The diffraction-limited storage ring frontier

Michael Borland for the APS-U Beam Physics Team

10 July 2015

Accelerator Systems Division

Argonne National Laboratory

Work supported by the U.S. Department of Energy, Office of Science, under Contract No. DE-AC02-06CH11357.

Outline

- X-ray brightness, beam emittance, and the diffraction limit
- Multi-bend achromat lattices
- Challenges and solutions
  - Magnet strength
  - Vacuum systems
  - Tolerances and correction
  - Nonlinear dynamics
  - Injection
  - Intrabeam scattering
  - Beam lifetime
- Advanced IDs and x-ray performance
- Summary

X-ray Brightness

- Brightness can be expressed as

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

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

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

- Electron beam provides "diffraction-limited" radiation when

$$\epsilon_{x,y} \leq \frac{1}{2}\epsilon_r \approx \frac{\lambda}{4\pi} \qquad \beta_{x,y} = \beta_r \approx \frac{L_u}{\pi}$$

- In this case, the coherent fraction can be quite high

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

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

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

$$\epsilon_x : 1 \sim 5\text{nm} \qquad \epsilon_y : 1 \sim 40\text{pm}$$

so we are several orders of magnitude away from diffraction-limited performance in horizontal

Emittance Scaling

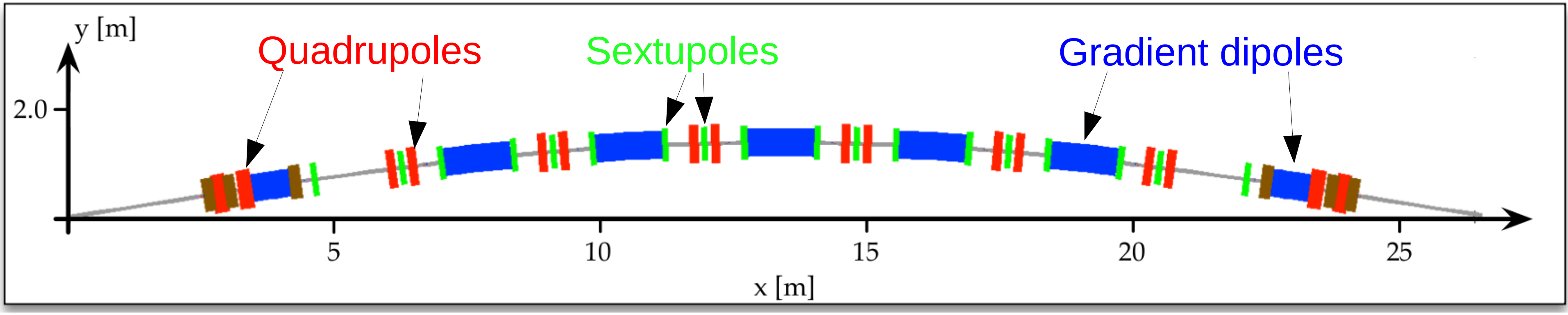
- Emittance is governed by[1]

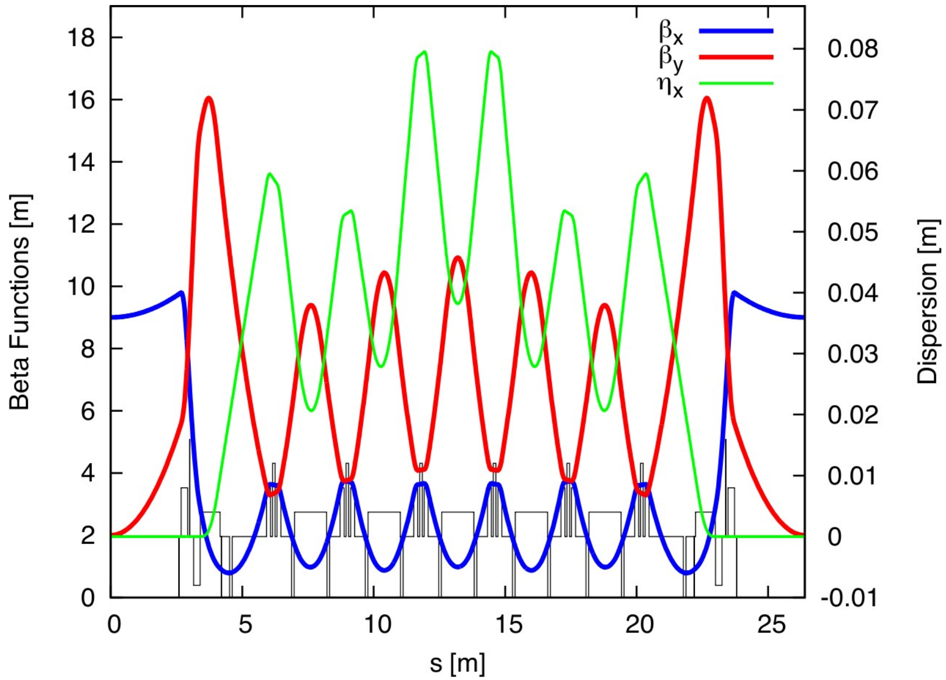
$$\epsilon_0 \sim \frac{E^2}{(N_s M)^3}$$

- 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
- First explorations in mid 1990's[2-5]
- Various advanced ring designs help illustrate potential and challenges
  - MAX-IV (Sweden)[6]
  - ALS-U (US)[7]
  - ESRF-II (France)[8]
  - APS-U (US)[9]
- Many projects omitted in the interest of time

1:J. Murphy, NSLS Light Source Data Booklet.
2:Einfeld *et al*., NIM A 335, 1993
3:Joho *et al*., EPAC 94;
4:Einfeld *et al*., PAC95
5:Kaltchev *et al*., PAC95.
6:S. Leemann *et al*., PRSTAB 12, 120701 (2009).
7:C. Steier, SRN 27, 19 (2014).
8:L. Farvacque *et al*., IPAC13, 79 (2013).
9:G. Decker, SRN 27, 13 (2014).

MAX-IV Multibend Achromat Lattice



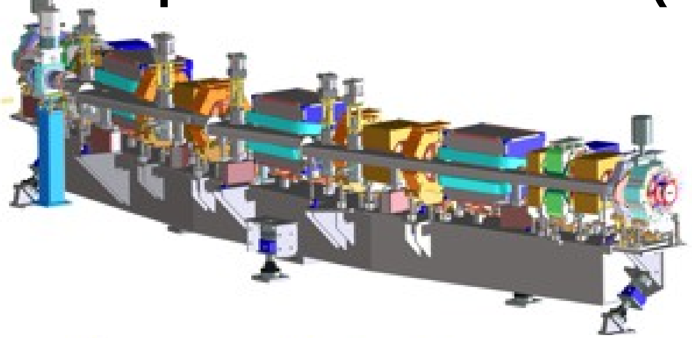


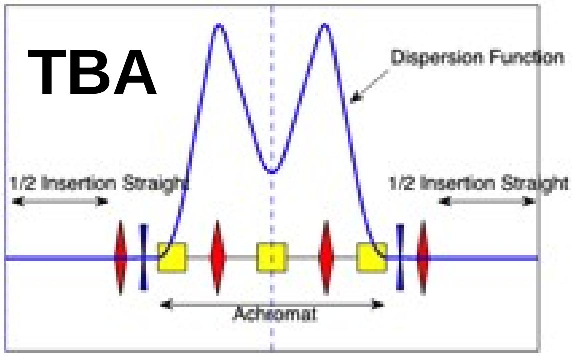
- 3 GeV, w/528-m circumference
- Relatively uniform, small dispersion and beta functions in the central section of each cell
- Natural emittance 326 pm
  - DBA NSLS-II reaches 1 nm with 792-m circumference and damping wigglers
- Commissioning in Aug. 2015

All figures courtesy S. Leemann, MAX-Lab.

Multi-Bend Achromat Lattices Enable Small Electron Emittance and High X-Ray Brightness

ALS today
triple-bend achromat (TBA)

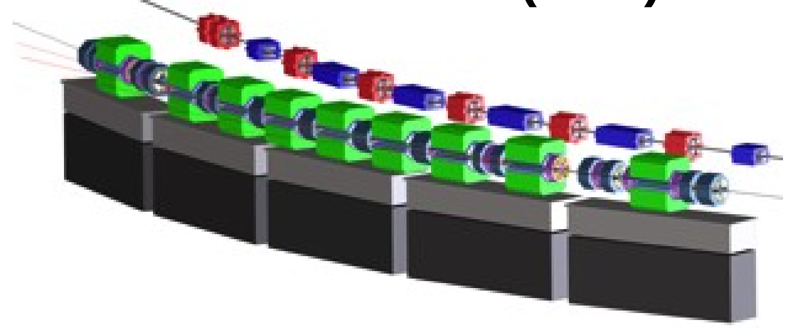


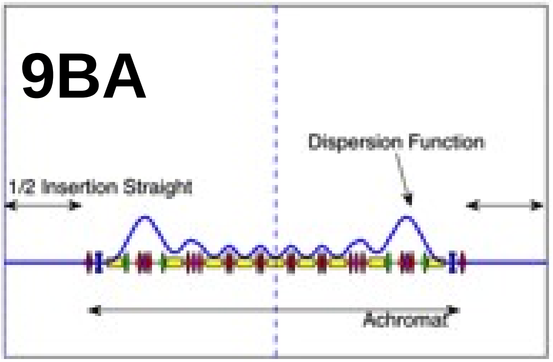


$$\varepsilon_x = 2000 \text{ pm} @ 1.9 GeV$$

12 cells, 192m circumference

ALS-U
multi-bend achromat (9BA)

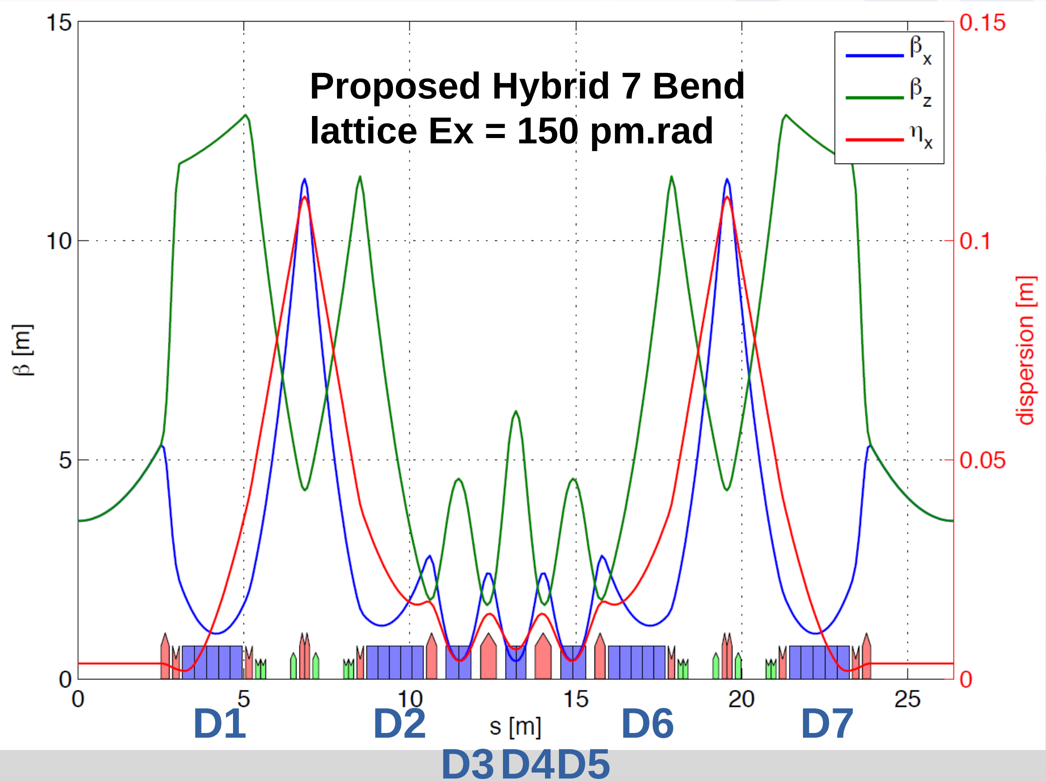




$$\varepsilon_x = 52 \text{ pm} @ 2.0 GeV$$

$$\varepsilon_x = C_L \frac{E^2}{N_D^3}$$

The ESRF 6 GeV low emittance lattice



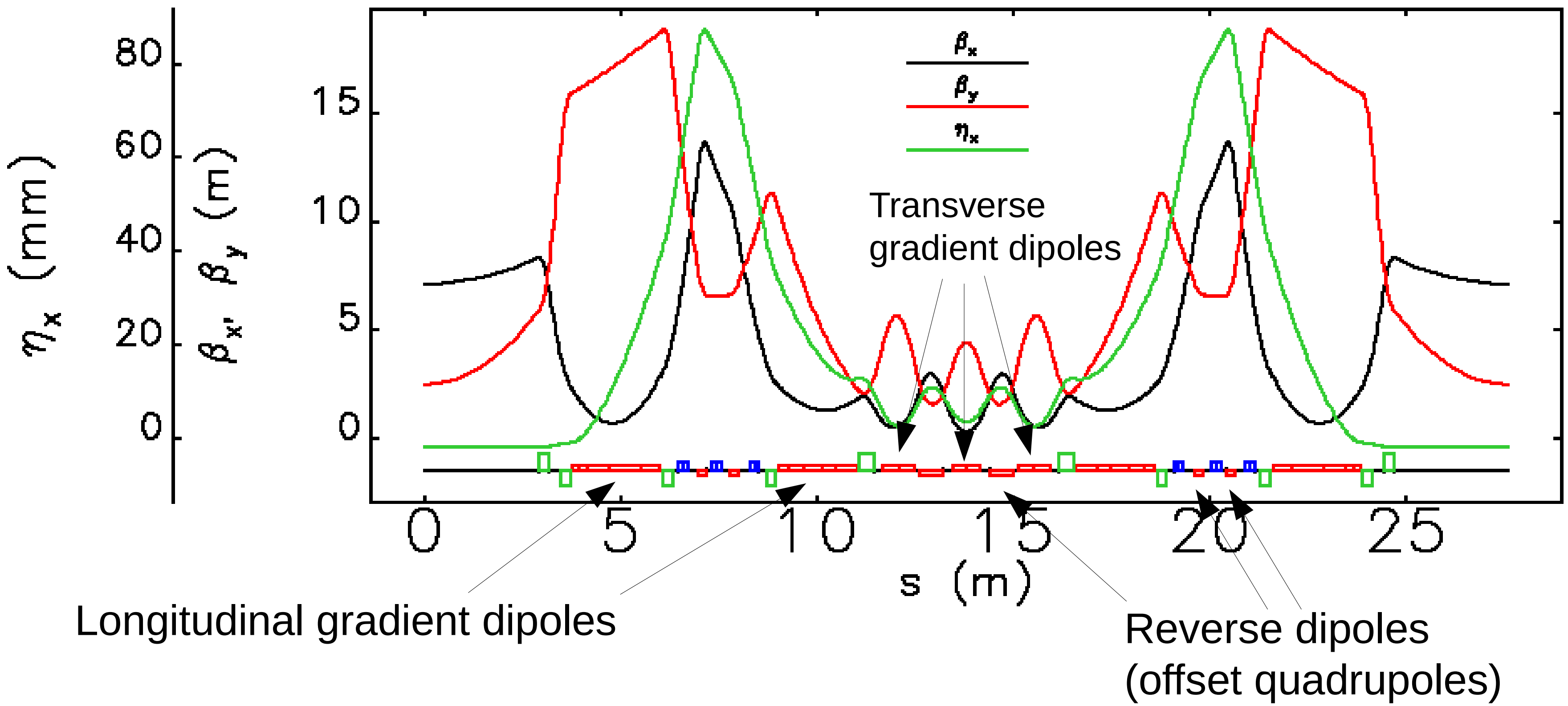
Blue: Dipoles Red: Quadrupoles Green: sextupoles

- 7 bending magnets D1to D7
  - reduce the horizontal emittance
  - Diffraction-limited to 0.7 keV
- Space between D1-D2 and D6-D7
  - *β-functions and dispersion allowed to grow*
  - chromaticity correction with efficient sextupoles
- Dipoles D1, D2, D6, D7
  - longitudinally varying field to further reduce emittance
- Central part alternating
  - combined dipole-quadrupoles D3-4-5
  - high-gradient focusing quadrupoles

Courtesy P. Raimondi, ESRF.

APS-U Hybrid 7+6BA Lattice Concept

$$6\ \text{GeV}\quad \epsilon_{\text{eff}} = 53\ \text{pm}\quad \sigma_\delta = 0.106\%$$

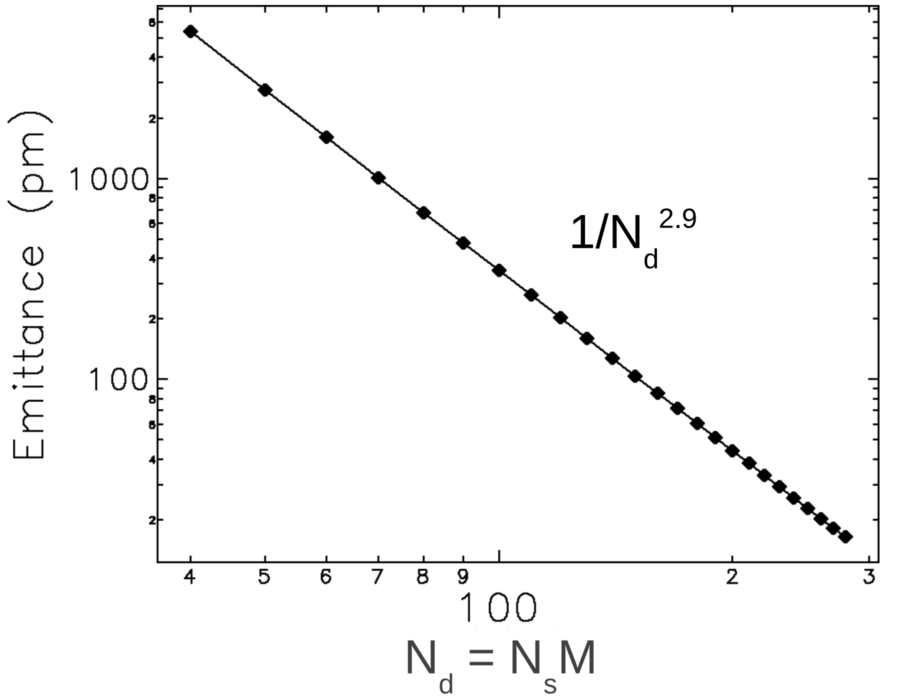


- Inspired by ESRF-II design[1]
- Contemplating 6 weak reverse dipoles[2] to improve dispersion control
  - Lower emittance, longer lifetime

1: L. Farvacque *et al.*, IPAC13, 79.
2: A. Streun, NIM A 737, 148 (2014).

Fundamental Challenges of Low Emittance

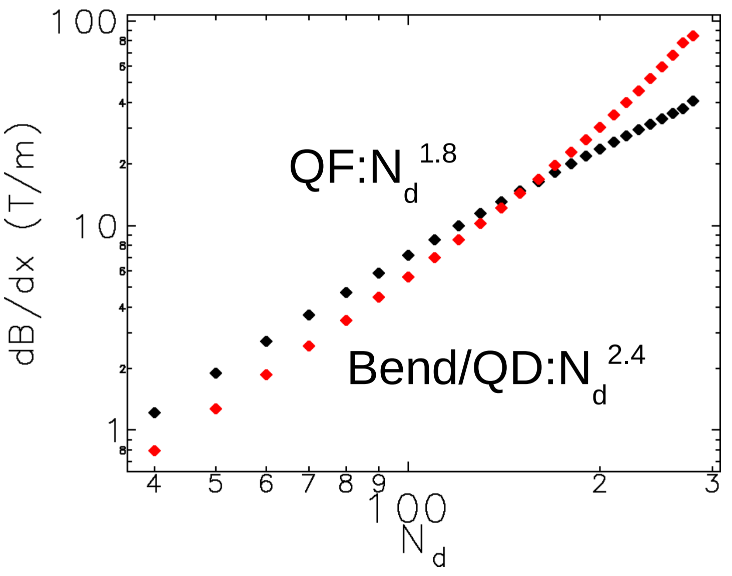
- To reduce the dispersion function, must focus more frequently and more strongly
- Many strong quadrupoles → larger natural chromaticity
- Chromaticity sextupoles are less effective because of small dispersion
- Very strong sextupoles introduce strong higher-order aberrations
  - Increased difficulties with injection, beam lifetime
- We used a model 4.5 GeV, 600-m ring to study scaling of ring parameters[1]

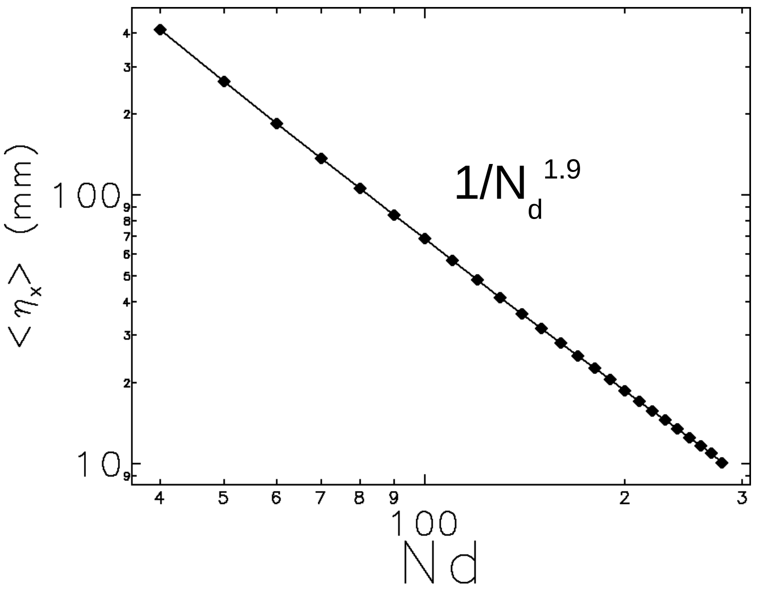


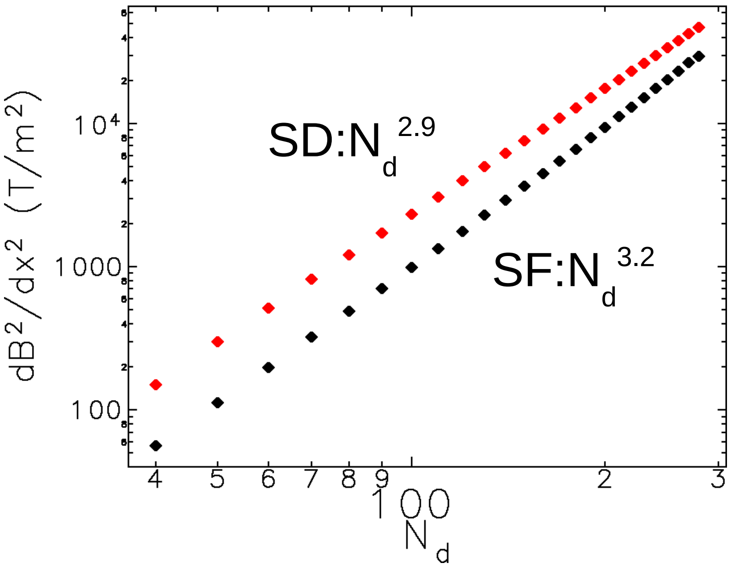
1: M. Borland, *et al*. J. Synch. Rad 21, 912-936 (2014).

Scaling of Magnet Strengths

- Emittance decrease is dramatic, 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







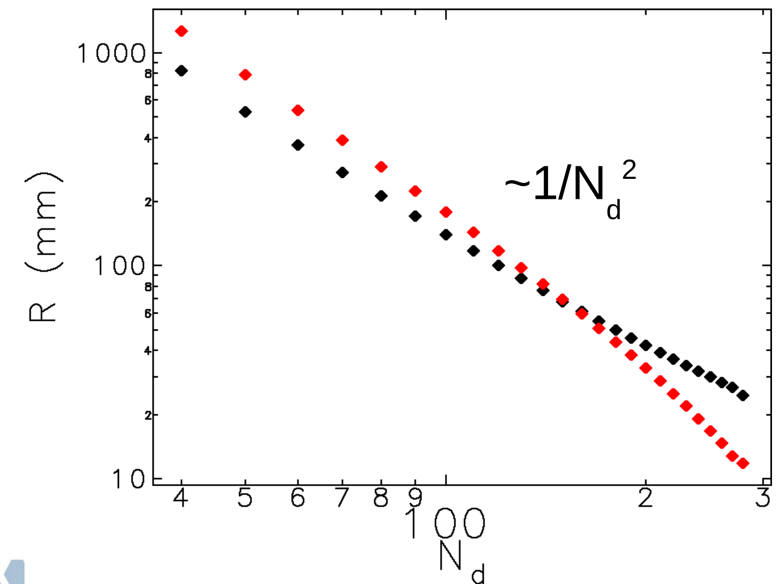
Scaling of Magnet Apertures

- Required magnet bore radius R

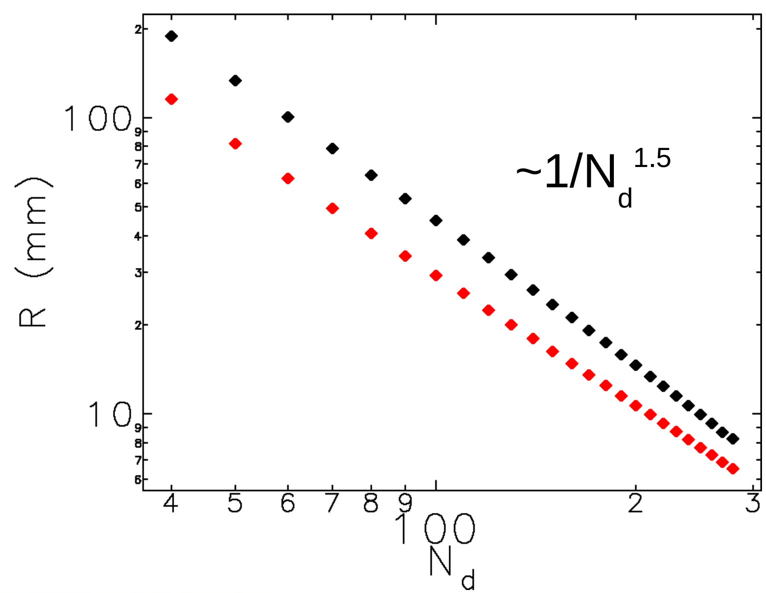
$$R_Q = \frac{B_{\text{tip}}}{B'} \qquad\qquad R_S = \sqrt{\frac{2B_{\text{tip}}}{B''}}$$

- Assuming 1T pole tip field, for ultra-low emittance, need ~10mm sextupole bores
  - Prohibitive for high-energy rings using MAX-IV style lattice
  - Better optics design (e.g., ESRF-II) can reduce sextupole strengths
- 12-13mm bore radii are typical for new ring designs
  - Present-day APS has 40 mm bore radii

Estimated QF(black) and BQD (red) bore

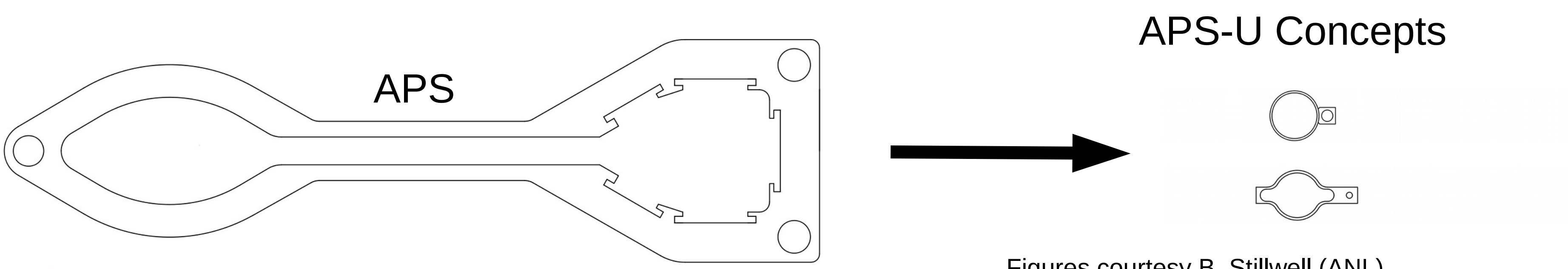


Estimated SF (black) and SD (red) bore



Vacuum System Challenges and Solutions

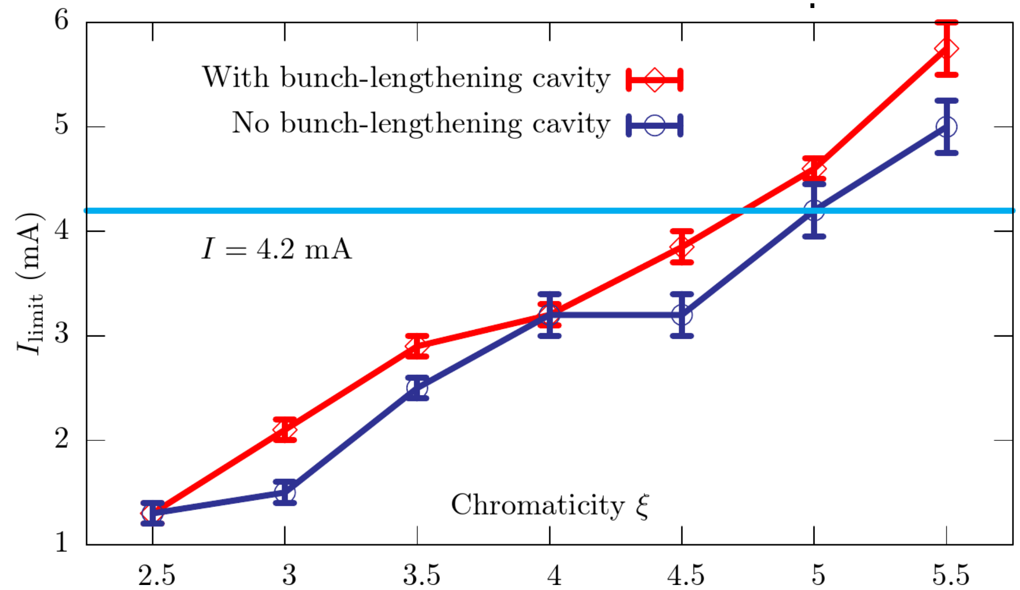
- Required small vacuum bores present many challenges, including
  - Handling of synchrotron radiation power
  - Achieving sufficiently low pressure
  - Maintaining sufficiently low beam impedance
  - Extraction of photons for users
- MAX-IV makes extensive use of NEG-coated copper chambers, minimal lumped pumping
  - Need for high-temperature activation of NEGs complicates installation
  - SIRIUS taking similar approach, but with integrated NEG heaters
- APS-U using a hybrid approach
  - NEG-coated Cu in central section, where space is most restricted and SR power is highest
  - Elsewhere, “traditional” NEG-pumped ante-chambers and lumped pumps
  - Workable approach in a larger ring, simplifies installation



Figures courtesy B. Stillwell (ANL).

Impedance and Single Bunch Current Limit[1]

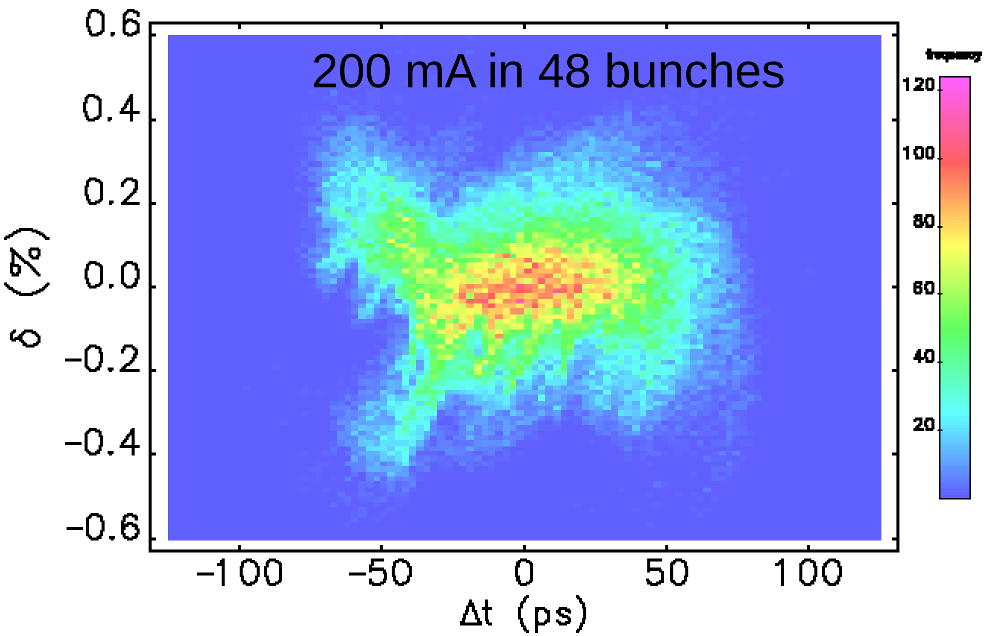
- APS-U targeting 4.2 mA/bunch for 48-bunch, 200-mA timing mode
  - Requires careful iteration of vacuum system design
  - Design of a lattice with sufficient positive residual chromaticity
- Prediction is that 4.2 mA is possible with chromaticity of +5
  - With latest design, margin higher than shown



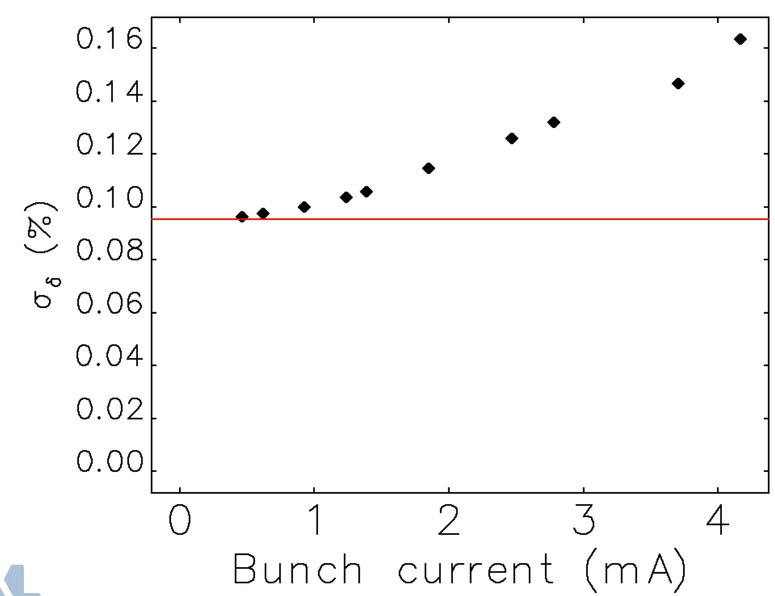
1: R. Lindberg et al., IPAC15, TUPJE077, TUPJE078.

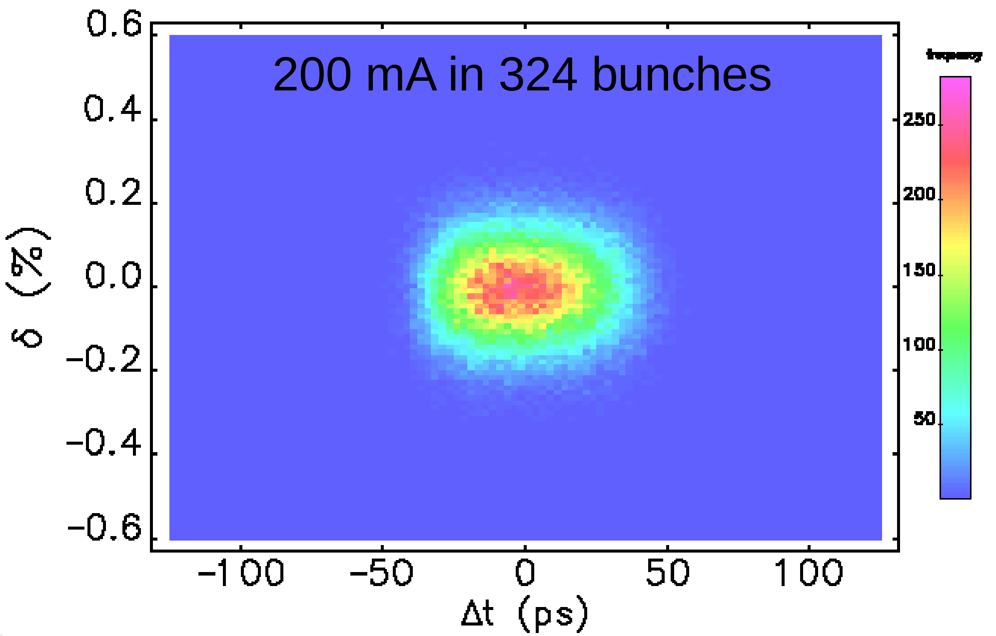
Resistive wall			Geometric contributions			
			Sector (×40)		Ring	
Metal	Diameter	Length	Element	Number	Element	Number
Cu	22 mm	224 m	Regular BPM	12	Injection kicker	4
Al	22 mm	605 m	ID BPM	2	Extraction kicker	4
SS	22 mm	80 m	ID transition	1	Feedback	2
Al	6 mm	175 m	Bellow	14	Stripline	1
Al	140 mm	20 m	Flange	52	Aperture	2
			Crotch absorber	2	Fundamental cavity	12
			In-line absorber	12	Rf transition	4
			Gate valve	4	4^{th} harmonic cavity	1

Longitudinal phase space impacted by impedance



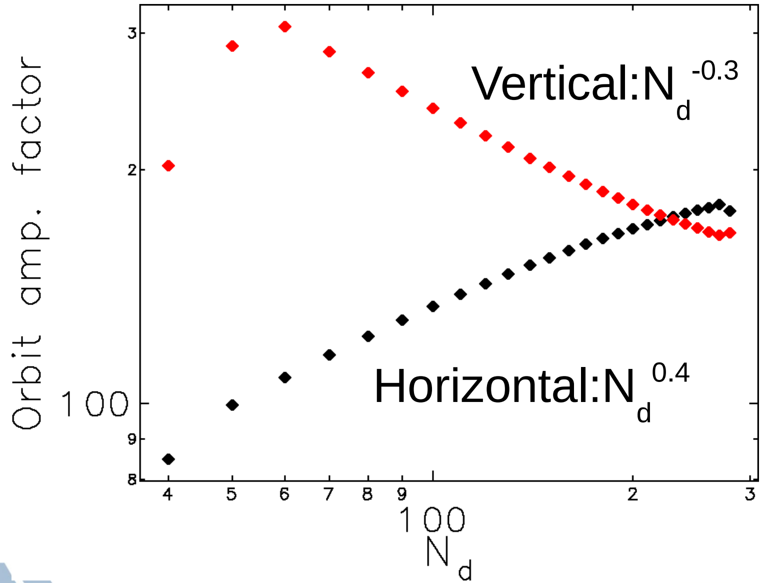
- Intense bunches are disrupted by microwave instability
  - No beam loss, but energy spread is inflated
- Threshold is at ~0.5 mA/bunch
  - In APS today, threshold is ~5 mA/bunch

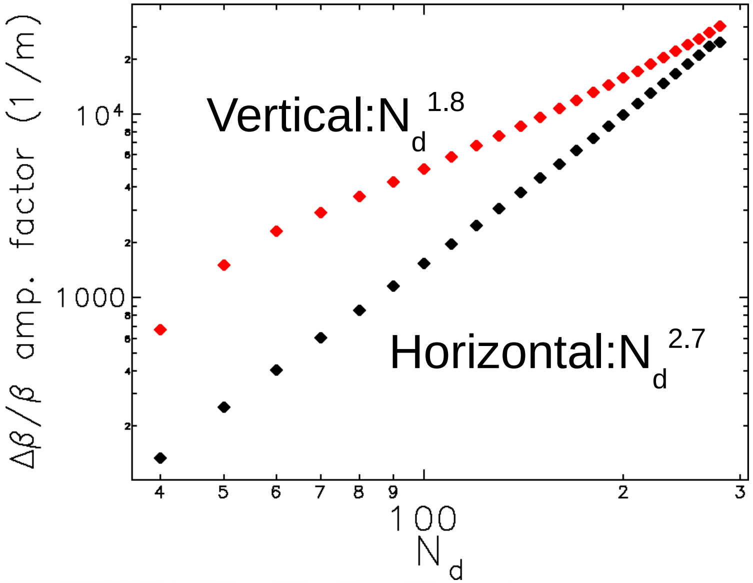




Scaling of Alignment Requirements

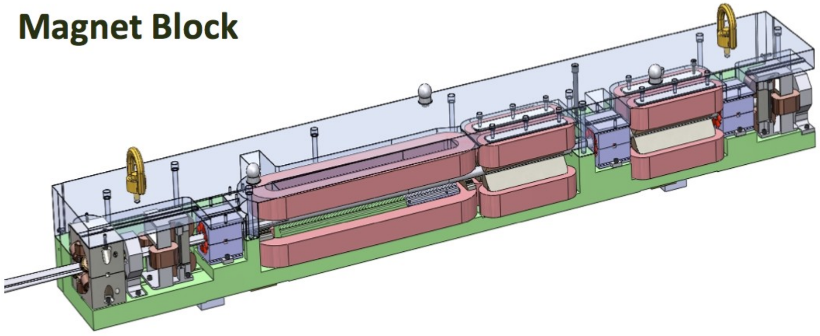
- Misaligned magnets perturb the beam
  - Misaligned quadrupoles → orbit kicks
  - Misaligned sextupoles → focusing and coupling errors
- Orbit amplification is generally about the same
  - Aided by significant reduction in beta functions
- Beta function modulation is much worse per unit misaligment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



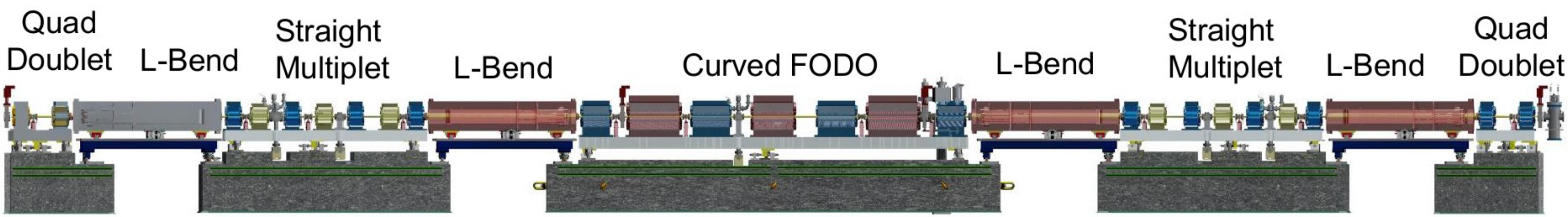


Magnet Alignment Strategies

- MAX-IV is using multi-magnet blocks
  - Magnets share a common yoke structure with ~20 micron precision
- So far, only used at MAX-Lab
  - Very complex assemblies
  - Magnetic measurement difficult
  - Difficult to scale to high energy (size, weight)
- NSLS-II demonstrated ~10 micron alignment using stretched-wire technique[1]
- APS-U considering hybrid strategy
  - Precision machined plates and mating surfaces on magnets
  - Alignment verification/remediation using stretched wire



Courtesy S. Leemann, MAX-Lab.



APS-U concept for magnet supports and alignment. Courtesy J. Collins, ANL.

1: A. Jain, private communication.

APS-U Commissioning Simulation[1]

- Commissioning involves coming to grips with imperfections of the real machine
- Performed a realistic simulation of commissioning steps, including
  - Error generation (see table)
  - First-turn trajectory correction
  - Orbit correction with small number of correctors
  - Orbit correction with reduced BPM displacement errors
    - Reflects expected improvement from beam-based alignment
  - Beta function correction
  - Coupling correction (minimizing cross-plane response matrix)
  - Emittance ratio adjustment to 10% at separated tunes
- Succeeded in 98% of cases

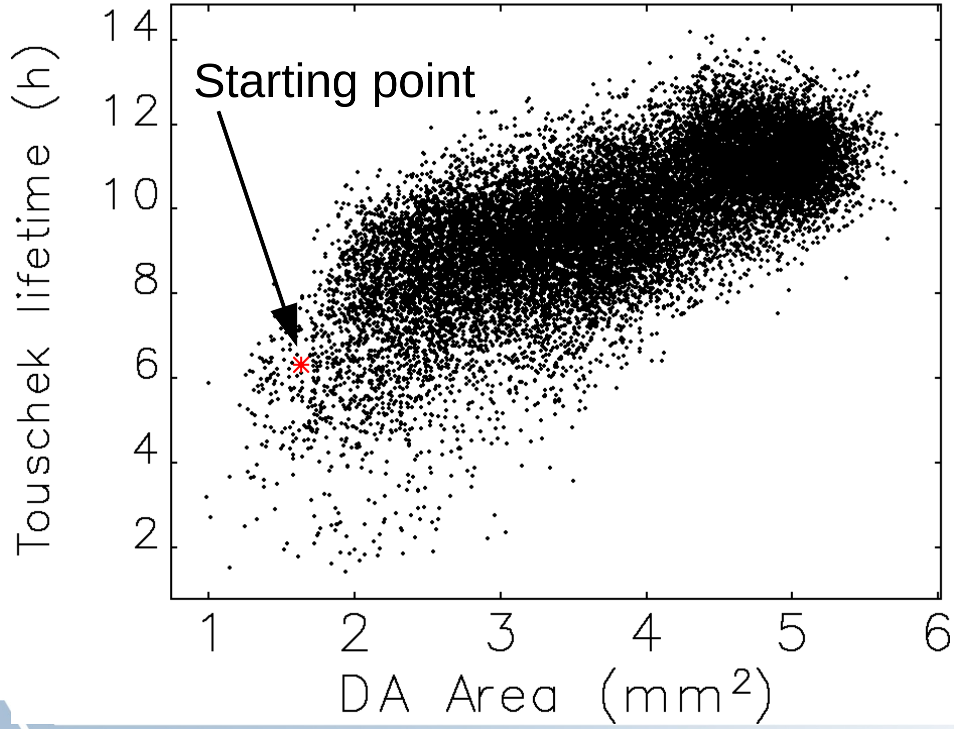
1: V. Sajaev *et al.*, IPAC15, to be published.

Girder misalignment	100 μm
Elements within girder	30 μm
Initial BPM offset errors	500 μm
Dipole fractional strength error	$1 \cdot 10^{-3}$
Quadrupole fractional strength error	$1 \cdot 10^{-3}$
Dipole tilt	$4 \cdot 10^{-4}$ rad
Quadrupole tilt	$4 \cdot 10^{-4}$ rad
Sextupole tilt	$4 \cdot 10^{-4}$ rad

These error levels appear readily achievable based on recent experience, e.g., NSLS-II.

Tracking-based Optimization[1,2]

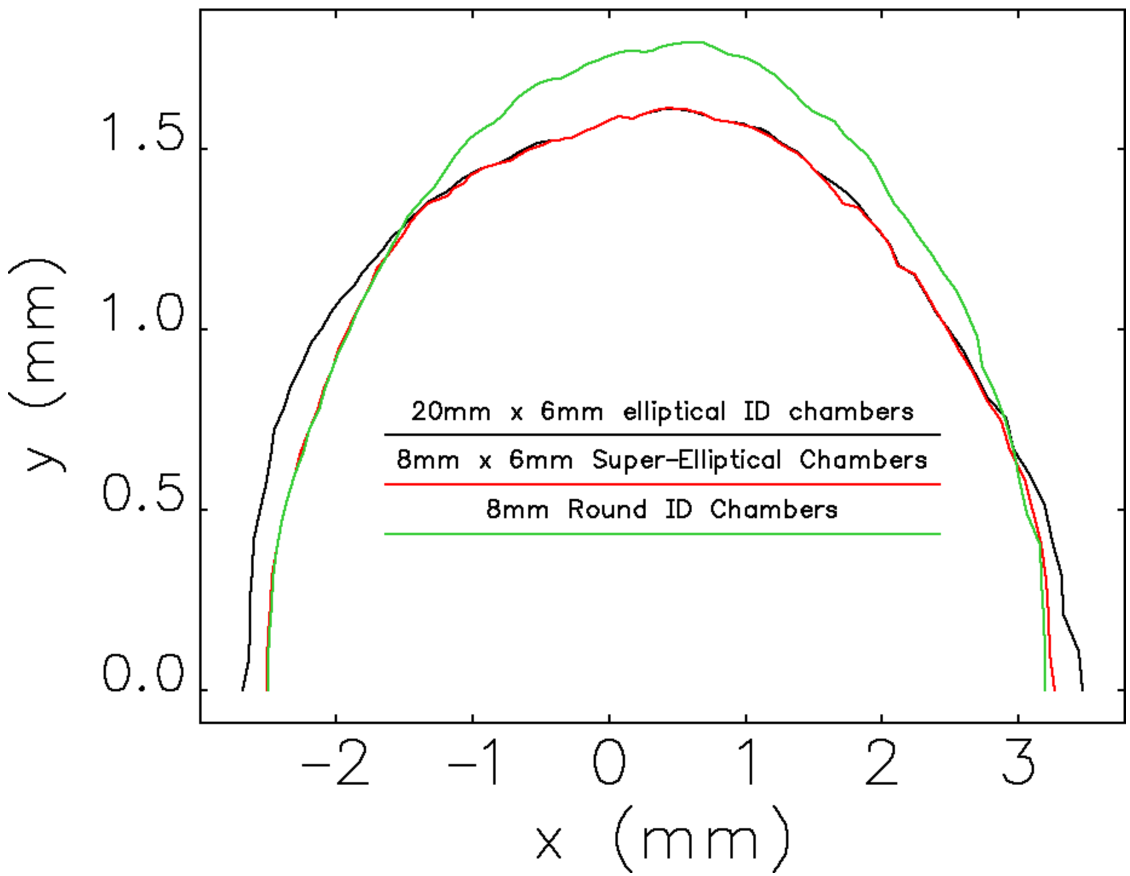
- Tracking-based optimization allows directly optimizing lattice and sextupoles for
  - Large dynamic acceptance
  - Large Touschek lifetime (via local momentum acceptance)
- Unlike theoretical approaches, can include
  - Effects of likely errors
  - Effects of radiation damping and synchrotron motion
  - Vacuum chamber dimensions

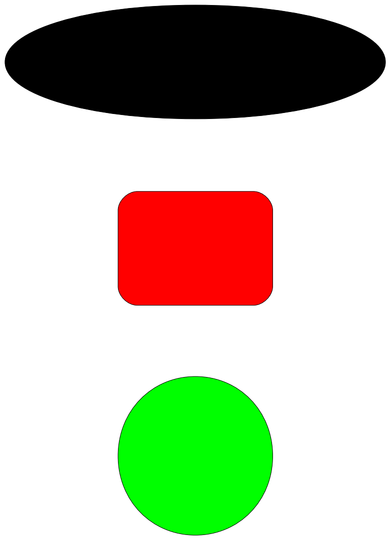


Tracking-based optimization makes significant improvements starting from ESRF-II scheme, even with initial tunes chosen for fourth-order achromatic condition.

1: See citations in M. Borland, IPAC12, 1035.
2: M. Borland, *et al*. J. Synch. Rad 21, 912-936 (2014).

APS-U 10th-Percentile DA w/ID Chambers

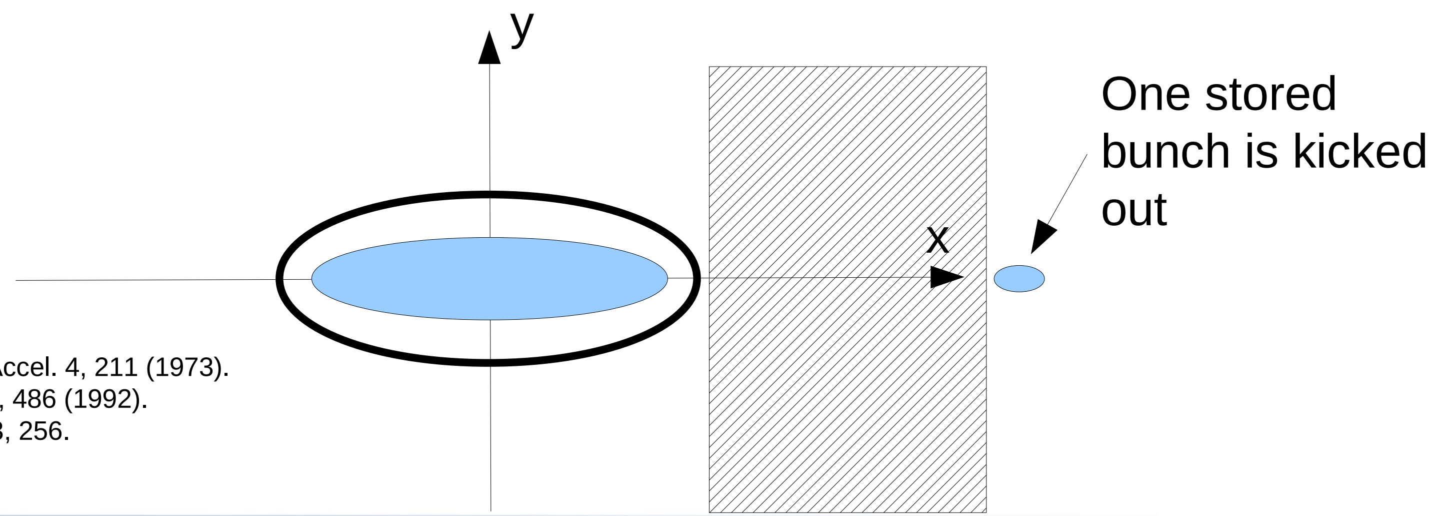




- Compared to a typical wide ID chamber, round or narrow chambers have little impact
- Option for vertically-deflecting devices, round-bore helical devices
  - Such devices not readily compatible with accumulation-based operation

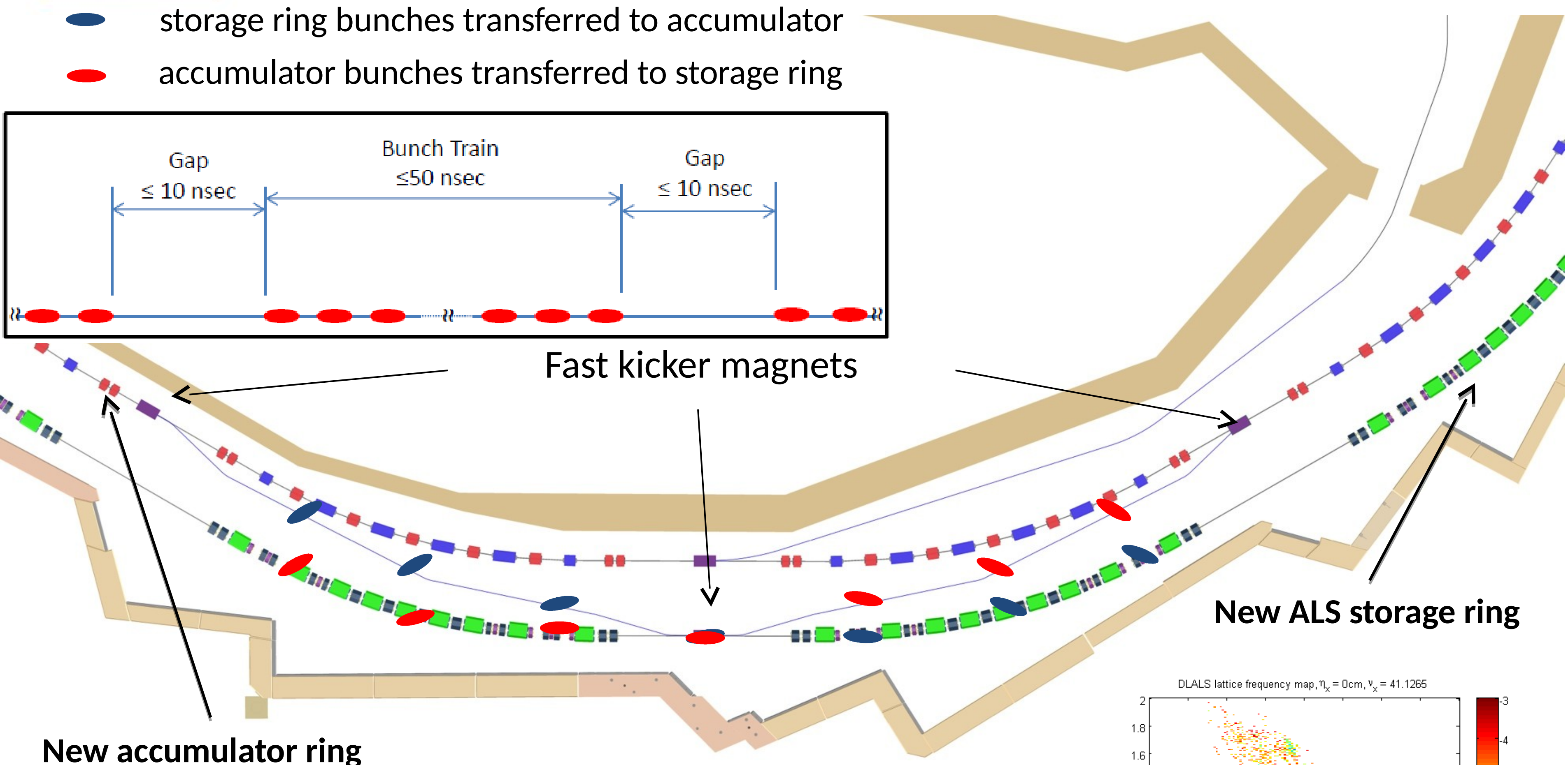
Swap-out Injection

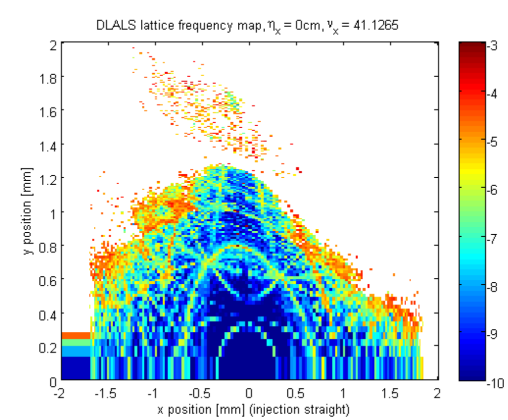
- On-axis "swap-out" injection[1,2,3] is an alternative to accumulation
  - Each injector shot replaces an existing stored bunch
  - DA must accommodate only the injected beam size
- Swap-out (APS-U and ALS-U) seems advantageous on balance
  - Pro:
    - Smaller horizontal physical apertures possible in IDs
    - Nonlinear dynamics optimization can emphasize lifetime instead of DA
    - Emittance can be pushed to smaller values
    - Less disturbance to stored beam
  - Con:
    - Single-bunch current limited by injector capability
    - Maximum number of bunches limited by fast kicker technology



1: E. Rowe *et al*., Part. Accel. 4, 211 (1973).
2: R. Abela *et al*., PAC91, 486 (1992).
3: L. Emery *et al*., PAC03, 256.

Swapping Accumulator and Storage Ring Beams



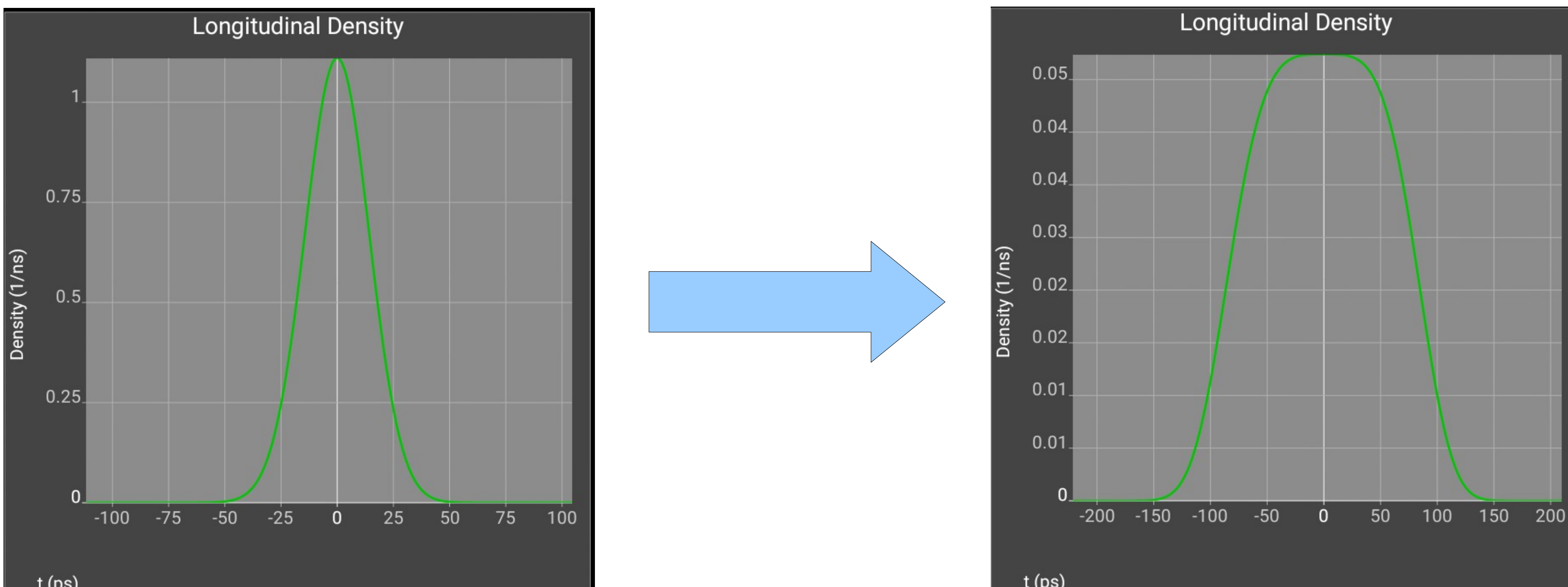


Swap-out injection [with an accumulator] was first proposed by M. Borland for possible APS upgrades

Courtesy C. Steier, ALS.

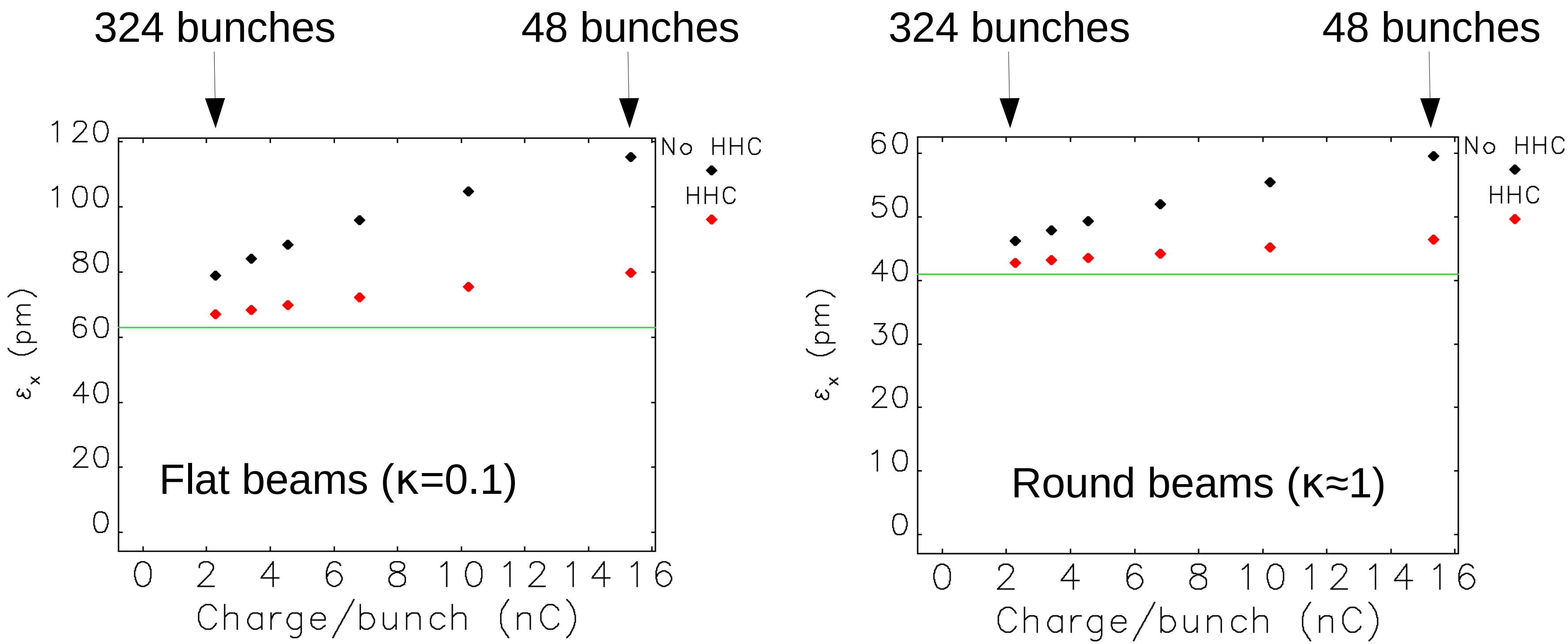
Intrabeam scattering and Touschek lifetime

- Low emittance beams have high particle density in bunches, leading to
  - Emittance growth due to intrabeam scattering (IBS)
  - More rapid particle loss due to Touschek scattering, scaling like $N_d^{3.5}$
- Counter-measures
  - Many weak bunches
  - Running with “round beams,” i.e., $\kappa=\varepsilon_y/\varepsilon_x\approx 1$
  - Bunch-lengthening using a higher harmonic cavity (HHC)



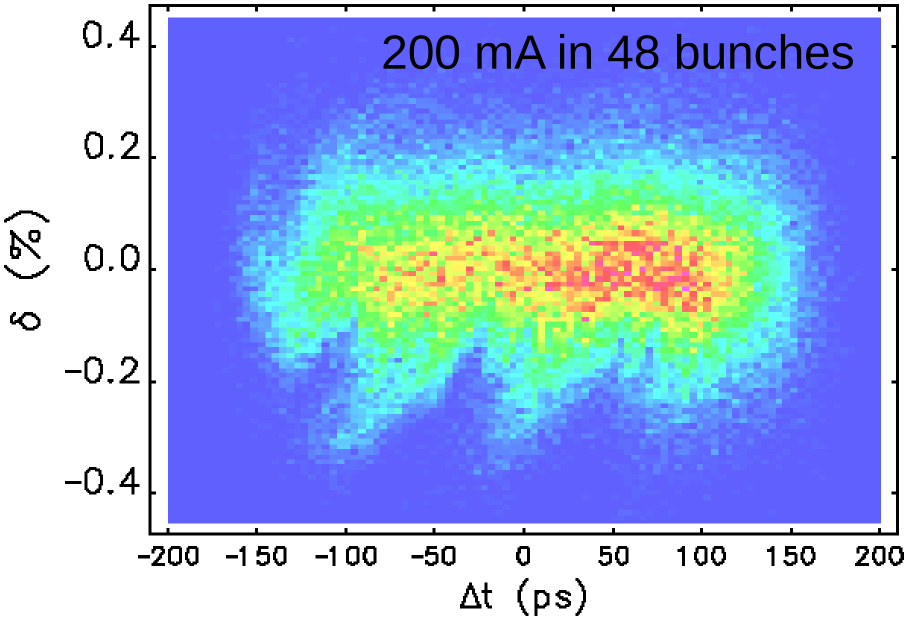
Computations from TAPAs, tinyurl.com/borlandTAPAs

Suppression of Intrabeam Scattering (IBS)



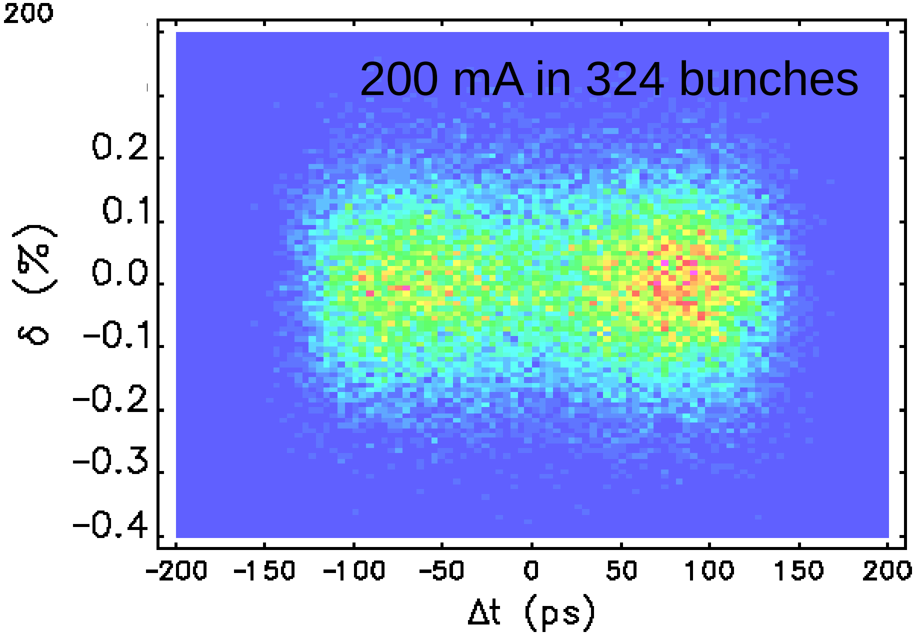
- Multiple scattering within a bunch leads to emittance and energy spread growth
- IBS effects not negligible even for 324 bunch flat beams
- HHC provides ~4-fold reduction in emittance increase from IBS
- “Round beams” also effective
  - Most readily compatible with on-axis injection

Effect of HHC (Passive, Optimal Detuning)



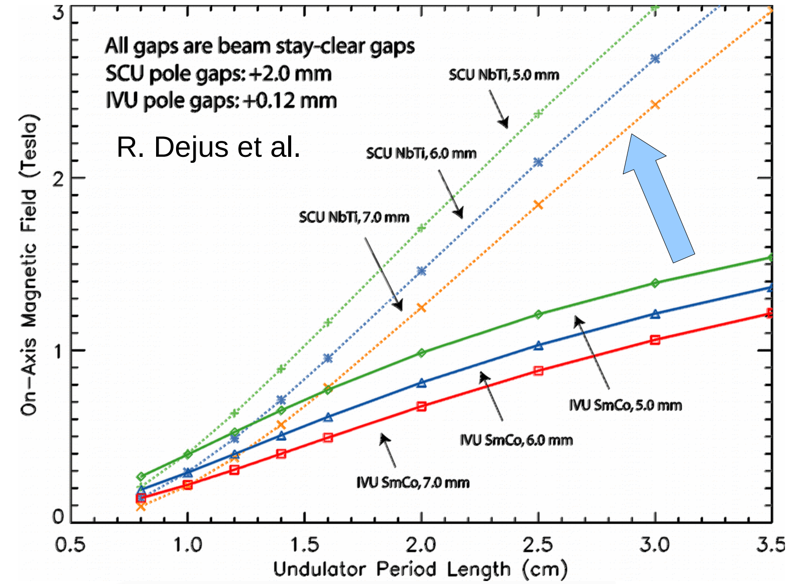
- Rms bunch duration exceeds 75ps
  - 12.5 ps at zero current
- Microwave instability is considerably quieter
- 324 bunch case has a somewhat split bunch

- For 48 bunches, Touschek lifetime improves ~2-fold
  - Less than nominal 4-fold because MWI already lengthened the bunch
- For 324 bunches, Touschek lifetime improves ~4-fold



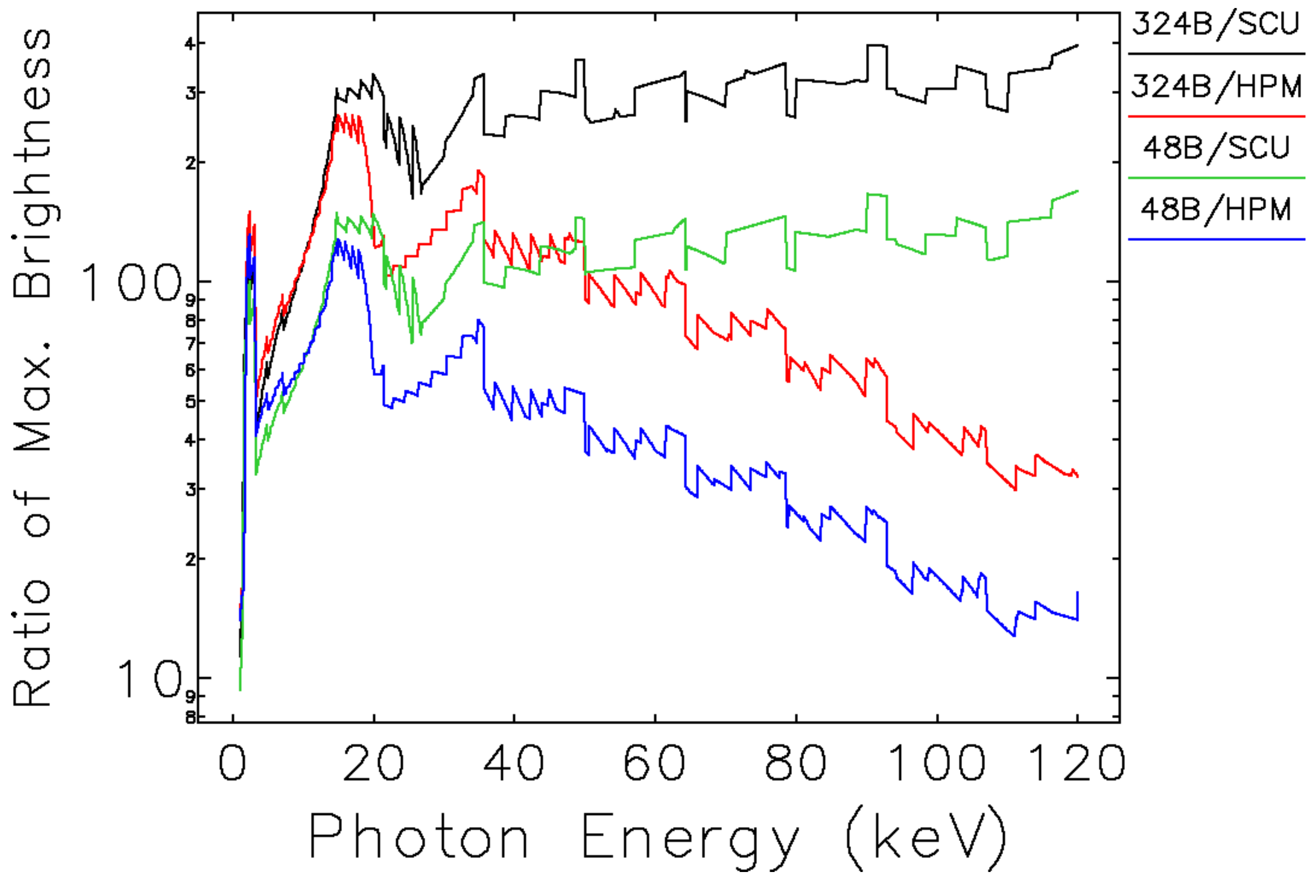
Advanced IDs

- Advanced IDs further boost brightness, flux
- Superconducting planar undulators[1]
  - Out-perform in-vacuum IDs even with NbTi superconductor
  - APS SCU in operation for >2 years
- Helical SCUs[2]
  - Bi-filar devices can provide arbitrary polarization with relatively fast switching
  - Suitable for 4GSRs using swap-out
- Horizontal-gap IDs[3]
  - Smaller, lighter, cheaper due to use of spring-based force compensation
  - Vertical polarization beneficial for beamline design, stability
  - Suitable for 4GSRs using swap-out



1: Y. Ivanyushenkov, IPAC14, 2053-2055.
2: Y. Ivanyushenkov, IPAC14, 2050-2052.
3: E. Gluskin, IPAC15, TUXC1.

APS-U X-ray Brightness Compared to APS Today

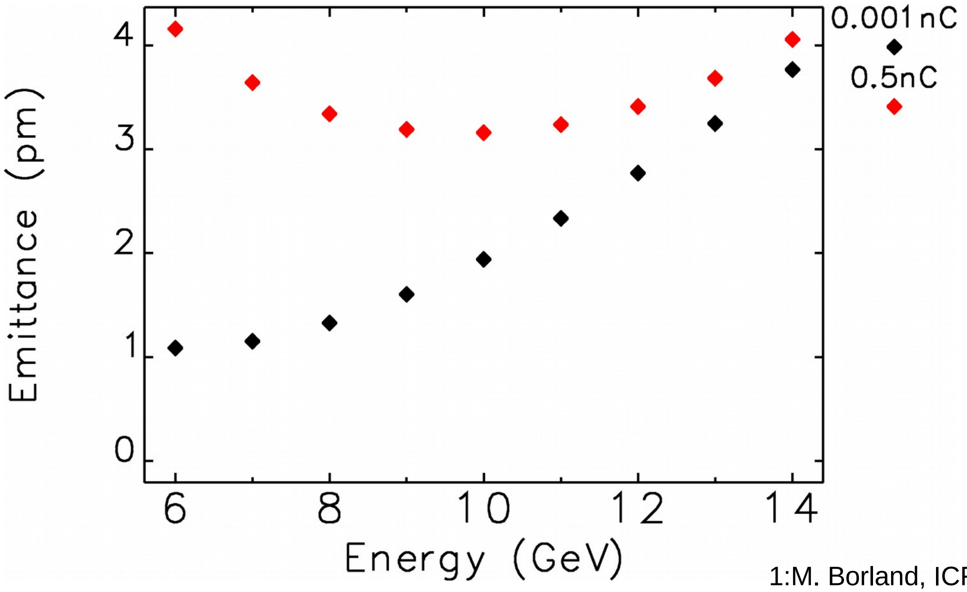


- Used κ=1 for 48 bunch mode and κ=0.1 for 324 bunch mode in "official" 67-pm lattice
- Assumed magnetic gap of 9 mm for 4.8-m HPM and 3.7-m SCU devices in APS-U
- Assumed APS High Heat Load (HHL) front end limits on power, power density

τUSR: A Tevatron-Sized USR[1]

$\tau \equiv 2\pi = 6.28...$

- What to do with Tevatron tunnel now?
- Exploratory light source design
  - Roughly match 6-straight, 6-arc geometry
  - Use PEP-X optics modules[2]
    - 6 arcs with 30 cells of 7BA giving N_s*M=1260
    - Relax cell tunes, giving ϵ_0=2.9 pm at 9 GeV
  - Preliminary optimization gives
    - Adequate DA for on-axis injection, 4.5 h gas-scattering lifetime
    - Adequate LMA for 3 h Touschek lifetime for 0.75nC/bunch



Emittance with IBS shows broad minimum between 9 and 11 GeV with a minimum of about 3 pm in both planes.

Diffraction-limited to 33 keV

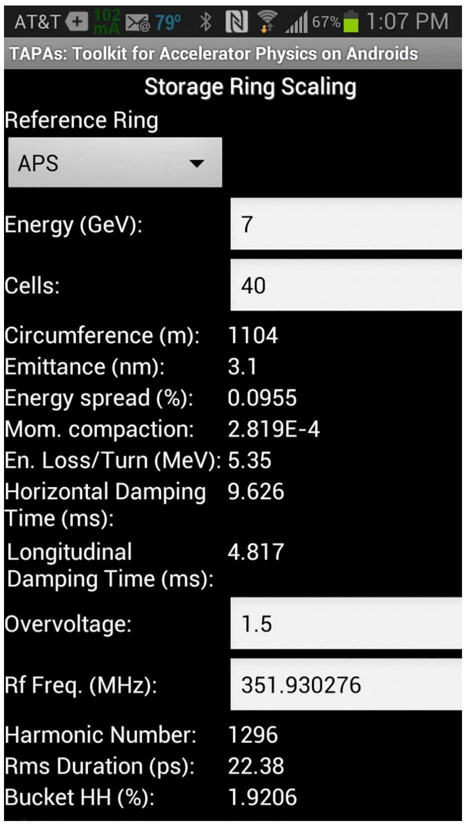
Further improvement possible with damping wigglers

1:M. Borland, ICFA Beam Dynamics Newsletter 57, 2012; IPAC12,TUPPP033.
2:R. Hettel et al., PAC 11, 2336 (2011).

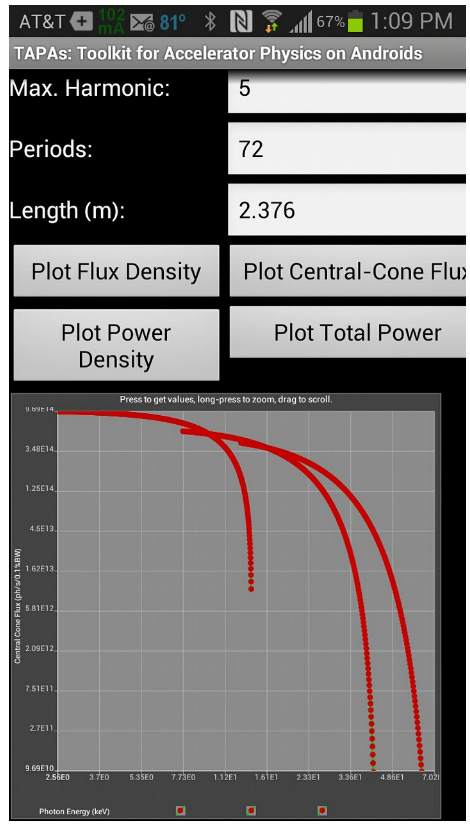
Explore light source physics

- A free Android app is available that lets you explore storage ring scaling
- Also has synchrotron radiation calculations, FELs, top-up/swap-out, etc.
- Search for “TAPAs Accelerator Physics” on the Google store

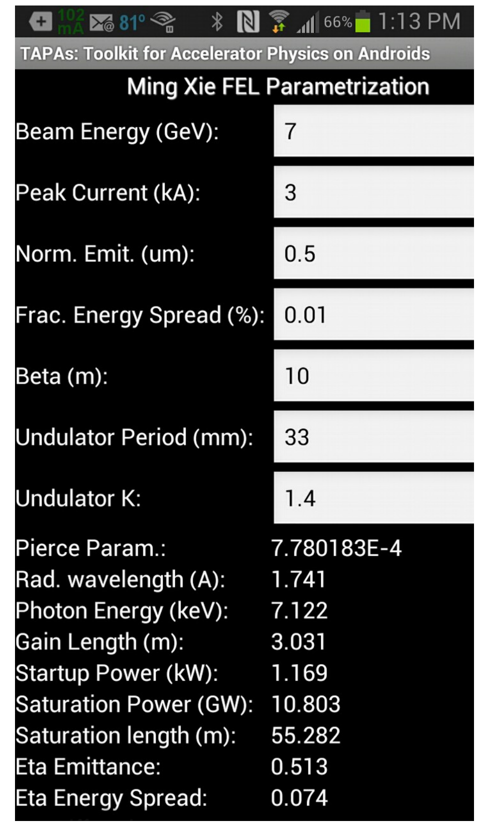
Ring scaling



Undulator radiation



FEL estimation



Conclusions

- 3rd generation storage ring light sources are among the most successful scientific tools ever built
- We've learned a great deal since the first of these sources began operating ~20 years ago
- There is world-wide activity to design and build 4th generation storage ring light sources
- 100x increases in brightness and 10x increases in flux are within reach
- Challenges are many, but all appear manageable
- Another order of magnitude appears feasible with much larger rings

Acknowledgments

- APS Upgrade Beam Physics team:

  A. Blednykh (BNL), T. Berenc, M. Borland, J. Calvey, J. Dooling, L. Emery, K. Harkay, R. Lindberg, V. Sajaev, Y. Sun, A. Xiao

- Also contributing:

  H. Cease, J. Carter, J. Carwardine, G. Decker, S. Henderson, A. Jain, M. Jaski, J. Kerby, R. Soliday, B. Stillwell, A. Zholents, …

- Early version of H7BA lattice used file provided by ESRF

- Computing:
  - Argonne Laboratory Computing Resources Center (LCRC), Blues cluster
  - Accelerator Systems Division, Weed cluster