The SLS

Storage Ring based light sources

Andreas Streun, PSI Villigen, Switzerland

- The needs of materials research
- The properties of synchrotron radiation
- Electron storage rings as light sources
- The Swiss Light Source SLS
- Achievements of SLS operation
- Summary & outlook

JUAS visit to PSI, Feb. 26-27, 2013

Materials research: particles

Neutral particles

penetrating matter

(no Coulomb interaction)

→ diffraction experiments

⇨ **neutrons**

⇨ **SINQ**

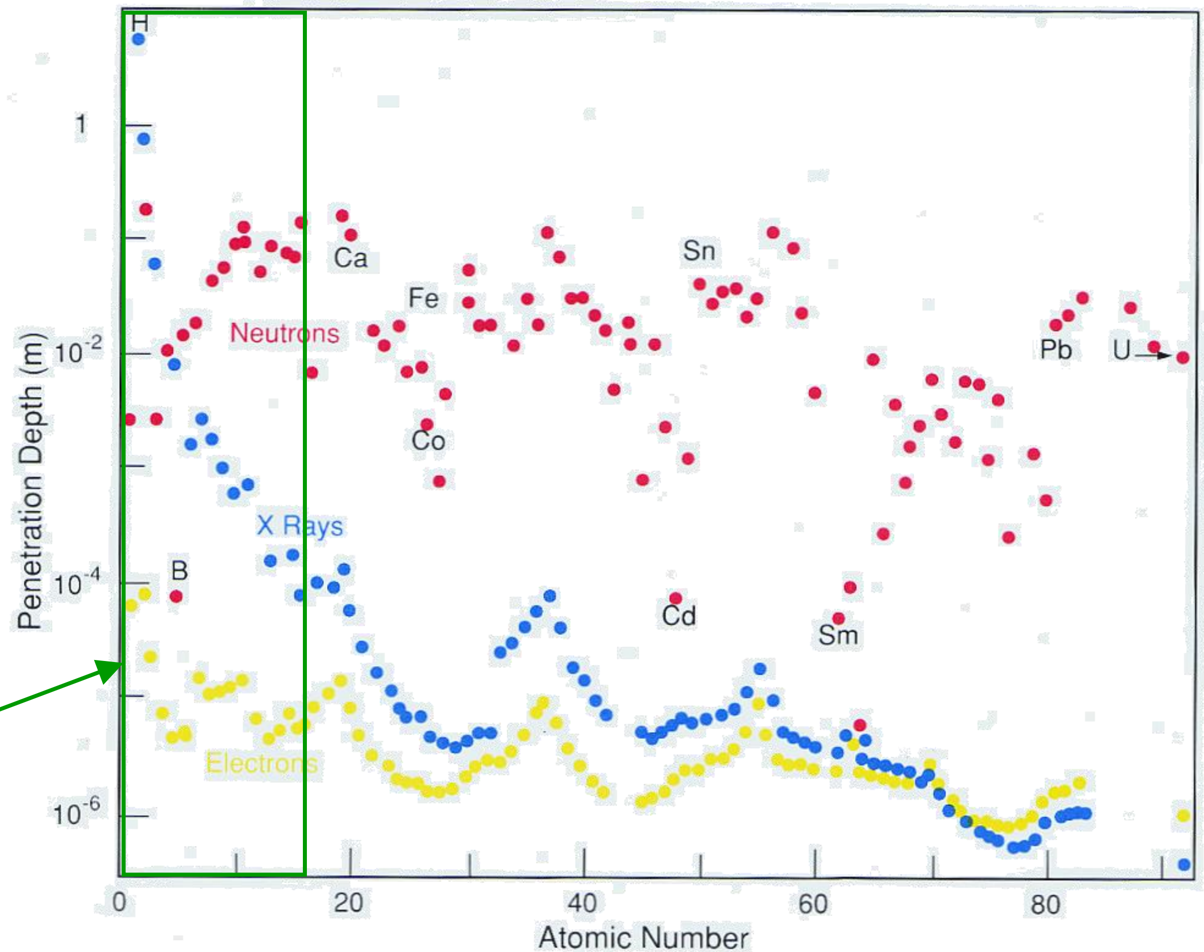
⇨ **photons**

✚ organic matter

✚ very high flux

⇨ **SwissFEL**

⇨ **SLS**



Penetration depth for **neutrons**, **photons**, **electrons** of 1.4Å as a function of atomic number **Z**

Figure taken from Roger Pynn, Neutron scattering - a primer, Los Alamos neutron scattering center, 1989

Materials research: energy

- Molecular scales
  $\sim 1\text{Å} = 10^{-10}$ m
  (Range $10^{-11} \ldots 10^{-7}$ m)
- scale of structure
  ⇕
  size of probe
- Photon wavelength
  $\lambda \sim 1\text{Å}$
- Photon energy
  $E = pc \sim 10$ **keV**
- Neutrons: $E_{\text{kin}} \sim 0.1$ eV

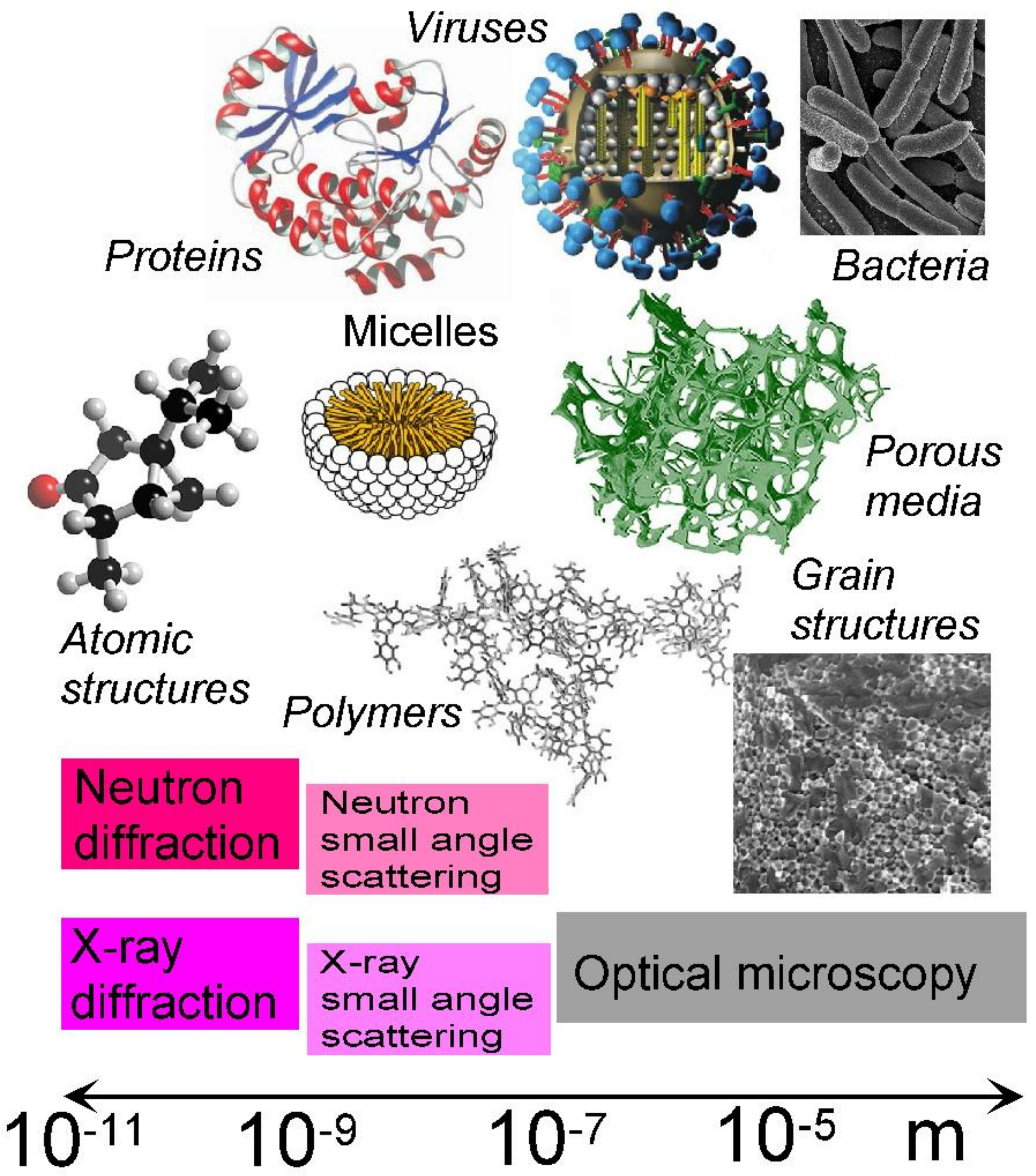


Figure based on Roger Pynn, *Neutron scattering - a primer,* Los Alamos neutron scattering center, 1989 ➚

Materials 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

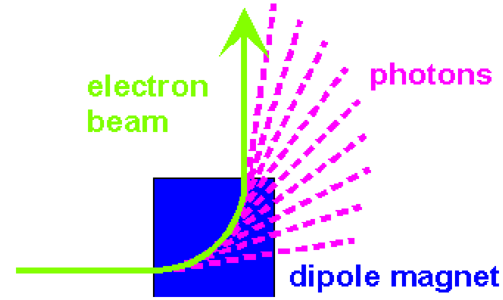
- figure of merit: ***Brightness***

= 6-dimensional *invariant* photon phase space density

$$= \frac{\text{photons}}{(\text{area}) \times (\text{solid angle}) \times (\text{time}) \times (\text{energy interval})}$$

- brightness unit: $\dfrac{\text{photons}}{\text{s mm}^2\,\text{mrad}^2\,\text{BW}}$

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

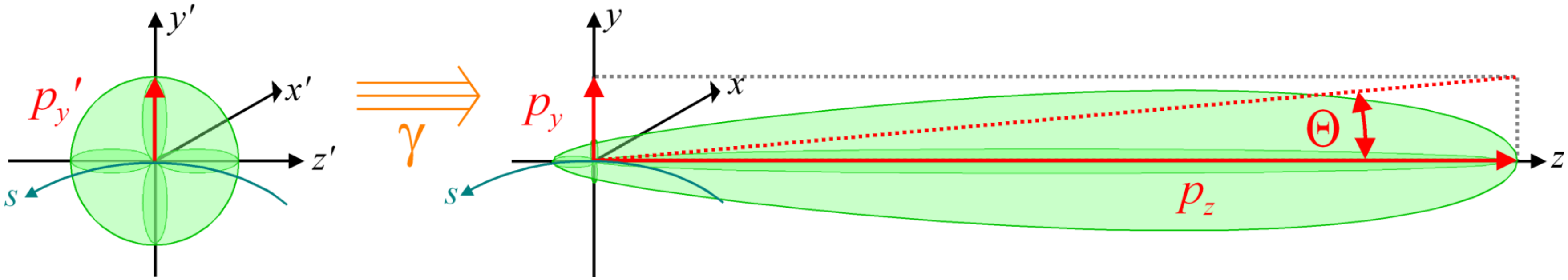
$$P[\text{kW}] = 88.5\,\text{kW} \times I_{beam}[\text{A}] \frac{(E\,[\text{GeV}])^4}{R\,[\text{m}]}$$

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

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

Synchrotron radiation: collimation

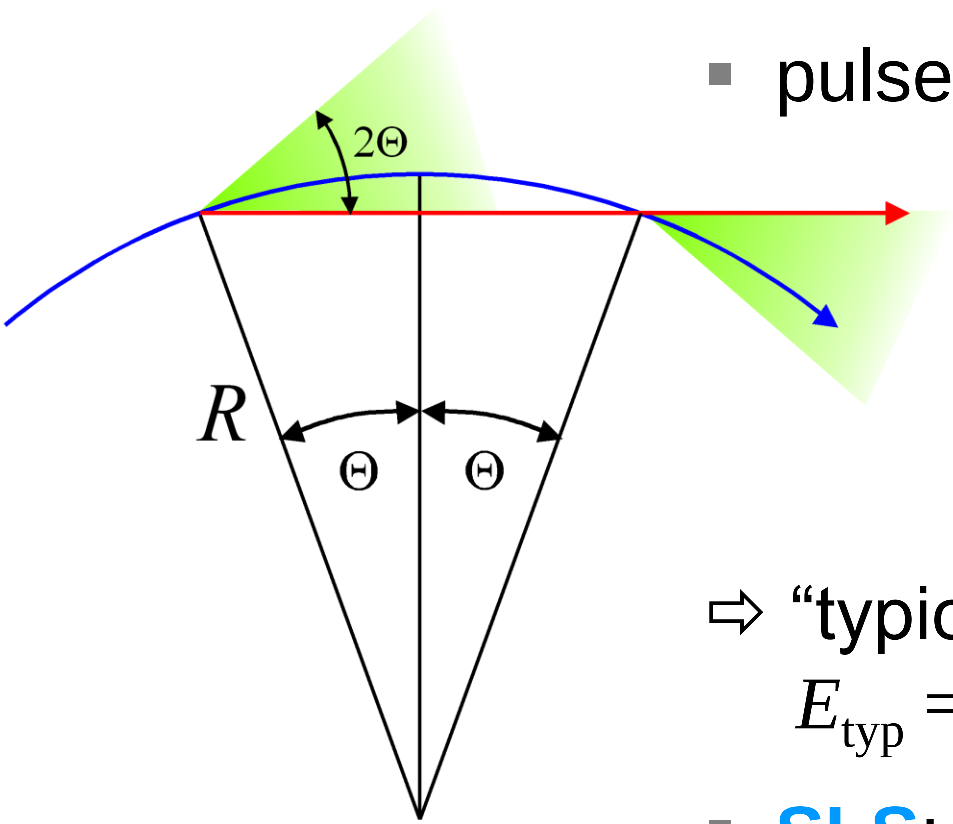
- Lorentz transformation to laboratory system



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

- Collimation angle: $\Theta = p_y/p_z = 1/\gamma$
- **SLS** : $\Theta = 0.2$ mrad
  ⇨ beam spot $\varnothing$ 1 cm after 25 m

Synchrotron radiation: photon energy



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

electron – photon

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

⇨ “typical” energy

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

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

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

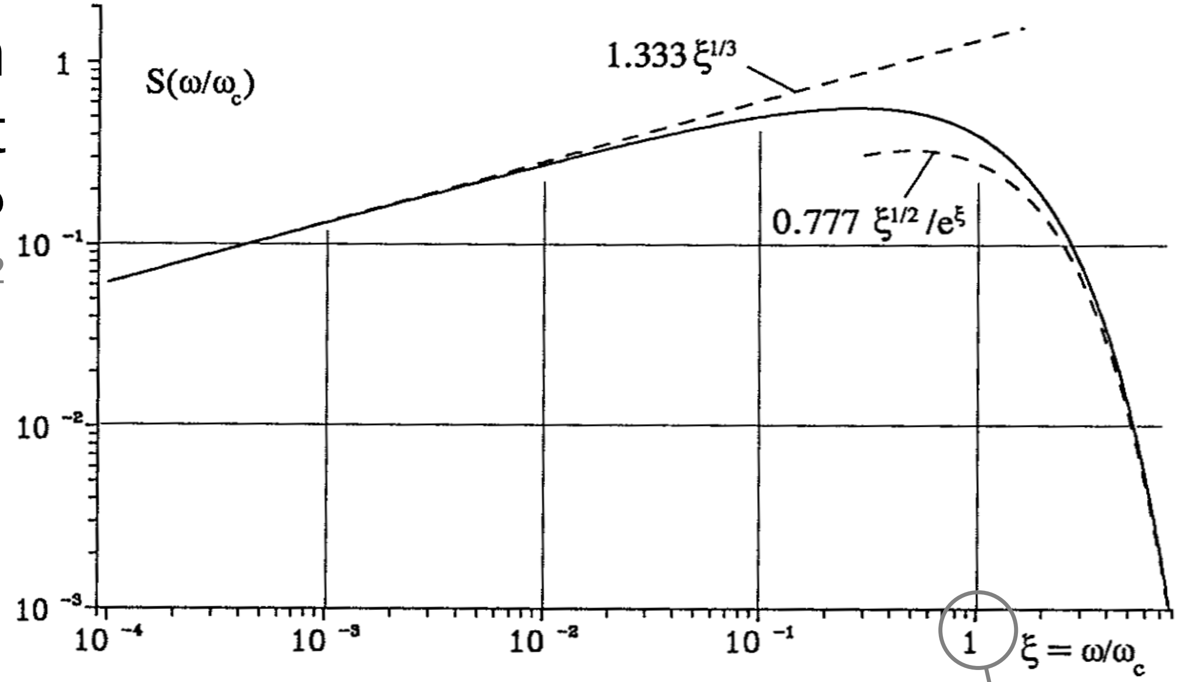
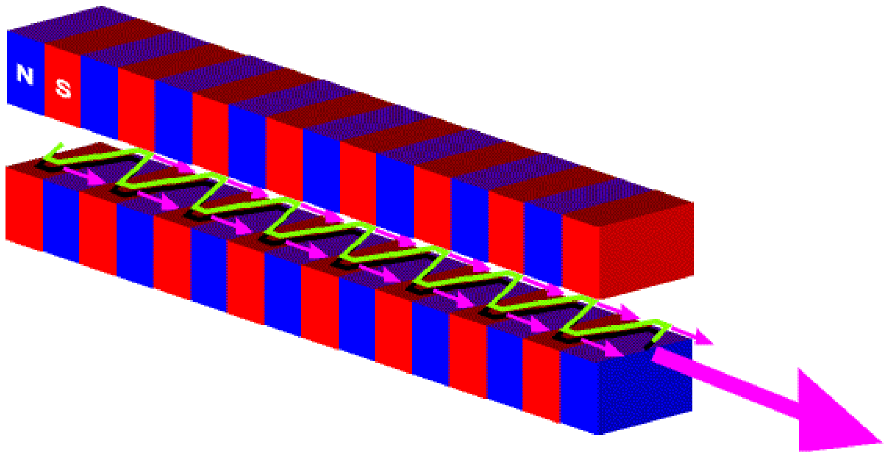


Fig. 7.12. Universal function: $S(\omega/\omega_c) = \frac{9\sqrt{3}}{8\pi} \frac{\omega}{\omega_c} \int_{\omega/\omega_c}^{\infty} K_{5/3}(x)\,dx$

- 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**: $E_c = 5.3\text{ keV} \; (B = 1.4\text{ T}, \; E = 2.4\text{ GeV})$

Synchrotron radiation: Undulator

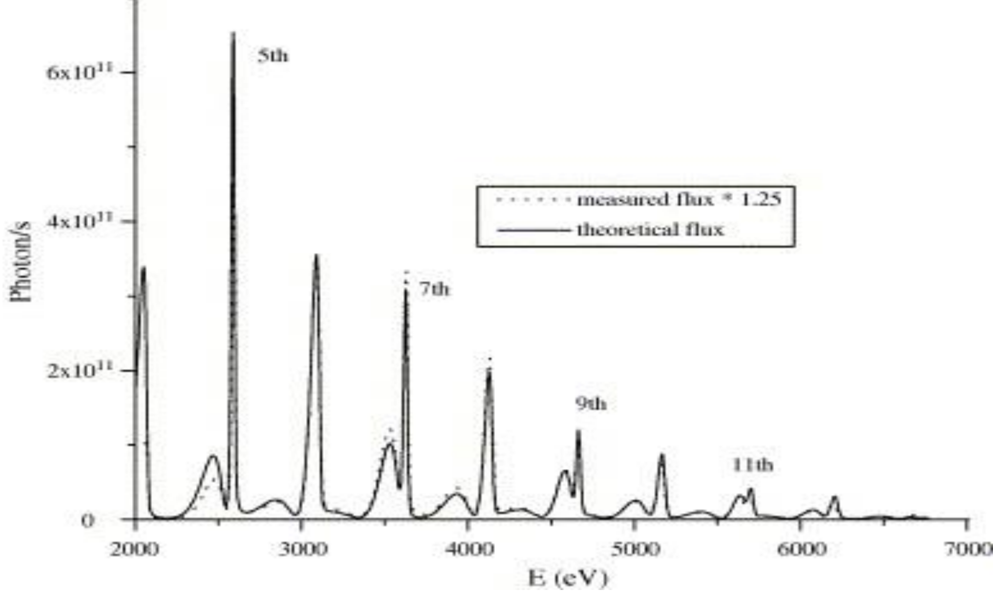


- many small dipoles
  N ~ 20...100 periods
- angle/pole < $1/\gamma$
  ($1/\gamma$ = radiation opening angle)

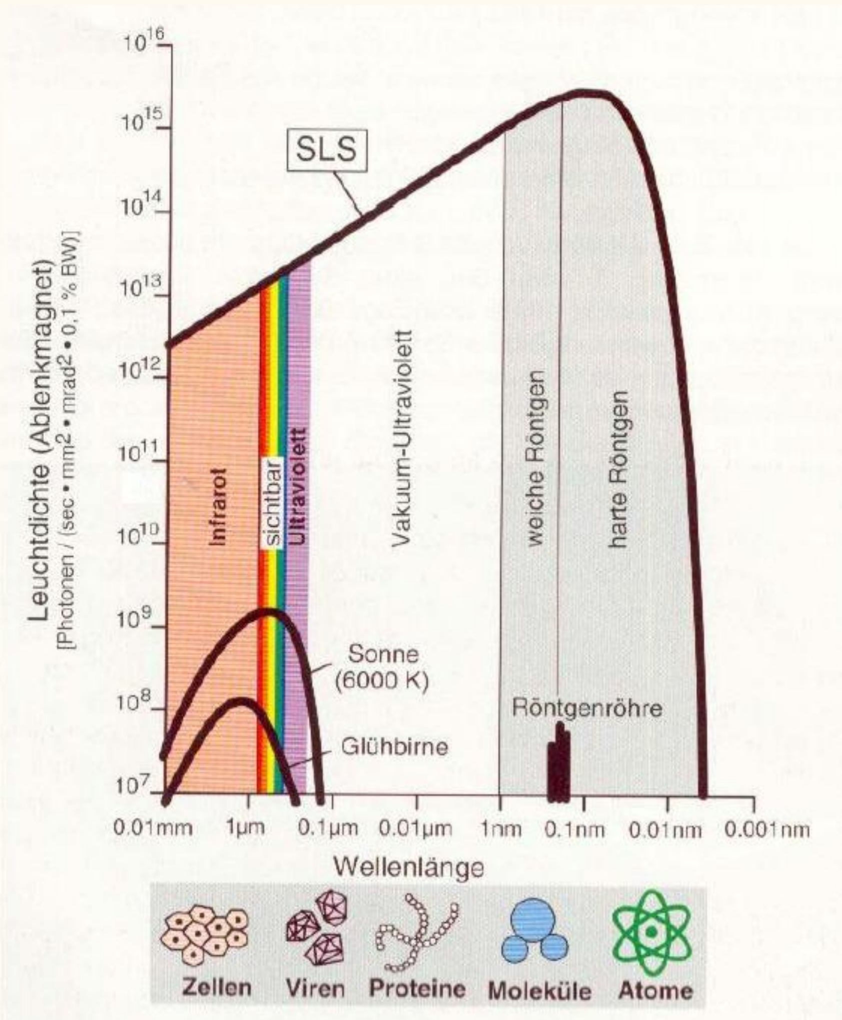
⇨ interference

⇨ line spectrum

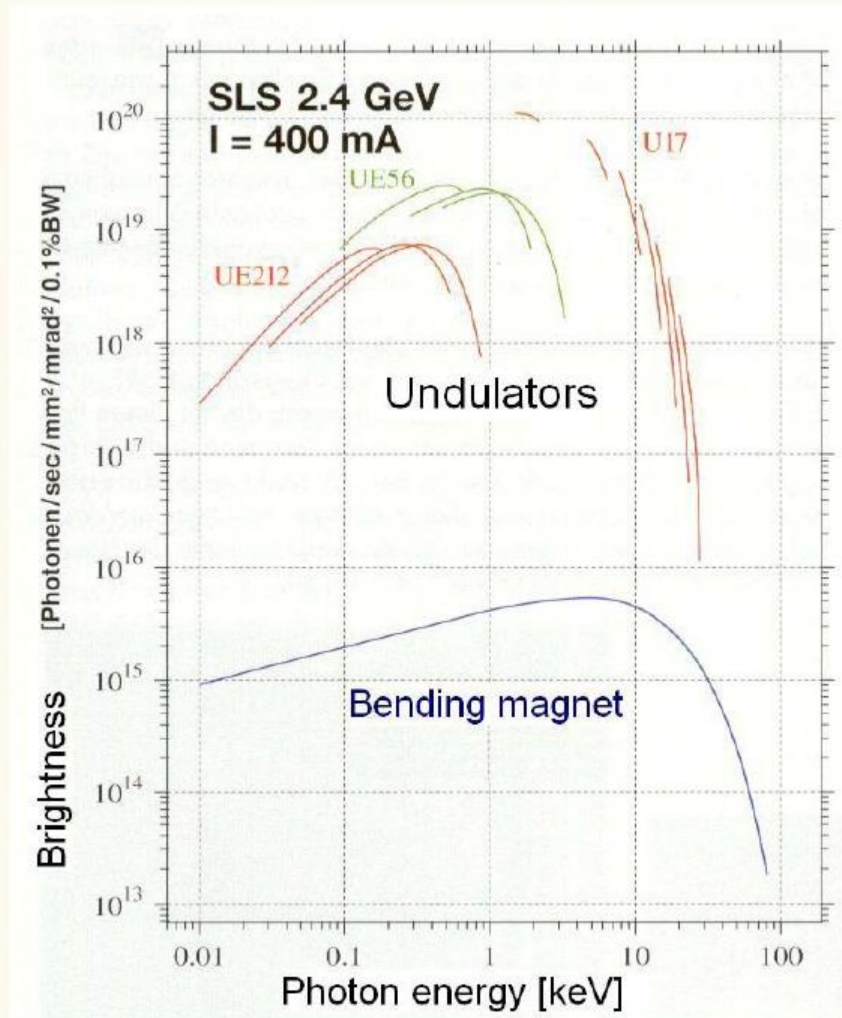
SLS UE54 undulator →



Synchtron radiation: undulator brightness



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



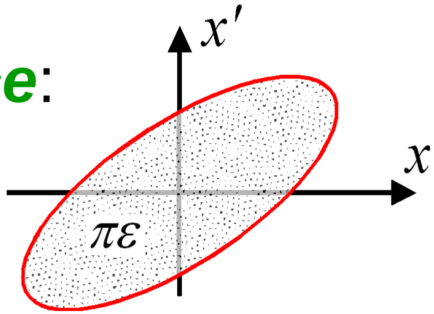
Undulator brightness in comparison to bending magnet brightness

Synchrotron radiation: brightness

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

$\dot{N}(E)$ 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

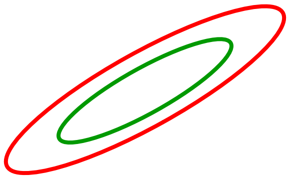
vertically diffraction limited source

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

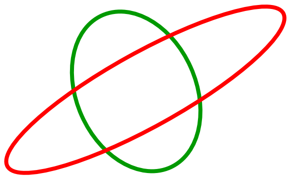
- e.g. protein crystallography: $E \sim 10$ keV ⇨ $\varepsilon_r \sim 10$ pm

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

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



matched: +

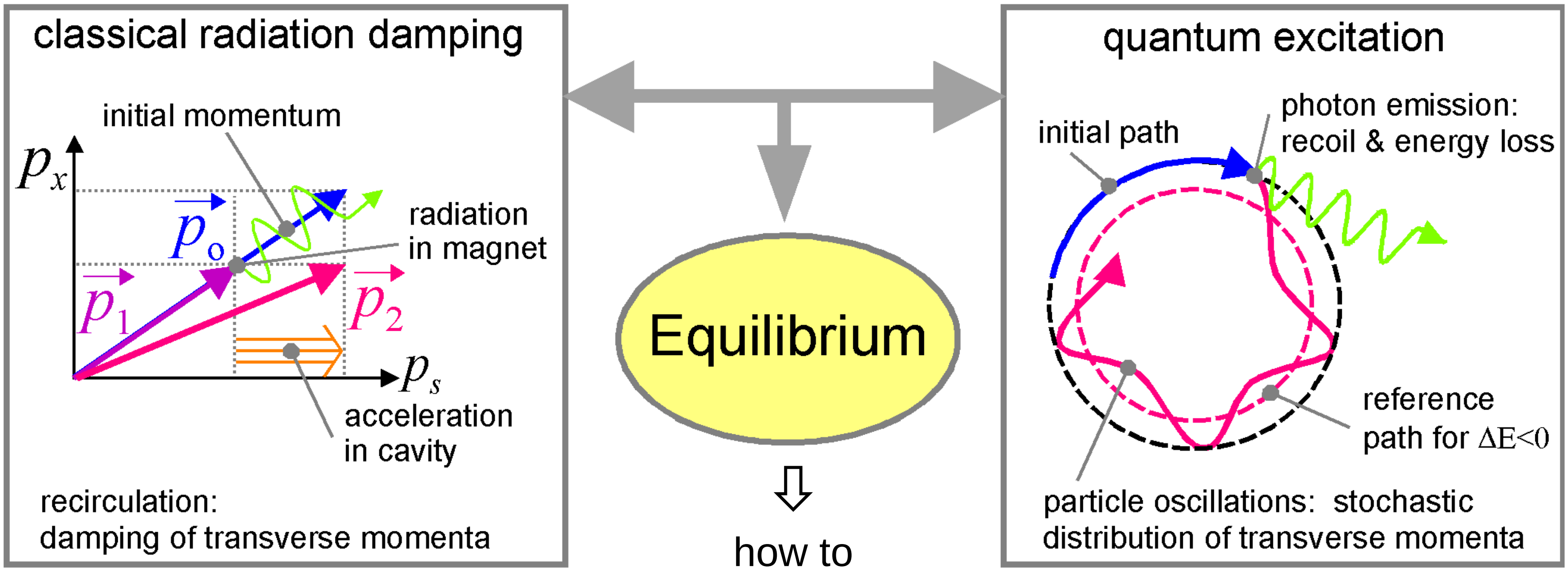


unmatched: ⊕

Horizontal emittance in electron storage ring:

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

independent from initial conditions !



⇧ maximize this -- and -- minimize this ⇧

?

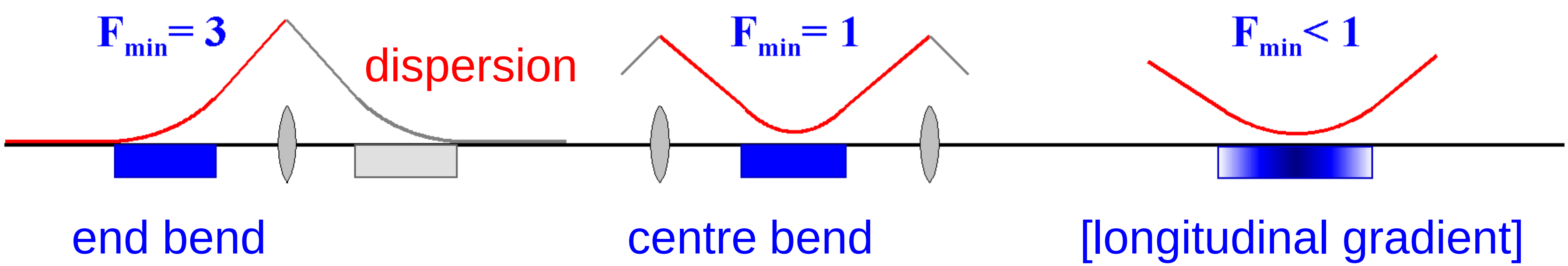
Beam energy
Deflection angle *per* dipole
Beam optics...

Minimum emittance

$\varepsilon_x \approx 1/6\ \mathrm{pm}\ (E[\mathrm{GeV}])^2\ (\Phi[\ ])^3\ F$

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

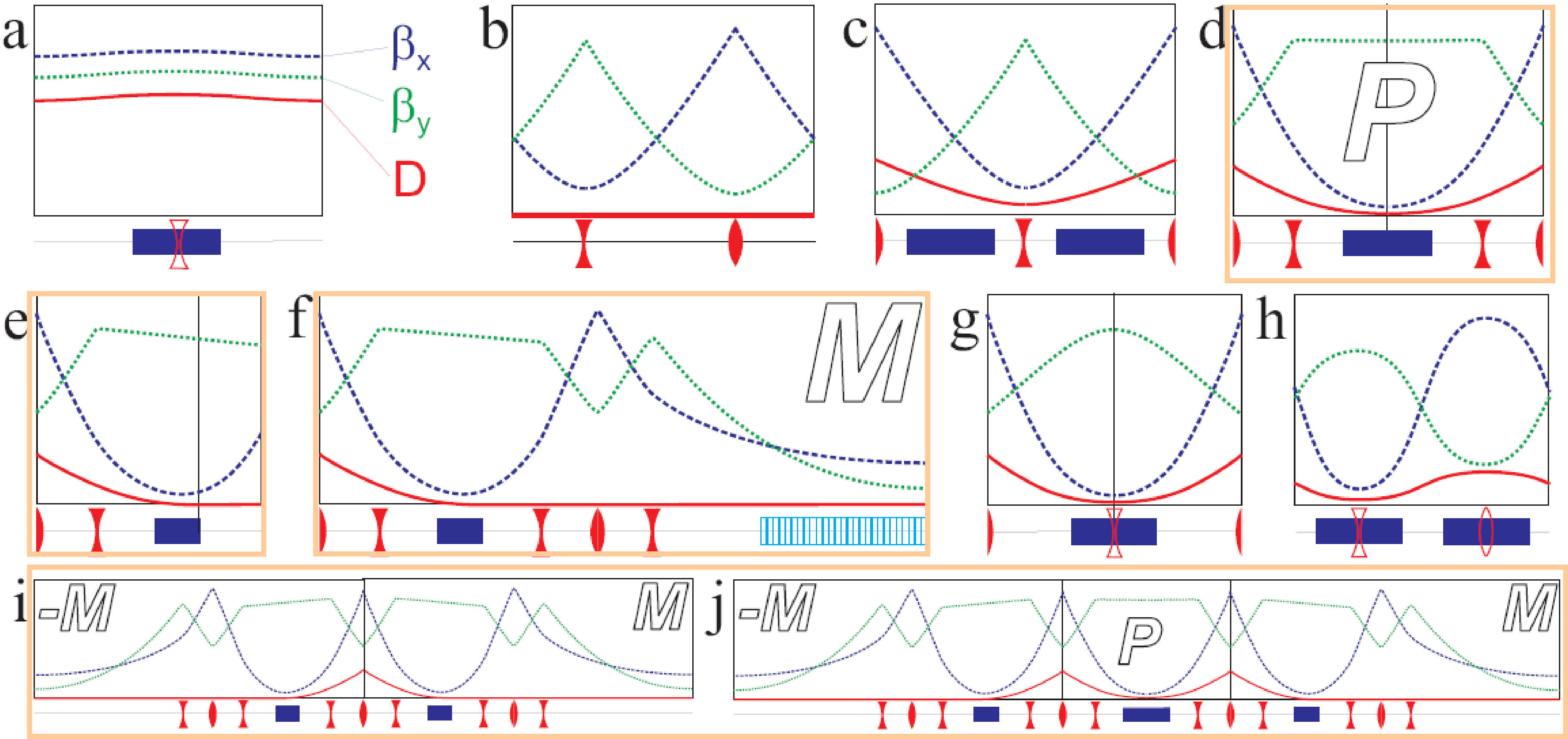
⇨ focus to magnet center: $F \approx 2..5 \times F_{min}$



many dispersion-free straight sections for undulators:

⇨ combine end & centre bends to double/triple/N-bend ***achromats*** (DBA, TBA, NBA)

Storage ring: building low emittance lattices...



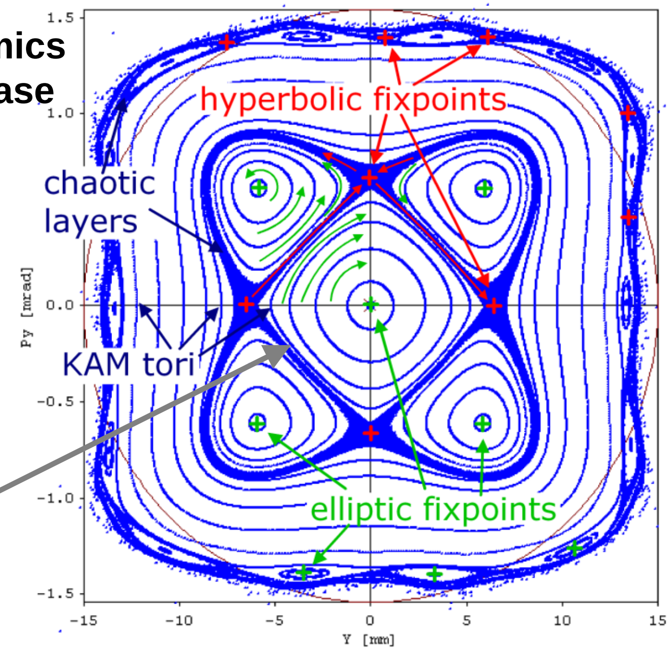
β_z = "beta function" = normalized beam size = σ_z^2/ε_z (z = x;y)

D = dispersion = off-momentum orbit = $\Delta x/(\Delta p/p)$

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

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



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

SLS magnets

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

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 $= 0.20\ \mathrm{pm}$

⇨ ultimate limit of vertical emittance

Coupling emittance

- Magnet misalignments and imperfections:
  displacements and rotations

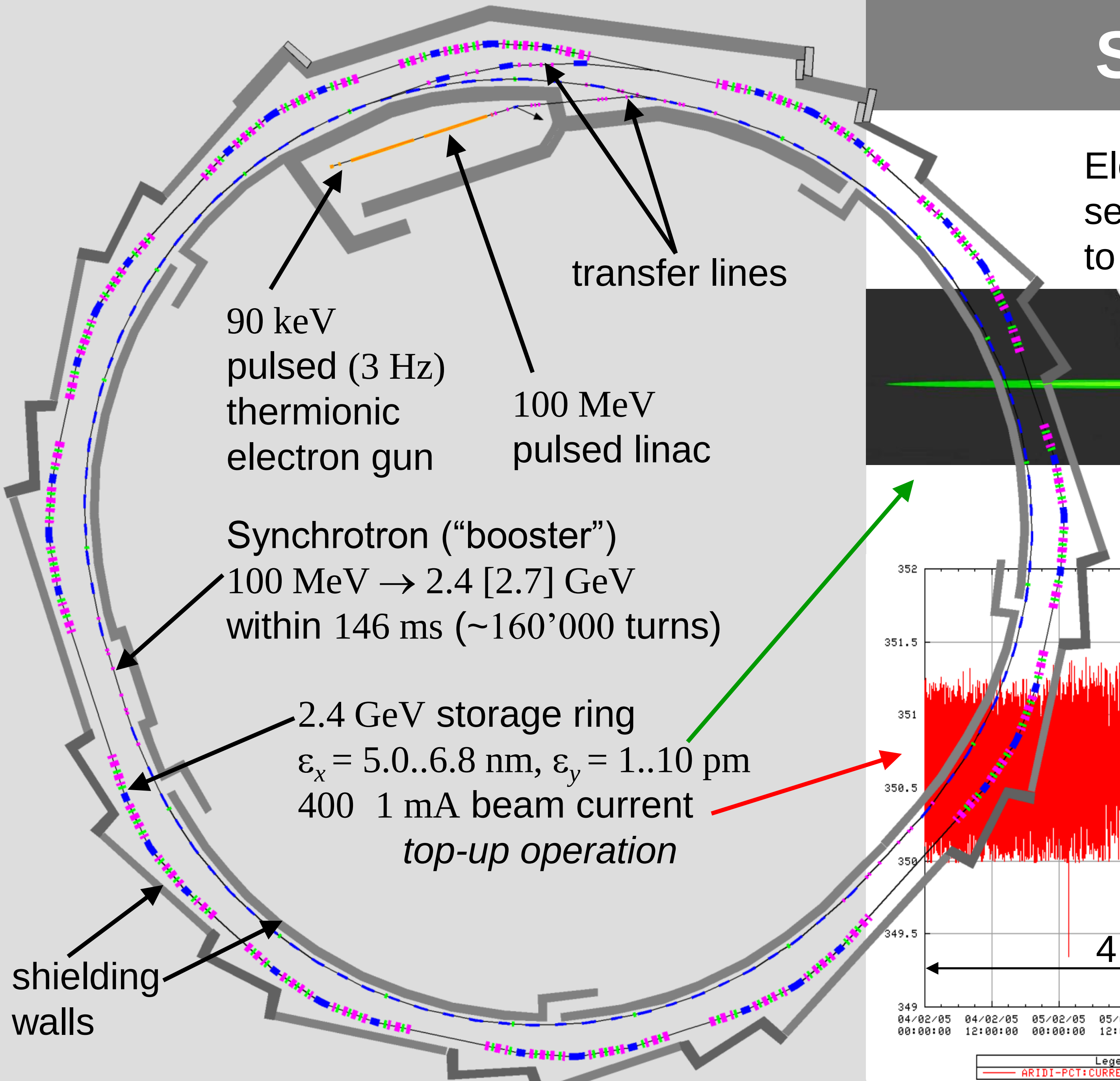
⇨ spurious vertical dispersion: vertical quantum excitation

⇨ betatron coupling: horizontal oscillation ⇨ vertical oscillation

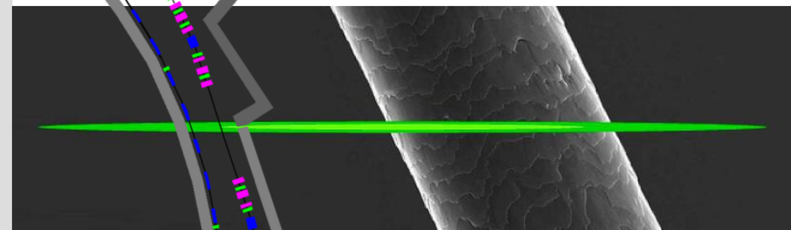
Vertical equilibrium emittance

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

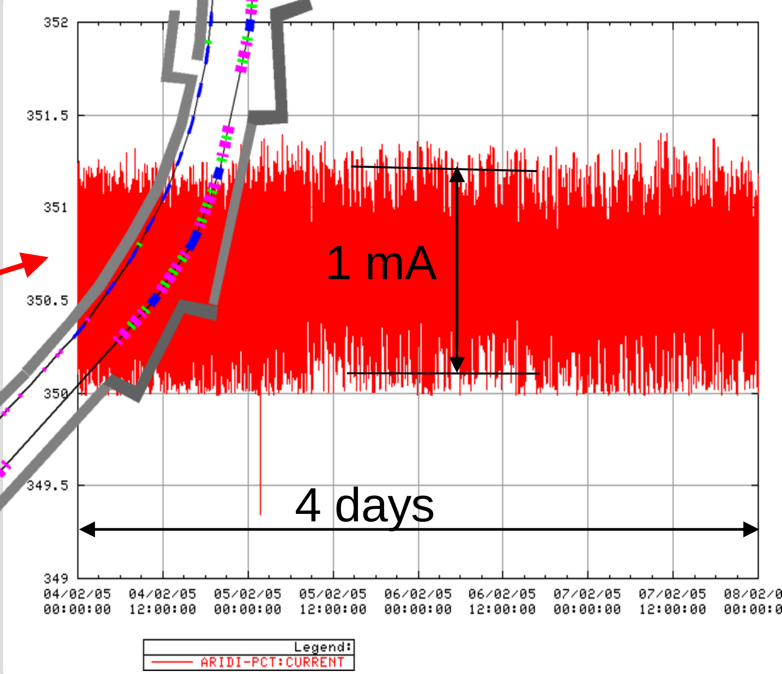
SLS: layout



Electron beam cross section in comparison to human hair



Current vs. time



SLS: storage ring lattice

12 TBA:

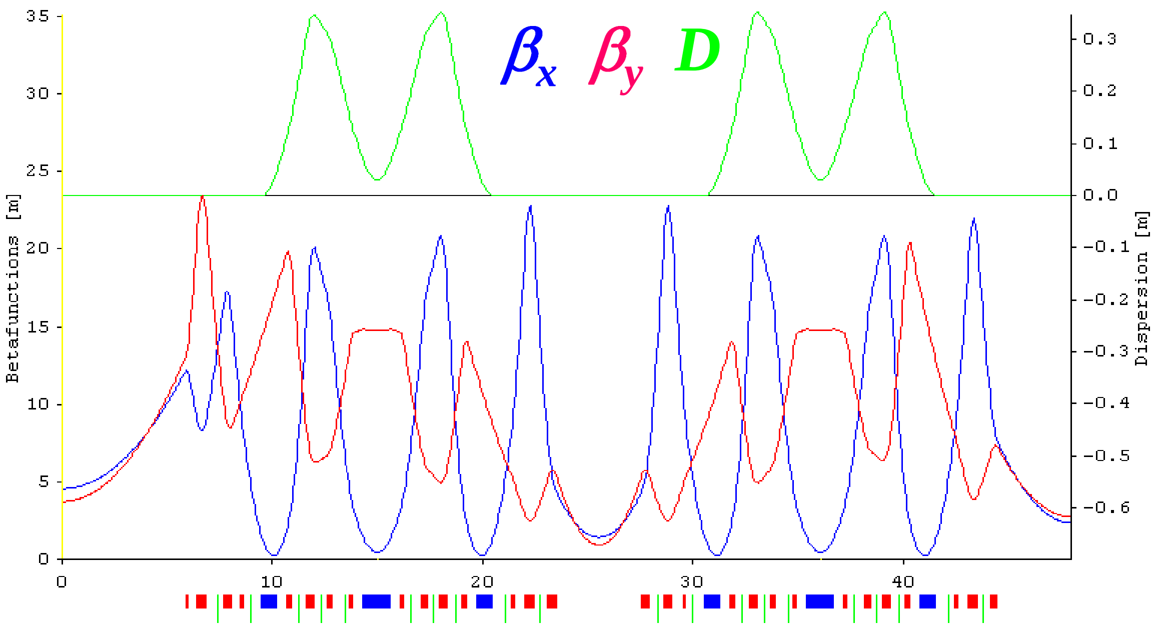
8 /14 /8

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: comparison to other ~3 GeV light sources

		SLS	SOLEIL	DIAMOND	ALBA	MAX-IV	NSLS-II
Start of operation		2001	2006	2007	2010	2015	2015
Energy	GeV	2.40	2.75	3.00	3.00	3.00	3.00
Circumference	m	288	354	562	267	528	792
Emittance ε	nm	5.50	3.70	2.70	4.30	0.34	2.00
...effective*	nm	5.50	6.29	2.95	5.84	0.34	2.00
...with IDs	nm	5.00				0.17	0.60
Current	mA	400	500	300 (500)	400	500	500
Lattice type		12xTBA	16xDBA	24xDBA	16xDBA	20x7-BA	30xDBA

*including beam size increase due to non-zero dispersion at source points

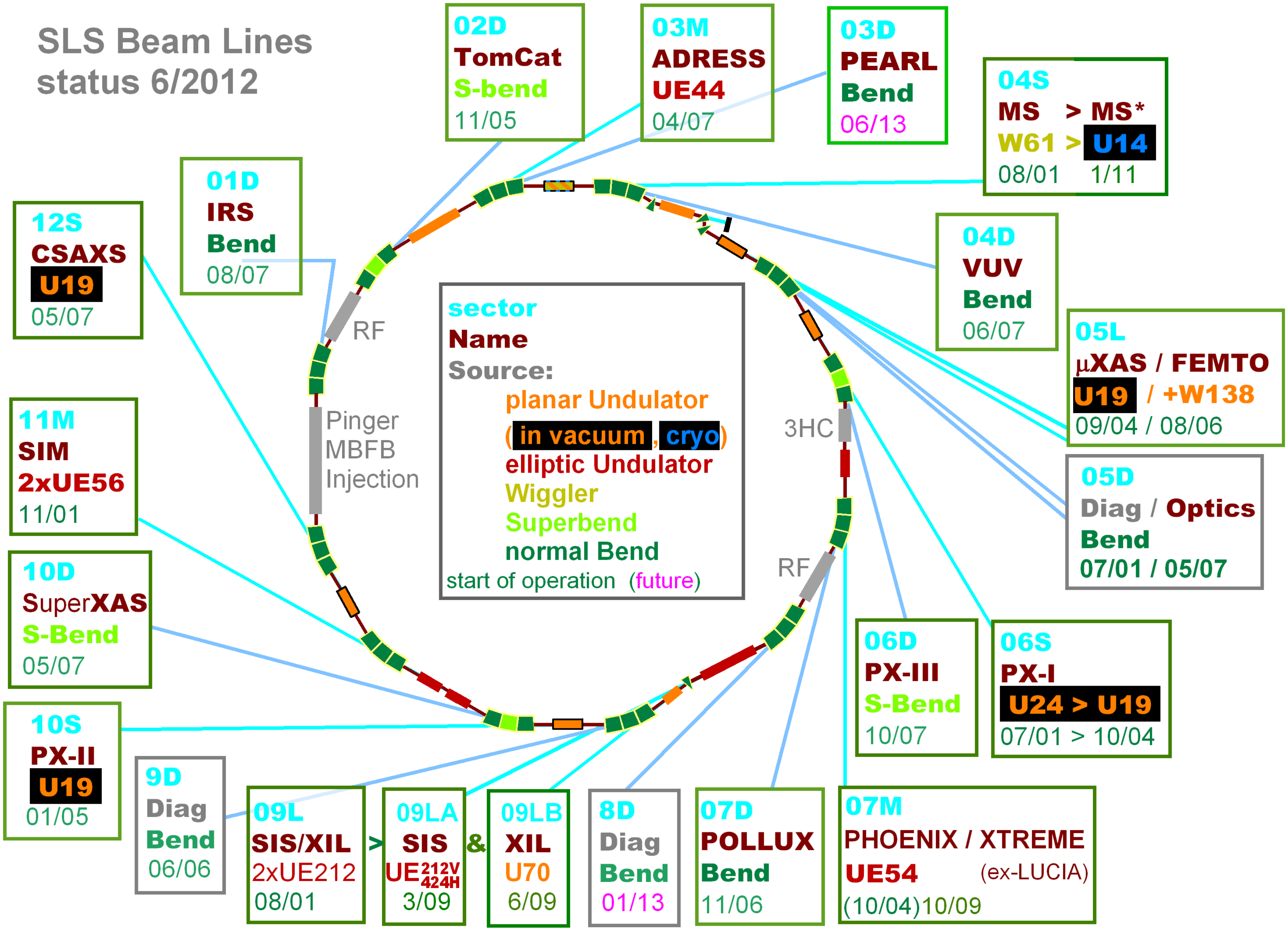
"SLS-generation"

- ε_{eff} ~ 3..10 nm
- insertion devices have little effect

next generation

- < 1 nm effective emittance
- large circumference: $\varepsilon \sim (N_{bend})^{-3}$
- strong insertion devices effects

SLS: beam lines overview



SLS: beam lines properties

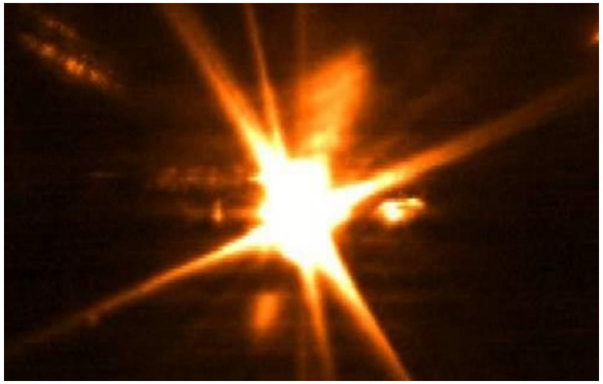
Sector	Beamline	Methods	Source	Energy range	Polarization
X01DC	IRS		bend	1 meV – 1.5 eV	↔
X02DA	TOMCAT		superbend	8 – 45 keV	↔
X03MA	ADRESS	ARPES, RIXS	UE44	0.4 – 1.8 keV	↔↕↻↺
X04SA	MS	PD, SD, XTM	W61	5 – 40 keV	↔
X04DB	VUV		bend	5 – 30 eV	↔
X05LA	μXAS/FEMTO	XAS	U19	5.7– 19.5 keV	↔
X06SA	PX-II		U19	5.7 – 17.5 keV	↔
X06DA	PX-III		superbend	6 – 17.5 keV	↔
X07MA	LUCIA	XAS	UE54	0.8 – 8 keV	↔↻↺
X07DA	PolLux	STXM	bend	0.2 – 1.2 keV	↔↻↺
X09LA	SIS/XIL	HR-PES, XES / EUV-IL	2xUE212	10 – 800 eV	↔↕↻↺
X10SA	PX-II		U19	6.5 – 20 keV	↔
X10DA	superXAS	XAS	superbend	5 – 35 keV	↔
X11MA	SIM	PEEM, XCD	2xUE56	90 eV – 2 keV	↔↕↻↺
X12SA	cSAXS	cSAXS	U19	5.5 – 19.5 keV	↔

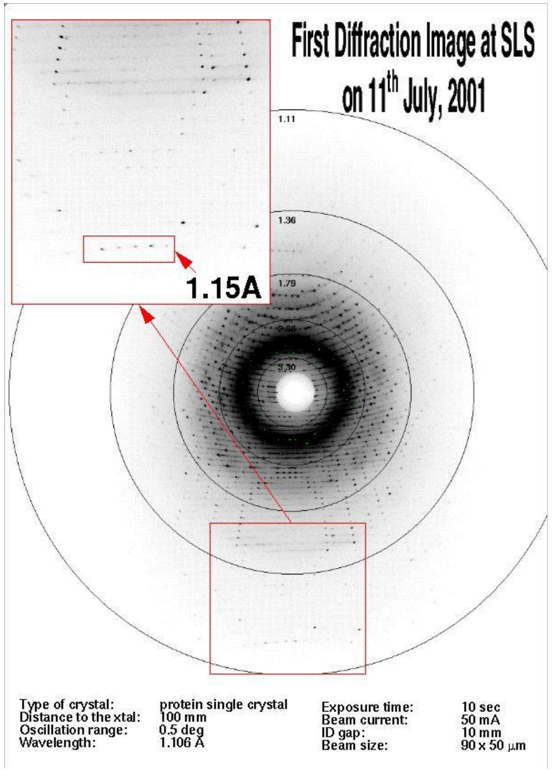
Beamline acronyms	
ADRESS	Advanced resonant spectroscopies
FEMTO	(Femto-second laser beam slicing for sub-ps X-ray pulses)
LUCIA	Line for ultimate characterisations by imaging and absorption
MS	Materials sciences
PX	protein crystallography
SIM	Surfaces and interfaces microscopy
SIS	Surfaces and interfaces spectroscopy
TOMCAT	Tomographic microscopy and coherent radiology experiments
VUV	Vacuum ultraviolet

Method acronyms	
ARPES	Angle resolved photoelectron emission spectroscopy
cSAXS	coherent small angle X-ray scattering
EUV-IL	Extreme ultraviolet interference lithography
HR-PES	high resolution photoemission spectroscopy
IRS	Infra red spectroscopy
PEEM	photo emission electron microscopy
RIXS	resonant inelastic X-ray scattering
STXM	Scanning transmission X-ray micro-spectroscopy
XAS	X-ray absorption spectroscopy
XCD	X-ray magnetic circular dichroism
XES	X-ray emission spectroscopy
XIL	X-ray interference lithography
XTM	X-ray tomography

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: budget

in **MCHF** (costs < 2002)

Total Project Budget	**159**	(no salaries included)
Building	**63**	("turn key", incl. infrastructure)
Accelerators	planned	spent
General	**12**	**11**
Linac	**6**	**6**
Booster	**12**	**11**
Storage Ring	**42**	**40**
total	**96**	**92**
4 initial beam lines	**24**	**28**

4 (shifted from accelerators to beam lines)

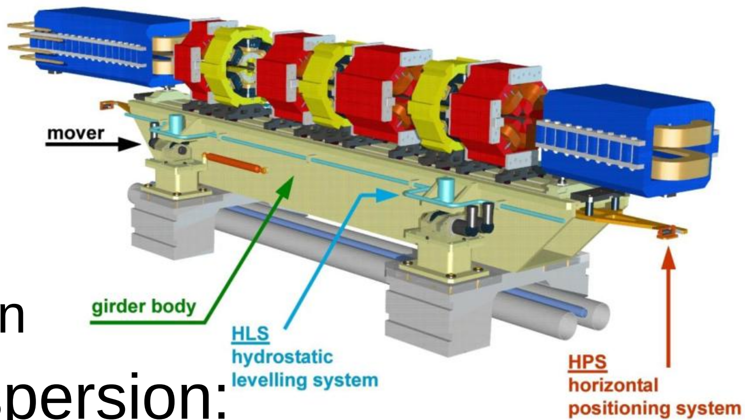
+ SLS related PSI budget ~ 90

Achievements: beam stability

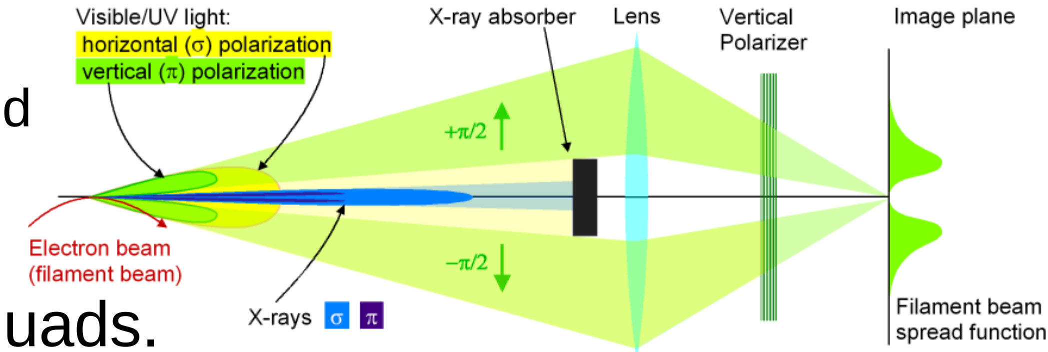
- Top up operation: thermal stability
- Beam position monitors: resolution $< 0.3\ \mu m$
- Digital power supplies:
  stability and reproducibility < 30 ppm
- Frequent beam based BPM calibration
  (“beam based alignment”)
- Undulator feed forward tables
- Fast orbit feedback system (< 100 Hz)
- Photon-BPM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

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

Achievements: optics corrections

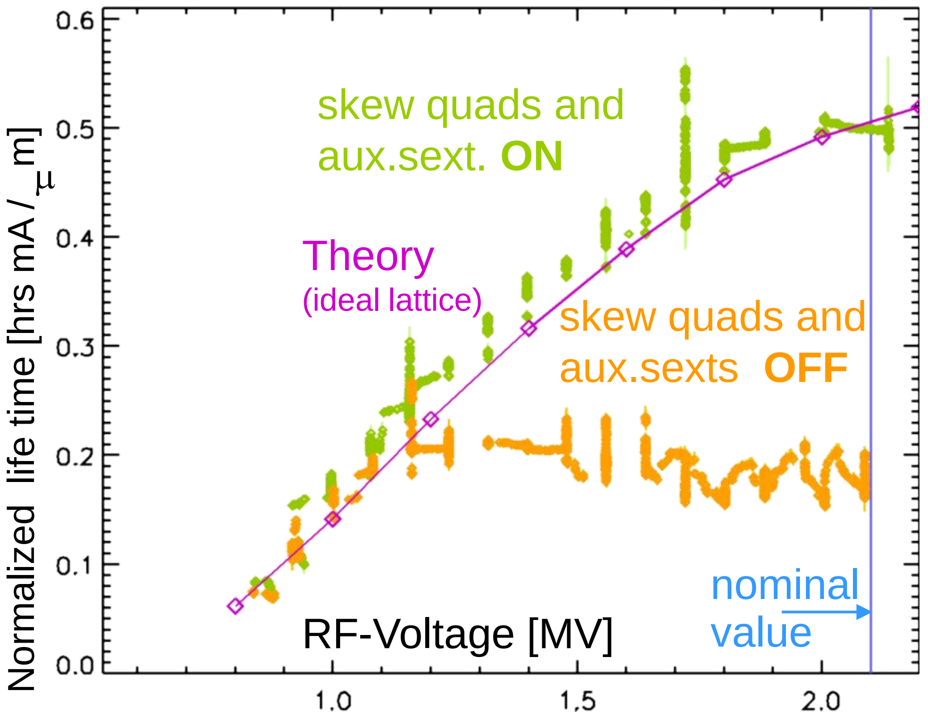
- correction of beta functions tuning 177 quadrupoles

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

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

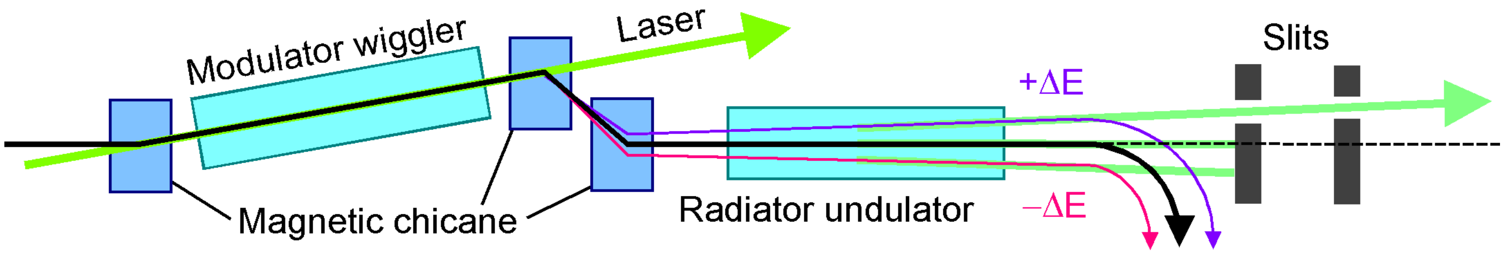
⇨ momentum acceptance (=momentum dependent dynamic aperture) restored.

⇨ beam lifetime in agreement with design calculations.



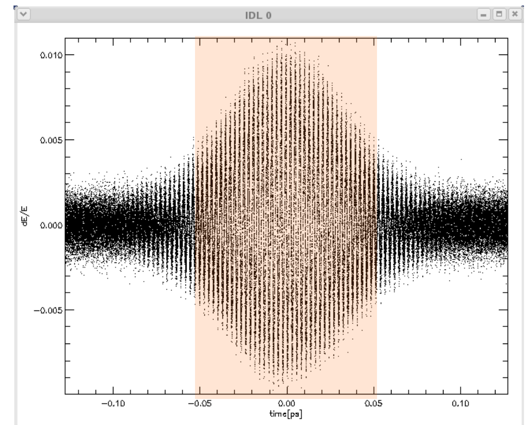
Measured beam lifetime (normalized to σ_y and bunch current) as a function of RF voltage

Achievements: FEMTO



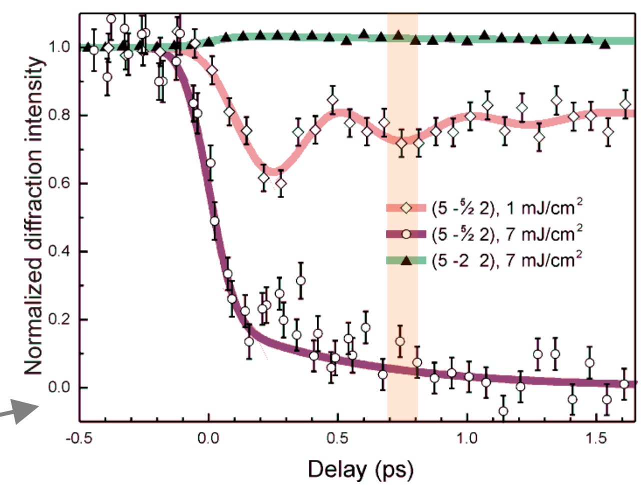
Tunable sub-picosecond X-ray source

- 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



100 fs

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



Summary and outlook

- 12 years of positive experience with SLS
  - Experimental program
  - Accelerator operation
  - World records: stability and vertical emittance
  - Femto: unique source of sub-ps X-rays
- Complementary: SLS ⇔ SwissFEL
  - FEL: few beam lines, very high peak brightness
  - Storage ring: many beam lines, excellent stability
- Future storage ring based light sources
  - factor 10..100 lower horizontal emittance

  ⇨ major SLS upgrade > 2020 ?