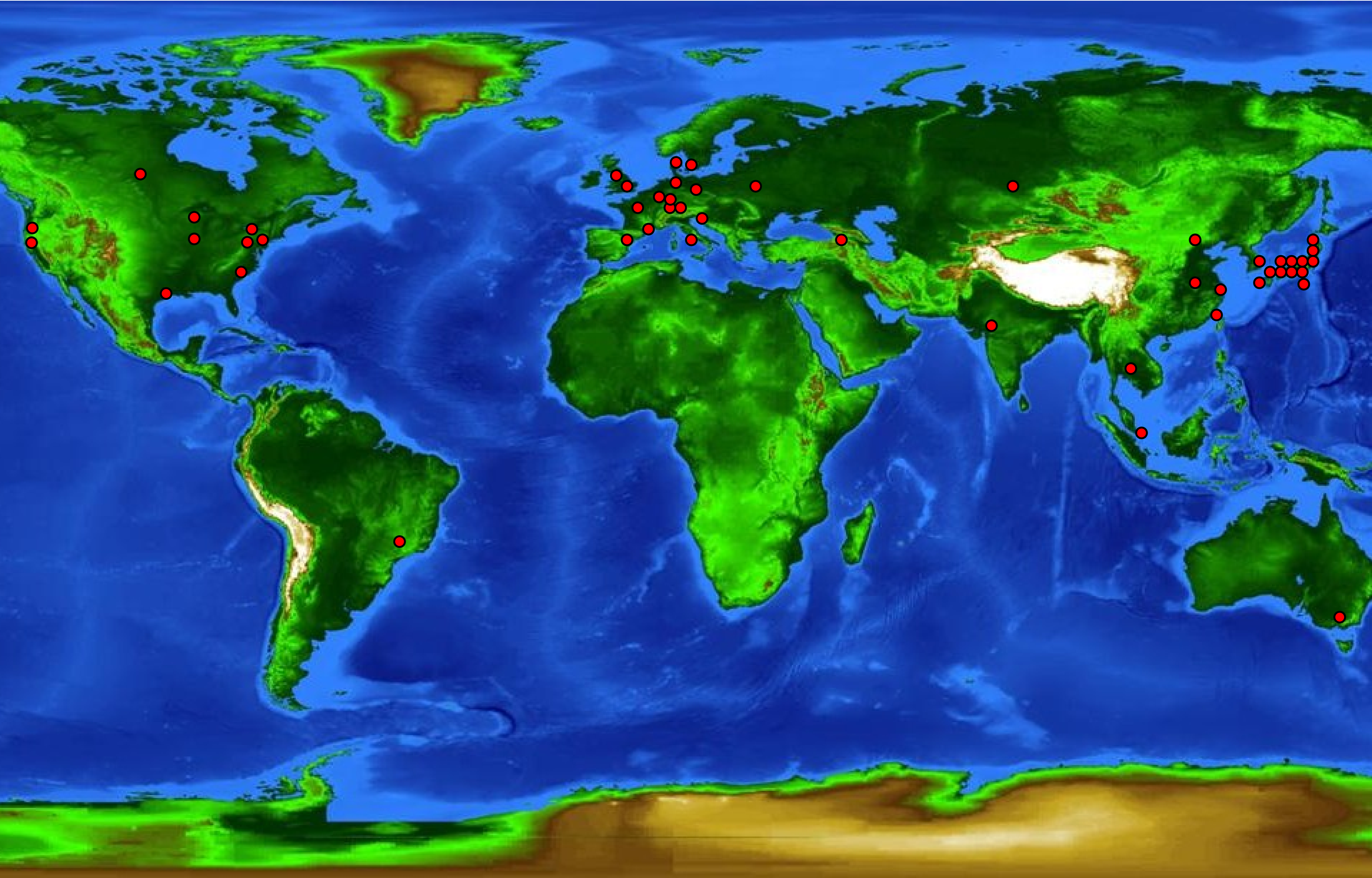
Light sources challenges

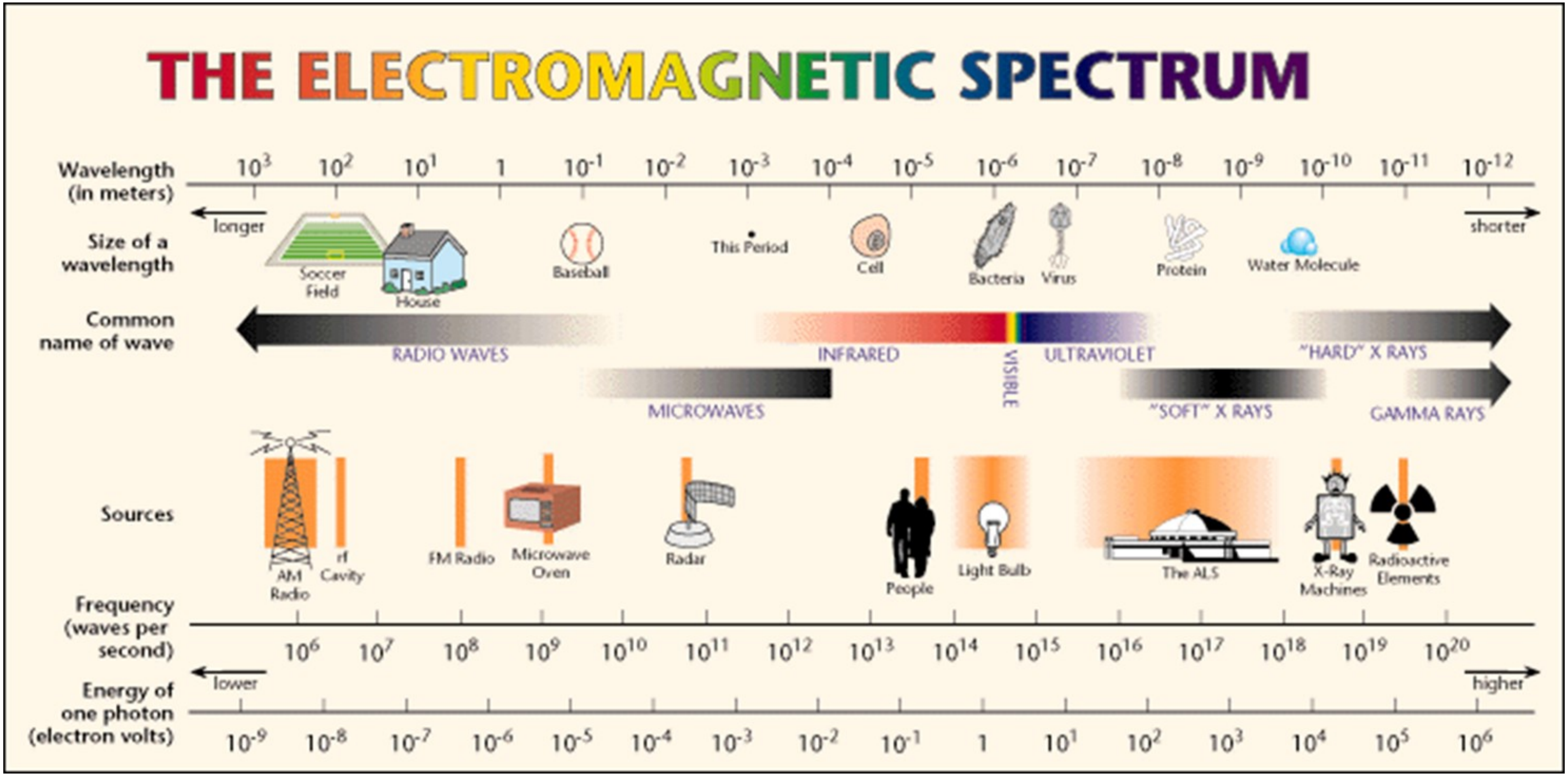
Lenny Rivkin

Paul Scherrer Institute (PSI)
and
Swiss Federal Institute of Technology Lausanne (EPFL)

60’000 users world-wide and growing



Synchrotron Light Sources

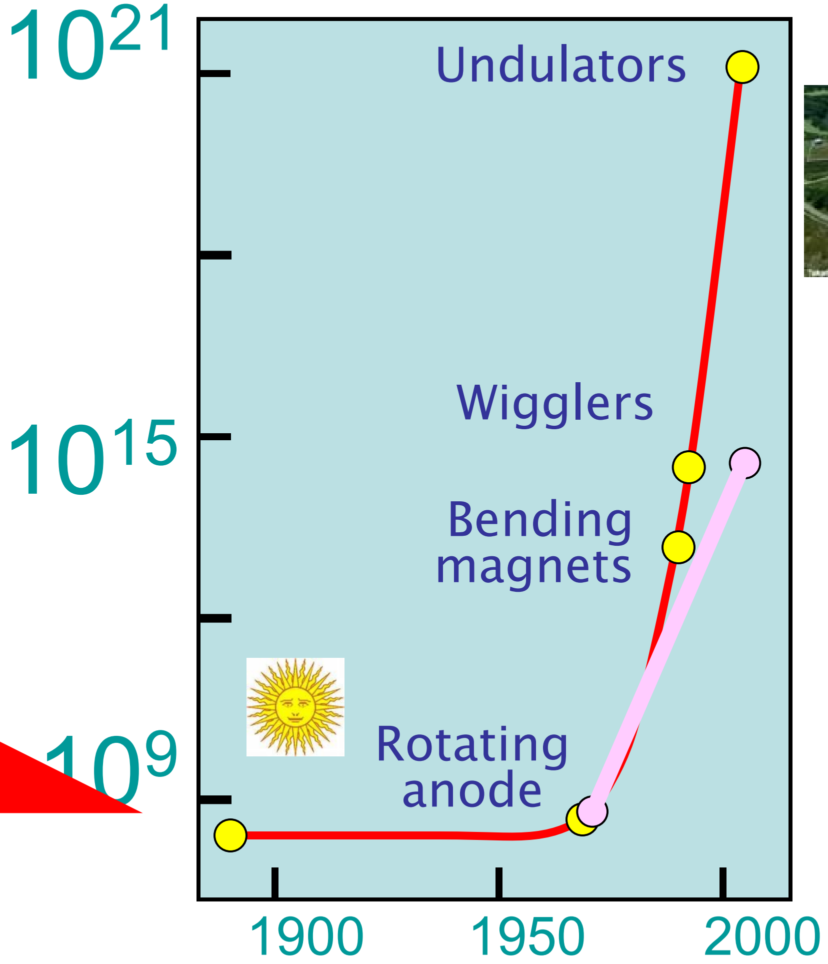


Wavelength continuously tunable !

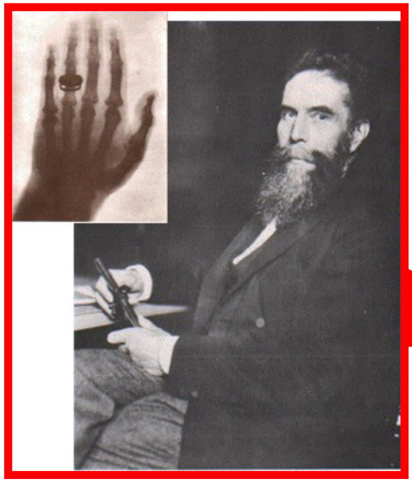
Steep rise in brightness

the second wave

XFEL



Moore's Law for semiconductors

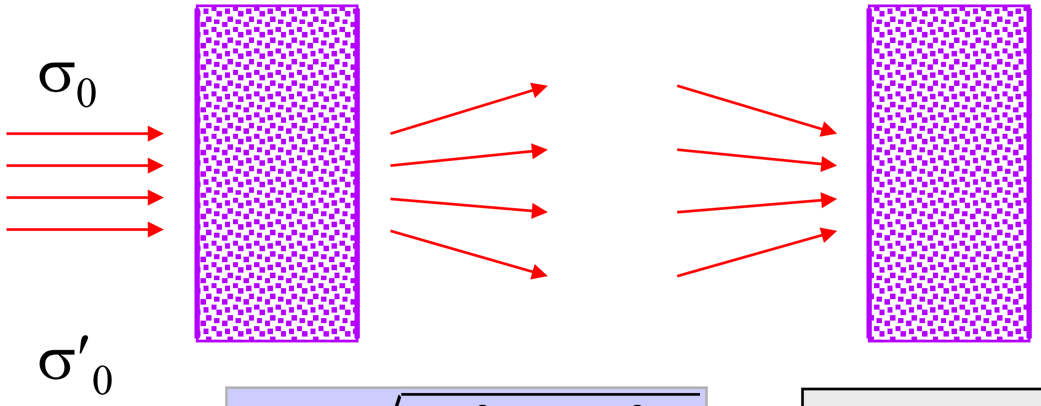


Roentgen (exposure: 20 min)

Higher brightness: more photons on small sample or through a pinhole of ~ λ: coherence

- measurements on very small probes (few μm crystals)
- short measurement times
- high transverse coherence
    - phase contrast imaging
- stringent stability requirements

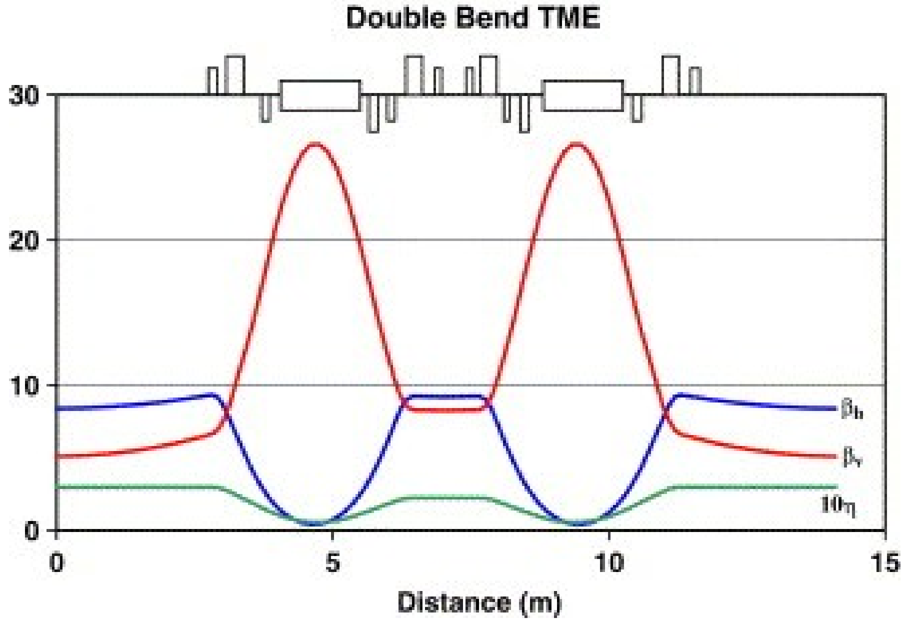
Minimum emittance lattices



$$\sigma' = \sqrt{\sigma'^2_0 + \sigma'^2_{MS}}$$

$$\sigma'_0 \gg \sigma'_{MS}$$

to minimize the blow up due to multiple scattering in the absorber we can **focus** the beam



$$\varepsilon_{x0} = \frac{C_q E^2}{J_x} \cdot \theta^3 \cdot F_{latt}$$

$$F_{min} = \frac{1}{12\sqrt{15}}$$

Non-linear dynamics challenge in rings

- Chromatic sextupoles used to correct large chromaticities bring with them strong non-linearities
- Longitudinal dynamics is dominated by non-linearities of the RF system

- need to correct these to have large enough transverse and longitudinal acceptance for injection and lifetime

- need small emittance, but not too small: diffraction limit (could trade for longitudinal phase space)

- need short pulses: down to transform limit (could trade for transverse phase space)

Methods for nonlinear optimization

analytical

1^{st} & 2^{nd} order perturbation theory

→ *maps, resonance drive terms, tune shifts with amplitude …*

- ⊕ quick calculation
- ⊕ interactive optimization (semi-analytic minimization)
- ⊖ no prediction of performance (perturbation!)

→ *"the art of weighting…"*

⟹ **Design**

⟺

Iterate

⟺

numerical

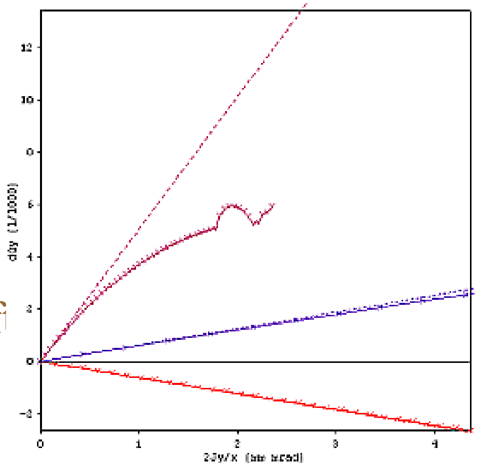
Particle tracking

→ *Poincaré plots, dynamic aperture scans, particle spectra…*

- ⊖ slow calculation
- ⊖ difficult to use in minimizer (fractal parameter space!)
- ⊕ valid prediction of performance
  → complete & correct model

⟹ **Proof**

Example:
amplitude dependant tune shif
$dQ_y / d2J_{y/x}$

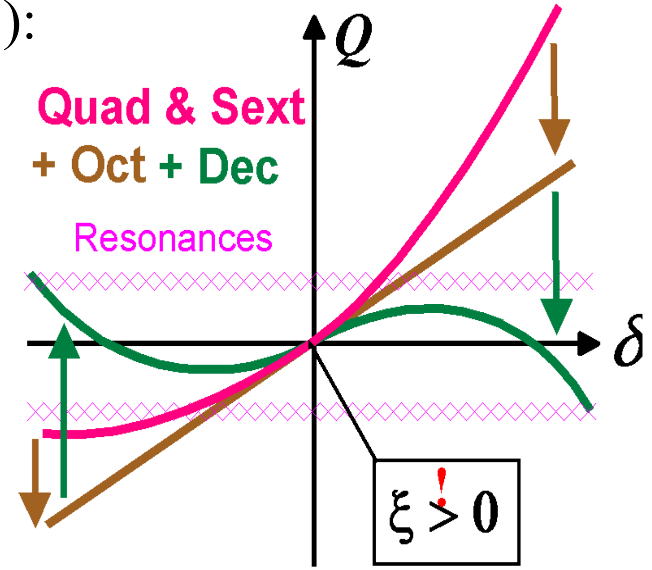


------ analytical
×××× tracking and FFT

Higher multipoles

Control in **1st order** sextupole effects of 2nd and 3rd order

- **Octupoles:**
  - linear amplitude dependent tune shifts (ADTS): $\partial Qx/\partial Jx,\ \ \partial Qx/\partial Jy=\partial Qy/\partial Jx,\ \ \partial Qy/\partial Jy$
  - quadratic chromaticities: $\partial^2 Qx/\partial\delta^2,\ \ \partial^2 Qy/\partial\delta^2$
- **Decapoles:**
  - cubic chromaticities: $\partial^3 Qx/\partial\delta^3,\ \ \partial^3 Qy/\partial\delta^3$
  - quadratic ADTS and off-energy linear ADTS
- Weak multipoles: tolerable side-effects (i.e. resonances) [?]
- Shape (minimize) beam footprint $\{Q_{x/y}(J_{x/y},\delta)\}$ in tune space
  - provide sufficient horizontal dynamic aperture for injection.
  - provide sufficient energy acceptance for Touschek lifetime.
- Provide knobs for control room (linear systems).



Damping wigglers and other tricks

Increase the energy radiated per turn with wiggle magnets (PETRA III, NSLS II, MAX IV, PEP-X)

$$\boxed{\tau = \frac{E}{P_\gamma + P_{wig}}}$$

- large gain in case of weak bends
- much shorter damping time
- increased energy spread and bunch length
  (helps with IBS blow-up and Touschek lifetime)
- emittance decrease if in dipersion free sections

Damping partition numbers (combined function magnets)

- emittance reduction up to x2
- energy spread increase (cf. above)

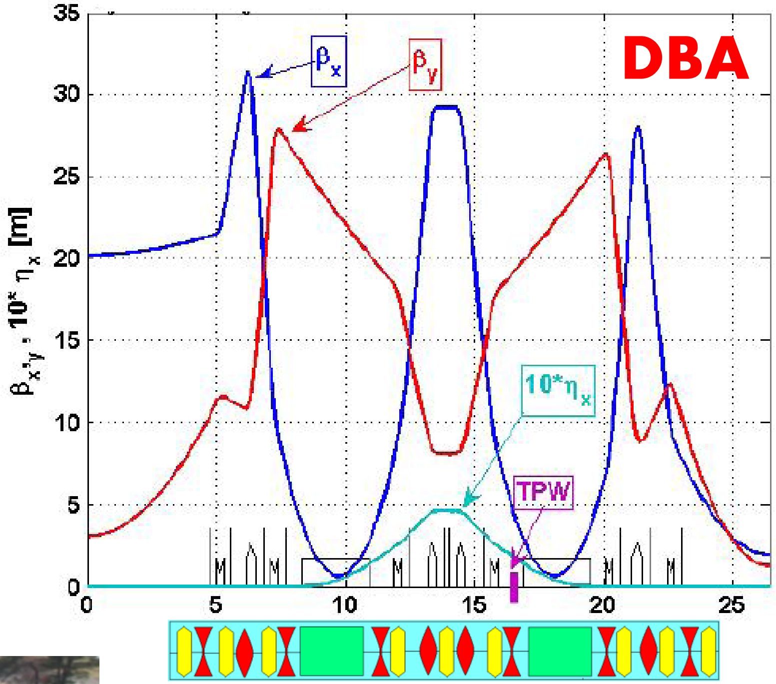
The next wave of ring based light sources

Pushing towards the diffraction limit at 1 Å wavelength

$$\varepsilon \sim \frac{\lambda_{photon}}{10}$$

		NSLS II	MAX IV	PEPX
Energy	GeV	3	3	4.5
Emittance	m · rad	1nm / 8 pm	0.3 nm	0.03/0.01
Circumf.	m	792	528	2200
Lattice		DBA	MBA	MBA

NSLS II under construction at Brookhaven

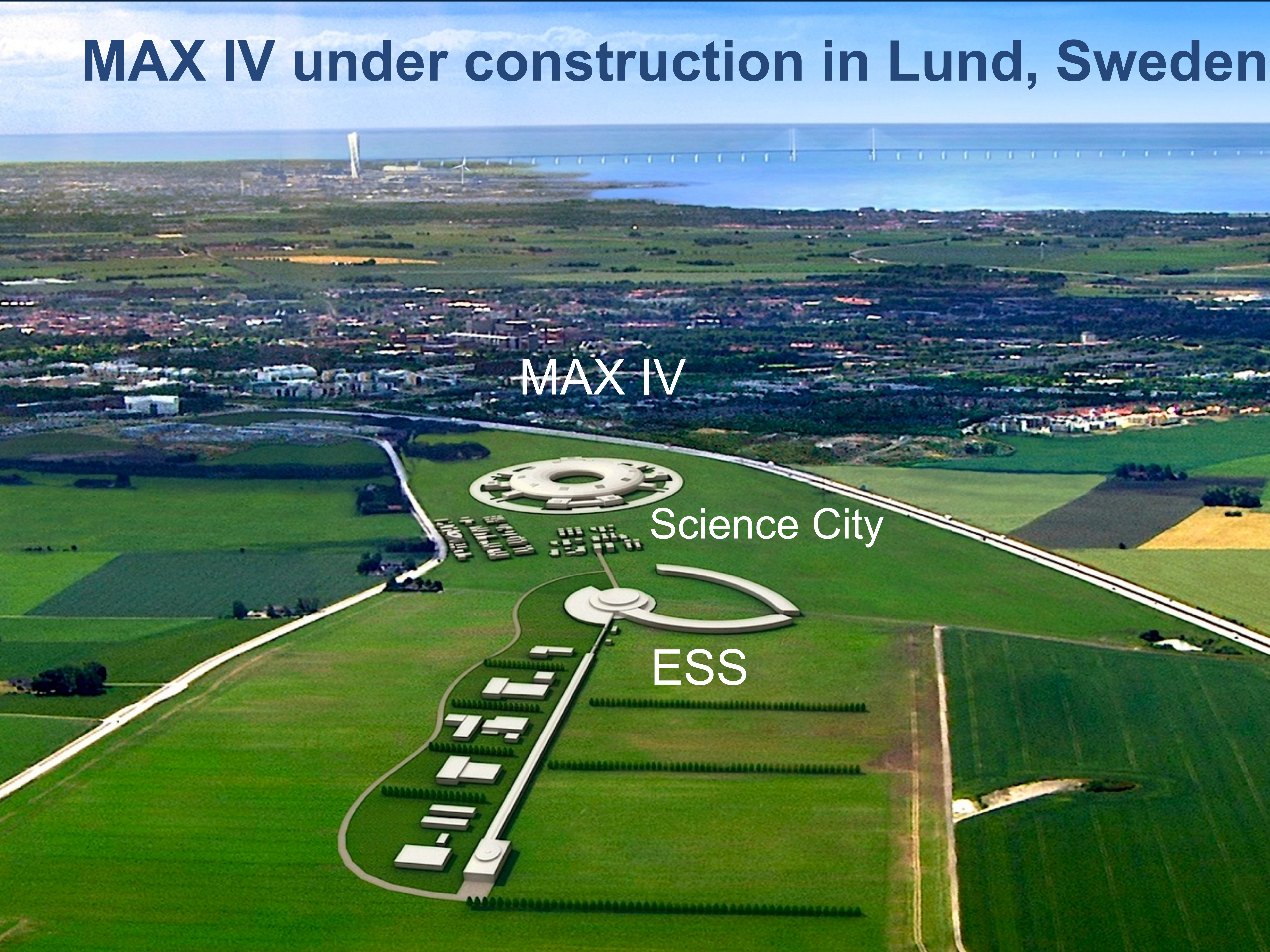


Low emittance, beam lifetime Touschek limited

- To achieve large Dynamic Aperture

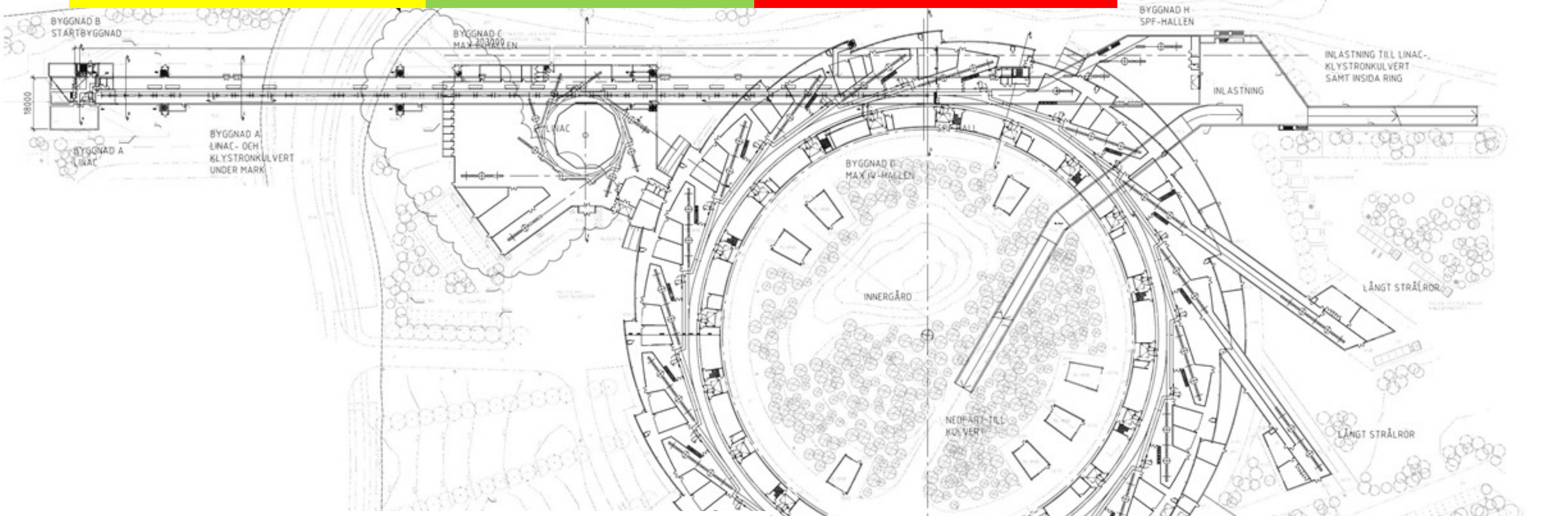
➔ small field errors required:
systematic errors $\Delta B/B=10^{-4}$, nonsystematic $\Delta B/B10^{-5}$ @ 25mm

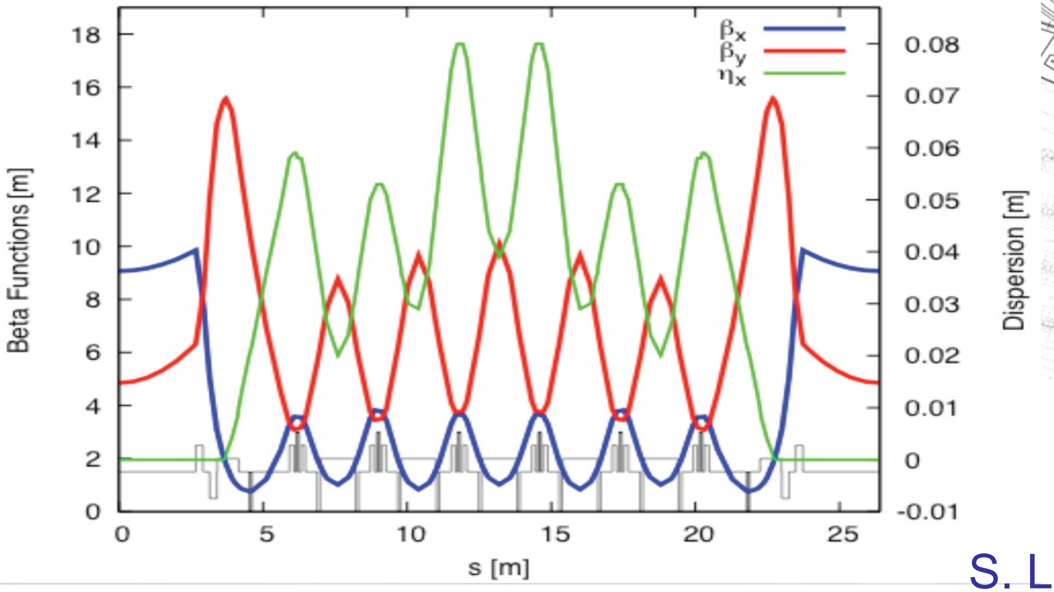
MAX IV under construction in Lund, Sweden



MAXIV: Multi (7)-Bend Achromat lattice

3.6 GeV Linac **1.5 GeV Ring** **3 GeV Ring**

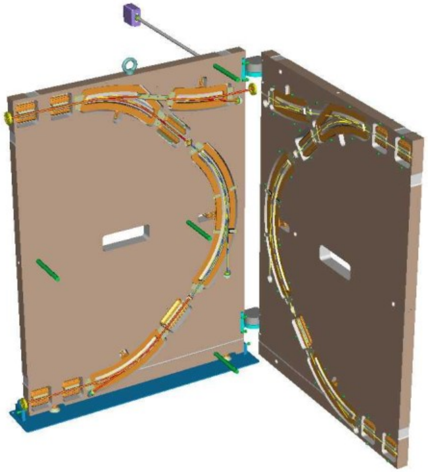


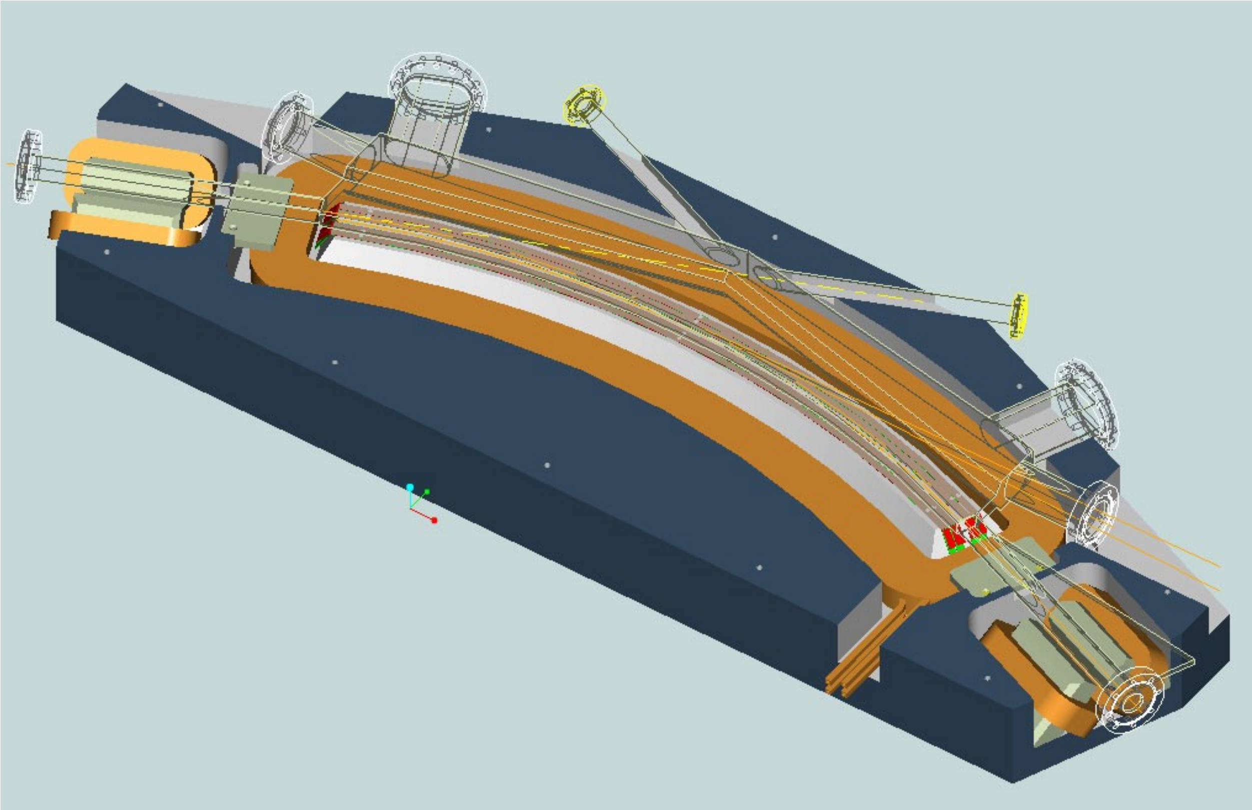


S. Leemann

MAX IV: innovative magnet structures

Magnets sharing a common yoke



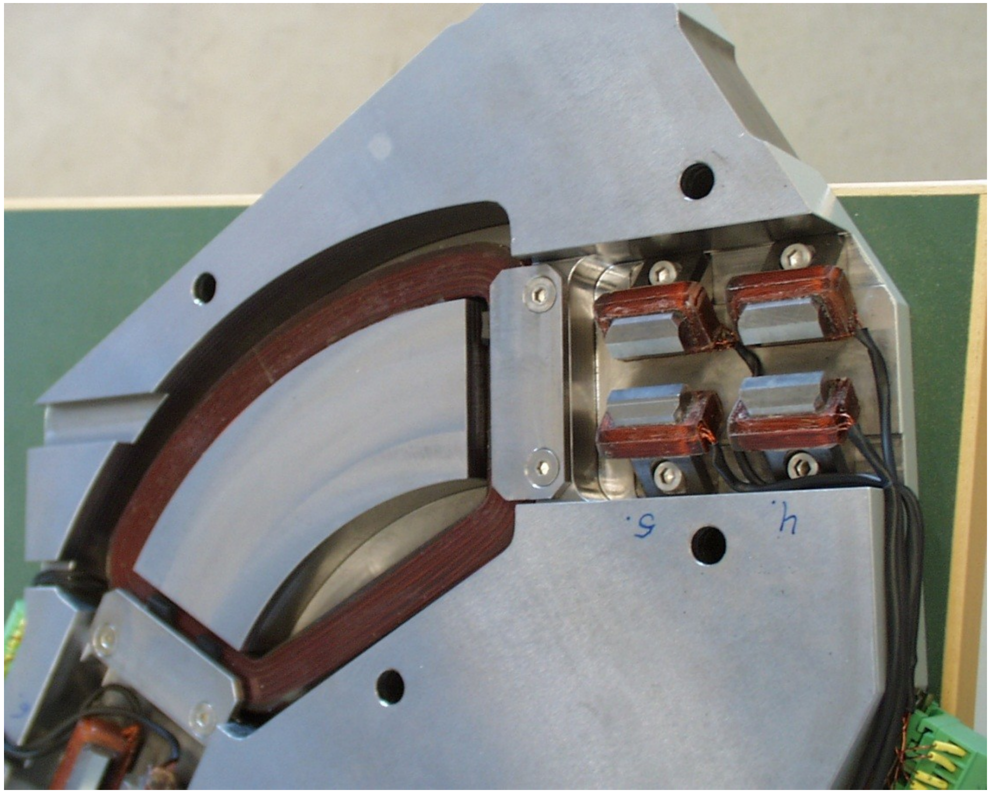


Very compact, economical ring design

MAXIV: innovative magnet structures

Challenges the existing models of ring elements

- proper magnet model
- fringe field control
- cross-talk
- hysteresis effects

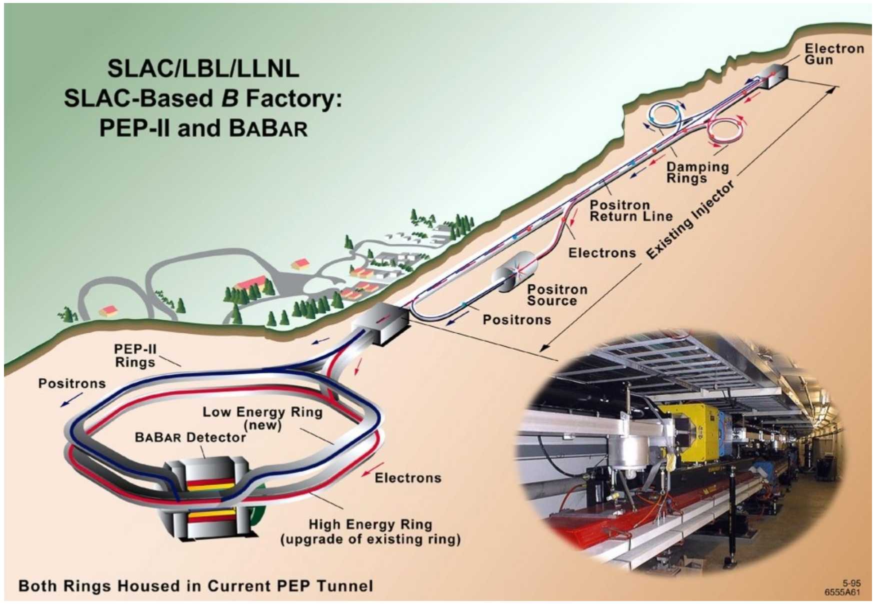


PEP–X: diffraction limited source

Large (2.2 km) tunnel could be filled with MBA cells and some of the straight sections with wiggler magnets

- MBA lattice can reach 30 pm emittance
- 90 meters of wigglers could reduce it to 10 pm

Diffraction limited source in both x&y planes



Y. Nosochkov

Model vs. reality

Great progress has been achieved in modeling rings to greater precison (e.g. LHC)

«Flight simulator» is indispensable for designing and building these inherently non-linear rings

Emittance blow-up and beam lifetime effects due to e.g. Intra-Beam Scattering (IBS) must be included

KISS: We build what we can model, a few rings were built with rectangular bending magnets, since only those were modeled in the code

Measurements: vertical dispersion

> «Door meten tot weten»
> *Heike Kamerlingh Onnes*

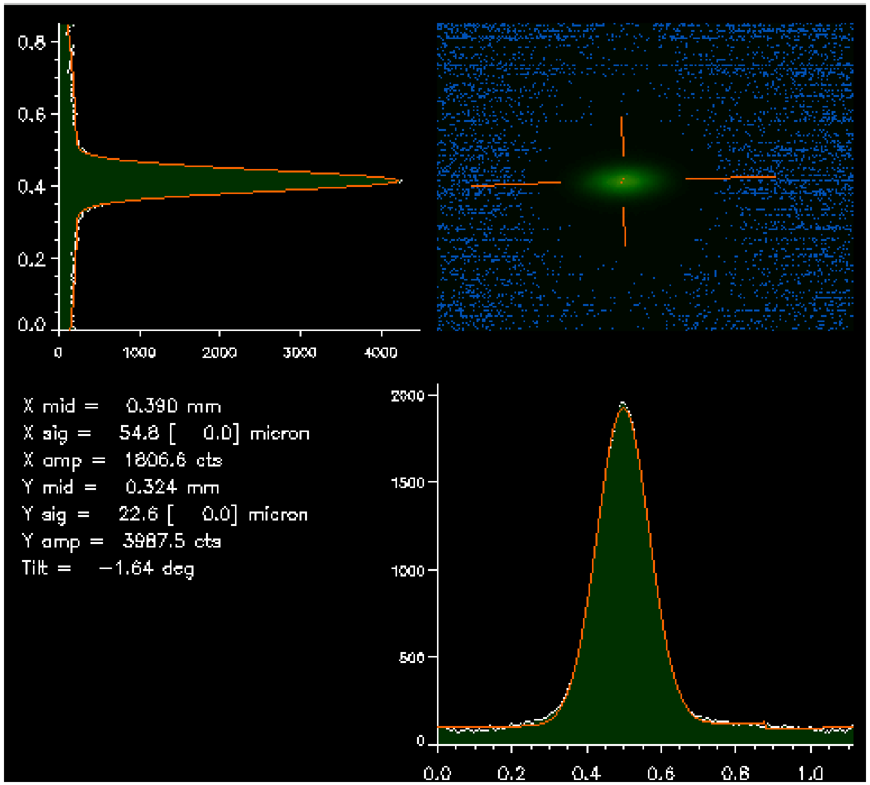
Coupling control to achieve small vertical emittance

- skew quadrupole in places with no dispersion
- vertical dispersion (spurious or not)

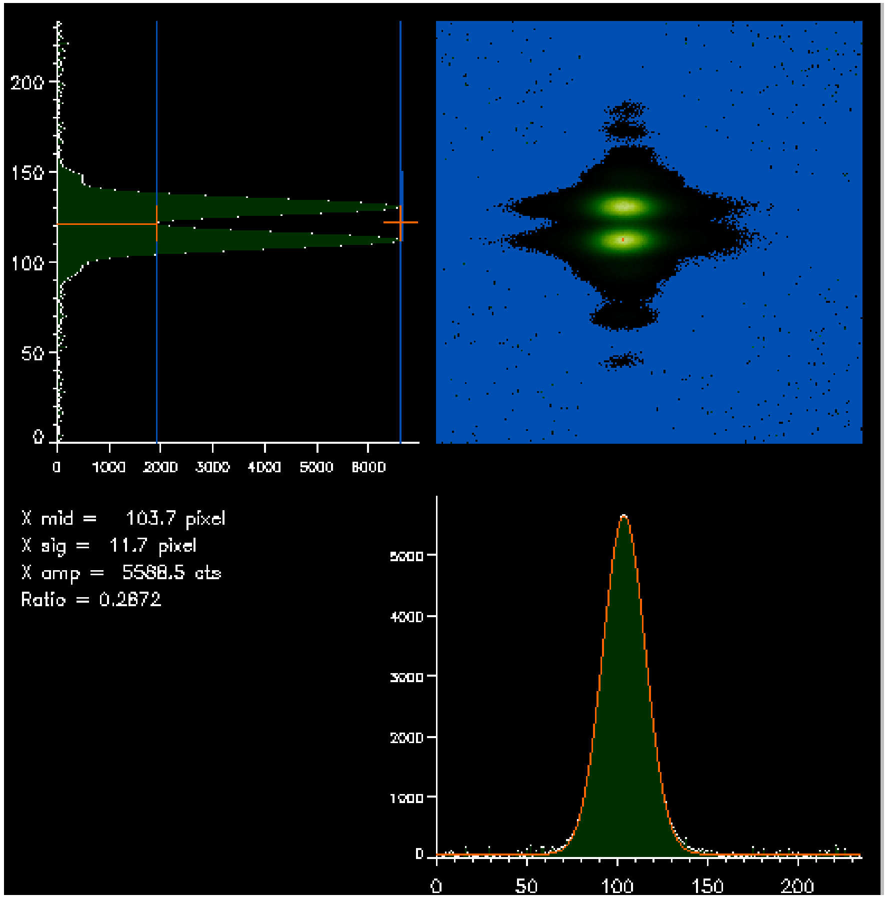
Good progress in vertical dispersion measurement resolution:

- down to 0.1 mm !

Measurements: micron size beams



X mid = 0.390 mm
X sig = 54.8 [0.0] micron
X amp = 1806.6 cts
Y mid = 0.324 mm
Y sig = 22.6 [0.0] micron
Y amp = 3987.5 cts
Tilt = −1.64 deg



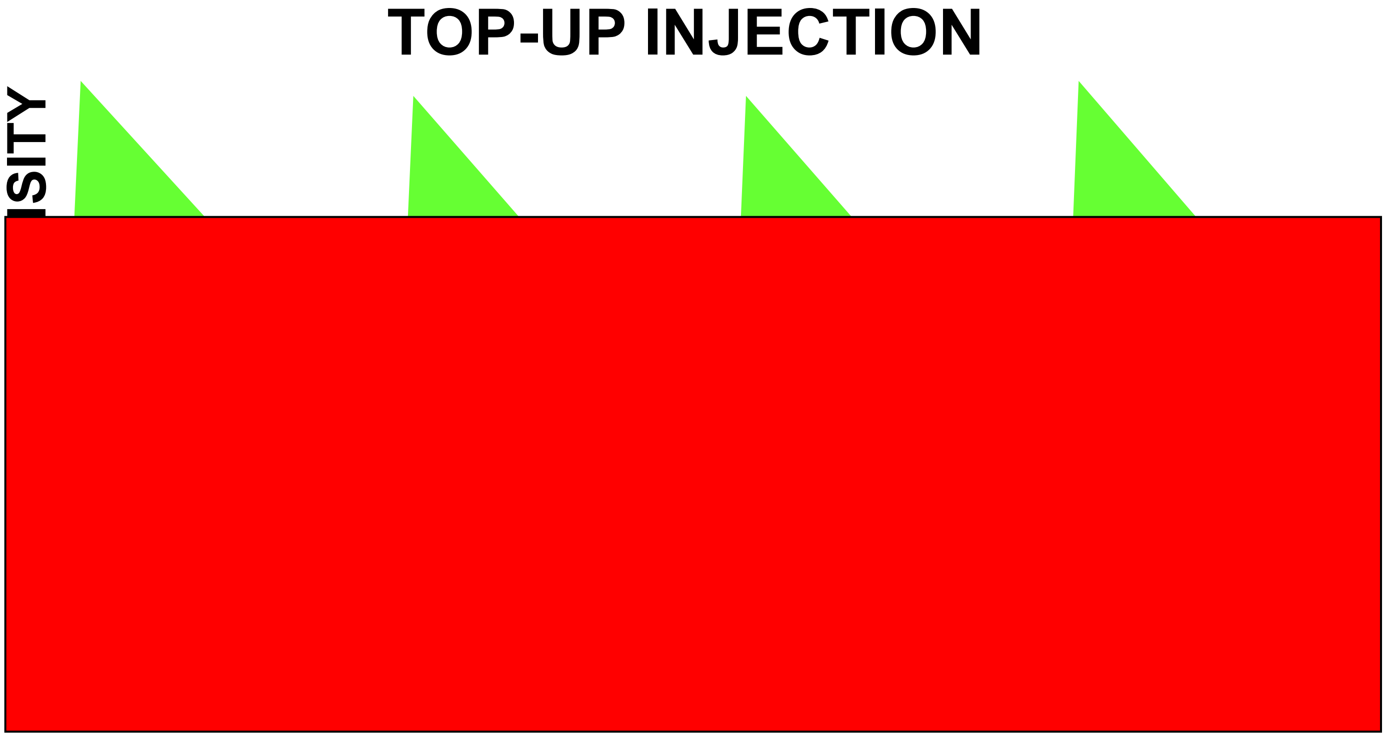
X mid = 103.7 pixel
X sig = 11.7 pixel
X amp = 5568.5 cts
Ratio = 0.2672

High resolution beam size monitors
in X-rays and vertically polarised visible light

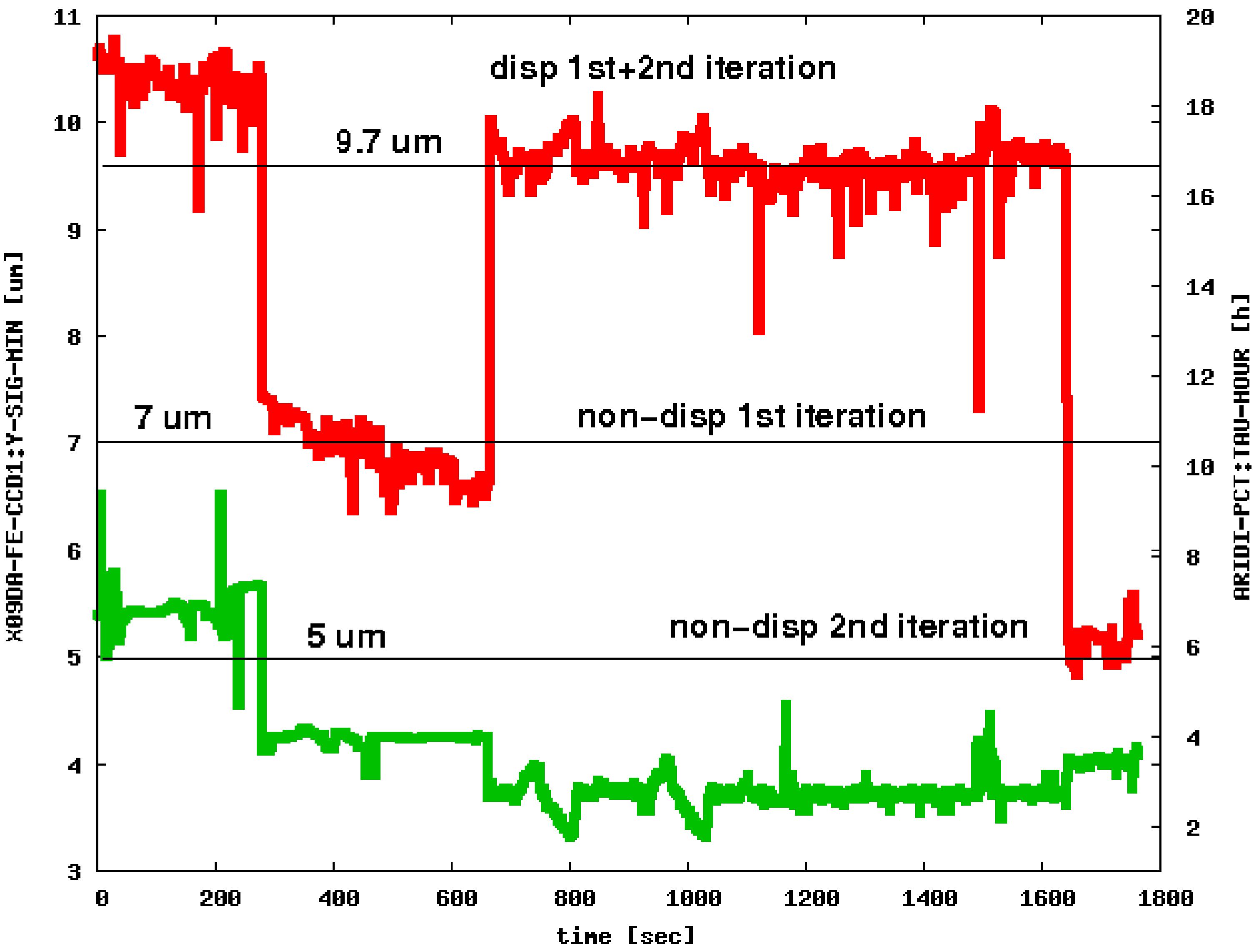
Å. Andersson

Top–up operation: unprecedented stability

- Used both at light sources and in colliders (trickle–in injection
- Opportunity for more precise measurements, no current dependent BPM noise



Small vertical emittance studies at SLS

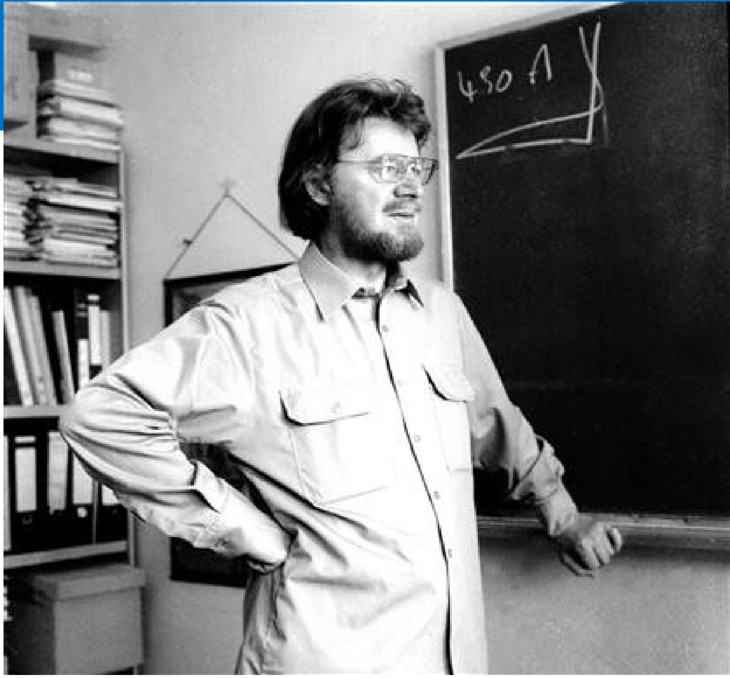


Vertical emittance limit

- Electron in a storage ring's dipole fields is accelerated, interacts with vacuum fluctuations

«accelerated thermometers show increased temperature»

- synchrotron radiation opening angle is $\sim 1/\gamma$-> a lower limit on equilibrium vertical emittance



John Stewart Bell (1928 – 1990)

- e.g. recent observation at SLS of less than 2 pm·rad, less than x10 above the limit (LOCO, vert. disp 1 mm, non-dispersive skew quads, BPM tilts, etc...)

TIARA collaboration SVET (CERN, INFN/LNF, MAX-IV, PSI) to reach below **1 pm·rad** or 5 nm·rad normalised (CLIC)

cf. SLS talk by Masamitsu Aiba this afternoon

Light sources challenges

Design and modeling of

- inherently non-linear very low emittance rings with sufficient apertures
- taking into account properly the collective effects
- better measurements techniques to monitor and develop tuning tools fully integrated with the on-line model
- better stability of the photon source (feedbacks)

Approach the quantum limit on vertical emittance, there may be some interesting surprises there

Thank you