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
- Upgrade plans
- Summary & outlook

JUAS visit to PSI, Feb. 27-28, 2014

Materials research: particles

Neutral particles

penetrating matter

(no Coulomb interaction)

→ diffraction experiments

⇨ **neutrons**

⇨ **SINQ**

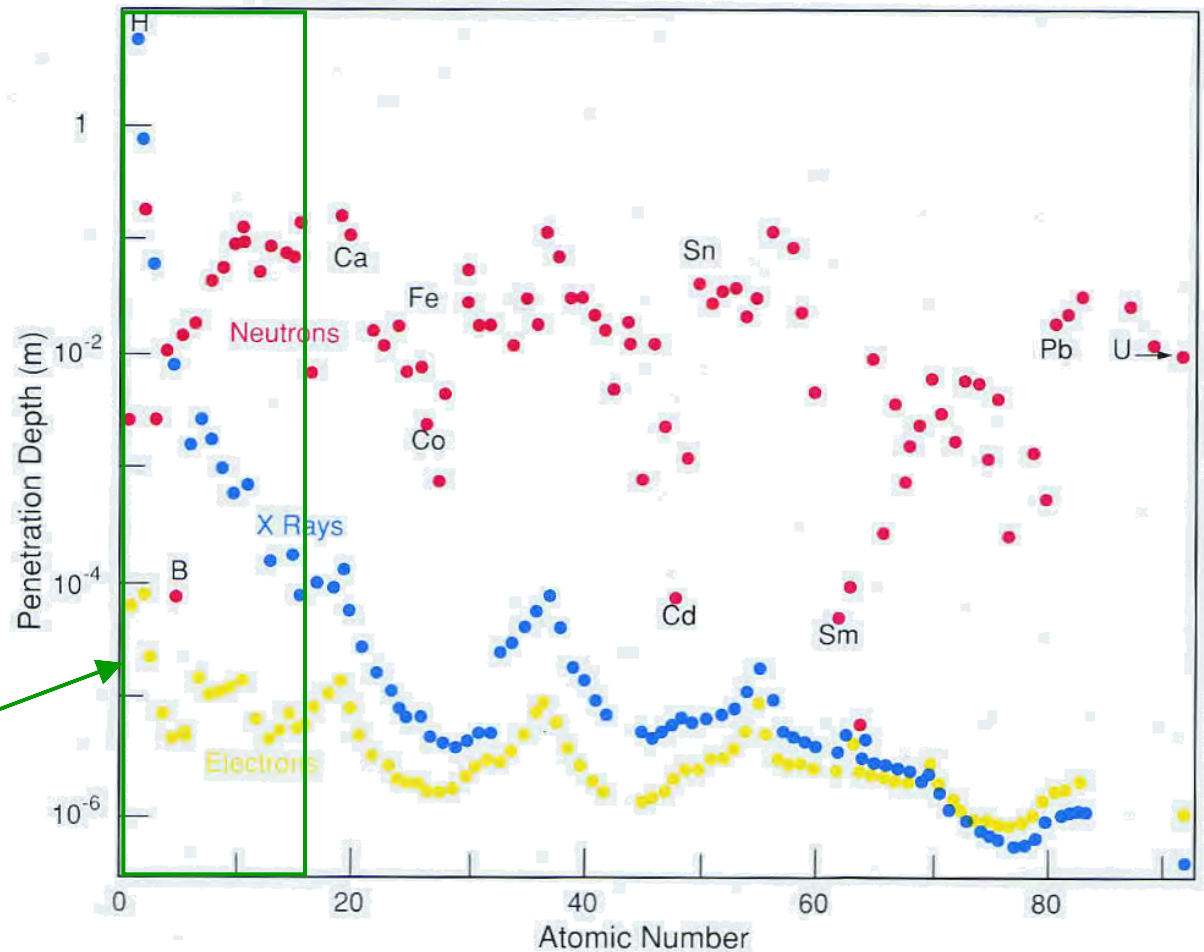
⇨ **photons**

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

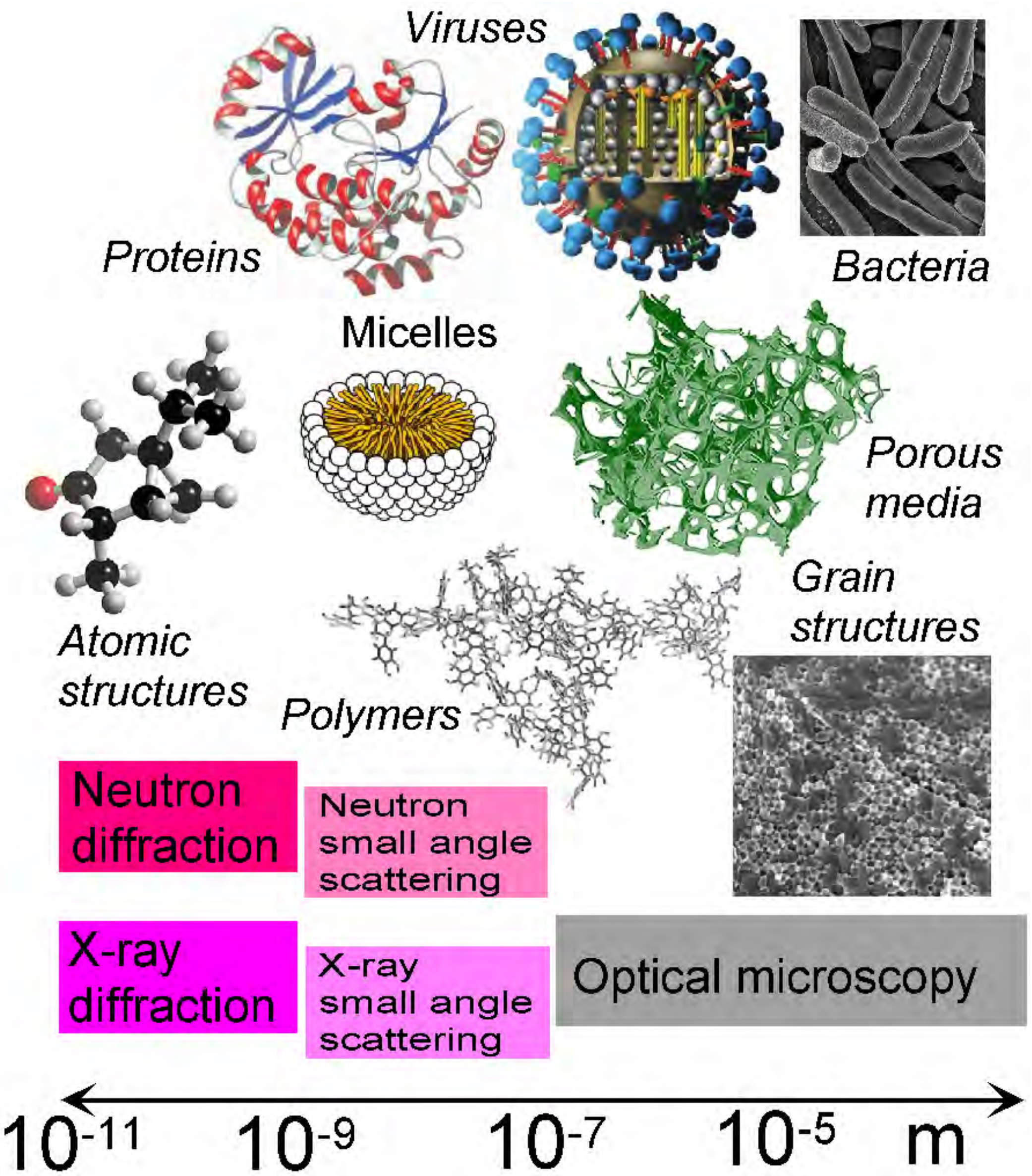


Figure based on Roger Pynn, *Neutron scattering - a primer,* Los Alamos neutron scattering center, 1989 ➚

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

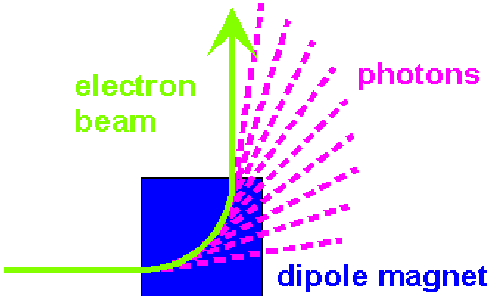
- figure of merit: ***Brightness***

= 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: $\dfrac{\text{photons}}{\mathrm{s\,mm^2 mrad^2 BW}}$

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

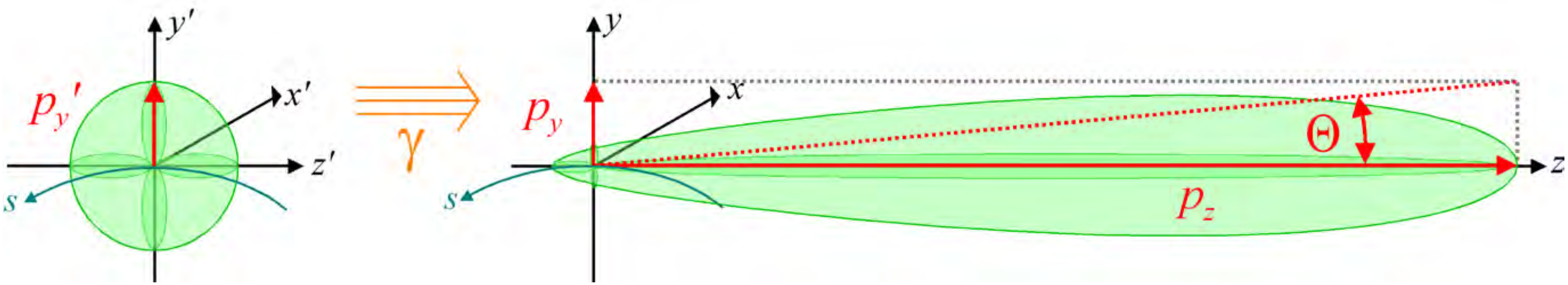
$$P[\mathrm{kW}] = 88.5\,\mathrm{kW} \times I_{beam}[\mathrm{A}] \frac{(E\,[\mathrm{GeV}])^4}{R\,[\mathrm{m}]}$$

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

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

Synchrotron radiation: collimation

- Lorentz transformation to laboratory system

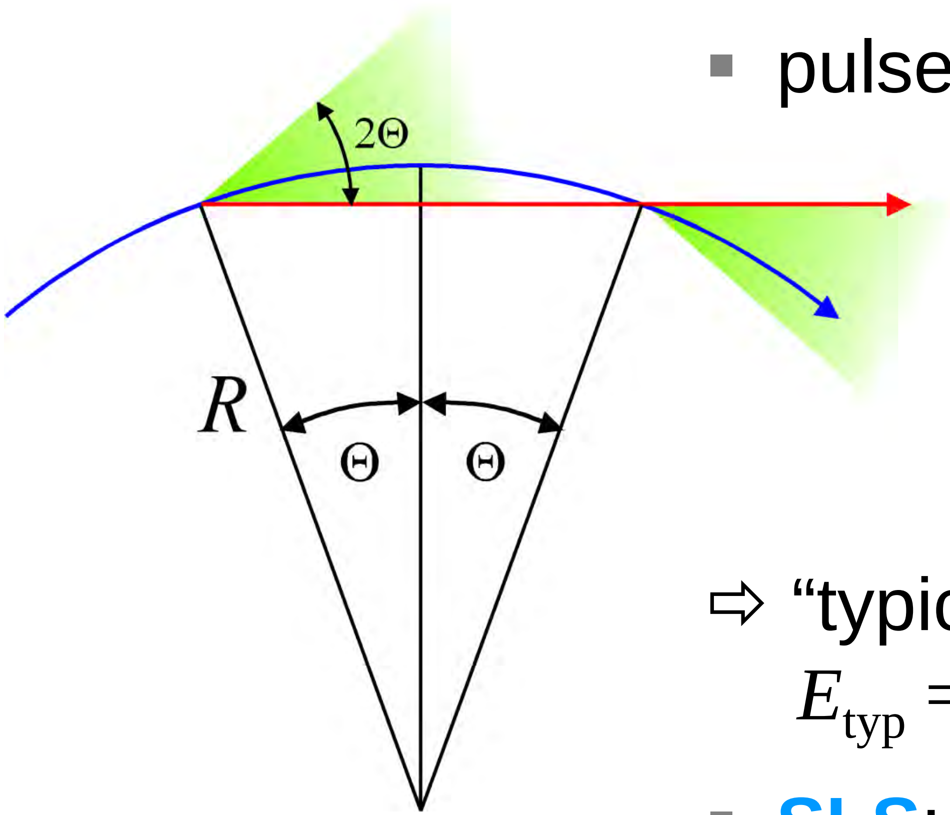


$p_y' = E'/c \quad p_z' = 0$ $\qquad$ $p_y = p_y' \quad p_z = \gamma E'/c = \gamma p_y$

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

  ⇨ beam spot ∅ 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

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

- **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

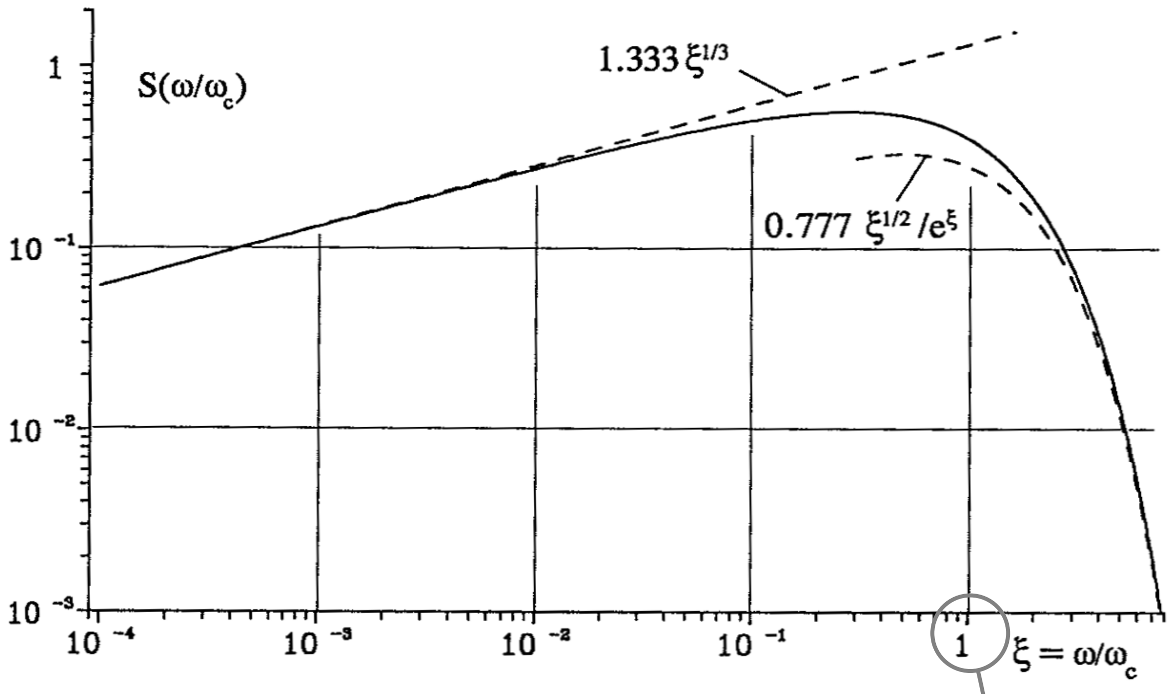
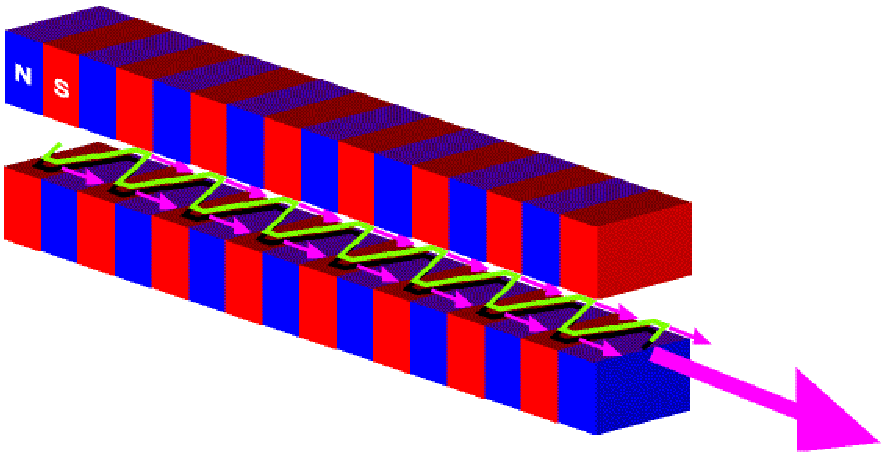


Fig. 7.12. Universal function: $S(\omega/\omega_c) = \frac{9\sqrt{3}}{8\pi}\frac{\omega}{\omega_c}\int_{\omega/\omega_c}^{\infty} K_{5/3}(x)\,dx$

- 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$)$

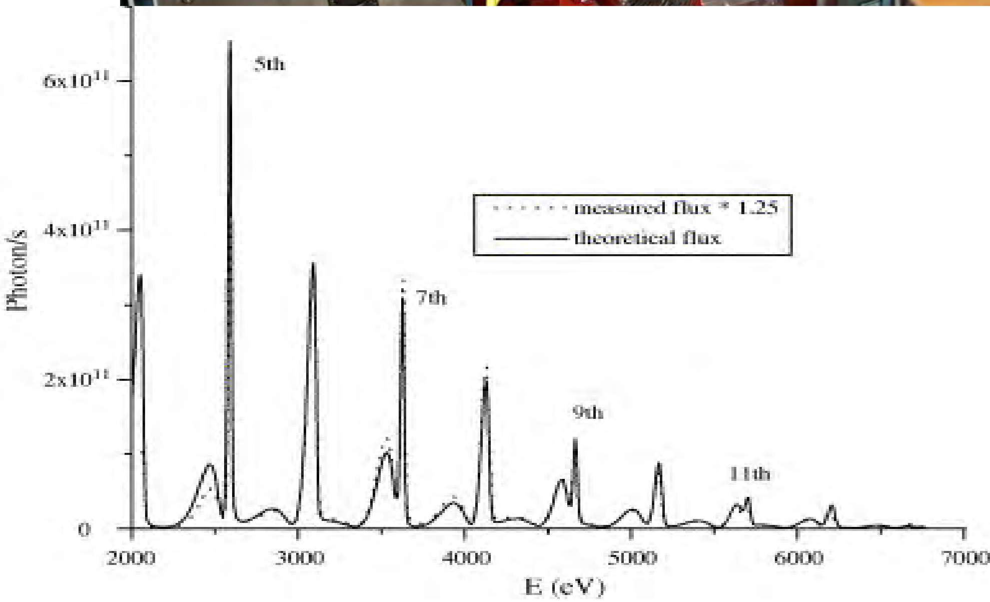


- many small dipoles
  N ~ 20...100 periods
- angle/pole < $1/\gamma$
  ($1/\gamma$ = radiation opening angle)

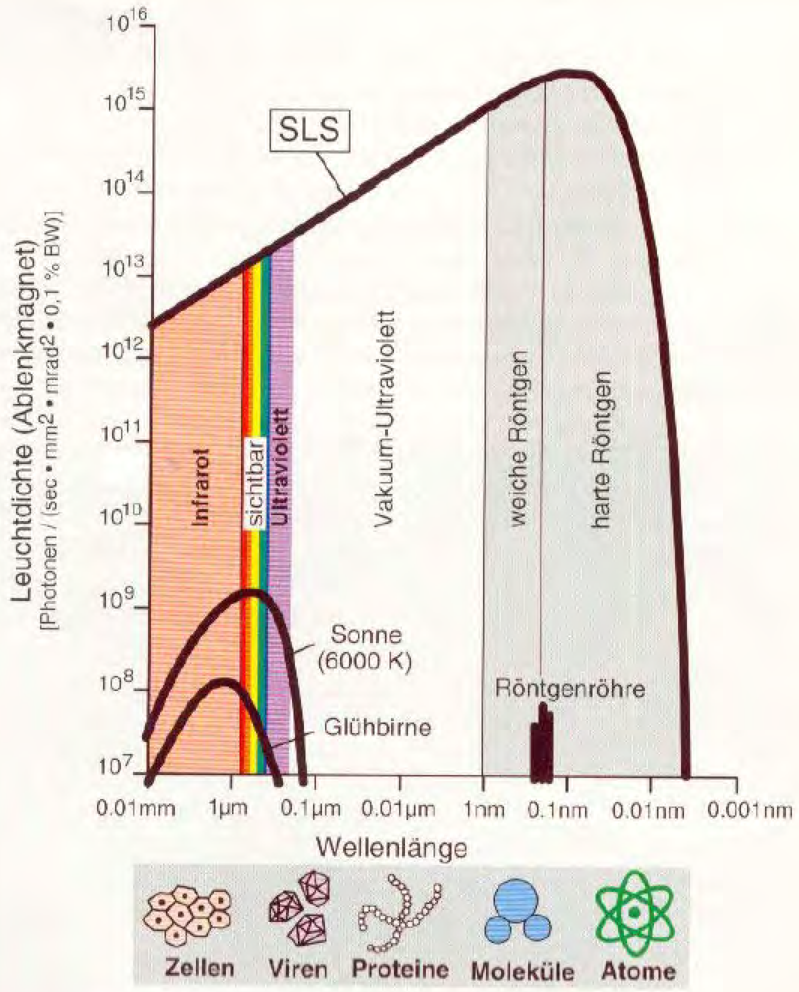
⇨ interference

⇨ line spectrum

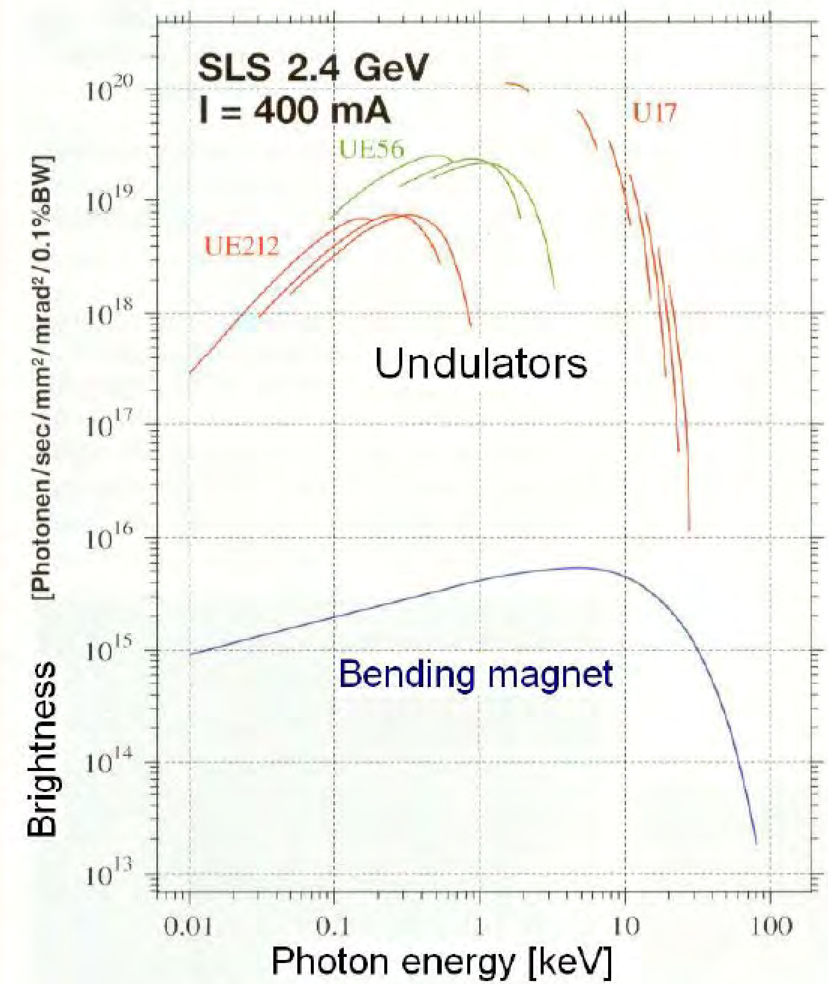
SLS UE54 undulator →



Synchtron radiation: undulator brightness



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



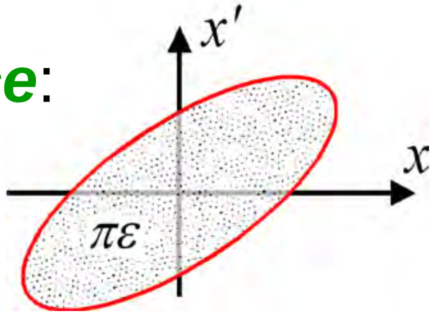
Undulator brightness in comparison to bending magnet brightness

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: $\mathrm{mm{\cdot}mrad}$, $\mathrm{nm{\cdot}rad}$, $\mathrm{pm{\cdot}rad}$
- **SLS** emittances : $\varepsilon_x = 5.5$ nm , $\varepsilon_y \sim 1...10$ pm

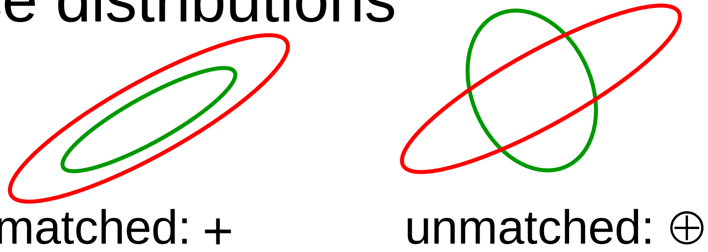
ε_r (E) *diffraction* emittance: $\varepsilon_r \approx \lambda/4\pi$ $(\lambda = hc/E)$

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

vertically diffraction limited source

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

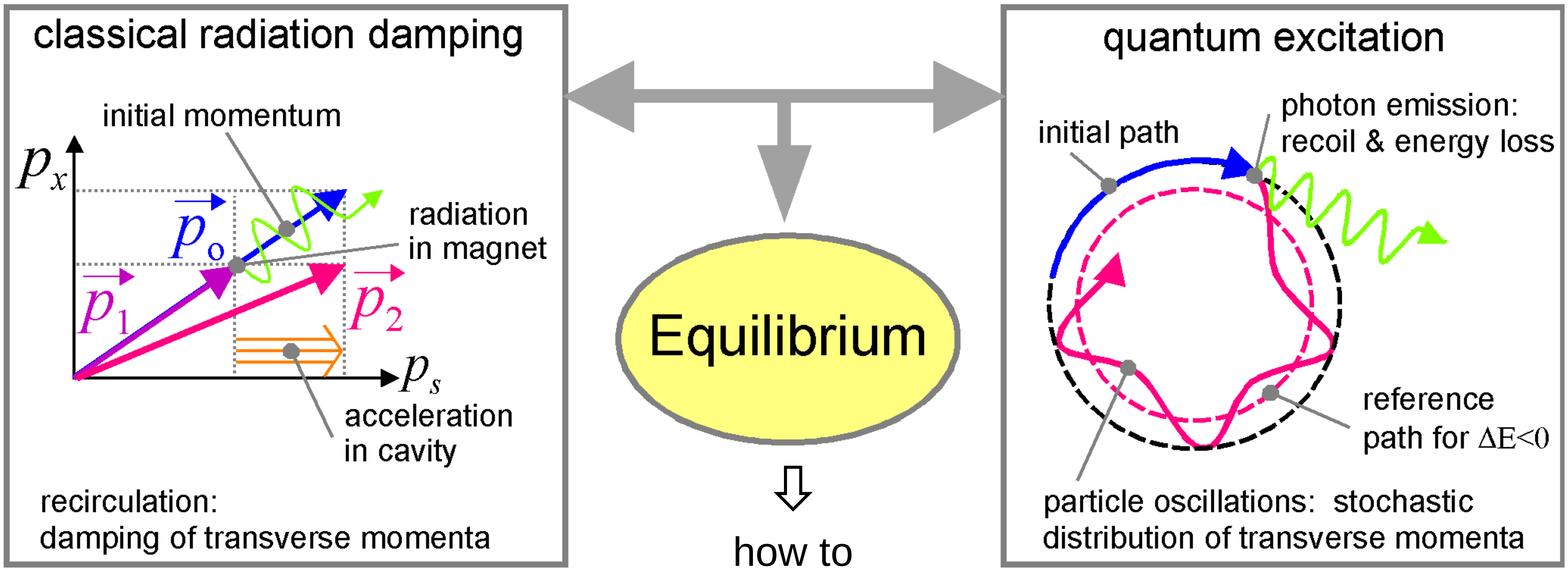
- *matched* distributions: $\oplus$ ⇨ $+$
  (same aspect ratio and tilt)



Horizontal emittance in electron storage ring:

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

independent from initial conditions !



⇧ maximize this -- and -- minimize this ⇧

?

Storage ring: low emittance lattice

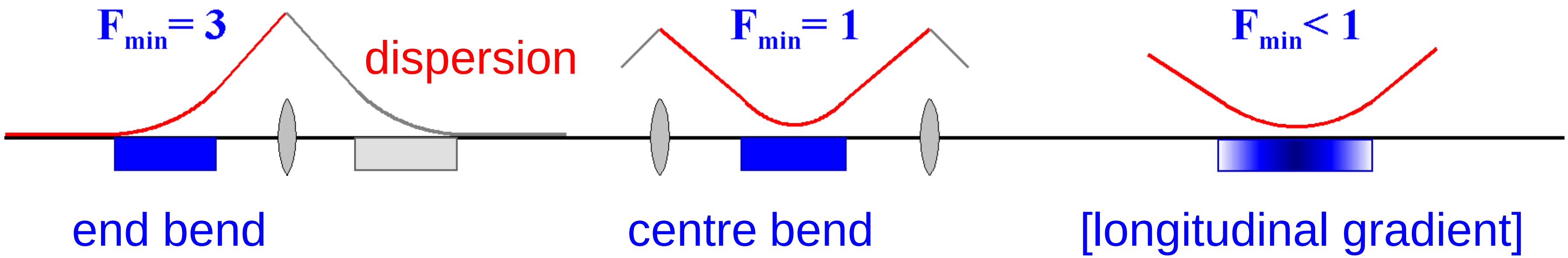
Beam energy
Deflection angle *per* dipole
Beam optics...

Minimum emittance

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

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

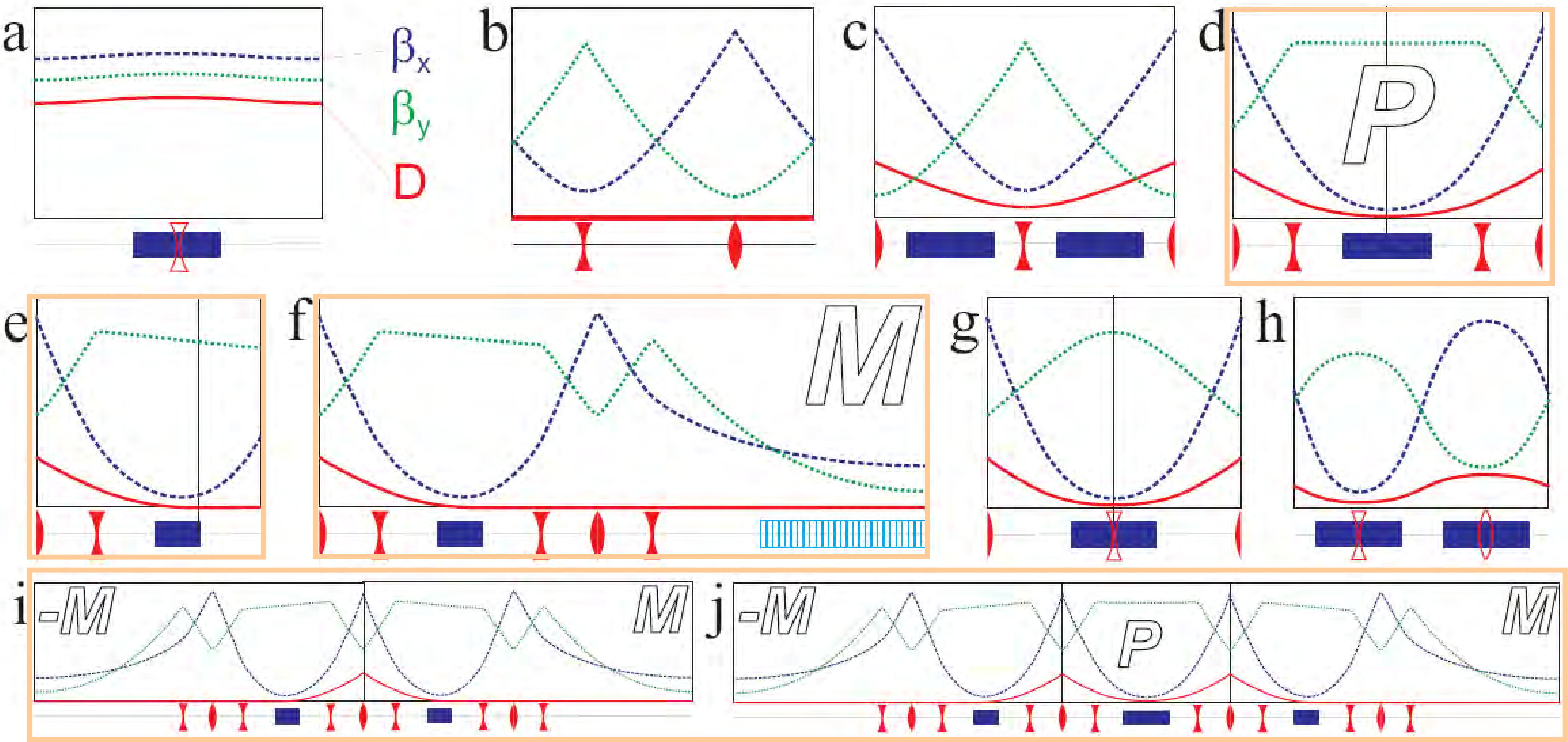
⇨ focus to magnet center: $F \approx 2..5 \times F_{min}$



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...



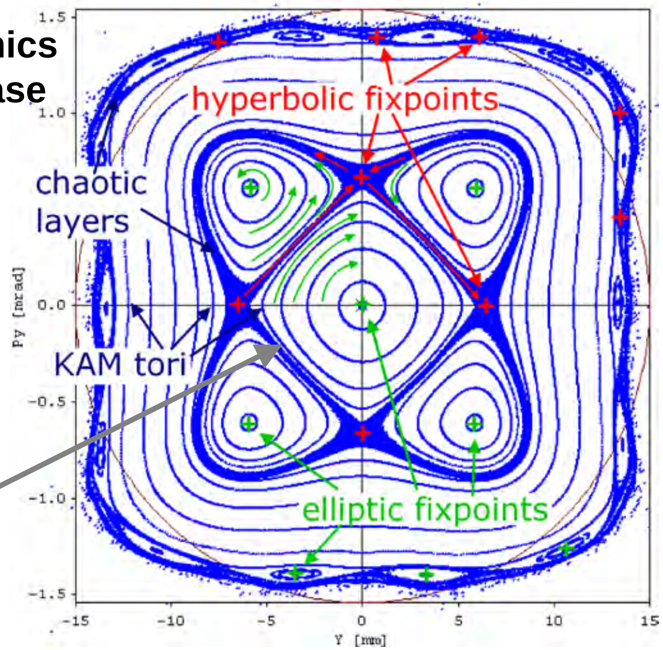
β_z = "beta function" = normalized beam size = σ_z^2/ε_z (z = x;y)

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 $= 0.20$ pm

⇨ ultimate limit of vertical emittance

Coupling emittance

- Magnet misalignments and imperfections:
  displacements and rotations

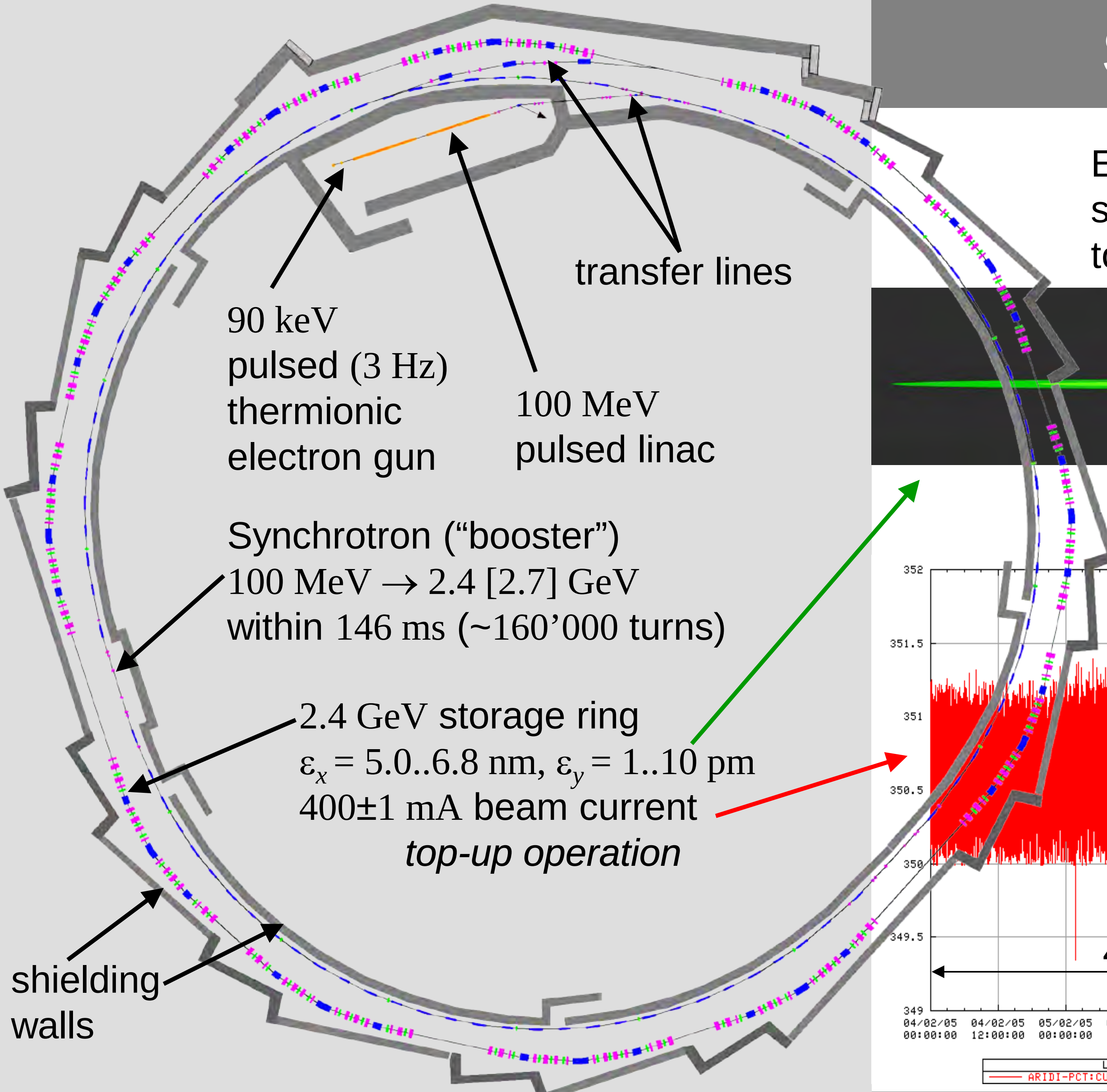
⇨ spurious vertical dispersion: vertical quantum excitation

⇨ betatron coupling: horizontal oscillation ⇨ vertical oscillation

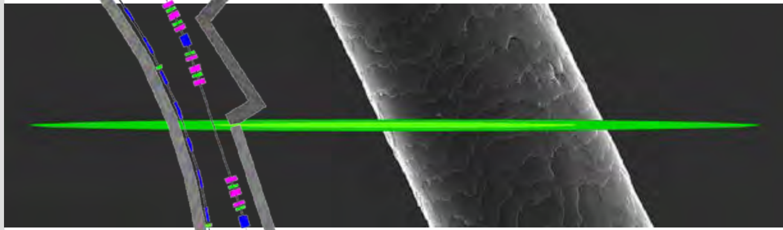
Vertical equilibrium emittance

- usually: coupling emittance >> quantum emittance

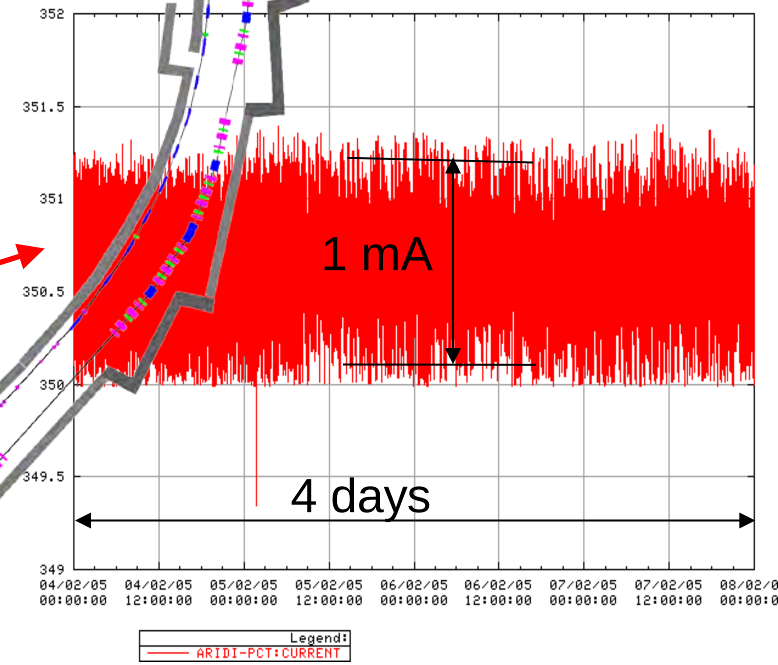
SLS: layout



Electron beam cross section in comparison to human hair



Current vs. time



SLS: storage ring lattice

12 TBA:

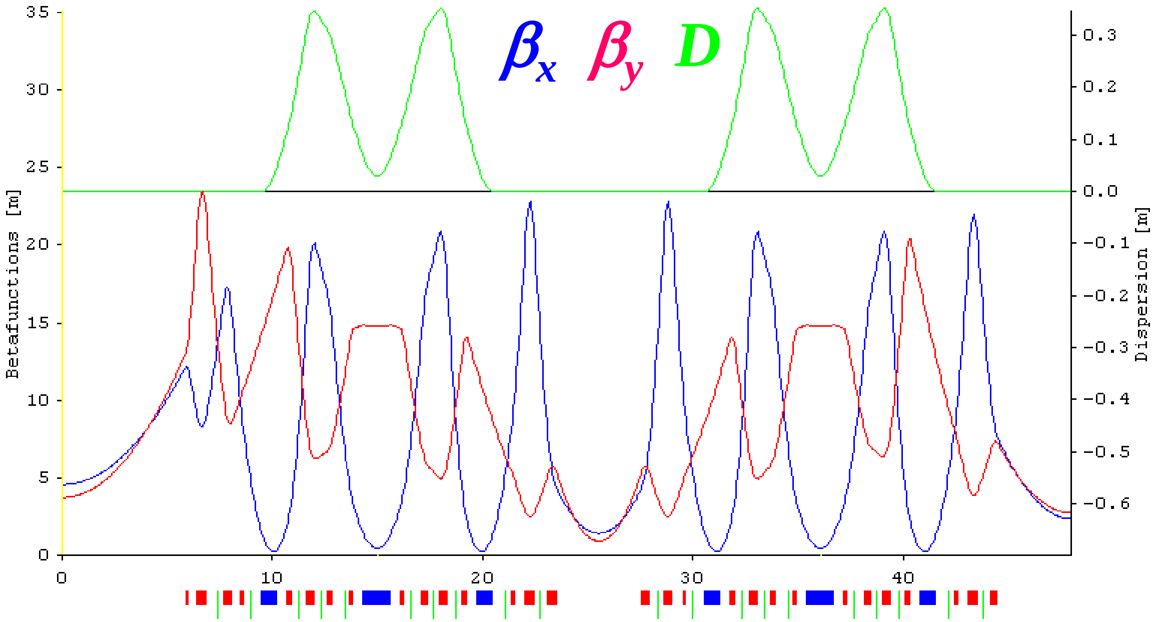
8°/14°/8°

12 straights:

3 x 11.5 m

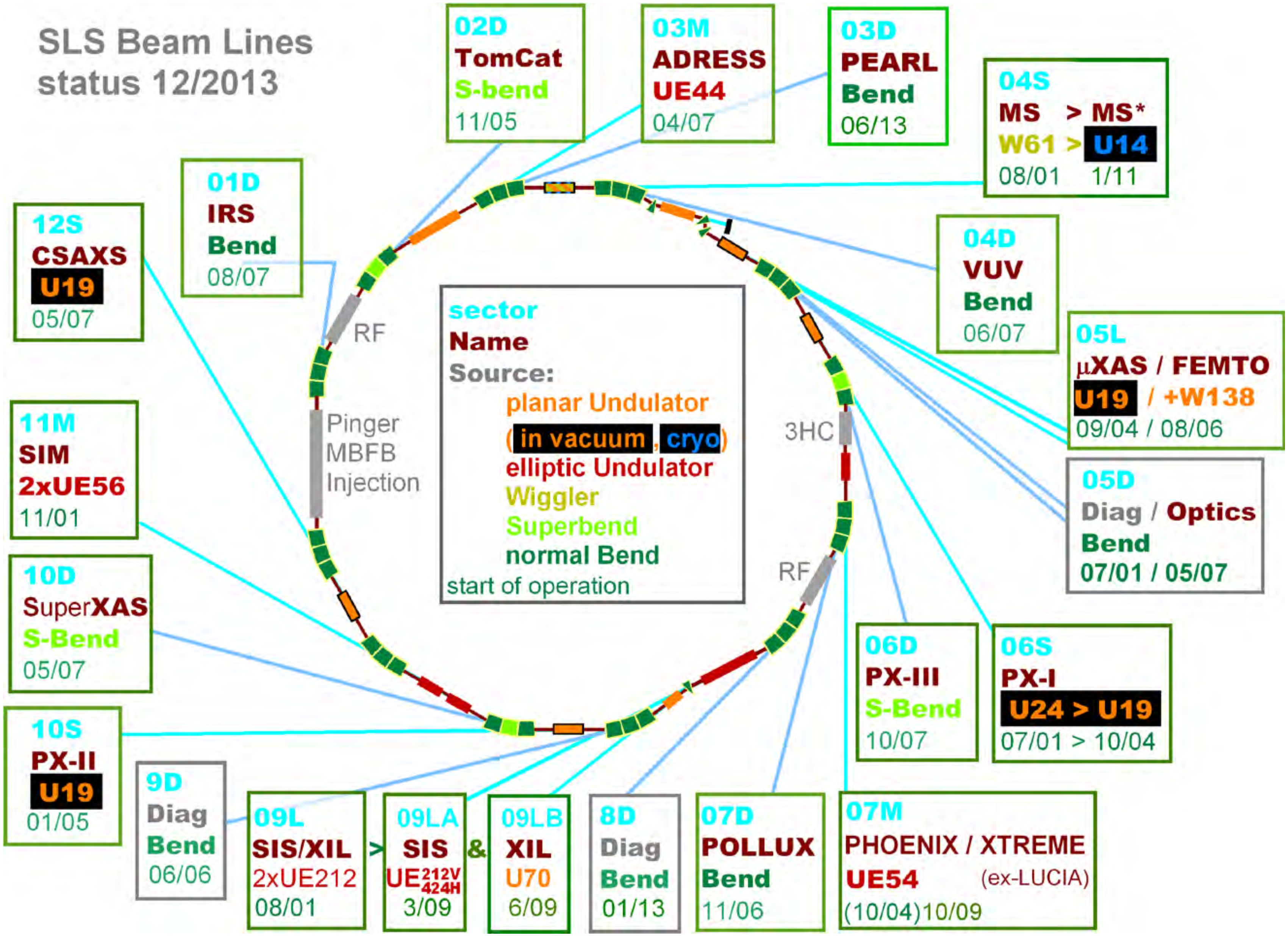
3 x 7.0 m

6 x 4.0 m



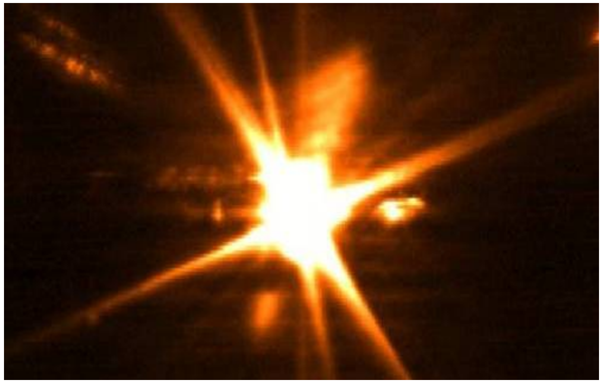
Energy	**2.4 GeV**		Mom. compaction	**$6.3 \cdot 10^{-4}$**
Emittance	**5 nm rad**		Radiation loss	**512 keV**
Circumference	**288 m**		Damping times	**9 / 9 / 4.5 ms**
Radio frequency	**500 MHz**		Energy spread	**$8.9 \cdot 10^{-4}$**
Tunes	**20.41 / 8.17**		rms bunch length	**3.5 mm**
Chromaticities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

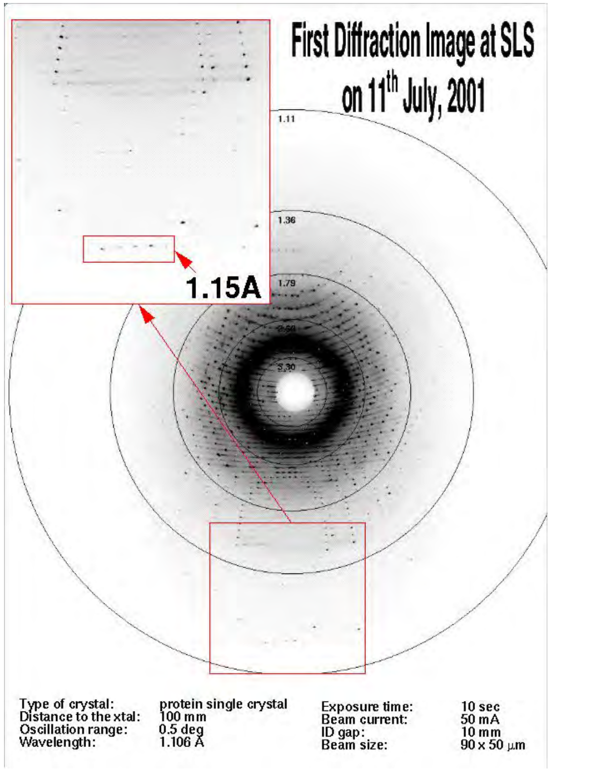
all data before FEMTO upgrade, without insertion devices and without harmonic cavities


SLS Beam Lines
status 12/2013
sector
Name
Source:
planar Undulator
(in vacuum, cryo)
elliptic Undulator
Wiggler
Superbend
normal Bend
start of operation
01D IRS Bend 08/07
02D TomCat S-bend 11/05
03M ADRESS UE44 04/07
03D PEARL Bend 06/13
04S MS > MS* W61 > U14 08/01 1/11
04D VUV Bend 06/07
05L µXAS / FEMTO U19 / +W138 09/04 / 08/06
05D Diag / Optics Bend 07/01 / 05/07
06D PX-III S-Bend 10/07
06S PX-I U24 > U19 07/01 > 10/04
07M PHOENIX / XTREME UE54 (ex-LUCIA) (10/04)10/09
07D POLLUX Bend 11/06
8D Diag Bend 01/13
09LB XIL U70 6/09
09LA SIS UE212V 424H 3/09
&
>
09L SIS/XIL 2xUE212 08/01
9D Diag Bend 06/06
10S PX-II U19 01/05
10D SuperXAS S-Bend 05/07
11M SIM 2xUE56 11/01
12S CSAXS U19 05/07
RF
Pinger
MBFB
Injection
3HC
RF

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



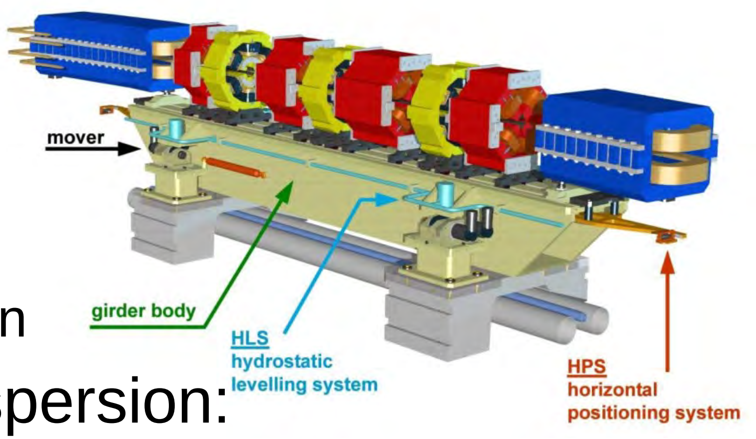


Achievements: beam stability

- Top up operation: thermal stability
- Beam position monitors: resolution $< 0.3\ \mu\text{m}$
- 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 $<1\ \mu\text{m}$ rms (at frontends)

Achievements: ultra-low vertical emittance



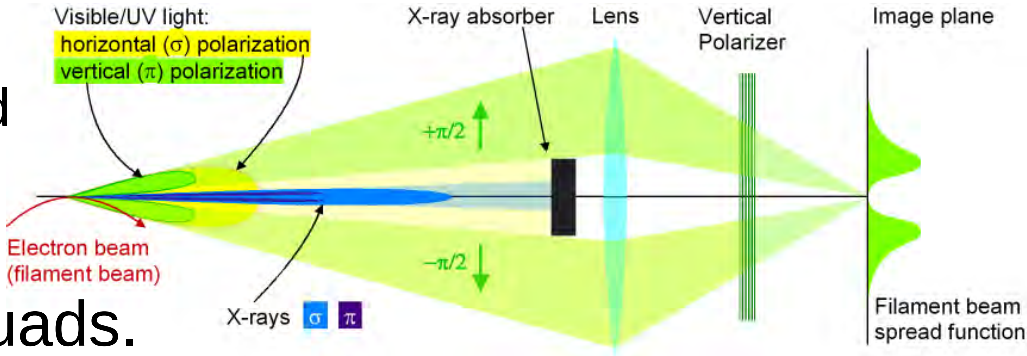
- Dynamic girder alignment system

⇨ 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

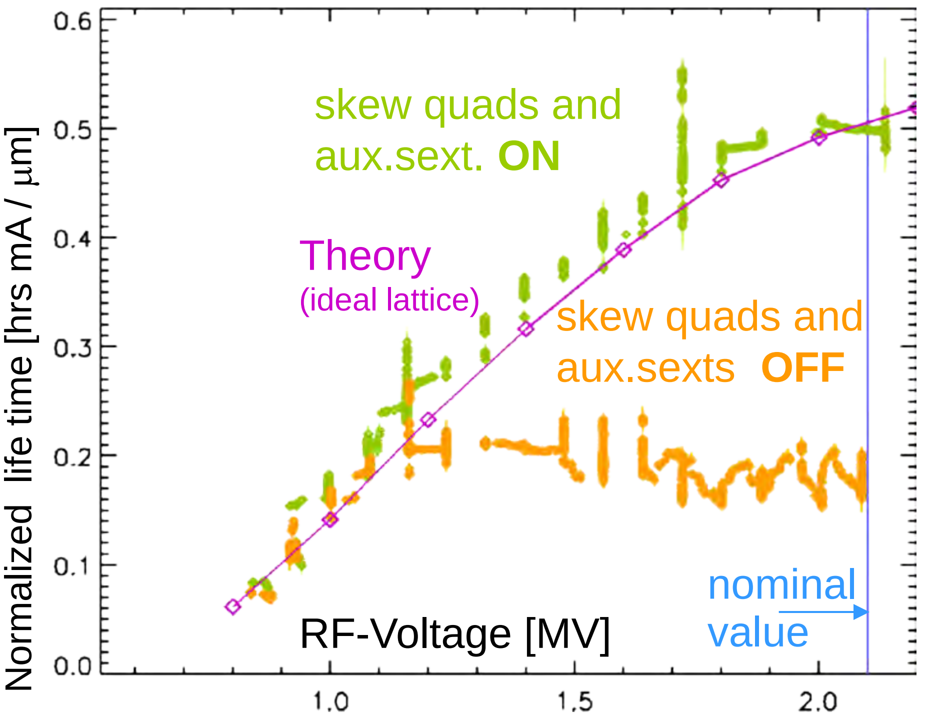
- correction of beta functions tuning 177 quadrupoles

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

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

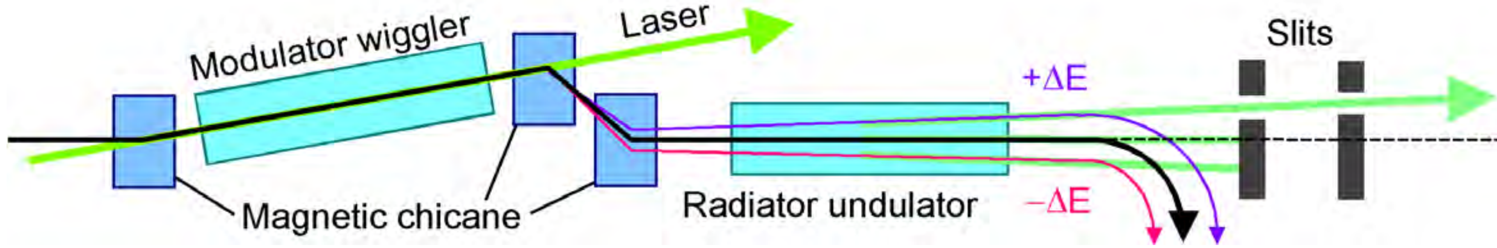
⇨ momentum acceptance (=momentum dependent dynamic aperture) restored.

⇨ beam lifetime in agreement with design calculations.



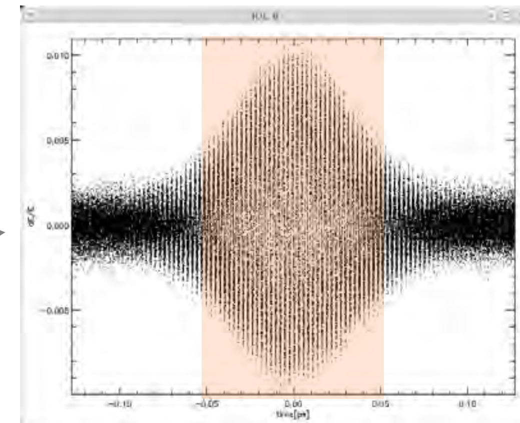
Measured beam lifetime (normalized to σ_y and bunch current) as a function of RF voltage

Achievements: FEMTO



Tunable sub-picosecond X-ray source

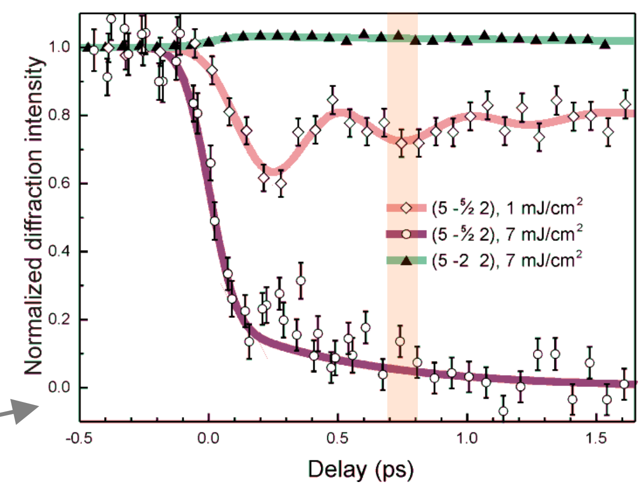
- 50 fs FWHM high power laser
- Modulator wiggler
  - energy modulation in thin slice of bunch
- Magnetic chicane
  - translation of modulation to horizontal separation
- Radiator undulator
  - source of X-ray synchrotron radiation
- Beam line optics (slits & toroid)
  - extraction of radiation from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



100 fs

$\Rightarrow$ 150 fs FWHM X-ray pulses

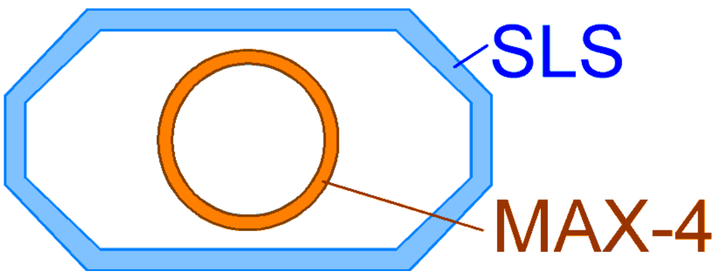
- low flux, but high stability
- time resolved sub-ps X-ray experiments

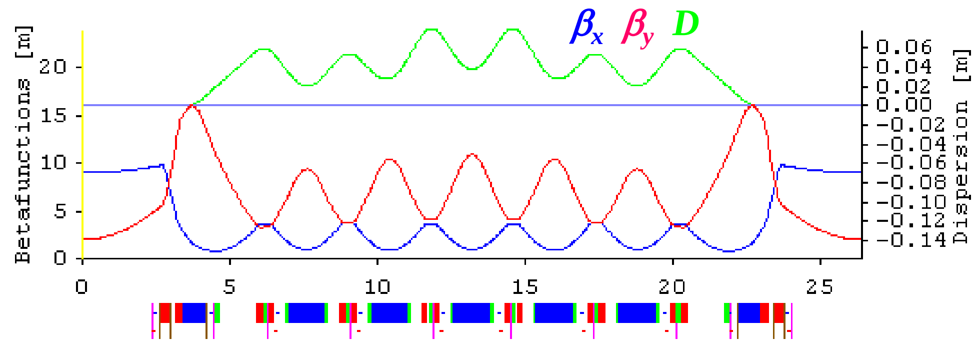


SLS upgrade: a new generation of rings

Pioneer work: MAX IV (Lund, Sweden)

Aperture reduction ⟷ **Multi-Bend Achromat**





Small magnet bore:
high gradient → short & strong multipoles

⇨ short lattice cells

⇨ many lattice cells

⇨ low angle per bend

Narrow beam pipe:
pumping by distributed getter metal (NEG)

Emittance ~ (bend angle)^3

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

SLS upgrade: new light sources

> 2020 : SLS no longer competitive !

Machines under construction

NSLS-II	2.0 nm (→ 600 pm with DW [damping wiggler]) @ 3 GeV, 2014
MAX-IV	**340 pm** (→ 170 pm with DW) **@ 3 GeV, 2015**
SIRIUS	**280 pm @ 3 GeV, 2016**

Light source lattice upgrade plans, keeping tunnel and beam lines

ESRF	4.0 nm @ 6 GeV	→ 160 pm (2019 ?)
Spring-8	3.4 nm @ 8 GeV	→ 68 pm @ 6 GeV (2020 ?)
APS	3.1 nm @ 7 GeV	→ 60 pm @ 6 GeV (2020 ?)
ALS	2.0 nm @ 1.9 GeV	→ 52* pm @ 2 GeV (2020 ?)
SLS	**5.0 nm @ 2.4 GeV**	**→ 100 pm @ 2.4 GeV ?**

Re-use of HEP machines, keep tunnel and parts of old lattice

PETRA-III	→ 1 nm (with DW) @ 6 GeV, 2008 ✓
PEP-X USR	→ 29 pm (→ 11 pm with DW) @ 4.5 GeV
Tevatron-USR	→ 3* pm @ 9 GeV

*fully coupled: $\varepsilon_y = \varepsilon_x$

SLS-2 upgrade: concept

Constraints

- keep building, tunnel and injector complex
  - challenge: relatively small circumference of only 288 m
- keep all beam lines (undulators and dipoles)

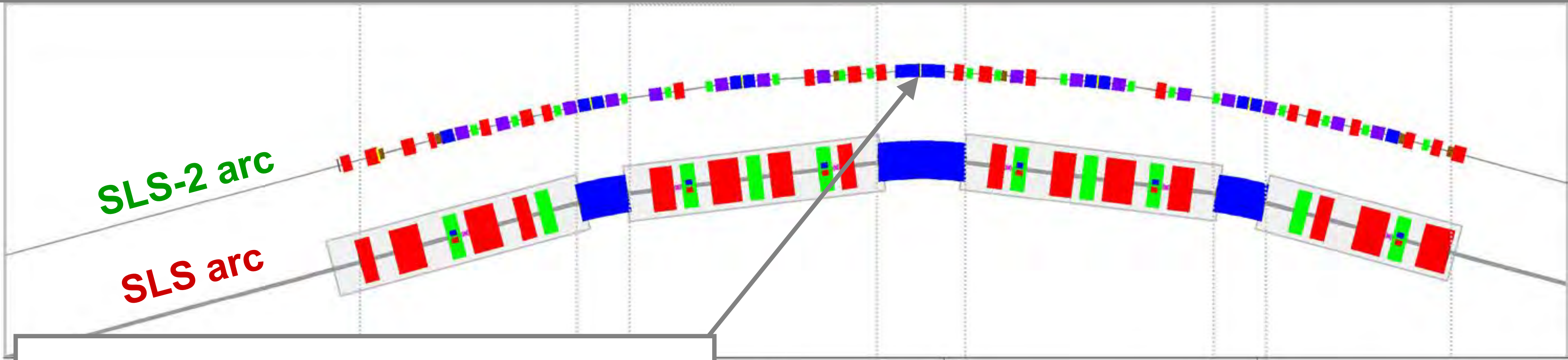
Concept

- use longitudinal gradient superbends
  - field variation $B_y(s) \rightarrow$ low emittance
  - hard X-rays for users: 6T peak field $\rightarrow$ $40\text{-}100\ \text{keV}$ photons

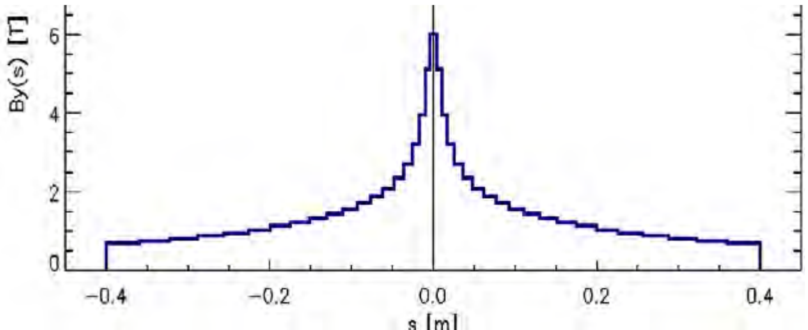
Plan

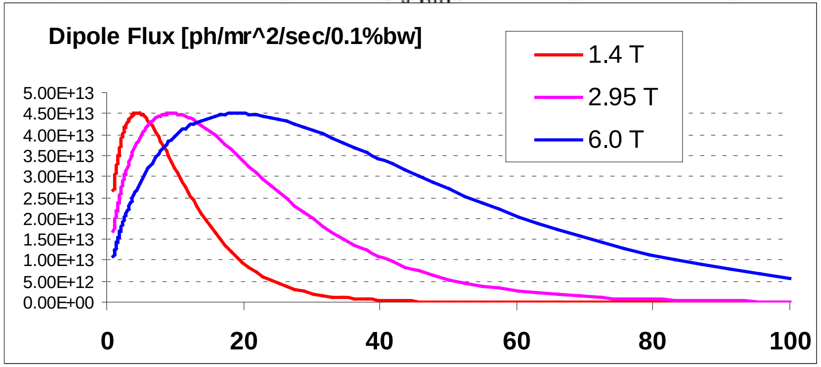
- Letter of Intent submitted to government (Jan. 2014)
  ⇨ get onto “road map” for 2021-24
- Time schedule and cost estimate:
  - 2014-17 pre-studies & conceptual design report.
  - 2017-20 detailed design report & prototypes.
  - 2021-24 construction & commissioning.

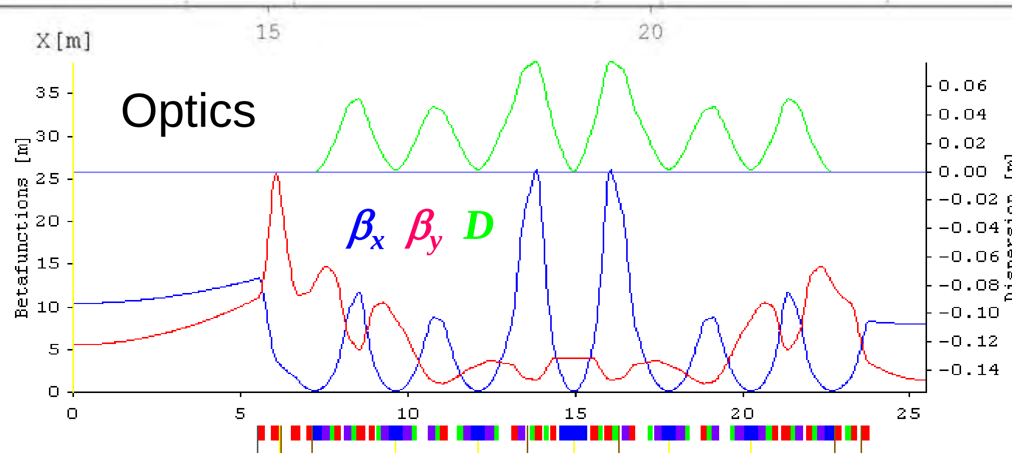
SLS-2 upgrade: draft design for $\varepsilon < 100$ pm



8º longitudinal gradient **6T**-superbend for hard X-ray flux and low emittance







Emittance reduction

5020 pm (SLS)

⇩ ⇩ ⇩ ⇩ ⇩

87 pm (SLS-2)

?

Summary and outlook

- 13 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
- Upgrade plans
  - factor 50 lower horizontal emittance ?

  ⇨ major SLS upgrade > 2020 ?

backup slides

SLS: budget

in **MCHF** (costs < 2002)

	planned	spent	
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**
4 initial beam lines	**24**	**28**	← **4**

+ SLS related PSI budget ~ 90