International ICFA mini-Workshop on
NOnlinear dynamics and
Collective **E**ffects in particle beam physics
Arcidosso, Italy / 19 - 22 September 2017

"Potentialities and Compromises in the Design of Diffraction Limited Storage Rings"

Richard Walker
Diamond Light Source, UK

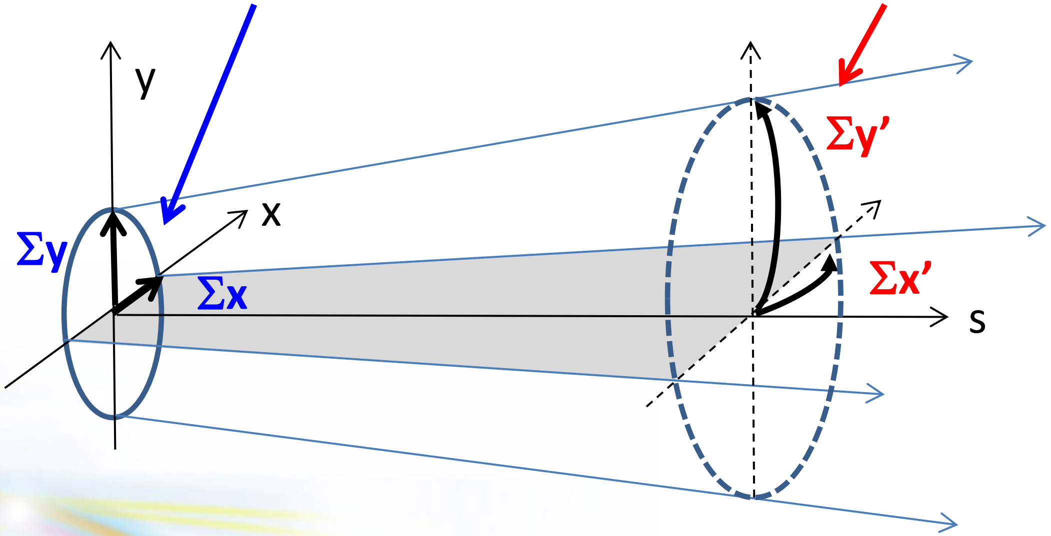
r.p.walker@diamond.ac.uk
www.diamond.ac.uk

1. What is the “Diffraction Limit” ?

… when, *for a given photon energy*, **the properties of the radiation are dominated by the intrinsic properties of the emitted photons, not the electron beam.**

Then, the radiation *Brightness* **is not degraded by the electron beam emittance and the radiation is** *transversely coherent*.

Brightness = flux per unit bandwidth (F),
per unit source area (Σx Σy), per unit solid angle, (Σx’ Σy’)



standard units: photons/s/mm^2/mrad^2/0.1%bandwidth

Brightness is usually defined as follows:

$$\mathcal{B} = \frac{F}{4\pi^2 \Sigma_x \Sigma_y \Sigma_{x'} \Sigma_{y'}}$$

F = total flux per unit spectral bandwidth

where the effective source sizes and divergences are convolutions between the electron and intrinsic photon sizes and divergences:

$$\Sigma_x = \left(\sigma_x^2 + \sigma_R^2\right)^{1/2}, \quad \Sigma_y = \left(\sigma_y^2 + \sigma_R^2\right)^{1/2}$$

$$\Sigma_{x'} = \left(\sigma_{x'}^2 + \sigma_{R'}^2\right)^{1/2}, \quad \Sigma_{y'} = \left(\sigma_{y'}^2 + \sigma_{R'}^2\right)^{1/2}$$

This is an approximation, based on both electrons and photons having Gaussian distributions. True for electrons, not for photons …

Using emittances and beta functions:

- for the electrons: $\sigma_{x,y} = \sqrt{\varepsilon_{x,y}\,\beta_{x,y}}, \quad \sigma_{x',y'} = \sqrt{\varepsilon_{x,y}/\beta_{x,y}}$

- for the photons: $\sigma_R = \sqrt{\varepsilon_R\,\beta_R}, \quad \sigma_{R'} = \sqrt{\varepsilon_R/\beta_R}$

$$\boxed{\mathcal{B} = \frac{F}{4\pi^2\left(\varepsilon_x^2 + \varepsilon_R^2 + \varepsilon_x\varepsilon_R\left(\frac{\beta_x}{\beta_R} + \frac{\beta_R}{\beta_x}\right)\right)^{1/2}\left(\varepsilon_y^2 + \varepsilon_R^2 + \varepsilon_y\varepsilon_R\left(\frac{\beta_y}{\beta_R} + \frac{\beta_R}{\beta_y}\right)\right)^{1/2}}}$$

Brightness is maximized when $\beta_x = \beta_y = \beta_R$, then:

$$\boxed{\mathcal{B} = \frac{F}{4\pi^2\left(\varepsilon_x + \varepsilon_R\right)\left(\varepsilon_y + \varepsilon_R\right)}}$$

So far so good …

… but, how do you define the photon properties $\sigma_R, \sigma_{R'}, \varepsilon_R, \beta_R$?

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

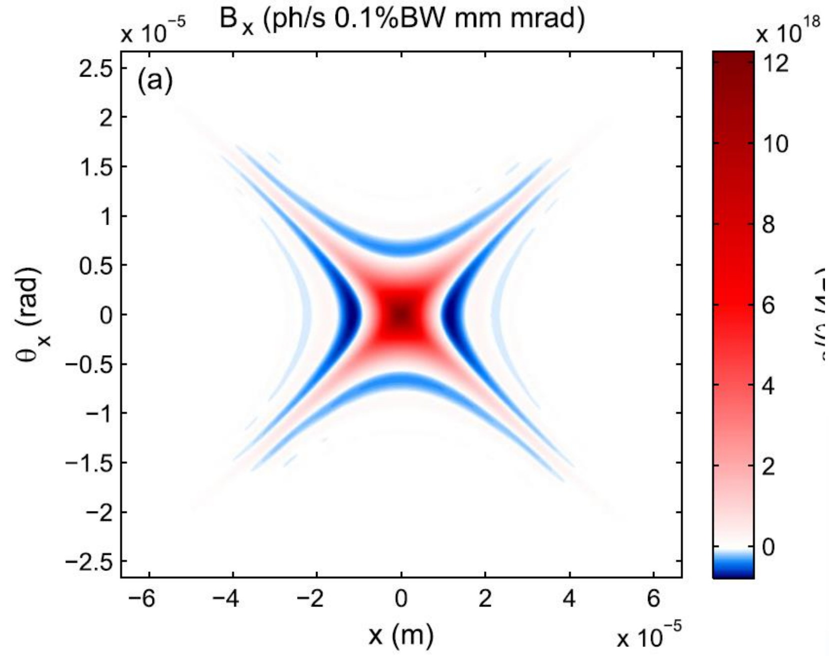
so which is correct ? (and does it matter ?) …

† also in the X-ray Data Booklet, http://xdb.lbl.gov/

The best available definition of Brightness is based on the Wigner distribution :

$$W(x,x',y,y') = \frac{2\varepsilon_o c}{h\,\lambda^2}\,\frac{I}{e}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} E_x^*\left(x'+\frac{\xi_x}{2},\, y'+\frac{\xi_y}{2}\right) E_x\left(x'-\frac{\xi_x}{2},\, y'-\frac{\xi_y}{2}\right) *$$

$$\exp\left(-i\,\frac{2\pi}{\lambda}\left(x\xi_x + y\xi_y\right)\right) d\xi_x\, d\xi_y$$

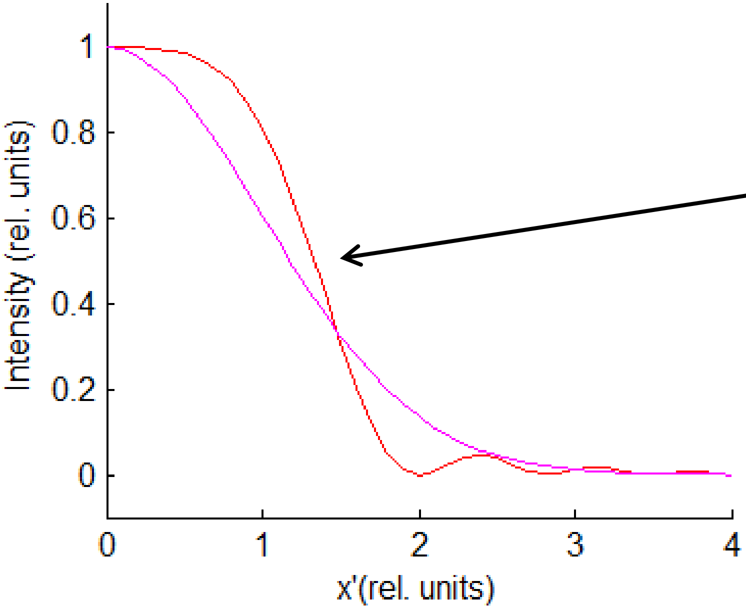


The disagreement over how to approximate this with a simple formula is not surprising:

- the photon distribution is not Gaussian,
- it is not separable into f(x), f(y),
- the projected distributions (which are often used) are not the same as the cuts along any given axis.

I. Bazarov, PRSTAB 15, 050703 (2012)

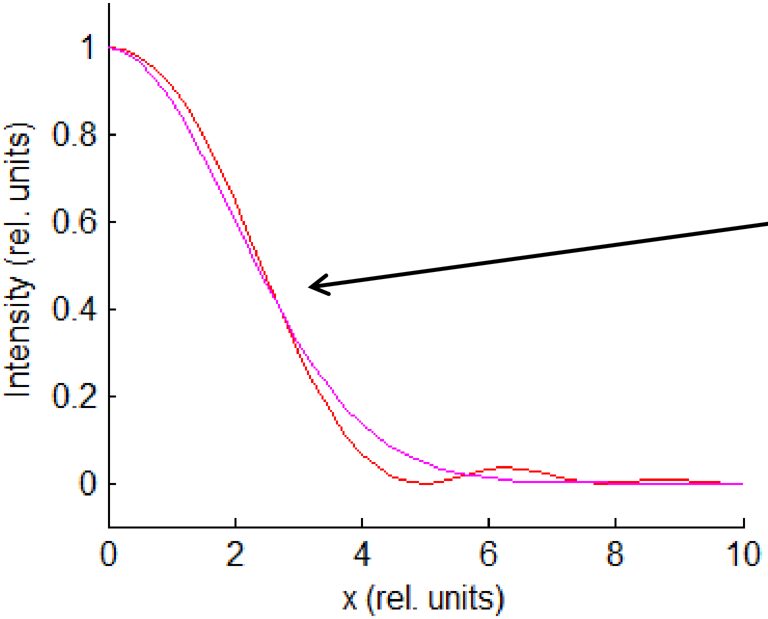
Projected intensity distributions



projected intensity (red)

Gaussian (magenta) $\sigma_{R'} = \sqrt{\lambda/2L}$

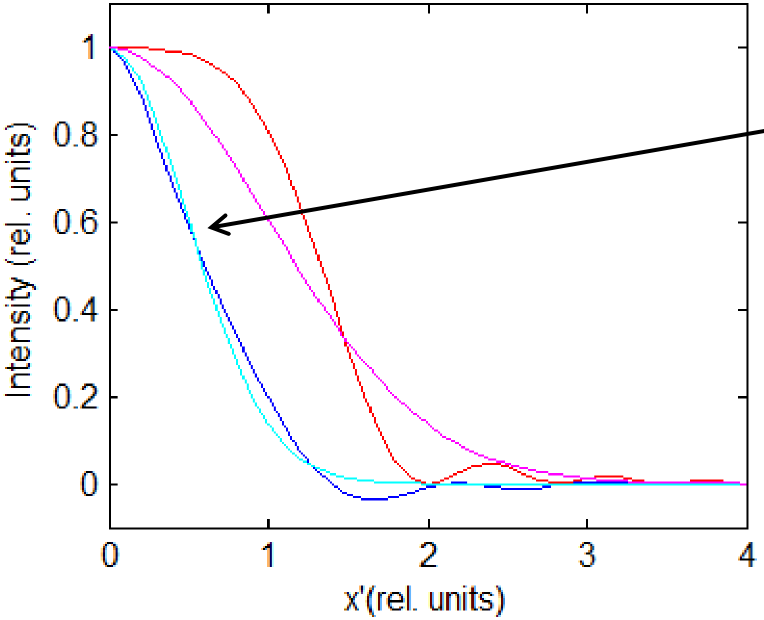
$$\varepsilon_R = \lambda/2\pi, \quad \beta_R = L/\pi$$ ❸



projected intensity (red)

Gaussian (magenta) $\sigma_R = \frac{1}{2\pi}\sqrt{2\lambda L}$

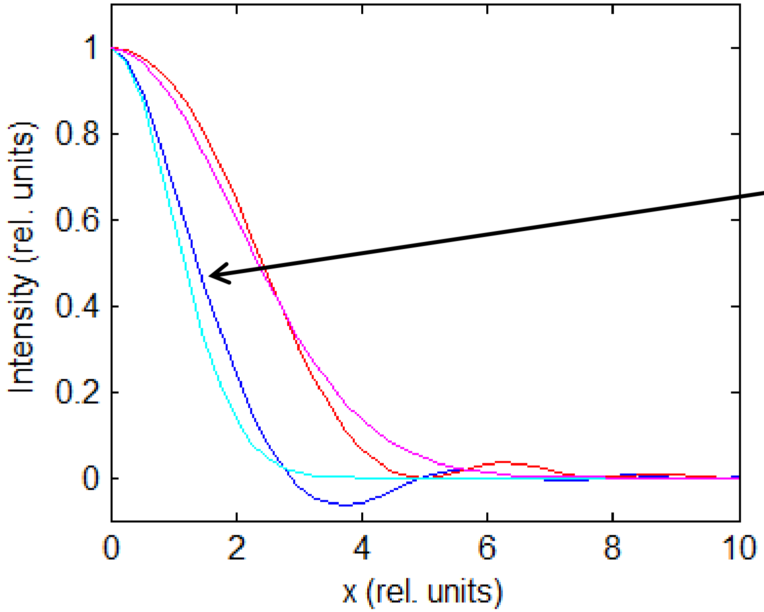
Cuts in phase space



W(0,x',0,0) (blue)

Gaussian (cyan) $\sigma_{R'} = \sqrt{\lambda/8L}$

$$\varepsilon_R = \lambda/8\pi, \quad \beta_R = L/\pi$$



W(x,0,0,0) (blue)

Gaussian (cyan) $\sigma_R = \frac{1}{4\pi}\sqrt{2\lambda L}$

→ rms values of the projected distributions are twice the those of the cuts in phase space …

On the other hand ..

from the definition of the Wigner function it follows directly, for zero emittance:

$$W_0 = \frac{F}{(\lambda/2)^2}$$

and equating this with the Brightness formula: $\mathcal{B} = \frac{F}{4\pi\,\varepsilon_R^2}$

we have by definition: $\varepsilon_R = \lambda/4\pi$

This also leads to a definition of the coherent flux as: $F_{coh.} = \mathcal{B}\left(\frac{\lambda}{2}\right)^2$

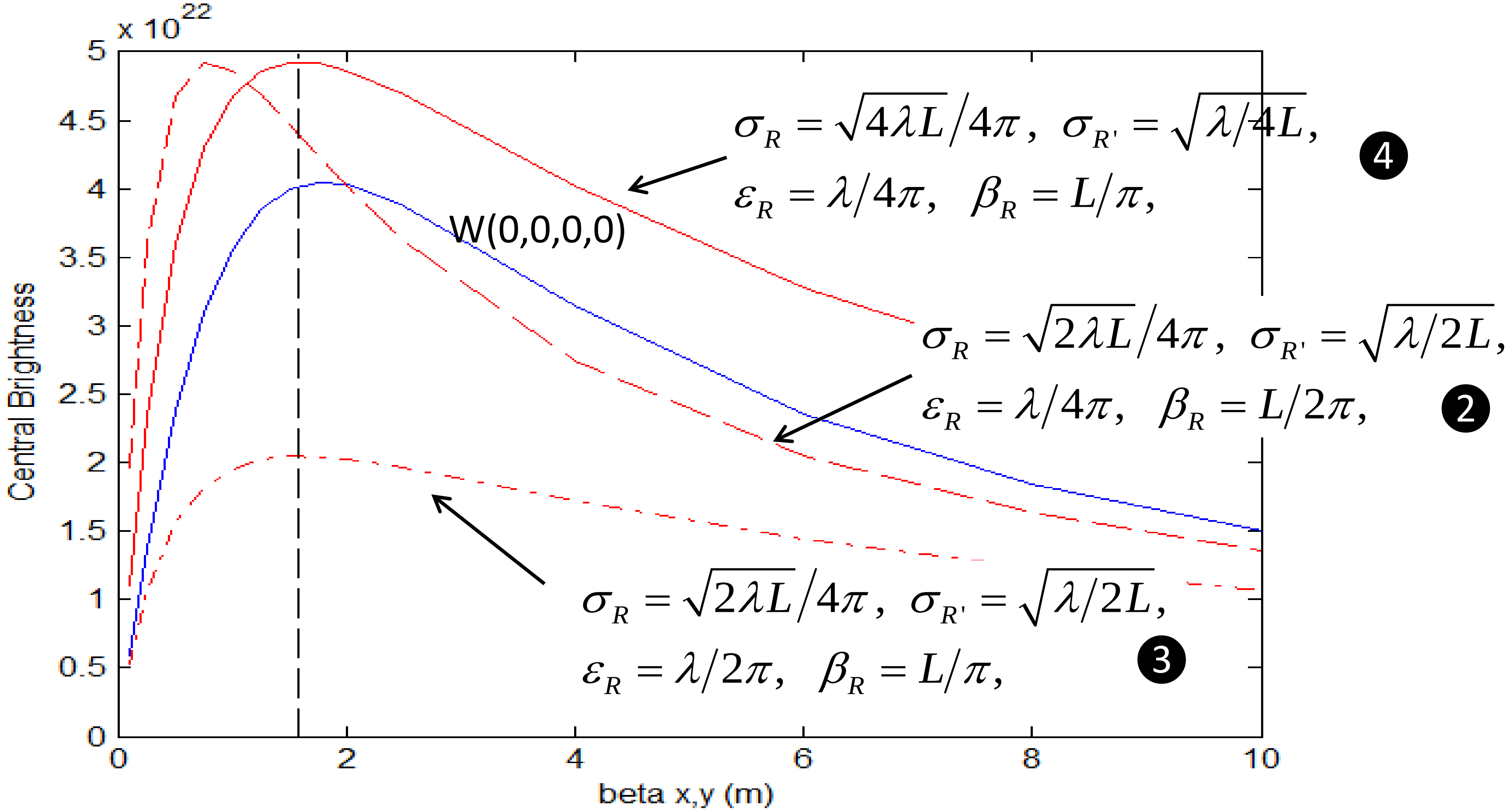
and the coherent fraction $= \frac{F_{coh.}}{F}$ which for zero emittance, = 1

As an aside, note that one can't use: $F_{coh.} = \mathcal{B}\left(\frac{\lambda}{2}\right)^2$

together with the approximate formula with $\varepsilon_R = \lambda/2\pi$

otherwise one obtains the ridiculous result: $\frac{F_{coh.}}{F} = \frac{1}{4}$

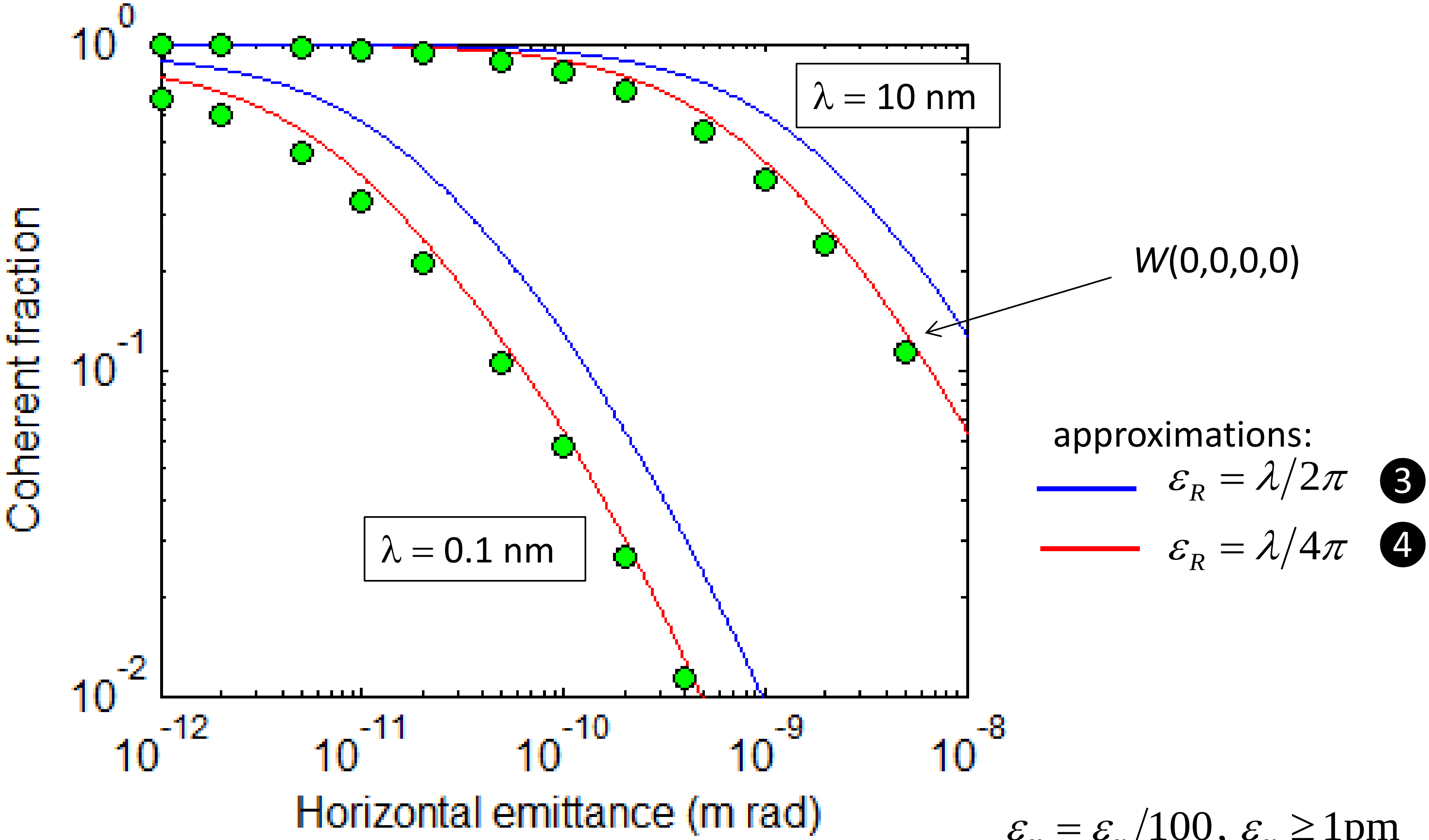
So which approximate formula is more accurate ?



$$\sigma_R = \sqrt{4\lambda L}/4\pi, \ \sigma_{R'} = \sqrt{\lambda/4L}, \ \varepsilon_R = \lambda/4\pi, \ \beta_R = L/\pi,$$ ④

$$\sigma_R = \sqrt{2\lambda L}/4\pi, \ \sigma_{R'} = \sqrt{\lambda/2L}, \ \varepsilon_R = \lambda/4\pi, \ \beta_R = L/2\pi,$$ ②

$$\sigma_R = \sqrt{2\lambda L}/4\pi, \ \sigma_{R'} = \sqrt{\lambda/2L}, \ \varepsilon_R = \lambda/2\pi, \ \beta_R = L/\pi,$$ ③



$$\varepsilon_y = \varepsilon_x/100,\ \varepsilon_y \geq 1\mathrm{pm}$$

$$\beta_{x,y} = L/\pi$$

→ The best approximation therefore appears to be:

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

Note that the Gaussian model is only an approximation:

… it's not 100% accurate

… it takes no account of detuning

… it takes no account of energy spread

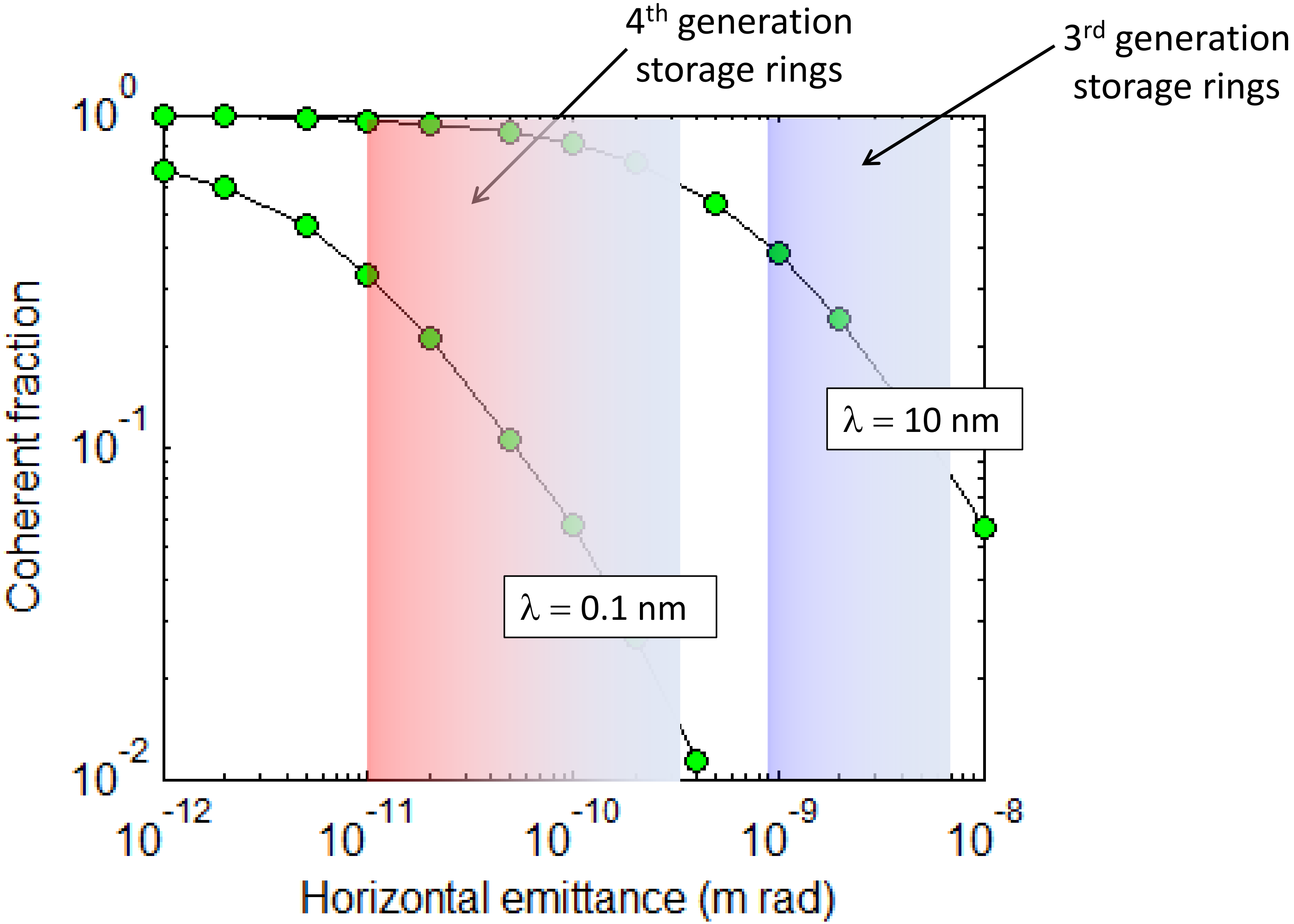
And in any case:

- is peak Brightness the best figure-of-merit for experiments ?, or would some sort of average Brightness be more appropriate ?
- Brightness is not the only parameter:

  εx = 100 pm, εy = 1 pm gives a factor 3.5 more Brightness at 0.1 nm than $\varepsilon x = \varepsilon y$ = 50 pm, but there are some advantages to '***round beams***' …

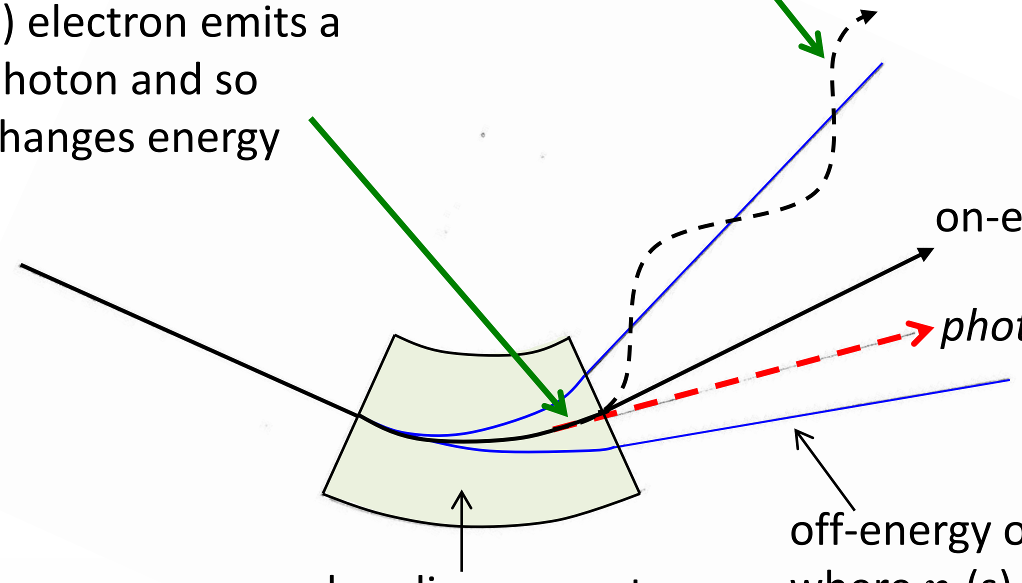
  … better match to the quality of optics; better match to circular zone plates
  … reduces Intra Beam Scattering and increases Touschek lifetime.

2. How to approach the Diffraction Limit ?



How to reduce the electron beam emittance ?

Where does emittance come from ? …



2) electron oscillates about off-energy orbit

1) electron emits a photon and so changes energy

on-energy orbit, ΔE=0

photon

bending magnet

off-energy orbits, $x(s) = \eta(s)\,\Delta E$ where η (s) is the dispersion function

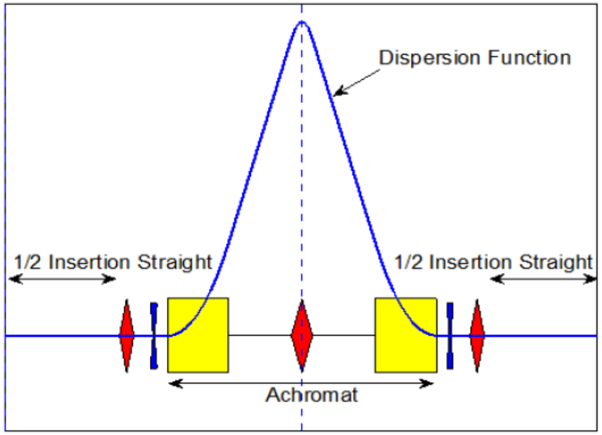
… emitting photons in a bending magnet or insertion device excites betatron oscillations

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

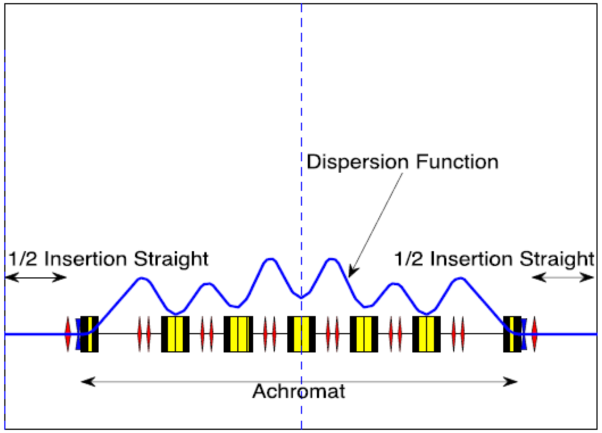
$$H(s) = \underbrace{\gamma\eta^2 + 2\alpha\eta\eta' + \beta\eta'^2}$$

1) Reduce the dispersion, η(s) and η’(s), in the bending magnets

Double Bend Achromat (DBA)



Multi Bend Achromat (MBA)



$$\boxed{\varepsilon_x \sim \frac{Energy^2}{N_{bend}^3}}$$

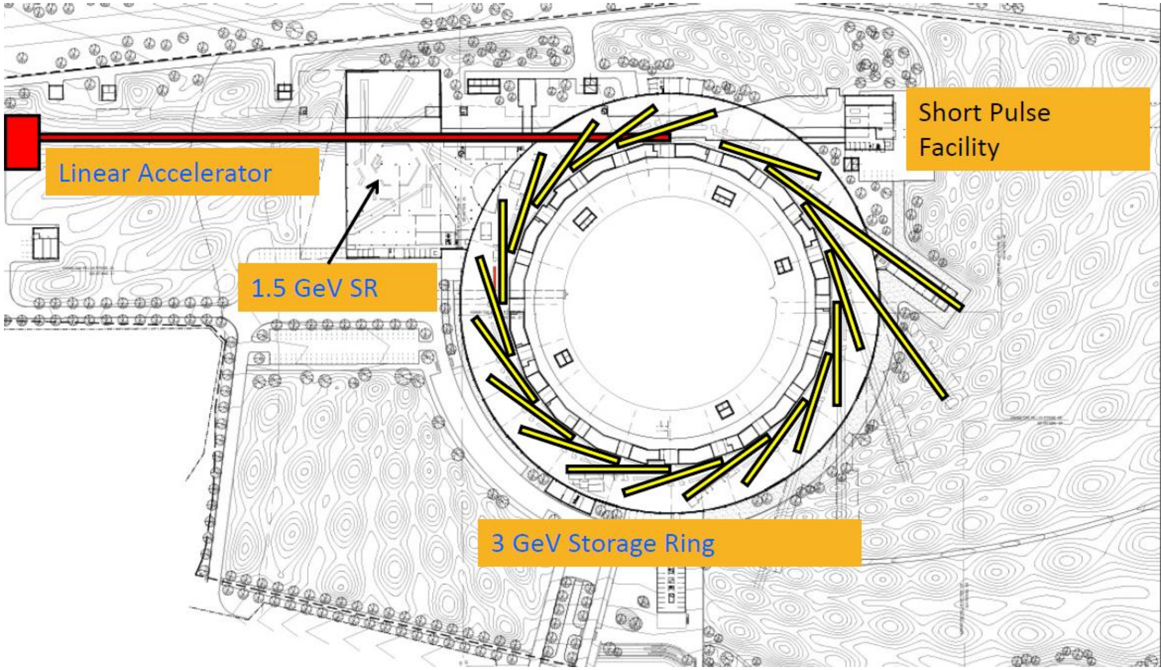
(provided other conditions can be satisfied)

MBA Lattices have been studied for many years …

Year	Ring	E (GeV)	C (km)	MBA	ε_{xo}	Reference
1993	ROSY-II	3	0.2	4BA	3 nm	Einfeld & Plesko, PAC'93
1994	SLS	2.1	0.25	7BA	3.2 nm	Joho et al., EPAC'94
1995	DIFL	3	0.4	7BA	0.56 nm	Einfeld et al., PAC'95
2000	USR	7	2	4/5BA	0.3 nm	Ropert et al., EPAC'00
2005	XPS7	7	1.1	6BA	78 pm	Borland, NIM 2006
2006		6	2.0	10BA	34 pm	Tsumaki & Kumagai, NIM 2006
2008	MAX-IV	3	0.53	7BA	0.31 nm	Eriksson et al, NIM 2008
2009	USR7	7	3.16	10BA	30 pm	Borland, AIP Proc.
2011	PEP-X	4.5	2.2	7BA	29 pm	Nosochkov et al., IPAC'12
2012	τUSR	9	6.3	7BA	2 pm (full coupling)	Borland, ICFA Beam Dynamics Newsletter 57, 2012

… before finally becoming a reality in MAX-IV, the first of a new generation of storage ring light sources.

1st beam:
25/08/15



New Rings based on MBA Lattices

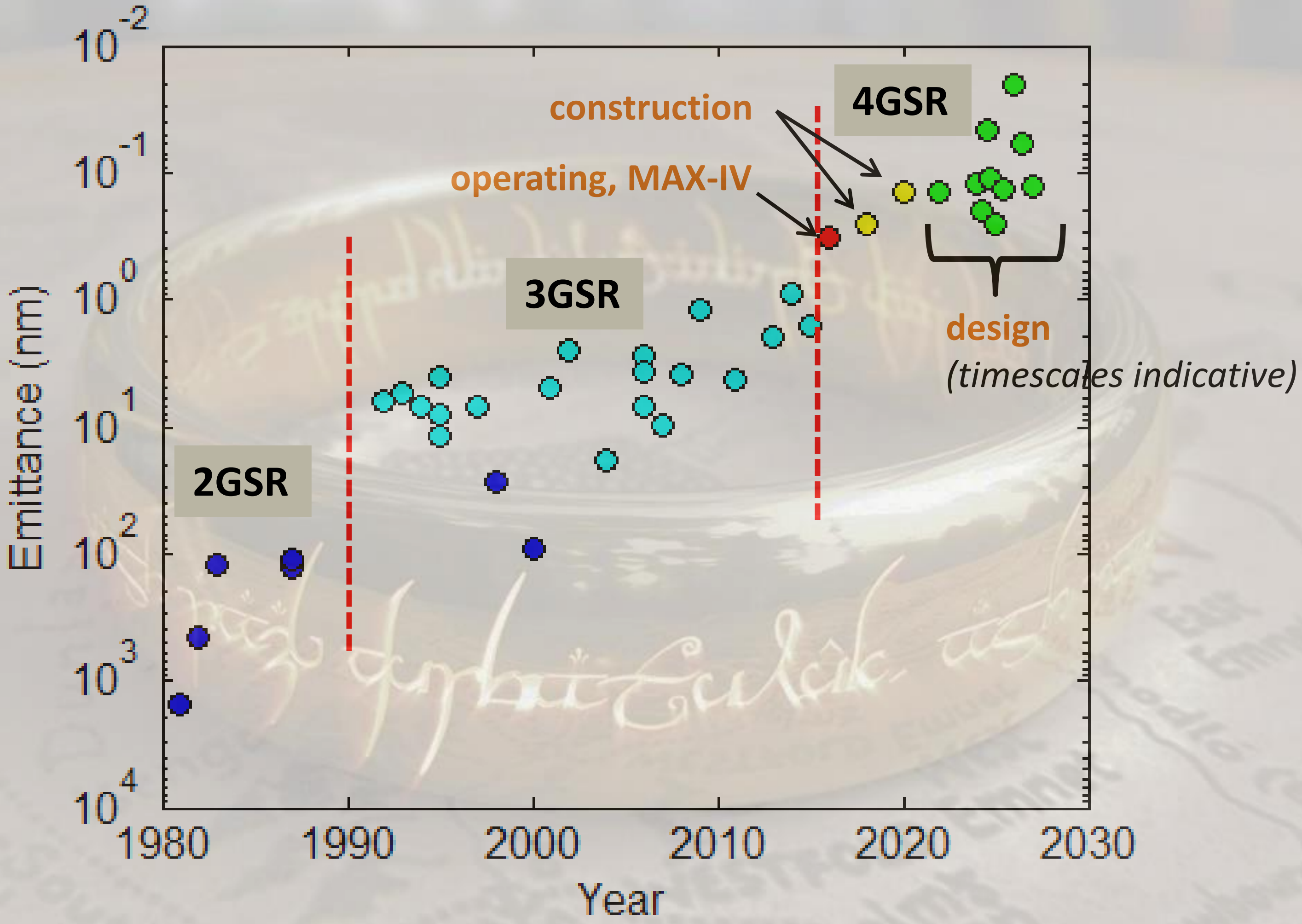
Ring	Country	E (GeV)	C (m)	Lattice	Emittance	Status
MAX-IV	Sweden	3	528	7BA	330 pm	operating
Sirius	Brazil	3	518	5BA	250 pm	construction (2018)
ILSF	Iran	3	528	5BA	275 pm	pre-construction (2025)
CANDLE	Armenia	3	269	4BA	435 pm	study
HALS	China	2	648	6BA	18 pm	study
HEPS	China	6	1260	7BA	59 pm	study; R&D
KEK-LS	Japan	3	571	8BA	130 pm	study
SLiT-J	Japan	3	354	4BA	920 pm	study
SPS-II	Thailand	3	321	6BA	970 pm	study
TURKAY	Turkey	3	477	4BA	510 pm	study

Upgraded Rings based on MBA Lattices

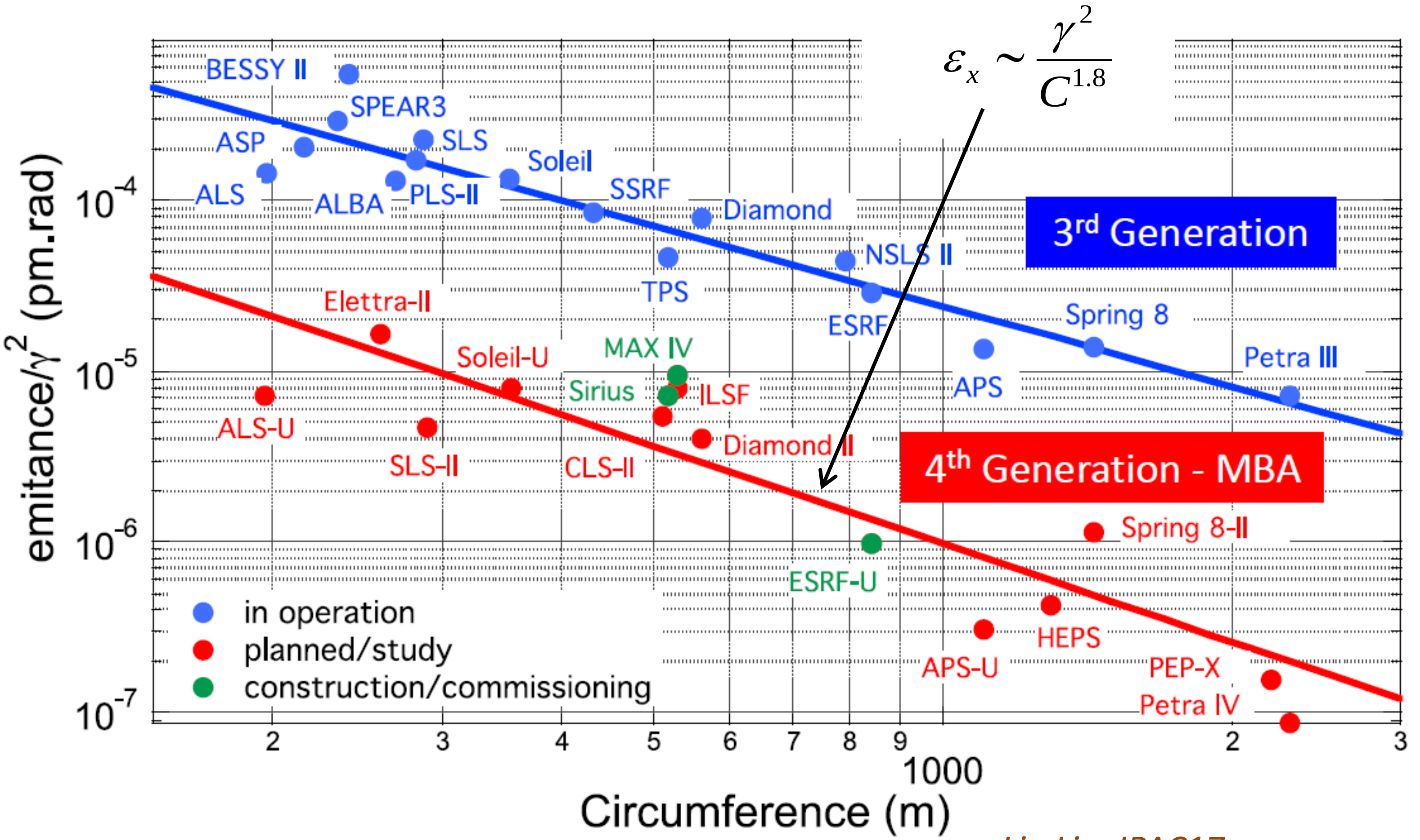
Ring	Country	E (GeV)	C (m)	Lattice	Emittance	Status
ESRF-EBS	France	6	844	7BA	140 pm	construction (2020)
APS-U	USA	6	1104	7BA	46 pm	pre-construction
ALS-U	USA	2	197	9BA	109 pm	study; R&D
Diamond-II	UK	3	562	6BA	125 pm	study
ELETTRA 2.0	Italy	2	259	6BA	250 pm	study
PETRA-IV	Germany	6	2304	7BA	10-30 pm	study
SLS-II	Switzerland	2.4	288	7BA	138 pm	study
SOLEIL-II	France	2.75	354	6/7BA	~ 200 pm	study
Spring-8-II	Japan	6	1435	5BA	140 pm	study; R&D
SSRF-U	China	3	432	7BA	203 pm	study

The Quest for the Brightest Ring .....

MBA Lattices are a new generation of synchrotron light source:



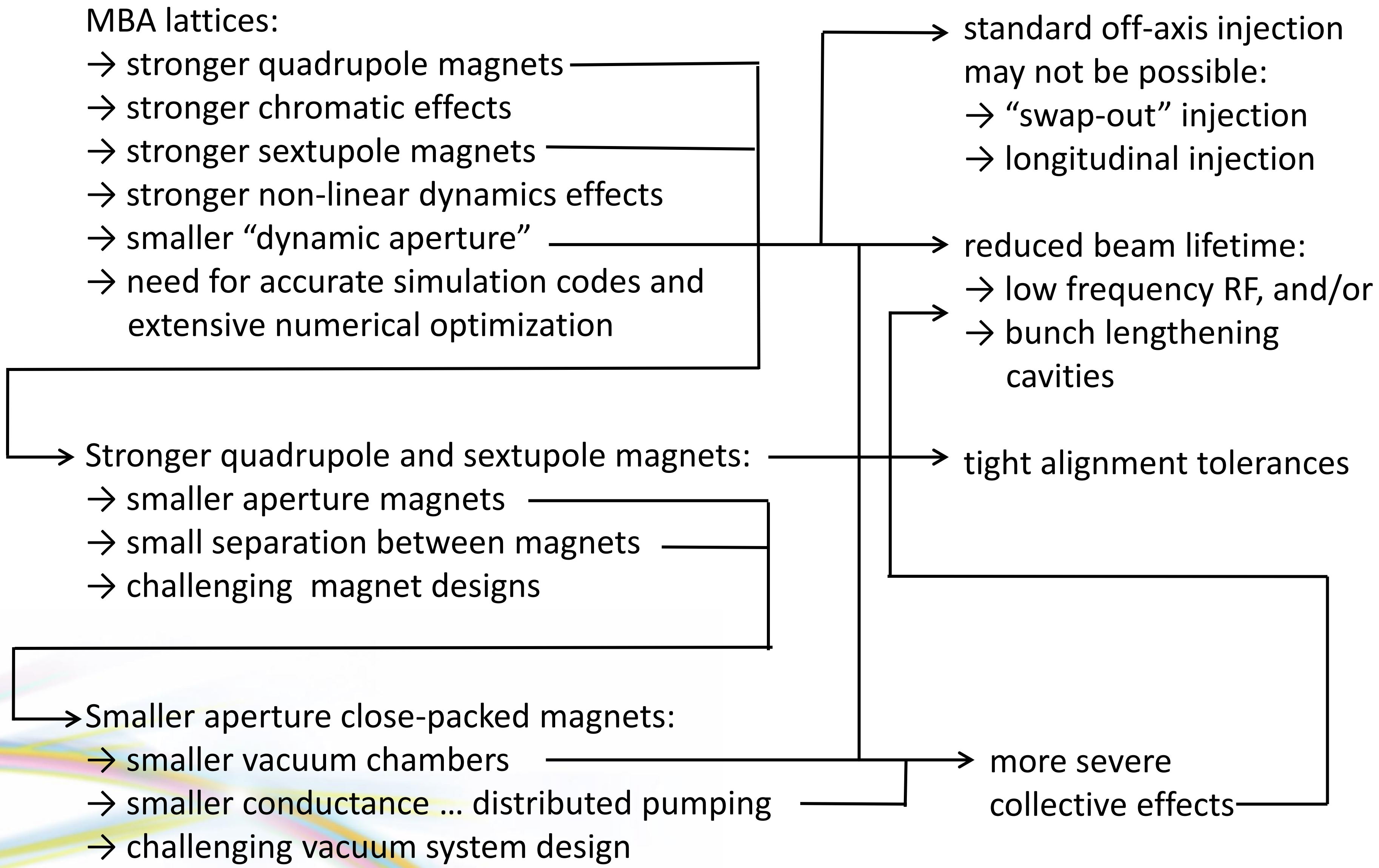
The leap from the 3rd to the 4th generation becomes clearer on this plot:



$$\varepsilon_x \sim \frac{\gamma^2}{C^{1.8}}$$

Liu Lin, IPAC17,
adapted from R. Bartolini, LER, Oxford, July 2013

So why has it taken so long ?! …



MBA lattices:
- → stronger quadrupole magnets
- → stronger chromatic effects
- → stronger sextupole magnets
- → stronger non-linear dynamics effects
- → smaller "dynamic aperture"
- → need for accurate simulation codes and extensive numerical optimization

Stronger quadrupole and sextupole magnets:
- → smaller aperture magnets
- → small separation between magnets
- → challenging magnet designs

Smaller aperture close-packed magnets:
- → smaller vacuum chambers
- → smaller conductance … distributed pumping
- → challenging vacuum system design

standard off-axis injection may not be possible:
- → "swap-out" injection
- → longitudinal injection

reduced beam lifetime:
- → low frequency RF, and/or
- → bunch lengthening cavities

tight alignment tolerances

more severe collective effects

… or put simply:

So what has allowed MAX-IV and the 4th Generation to happen?

- Crucial has been the development of better accelerator physics modelling and optimization methods, giving greater confidence in designs.

- New technology ?
  - NEG coating ? .. used successfully in MAX-IV, and will be used in many future projects, but may not be strictly necessary in all cases e.g. ESRF-EBS has vey little NEG coating.
  - compact high gradient magnets, yes (but the technology is not that revolutionary).
  - integrated magnets … used successfully in MAX-IV, but not being taken up for other projects.

- Other design choices such as low frequency RF and no bending magnet ports have helped simplify the design of MAX-IV, but may not be necessary in all cases.

- **Above all … having the confidence (nerve) to do it !**

Engineering Developments

MAX-IV Integrated Magnets

photo: Anna Olsson, Scanditronix Magnet AB

photo: Anna Olsson, Scanditronix Magnet AB

quad. r_0 =12.5 mm
40 T/m

machined out of solid iron block, up to 3.4m long:

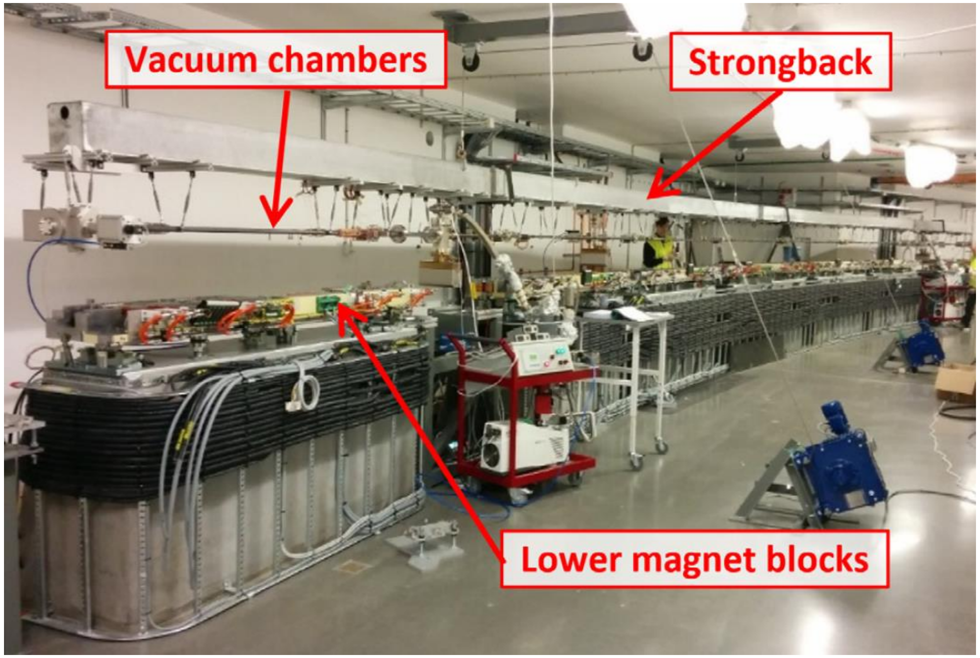
- reduces vibrations
- high accuracy of relative alignment
- simplifies installation

but:

- complicates magnetic measurement
- difficult for subsequent interventions

M. Johansson, JSR 21 (2014) 884.

MAX-IV Vacuum System

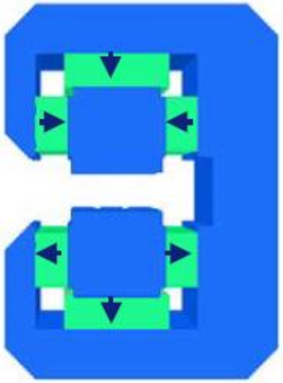


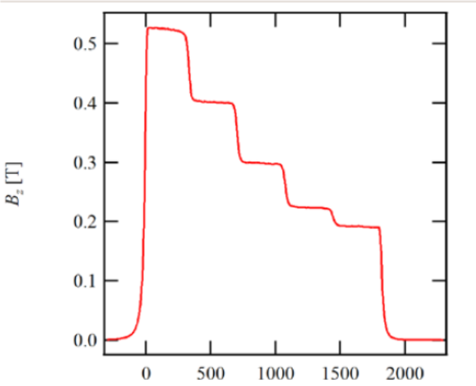
- ~ 20 m long vacuum string
- Cu/stainless steel
- inside radius 11 mm
- 100% NEG coated
- ex-situ bakeout only
- no bending magnet ports

Al-Dmour et al, JSR 21 (2014) 878.
Al-Dmour et al., IPAC17

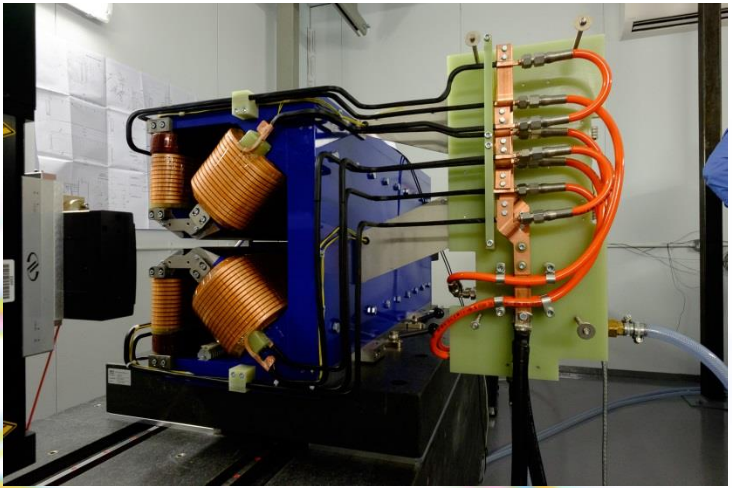
ESRF-EBS Magnets

longitudinal gradient **permanent ma**gnet dipoles -

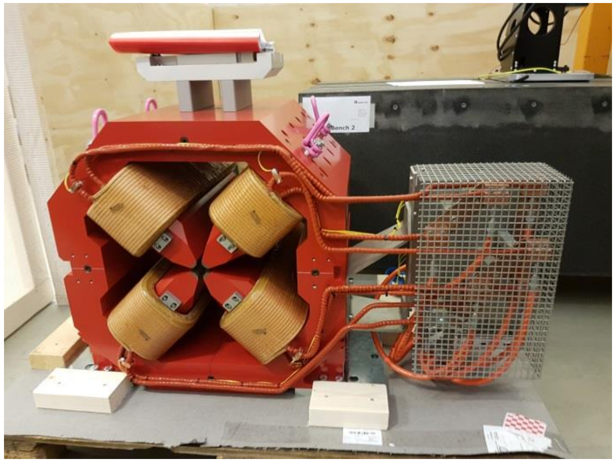




dipole-quadrupole magnets
0.57T, 37 T/m



high gradient quadrupole
r_0 = 12.7 mm, 91 T/m



(APS-U, r_0 = 13 mm, 98 T/m)

ESRF-EBS Girders

ESRF-EBS "mock-up": one complete cell, 4 girders, under vacuum, Sep. 2017.

Lattice Development - Other ways to reduce emittance:

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

2) Optimize the term *H*/ρ, using Longitudinal Gradient Bends

i.e. field is large, ρ small, when dispersion small; field is small, ρ large, when dispersion increases.

3) Provide extra bending ρ(s) with low dispersion, using Damping Wigglers

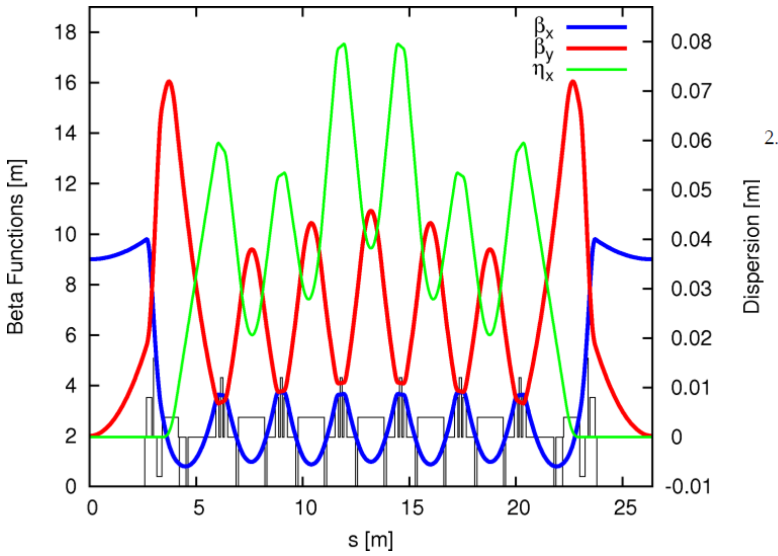
e.g. as employed at PETRA-III and NSLS-II; can be effective when the main bending field is relatively low; they also help reduce IBS, but

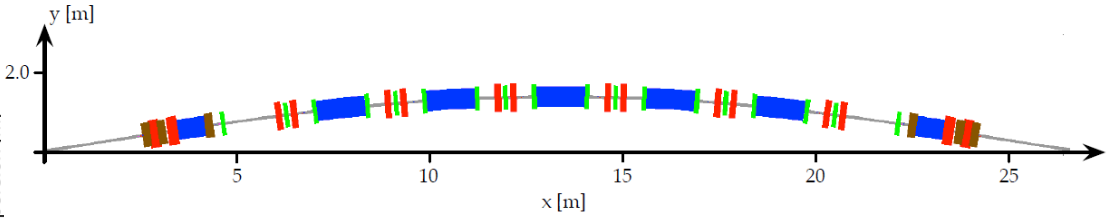
- increase RF power requirements, take up valuable straight section space, give rise to a high power loading on the vacuum vessels, increase energy spread and complicate beam dynamics.

4) Increase the "damping partition" Jx, using gradient dipole magnets, or gradient (Robinson) wigglers

- can reduce emittance by ~x2, but this will increase energy spread by √2

MAX-IV 7BA

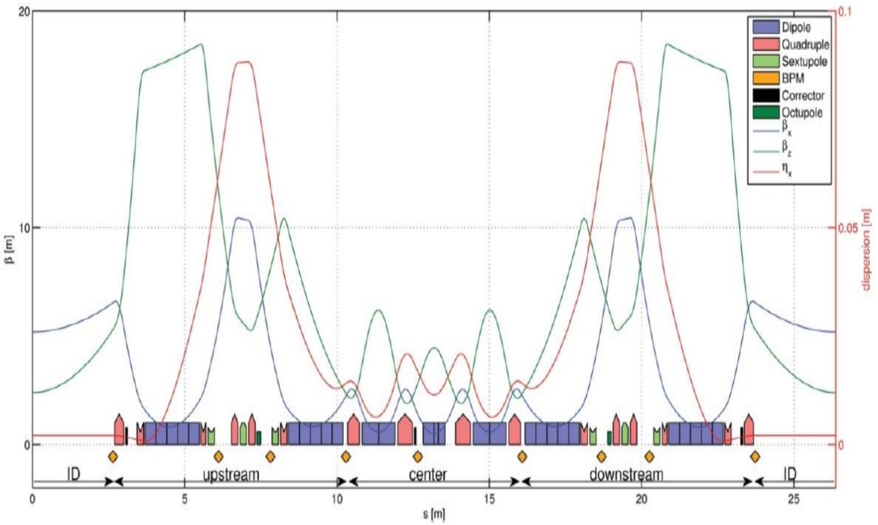




gradient dipoles (blue), quadrupoles (red), sextupoles (green), octupoles (brown)

NB] sextupoles distributed throughout the cell (similarly in the Sirius 5BA lattice)

ESRF “hybrid-7BA”



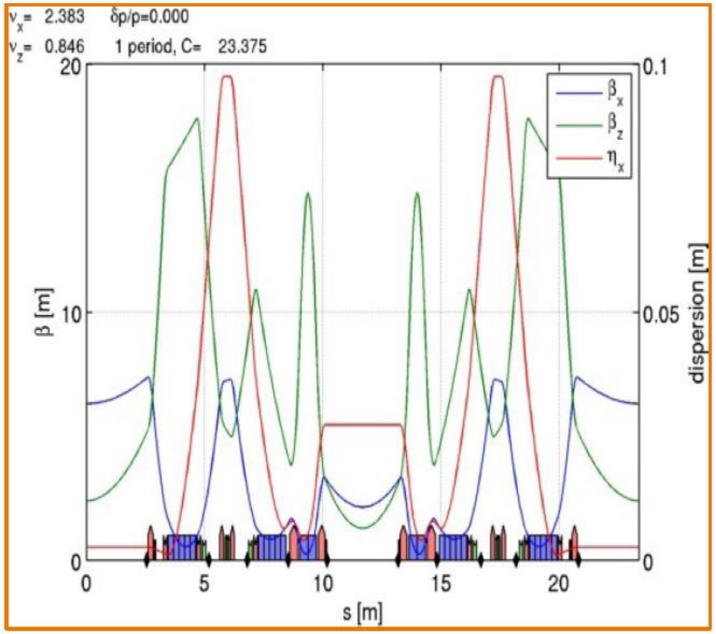
“dispersion bumps” formed from the outer pairs of dipole

- sextupoles only in the dispersion bumps, with appropriate phase difference
- no sextupoles in the central “FODO” region

L. Favacque et al., IPAC 2013

Variants of the "hybrid-7BA":

Compromise between lowest emittance and increased capacity for Insertion Devices

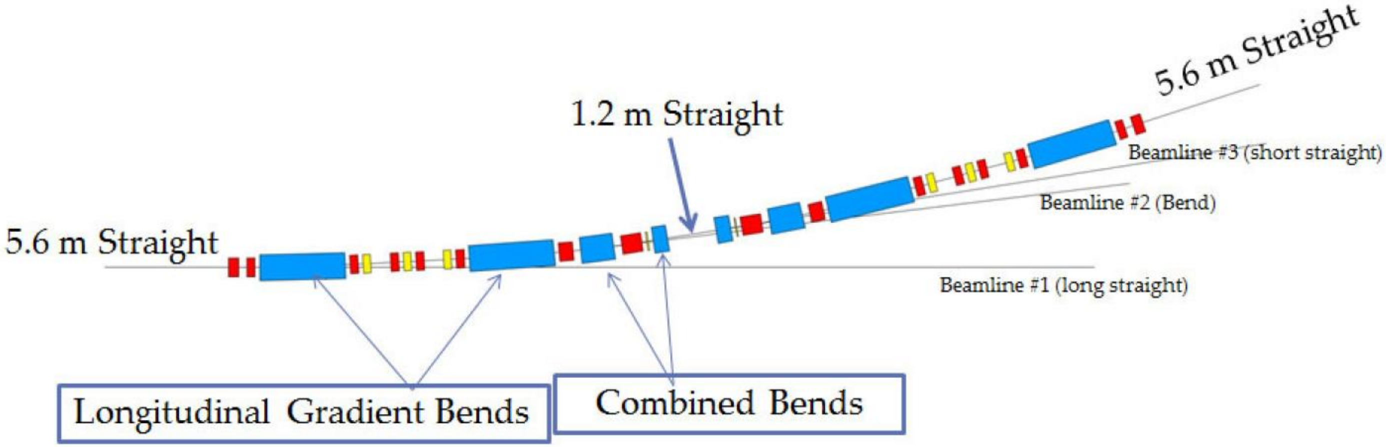


Diamond "DTBA" (double-triple bend achromat)
- creating a central straight section long enough for an additional insertion device.

A. Alekou et al, IPAC16

KEK-LS "DQBA" (double-quadruple bend achromat)

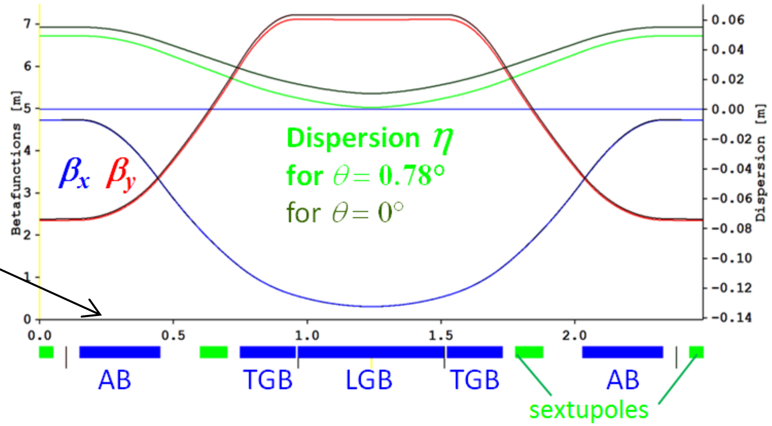
T. Honda, IPAC17



Anti-Bends or Reverse Bends†

- an extra "knob" to "disentangle" dispersion and beta functions and so allow better optimization of lattice functions in order to minimize emittance.

- Incorporated in the proposed **SLS-II** lattice: x 4 reduction in emittance

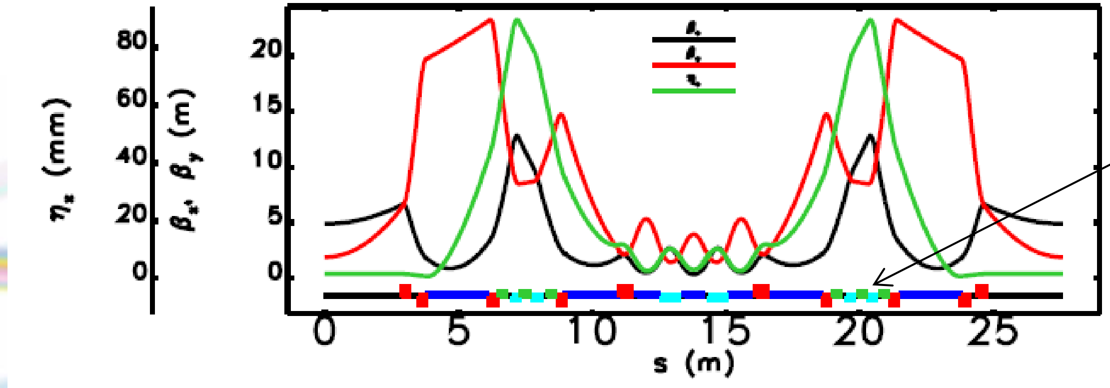


anti-bends

$$\sum_i |\theta_i| = 585^o$$

A. Streun, 2nd LERD workshop, Dec. 2016

- Incorporated in the candidate **APS-U** lattice



reverse bends (cyan),
(actually offset quadrupoles)
reduces ex 67 to 42 pm

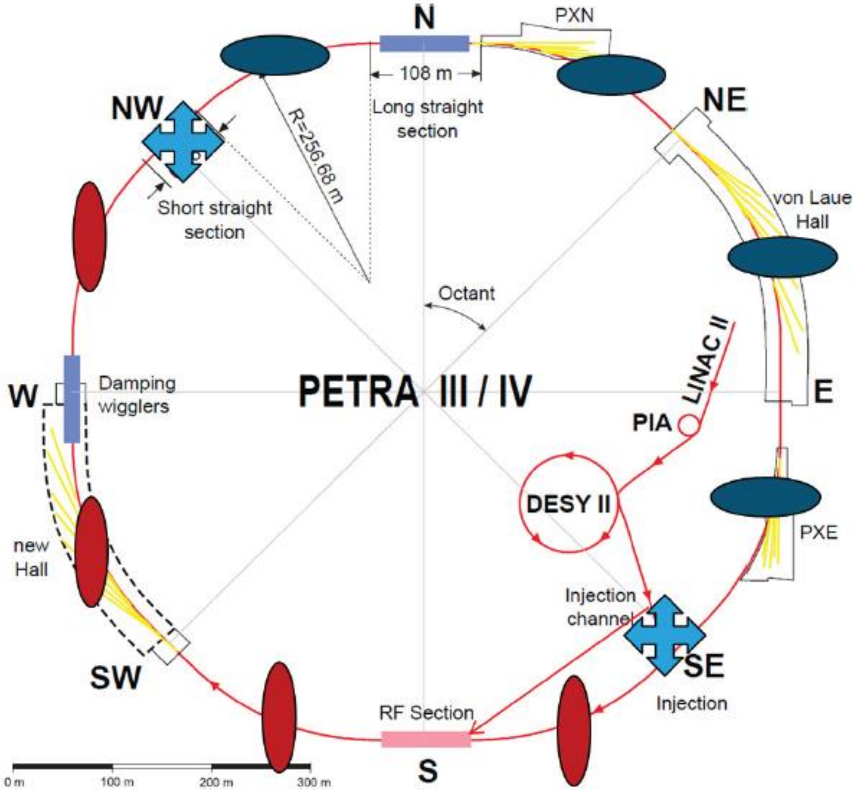
M. Borland et al., NAPAC 2016

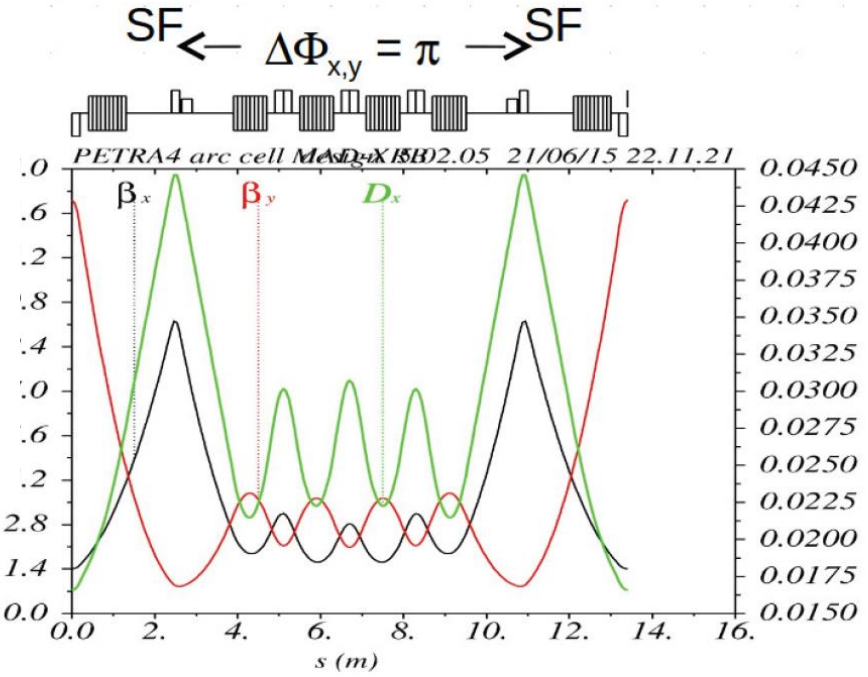
† *J.P. Delahaye and J.P. Potier, PAC 1989*
A. Streun, NIM A737 (2014) 148.
A. Streun and A. Wrulich, NIM A770 (2015) 98.

Phase Space Exchange Lattice†

- one of the options being studied for the PETRA-IV Upgrade
- produces a round-beam with εx=εy ~ 25pm

I. Agapov et al., IPAC17





- horizontal chromaticity corrected in one part of the ring , vertical in the other …
- large dynamic aperture
- off-axis injection possible

---

† *R. Talman, Phys. Rev. Lett., 74 (1995) 1590.*
S. Henderson, PAC '99

Round Beams

e.g.

- ALS-U $\varepsilon x = \varepsilon y = 70$ pm
- APS-U timing mode $\varepsilon x = \varepsilon y = 32$ pm
- PETRA-IV $\varepsilon x = \varepsilon y \sim 10\text{-}30$ pm

How?

- emittance exchange (PETRA-IV)
- horizontal field wigglers (Bogomyagkov et al, LER Workshop, Frascati 2014)
- sitting on the linear coupling resonance; on-axis injection only
- coupling resonance excitation with dynamic skew-quadrupole
  (P. Kuske, Workshop on Round Beams)

Workshop on Round Beams, SOLEIL, 14-15th June 2017
https://www.synchrotron-soleil.fr/fr/evenements/mini-workshop-round-beams

See talks on Thursday morning:
"Production of round beams in storage ring light sources", P. Kuske
"Production of round beams at PETRA IV", I. Agapov

3. 4GSRs involve compromises

- lower emittance vs. cost
  (larger circumference, more complex technology, more complex injector - especially for on-axis injection)

- lower emittance vs. risk

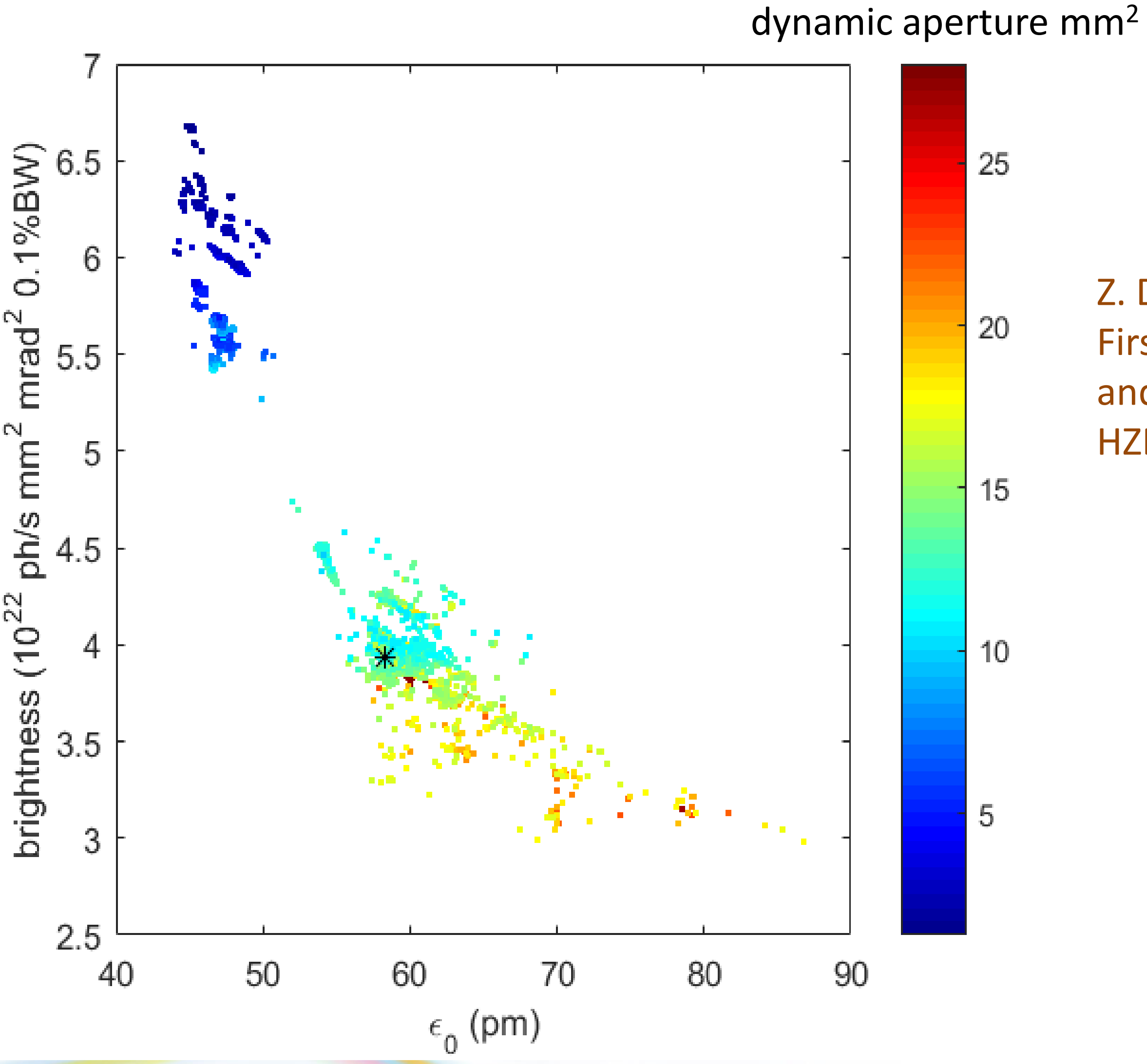
- lower emittance vs. short bunch lengths
  (may need low frequency RF and/or harmonic cavities to lengthen the bunch for lifetime)

- lower emittance vs. more insertion devices

- lower emittance vs. flexibility
  (may have to give up special lattice modifications which are incompatible with low emittance e.g. double mini-β schemes, femtoslicing etc.)

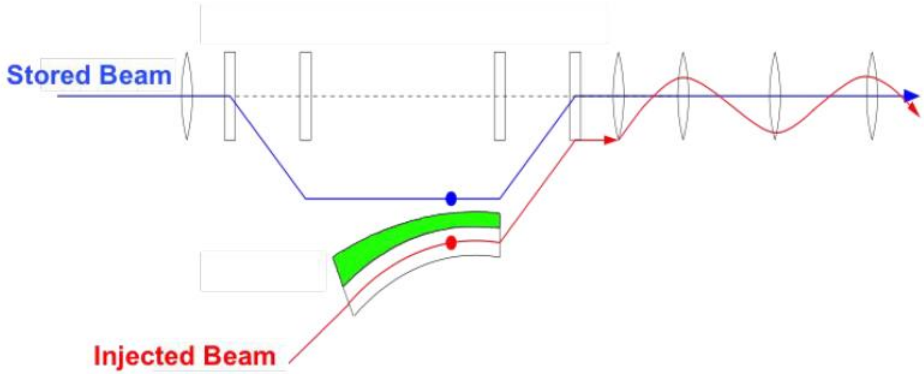
- smaller apertures might restrict the range of photon energies:
  … difficult to extract IR & UV
  … difficult to extract vertically/circularly polarized radiation at low photon energies

Compromise between lower emittance and larger Dynamic Aperture

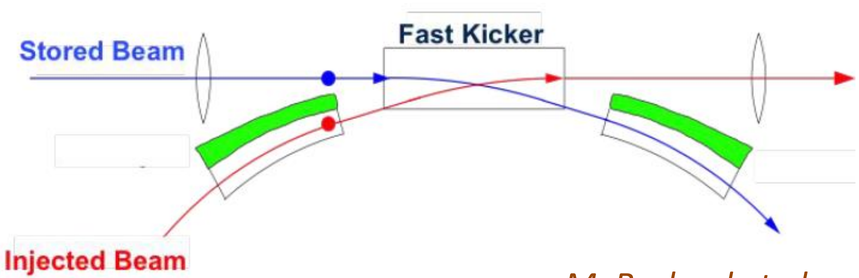


Z. Duan/Y. Jiao,
First Topical Workshop on Injection and Injection systems.
HZB (BESSY II), 28-30th August 2017

On-axis injection: “Swap-out” †



Traditional off-axis injection



On-axis swap-out injection

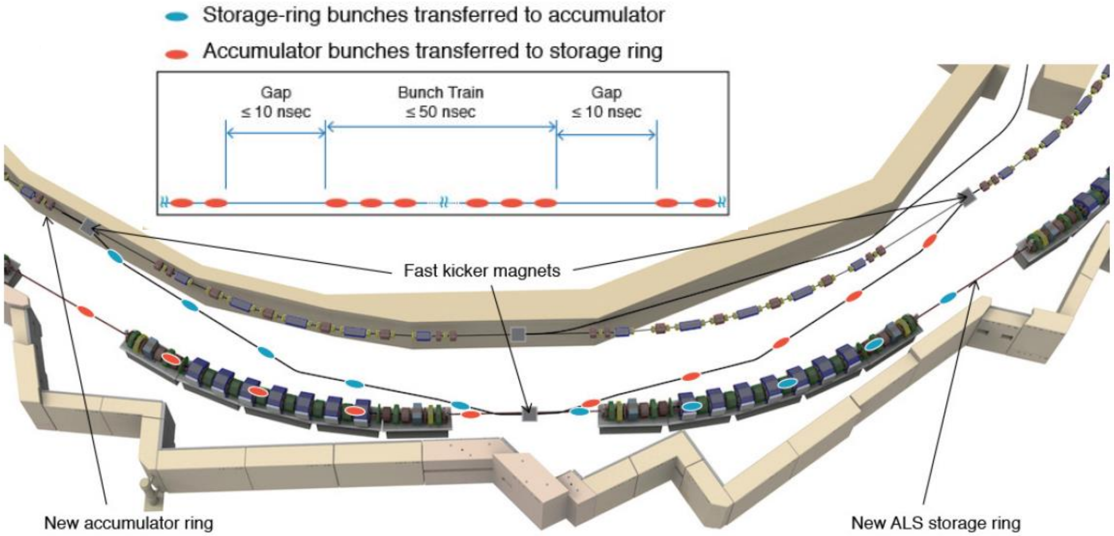
M. Borland et al., NAPAC16

- each injected bunch replaces an existing bunch of the stored beam, with full charge
- extracted bunch can be re-used (with an accumulator ring) or dumped
- dynamic aperture need only accommodate the injected beam emittance, not the injected beam oscillation
- allows the possibility of compromising dynamic aperture to achieve lower emittance
- horizontal physical apertures can also be reduced, advantageous for IDs
- stringent requirements on kicker/pulser pulse profiles and stability

† *L. Emery & M. Borland, PAC03*

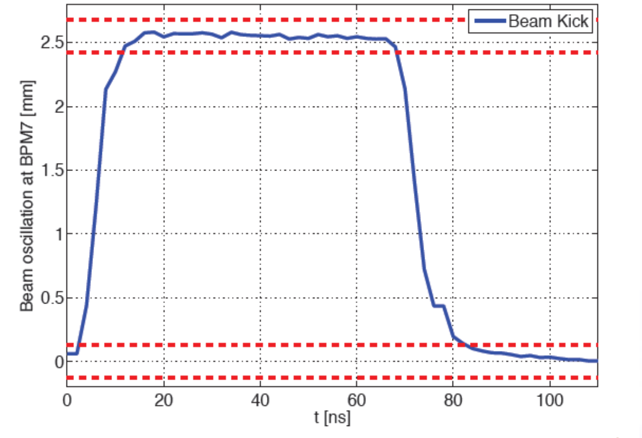
Swap-out injection will be used for ALS-U and APS-U

- ALS-U will swap-out bunch trains, with an accumulator ring

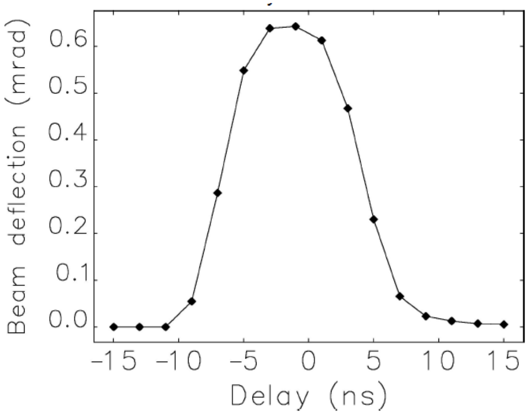


- APS-U will swap out single bunches, and dump them
  - fast kicker for 324-bunch mode, < 20 ns pulse length
  - high charge for 48-bunch mode, 15 nC per bunch

in both cases, prototype stripline kickers and pulsers meet the specifications:



C. Steier et al., IPAC17



M. Borland et al., NAPAC16

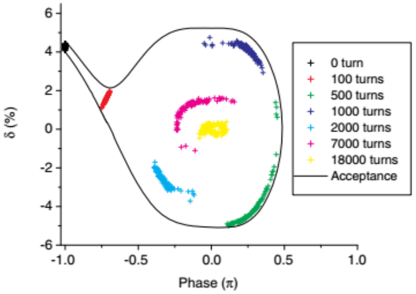
On-axis injection: longitudinal plane

- many schemes, some very new

- all involve injecting off-phase, and off-energy, <u>in-between</u> circulating bunches,
→ kicker pulse duration < bunch spacing
→ low RF frequency and fast kicker magnets

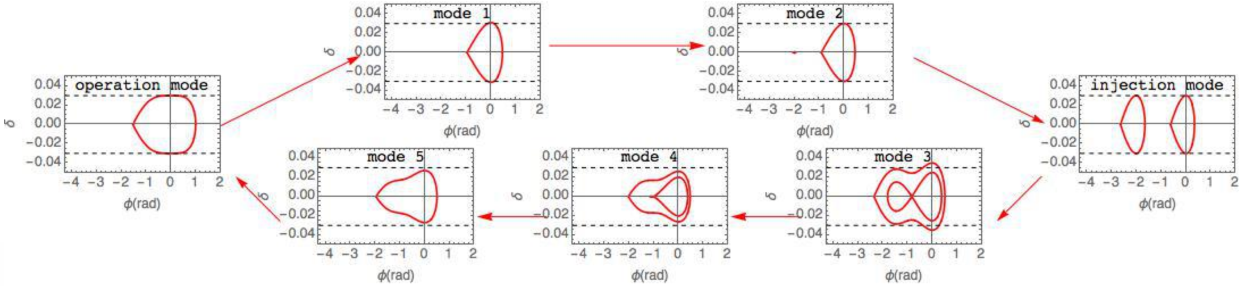
- “golf club” scheme

M. Aiba et al., PRSTAB, 2015



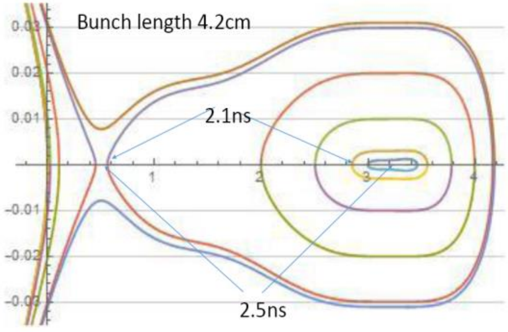
- double RF gymnastics

Z. Duan, HEPS



- triple static RF

G. Xu, HEPS



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

4. The Future …

"Prediction is very difficult, especially about the future",
Niels Bohr.

Is there an ultimate limit ???

There appears to be no fundamental physical limit to reaching the X-ray diffraction limit:

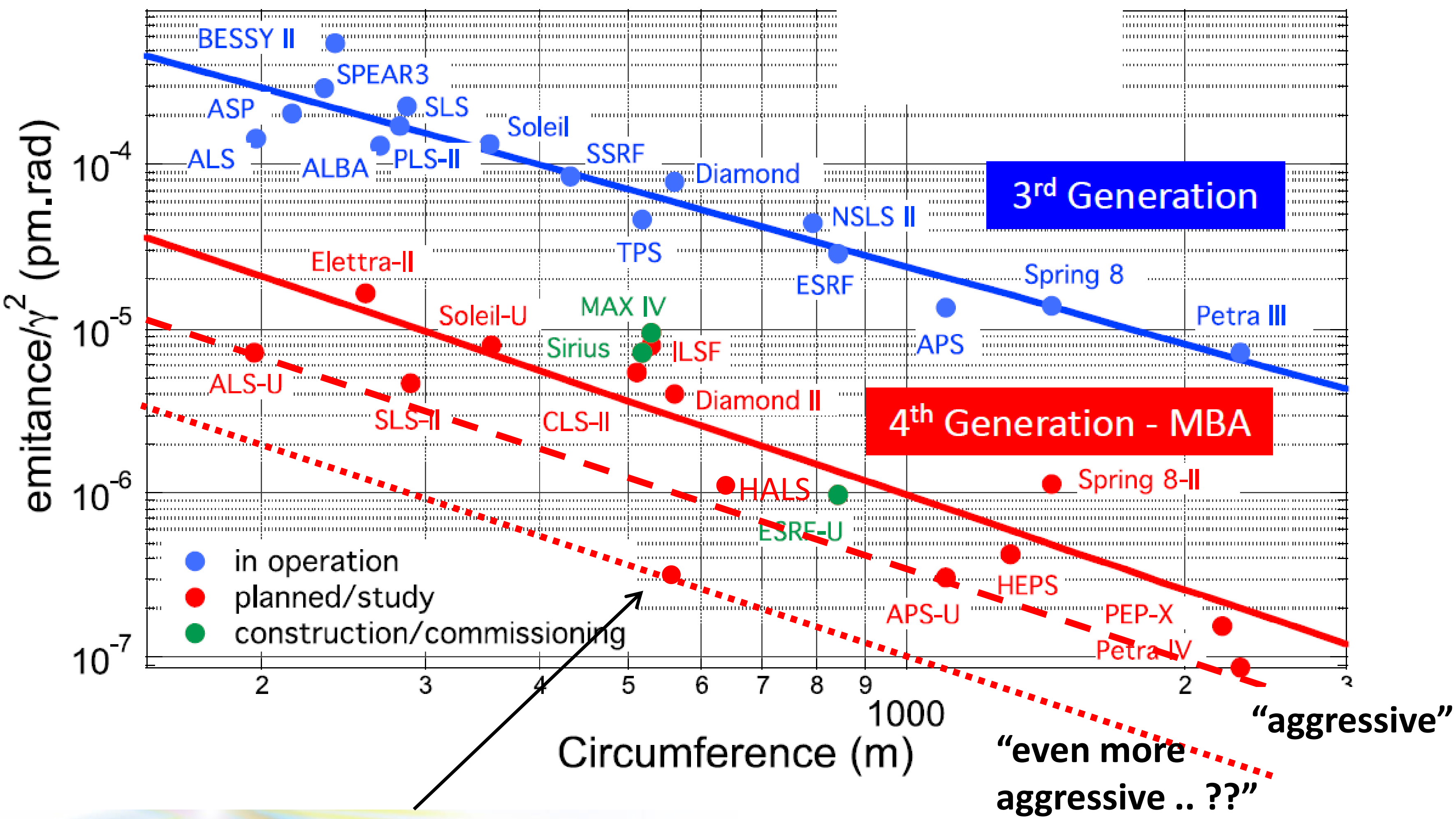
- the "quantum limit" is much smaller, $\varepsilon_{x,y} \approx \frac{C_q}{4} \frac{\langle \beta_{x,y} \rangle}{J_{x,y}\, \rho}$ $<$ 0.3 pm

- ε_y = 2-10 pm vertical emittance is routine and sub-pm has been measured,
e.g. $\varepsilon_y = 0.9 \pm 0.3$ pm measured at the Australian Synchrotron

K.P. Wootton et al., PRSTAB 17, 112802 (2014)

The challenge is to reach the desired emittance in a reasonable circumference ..

Can the technology be pushed further ?



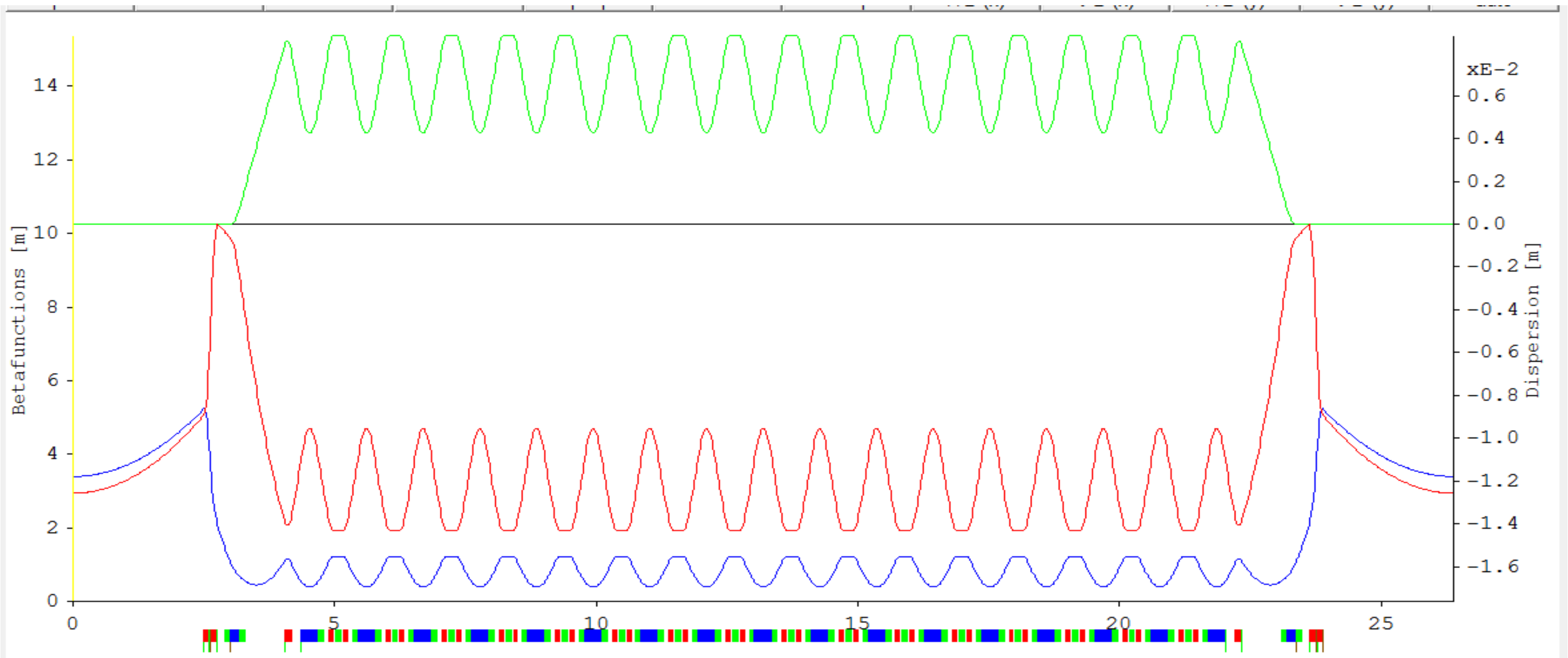
“aggressive”

“even more aggressive .. ??”

10 pm at 3 GeV in 550m ?

A possible future direction …

“Beyond MAX-IV” P. Tavarez, Low Emittance Ring Workshop, Lund, Nov. 2016



- 3 GeV, C=528 m
- 19 BA
- ε_{xo} = 16 pm
- ~ 200 T/m quadrupoles, r_o = 5.5 mm … permanent magnets
- IBS will be severe … multiple RF frequencies

Storage Ring Light Sources have a bright future ...

thanks for your attention !