Storage ring based light sources

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  - History of light sources
  - Accelerators for science
  - Light source generations
  - The role of storage rings
- Light sources all over the world
- Performance
  - How to get low emittance
  - A performance comparison
  - The challenge: dynamic aperture
  - The trump: stability
- The "π-generation" : seven trends in lattice design
- Beyond storage rings: the energy recovery linac
- Conclusions

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CANDLE-DESY-PSI Collaboration Workshop
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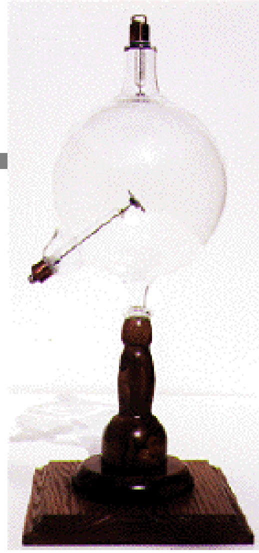
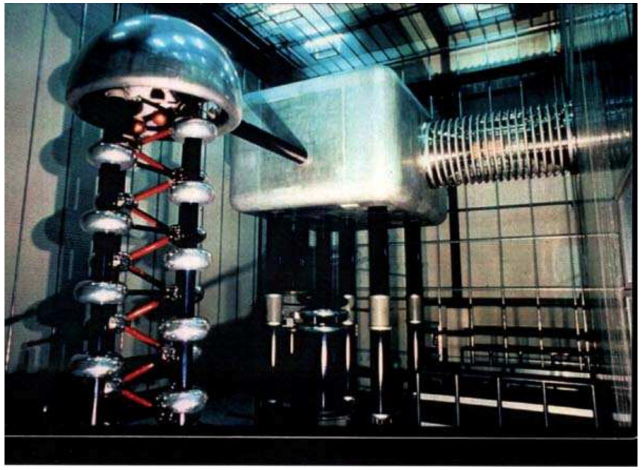
Pre- History



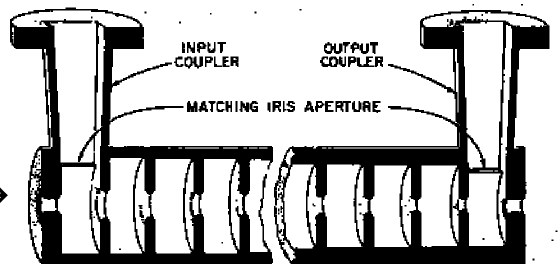
≤1890: cathode rays
Lenard et al.

1895: X-rays
Röntgen (nobel prize 1901)

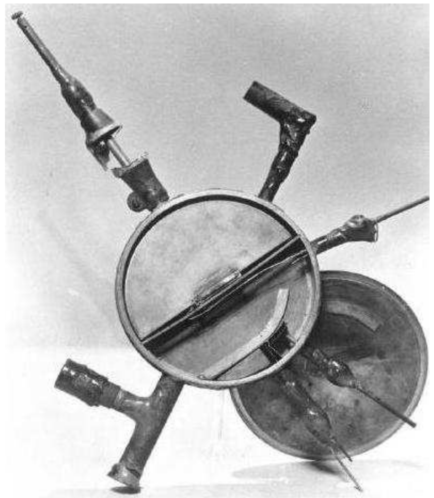
1920...1930: high voltage generators →
Marx, Cockcroft/Walton, van der Graaff



1925/28: RF acceleration→
Ising, Widerøe

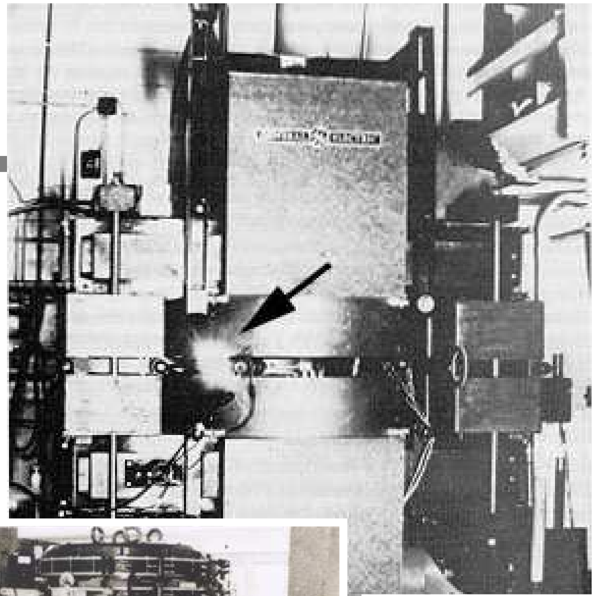


1932: the cyclotron → →
Lawrence/Livingston



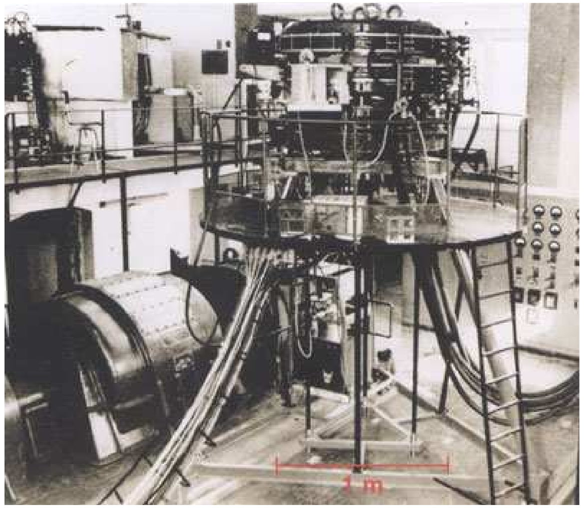
1940: the betatron →
Kerst

History



1945: the **synchrotron !**
Veksler, McMillan

1947: synchrotron radiation →
Langmuir et al.



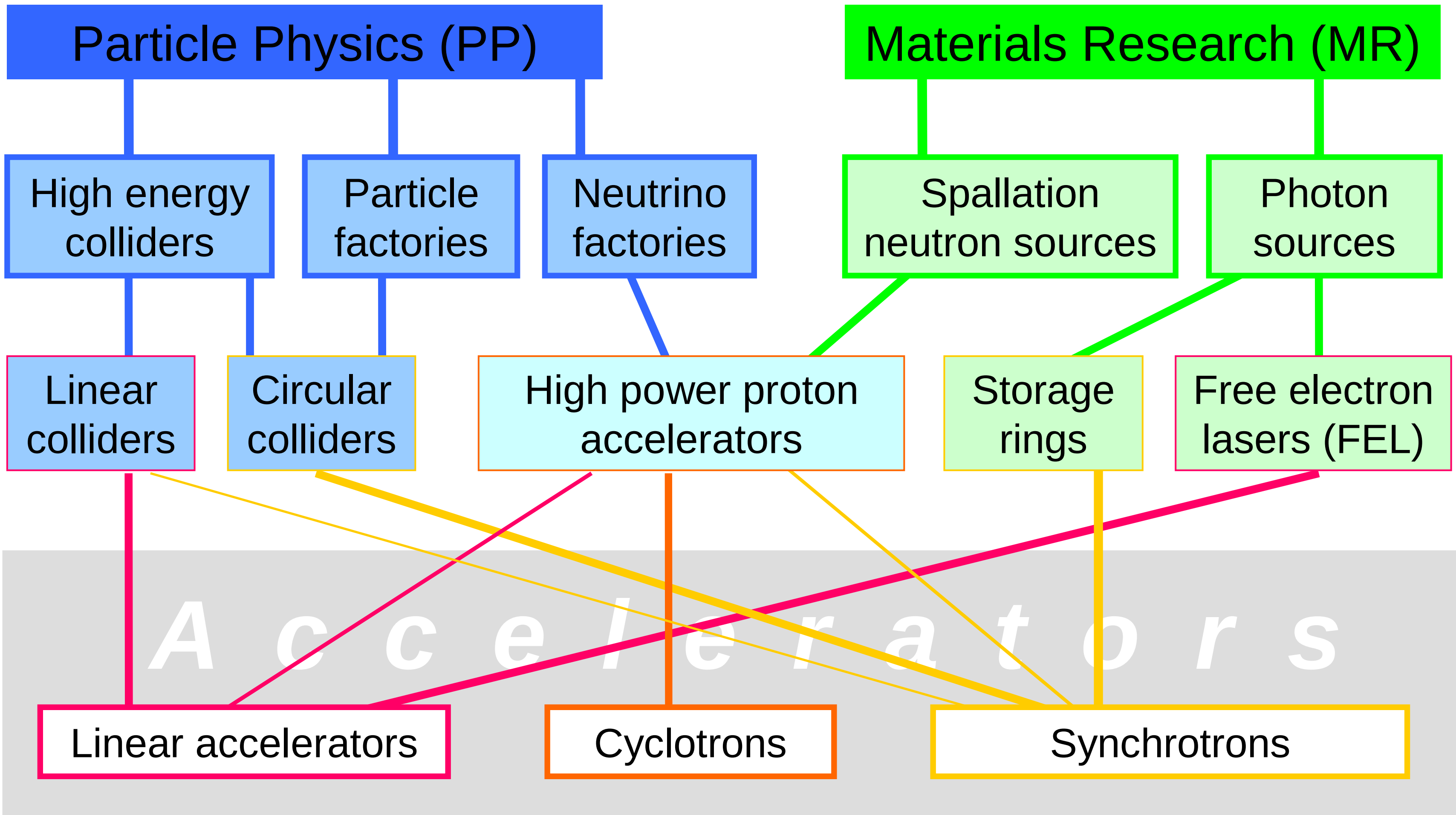
1958: alternating gradient focusing
Courant/Snyder

1962: **e^+e^-** collisions →
AdA Frascati

1964: first double ring collider (**e^-e^-**) →
VEP-1 Novosibirsk

1989: **LEP** 27 km **e^+e^-** collider (2×104 GeV)

Accelerators for science



Light source generations

1st generation (60's/70's): : parasitic use of PP rings
SURF (1962), DESY (1964), INS-SOR
ACO, SPEAR, DORIS, VEPP-3 ...

2nd generation (80's): dedicated rings, dipole radiation
SRS, NSLS, BESSY (all 1981), KEK-PF (1982), LURE (1984)

3rd generation (90's and later):
radiation mainly from IDs, many straights, $\varepsilon = 3..10$ nm
ESRF, ALS , ELETTRA , PLS (all 1994) , APS (1996)
BESSY-2, SLS, SOLEIL, DIAMOND, ALBA, CANDLE ...

π – generation: (≥2010):
ID dominated lattice, use of damping wigglers, $\varepsilon < 1$ nm
PETRA-3 (2010), MAX-4 (2015), NSLS-2 (2015)

4th generation (≥2010):

- X-ray free electron lasers (pulsed): $\varepsilon \sim 10$ pm + *SASE*
  LCLS, EuroFEL, SwissFEL
- energy recovery linacs (continuous): $\varepsilon \sim 10..100$ pm
  X-ray ERL projects: CESR, KEK
- "ultimate light source": large ring, frequent injections, $\varepsilon \sim 10$ pm

The role of storage rings

Advantages

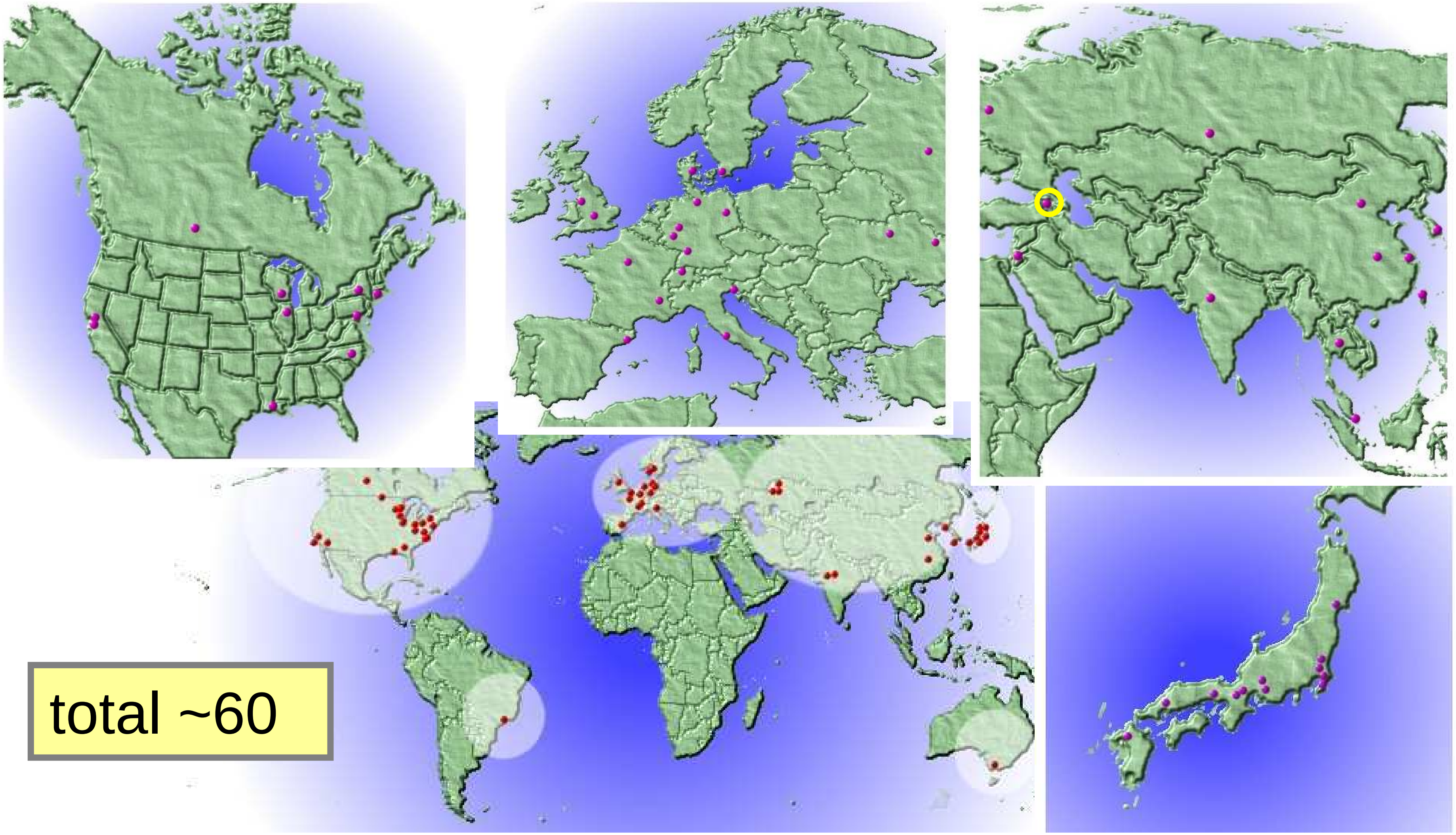
- Economic: many beam lines: **10...50**
- Reliable: 95% – 99% availability
- Very stable: < **1** μ**m** at frontend for days
- Bright: low vertical emittance: **~8 pm = 1Å/4**π

Disadvantages

- Large horizontal emittance: >> **100 pm**
- Long pulses: > **10ps** FWHM
  except low flux laser beam slicing: **100 fs** FWHM

➔ can take large work loads (e.g. protein cristallography)
➔ used mainly for not time resolved experiments
➔ complementary to X-FELs

Light sources world map

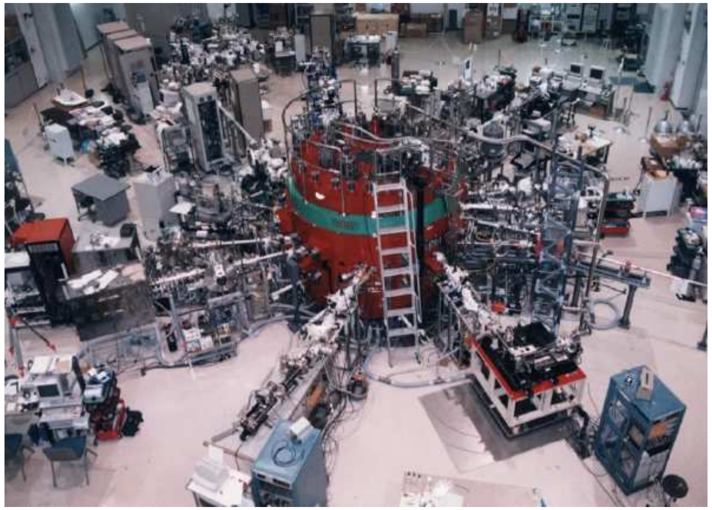


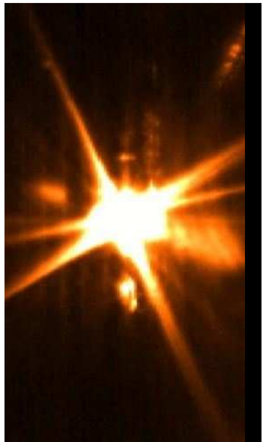
total ~60

clickable world map at **http://www.srs.ac.uk/srs/SRworldwide/**

Light source examples

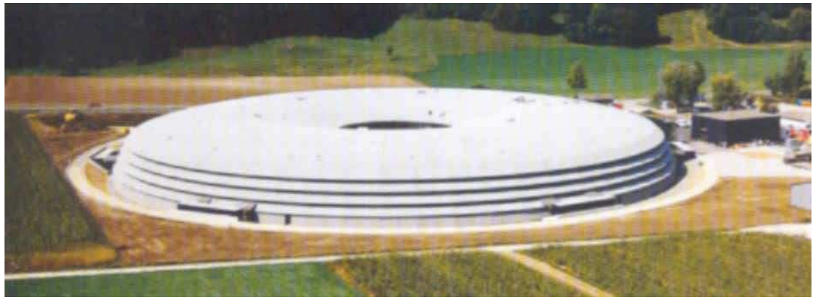
AURORA 0.65 GeV, π m



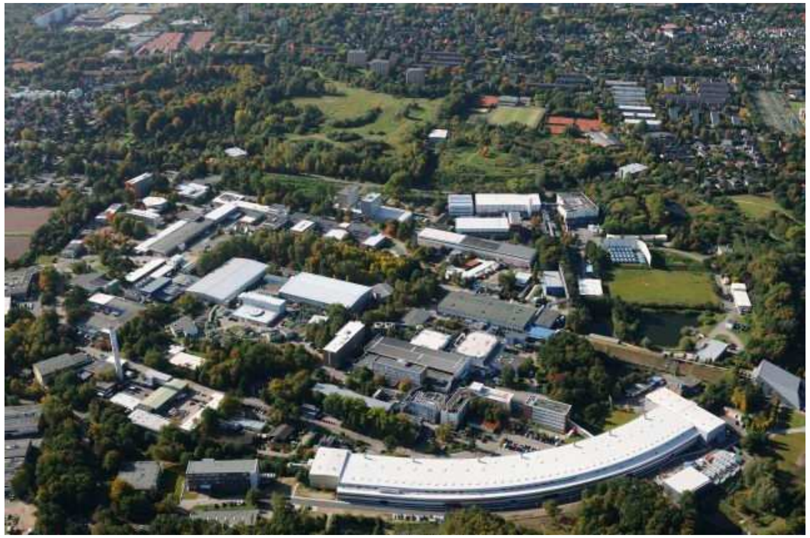


15.12.2000: first light from SLS

SLS 2.4 GeV, 288 m



PETRA-3 6 GeV, 2304 m



SPRING-8 8 GeV, 1436 m

Emittance

↖ 2470 nm

5 nm ↗

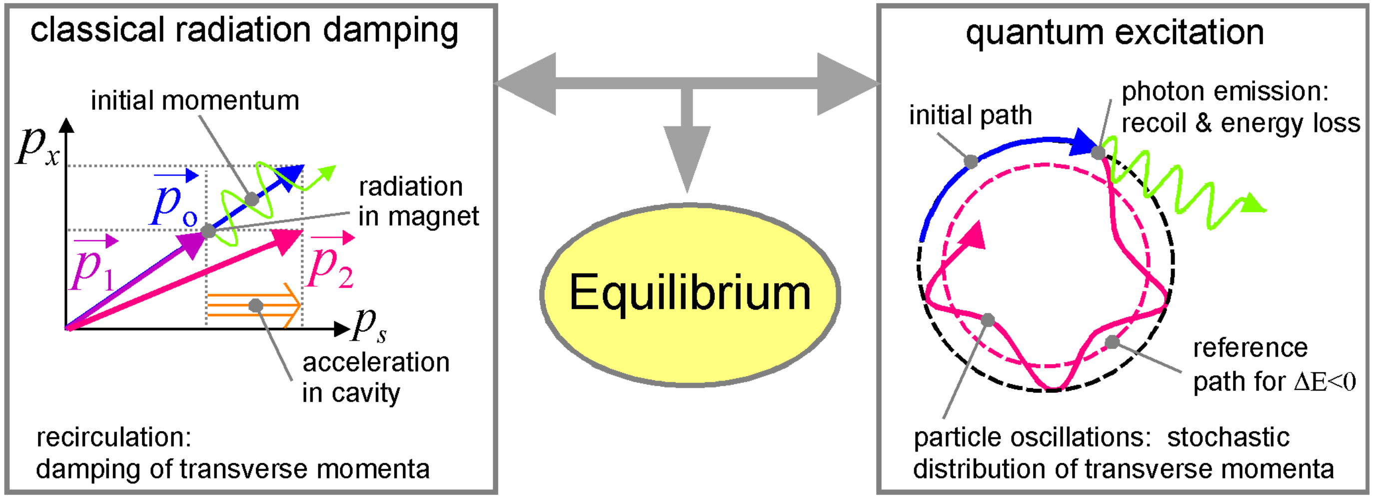
← 7 nm

1 nm →

Storage ring emittance

Horizontal emittance

- determined by radiation equilibrium
- independent of injected beam properties
- minimize by lattice design:



⇒ dipole dominated (isomag.) lattice $\varepsilon_x \sim E^2\, \Phi^3\, F \,/\, J_x$

⇒ damping wiggler dominated lattice $\varepsilon_x \sim E^2\, B_w^{\,3}\, \lambda_w^{\,2}\, \beta_{xw} \,/\, J_x$

energy, angle per dipole, beam optics, wiggler field and period, damping partition

Vertical emittance (of a *flat* lattice)

- rather low by nature ($\varepsilon_y <$ 1 pm)
- determined by coupling: $\varepsilon_x / \varepsilon_x > 5\cdot 10^{-4}$

Low emittance recipes

Parameters for emittance minimization (E is given)

F : focus in each dipole: all light sources

- ⇒ limits reached (**F ~ 5**, theoretical limit **F=1** out of reach)
- ⇒ allow dispersion in straights (→ **F/3**): SOLEIL, ALBA...
- ⇒ longitudinal gradient bend (**F < 1 ?**): *not yet used*

J_x: use gradient dipoles to shift damping from longitudinal to horizontal: ALBA, MAX-IV...

- ⇒ max. factor ½ in ε , increase of energy spread

Φ : use very many lattice cells: low angle per dipole: MAX-IV

- ⇒ large circumference
- ⇒ magnet and vacuum chamber miniaturization

B_w , λ_w : use damping wigglers

PETRA-III (→ ε / 4.5), NSLS-II (→ ε / 3), MAX-IV (→ ε / 2)

- ⇒ high radiated power (PETRA-III: 1.1→ 6.0 MW!)
- ⇒ many damping wiggler straights → large circumference

Performance comparison

score ~ (emittance / scaled emittance $)^{-1}$

score $= K \cdot \frac{1}{\varepsilon} \cdot \frac{E^{7/2}}{(C-S)^3} \cdot \frac{1}{J_x} \cdot f(M, D_s/D_{max})$

K = a constant ε = emittance
S = total straight length
M = achromat type (MBA)

E = beam energy C = circumference
J_x = horizontal damping partition
D_s, D_{max} = straight and max. dispersion

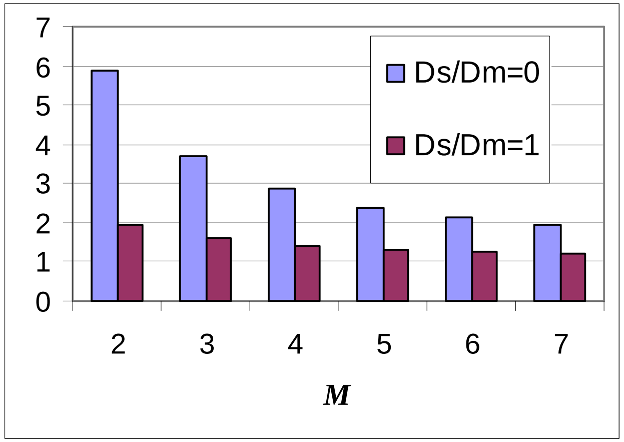
Emittance scaling:

$$\boldsymbol{\varepsilon \sim E^2 / J_x \cdot N_{bend}^{-3}}$$

$\mathbf{N_{bend}}$ ≈ arc length / cell length = $(C - S)/L_{cell}$
approx. cell length scaling: $L_{cell} \sim \sqrt{E}$

Function taking into account lattice type and matching to straights:

$$f(M, D_s/D_{max}) = \left(\frac{M+1/2}{M}\right)^3 \cdot \left(1 + \frac{4}{M} \cdot \left(1 - \frac{D_s}{D_{max}}\right)\right)$$



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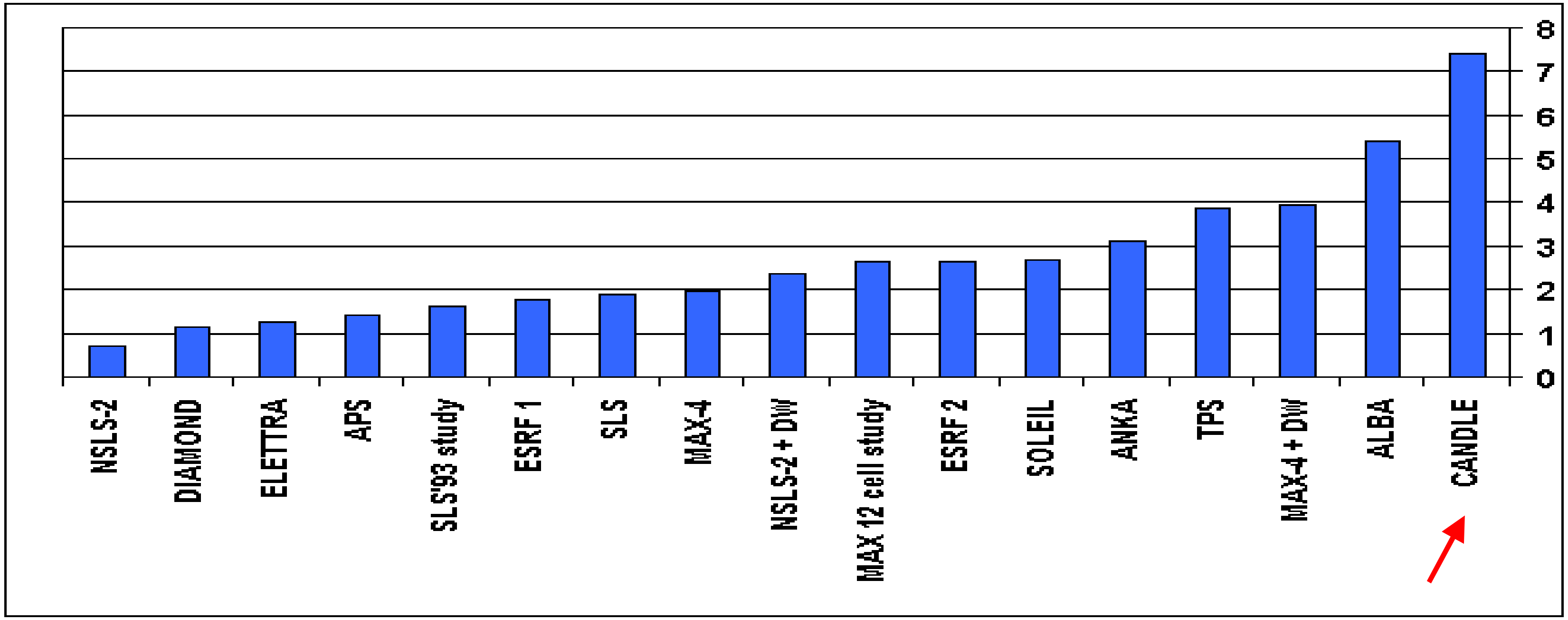


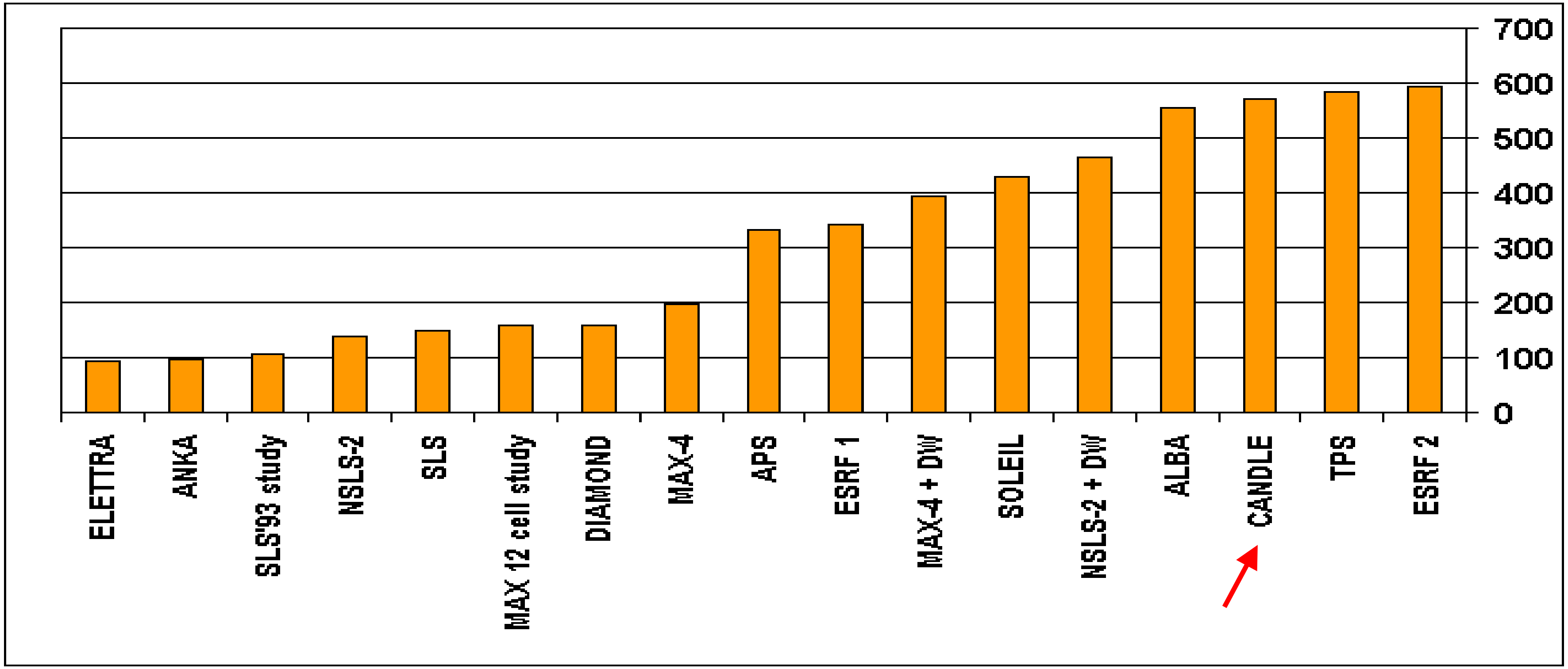
Performance comparison

too much weight on compactness of ring ?

users also want many straights !

don't punish large rings for providing many straights!

⇒ **new score** = previous score × total straight length S



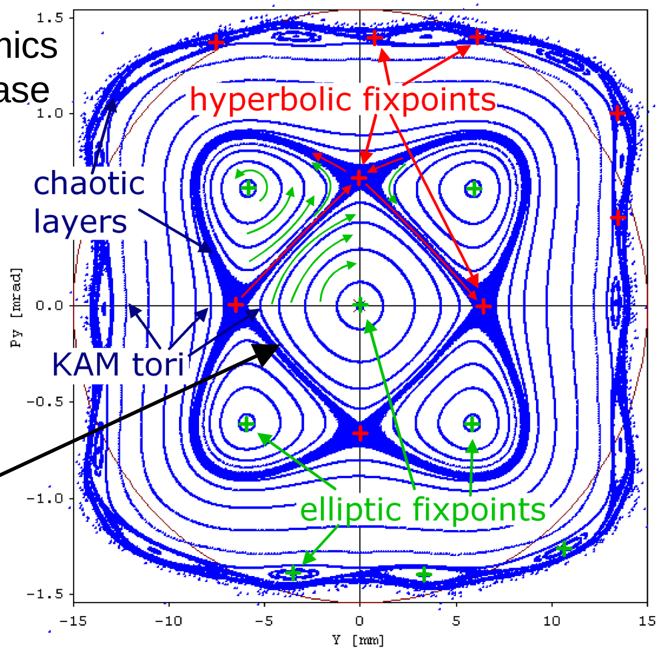
Challenge: dynamic aperture

Low emittance lattice

- ⇨ 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")
- ☠ short lifetime of stored beam
- ☠ no injection, or only at low rate

⇒ main design challenge for rings !

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



To do:

- ⇨ find optimum sextupole scheme
  → design task
- ⇨ correct machine imperfections
  → commissioning task

Example: SLS magnets

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

Trump: beam stability

- Top up operation: thermal stability
- Beam position monitors
  resolution < 0.3 μm*
- Digital power supplies
  stability and reproducability < 30 ppm*
- Frequent beam based BPM calibration
  ("beam based alignment")
- Insertion Device feed forward tables
- Fast orbit feedback system (0dB @ 100 Hz)*
- Photon-BPM integration in FOFB
- Filling pattern feedback system

* Numbers for SLS, partially subject to further upgrade

⇒ Photon beam stability **<1 μm** rms* at frontend

Seven trends in storage ring design

1. Specialized machines: MAX-Lab

- large low-emittance ring for X-ray beam lines
- small medium emittance ring for VUV beam lines
- X-FEL for time resolved beam lines

2. Use of damping wigglers

PETRA-III ($\rightarrow \varepsilon / 4.5$), NSLS-II ($\rightarrow \varepsilon / 3$), MAX-IV ($\rightarrow \varepsilon / 2$)

- rather weak (long) arc dipoles
  to make DW dominant
- dispersion free straights
  otherwise anti-damping from insertion devices
- strong radiation damping
  for suppression of coupled bunch instabilities

The π–generation

3. Combined functions

- good codes: reduce flexibility
- Magnets:
  B+B' (CANDLE, ANKA),
  B+B'+B'' (SLS-Booster)
  B'+B''' (MAX study)
- Common yoke (MAX-3)
- Magnets fixed to girders (SLS)


figure taken from MAX-IV CDR

4. Use of "unusual" magnets

- longitudinal gradient bending magnets for lower emittance
- octupoles for 2^{nd} order chromaticities and amplitude dependent tune shifts (MAX-4)
- decapoles for 3^{rd} order chromaticities

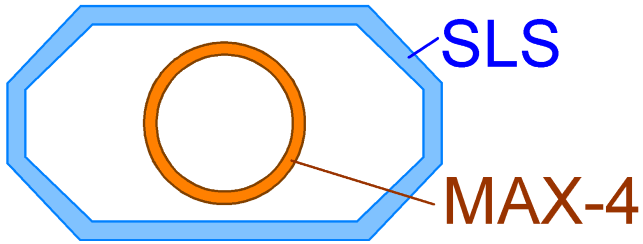
} Dynamic aperture optimization

The π–generation

5. Small apertures (MAX-4)

$$a_x = 2D_{\max}(\Delta E / E)_{acc} \qquad a_y = \sqrt{\beta_{y,\max} / \beta_{y,ID}}\, \frac{gap}{2}$$

- higher magnet gradients
- shorter magnets
- compact multi bend achromat: low dispersion



6. Low frequency (~100 MHz) RF system (MAX-4)

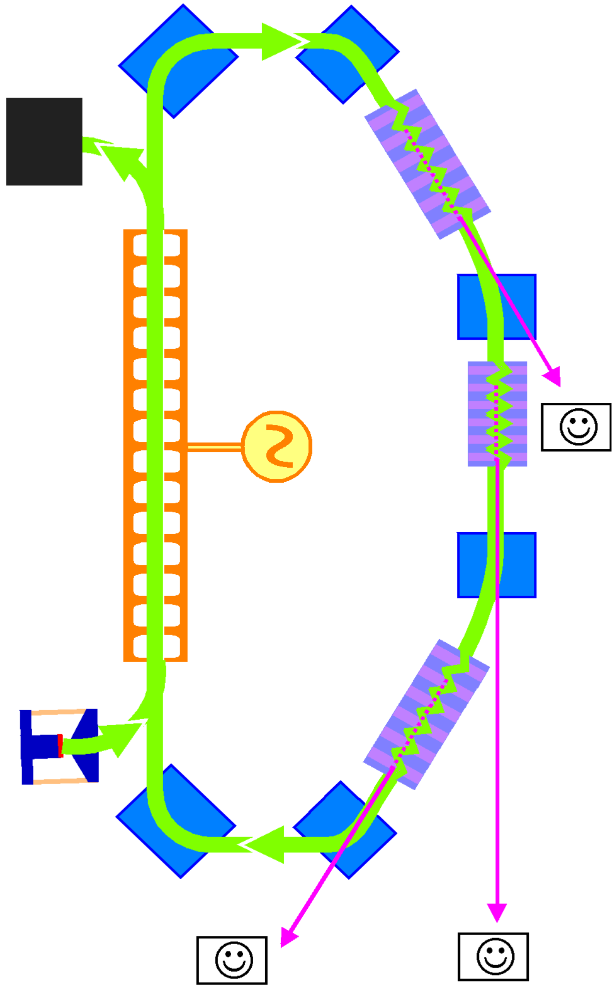
- damping of resistive wall instability
- efficient FM amplifiers (tetrodes)

7. Copper beam pipe as distributed absorber (MAX-4)

- Distributed absorber (low dipole field!)
- NEG coating for UHV

The energy recovery linac

...beyond storage rings: the ERL



- beam quality like a linac...
  - emittance: 10..100 pm*
  - bunch length 2 ps → 20 fs*
  - round beams
- ...else almost like a storage ring
  - current 10..200 mA*
  - quasi continuous (GHz rep rate)
  - many beam lines
  - flexible optics & time structure
- ➔ perfect storage ring successor
- ➔ complementary to XFEL
- serious challenges:
  - beam power, high intensity gun, s.c. linac design etc.
  - R&D going on worldwide (e.g. *Cornell ERL project)

Conclusions

- Storage rings are the base for SR research.
- Economic. ◆ Reliable. ◆ Stable.
- Complementary to X-FELs.
- ~60 SR-LS in operation, more to come.
- Interesting developments in "π-generation".
- ERLs may replace SRs in far future (?)
- Convincing CANDLE design:
  high performance from compact machine.