Design Considerations and Trade-Offs for 4th-Generation Storage Ring Light Sources

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Outline

- X-ray brightness
- Origin of emittance in storage rings
- Storage ring scaling and challenges of low emittance
  - Emittance
  - Magnet parameters
  - Nonlinear dynamics
  - Collective effects
  - Alignment
- Summary

X-ray Brightness

- The quality of a beam is expressed by the brightness

$$B \propto \frac{N_\gamma}{(\Delta\lambda/\lambda)\Delta t \Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'}}$$

(simplification)

- Approximate description of <u>single-electron</u> undulator radiation distribution (“intrinsic” or “diffraction” distribution)[1]

$$\epsilon_r = \sigma_r \sigma_{r'} \approx \frac{\lambda}{2\pi} \qquad \beta_r = \frac{\sigma_r}{\sigma_{r'}} \approx \frac{L_u}{\pi}$$

- The electron beam is described by (simplest case)

$$\sigma_q = \sqrt{\epsilon_q \beta_q} \qquad \sigma_{q'} = \sqrt{\frac{\epsilon_q}{\beta_q}}$$

where q=x or y and the emittances and beta functions are nominally free parameters

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

N.B.: there is disagreement about the exact numerical factors. E.g., some authors set the emittance and beta function to half the values shown here.

X-ray Brightness

- To maximize brightness, we minimize the denominator

$$\Sigma_q \Sigma_{q'} = \sqrt{\epsilon_q \beta_q + \epsilon_r \beta_r} \sqrt{\frac{\epsilon_q}{\beta_q} + \frac{\epsilon_r}{\beta_r}} \qquad q=x,y$$

- Minimized when

$$\beta_{x,y} = \beta_r \approx \frac{L_u}{\pi} \rightarrow \Sigma_q \Sigma_{q'} = \epsilon_q + \epsilon_r$$

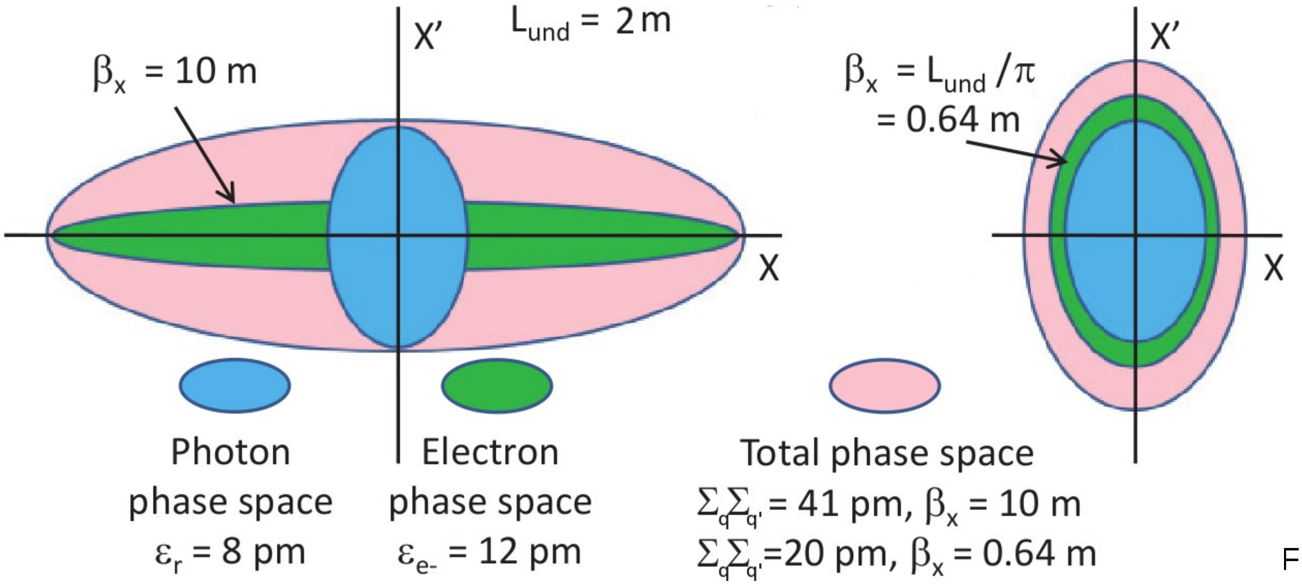


Figure courtesy R. Hettel

X-ray Brightness

- We are “diffraction-limited” when in addition to matching beta functions

$$\epsilon_{x,y} \leq \frac{1}{2}\epsilon_r \approx \frac{\lambda}{4\pi}$$

- In this case the coherent fraction is nearly 50%

$$f_c = \frac{\epsilon_r^2}{\Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'}} \gtrsim 44\%$$

How Close are We Now?

- For an undulator filling a typical 5-m-long straight

$$\beta_r = 1.6\text{m}$$

  which is feasible, though not always easy.
- Emittance is another matter

$$\begin{aligned} \epsilon_q[pm] &\lesssim \frac{100}{E_p[keV]} \\ \epsilon_q[pm] &\lesssim 8\lambda[\mathring{A}] \end{aligned} \Rightarrow \begin{aligned} 1\text{ keV} &\rightarrow \epsilon_q \lesssim 100\text{ pm} \\ 10\text{ keV} &\rightarrow \epsilon_q \lesssim 10\text{ pm} \end{aligned}$$

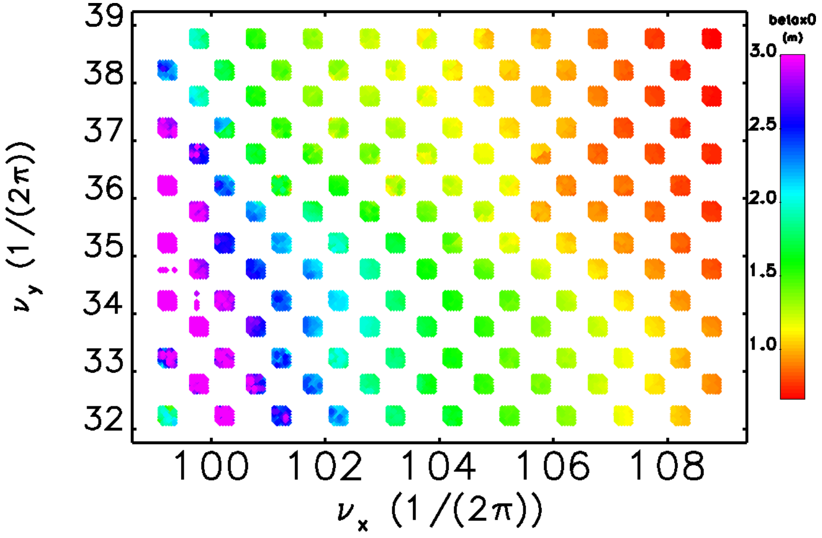
- For typical 3rd-generation rings

$$\epsilon_x : [1, 5]\text{nm} \qquad \epsilon_y : [1, 40]\text{pm}$$

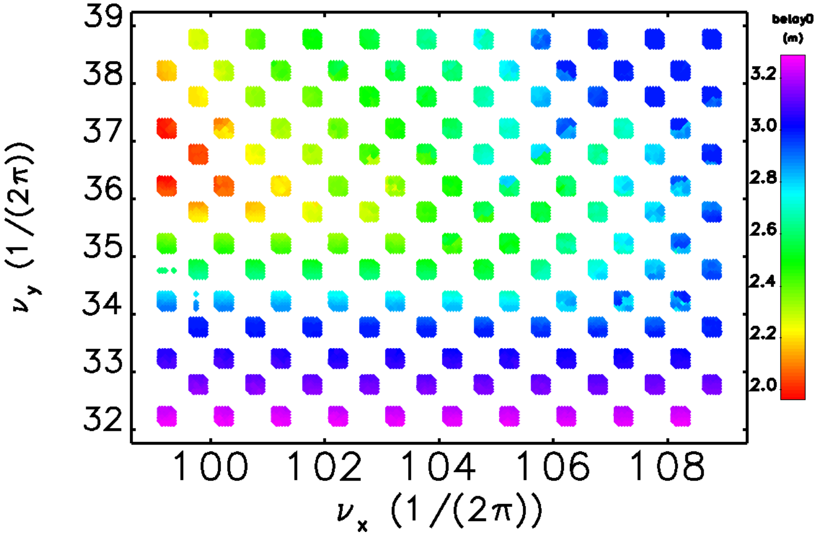
  so we are several orders of magnitude away from DL performance in horizontal

Example of Conflicts in Linear Optics Tuning

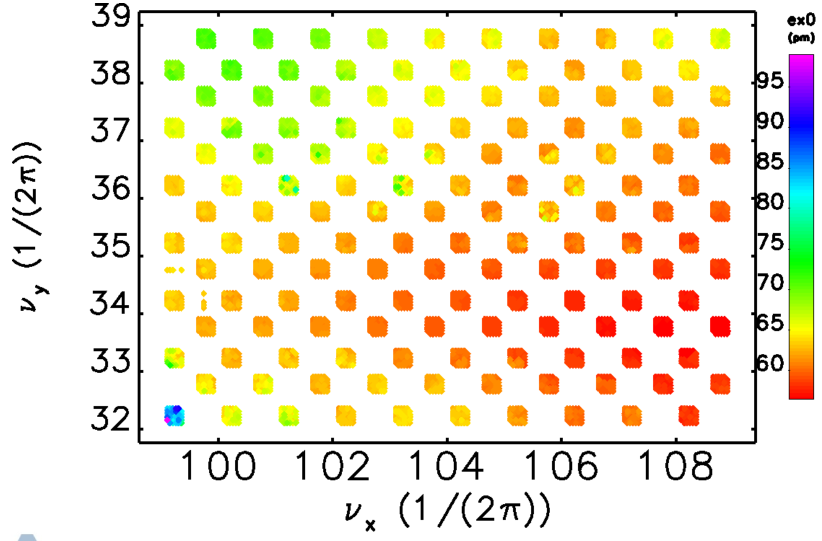
Horizontal beta function @ID



Vertical beta function @ID



Natural emittance (pm)

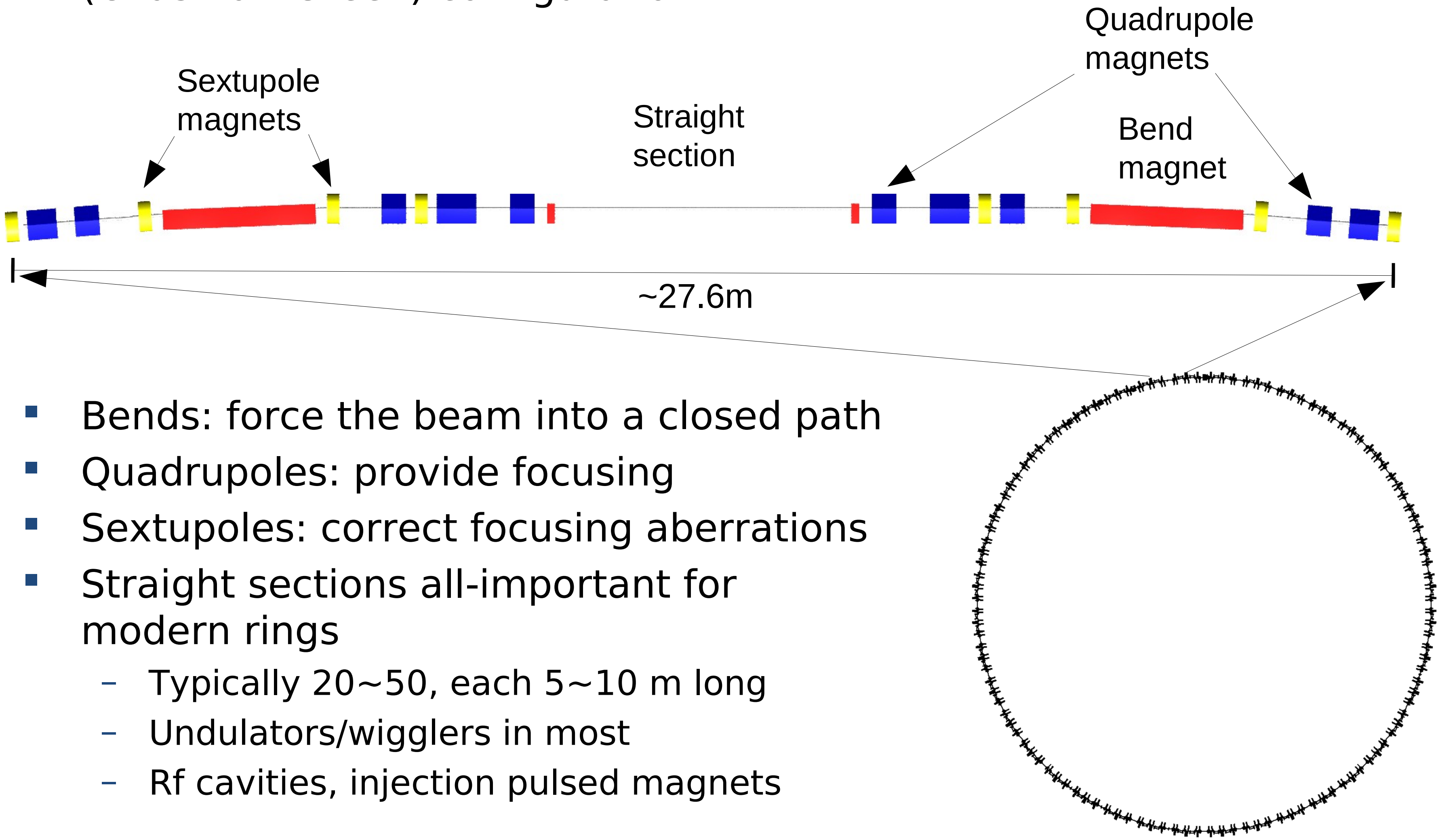


Minimizing the emittance is incompatible with reducing horizontal beta function to the ideal value of ~1.5 m

Best to optimize brightness directly for a specific photon energy

Contemporary Storage Ring Light Sources

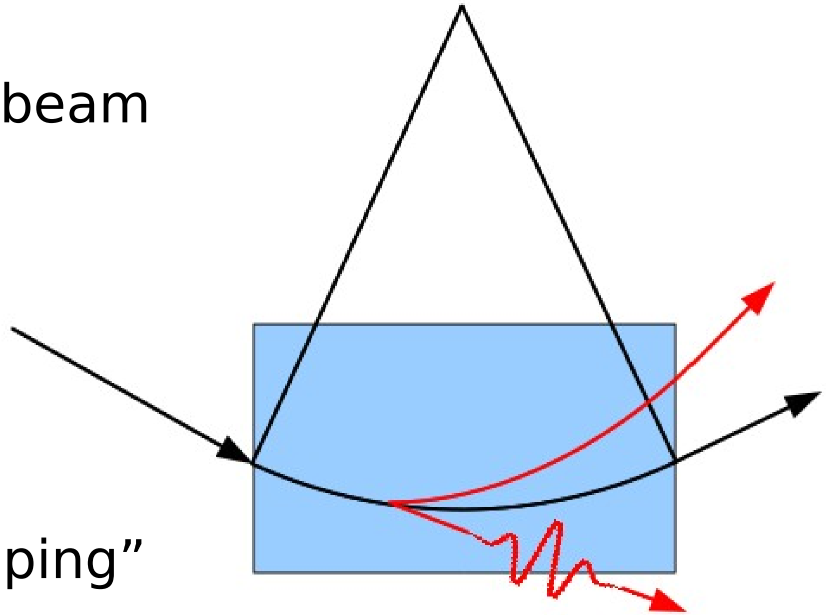
- Conventional storage rings (e.g., APS) typically have double-bend (Chasman-Green) configuration



- Bends: force the beam into a closed path
- Quadrupoles: provide focusing
- Sextupoles: correct focusing aberrations
- Straight sections all-important for modern rings
  - Typically 20~50, each 5~10 m long
  - Undulators/wigglers in most
  - Rf cavities, injection pulsed magnets

Quantum Excitation of Electron Beams

- Classical expression for synchrotron radiation gives average energy loss in a bending field
- Radiation emission also has a random character governed by quantum mechanics
  - Different electrons emit differently in identical conditions
- Hence, bending will diminish beam brightness
  - Directly by increasing energy spread
  - Indirectly by increasing bend-plane emittance
- This "quantum excitation" is opposed by "radiation damping" resulting in a well-defined equilibrium emittance



See, e.g., M. Sands, SLAC-121 (1972).

Emittance Scaling

- Emittance is governed by[1]

$$\epsilon_0 = F(\nu, \text{cell}) \frac{E^2}{(N_s N_d)^3} \qquad \underbrace{\propto \frac{E^2}{C^3}}_{\text{Fixed cell type}}$$

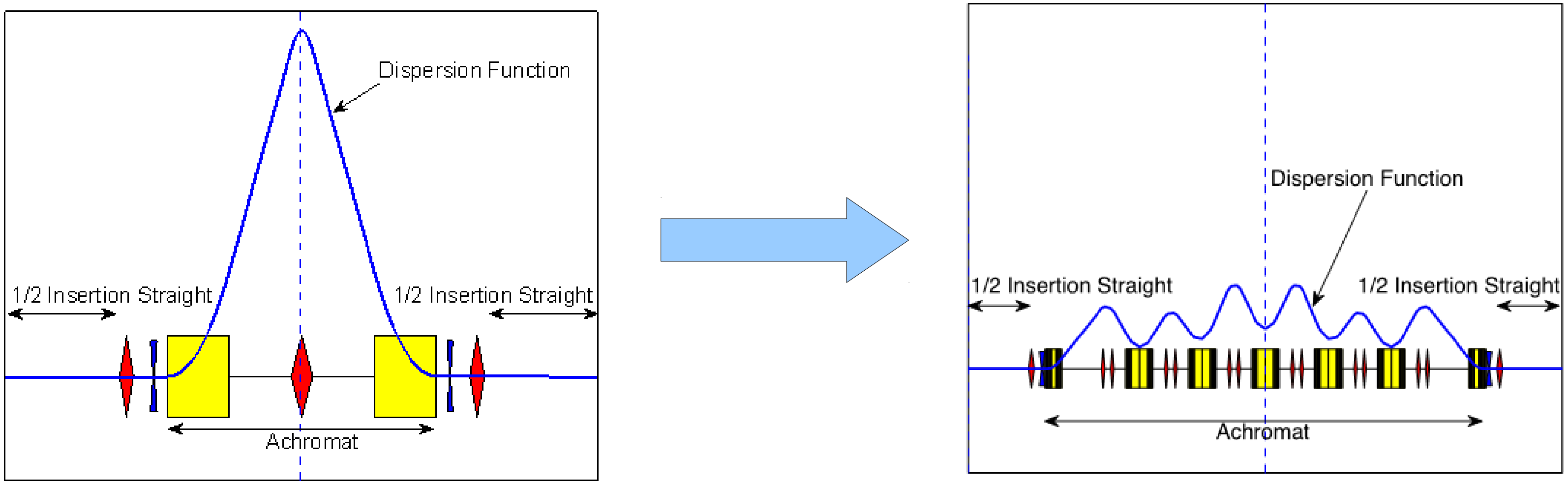
$$\epsilon_x = \frac{\epsilon_0}{1+\kappa} \qquad \epsilon_y = \kappa \epsilon_x$$

where N_s=#sectors and N_d=#dipoles/sector

- Simple explanation
  - Emittance is driven by randomness of photon emission in presence of dispersive (energy-dependent) orbits
  - Breaking up dipoles and putting focusing (quadrupoles) between the parts allows tightly controlling the magnitude of dispersive orbits

[1] J. Murphy, NSLS Light Source Data Booklet

From Double to Multi-Bend Achromats



All figures courtesy C. Steier, LBNL.

- Rings today have $N_d=2$ or (more rarely) 3
- Several groups proposed $N_d>3$ lattices in 1990s[1]
  - 7BA should have ~40x lower emittance than today's 2B(A) lattices
  - Typically emittances should drop from 2-4 nm to 50-100 pm
    - Diffraction-limited performance up to 1-2 keV
    - Much higher brightness and coherence over entire spectrum

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[1] Einfeld *et al*., NIM A 335, 1993; Joho *et al*., EPAC 94;: Einfeld *et al*., PAC95; Kaltchev *et al*., PAC95.

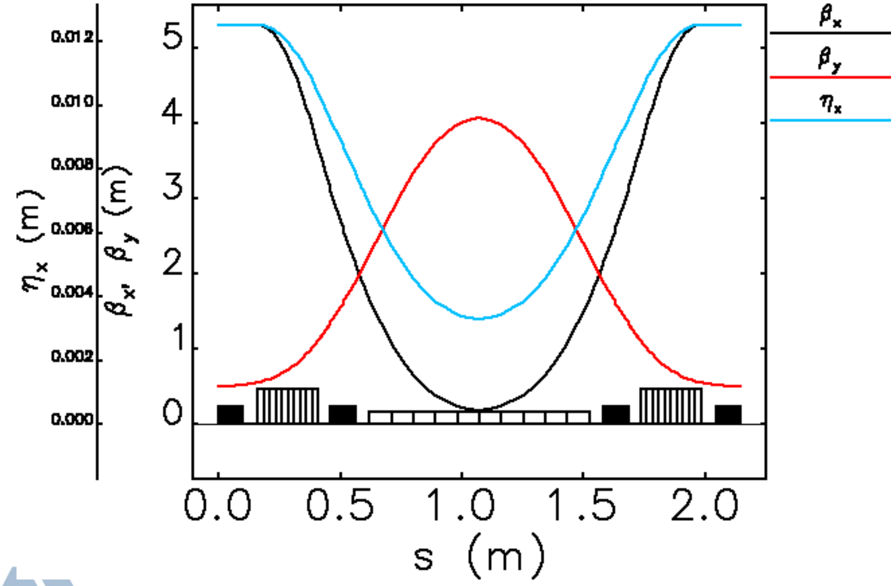
Challenges of Low Emittance

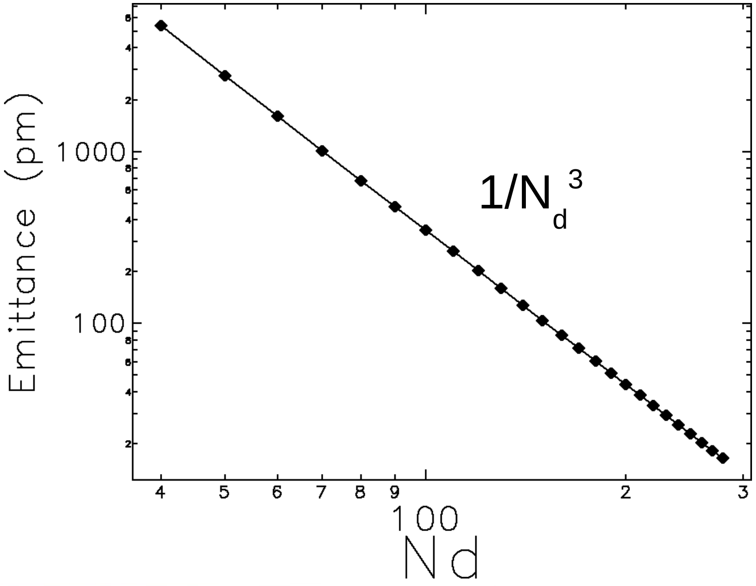
- Inescapable fact
  - To reduce the amplitude of dispersive orbits (“dispersion function”), must focus more frequently and more strongly
- Focusing (quadrupole) elements have chromatic aberrations
  - Sextupole magnets added to correct these
  - Stronger focusing means there is more chromaticity to correct
  - In addition, sextupole strength is inversely proportional to dispersion
- Strong sextupoles introduce strong higher order aberrations
  - More sextupoles or octupoles added to correct these...
  - This is a downward spiral if we are not careful
- In addition, there are collective phenomenon that get worse

Simplified Ring Model

- To illustrate difficulties and scaling, created a simplified ring model
  - No straight sections for IDs
  - Simple repetitive cell with “TME” configuration
  - Gradually increase the number of cells while keeping circumference fixed at 600 m
  - Energy of 4.5 GeV

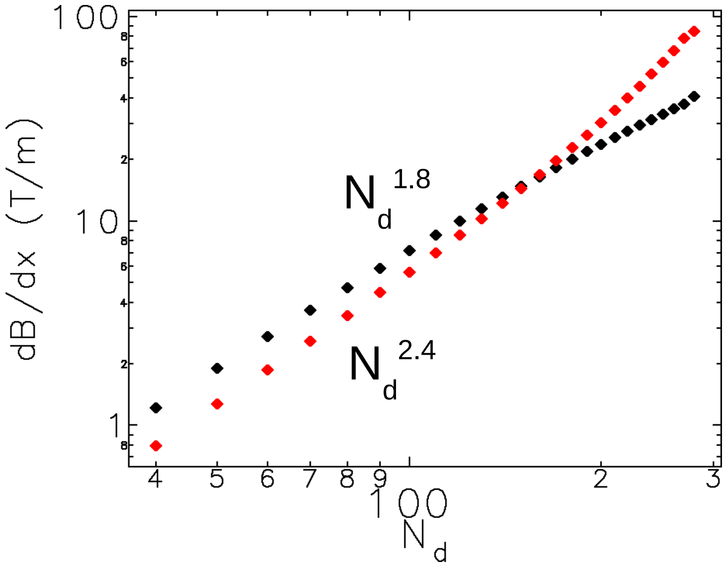
Lattice functions for N_d=280

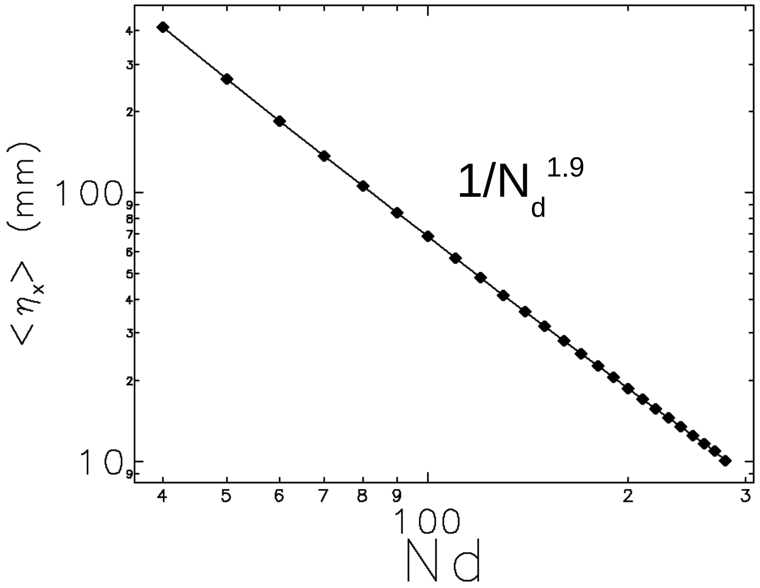


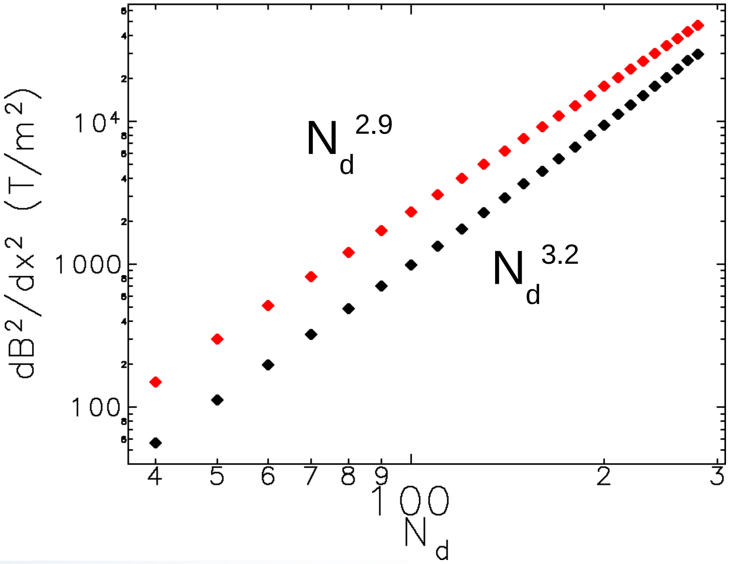


Scaling of Magnet Strengths

- Emittance decrease is nice, but…
  - Gradients grow like N_d^2
  - Average dispersion drops like $1/N_d^2$
  - Sextupole strength grows like N_d^3
- Need smaller magnet apertures to produce these strengths
- NB: exponents reduced if we scale ring circumference with N_d







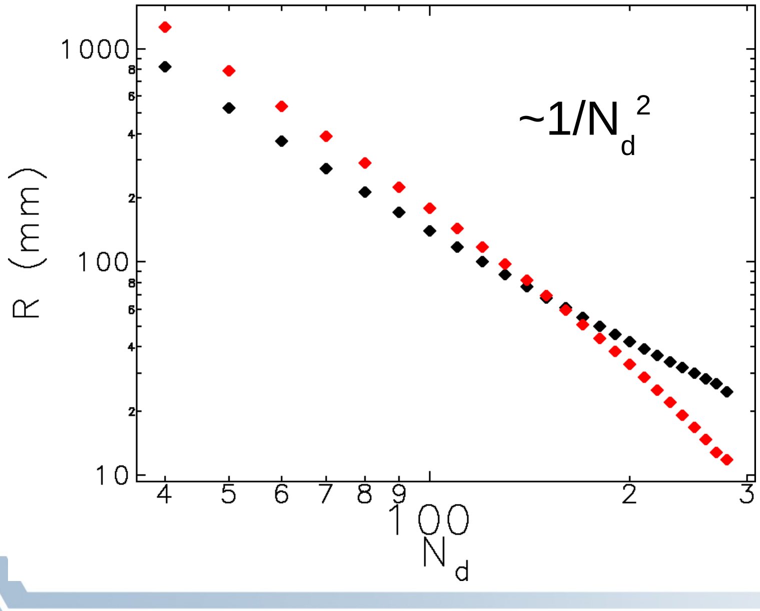
Scaling of Magnet Apertures

- Assume maximum pole-tip field of 1 T
- Compute the required magnet bore radius R

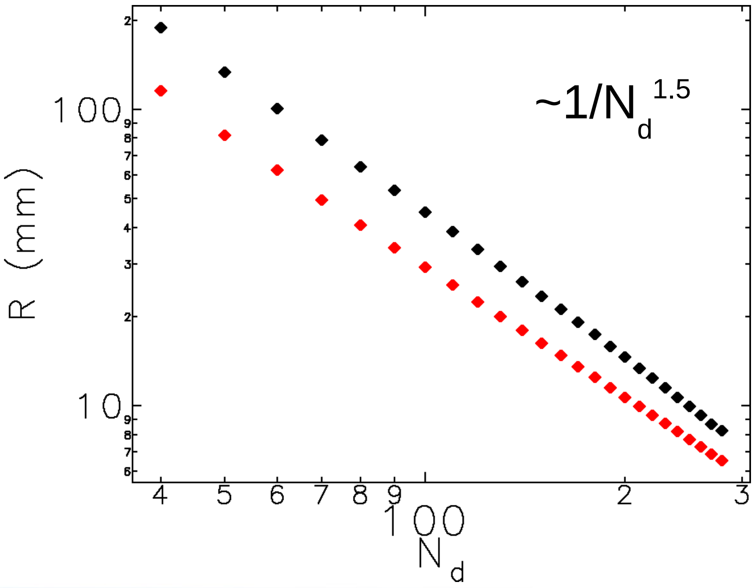
$$R_Q = \frac{B}{B'} \qquad R_S = \sqrt{\frac{2B_{\text{tip}}}{B''}}$$

- Conclusion: for ultra-low emittance, need ~10mm bores!
  - Vacuum bore must be even smaller

Maximum dipole/quadrupole bore

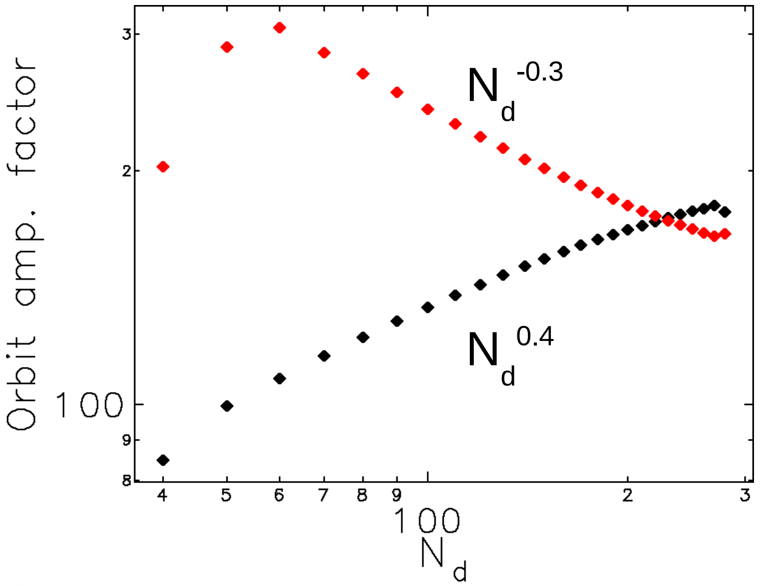


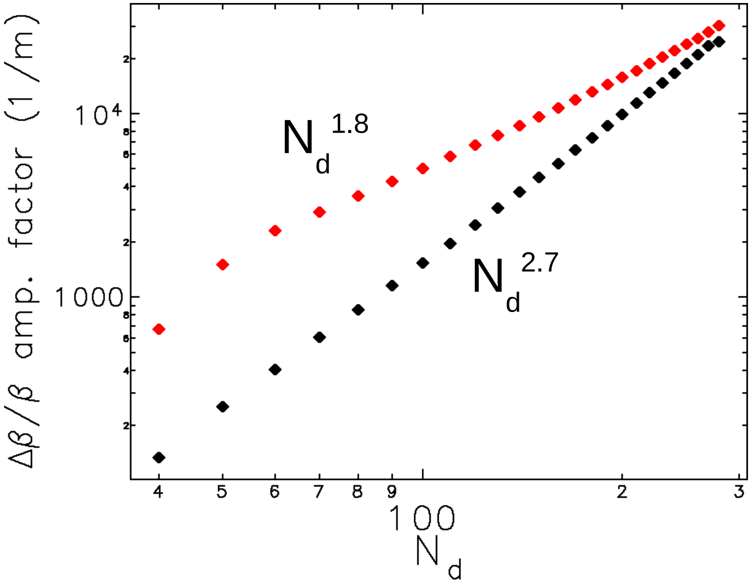
Maximum sextupole bore



Scaling of Alignment Requirements

- Misaligned magnets perturb the beam
  - Misaligned quadrupoles → orbit kicks
  - Misaligned sextupoles → focusing and coupling errors
- Orbit amplification is generally about the same
- Beta function modulation is much worse per unit misaligment
  - For DBA → 7BA, we'd need ~10-30x better alignment of sextupoles
  - E.g., 5-15 microns instead of 150





Nonlinear Dynamics

- Strength of chromatic correction sextupoles increases like N_d^3
- Based on this, if we aren't careful we'll see
  - Dynamic acceptance decreases like $1/N_d^3$
    - E.g,. 10-20mm DA goes to 0.25-0.5 mm for DBA → 7BA
    - Conventional injection impossible
  - Second order chromaticities increase $\sim N_d^3$
    - $\sim 1/N_d^{1.5}$ drop in momentum acceptance
    - Very short beam lifetime

$$x'' + k^2 x = \frac{1}{2} m x^2$$

$$\Downarrow$$

$$(Ax)'' + k^2 (Ax) = \frac{1}{2}(N_d^3 m)(Ax)^2$$

$$\Downarrow$$

$$A \sim \frac{1}{N_d^3}$$

Scaling argument due to L. Emery.

- Improved methods of arranging sextupoles and other nonlinear elements are the primary means of averting catastrophe
  - MAX-IV uses 5 sextupole and 3 octupole families[1]
  - ESRF-II design uses special linear optics to cancel sextupole kicks, plus octupoles[2]

1: S. Leemann et al., PRSTAB 12, 120701 (2009).
2: L. Farvacque et al., IPAC13, 79 (2013).

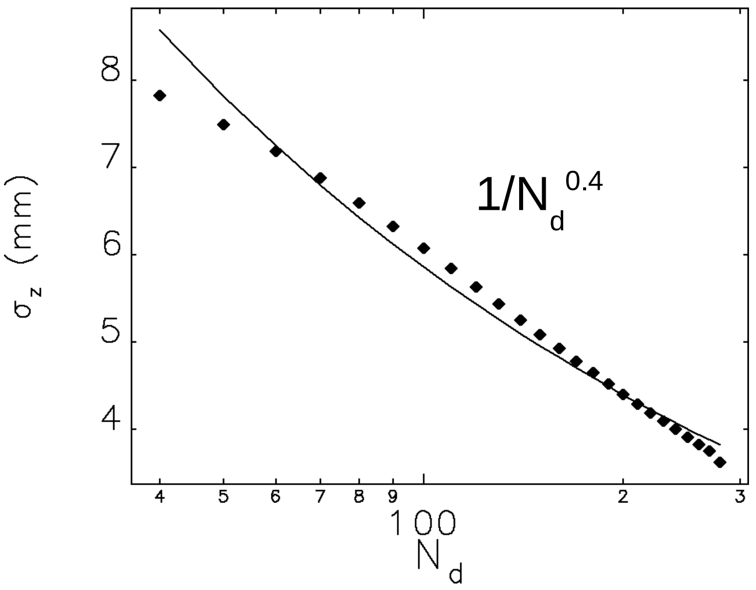
Dynamic Acceptance and Injection Requirements

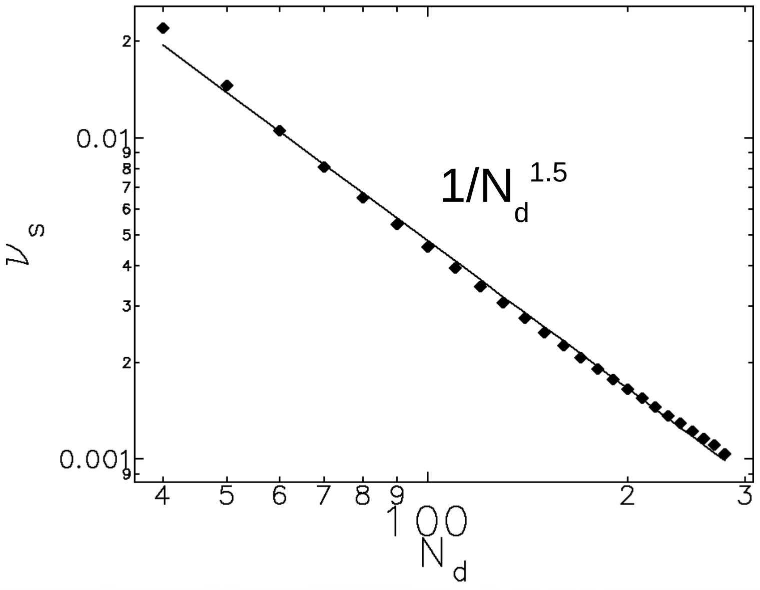
- Present-day rings use accumulation
  - Works only if dynamic acceptance is large enough, typ. >10 mm
  - Requires high-quality magnets out to large apertures
- If emittance is aggressively tuned, DA may be very small
  - Can only inject on-axis
  - By Liouville's theorem, old bunch is unavoidably extracted
  - Accumulation is impossible
- This "swap-out"[1] method is unworkable unless we have
  - Injector that can deliver at least a few nC in a bunch (or train), which is easy
  - Kickers with fast (~5-10 ns) rise and fall times
- Not everyone designing a 4GSR assumes swap-out, but it allows
  - More aggressive performance
  - Small horizontal gaps on IDs
  - Lower quality (easier, cheaper) magnets
- Historical note: "swap-out" mode was used by the first dedicated SR source, TANTALUS[2]

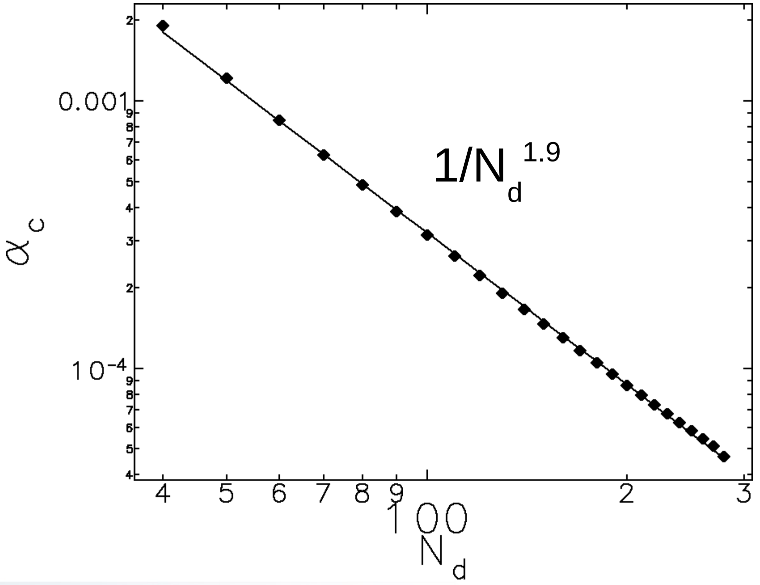
1: M. Borland, "Can APS Compete with the Next Generation," 2002; L. Emery et al., PAC03, 256.
2: E. Rowe et al., Part. Accel. 4, 211 (1973).

Scaling of Longitudinal Parameters

- Scaling of energy spread very weak
- Assuming constant rf acceptance, bunch length also scales weakly
  - Decreases, which is undesirable
- Synchrotron tune drops strongly, which suggests a problem with head-tail instabilities
- Indications for coupled-bunch thresholds are mixed



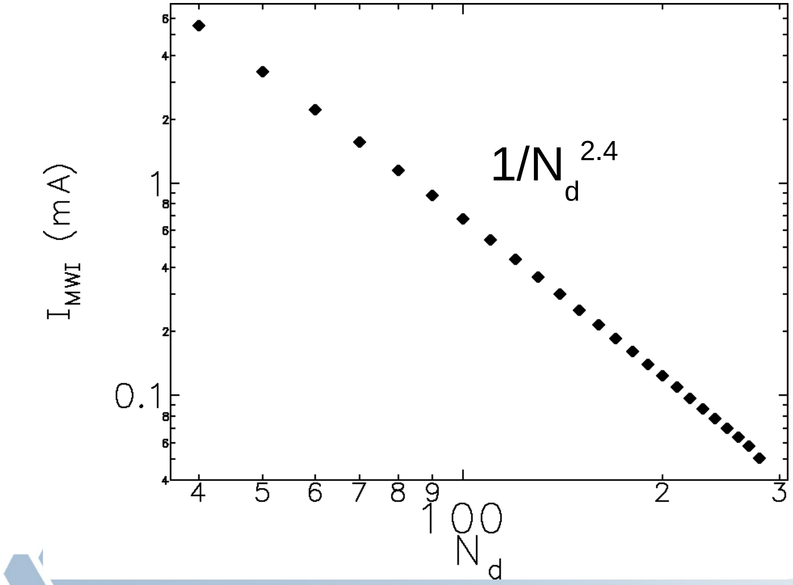




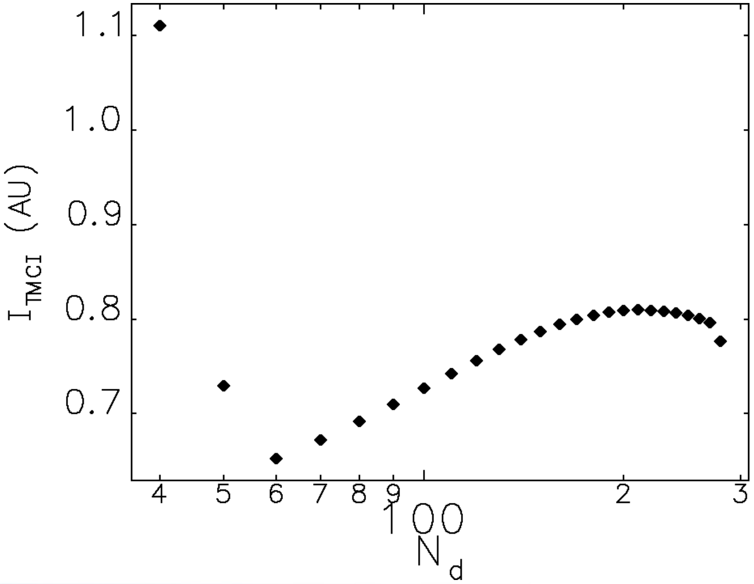
Scaling of Collective Instabilities

- Electromagnetic interaction with the vacuum chamber may
  - Limit total current (coupled-bunch instability)
  - Limit bunch current (single-bunch instability)
  - Blow up the energy spread, bunch length, or emittance (single-bunch instability)
- Assuming constant impedance (optimistic)
  - MWI threshold goes down rapidly, but can be moderated by deliberate bunch lengthening
  - TMCI looks innocuous, at least on these assumptions

MWI (energy-spread blow-up)



TMCI (single-bunch limit)



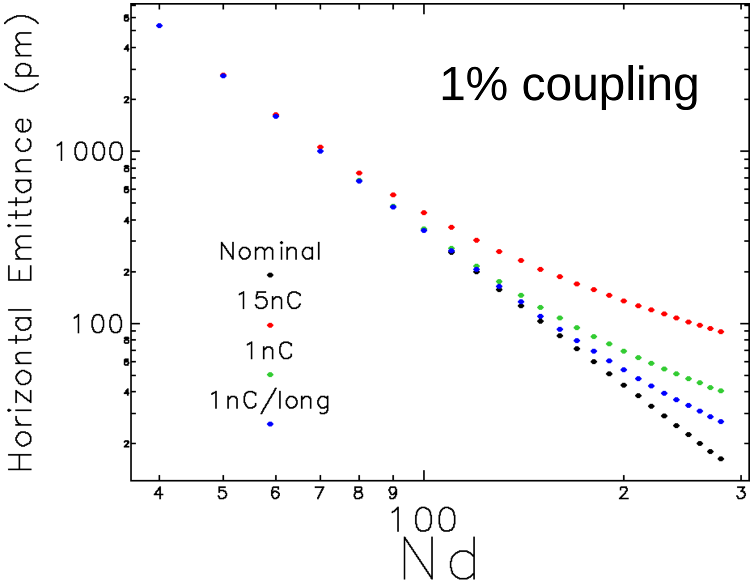
Scaling of Transverse Impedance

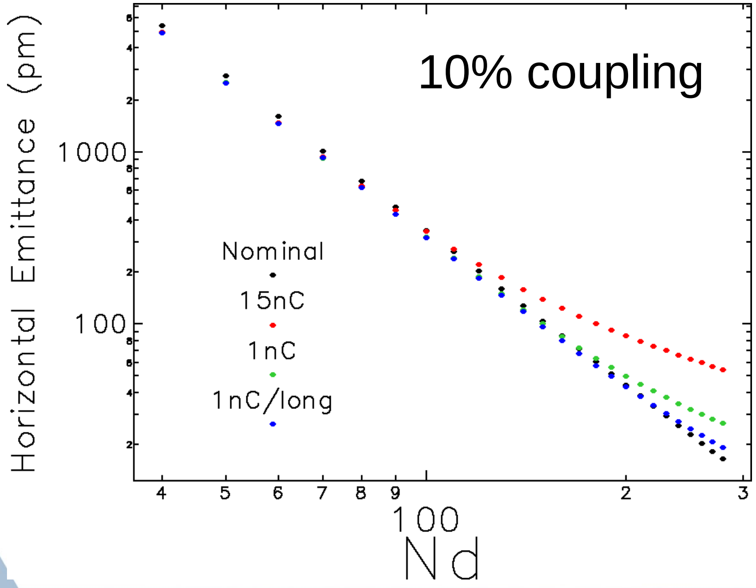
- Geometric impedance
  - This results from changes in the chamber dimensions, e.g.,
    - Transition from arc to ID chamber
    - Bellows liners, flanges,
    - BPMs
  - Changes rapidly with chamber dimensions: typ. $1/g^2$ to $1/g^4$
- Resistive impedance
  - This results from finite conductivity of chamber walls
  - $1/g^3$ dependence on chamber gap
- Gaps scale like $1/N_d^2$, so impedance would appear to scale quite strongly
- Mitigate problem by
  - Smoother chamber (adiabatic changes in g, smaller flange gaps, ...)
  - Higher-conductivity material (Cu instead of Al or SS)
  - Smaller average beta functions
  - Feedback systems, bunch lengthening, positive chromaticity
  - Detailed studies at APS[1] indicate this is workable for $N_d=7$
    - Even so, expect ~5-fold drop in maximum single-bunch current

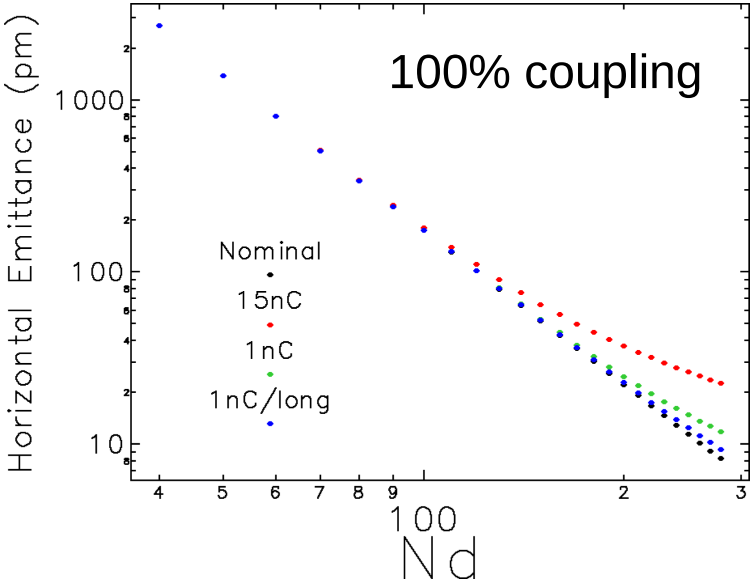
[1] Y.-C. Chae, private communication; also, Y.-C. Chae et al., PAC07,

Intrabeam scattering (IBS)

- Multiple scattering in a bunch
  - Increases emittance, energy spread
  - Fights beneficial E^2 scaling of emittance
- To deal with this, may use
  - Many low-intensity bunches
  - Increased vertical emittance
  - Bunch lengthening system
  - Higher beam energy

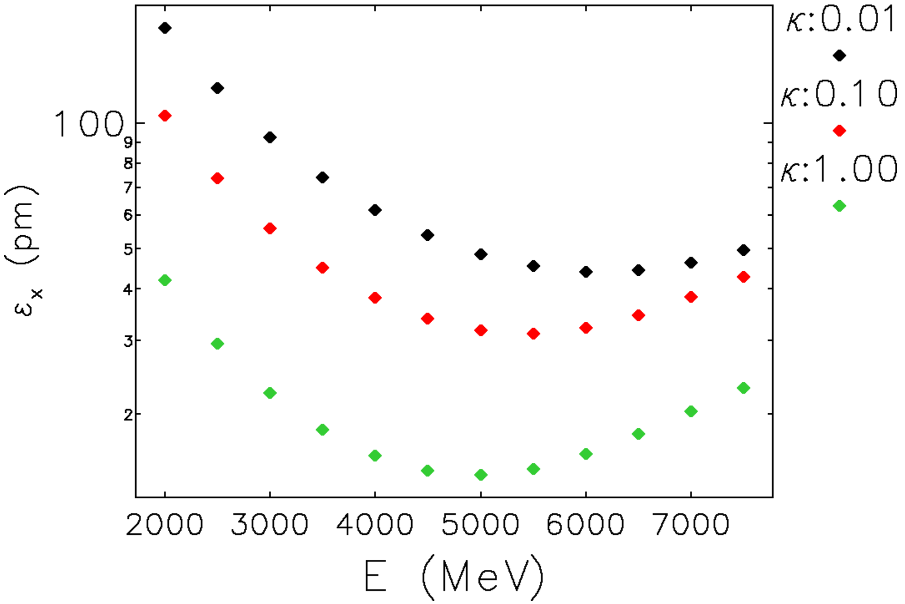


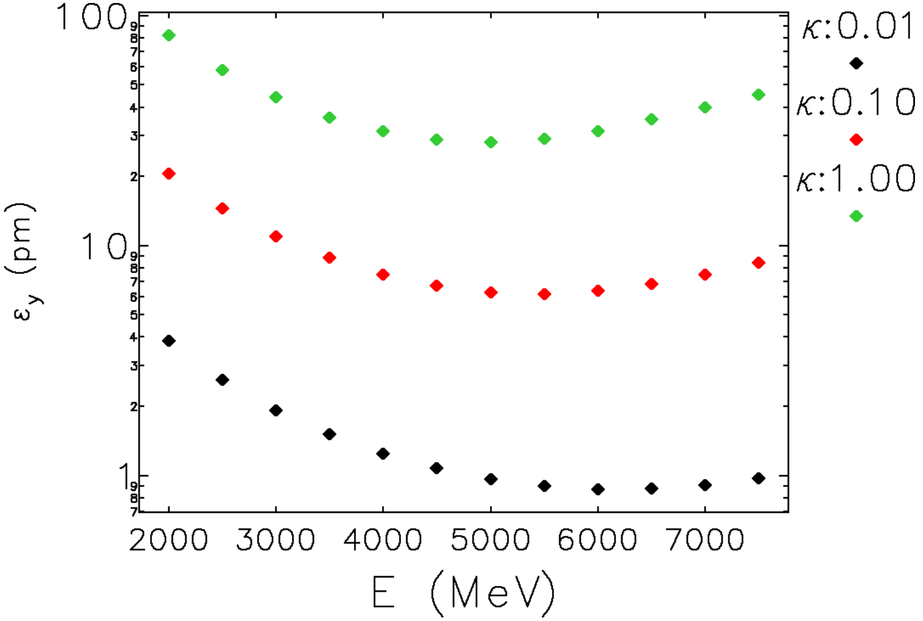




Intrabeam scattering (IBS)

- IBS prevents taking advantage of the beneficial E^2 scaling of emittance
- Particularly true if we want low coupling to maximize x-ray brightness
- For lower-energy 4GSRs, strong motivation to run with many weak bunches

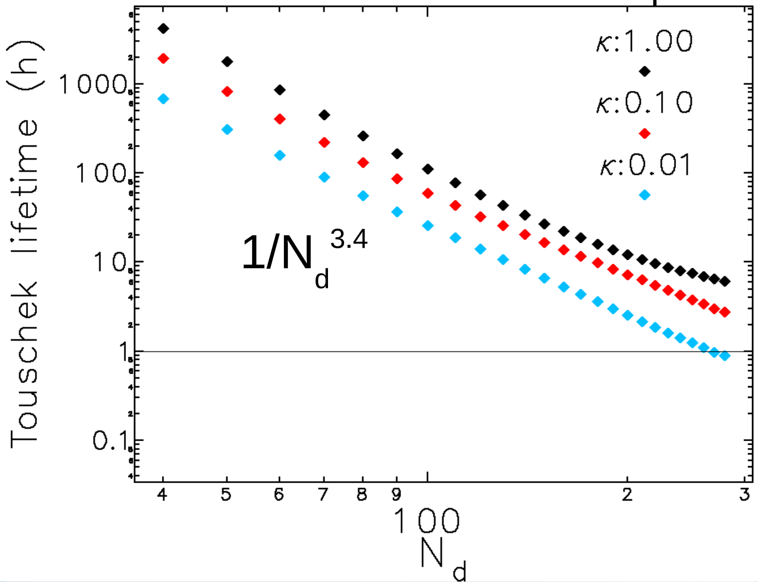




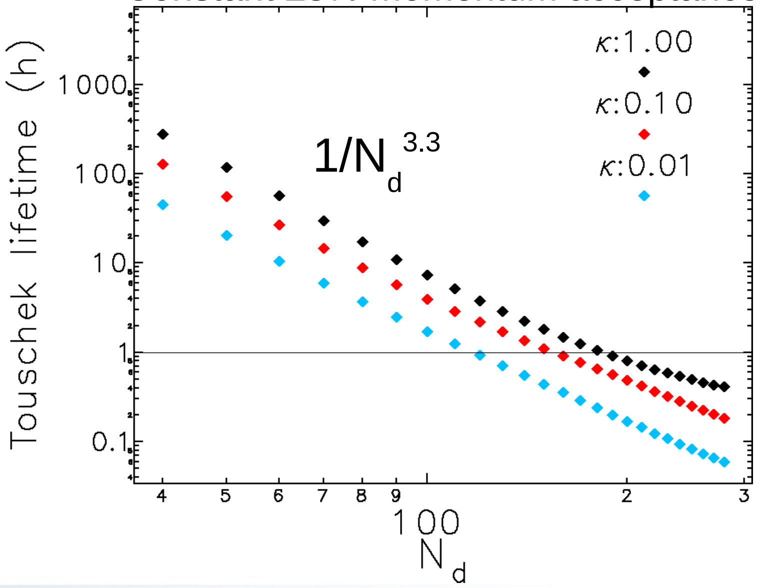
Touschek scattering

- Hard electron-electron scattering leading to large longitudinal momentum kicks
  - Particle loss if outside local momentum acceptance
- Together with the momentum aperture, Touschek scattering rate largely determines beam lifetime
- Scattering rate increases as bunch density increases
  - Motivates having many weak, long bunches, and large vertical emittance

1 nC/bunch
20mm bunch length
Constant ±3% momentum acceptance

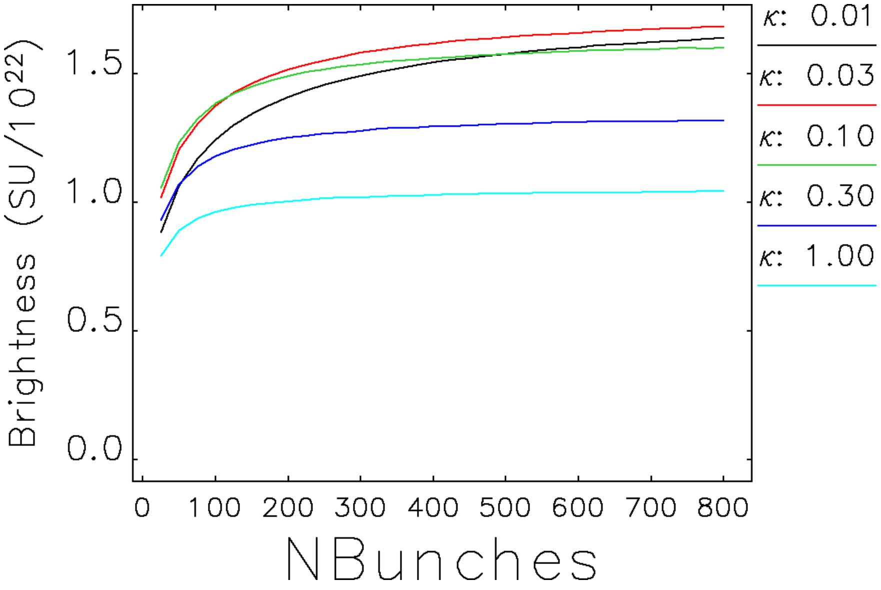


15 nC/bunch
20mm bunch length
Constant ±3% momentum acceptance



Operation with “Round Beams”

- Present rings have $\kappa=\varepsilon_y/\varepsilon_x \ll 1$
  - Improves brightness
  - Helpful for accumulation with small gap chambers
- When we make ε_0 very small, $\kappa \ll 1$ is less beneficial
  - Closer to diffraction limit in both planes
  - Drives up IBS and Touschek scattering rates
- Better approach is “round beams” and swap-out, $\kappa \approx 0.1$ to 1



Normal advantage of running low coupling is less apparent when there are few bunches, since IBS causes emittance to grow.

Example assumes ~10 keV photons from a 5-m undulator.

Summary of Scaling Studies

- Increasing the number of dipoles provides low emittance, but there are concerns
- Large number of dipoles, quadrupoles, and sextupoles needed
- Quadrupole and sextupole strengths very high
- Reduced dynamic and momentum acceptance
- Small magnet and vacuum bore necessary
- Potential for large increase in impedance
- Reduced instability thresholds
- Emittance blow-up and short lifetime for low-coupling, few-bunch modes
- Increased sensitivity to alignment and vibration

- Although none of these seem fatal, they can't be treated lightly and need detailed study

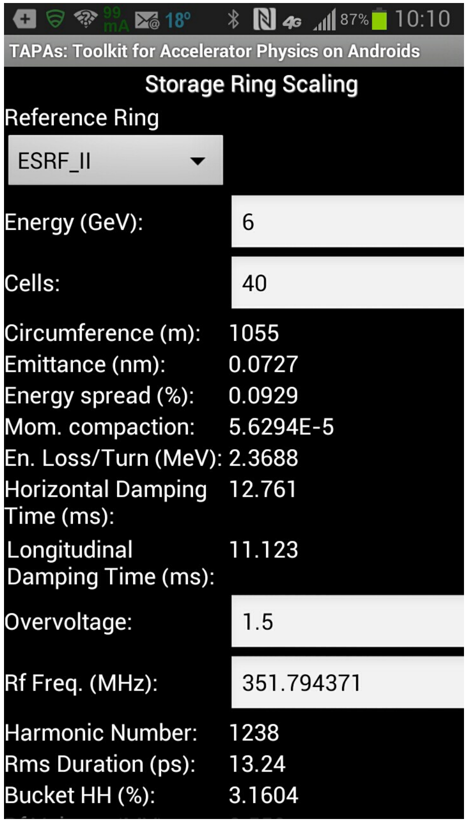
Are 4th-Generation Rings Within Reach?

- Top-up proves that short beam lifetime is workable (APS, SLS, ...)
- Routine, precision correction of accelerator optics (NSLS)
- Demonstration of few pm vertical emittance (e.g., SLS, PETRA-III, ESRF, SPring-8, ...)
- Advances in simulation fidelity and computational capabilities
- Advances in optimization techniques, including genetic algorithms
- New magnet technology (e.g., MAX-Lab) allows lower-cost, more tightly-packed lattices
- New vacuum technology (e.g., CERN, SOLEIL, MAX-Lab) allows narrow beam pipes and strong, small-bore magnets
- Development of ultra-precise alignment methods (NSLS-II)
- Demonstration of sub-micron and sub-microradian beam stability
- Demonstration at PETRA-III of 160 pm emittance at 3 GeV
- Realization that "swap-out" injection reduces aperture requirements, allows aggressive tuning, allows "poor"-quality magnets (APS)

Design Your Own Ring

- A free Android app allows exploring storage ring scaling
  - Also has synchrotron radiation calculations, FELs, top-up/swap-out, etc.
  - Search for “Michael Borland TAPAs” on the Google store

Ring scaling



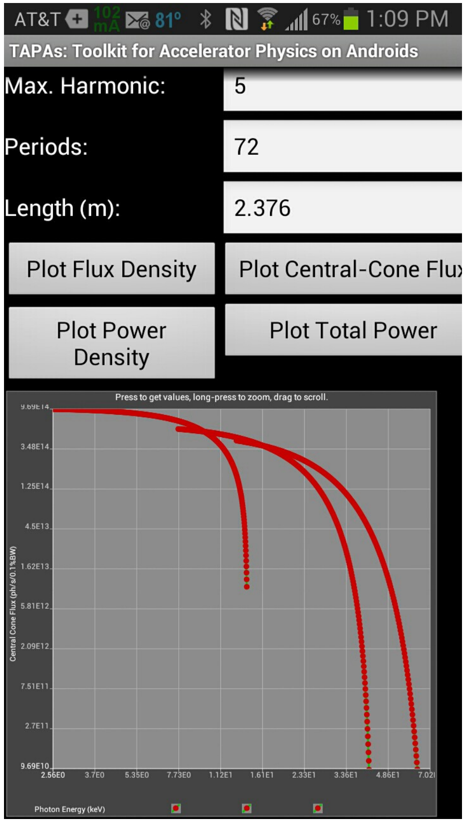
TAPAs: Toolkit for Accelerator Physics on Androids

Storage Ring Scaling

Reference Ring
ESRF_II

Energy (GeV): 6
Cells: 40
Circumference (m): 1055
Emittance (nm): 0.0727
Energy spread (%): 0.0929
Mom. compaction: 5.6294E-5
En. Loss/Turn (MeV): 2.3688
Horizontal Damping Time (ms): 12.761
Longitudinal Damping Time (ms): 11.123
Overvoltage: 1.5
Rf Freq. (MHz): 351.794371
Harmonic Number: 1238
Rms Duration (ps): 13.24
Bucket HH (%): 3.1604

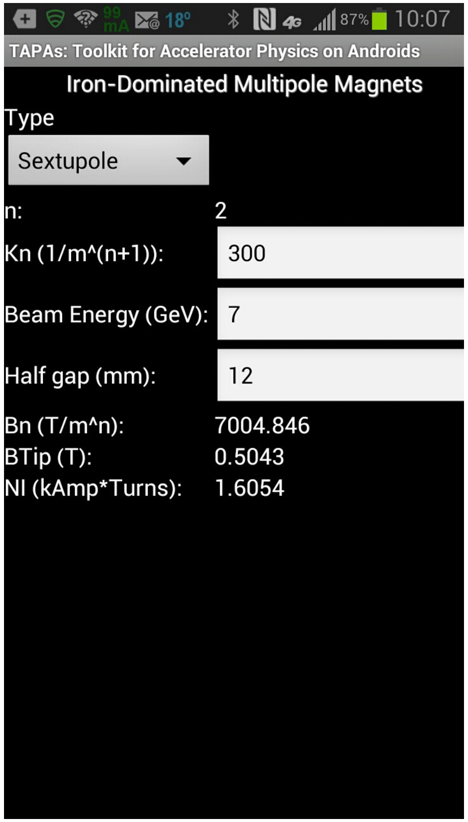
Undulator radiation



TAPAs: Toolkit for Accelerator Physics on Androids

Max. Harmonic: 5
Periods: 72
Length (m): 2.376

Magnet estimation



TAPAs: Toolkit for Accelerator Physics on Androids

Iron-Dominated Multipole Magnets

Type
Sextupole

n: 2
Kn (1/m^(n+1)): 300
Beam Energy (GeV): 7
Half gap (mm): 12
Bn (T/m^n): 7004.846
BTip (T): 0.5043
NI (kAmp*Turns): 1.6054

Conclusions

- Scaling analysis shows that there are challenges for 4th-generation rings
  - Magnet strengths are high
  - Magnets are closely packed
  - Vacuum chambers must be narrow
  - Collective effects are more challenging
  - Alignment is more challenging
  - Operating modes and methods may need to change
- We've learned a great deal since 3rd-generation sources began operating ~20 years ago
  - Much of the needed technology is available
  - 4th generation rings are within reach
  - There's even an app for it