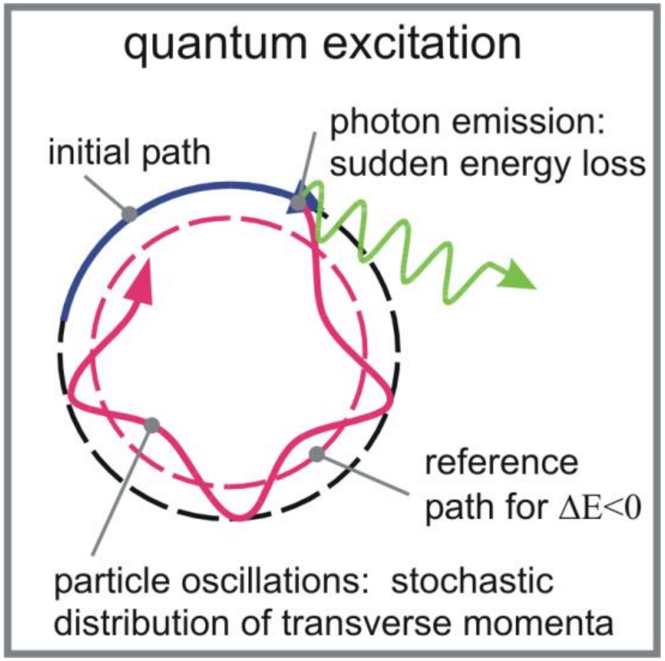
Horizontal emittance in electron storage ring:

↓radiation damping↓ ⇒ **equilibrium** ⇐ ↑quantum excitation↑

independent from initial conditions !







⇩

how to

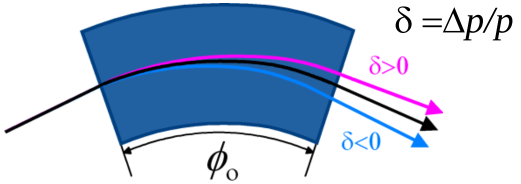
⇧ maximize this -- and -- minimize this ⇧

?

Storage ring: emittance optimization

- Maximum radiation damping
  - increase radiated power ⇨ pay with RF-power
    - High field bending magnets
    - Damping Wigglers (DW): $\Sigma\,|\text{deflection angles}| > 360°$
- Minimum quantum excitation
  - keep off-momentum orbit close to nominal orbit

$$\text{Dispersion} = \frac{\text{orbit}}{\text{momentum}} = \frac{X}{\Delta p / p}$$



⇨ minimize dispersion at locations of radiation (bends)
  - Horizontal Focusing into bends to suppress dispersion.
  - Multi-Bend Achromat lattice (MBA) many short (= small deflection angle) bends to limit dispersion growth.
  - Longitudinal Gradient Bend (LGB) highest radiation at region of lowest dispersion and v.v.

Storage ring: vertical emittance

Quantum emittance

- vertical emittance for ideal, *flat* lattice:
  no vertical dispersion ⇨ no excitation of oscillation
- only direct photon recoil (1/γ radiation cone)
- independent of beam energy
- **SLS** quantum emittance $= 0.20$ pm

⇨ ultimate limit of vertical emittance

Coupling emittance

- Magnet misalignments and imperfections:
  displacements and rotations

⇨ spurious vertical dispersion: vertical quantum excitation

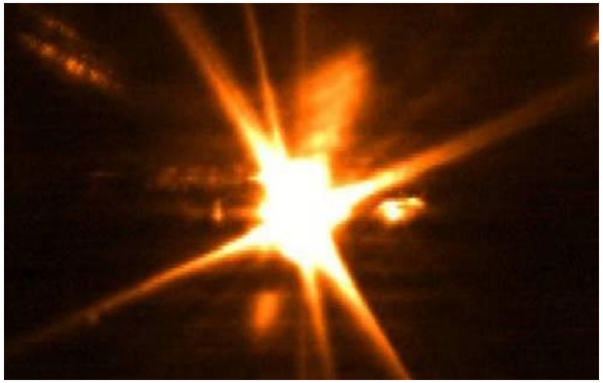
⇨ betatron coupling: horizontal oscillation ⇨ vertical oscillation

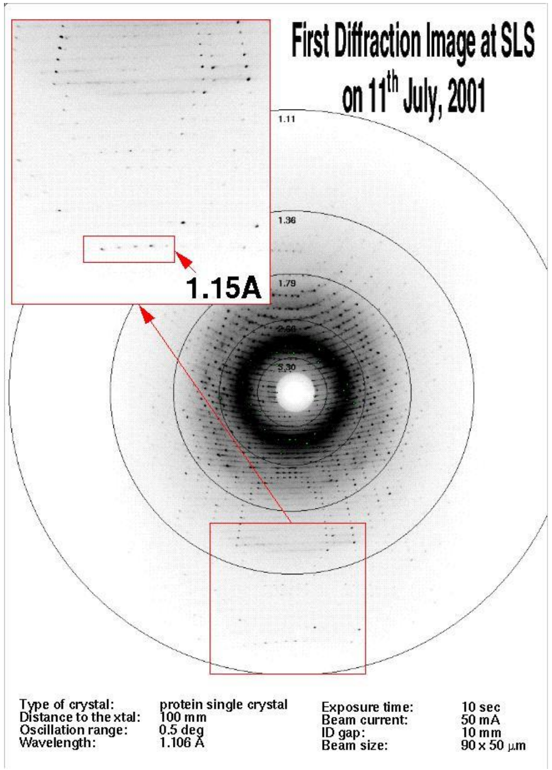
Vertical equilibrium emittance

- usually: coupling emittance **>>** quantum emittance

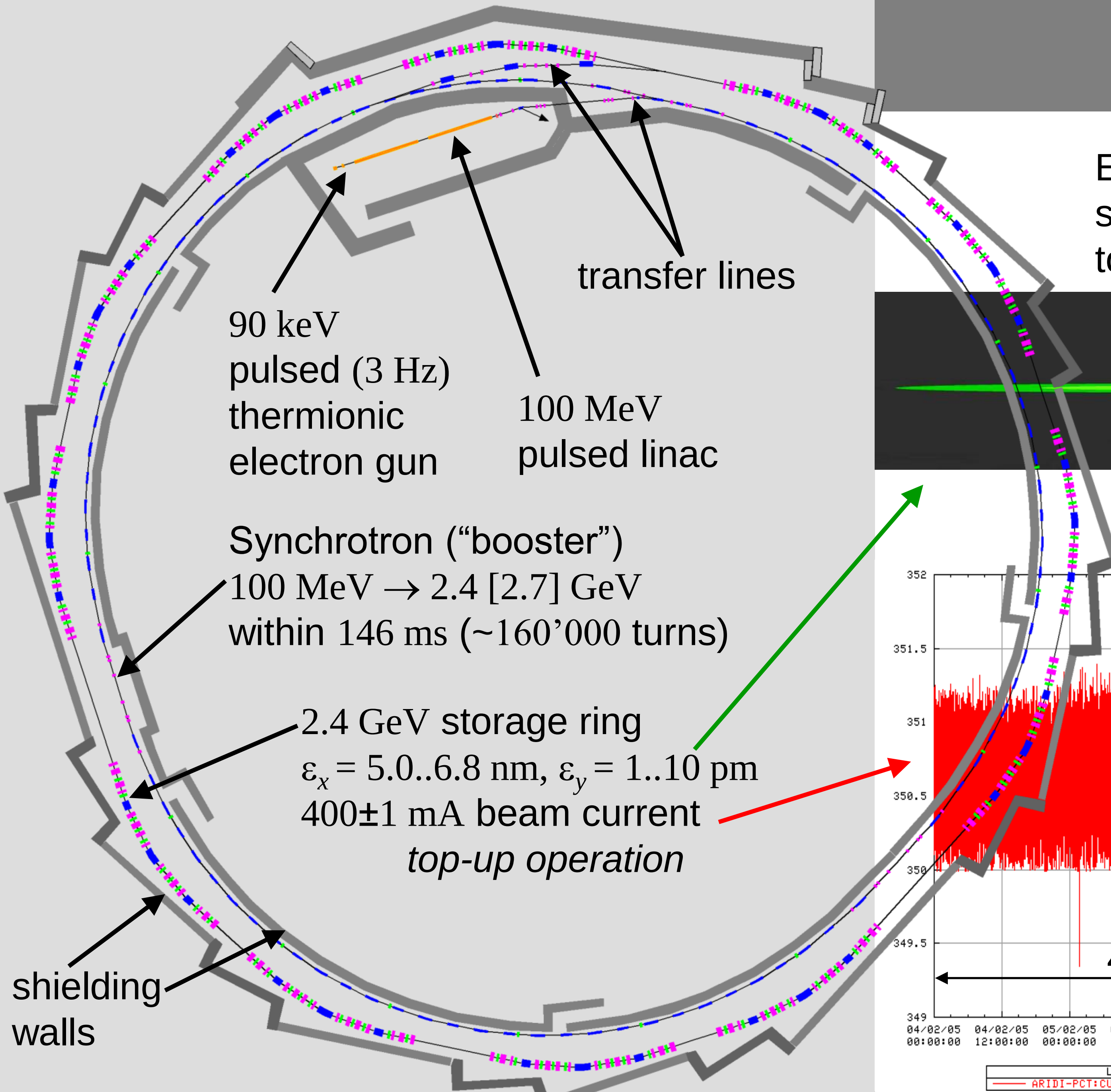
SLS: history

	1990	First ideas for a **Swiss Light Source**
	1993	Conceptual **Design** Report
June	**1997**	**Approval** by Swiss Government
June	**1999**	Finalization of **Building**
Dec.	**2000**	First **Stored Beam**
June	**2001**	Design current **400 mA** reached **Top up** operation started
July	**2001**	First **experiments**
Jan.	**2005**	**Laser beam slicing “FEMTO”**
May	**2006**	**3 Tesla super bends**
	2010	**~completion: 18 beamlines**
Dec.	**2011**	Vertical emittance record: 1 pm

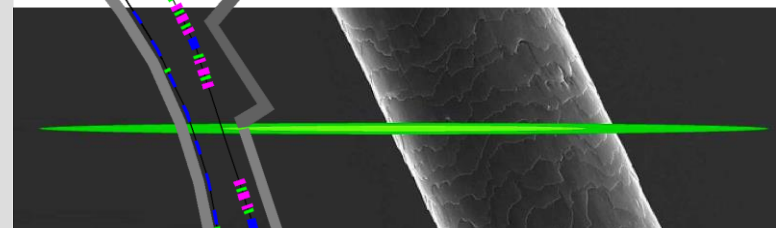




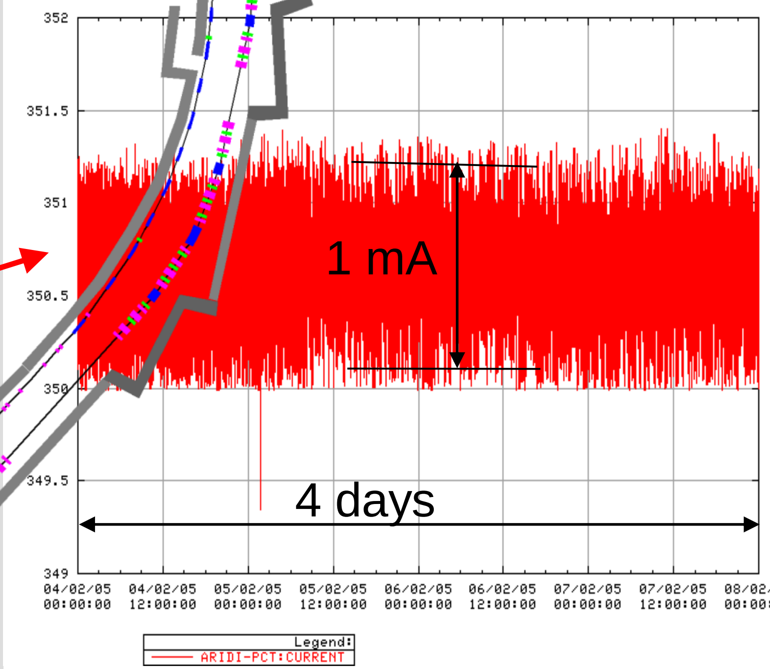
SLS: Layout



Electron beam cross section in comparison to human hair



Current vs. time

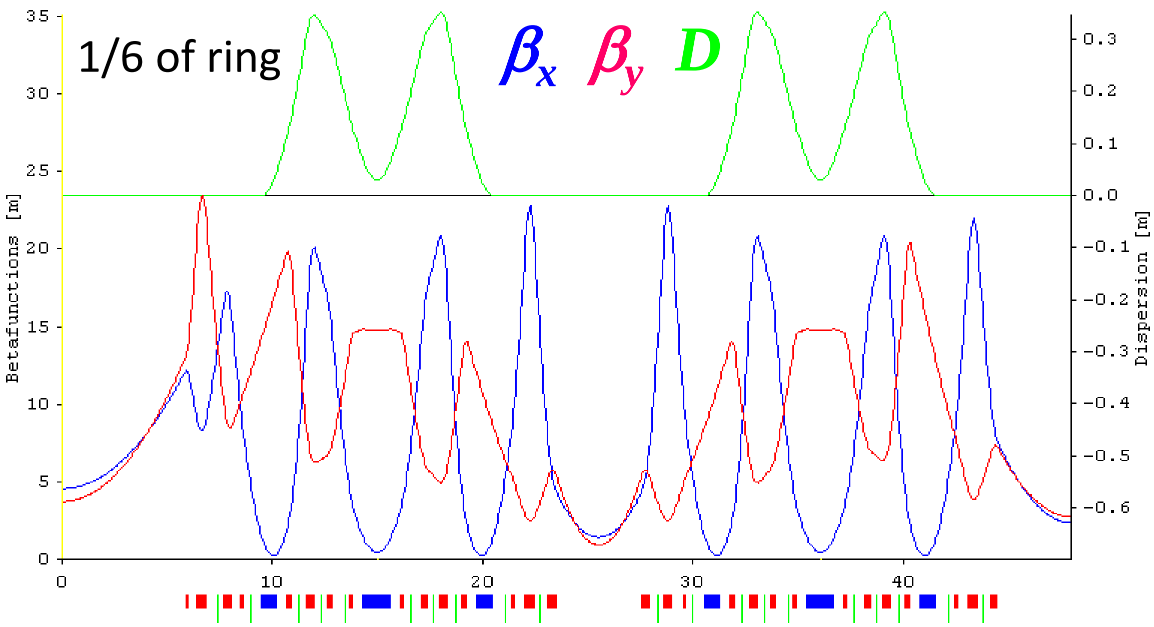


SLS: storage ring lattice

12 TBA:
8°/14°/8°

12 straights:

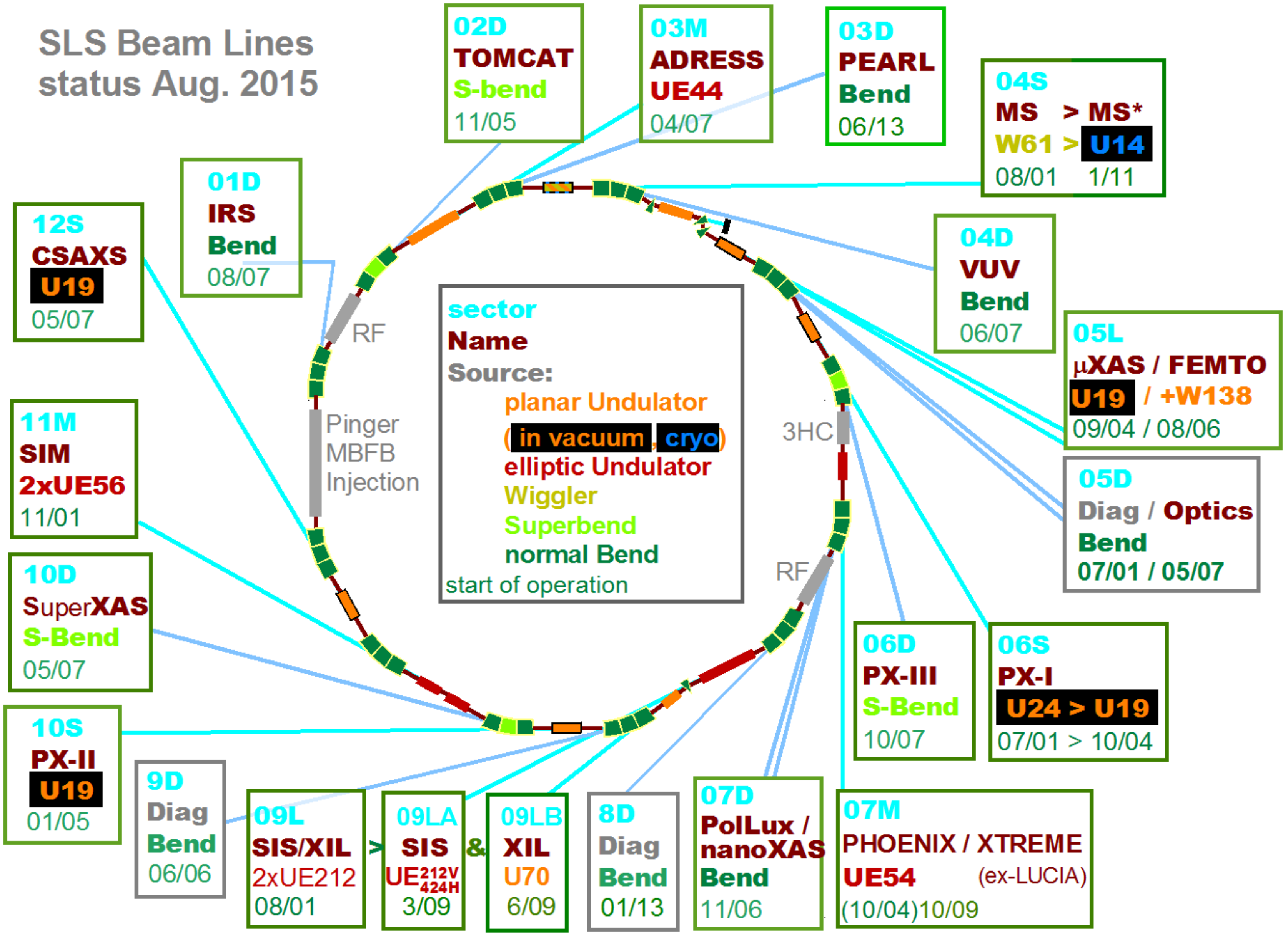
3 x 11.5 m
3 x 7.0 m
6 x 4.0 m



Energy	**2.4 GeV**		Mom. compaction	**$6.3 \cdot 10^{-4}$**
Emittance	**5 nm rad**		Radiation loss	**512 keV**
Circumference	**288 m**		Damping times	**9 / 9 / 4.5 ms**
Radio frequency	**500 MHz**		Energy spread	**$8.9 \cdot 10^{-4}$**
Tunes	**20.41 / 8.17**		rms bunch length	**3.5 mm**
Chromaticities	**-66 / -21**		Beam current	**400 mA**

all data before FEMTO upgrade, without insertion devices and without harmonic cavities

SLS: beam lines overview



SLS: major achievements

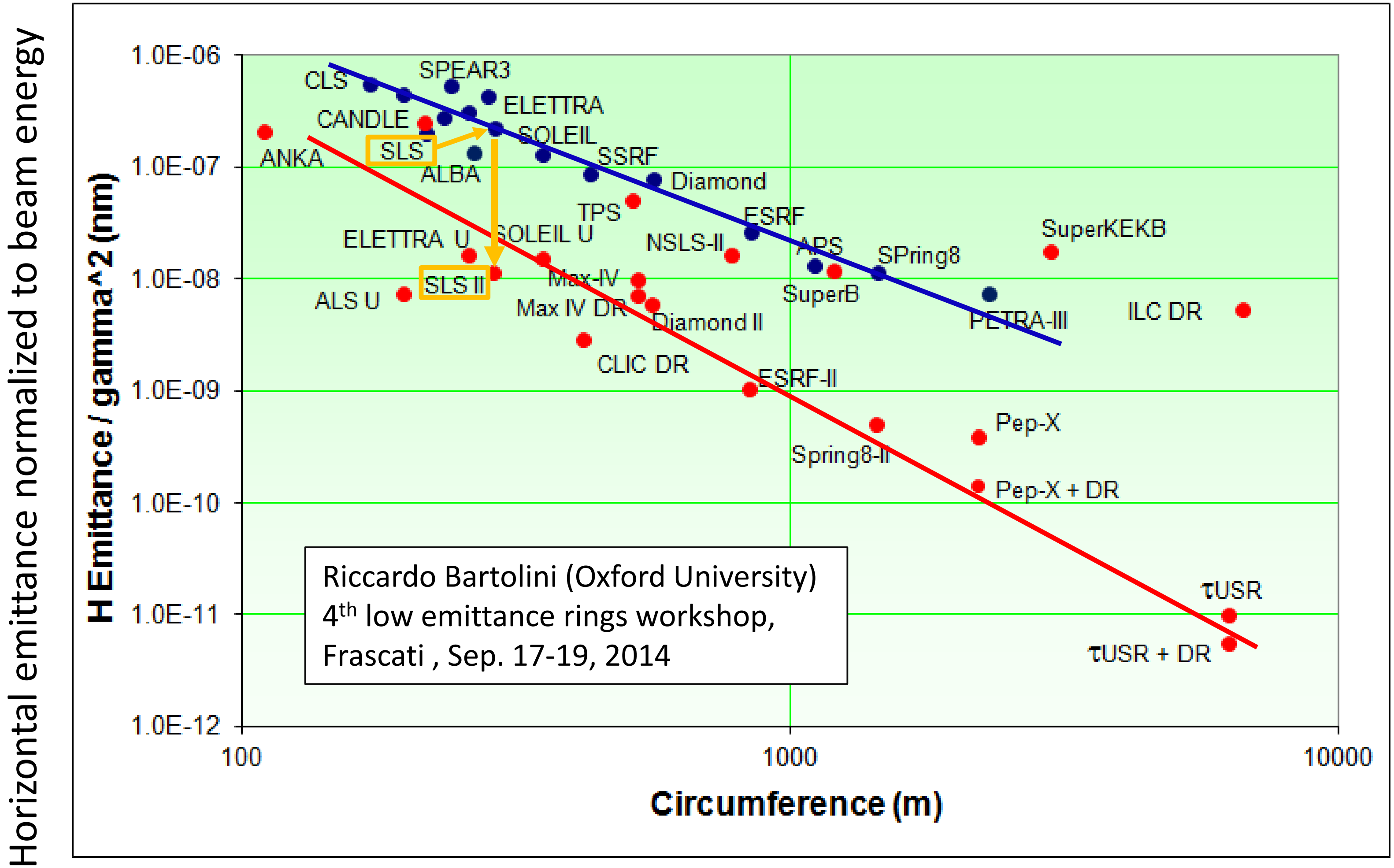
- **Rich scientific output**
  - > 500 publications in refereed journals/year
  - four spin-off companies
- **Reliability**
  - 5000 hrs user beam time per year
  - 97.3% availability (2005-2014 average)
- **Top-up operation since 2001**
  - constant beam current 400-402 mA over many days
- **Photon beam stability $< 1\ \mu m$ rms (at frontends)**
  - fast orbit feedback system (< 100 Hz)
  - undulator feed forward tables, beam based alignment, dynamic girder realignment , photon BPM integration etc...
- **Ultra-low vertical emittance: 0.9 ± 0.4 pm**
  - model based and model independent optics correction
  - high resolution beam size monitor developments
- **150 fs FWHM hard X-ray source FEMTO**
  - laser-modulator-radiator insertion and beam line

Summary and outlook

- **Synchrotron radiation for research**
  - High brightness X-rays for material science
  - Production in electron storage rings
- **15 years of positive experience with SLS**
  - Rich experimental program
  - Reliable accelerator operation
  - Sub-micron beam stability
  - Unique source of sub-picosecond X-rays (FEMTO)
- **SLS-2 upgrade plans**
  - Factor >30 lower horizontal emittance
  - A new type of storage ring lattice
  - Work in progress, to be completed by 2024

Backup slides

Upgrade: storage ring generational change



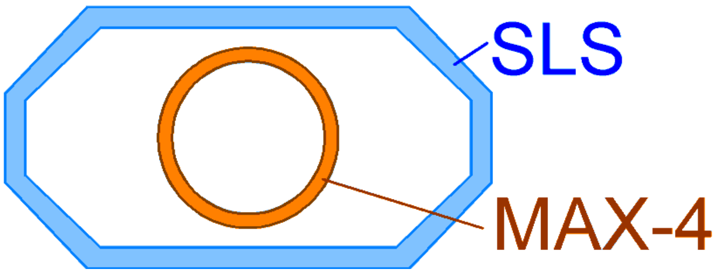
Storage rings in operation (•) and planned (•).

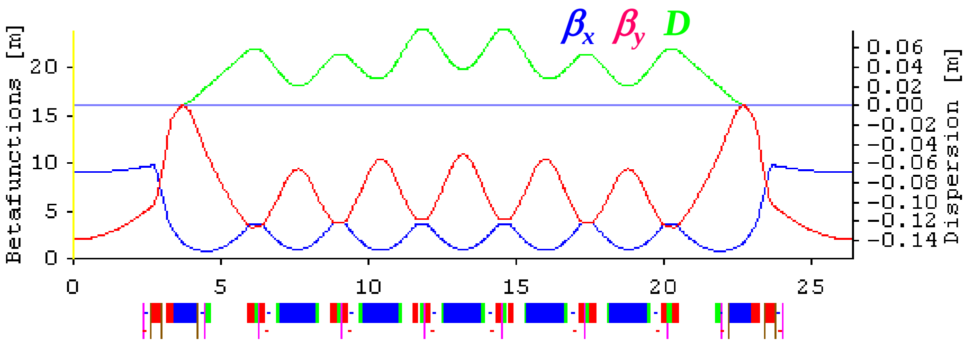
The old (—) and the new (—) generation.

Upgrade: new storage ring technology

Pioneer work: **MAX IV** (Lund, Sweden)

Aperture reduction ⟷ **Multi-Bend Achromat (MBA)**





Miniaturization of vacuum chambers and magnets

⇨ Small magnet bore.

⇨ High magnet gradient.

short & strong multipoles

⇨ short lattice cells

⇨ many lattice cells

⇨ low angle per bend (= dipole)

$$\text{emittance } \varepsilon \propto (\text{energy})^2 \times (\text{bend angle})^3$$

⇨ Emittance reduction from nm to 10...100 pm range

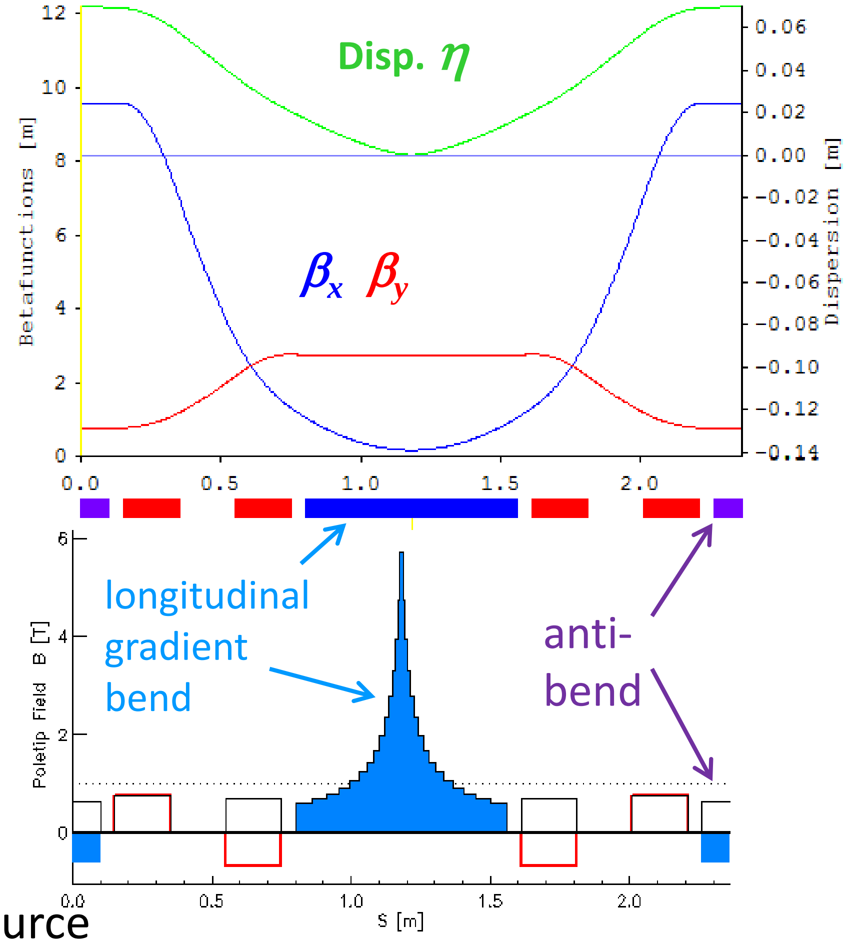
Upgrade: SLS-2 design concept

- Constraints
  - factor > 30 lower emittance → ≈ 150 pm
  - keep hall & tunnel.
  - re-use injector: booster & linac.
  - keep undulator positions.
  - upgrade in 6...9 months done.
- Challenge: *small circumference*

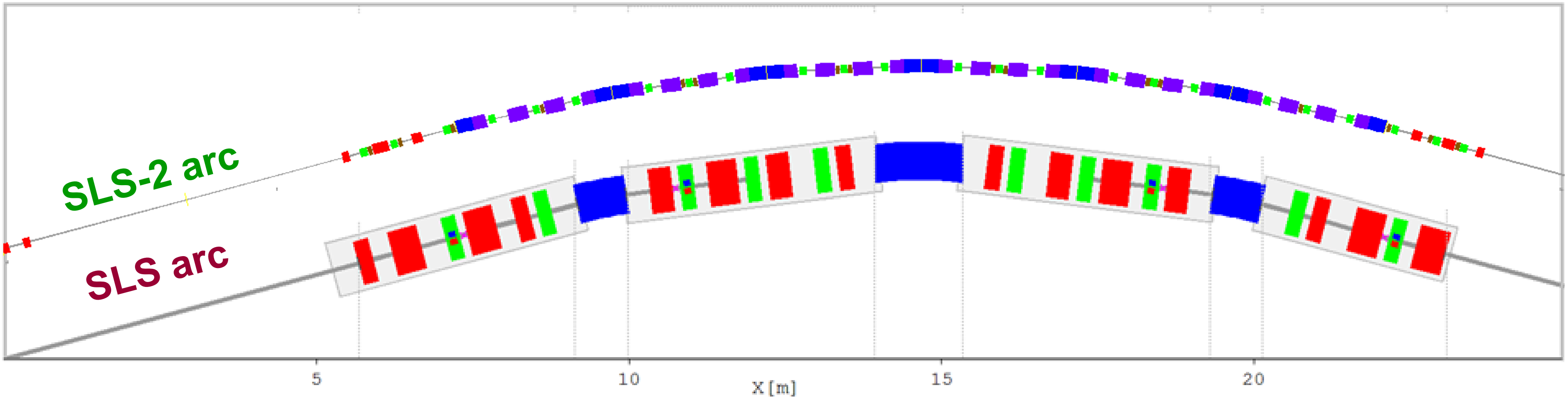
✘ MBA concept alone is insufficient

✓ New lattice design based on longitudinal gradient bends

- $B_y = B_y(s) \rightarrow$ lowest emittance
  - high field at low dispersion and v.v.
  - high peak field (4...6 T) ⇨ hard X-ray source
- "anti-bends" for dispersion matching



Upgrade: SLS-2 lattice layout



- TBA ⇨ **7BA** lattice: ½ + 5 + ½ cells of **LGB/AB type**
- Reduced circumference 288.00 m ⇨ **287.25 m**
  - in order to keep undulator positions (source points)
- periodicy 3: 12 arcs and 3 different straight types:
  - 6 × 4 m ⇨ **6 × 2.9 m** 3 × 7 m ⇨ **3 × 5.1 m**
  - split long straights: 3 × 11.5 m ⇨ **6 × 5.1 m**
- beam pipe: 64 mm x 32 mm ⇨ **∅ 20 mm**

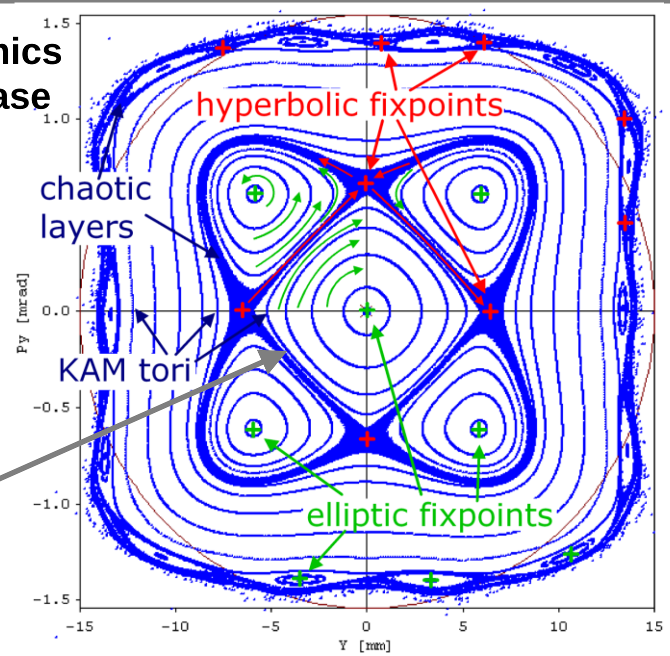
⇨ magnet aperture ∅ 26 mm

Storage ring: dynamic aperture challenge

- **Bright photon beams**
- ⇨ small electron beam
- ⇨ strong focusing
- ⇨ chromatic quadrupole errors
- ⇨ correction by sextupole magnets
- ⇨ nonlinear sextupole field $B \sim x^2$
- ⇨ deterministic chaos: particle losses beyond some amplitude: dynamic aperture
- ⇨ reduced lifetime of stored beam reduced rate of injection into ring

- ⇨ **To do**
- ⇨ find optimum sextupole scheme
- ⇨ correct machine imperfections
- ⇨ SLS 2009: measured lifetime agrees with calculation for the *ideal* machine.

non-linear dynamics in transverse phase space (y, p_y)



SLS magnets

42	dipoles
177	quadrupoles
120	sextupoles
12	undulators
144	dipole correctors
36	skew quadrupoles
12	sextupole correctors

Storage ring: minimum emittance

Horizontal emittance

(of a flat, iso-magnetic lattice)

Beam energy

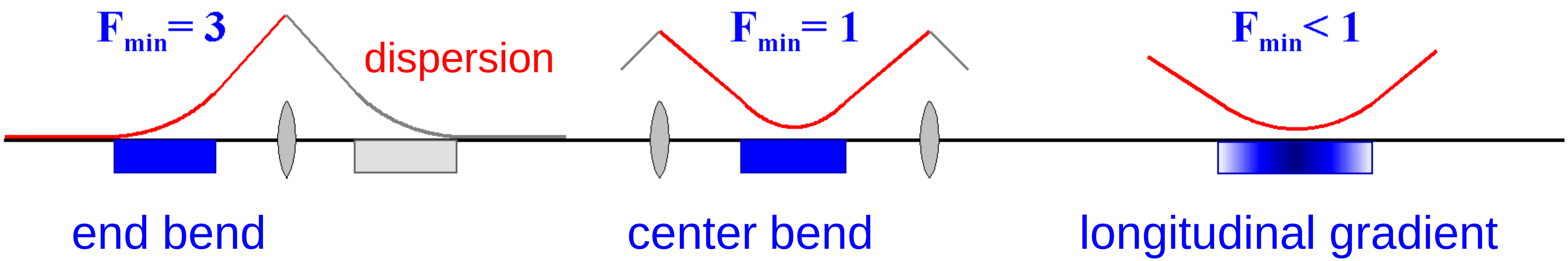
Deflection angle *per* dipole

Beam optics...

$$\varepsilon_x \approx 1/6 \text{ pm } (E\,[\text{GeV}])^2\,(\phi\,[°]\,)^3\,F$$

⇨ many (n) small dipoles: $\phi = 360°/n$

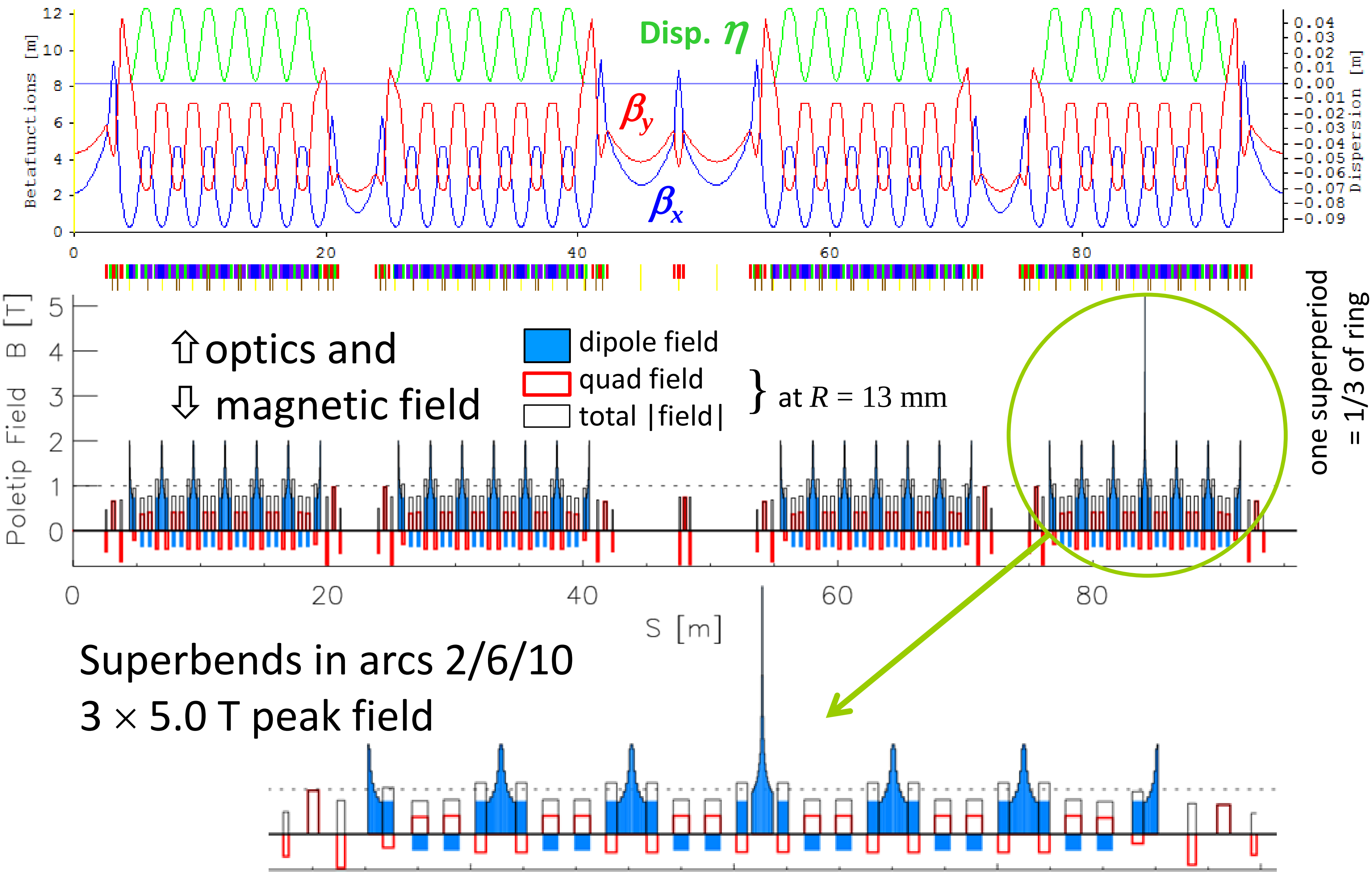
⇨ focus to magnet center: $F \approx 3...6 \times F_{min}$



many dispersion-free straight sections for undulators:

⇨ combine end & centre bends to double/triple/multi-bend achromats (DBA, TBA, MBA)

Upgrade: SLS-2 optics



Superbends in arcs 2/6/10

3 × 5.0 T peak field

Achievements: beam stability

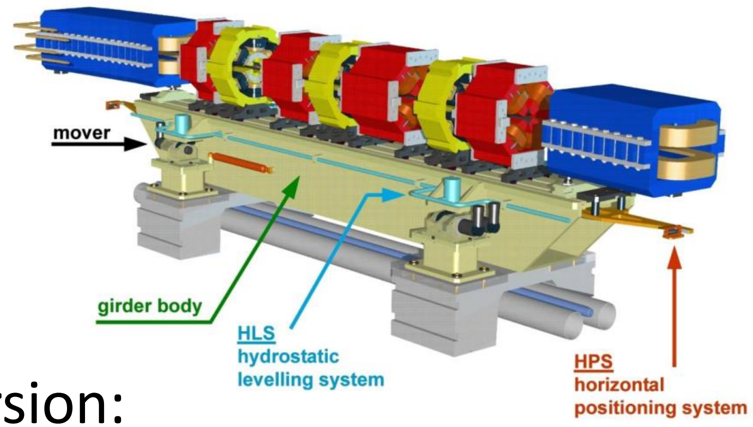
- Top up operation: thermal stability
- Beam position monitors: resolution $< 0.3\ \mu m$
- Digital power supplies:
  stability and reproducibility < 30 ppm
- Frequent beam based BPM calibration
  ("beam based alignment")
- Undulator feed forward tables
- Fast orbit feedback system (< 100 Hz)
- Photon-BPM integration in orbit feedback
- Filling pattern feedback system

⇨ Photon beam stability $<1\ \mu m$ rms (at frontends)

Achievements: ultra-low vertical emittance

- Dynamic girder alignment system

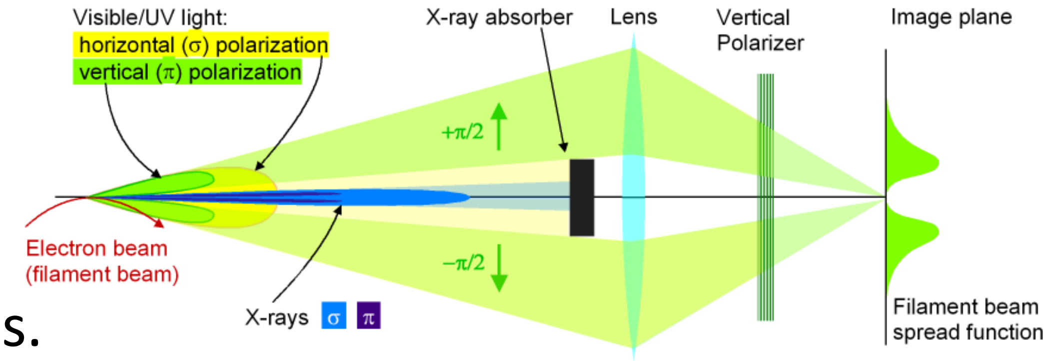
⇨ Vertical alignment *with* stored beam and orbit feedback.



- Measurement of coupling matrix:
  vertical orbit response to horizontal excitation
- Measurement of spurious vertical dispersion:
  vertical orbit as function of energy

⇨ Model based compensation using 36 skew quadrupoles.

- High resolution monitor:
  beam size from vertical polarized synchrotron light image



⇨ Random walk optimization of beam size using skew quads.

⇨ World record low vertical emittance:

$\varepsilon_y = 0.9 \pm 0.4$ pm (quantum limit: 0.2 pm)

Achievements: optics corrections

- correction of beta functions tuning 177 quadrupoles

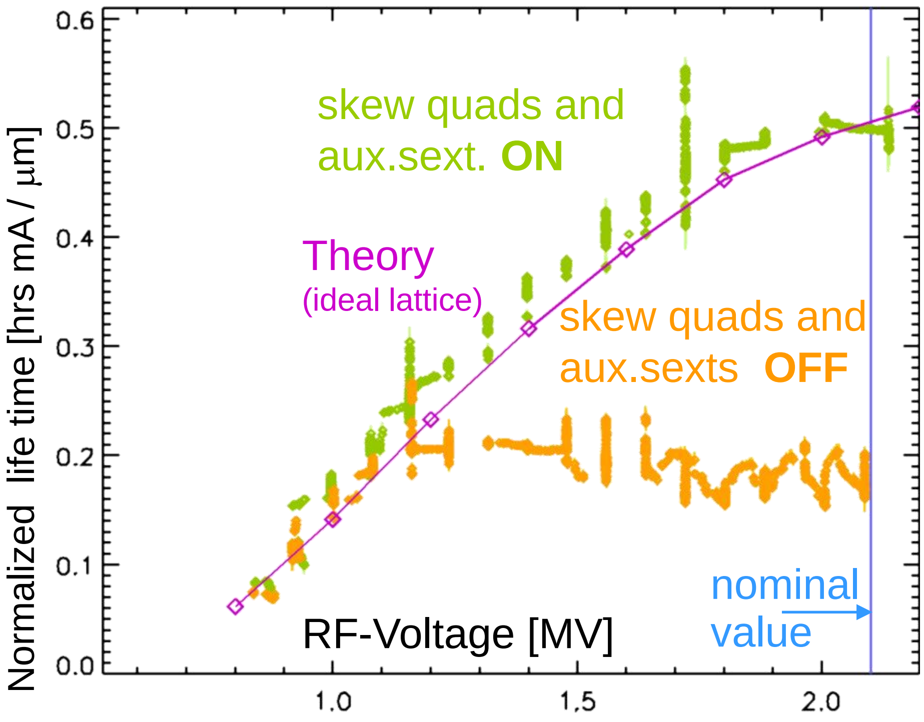
⇨ beta beat ($= \Delta\beta/\beta$) down to ~ 2% rms.

- suppression of coupling using 36 skew quadrupoles
- suppression of sextupole resonances using 12 auxiliary sextupoles

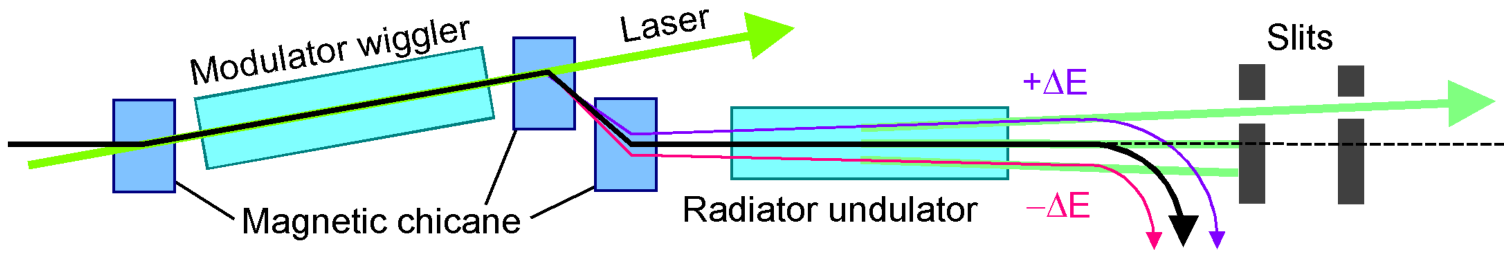
⇨ momentum acceptance (=momentum dependent dynamic aperture) restored.

⇨ beam lifetime in agreement with design calculations.

Measured beam lifetime (normalized to σ_y and bunch current) as a function of RF voltage



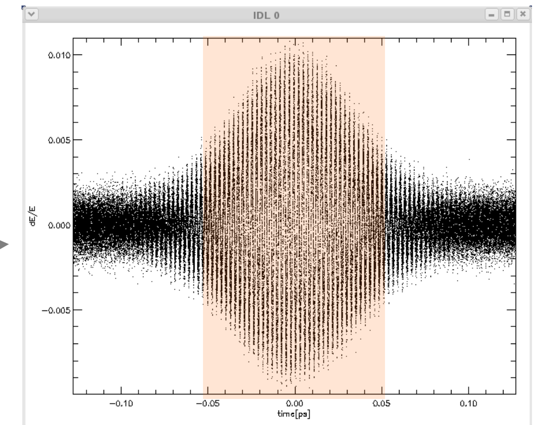
Achievements: FEMTO



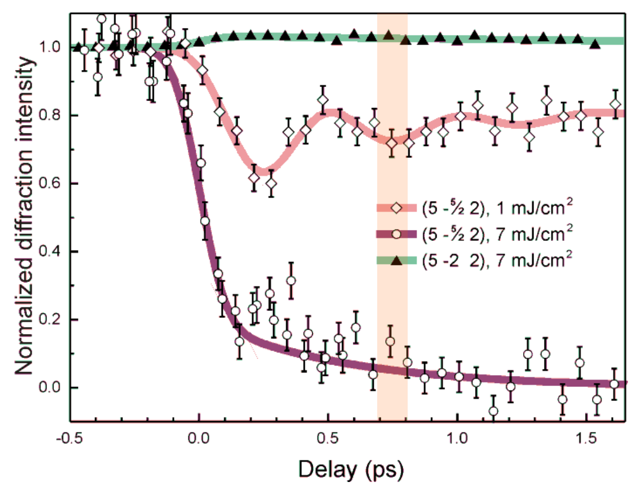
Tunable sub-picosecond X-ray source

- 50 fs FWHM high power laser
- Modulator wiggler
  - energy modulation in thin slice of bunch
- Magnetic chicane
  - translation of modulation to horizontal separation
- Radiator undulator
  - source of X-ray synchrotron radiation
- Beam line optics (slits & toroid)
  - extraction of radiation from modulation

⇒ 150 fs FWHM X-ray pulses
  - low flux, but high stability
  - time resolved sub-ps X-ray experiments



100 fs



Upgrade: new storage rings and upgrade plans

Name	Energy [GeV]	Circumf. [m]	Emittance* [pm]	Status
PETRA-III	6.0 3.0	2304	4400 → 1000 85 (round beam)	operational
MAX-IV	3.0	528	328 → 200	2015
SIRIUS	3.0	518	280	2016
ESRF upgrade	6.0	844	147	2019
DIAMOND upgrade	3.0	562	275	started
APS upgrade	6.0	1104	65	study
SPRING 8 upgrade	6.0	1436	68	study
PEP-X	4.5	2200	29 → 10	study
ALS upgrade	2.0	200	100	study
ELETTRA upgrade	2.0	260	250	study
SLS now	**2.4**	**288**	**5500**	**operational**
SLS-2	**2.4 (?)**	**288**	**100-200 ?**	**2024 ?**

*Emittance without → with damping wigglers