PAUL SCHERRER INSTITUT


WIR SCHAFFEN WISSEN – HEUTE FÜR MORGEN

Rasmus Ischebeck

Diffraction Limited Storage Rings

Joint Universities Accelerator School

Synchrotron X-Ray Sources

- 1st Generation: storage rings built for particle physics, and used parasitically for synchrotron radiation

- 2nd Generation: storage rings built for the purpose of generating synchrotron radiation

- 3rd Generation: optimized rings for low emittance; insertion devices (wigglers and undulators), top-up operation

- Generation 4a: free electron lasers
- Generation 4b: diffraction limited storage rings

Since we Have FELs, Why do we Still Need Synchrotrons?

🟦 The average brilliance in all existing FELs is low

🟢 Synchrotrons have many more beamlines than FELs

▲ Synchrotrons offer greater stability in pointing and pulse energy

★ All of the above

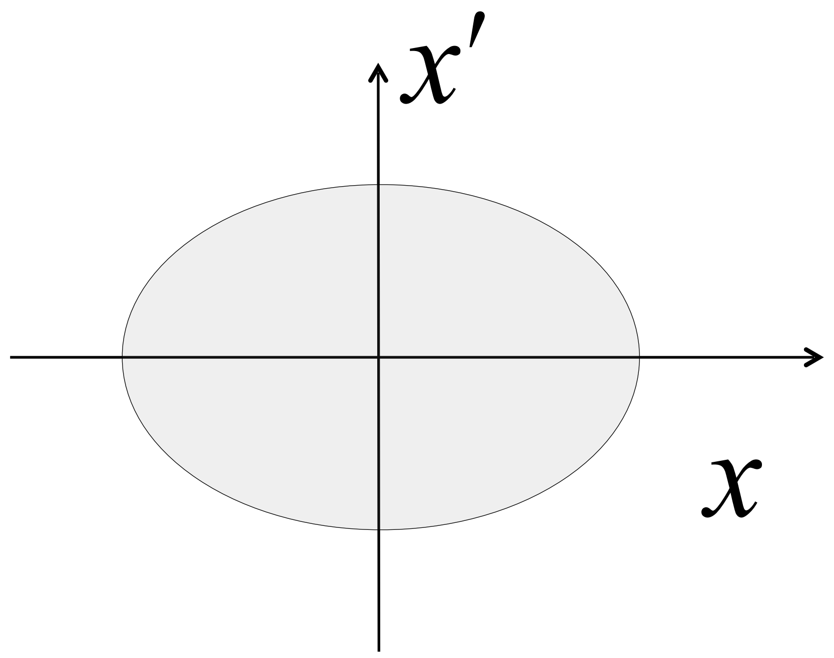
DLSR = diffraction limited storage ring

“diffraction limited” means

source (=electron beam) phase space << diffraction phase space

- ⇨ maximum brightness theoretically possible
- ⇨ full spatial coherence (point-like source)

Photon beam phase space = *convolution* of
diffraction phase space and **electron beam phase space**



2-d phase space **(no correlation, $\langle xx' \rangle = 0$)**

Area: **emittance** $\varepsilon_x = \sigma_x \cdot \sigma_{x'}$

Aspect ratio: **beta-function** $\beta_x = \sigma_x / \sigma_{x'}$

[rms] size $\sigma_x^2 = \varepsilon_x \cdot \beta_x$

[rms] divergence $\sigma_{x'}^{\ 2} = \varepsilon_x / \beta_x$

MAX-IV

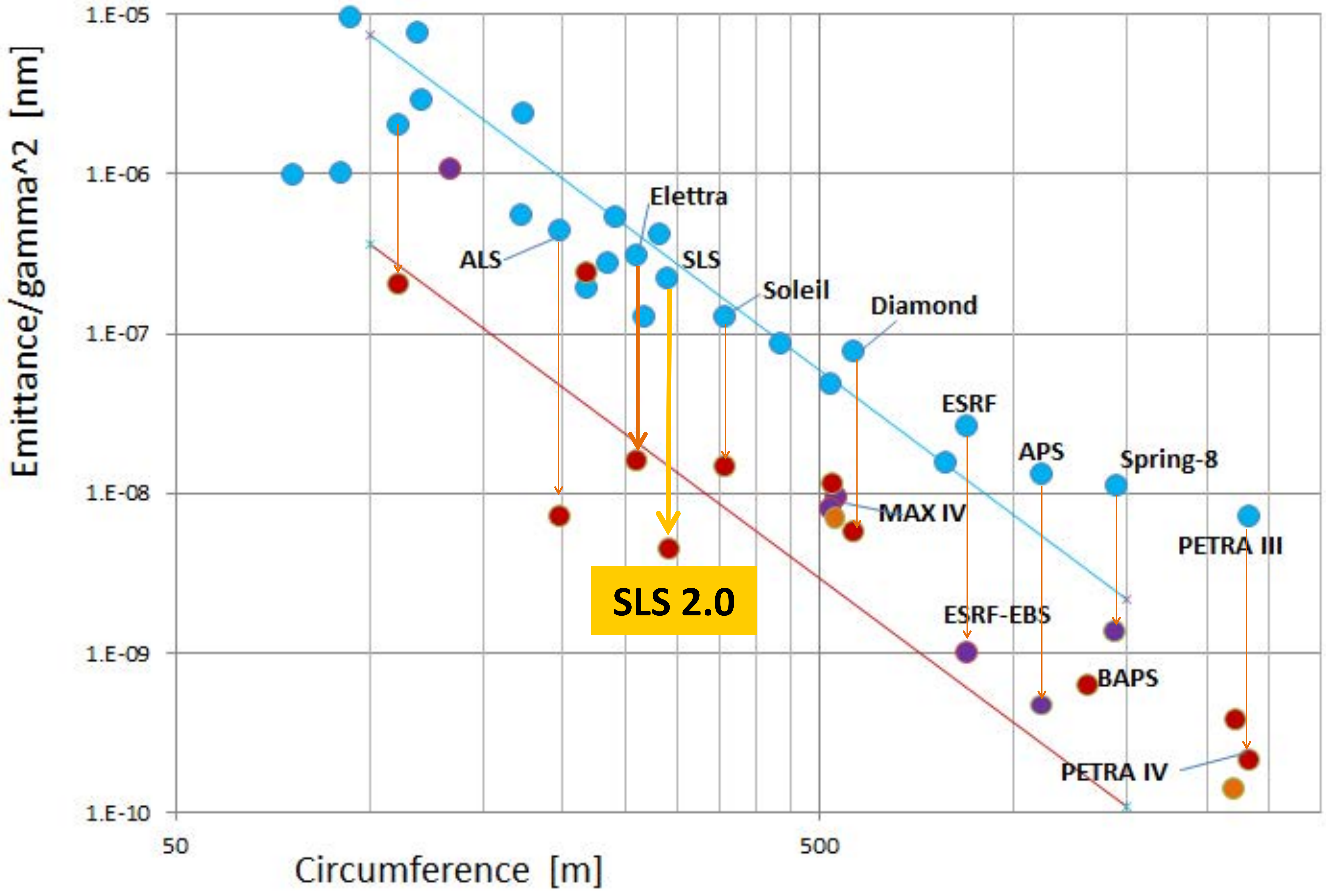
Swiss Light Source

PSI Bildarchiv

The New X-Ray Source Generation

Emittance normalized to energy vs. circumference

$\varepsilon_x \propto (\text{Energy})^2 / (\text{Circumference})^3$



Theoretical Emittance scaling

$$\varepsilon \;\propto\; \gamma^{2} C^{-3}$$

$$\ln\frac{\varepsilon}{\gamma^{2}} = K - 3\cdot\ln C$$

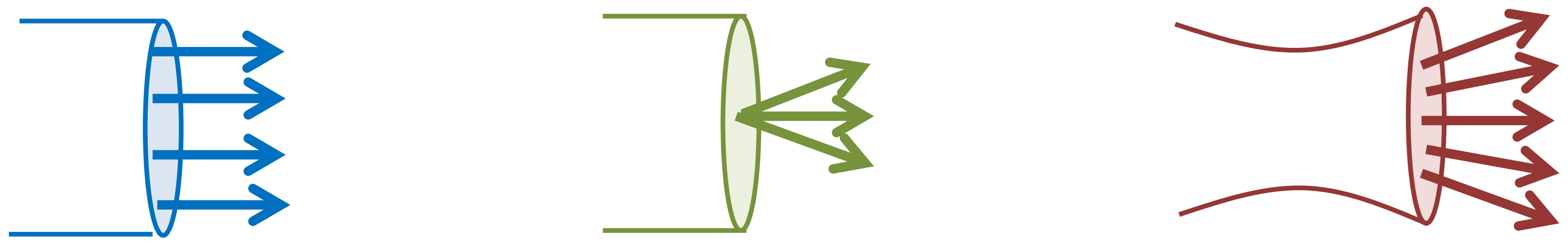
$K \approx 2 \rightarrow \approx -1$

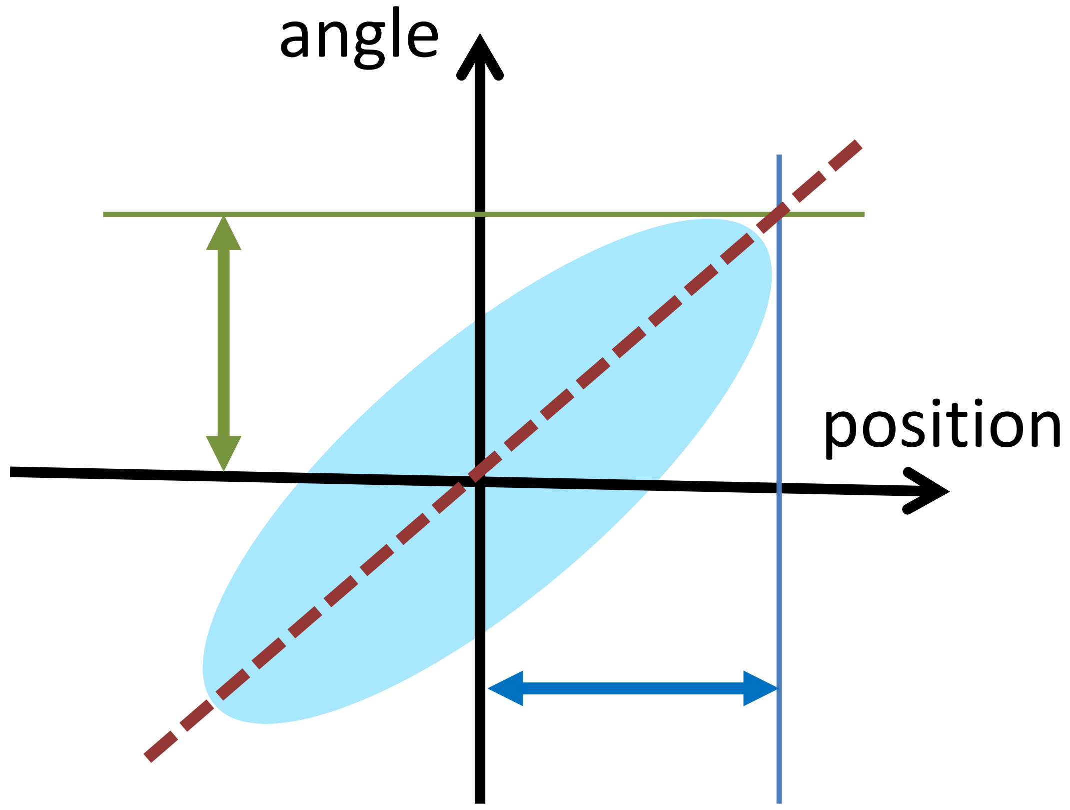
improvement ×20

↓ upgrade projects

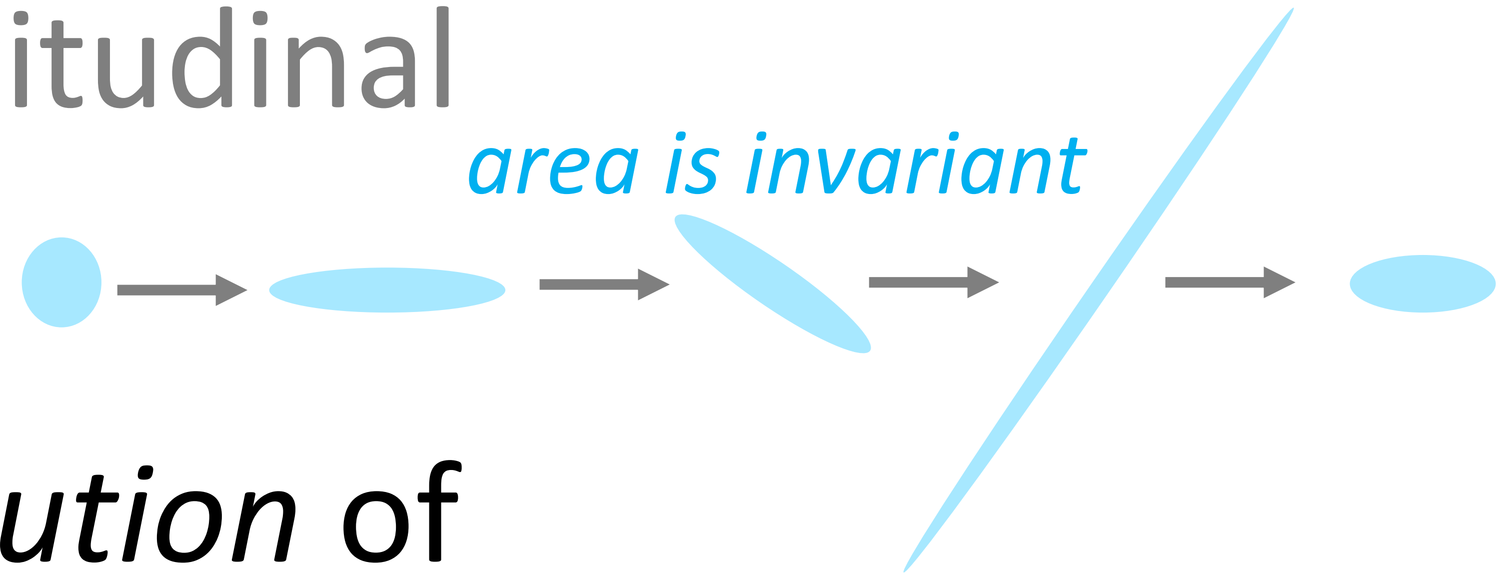
Emittance

- ε = size × divergence – correlation

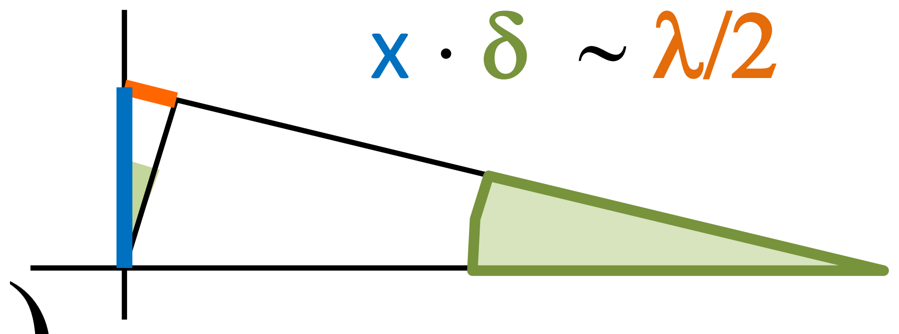




- $\varepsilon \cong$ phase space area
- ε unit = m·rad, nm·rad, pm·rad
- ε as 2-D quantity presumes decoupling horizontal ↔ vertical ↔ longitudinal



- ε is an invariant of motion
- $\varepsilon_{\gamma x/y}$ of photon beam is *convolution* of
  - *electron-*$\varepsilon_{x/y}$: property of storage ring
  - *diffraction-*$\varepsilon_r = \lambda/4\pi$ (λ = wavelength)



Photon Beam Emittance

(same for y)

$$\varepsilon_{\gamma x} = \varepsilon_x \oplus \varepsilon_r = \sqrt{(\varepsilon_x + \varepsilon_r)^2 + \varepsilon_x \varepsilon_r \left(\frac{\beta_r}{\beta_x} + \frac{\beta_x}{\beta_r} - 2 \right)} \xrightarrow{\beta_x = \beta_r} \varepsilon_x + \varepsilon_r$$

- $\varepsilon_{x/y}$ electron beam emittances (at dispersion free locations)
  - SLS: $\varepsilon_{x/y} =$ **5500** / **5** pm ⇨ **SLS-2**: $\varepsilon_{x/y} =$ **125** / **8** pm (**?**)
- $\varepsilon_r = \lambda/4\pi$ diffraction emittance → **8** pm for $\lambda =$**1** Å (≅ 12.4 keV)
- β ~ beam size / beam divergence → phase space orientation
- $\beta_{x/y}$ electron beam
  - SLS short straights: $\beta_{x/y} =$ **1.4** / **1.0** m
  - SLS [super]bends: $\beta_{x/y} =$ **0.45** / **14.0** m
- β_r diffraction
  - Undulator: $\beta_r \approx L / 2\pi$ → ≈ **0.3** m for $L = 2$ m
  - [super]bend: $\beta_r \approx 0.014$ m / B [T] → ≈ **0.0045** m for $B = 3$ T
- Convoluted photon beam emittances
  - Undulator @ SLS: $\varepsilon_{\gamma x/y} =$ **5520** / **15** pm ⇨ **SLS-2**: $\varepsilon_{\gamma x/y} =$ **145** / **19** pm
  - Superbend @ SLS: $\varepsilon_{\gamma x/y} =$ **5900** / **350** pm ⇨ **SLS-2**: $\varepsilon_{\gamma x/y} =$ **340** / **450** pm

Brightness and Coherence

$$\left.\begin{array}{r} B(\lambda) \\ CF(\lambda) \end{array}\right\} = \frac{1}{\varepsilon_{\gamma x}(\lambda)\times\varepsilon_{\gamma y}(\lambda)} \times \left\{\begin{array}{l} \dot{N}(\lambda)/\mathrm{BW} \\ \left(\varepsilon_r(\lambda)\right)^2 \end{array}\right.$$

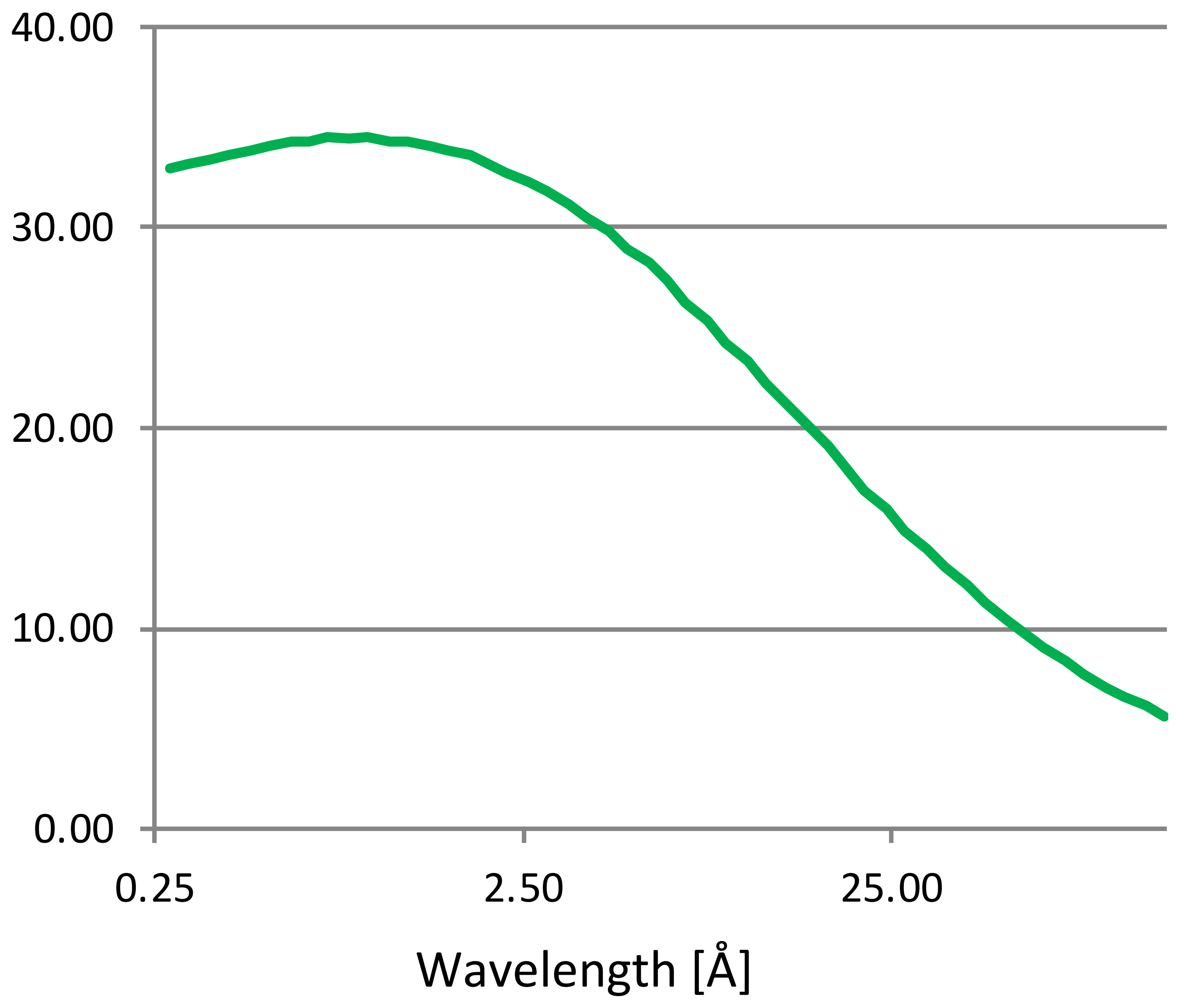
$\dot{N}(\lambda)$ spectral photon flux

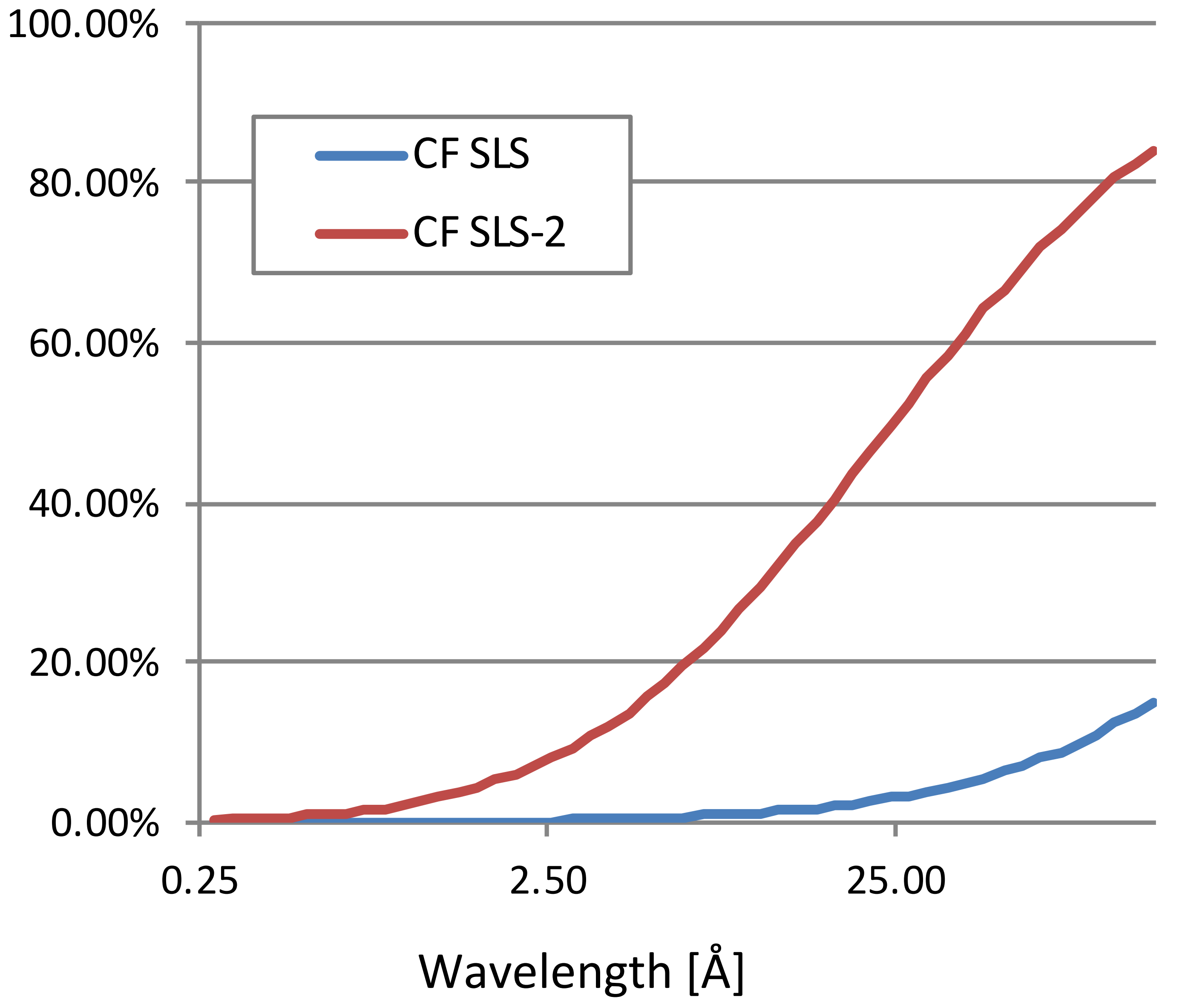
BW bandwidth of experiment

Possible increase of brightness and coherent fraction

for the SLS photon energy range (0.09...45 keV ≅ 0.25...140 Å)

[undulator beam lines only]


Brightness increase SLS-2/SLS


Coherent fraction for SLS-2 and SLS

Which Experiments Need Transverse Coherence?

- ■ Holography
- ● Single Crystal Diffraction
- ▲ Phase Contrast Imaging
- ★ All of the above

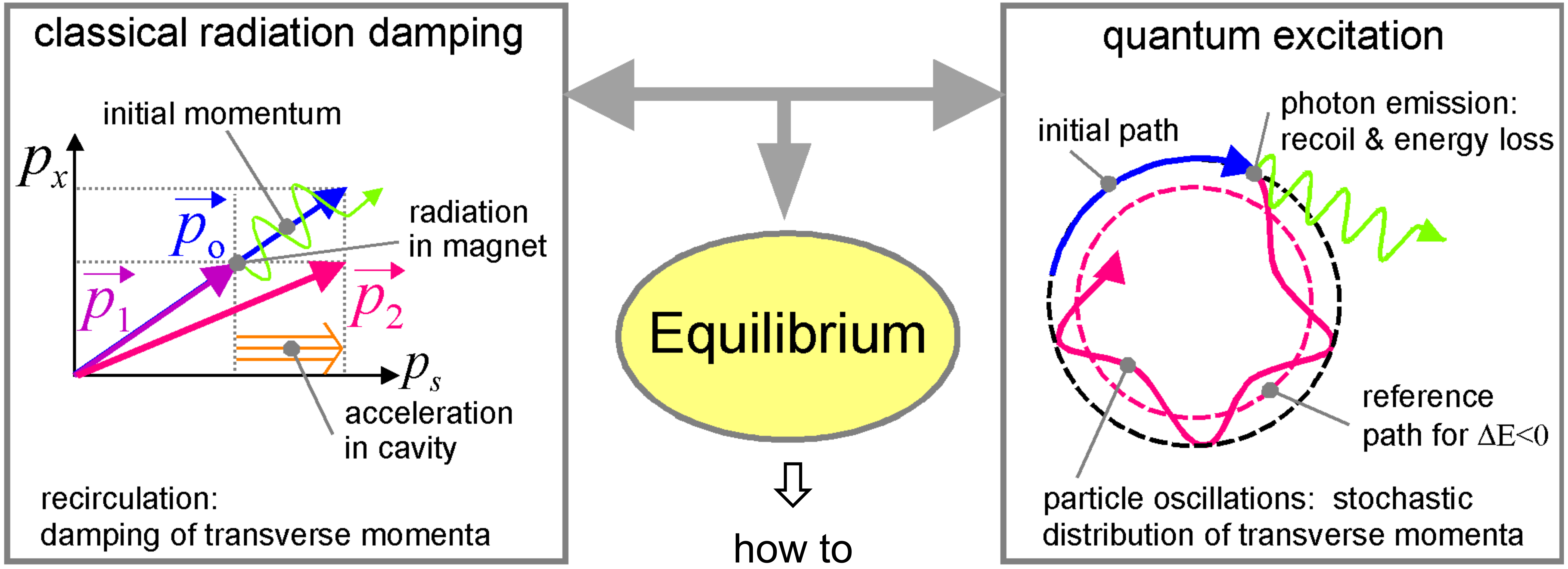
I Have Heard that Users Perform All of These Experiments at Synchrotrons. How Do They Achieve the Required Coherence?

Nick Veasey

Horizontal emittance in electron storage ring:

$\downarrow$radiation damping$\downarrow$ $\Rightarrow$ **equilibrium** $\Leftarrow$ $\uparrow$quantum excitation$\uparrow$

independent from initial conditions !



⇧ maximize this -- and -- minimize this ⇧

?

Electron Beam Emittance

- Maximum radiation damping
  - increase radiated power
    - Damping Wigglers ⇨ pay with RF-power
      - e.g. PETRA III: Power $1.1 \rightarrow 4.9$ MW ⇨ ε_x $4.4 \rightarrow 1.0$ nm
- 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)

- strong horizontal focusing into bends.
- Multi-Bend Achromat lattice
  many short (= small deflection angle) bends to limit dispersion growth.
- Longitudinal Gradient Bend
  highest radiation at region of lowest dispersion and v.v.

Electron Beam Emittance

Minimum horizontal emittance

Beam energy

Deflection angle *per* dipole

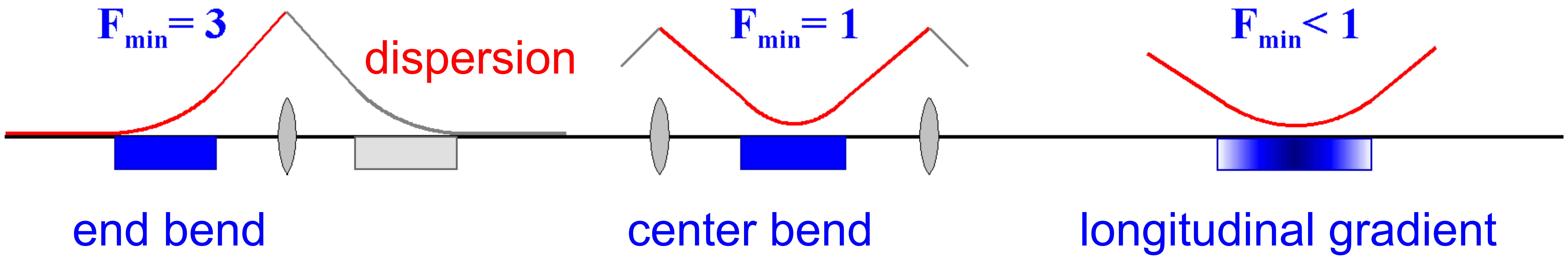
Beam optics...

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

SLS: 5500 pm

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

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

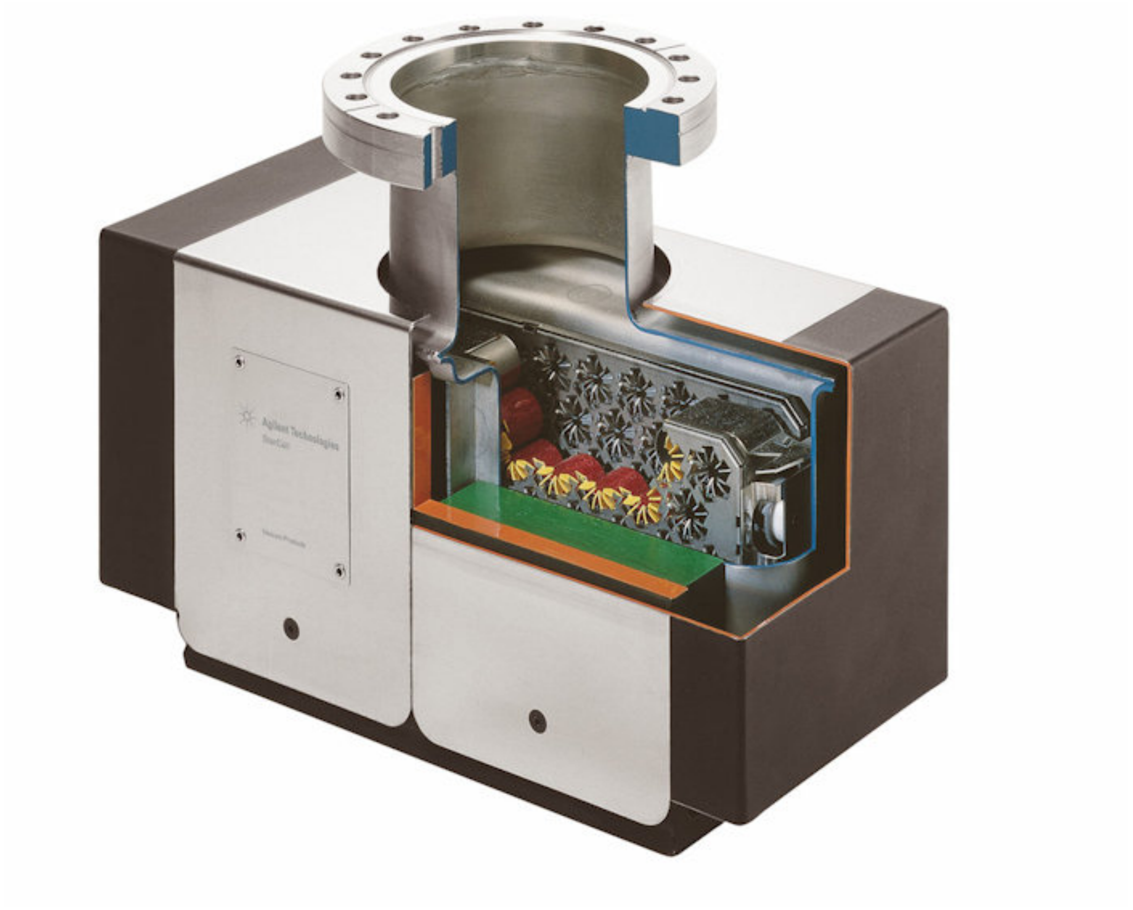


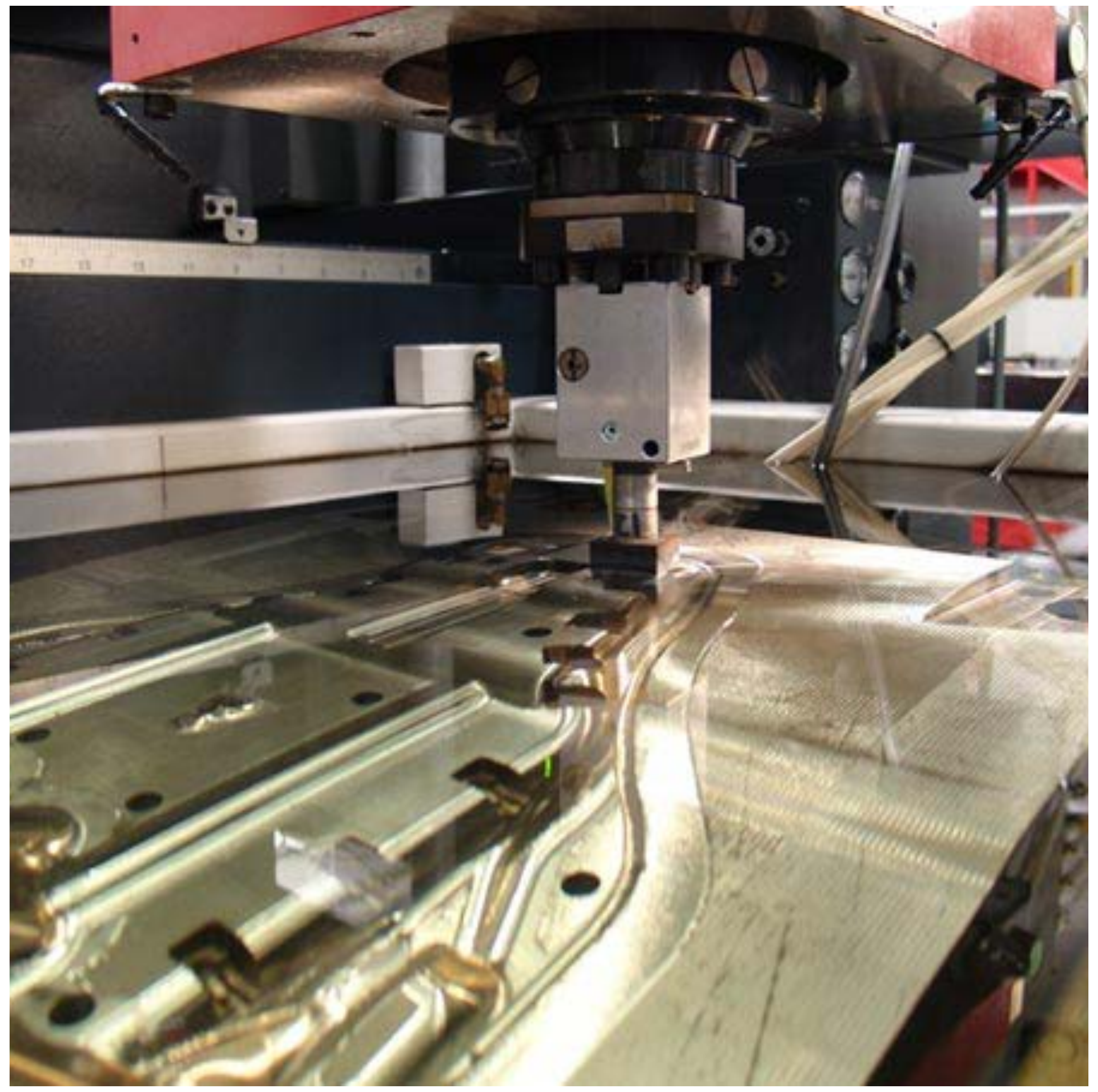
Vertical emittance (of a flat lattice)

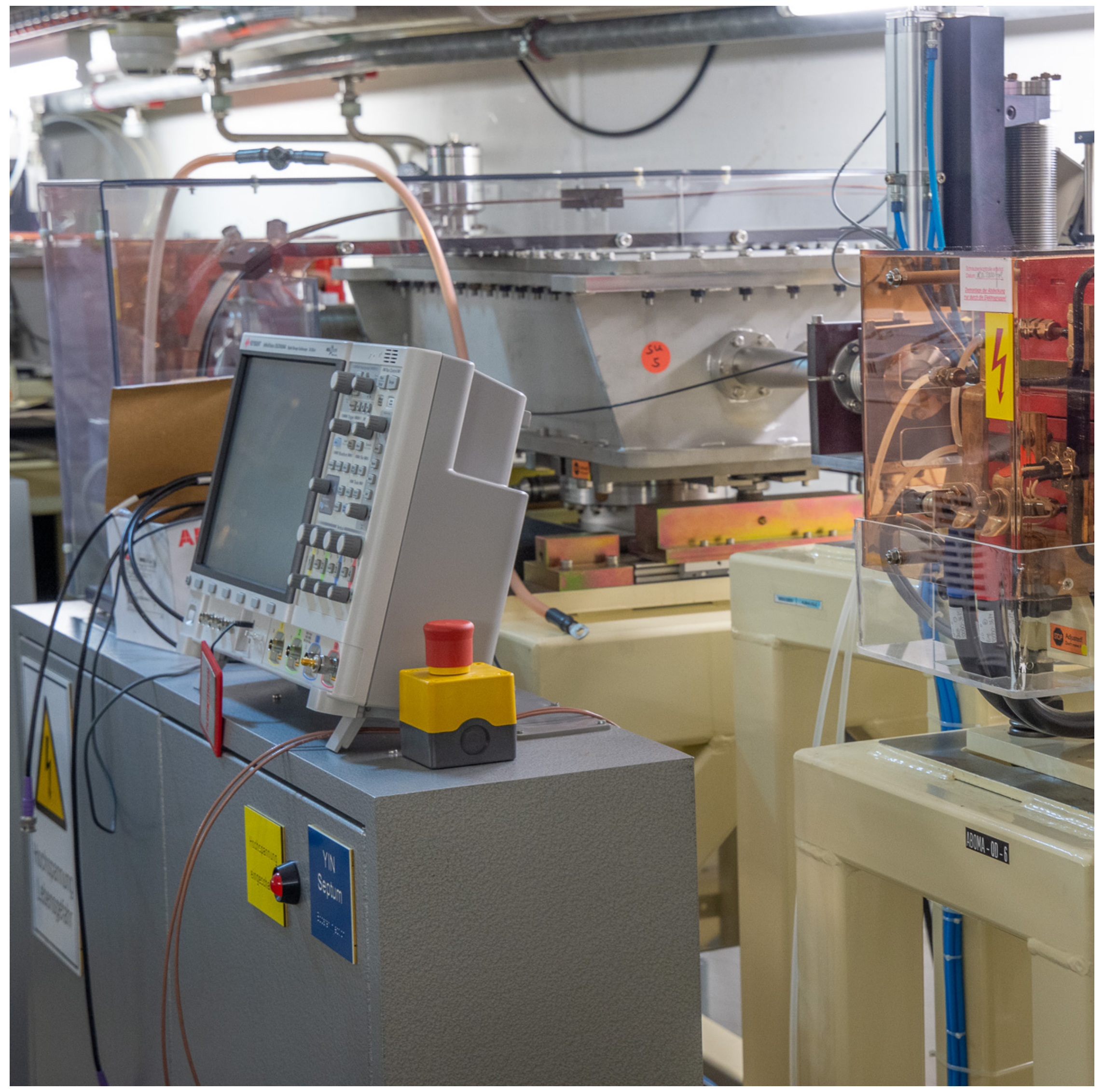
- equilibrium emittance small by nature **SLS** : 0.2 pm
- determined by lattice imperfections **SLS** : 1...10 pm

Technological Advances

- Vacuum technology: distributed pumping
- High precision machining
- New injection schemes
- Solid-state RF systems

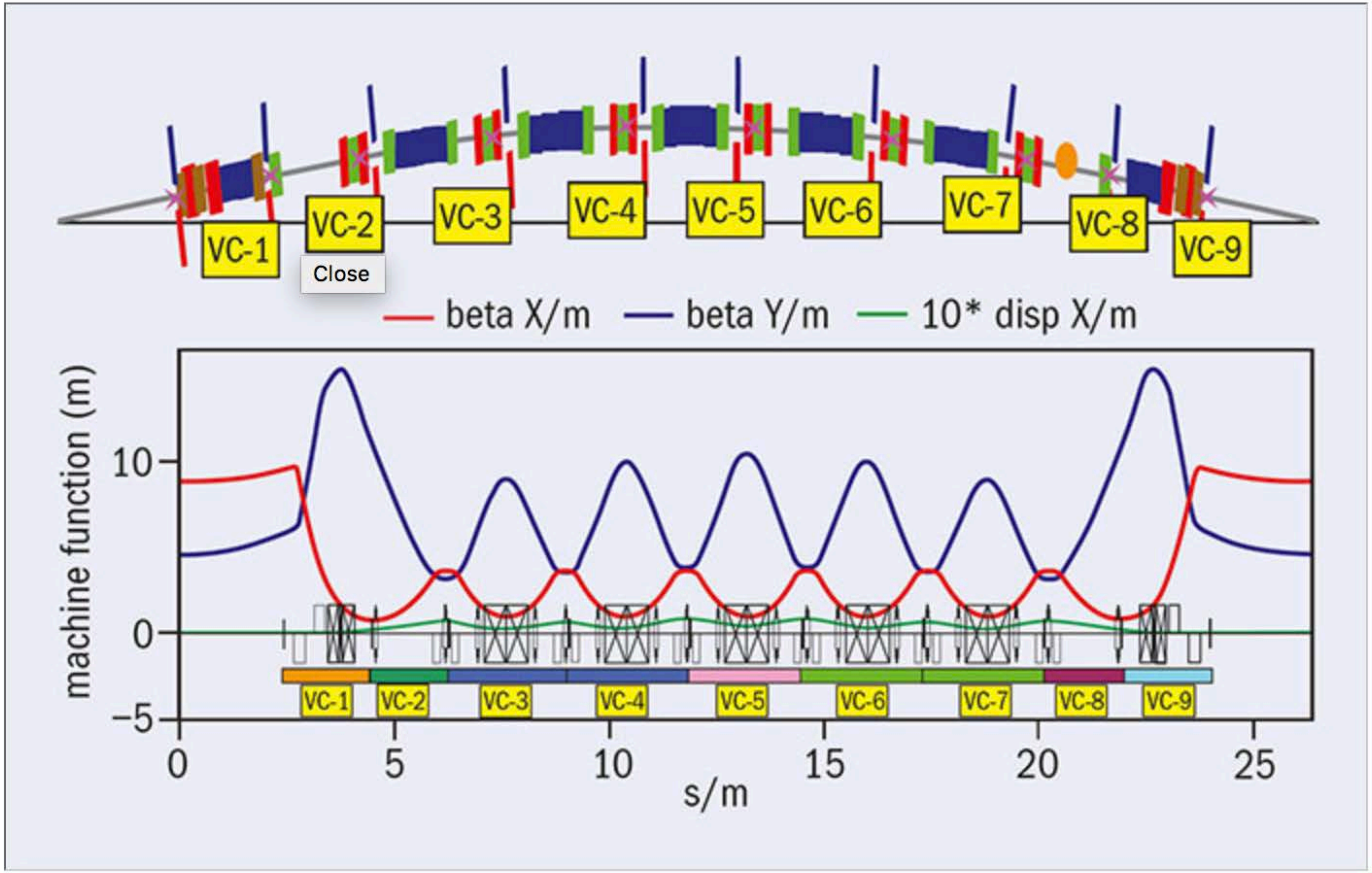






from left to right: Agilent, Wikimedia Commons, PSI Bildarchiv

Multi-Bend Achromats



Compact low emittance lattice concept

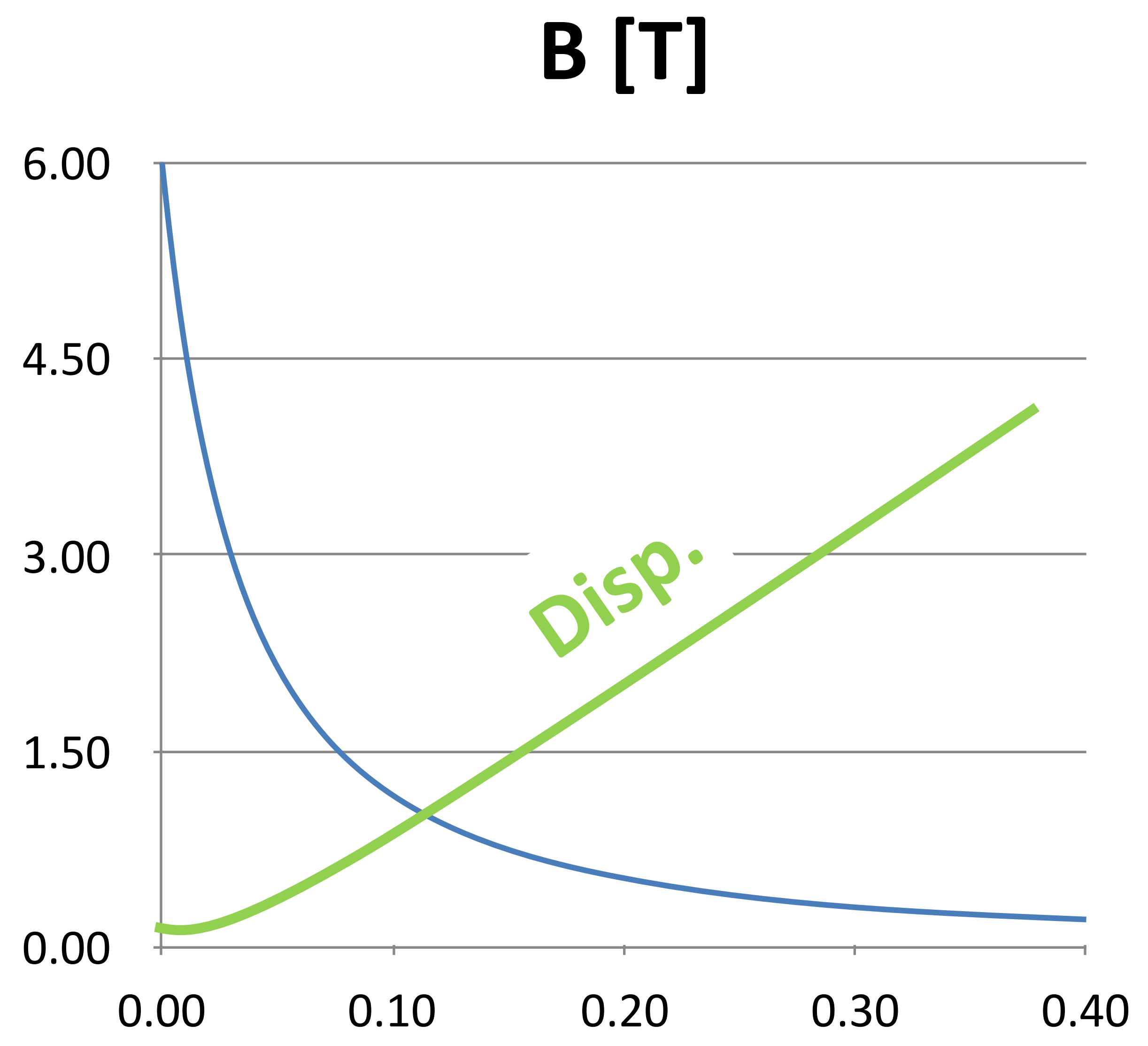
New concept

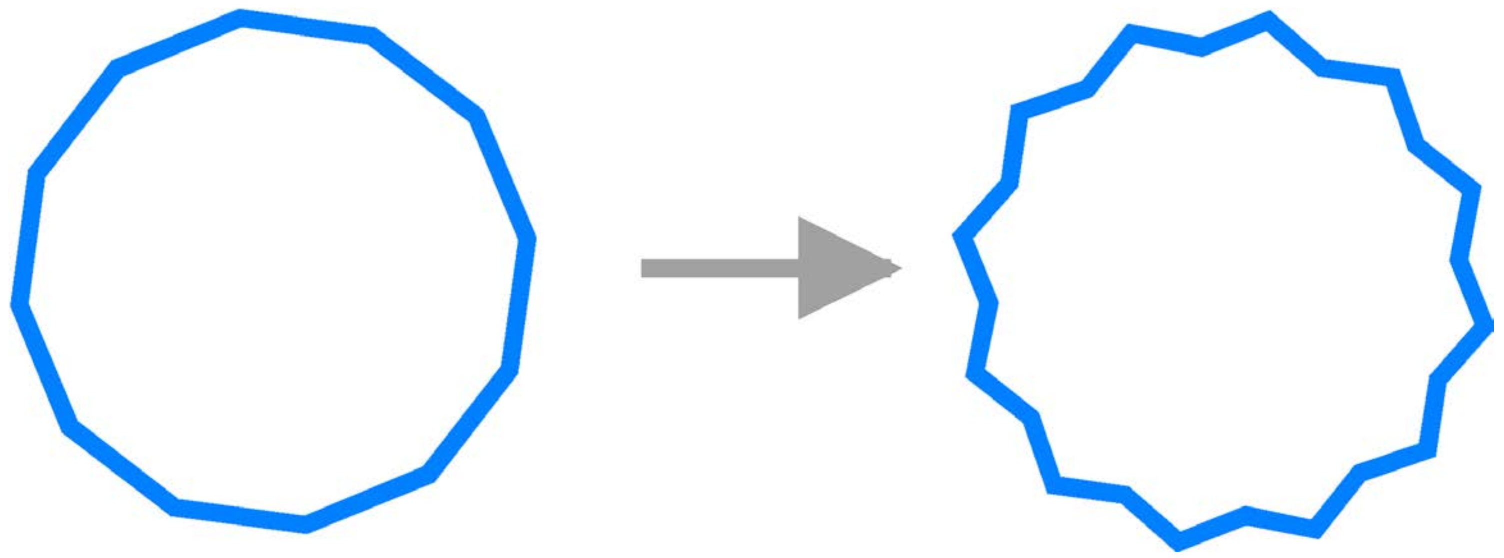
- Longitudinal gradient bends (LGB): field variation $B_y = B_y(s)$
  - $\varepsilon \propto \int$ (**dispersion**^{2}...) × (**B-field**)^3 ds
  - → high field at low dispersion and v.v.
- Anti-bends (AB): $B_y < 0$
  - matching of dispersion to LGB (disentangle horizontal focusing from dispersion matching)

⇨Factor ≈ 5 lower emittance

compared to a conventional lattice

⇨MBA + LGB/AB : factor ≈ 25!





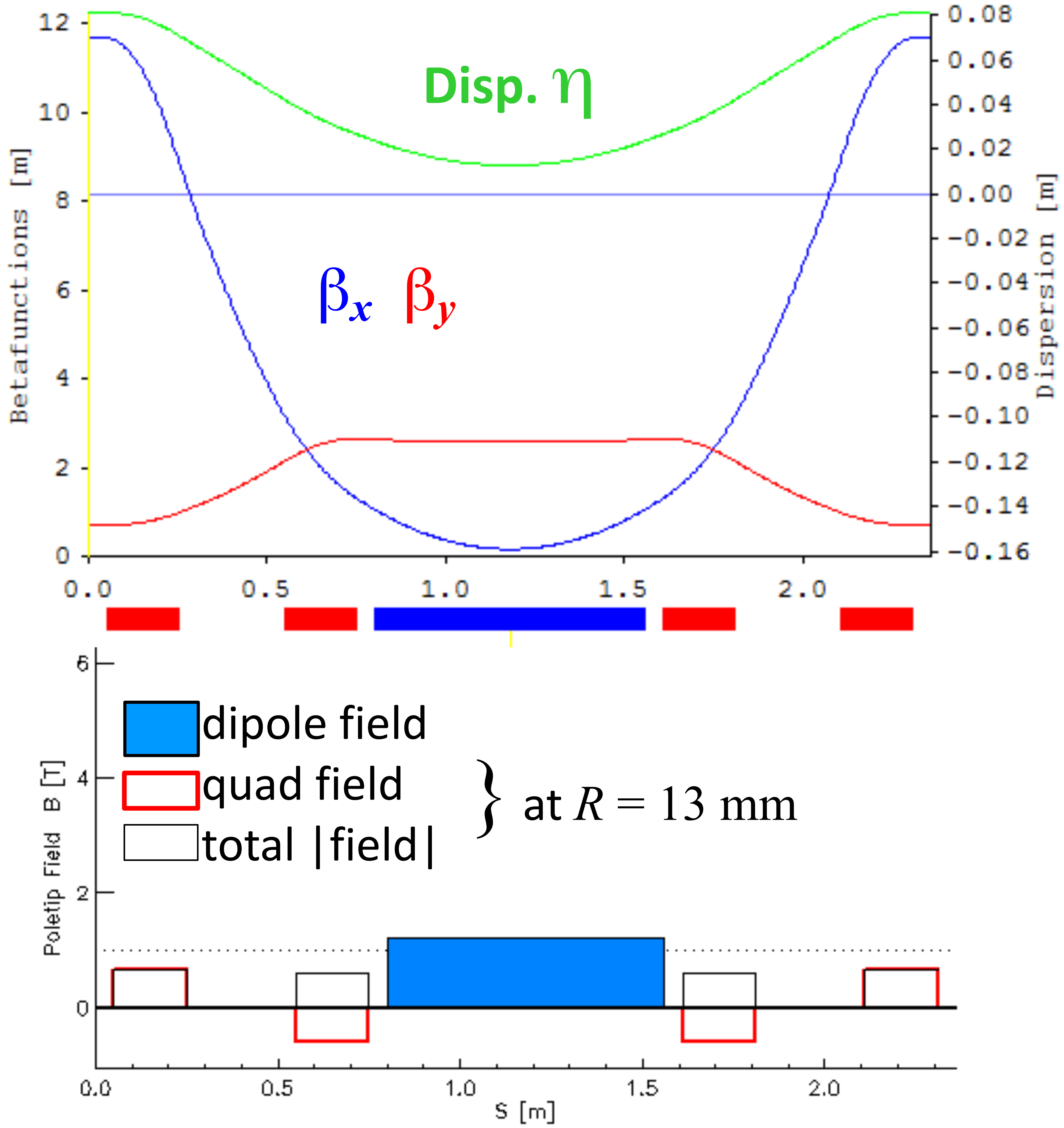
AS & A. Wrulich, NIM A770 (2015) 98–112

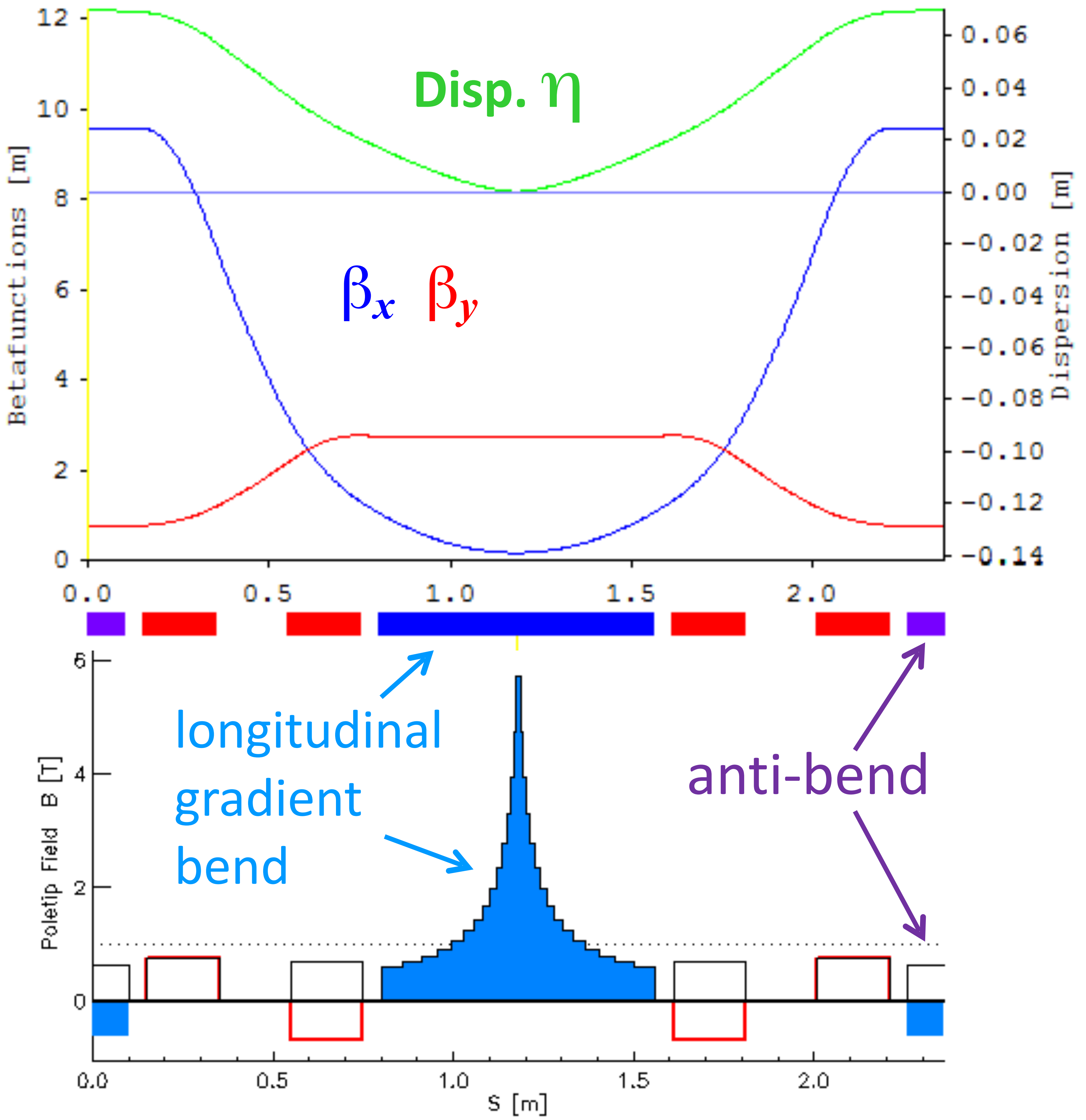
AS, NIM A737 (2014) 148–154

The LGB/AB cell for low emittance

- Conventional cell vs. longitudinal-gradient bend/anti-bend cell
  - both: angle 6.7°, $E = 2.4$ GeV, $L = 2.36$ m, $\Delta\mu_x = 160°$, $\Delta\mu_y = 90°$, $J_x \approx 1$

conventional: $\varepsilon = 990$ pm **LGB/AB:** $\varepsilon = 200$ pm



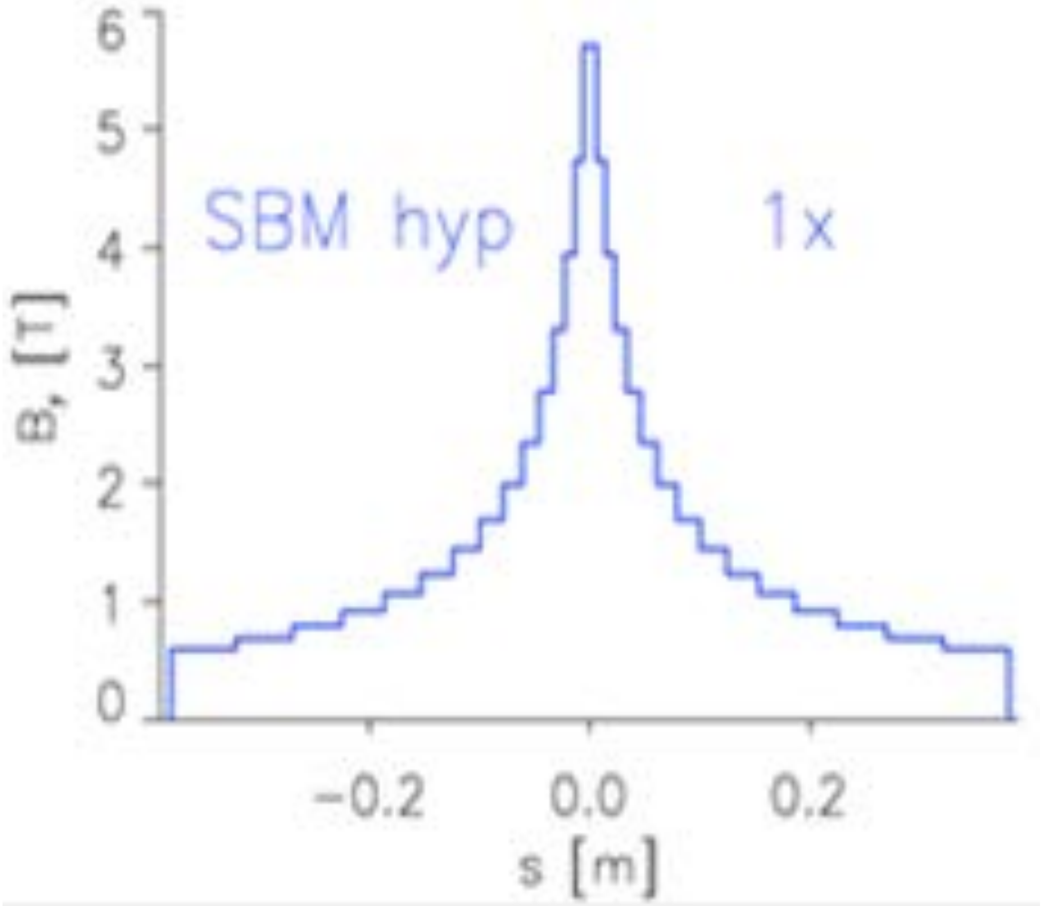


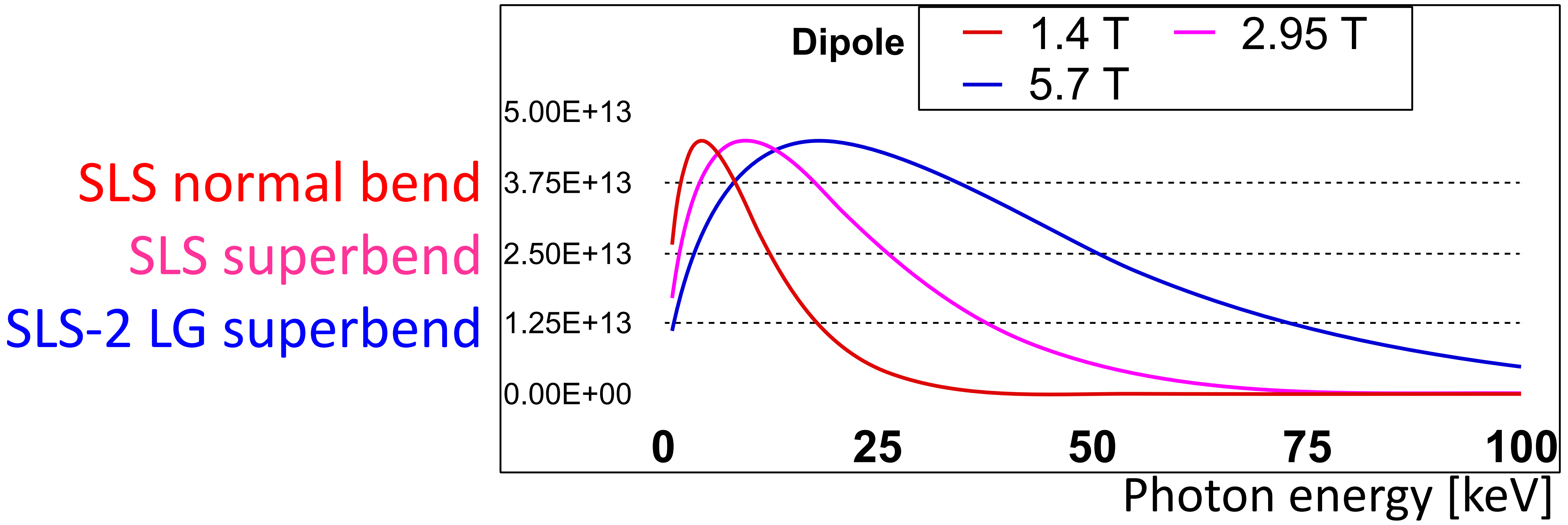
longitudinal gradient bend

anti-bend

Additional benefits of the LGB/AB cell

- Hard X-rays (≈ 80 keV) from high B-field peak ($4..6$ Tesla):





- ε-reduction due to increased radiated power from high field and from $\Sigma|$deflection angle$| > 360°$ (“wiggler lattice”).
- Beam dynamics: potentials for ease of chromaticity correction
  - rather relaxed optics for a low emittance lattice.
  - negative momentum compaction (like proton synchrotron below transition energy) : suppression of head-tail instability at *negative* chromaticity. (chromaticity is negative by nature)

Advanced options

- A new on-axis injection scheme
  - cope with reduced aperture (physical or dynamic)
  - use interplay of radiation damping and synchrotron oscillation in longitudinal phase space to inject off-energy, off-phase but on-axis.

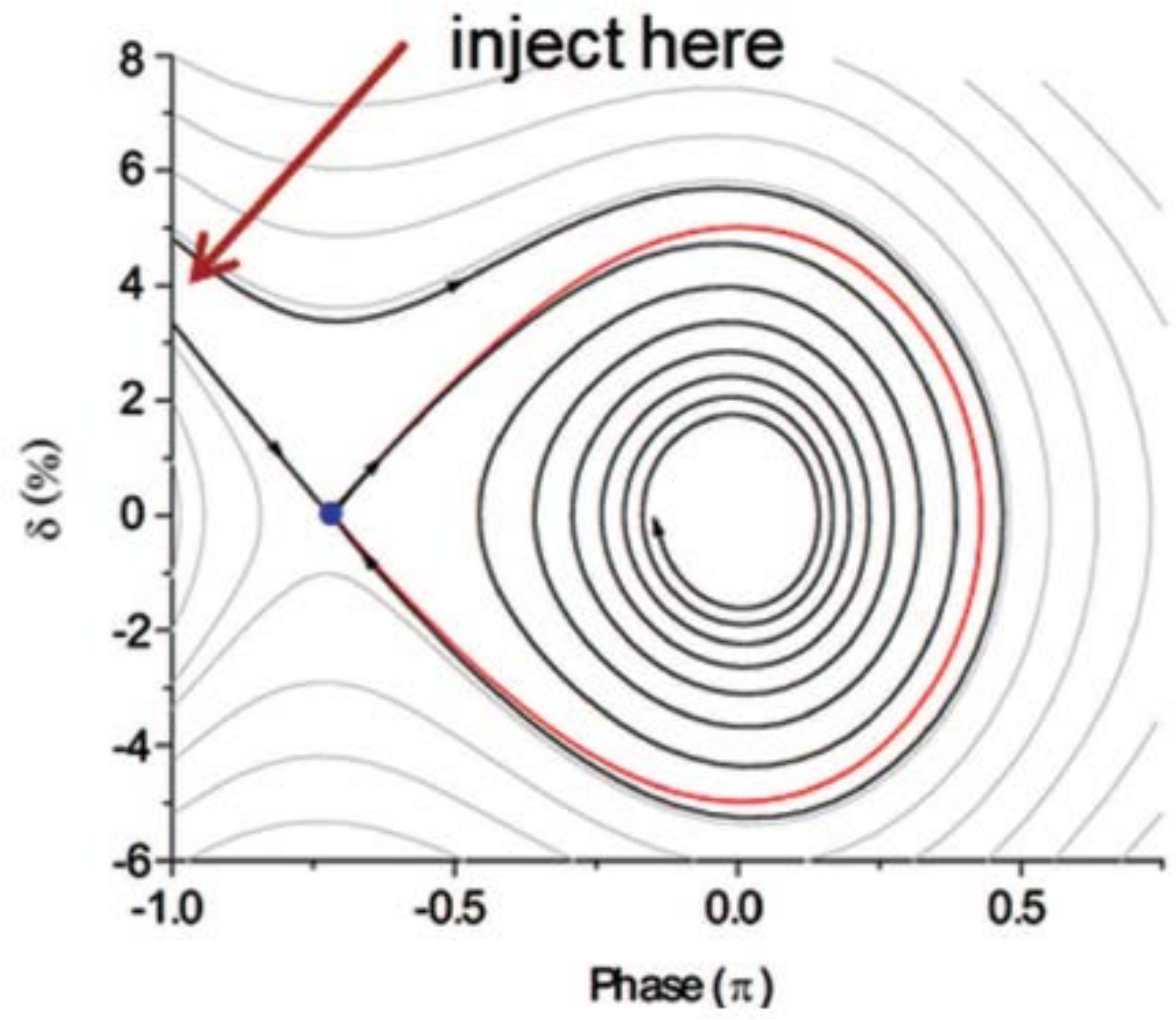
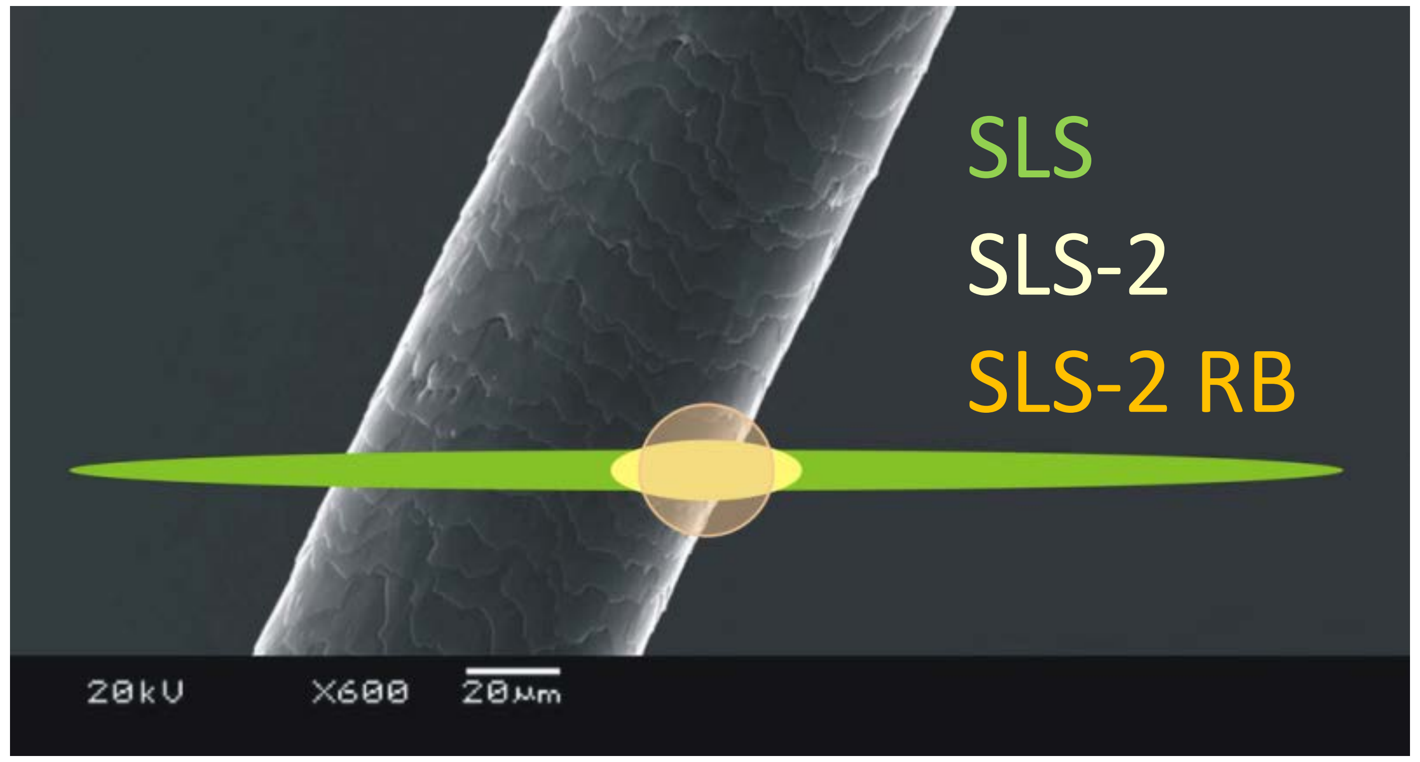


Figure taken from R. Hettel, JSR 21 (2014) p.843

🗎 M. Aiba, M. Böge, Á. Saá Hernández, F. Marcellini & AS, PR ST AB 18, 020701 (2015)

◆ Round beam scheme

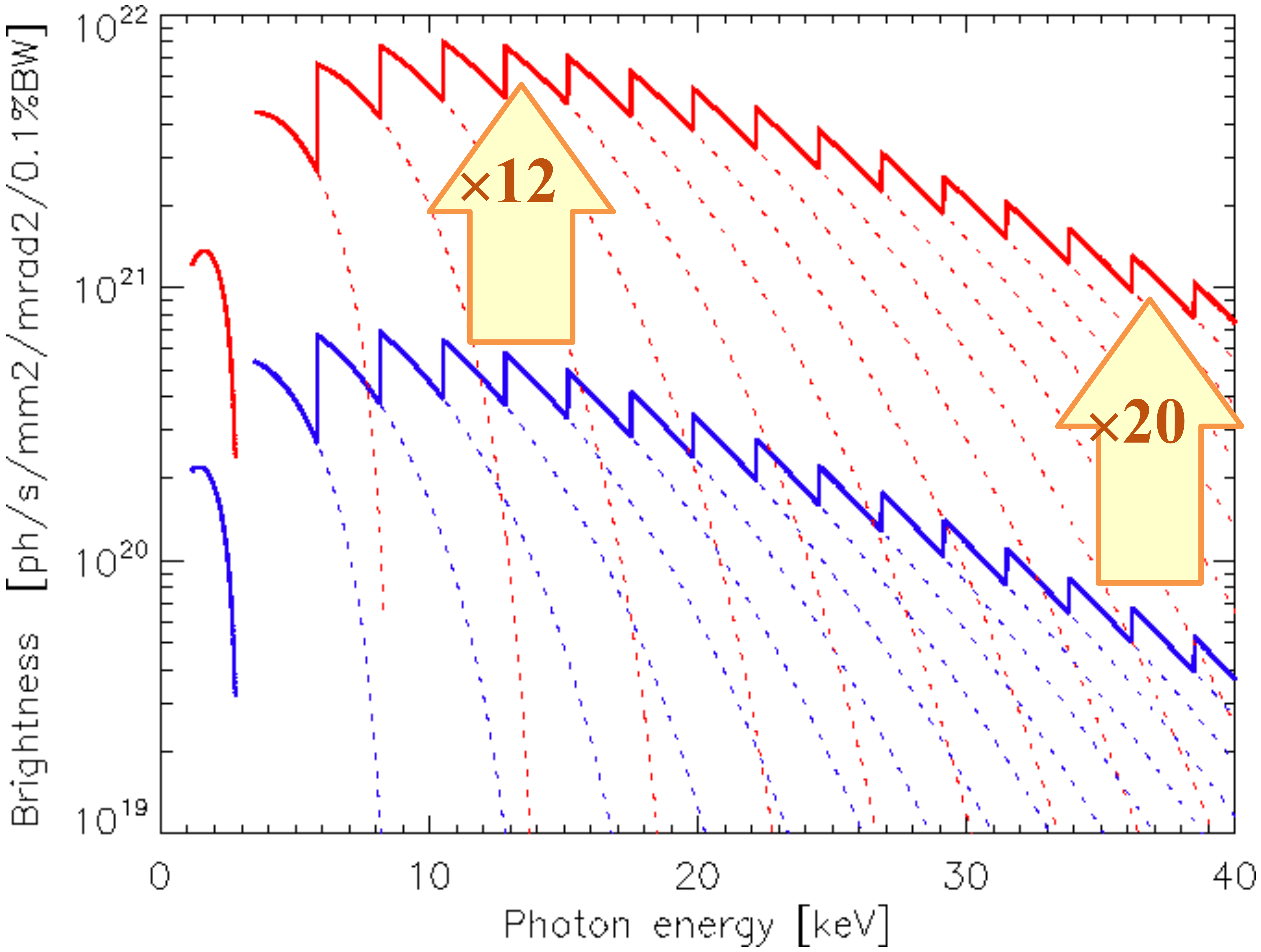
- Wish from users
- Maximum brightness & coherence
- Mitigation of intrabeam scattering blow-up
- "Möbius accelerator":
  beam rotation on each turn to exchange transverse planes



🗎 R. Talman (Cornell Univ.), PRL 74.9 (1995) 1590

Undulator brightness

Brightness of U19 at **SLS** and **SLS-2**



Brightness scales with photon beam emittance
(= electrons ⊕ diffraction)

Parameters for simple model:

$N_u = 100$ periods

$\lambda_u = 19$ mm period

gap g : ¼¾ λ_u

up to $h = 33^{\mathrm{rd}}$ harmonic

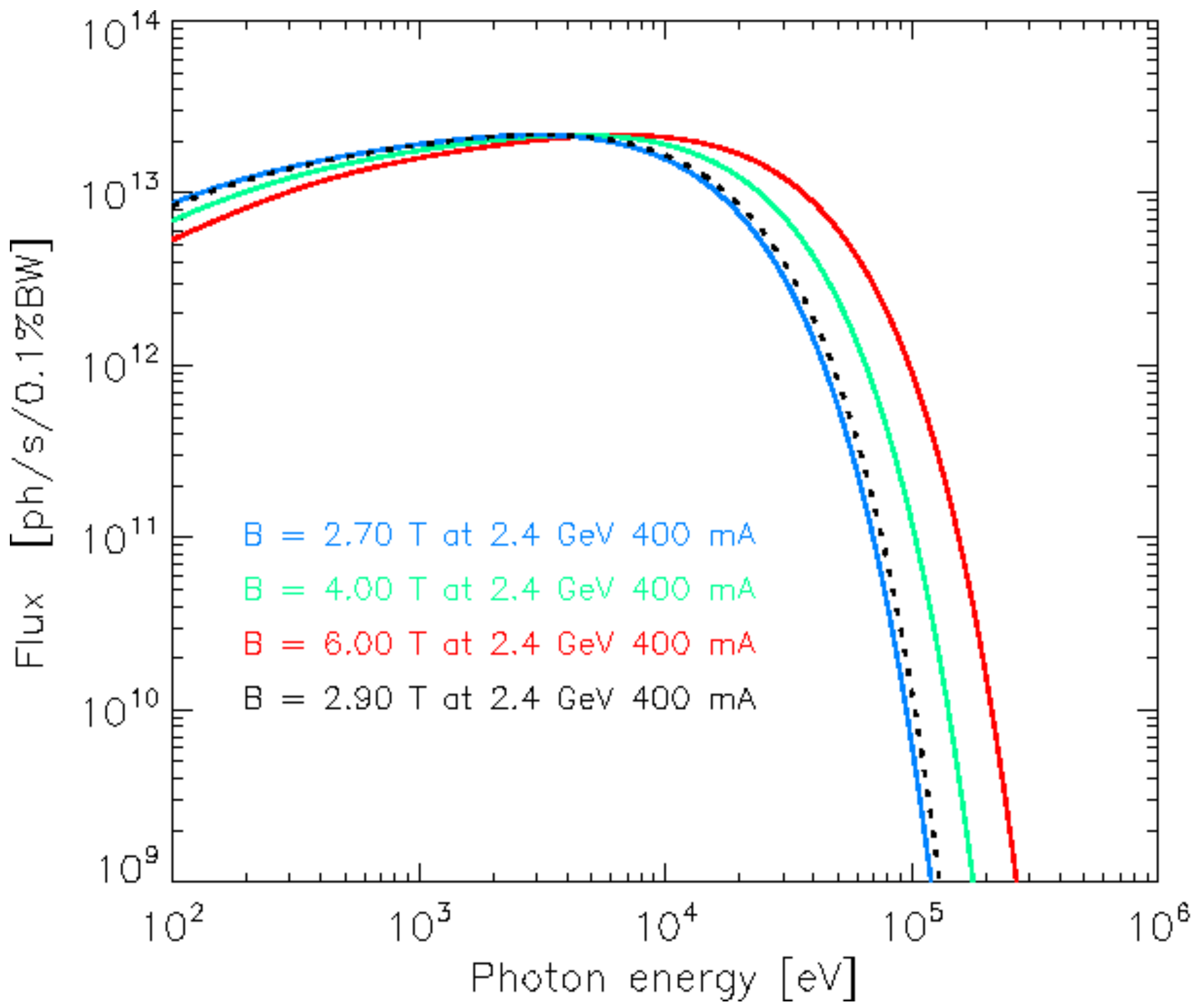
radiation into cone of

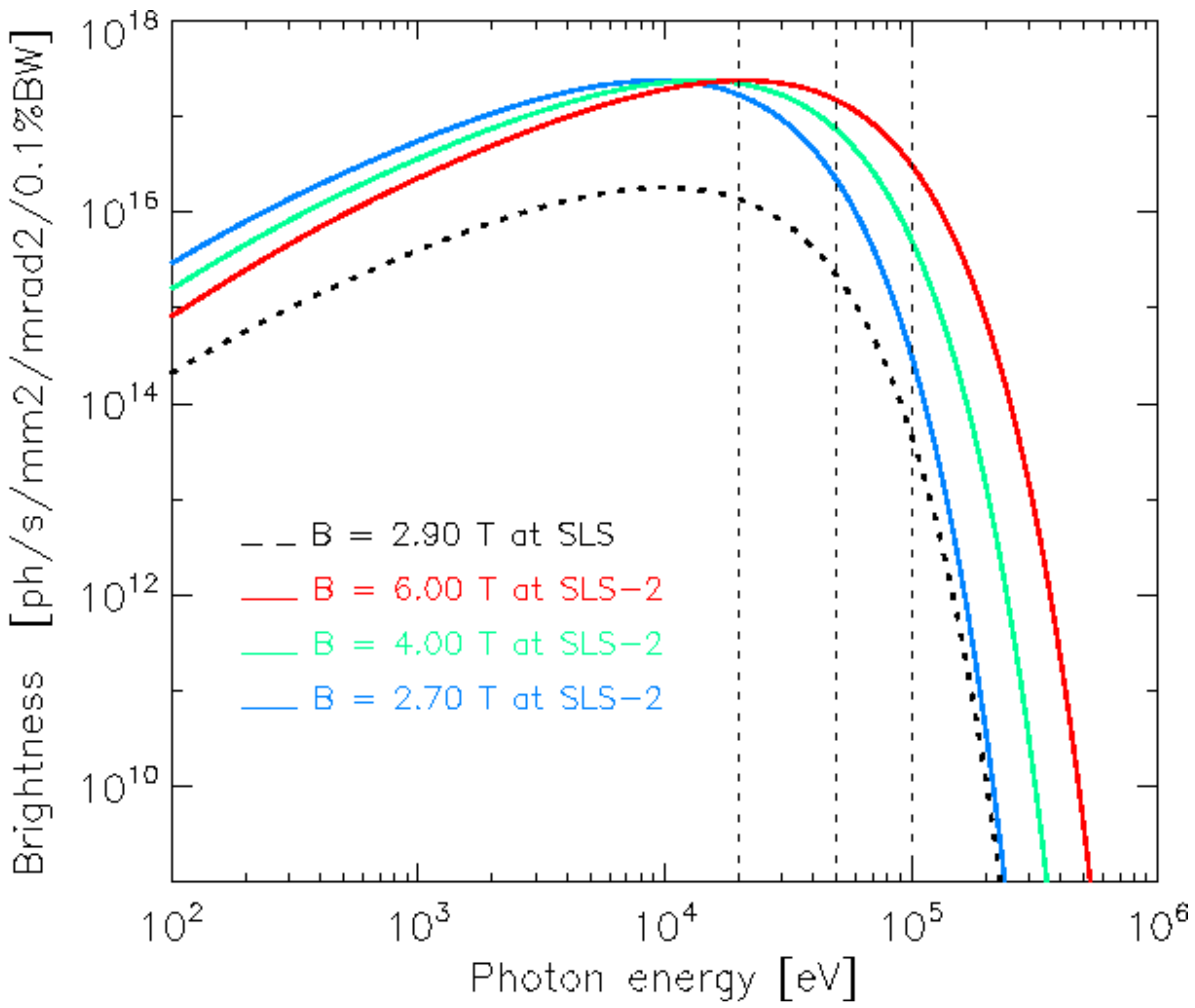
$$\sigma_{r'} \approx \sqrt{\frac{\lambda}{L_u}} \qquad L_u = N_u \lambda_u$$

$$\lambda = \frac{\lambda_u}{2\gamma^2 h}\left(1 + \tfrac{1}{2} K_u^2\right)$$

$$N\boxed{?}= 4\pi\alpha\, N_u (0.1\%\mathrm{BW}) \left(\frac{I}{e}\right) \xi \left(J_{\frac{h-1}{2}}(\xi) - J_{\frac{h+1}{2}}(\xi) \right) \qquad \xi = \frac{h K_u^2}{4 + 2K_u^2} \qquad K_u = \frac{B_o c}{(mc^2/e)} \frac{\lambda_u}{2\pi} \qquad B_o \approx 3.33 \exp\left[-\frac{g}{\lambda_u}\left(5.47 - 1.8 \frac{g}{\lambda_u}\right)\right]$$

Superbend flux and brightness





Fan opening angle ±0.5 mrad
convoluted into effective emittance

Cave

- Gaussian approximation of non-Gaussian
- only relevant for micro-focusing experiments, not for full field imaging

Brightness increase superbend

- - - 2.9 T at **SLS** → —— 6.0 T at **SLS-2**

20 keV → × 17

50 keV → × 67

100 keV → × 640

Questions?

Nick Veasey