The Evolution of 4th Generation Storage Ring Light Sources

Robert Hettel
APS Upgrade Project Director, ANL

Coherence in Particle and Photon Beams: Past, Present and Future
March 15, 2019

What’s in a name?

USR

- The term “ultimate storage ring” was first use in 2000:

  A. Ropert, J.M. Filhol, P. Elleaume, L. Farvacque, L. Hardy, J. Jacob, U. Weinrich, "**Towards the Ultimate Storage Ring-Based Light Source"**, Proc. EPAC 2000, Vienna.

- “Ultimate” may have many meanings, including providing everything for every user

DLSR

- Diffraction limited storage ring
- All storage rings are diffraction limited for some λ

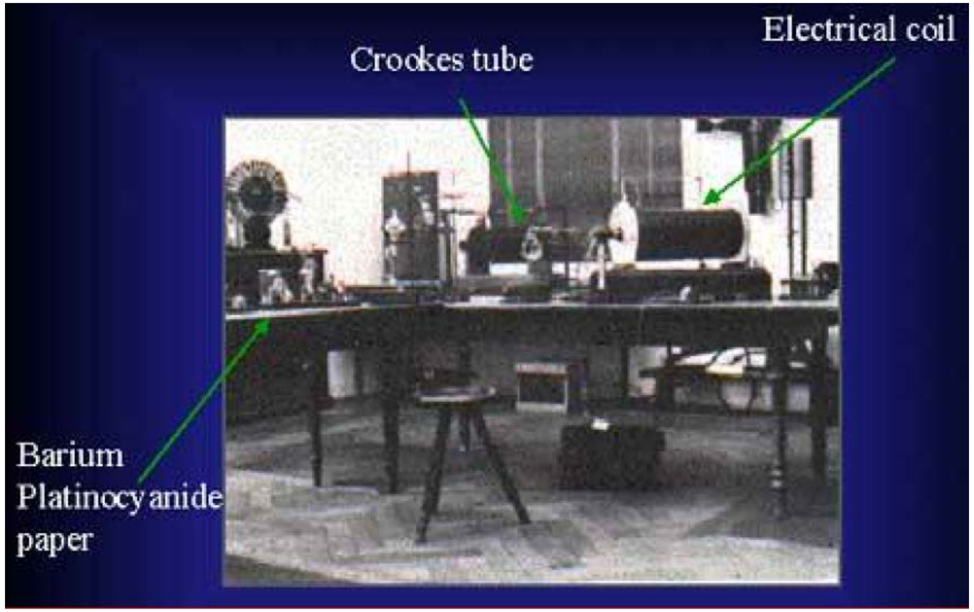
$$\varepsilon_r(\lambda) = \frac{\lambda}{4\pi}$$

4GSR

- 4th generation storage ring

The evolution of accelerator-driven X-ray sources in 100+ years

Wilhelm Röntgen 1845-1
Discovered X-rays in 1895



Röntgen's Laboratory in Wurzburg, Germany - 1895

HEPS Beijing

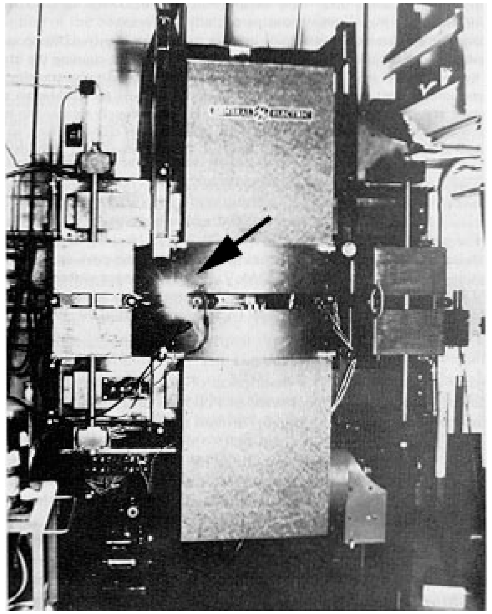
Circular particle accelerators

Ion cyclotron (1931)

Electron betatron (1935)

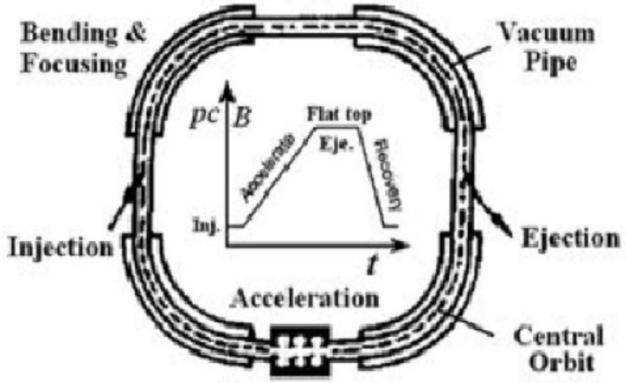
A German 6 MeV
electron betatron in 1942

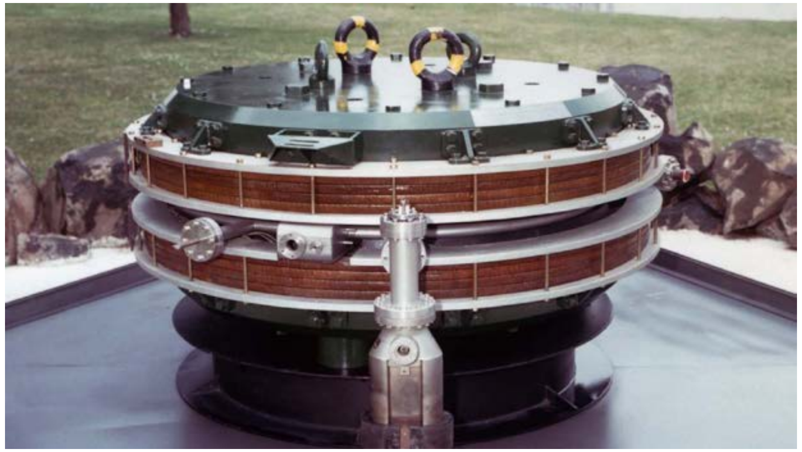
Electron synchrotron (1945)



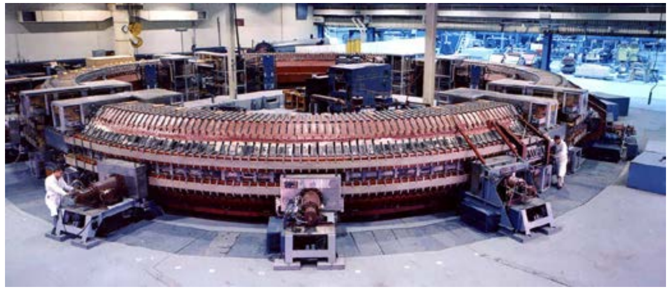
First observation of man-made "Schwinger radiation" from GE 70-MeV electron synchrotron - 1947
Pollock, Langmuir et al.

Ring-based synchrotrons and the first storage rings

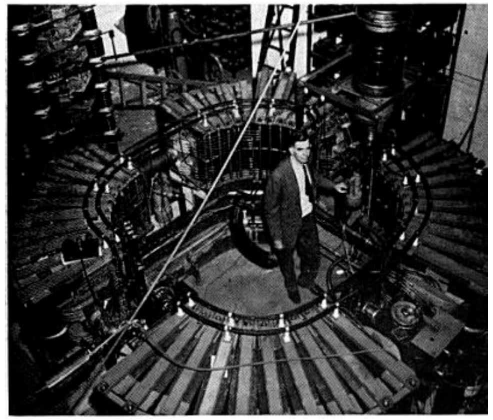




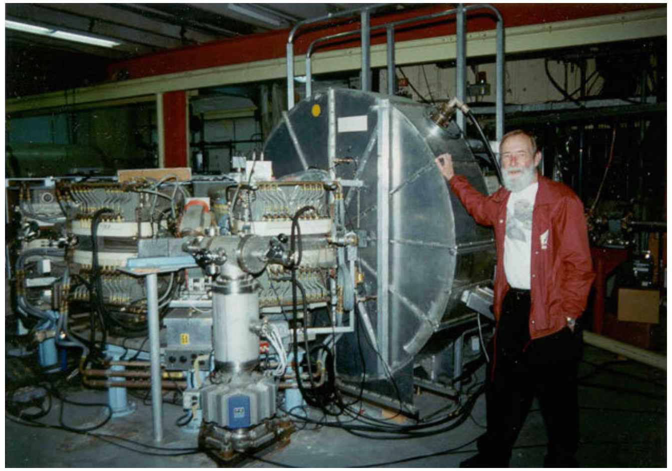
Anello di Accumulazione – ADA, ~1 GeV
B. Touschek, proposed 1960



Cosmotron – early 50s ~3 GeV
proton synchrotron



300 MeV electron synchrotron
at University of Michigan, 1949



1968 – Tantalus I - first
dedicated SR storage ring

1st generation of storage ring light sources

- Parasites on electron synchrotrons (1950s and 60s)

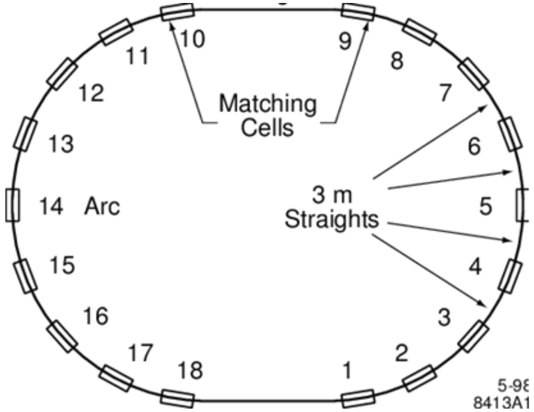
  Moscow Univ/Lebedev Inst, DESY, Roma Univ/Frascati, Bonn Univ, NBS/Washington DC, Univ of Tokyo, Cornell, CEA, NINA

- Parasites on e+/e- colliders (1970s +)

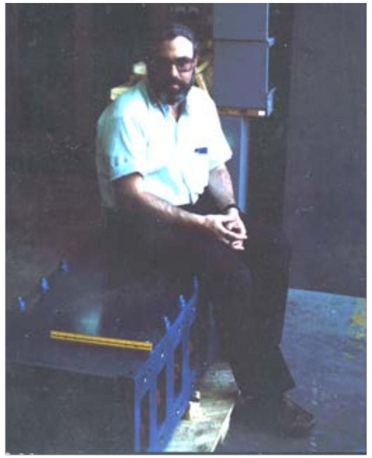
  SPEAR, DORIS, VEPP-3, DCI, CESR/CHESS, ...

- Bend magnet and wiggler X-ray sources

SPEAR 1971



SPEAR II FODO, dispersion in straights

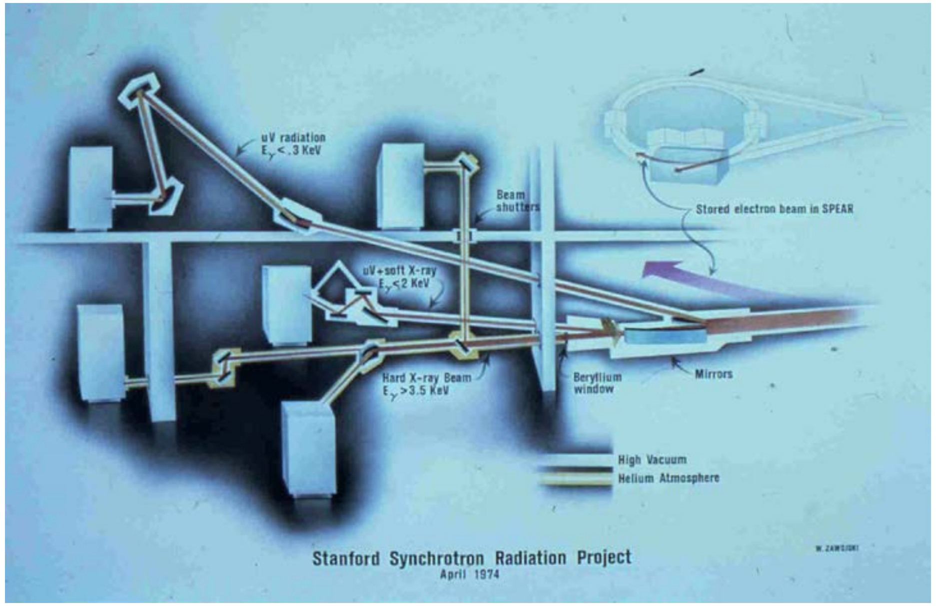


Herman Winick and his wiggler

SSRP beamlines

1971

1972

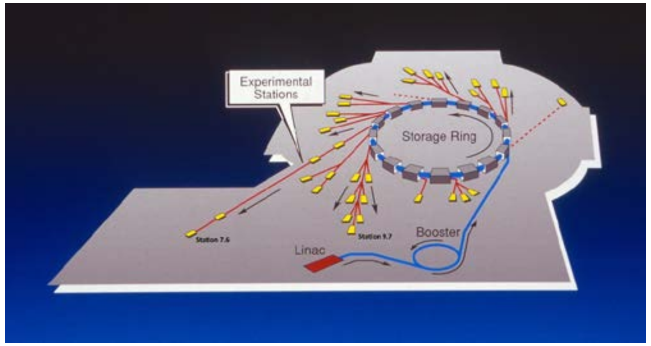


1974

2^{nd} generation of storage ring light sources

- **Parasitic or dedicated on storage rings using bend magnets and wigglers**
- **Typically FODO lattices, few hundred nm-rad emittances**

SOR-RING, SRS, Photon Factory, UV-SOR, NSLS-I, Aladdin, Super ACO, Hefei, …

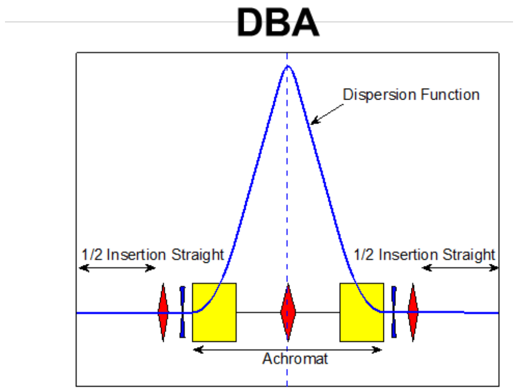


1981 - Daresbury SRS, first dedicated 2nd gen source (2.5 GeV)

1982 - Photon Factory (2.5 GeV)

NSLS – 1982 VUV, 1984 X-ray (2.5 GeV)

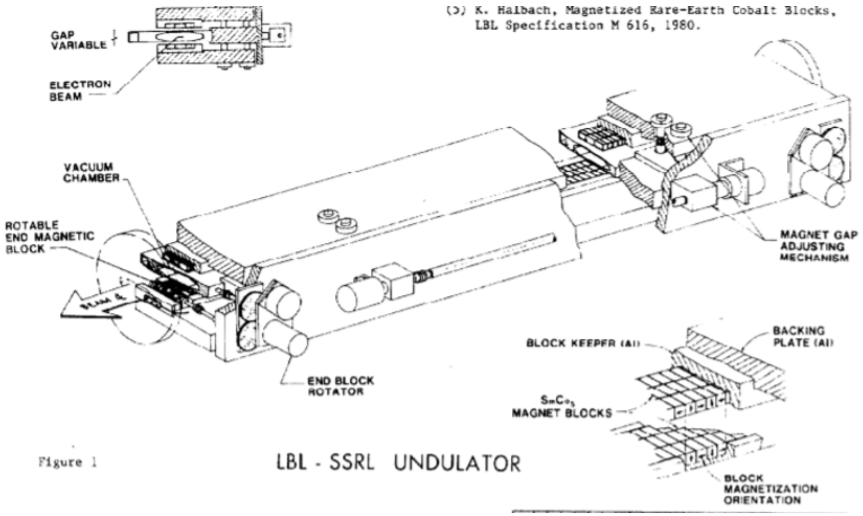
Chasman-Green lattice (DBA) becomes basis of 3rd generation, with variants



Ken Green,
Marty Blume,
Renata Chasman

Brightness and undulators

- **Narrow slits (spectroscopic resolution), small apertures, microfocus applications, etc., become more important**
- **Brightness becomes a metric of interest in late 70s and 80s**
- **Undulators become IDs of interest**
  - Vitaly Ginzburg showed theoretically that undulators could be built in a 1947 paper.
  - Julian Schwinger reduced the necessary calculations to Bessel functions in 1949.
  - Hans Motz and his coworkers at Stanford University demonstrated the first linac undulator in 1952.
  - Installation of undulators in storage rings at the Lebedev Institute in Moscow and the Tomsk Polytechnic Institute in 1970s.
  - Undulators only became practical devices for insertion in synchrotron light sources in 1981, when teams at the LBNL, SSRL, and at BINP developed permanent magnetic arrays, known as Halbach arrays,



Klaus Halbach with Kwang-Je Kim witha model of an undulator that Halbach designed in 1986

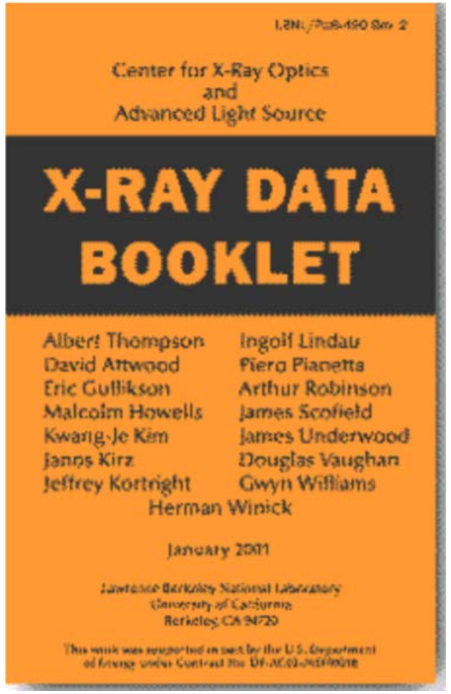
Brightness and coherence formulation

Nuclear Instruments and Methods in Physics Research A246 (1986) 71–76
North-Holland, Amsterdam

BRIGHTNESS, COHERENCE AND PROPAGATION CHARACTERISTICS OF SYNCHROTRON RADIATION *

Kwang-Je KIM

Center for X-ray Optics, Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720, USA



AIP Conference Proceedings **184**, 565 (1989)

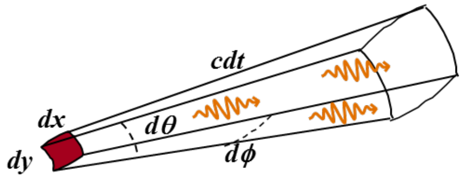
CHARACTERISTICS OF SYNCHROTRON RADIATION

Kwang-Je Kim

Center for X-ray Optics
Accelerator and Fusion Research Division
Lawrence Berkeley Laboratory, Berkeley, CA 94720

others:
R. Walker
R. Coisson
......

Brightness and coherence



Spectral brightness: photon density in 6D phase space

$$B_{avg}(\lambda) \propto \frac{N_{ph}(\lambda)}{(\varepsilon_x\ (e-) \oplus \varepsilon_r\ (\lambda)(\varepsilon_y\ (e-) \oplus \varepsilon_r\ (\lambda))(s \cdot \%BW)}$$

Coherent fraction:

$$f_{coh}(\lambda) = \frac{\varepsilon_r^2(\lambda)}{(\varepsilon_x\ (e-) \oplus \varepsilon_r\ (\lambda)(\varepsilon_y\ (e-) \oplus \varepsilon_r\ (\lambda))}$$

Coherent flux:

$$F_{coh}(\lambda) = f_{coh}(\lambda) \cdot F(\lambda) = B_{avg}(\lambda) \cdot \left(\frac{\lambda}{2}\right)^2$$

$$\boldsymbol{\varepsilon_r(\lambda) = \sigma_r(\lambda)\sigma'_r(\lambda) = \frac{\lambda}{4\pi}}$$

(ε_r = 8 pm-rad for λ = 1Å)

Brightness: phase space method in wave optics

KJK, 1986 and before

- General representation brightness that accommodates diffraction, transverse and longitudinal extent of source, near field distribution, and that can be propagated with transport matrices
- In wave optics, distinct position in phase space not possible - Heisenberg uncertainty principle
- Fourier transform of mutual coherence function of electric fields

$$\mathscr{B}(x,\phi) = \text{const.} \int d^2\xi \left\langle \mathscr{E}^*\left(\phi + \frac{\xi}{2}\right) \mathscr{E}\left(\phi - \frac{\xi}{2}\right) \right\rangle e^{-ikx\xi} = \frac{\text{const.}}{\lambda^2} \int d^2u \left\langle E^*\left(x + \frac{u}{2}\right) E\left(x - \frac{u}{2}\right) \right\rangle e^{ik\phi u}$$

$$\mathscr{E}(\phi) = \frac{1}{\lambda^2} \int E(x)\, e^{-ik\phi x} d^2x \qquad E(x) = \int \mathscr{E}(\phi)\, e^{ik\phi x} d^2\phi,$$

$$\frac{d^2\mathscr{F}}{d^2\boldsymbol{\varphi}} = \int \mathscr{B}(\mathbf{x},\boldsymbol{\varphi};z)\, d^2\mathbf{x} \qquad \frac{d^2\mathscr{F}}{d^2\mathbf{x}} = \int \mathscr{B}(\mathbf{x},\boldsymbol{\varphi};z)\, d^2\boldsymbol{\varphi}$$

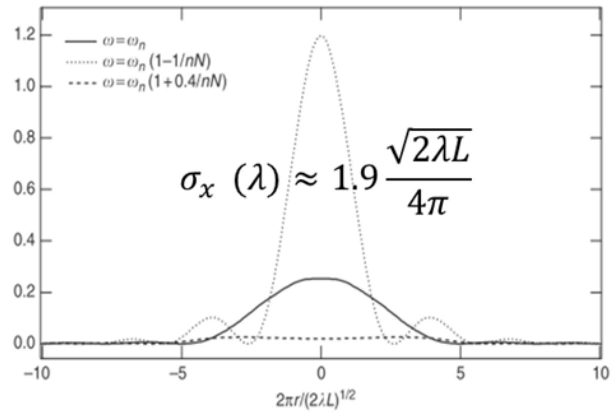
Wigner quasi-probability distribution - 1932

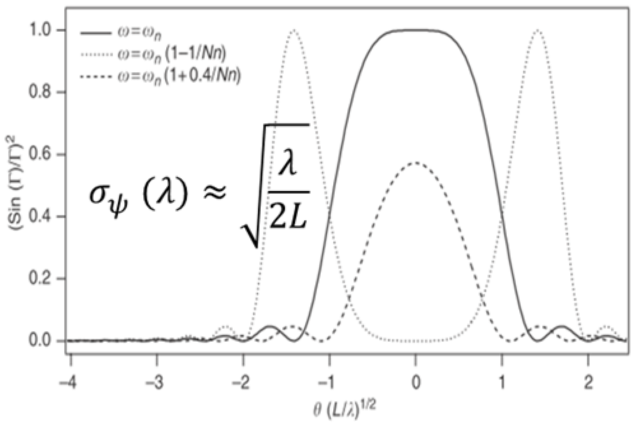
$$W(x,p) \stackrel{\text{def}}{=} \frac{1}{\pi\hbar} \int_{-\infty}^{\infty} \psi^*(x+y)\psi(x-y) e^{2ipy/\hbar}\, dy = \frac{1}{\pi\hbar} \int_{-\infty}^{\infty} \varphi^*(p+q)\varphi(p-q) e^{-2ixq/\hbar}\, dq$$

φ is Fourier transform of ψ

Photon diffraction-limited emittance...?

P. Elleaume, in *Wigglers, Undulators, and Their Applications*, 2003.





$$\varepsilon_r(\lambda) = \frac{\lambda}{2\pi}$$

How many π's do you divide from λ to get the undulator radiation emittance?

AOP-TN-2018-024

Ryan Lindberg — March 27, 2018

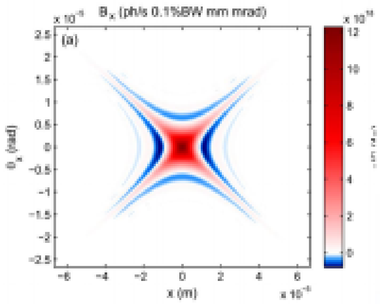
Diffraction limited emittance from undulator

R. Walker, NOCE 2017

	$\sigma_{R'}$	σ_R	$\varepsilon_R = \sigma_R\sigma_{R'}$	$\beta_R = \sigma_R/\sigma_{R'}$
Kim (NIM 1986)†	$\sqrt{\lambda/L}$	$\sqrt{\lambda L}/4\pi$	$\lambda/4\pi$	$L/4\pi$
Kim (PAC 1987)	$\sqrt{\lambda/2L}$	$\sqrt{2\lambda L}/4\pi$	$\lambda/4\pi$	$L/2\pi$
Borland (IPAC 2012) Hettel & Borland (PAC 2013) Hettel (IPAC 2014)	$\sqrt{\lambda/2L}$	$\sqrt{2\lambda L}/2\pi$	$\lambda/2\pi$	L/π
Huang (IPAC 2013)	$\sqrt{\lambda/2L}$	$\sqrt{2\lambda L}/4\pi$	$\lambda/4\pi$	$L/2\pi$
Lindberg & Kim (PRSTAB 2015)	$\sqrt{\lambda/4L}$	$\sqrt{\lambda L}/2\pi$	$\lambda/4\pi$	L/π
Liu (IPAC 2017)	$\sqrt{\lambda/2L}$	$\sqrt{2\lambda L}/2\pi$	$\lambda/2\pi$	L/π

Elleaume →

so which is correct ? (and does it matter ?) ...



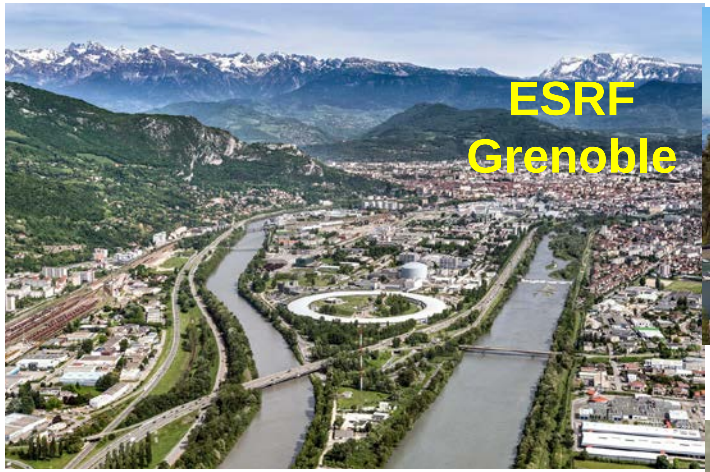
I. Bazarov, PRSTAB 15, 050703 (2012)

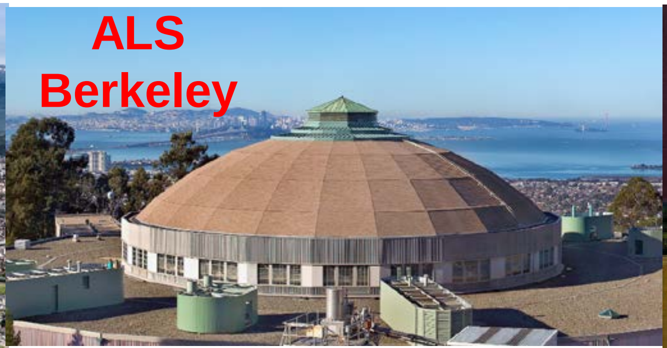
Wigner radiation distribution

3rd generation of storage ring light sources

Dedicated facilities optimized for undulators, <10 nm-rad emittances

- ESRF
- APS
- SPring-8
- ALS
- ALBA
- BESSY-II
- SPEAR3
- SLS
- DLS
- Soleil
- Elettra
- SSRF
- TPS
- PLS
- NSLS-II
- etc.





A Comparison of the Chasman-Green and Triple Bend Achromat Lattices

A. Jackson | March 1986

Light sources around the world

Low emittance lattices and the diffraction limit

$$\varepsilon_{diff}(\lambda) = \frac{\lambda}{4\pi}$$

$$\varepsilon_X \sim F(lattice)\frac{E^2}{N_d^3}$$

$$\varepsilon_x = C_q \frac{\gamma^2}{J_x} \frac{\oint \mathcal{H}(s)/\rho(s)^3 ds}{\oint 1/\rho(s)^2 ds}$$

$$\varepsilon_x = \frac{1}{1+\kappa}\varepsilon_0 \qquad \varepsilon_y = \frac{\kappa}{1+\kappa}\varepsilon_0$$

$$\mathcal{H}(s) = \gamma(s)\eta(s)^2 + 2\alpha(s)\eta(s)\eta'(s) + \beta(s)\eta'(s)^2$$

$$\gamma(s) = \frac{1+\alpha(s)^2}{\beta(s)} \qquad \alpha(s) = \frac{-\beta'(s)}{2}$$

$$\frac{\varepsilon_W}{\varepsilon_0} \approx \frac{1}{1 + {}^{U_W}/_{U_0}}$$

damping wigglers

Dawn of the 4th generation MBA era – on paper

NIM A 335, 1993
2 GeV, 400 m
400 pm
5BA

A modified QBA optics for low emittance storage rings

D. Einfeld [a] and M. Plesko [b]

[a] *Research Center Rossendorf Inc., P.O. Box 510119, D-01314 Dresden, Germany*
[b] *Sincrotrone Trieste, Padriciano 99, I-34012 Trieste, Italy*

EPAC 94
2.1 GeV, 252 m
3200 pm
6 straights
7BA

Design of a Swiss Light Source (SLS)

W. Joho, P. Marchand, L. Rivkin, A. Streun
Paul Scherrer Institute

actually built:
2.4 GeV, 288 m
5500 nm
12 straights
3BA

PAC 95
3 GeV, 400 m
500 pm
7BA

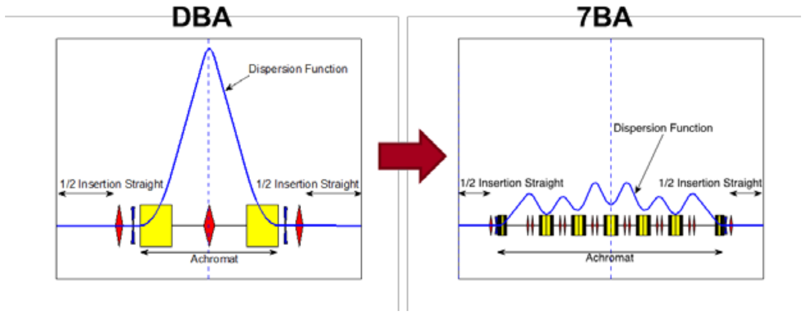
Design of a Diffraction Limited Light Source (DIFL)

D. Einfeld, J. Schaper, Fachhochschule Ostfriesland, Constantiaplatz 4, D-26723 Emden
M. Plesko, Institute Jozef Stefan, Jamova 39, P.O.B. 100, SLO-61111 Ljubljana

EPAC 2000
6 GeV, 2 km
MBA

TOWARDS THE ULTIMATE STORAGE RING-BASED LIGHT SOURCE

A. Ropert, J.M. Filhol, P. Elleaume, L. Farvacque, L. Hardy, J. Jacob, U. Weinrich
ESRF, Grenoble, France



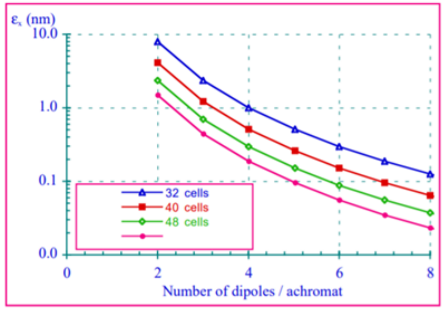


Figure 2: Emittance scaling with the number of cells and of bending magnets

MAX-IV - Sweden

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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

www.elsevier.com/locate/nima

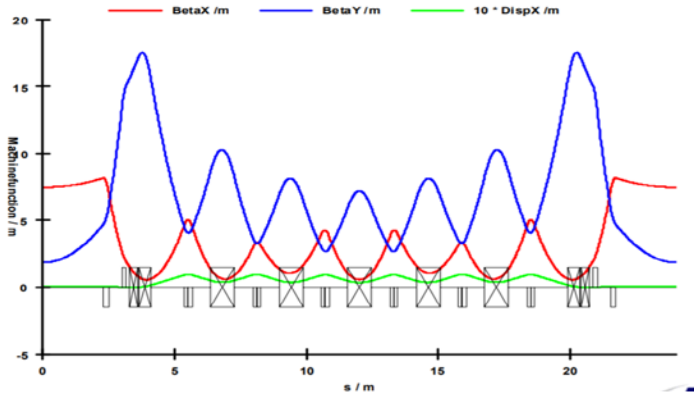
MAX-IV lattice, dynamic properties and magnet system

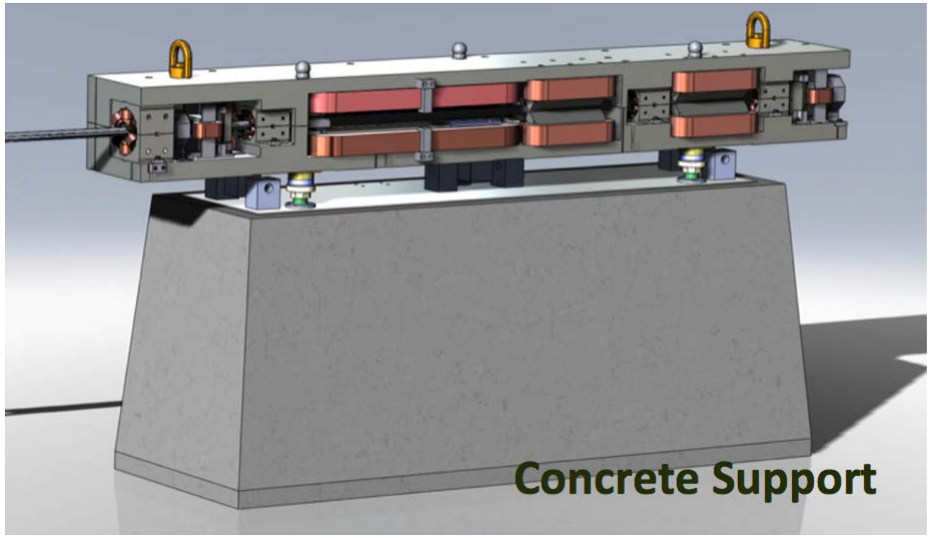
H. Tarawneh[a,*], M. Eriksson[a], L-J. Lindgren[a], B. Anderberg[b]

[a] *MAX-Lab, Lund University, Box 118, Lund 221 00, Sweden*
[b] *AMACC, Uppsala, Sweden*

Received 6 May 2003; accepted 8 May 2003

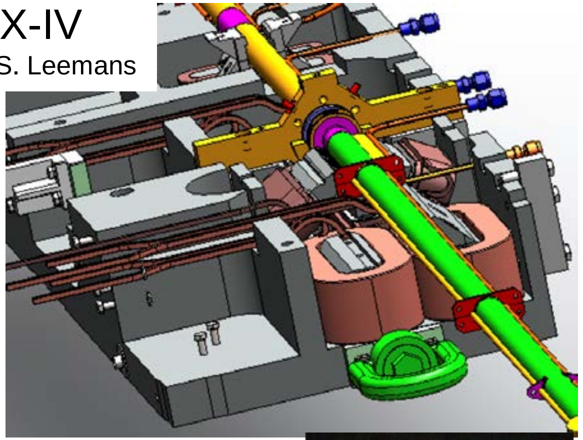
2003: 3 GeV, 528 m
330 pm
7BA

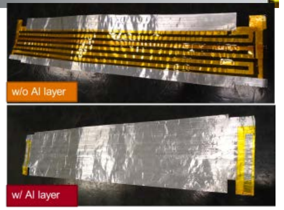




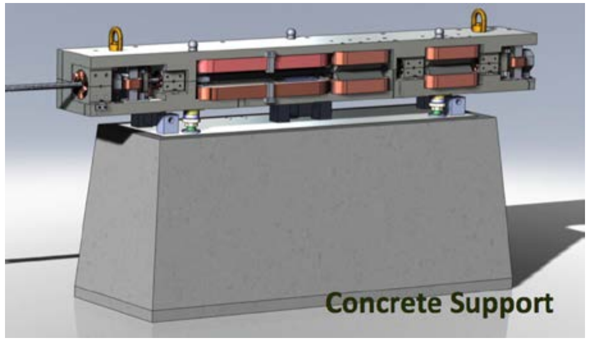
Small aperture magnets made possible with NEG-coated chambers

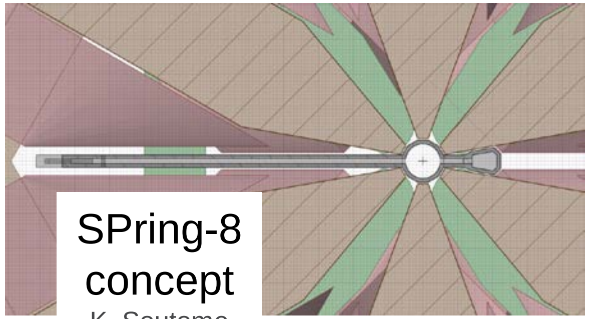
MAX-IV
Courtesy S. Leemans



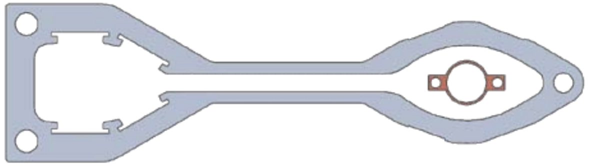


heater tape for in-situ NEG bake-out Sirius





SPring-8 concept
K. Soutome

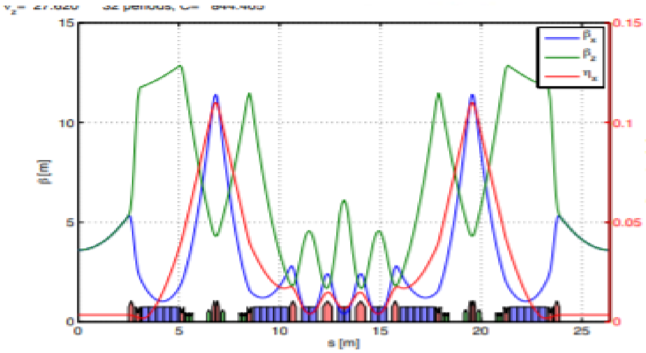


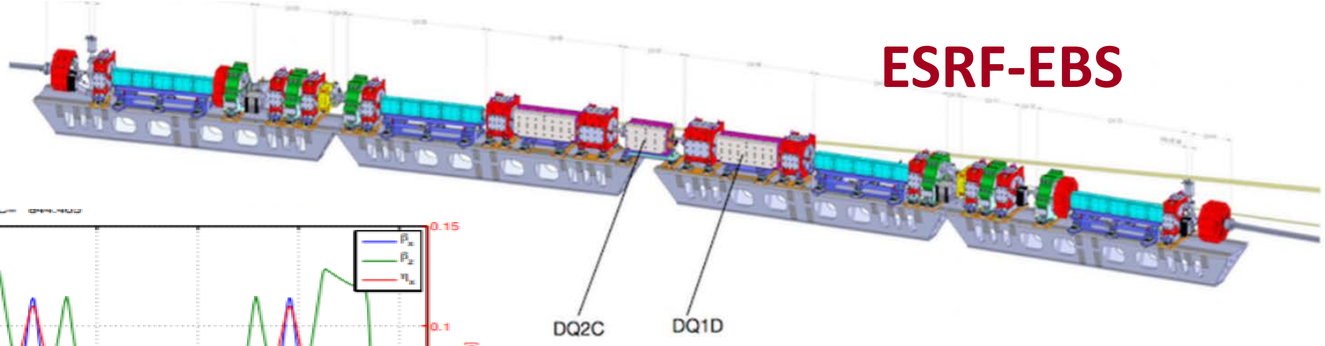
APS and APS-U chambers

4GSRs in the works

Sirius - Brazil

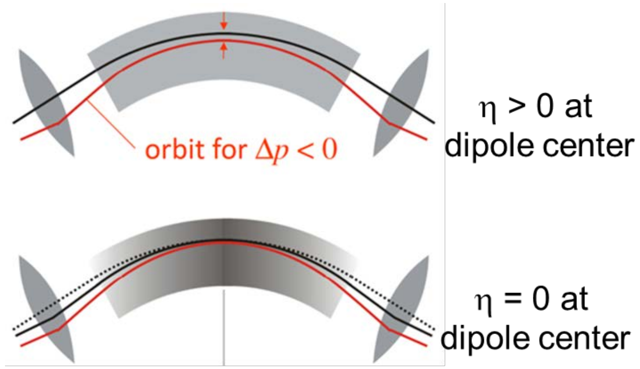
479.7m, 3 GeV, 280-pm, 5BA





ESRF-EBS

844 m, 6 GeV, 200 mA, 150-pm
hybrid 7BA (Raimondi) + permanent magnet longitudinal gradient dipoles (Wrulich, 1992)

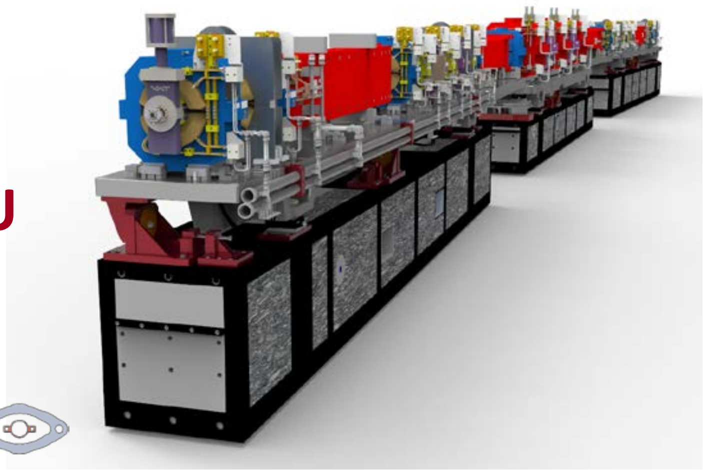


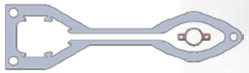
courtesy A. Nadji

SLS-2

- 288 m, 2.4 GeV, 400 mA, 98-126 pm
- 7BA + longitudinal gradient dipoles + antibends (Streun)
- Longitudinal injection being considered

APS-U





1100-m, 6 GeV, 200-mA, 42-pm
hybrid 7BA + longitudinal gradient dipoles + antibends, swap-out injection (Borland et al.)

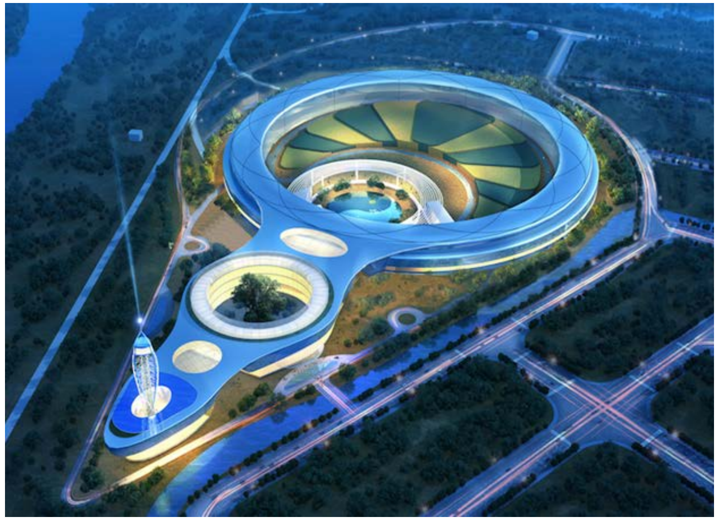
4GSRs in the works – cont.

SPring-8-II

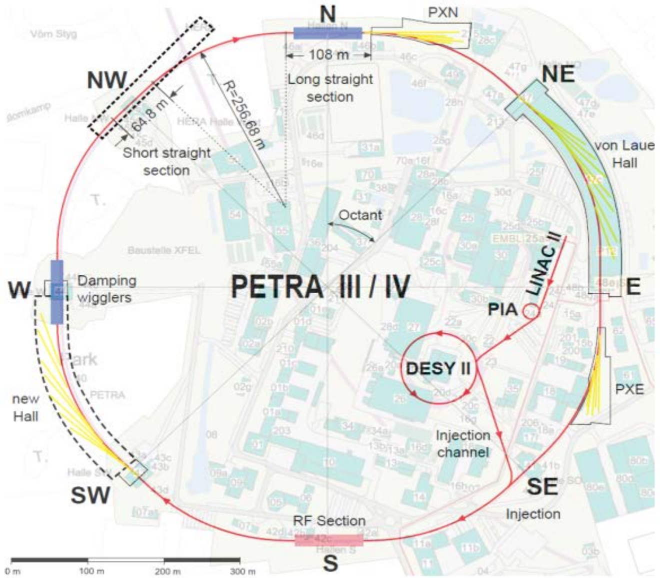
6-GeV SACLA FEL
SPring-8 has it all....

1435.4 m, 6 GeV, 100 mA, 149-pm
hybrid 5BA + longitudinal gradient dipoles
6-GeV injection from linac

HEPS
Beijing



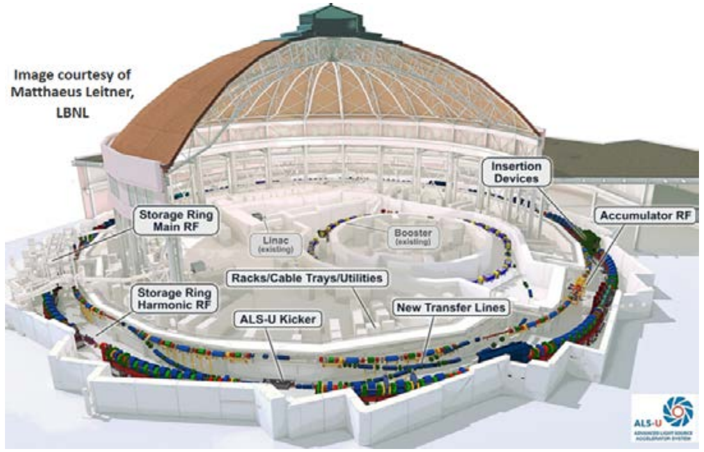
1360 m, 6 GeV, 200 mA, 34 pm
7HBA, longitudinal bends, reverse bends
Booster/accumulator for swap out/recovery
Investigating longitudinal injection



2304 m, 6 GeV, 500 mA,
~10 pm, h7BA, reverse bends
XFELO?

PETRA-IV
early planning

ALS-U



197 m, 2 GeV, 500 mA,
< 85 pm, 9BA, reverse
bends, accumulator for
swap-out/recovery

Current upgrade based on MBA structure

Storage Ring	E (GeV)	C (m)	Emittance* (pm.rad)	Lattice	Status
ESRF-EBS (France)	6	844	140	7BA	Construction (2020)
ALS-U (USA)	2	197	109	9BA	Study & RD
APS-U (USA)	6	1104	42	7BA	Pre-construction
Diamond-II (UK)	3 (3.5)	562	150	7BA	Study
ELETTRA 2.0 (Italy)	2	259	250	6BA	Study (funded)
PETRA-IV (Germany)	6	2304	10 - 30	7BA	Study
SLS-II (Switzerland)	2.4	290	100	7BA	Study & RD
SOLEIL-U (France)	2.75	354	72	7BA	Study
SPring-8-II (Japan)	6	1435	140	5BA	Study & RD
SSRF-U (China)	3	432	203	7BA	Study

*: natural emittance, no IBS included

courtesy A. Nadji, Soleil

New projects based on MBA structure

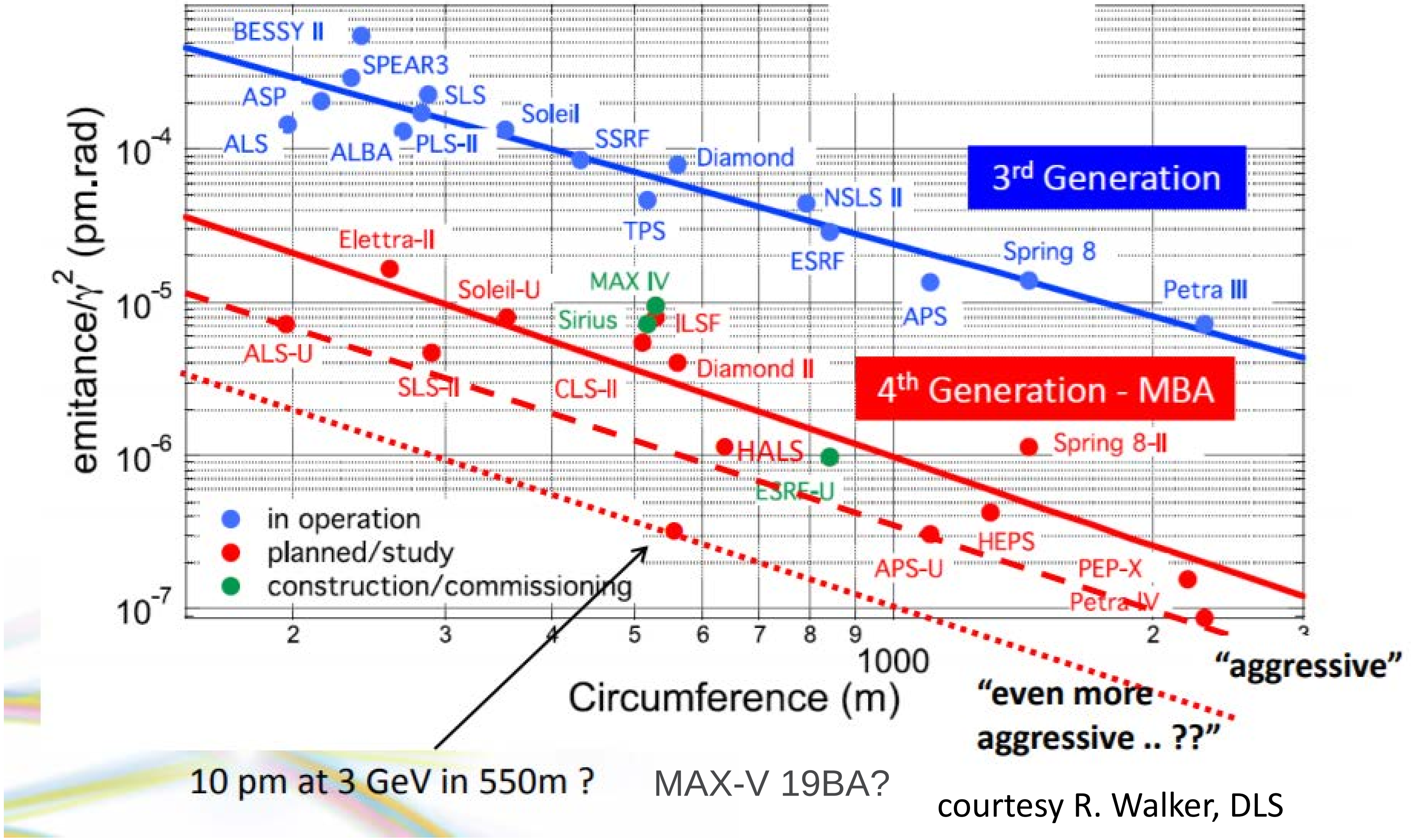
Storage Ring	E (GeV)	C (m)	Emittance* (pm.rad)	Lattice	Status
MAX IV (Sweden)	3	528	330	7BA	operation
Sirius (Brazil)	3	518	250	5BA	Construction (end 2018)
CANDLE (Armenia)	3	269	435	4BA	Study
CLS-II (Canada)	3	619	81 (36)	9BA	Study
HALS (China)	2	648	23	6-8BA	Study
HEPS (China)	6	1260	34	7BA	Pre-construction
ILSF (Iran)	3	528	275	5BA	Study
KEK-LS (Japan)	3	571	130	8BA	Study
SLIT-J (Japan)	3	354	920	4BA	Study
SPS-II (Thailand)	3	321	970	6BA	Study
TURKAY (Turkey)	3	477	510	4BA	Study

*: natural emittance, no IBS included

courtesy A. Nadji, Soleil

10

Trends in storage ring lattice design

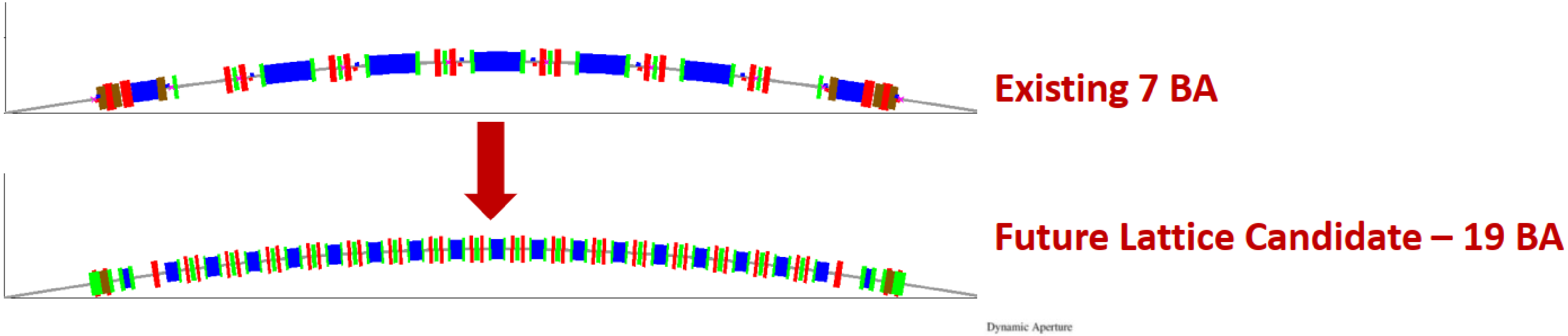


MAX-V 19BA?

courtesy R. Walker, DLS

More aggressive lattices?

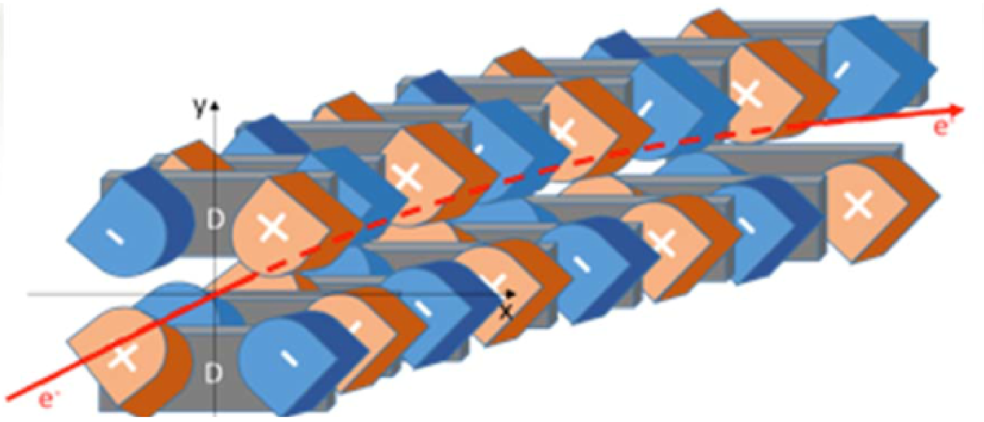
Example: 16 pm rad lattice in the MAX IV tunnel (528 m circumference)



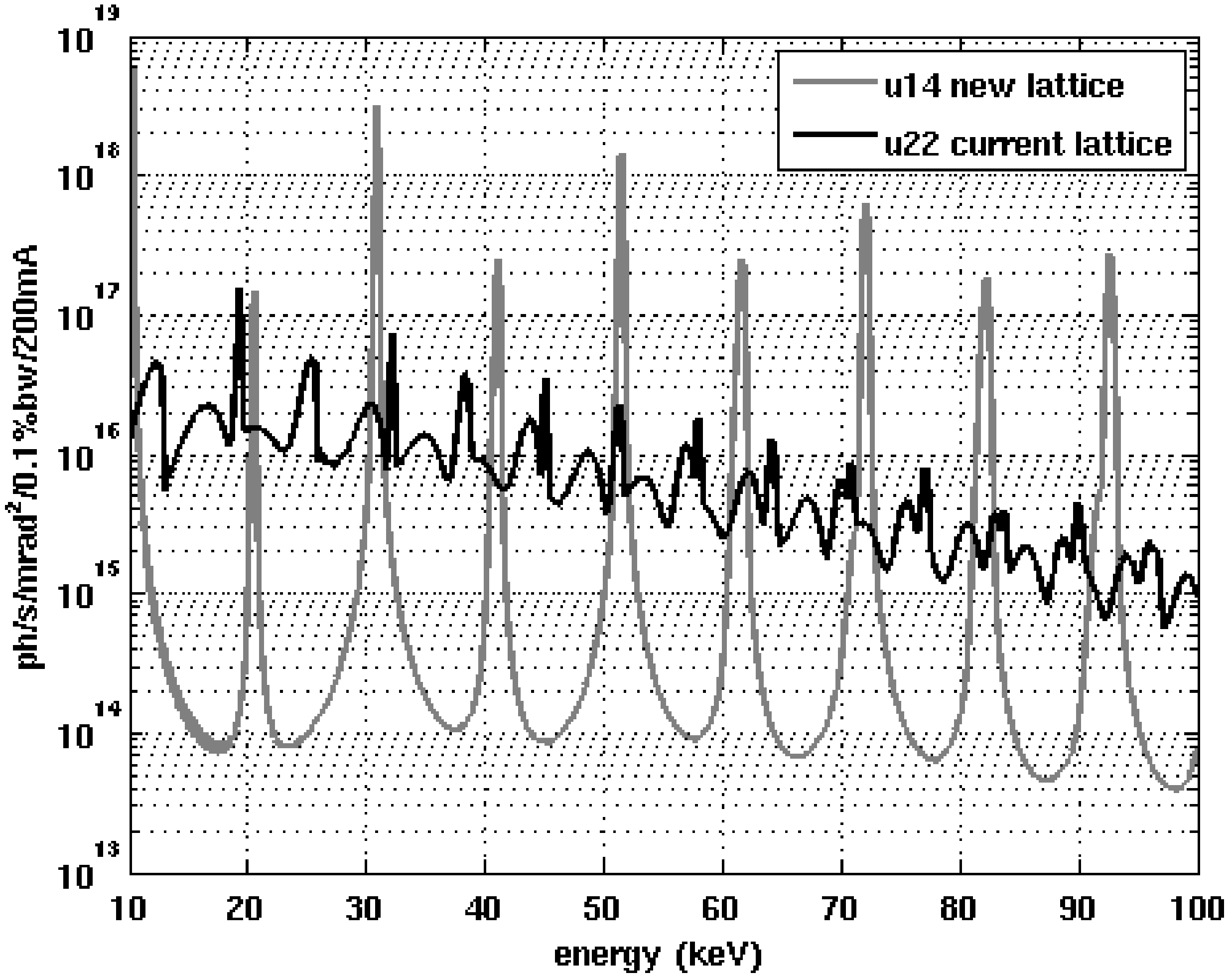
"Complex Bend" – T. Shaftan

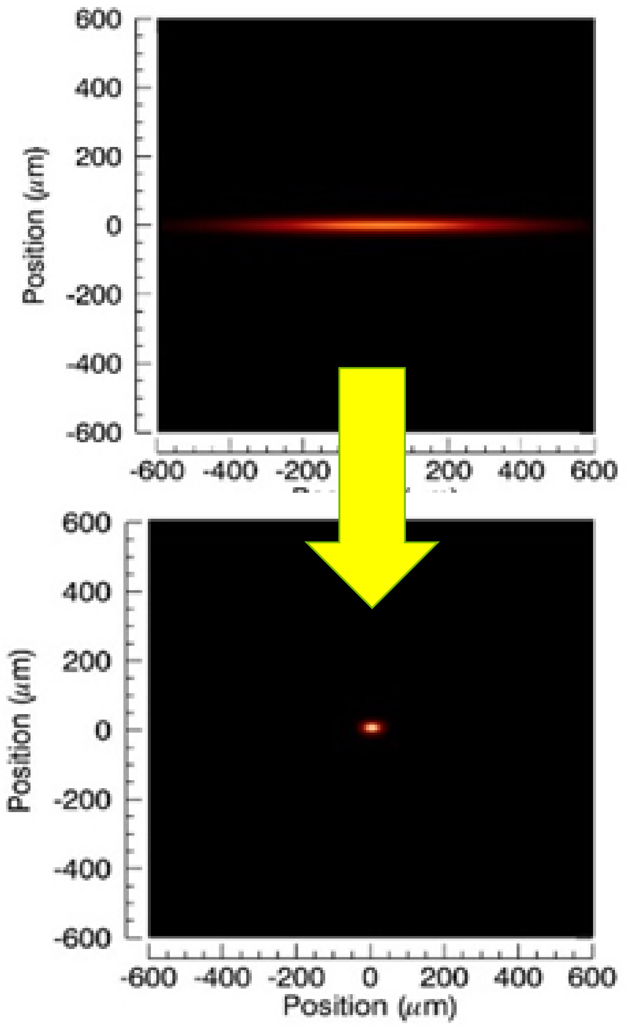
Transition from individual dipoles to multiple dipole poles in a wiggler-type structure

- APS DBA: 40x2=80 **dipoles**→
- APS-U MBA: 40x7=280 **dipoles**→
- NSLS-II upgrade: 30x2**x20**=1200 **poles**



Diffraction limited source



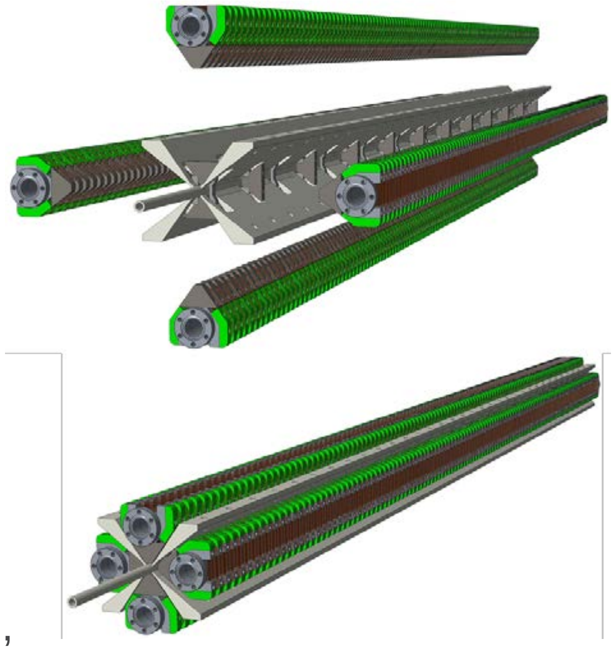


courtesy C. Steier

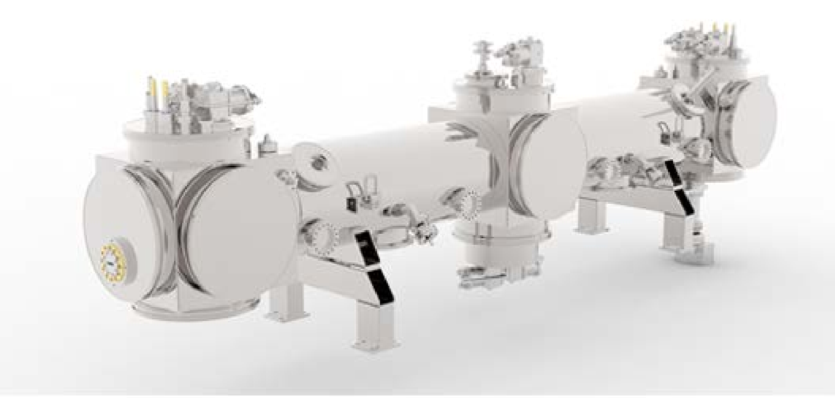
New IDs for APS-U

Super Conducting Arbitrary Polarizing Emitter (SCAPE)

- A 4-jaw superconducting undulator for providing variable polarization source for use in POLAR beamline, APS-U
- Two ~1.3 m long devices in one cryostat
- Provides both circular and linear polarization

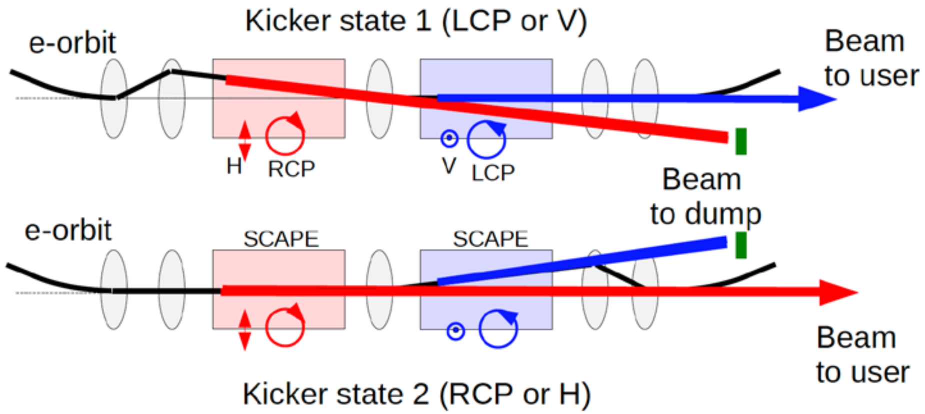


E. Anliker, J. Fuerst, E. Gluskin, Q. Hasse, Ivanyushenkov, M. Kasa, I. Kesgin, J. Lerch, Y. Shiroyanagi, E. Trakhtenberg



SC planar undulators

fast orbit switching



Photon transport simulation tools

Levels of simulation: accuracy vs efficiency

Analytical method

- Mathematica/Excel
- Gaussian beam profile
- Optics acceptance
- Focusing condition using geometric magnification and diffraction formula
- Fast optimization of the beamline layout with reasonable accuracy

Numerical method

- *SHADOW*, Ray, McXtrace, xrt
- ***HYBRID*** (add diffraction)
- SRW, Phase
- More accurate source profile
- Effects of non-ideal optics
- Effects of optics vibration and misalignment
- Beam intensity, spot size, divergence, and energy spectra
- Optics specification and mechanical requirements

Mutual coherence

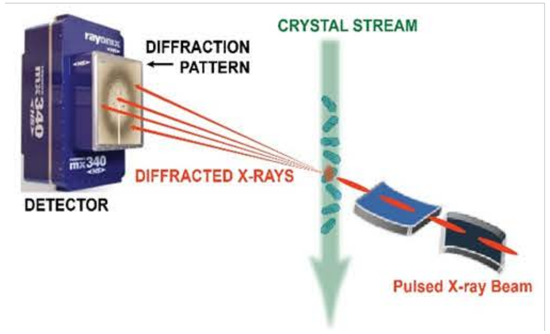
- **The Mutual Optical Intensity (MOI) model**
- Multi-electron SRW
- Coherent mode decomposition method
- Comsyl
- Partially coherent source and propagation through optics
- Local coherence and wavefront

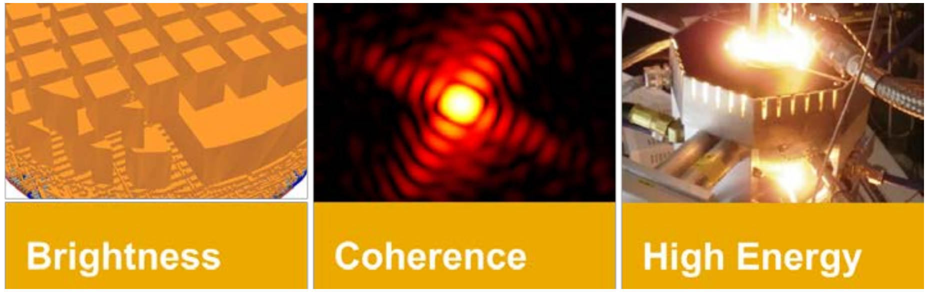
Coherent wavefront preservation

4GSRs enable pivotal research across disciplines

Small-Beam Scattering & Spectroscopy

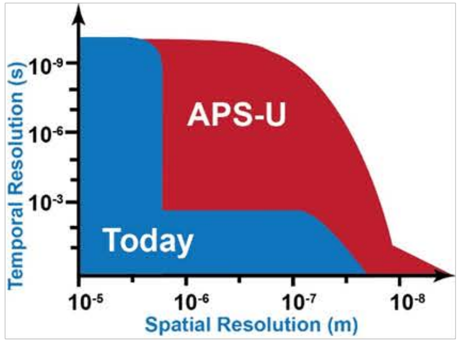
- Nanometer imaging with chemical and structural contrast; few-atom sensitivity
- Room-temperature, serial, single-pulse pink beam macromolecular crystallography





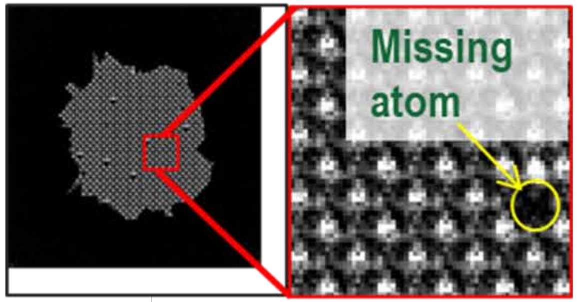
Resolution with Speed

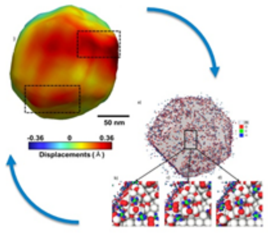
- Mapping all of the critical atoms in a cubic millimeter
- Detecting and following rare events
- Multiscale imaging: enormous fields of view with high resolution



Coherent Scattering & Imaging

- Highest possible spatial resolution: 3D visualization; imaging of defects, disordered heterogeneous materials
- XPCS to probe continuous processes from nsec onward, opening up 5 orders of magnitude in time inaccessible today,

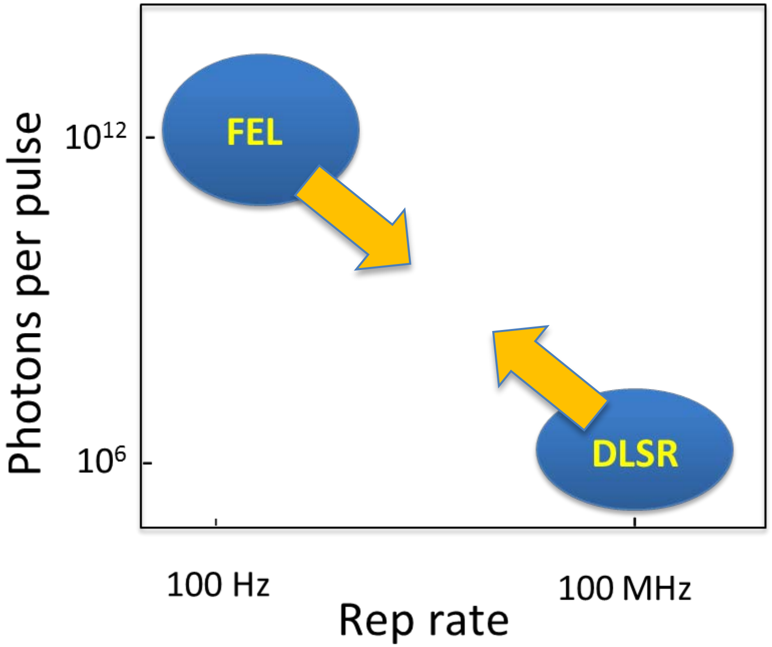




Exploit high performance computing, artificial intelligence

Automatic control of experiments, high volume data acquisition, analysis and reconstruction

Ultimate storage rings?



FELs becoming more ring-like: higher rep rate, reduced photons/pulse (e.g. LCLS-II)

Can rings become more FEL-like: increased ph/pulse, reduced energy spread, short pulses, lasing?

Transverse and longitudinal transform-limited beams?

FELs on rings

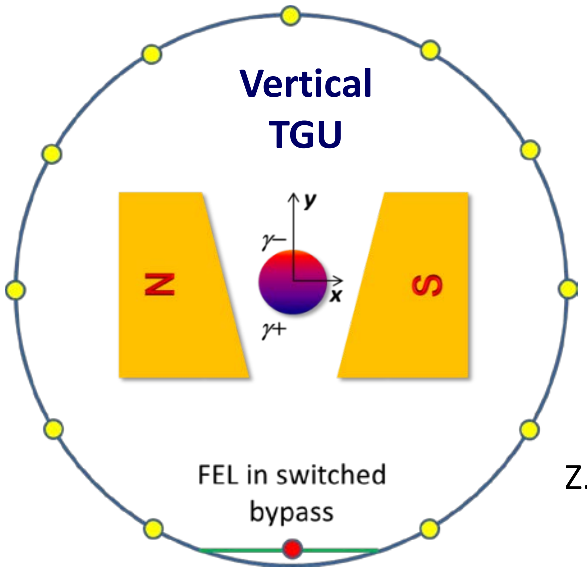
Nuclear Instruments and Methods in Physics Research A318 (1992) 730–735
North-Holland

40 Å FEL designs for the PEP storage ring

Alan S. Fisher and Juan C. Gallardo
*Brookhaven National Laboratory *, Building 510D, Upton, NY 11973, USA*

Heinz-Dieter Nuhn, Roman Tatchyn and Herman Winick
*Stanford Synchrotron Radiation Laboratory **, SLAC, Bin 69, P.O. Box 4349, Stanford, CA*

Claudio Pellegrini
Department of Physics, University of California, Los Angeles, CA 90024-1547, USA



2013: PEP-X
4.5 GeV
300 Apk, 1 ps
1.5 nm FEL

Bunch switched into FEL bypass (10-100 kHz)

Z. Huang, Y. Cai, Y. Ding
IPAC 2013

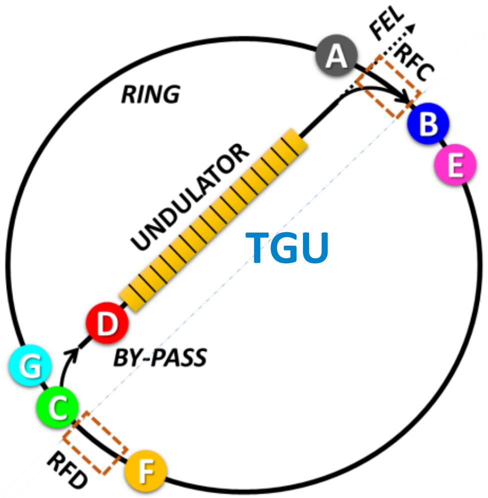
Steady state analysis of short-wavelength, high-gain FELs in a large storage ring

Z. Huang, K. Bane, Y. Cai, A. Chao, R. Hettel
Stanford Linear Accelerator Center, Stanford, CA 94309

C. Pellegrini
University of California at Los Angeles, Los Angeles, CA 90095

2007: PEP-X
4.5 GeV, 300 Apk, 10 ps
10 nm FEL

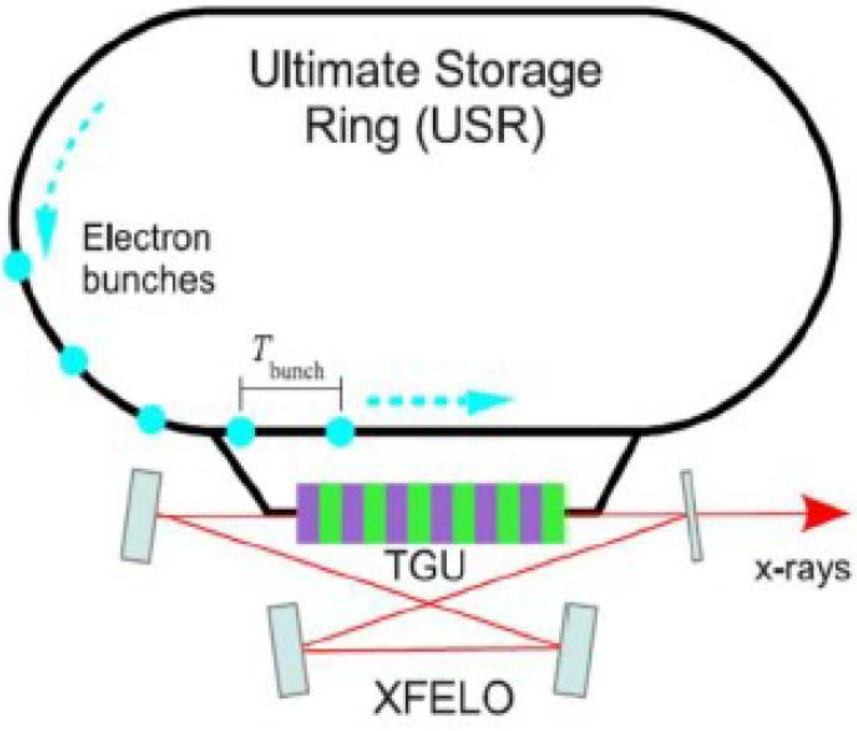
2015: Eletttra
1 GeV 455 Apk,
0.7 ps
25 nm FEL



OPERATING SYNCHROTRON LIGHT SOURCES WITH A HIGH GAIN FREE ELECTRON LASER

S. Di Mitri[#], M. Cornacchia, Elettra-Sincrotrone Trieste S.C.p.A., Basovizza, IT-34149, Italy

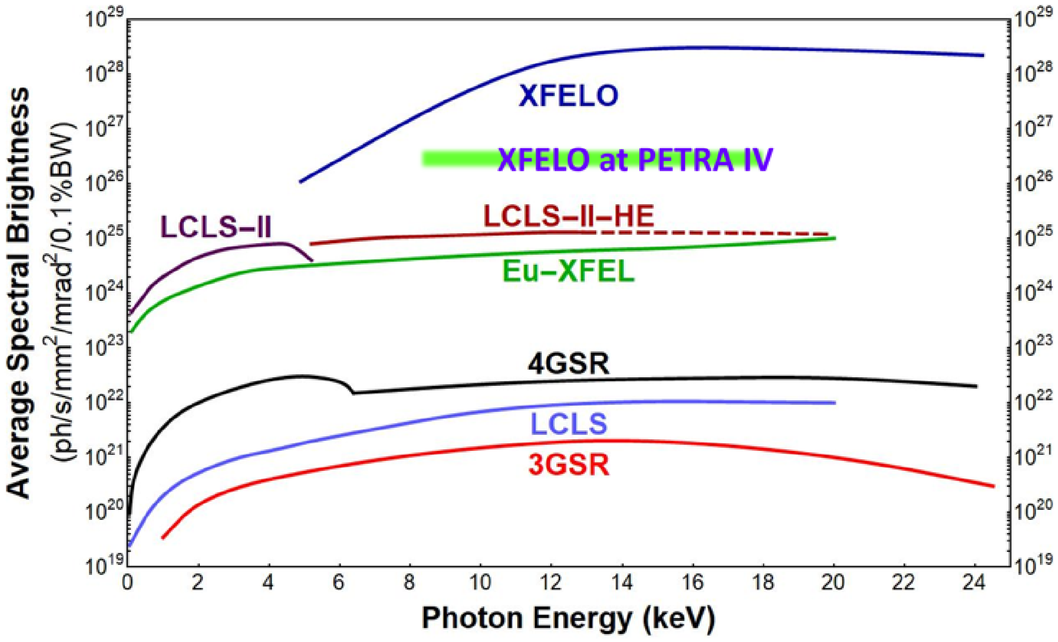
XFELO on 4GSR



K-J Kim, R. Lindberg

This workshop: Yong- Chul Chae[1], Ryan Lindberg[3], Ilya Agapov[1], Wolfgang Hillert[2], Kwang-Je Kim[3], Ralf Röhlsberger[1]

2018: PETRA-IV
6 GeV, 40 Apk, 5 ps
9.4/9.4 pm, 18/3.6 pm, etc.
3 MHz rep rate
14.4 keV FEL
under consideration

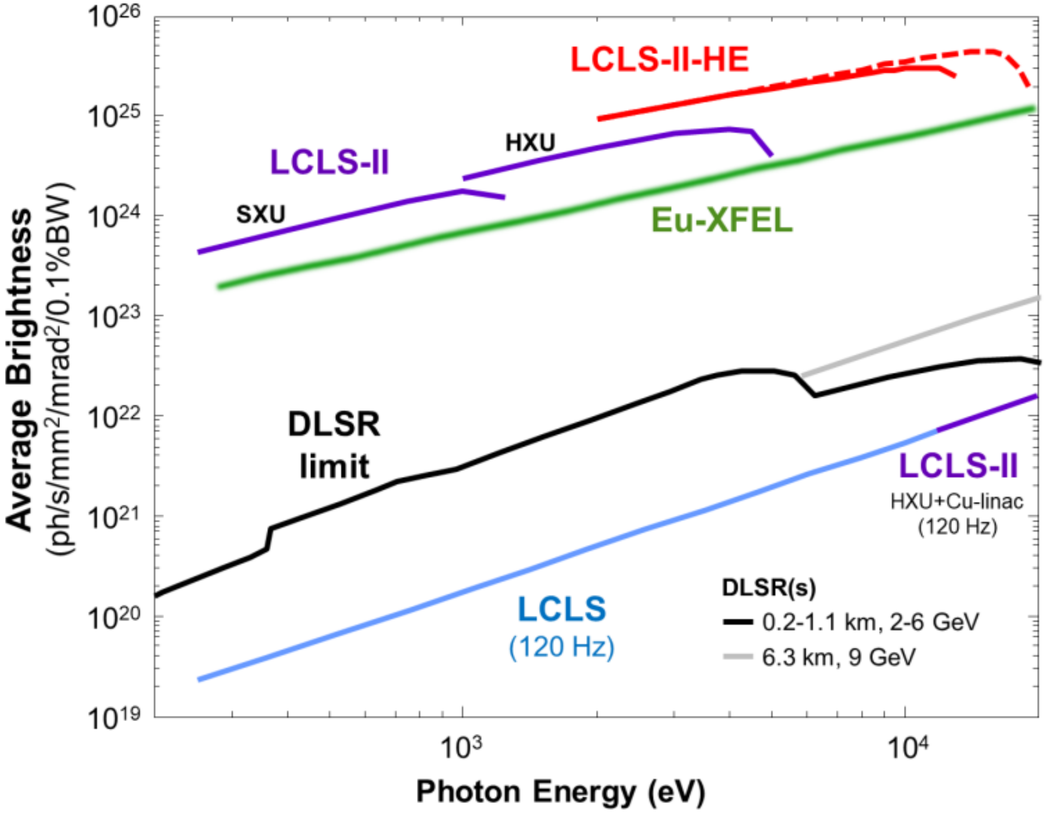


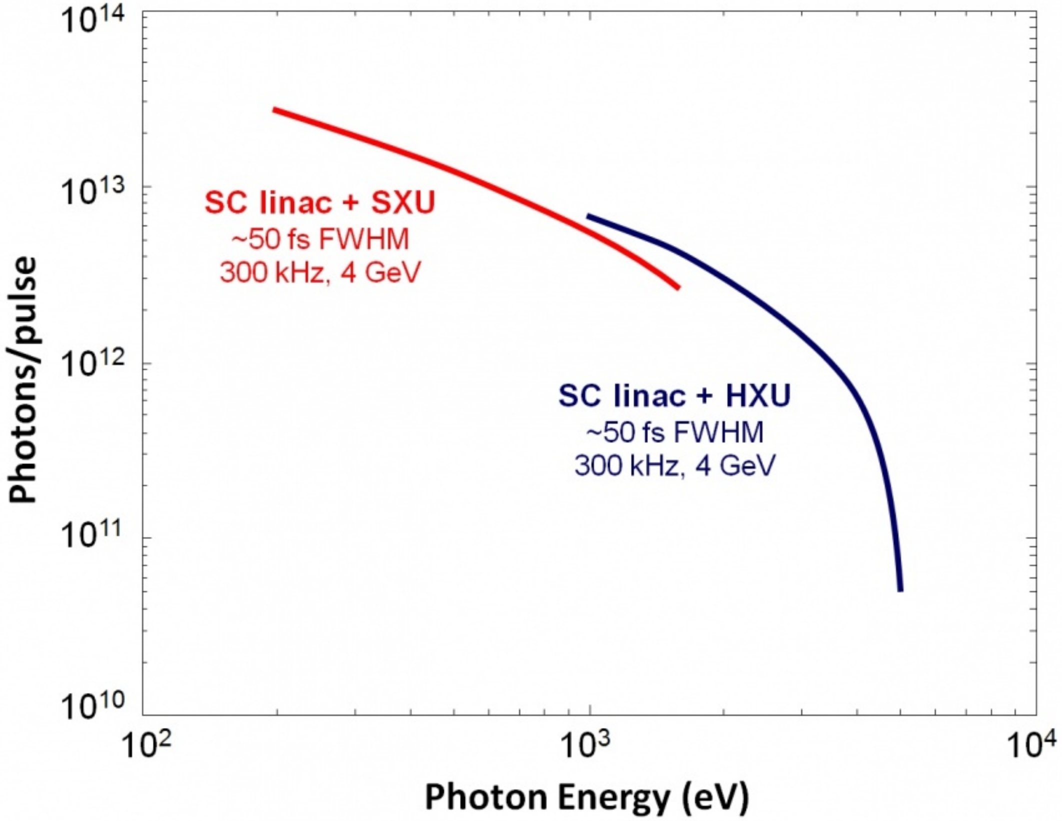
photon BW ~ 10^{-6}

Will ERL light sources be back?

back-up

Why bother with storage rings?





Because....

- Rings serve a much larger community of simultaneous users
- Spectral agility
- A much lower cost per user and per photon
- Rings also have a 6D stability advantage over pulsed linac FELs (it could be a different story for CW linac FELs)
- Tickle and probe
- Take the CW FEL brightness and divide by 30+ ports and you lose a factor of 30+

Storage Rings

Near continuous sources with high average brightness, wide tunable energy range, and high stability enable:

- Imaging and spatially resolved spectroscopies of complex systems and processes
- Study of systems evolving on hierarchical time and length scales
- Probing intrinsic atomic fluctuations with un-clocked correlation spectroscopies
- Balanced flux on sample to follow processes (interact but do not destroy)
- Diverse, highly optimized, multiplexed end stations solving critical problems for a wide range of scientific and technological communities and numerous user groups

Free-Electron Lasers

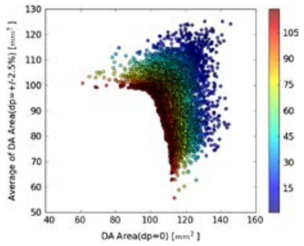
Sources with ultra-high peak and average brightness with full spatial coherence enable:

- Resolving ultrafast processes critical for emergent properties, excited-state transient phenomena, bond breaking and formation
- Development and application of non-linear x-ray techniques
- Near-instantaneous snapshots of processes in isolated areas (diffract before destroy)
- A small number of end stations addressing carefully selected, high-profile problems

courtesy S. Streiffer

"Brightness isn't everything" – B. Stephenson, ex APS Director

Advanced simulation, tracking and analysis tools



Symplectic Tracking based methods

DA, MA separated

DA, MA together

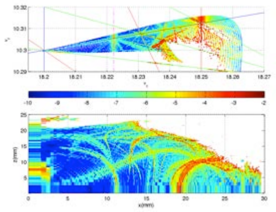
from L. Nadolski, ICFA LowEring, Oxford 7/13

Direct tracking based optimization

GLASS

Analytical based method

Genetic Algorithm
MOGA



Lie Algebra/Differential Algebra

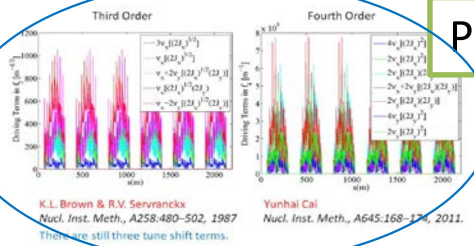
Resonance Driving Terms
RDT minimization

Amplitude Tuneshift minimization

Frequency Maps
FMA
Diffusion factor

Nonlinear "LOCO"

Canceling Sextupole Resonances



Phase advances

Interleaved sextupoles

Resonance identification

Robustness to magnetic, alignment errors

Robustness ID configurations

Tracking codes: **PTC** **MADX** **TRACY** **AT** **LEGO** **OPA** **ELEGANT**

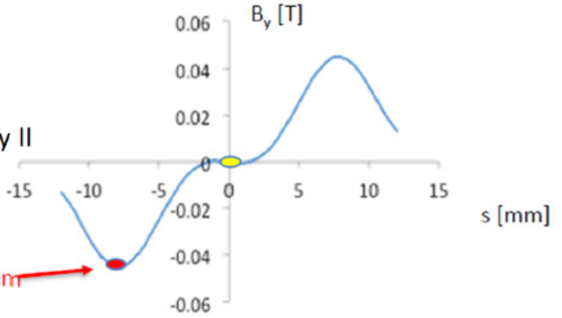
New Injection Schemes

Off-axis injection : Nonlinear Injection Kicker

MAX IV

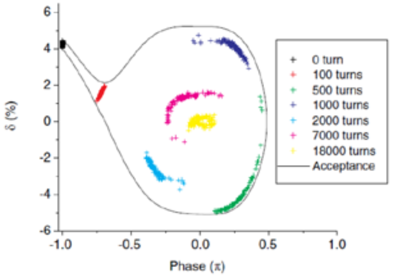
Sirius

Used at Bessy II



On-axis injection: Longitudinal plane

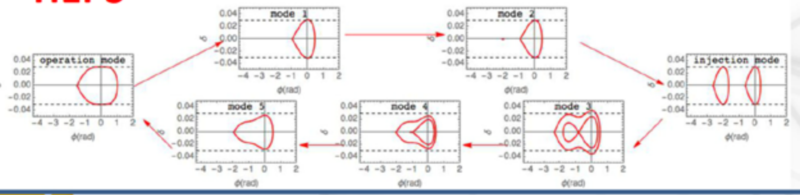
"golf club" scheme



M. Aiba et al. PRSTAB 18, 020701 (2015)

On-axis longitudinal injection by RF gymnastics of a double-frequency system

HEPS

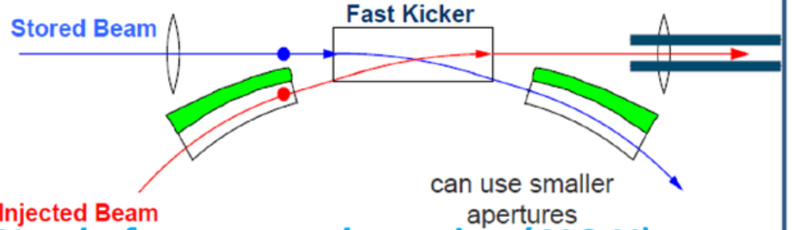


ALS-U

APS-U

On-axis swap-out injection

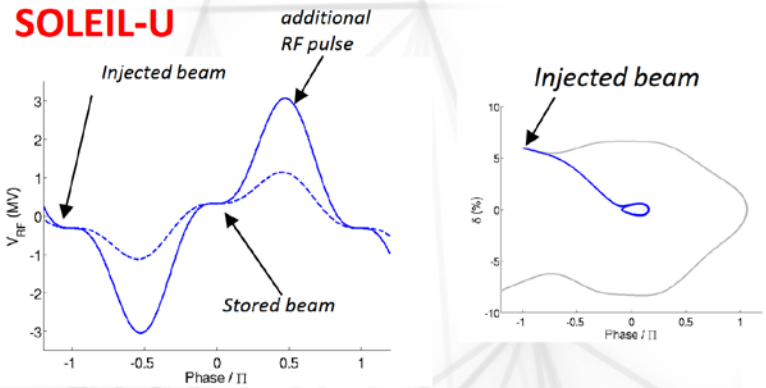
(initially proposed by M. Borland)



Need of an accumulator ring (ALS-U)

Off-momentum injection on chromatic orbit with a Non Linear Kicker and an Extra RF Pulse

SOLEIL-U



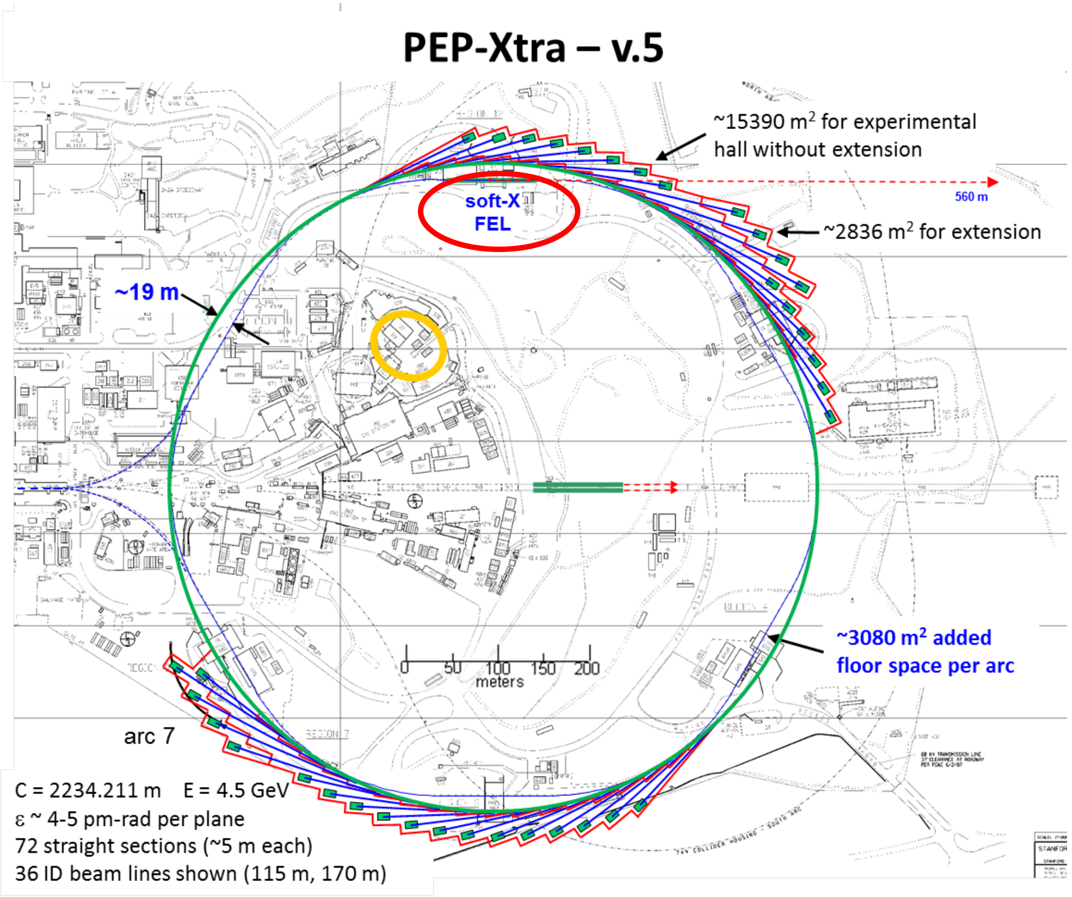
Topical Workshop on Injection and Injection Systems, BESSY-II, Aug. 28-30th, 2017 https://indico.cern.ch/event/635514/ 29

courtesy A. Nadji

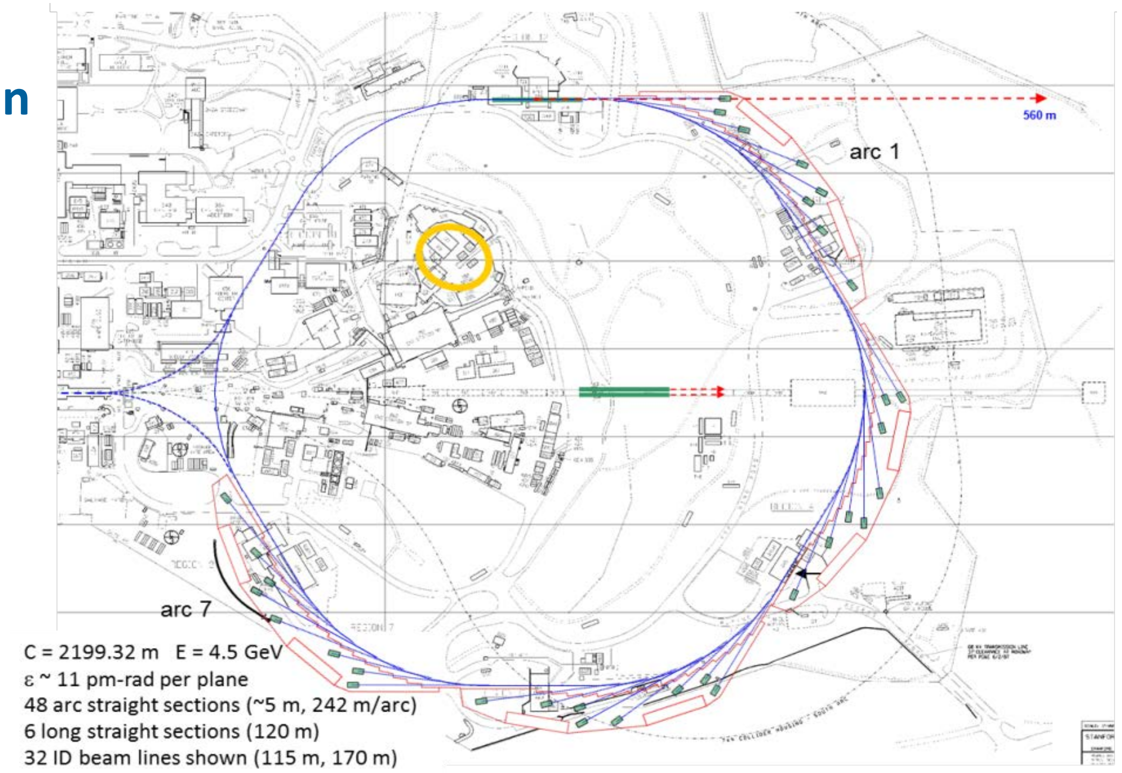
PEP-X

2007: PEP3 study started

2009: 2.2-km hexagon
4.5 GeV, 1.5 A
160 pm w/ DW,
DBA



PEP-Xtra: 2.2-km circle
6 GeV, 200 mA
5/5 pm w/DW
7BA



2013: 2.2-km hexagon
6 GeV, 200 mA
11/11 pm w/DW
7BA