Beam dynamics and magnet design challenges for 4th-generation storage ring light sources

Michael Borland

December 1, 2014

Accelerator Systems Division

Outline

- What do storage ring light source users want?
- Multi-bend achromat lattices
- Scaling of lattice and magnet properties
- Beam dynamics issues for low-emittance rings
- Example: Advanced Photon Source (APS) upgrade
- Summary of magnet requirements

What Do SR Users Want?

- No universal agreement!
- Common desire: emittance so small that it might as well be zero
  - Brightness is as high as possible for a given beam current

$$B \propto \frac{N_\gamma}{(\Delta\lambda/\lambda)\Delta t \Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'}} \rightarrow \frac{4\pi^2 N_\gamma}{(\Delta\lambda/\lambda)\Delta t \lambda^2}$$

  - Beams are transversely coherent and can be focused tightly
- While not every experiment benefits from brightness
  - It's traditionally the most-emphasized quantity
  - Emittance is well understood and gives a simple goal

How Close are We to Ultimate Performance?

- Within factors of ~2, we'd like

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

- In more practical terms

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

- For typical 3rd-generation rings

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

so we are several orders of magnitude away from DL performance

Emittance Scaling

- Emittance is governed by[1]

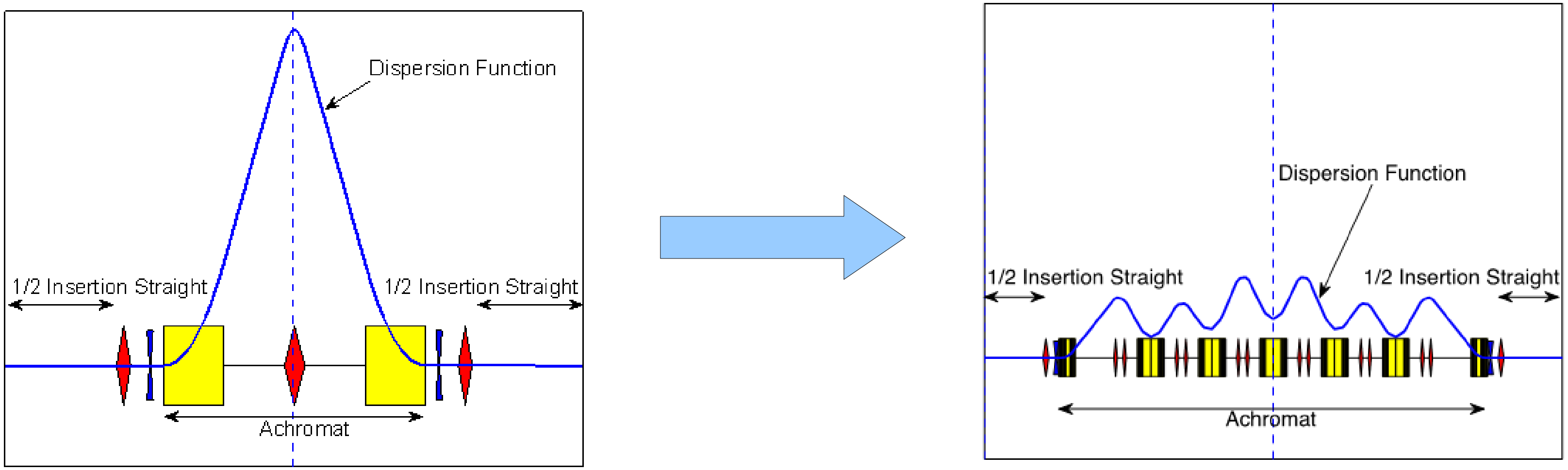
$$\epsilon_0 = F(\nu, \text{type})\frac{E^2}{N_d^3} \quad \underbrace{\propto \frac{E^2}{C^3}}_{\text{Fixed cell type}}$$

where N_d is the number of dipoles in the ring

- 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

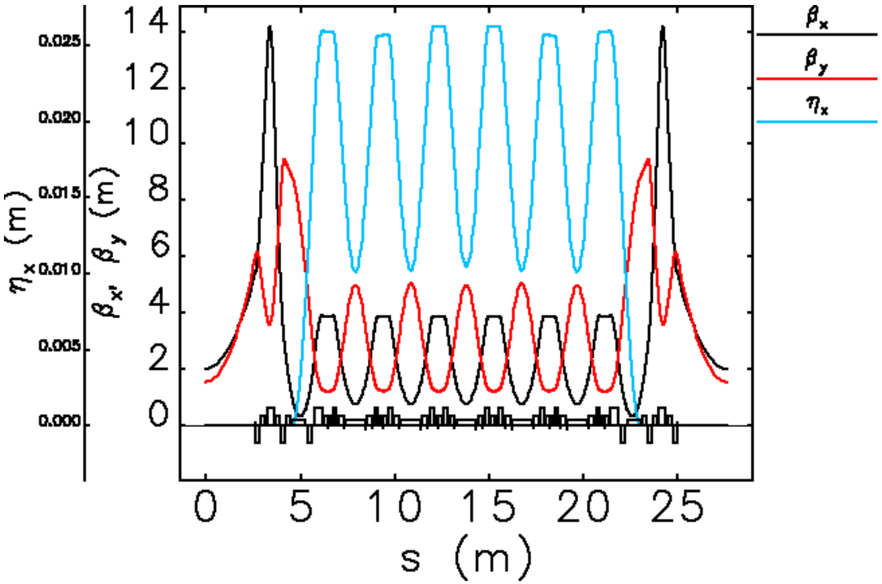


- Rings today have $N_d=2N_s$ or (more rarely) $3N_s$
- Several groups proposed $N_d/N_s>3$ lattices in 1990s[1]
- 7BA should have ~40x lower emittance than 2B(A)

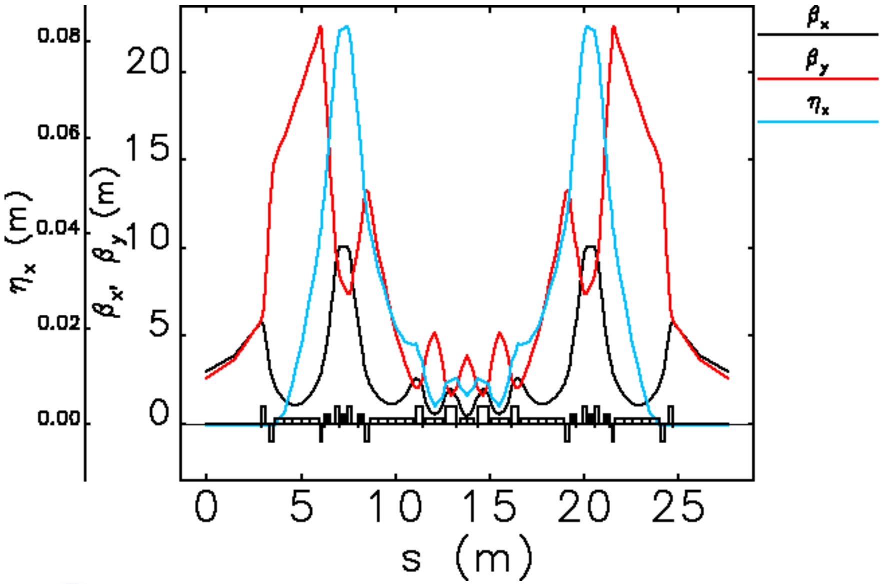
[1]: Einfeld *et al*., NIM A 335, 1993; Joho *et al*., EPAC 94;: Einfeld *et al*., PAC95; Kaltchev *et al*., PAC95.

Figures courtesy C. Steier, LBNL.

MAX-IV[1] vs ESRF[2] Style 7BA Lattices



- “Typical” MAX-IV style lattice
- Small dispersion throughout relatively uniform arcs
- Sextupoles distributed through arcs
- Geometric sextupoles or octupoles outside arcs

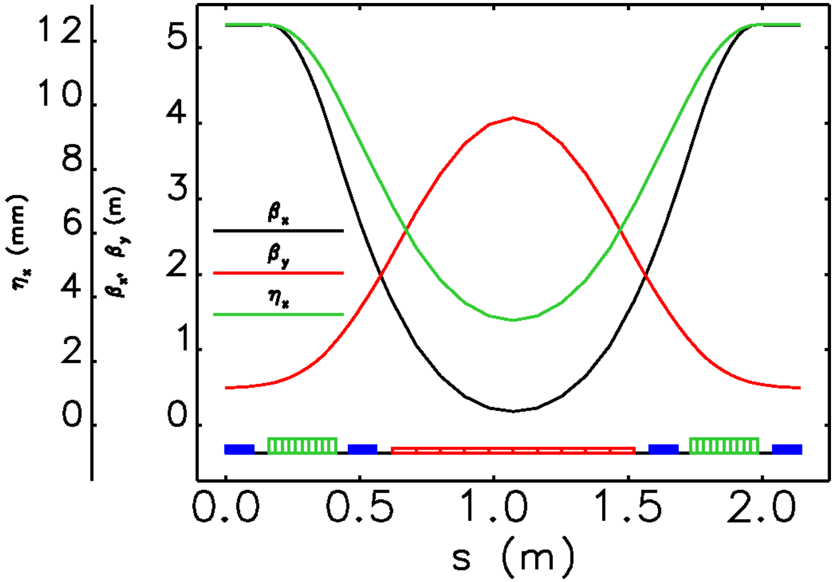


- “Typical” ESRF-style lattice
- Dispersion bump between longitudinal gradient dipoles
- Sextupoles only in dispersion bump
  - Factor of 2 to 4 weaker than in MAX-IV style lattice
- Octupoles possible in dispersion bump

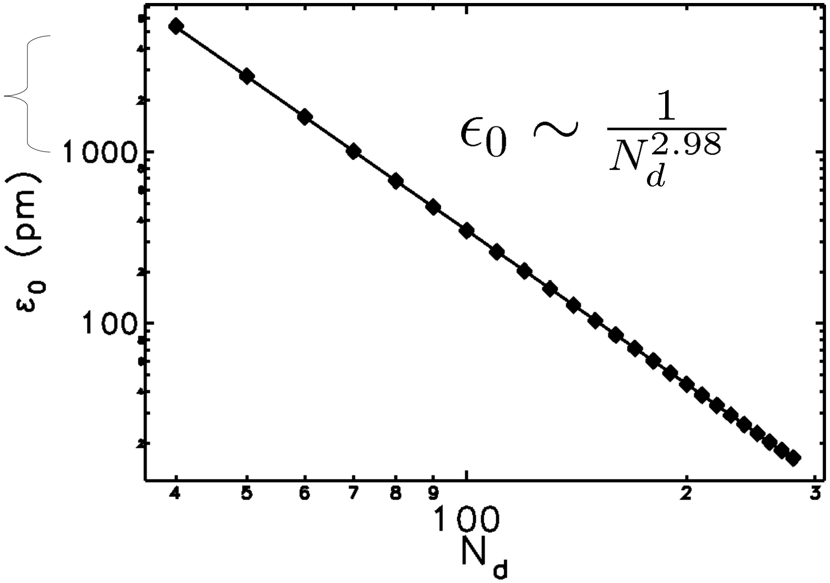
1: S. Leemann *et al*. PRSTAB 12:120701, 2009
2: L. Farvacque *et al*., IPAC13, 79.

Model Storage Ring for Understanding Scaling

- We looked at a model storage ring consisting of series of identical cells[1]
  - 600-m circumference, 4.5 GeV
- For fixed circumference, varied number of cells, looked at implications
  - Magnet strength, bore
  - Tolerances
  - Nonlinear dynamics



Present-day rings



In-construction and next-generation rings and concepts

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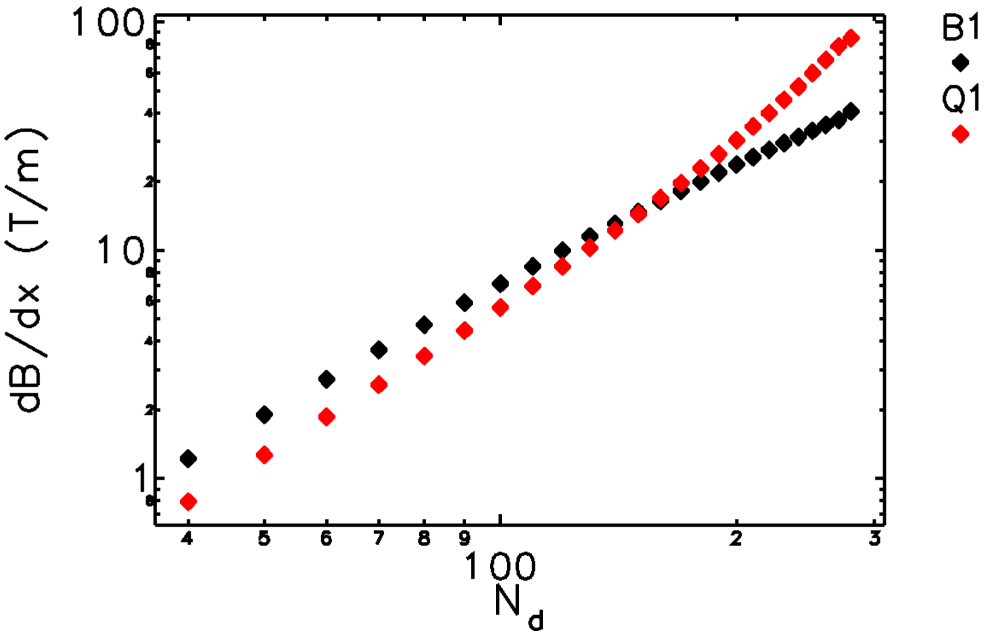
[1] 1: M. Borland *et al.*, J. Synch. Rad., **21**, 912-936 (2014).

Scaling of Gradients

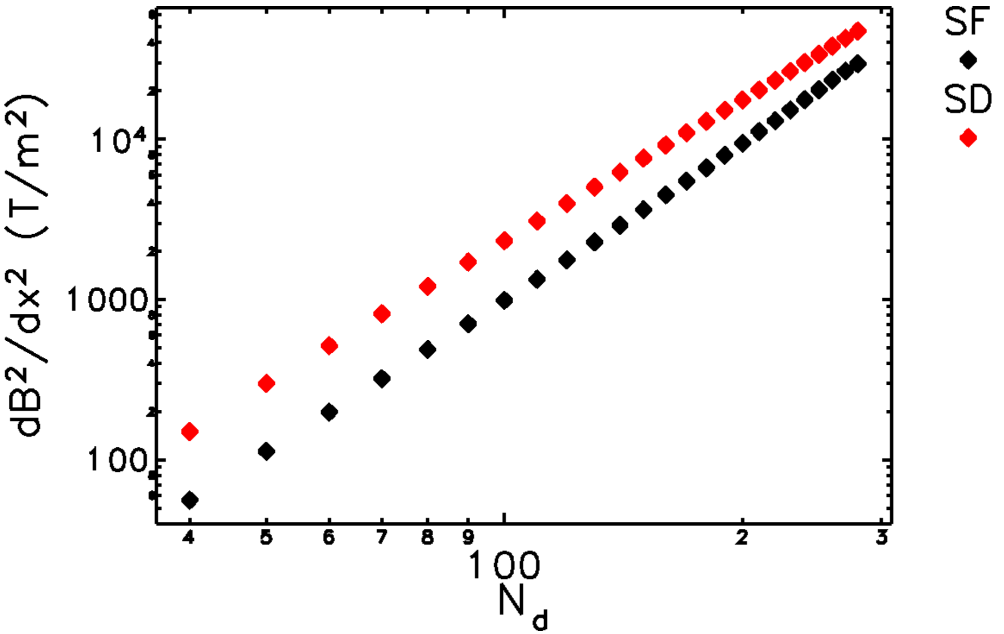


$$\left(\frac{dB_y}{dx}\right)_{\text{quads}} \sim N_d^{2.4}$$

$$\left(\frac{dB_y}{dx}\right)_{\text{bends}} \sim N_d^{1.8}$$

- Explanation:
  - Focal lengths scale like the distance between quadrupoles (G~N_d)
  - Quadrupoles must get shorter due to shrinking cell length (G~N_d)
- If we go from a DBA to a 7BA, expect 10-to-20-fold increase in required gradients
  - In reality, 5-fold increase is being contemplated (e.g., APS upgrade)
    - Keep quadrupoles longer in order to restrain gradients
    - Reduce space between magnets to alleviate pressure lengths

Scaling of Sextupole Strengths

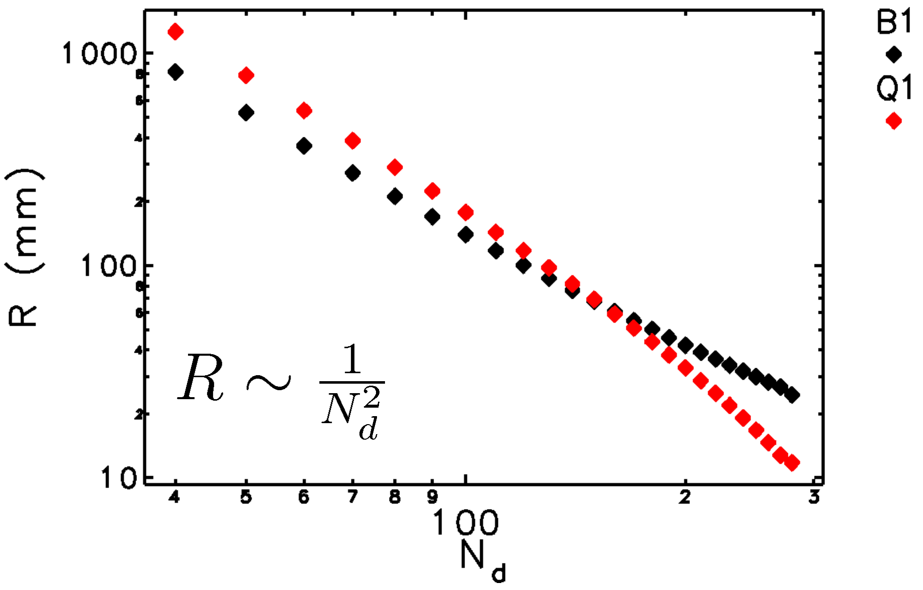


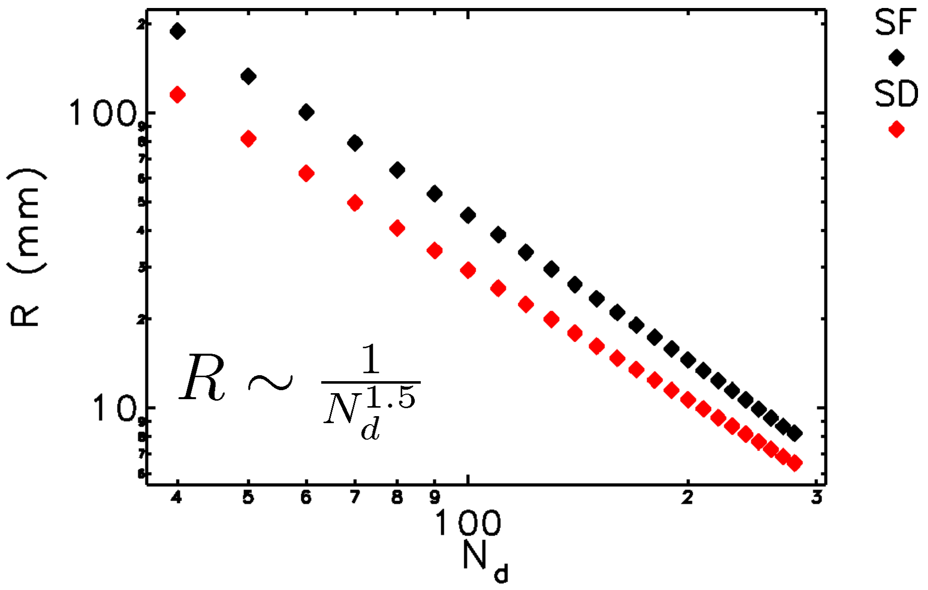
$$\left(\frac{d^2 B_y}{dx^2}\right)_{\mathrm{SF}} \sim N_d^{3.2}$$

$$\left(\frac{d^2 B_y}{dx^2}\right)_{\mathrm{SD}} \sim N_d^{2.9}$$

- Explanation:
  - Dispersion scales like $1/N_d^2$
  - Tune and therefore natural chromaticity scale like N_d
  - Assumed here that sextupole length was fixed
- If we go from a DBA to a 7BA, expect ~50-fold increase in required sextupole strengths
  - This is very close for a MAX-IV-style lattice replacing the existing APS ring

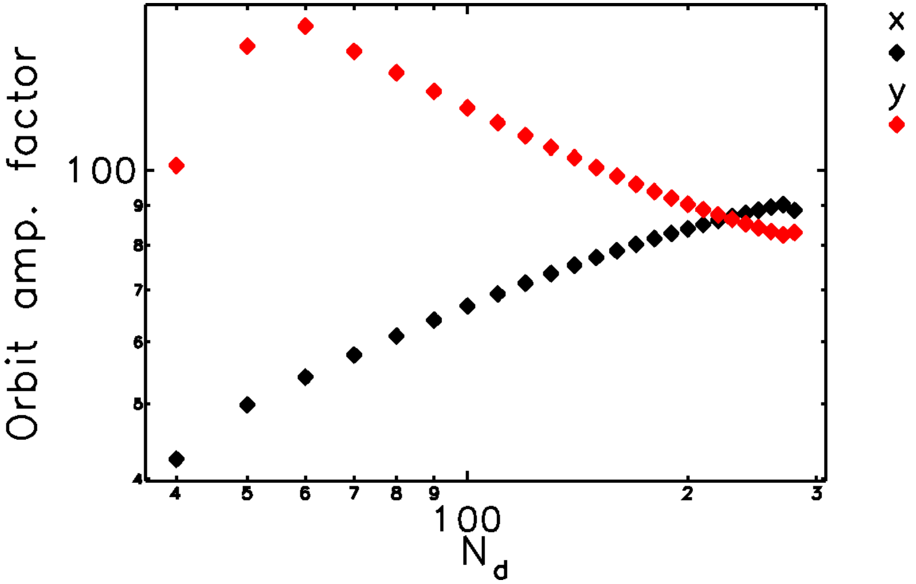
Scaling of Magnet Bores

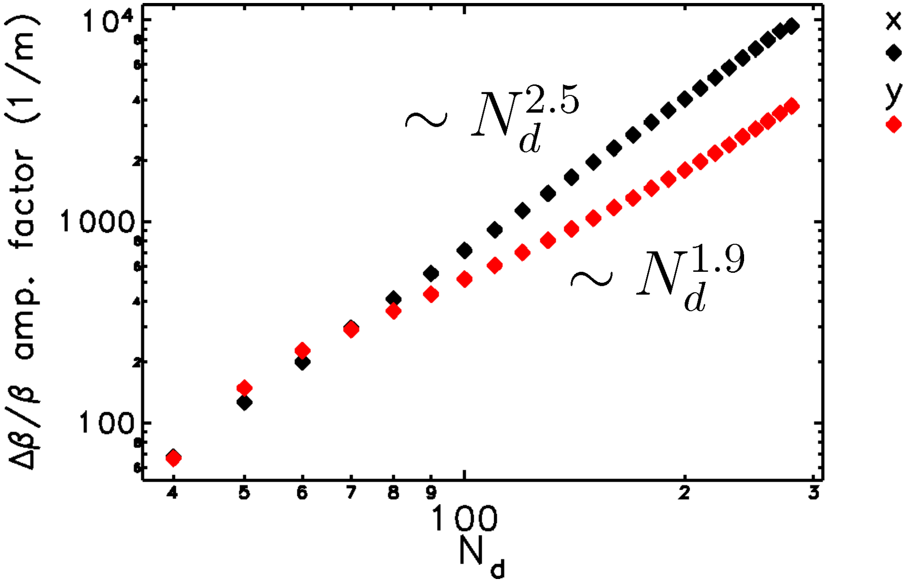




- Assumed pole-tip field was fixed at 1 T
- If we go from a DBA to a 7BA, expect
  - 12-fold (6-fold) decrease in quadrupole (sextupole) bore radii
  - E.g., 3-6 mm bore radii for an APS 7BA replacement ring!
- In reality
  - 3rd generation ring magnets often have low pole tip fields
  - 4th generation ring magnets must be pushed further into saturation
  - 4th generation rings must have closer spacing of magnets to maximize length
  - ~12 mm bore radius seems workable for several projects

Scaling of Alignment Requirements





- Misalignment of magnets creates various issues
  - Misaligned quads/gradient dipoles create orbit errors
  - Misaligned sextupoles create optical errors
- Scaling of orbit amplification factors is weak, partly beneficial
  - Although gradients are stronger, beta functions are smaller
- Scaling of beta-beat factor per unit displacement is very strong
  - Tends to scale with sextupole strength (~N_d^3) and number (~√(N_d))
  - Moderated again by reduction in beta functions
  - Implication is that ~150 µm alignment requirement for 3GSRs becomes 5-15 µm
    - For APS upgrade, using 30 µm with assumed LOCO-based correction

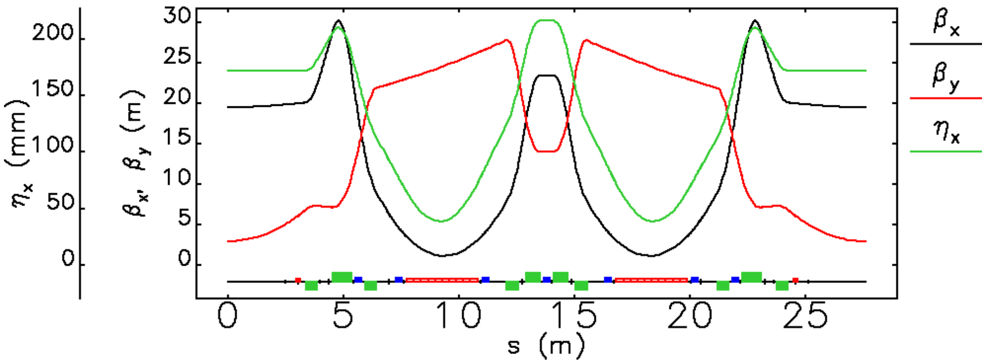
$$\left\{\begin{array}{l}\beta_x \sim 1/N_d \\ \beta_y \sim 1/N_d^{1.6}\end{array}\right.$$

Nonlinear Dynamics Issues

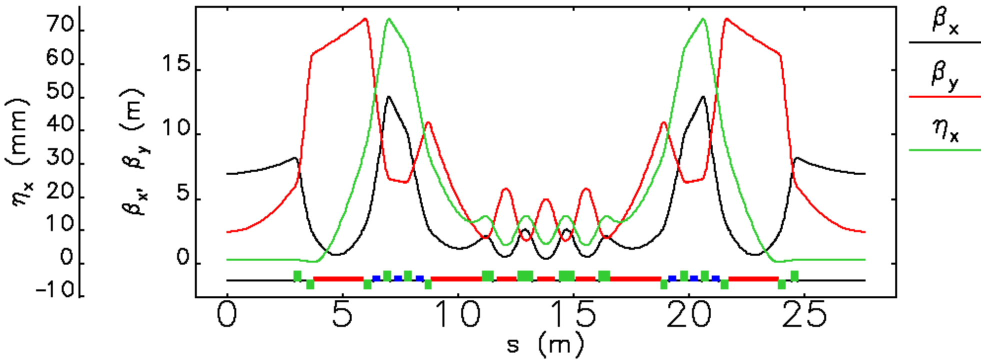
- Focusing elements have chromatic aberrations
  - Sextupole magnets added to correct these
  - Introduces higher-order aberrations that limit dynamic acceptance
  - Scaling analysis indicates that dynamic acceptance decreases like $1/N_d^2$
  - Indicates that injection efficiency will be a challenge
- Lattices have higher-order chromaticity from sextupoles, gradient dipoles, etc.
  - Scaling study indicates these increase like $N_d^{1.6}$
  - Momentum acceptance expected to drop precipitously
  - Indicates that Touschek lifetime will be a challenge
- Modern approaches to nonlinear dynamics optimization fight against this
  - Inclusion of many families of sextupoles, as well as octupoles[1,2]
  - Resonant driving term minimization and cancellation schemes[3,2,4]
  - Tracking-based optimization of dynamic and momentum acceptance[5]
- In addition
  - Top-up allows entertaining shorter lifetimes than previously
  - On-axis "swap-out" injection allows working with small DA[6]

1:S.C.Leemann *et al*., PRSTAB.12.120701; 2:L.Farvacque *et al*.,IPAC13, 79; 3:J.Bengtsson, SLS Note 9/97.
4:Y.Cai *et al*., PRSTAB.15.054002; 5: See ref. list in M. Borland *et al*., J. Synch. Rad., **21** (2014); 6: L. Emery *et al*. PAC03, 256.

APS Upgrade Lattice



APS today:
7 GeV, 100 mA
Double-bend sectors
3100 pm emittance



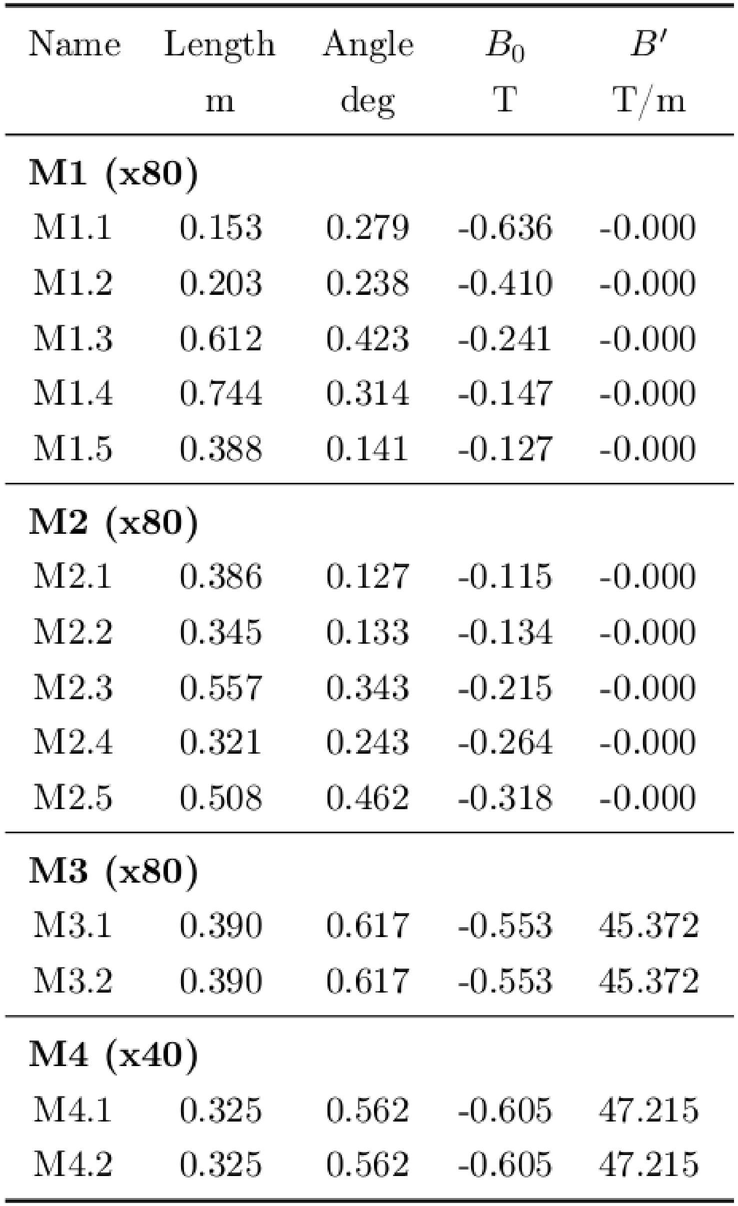
Proposed upgrade:
6 GeV, 200 mA
Hybrid 7-bend sectors
67 pm emittance

- Upgrade lattice is modeled after ESRF's Hybrid MBA design[1]
- Four longitudinal gradient dipoles (LGDs), three transverse gradient (dipoles)
- LGDs help create dispersion bump that decreases sextupole strength ~3-fold compared to MAX-IV-style lattice
- TGDs help provide requisite phase advance between dispersion bumps to cancel some sextupole kicks

1:L.Farvacque *et al.*,IPAC13, 79;

Dipole Parameters

Present APS dipoles:
0.6 T field with no gradient



Name	Length m	Angle deg	B_0 T	B' T/m
M1 (x80)				
M1.1	0.153	0.279	-0.636	-0.000
M1.2	0.203	0.238	-0.410	-0.000
M1.3	0.612	0.423	-0.241	-0.000
M1.4	0.744	0.314	-0.147	-0.000
M1.5	0.388	0.141	-0.127	-0.000
M2 (x80)				
M2.1	0.386	0.127	-0.115	-0.000
M2.2	0.345	0.133	-0.134	-0.000
M2.3	0.557	0.343	-0.215	-0.000
M2.4	0.321	0.243	-0.264	-0.000
M2.5	0.508	0.462	-0.318	-0.000
M3 (x80)				
M3.1	0.390	0.617	-0.553	45.372
M3.2	0.390	0.617	-0.553	45.372
M4 (x40)				
M4.1	0.325	0.562	-0.605	47.215
M4.2	0.325	0.562	-0.605	47.215

Two types of 5-segment longitudinal-gradient dipole.

Segments have variable length.

Up to 5-to-1 field ratio within magnet.

Curved magnets to preserve GFR.

Want ±5% variable gradient.

Quadrupole Parameters

Element Name	Length m	K_1 $1/m^2$	B' T/m
Q1	0.238	3.601	-72.1
Q2	0.238	-2.787	55.8
Q3	0.238	-2.256	45.1
Q4	0.238	3.203	-64.1
Q5	0.238	1.693	-33.9
Q6	0.238	-2.444	48.9
Q7	0.438	3.562	-71.3
Q8	0.592	4.086	-81.8

Vanadium permendur pole tips with mushroom poles req'd

All carbon steel construction with mushroom poles. Could use VP tips to reduce lengths.

Vanadium permendur pole tips required. Include steering windings.

In contrast, present APS quadrupoles are 0.5-0.8 m in length with gradients of less than 21 T/m

Sextupole Parameters

Element Name	Length m	K_2 $1/m^3$	B'' T/m^2
S01A:S1	0.256	-165.1	3305.2
S01A:S2	0.256	227.1	-4545.4
S01A:S3	0.256	-151.3	3028.4
S01B:S3	0.256	-155.9	3121.1
S01B:S2	0.256	230.7	-4616.7
S01B:S1	0.256	-153.0	3061.5
S02A:S1	0.256	-157.5	3151.3
S02A:S2	0.256	227.5	-4553.2
S02A:S3	0.256	-155.9	3120.5
S02B:S3	0.256	-152.3	3048.2
S02B:S2	0.256	233.1	-4665.7
S02B:S1	0.256	-157.0	3142.4

Sextupole pattern repeats every two sectors, giving more knobs for nonlinear dynamics optimization.

Optimization is entirely tracking-based, emphasizing DA and Touschek lifetime

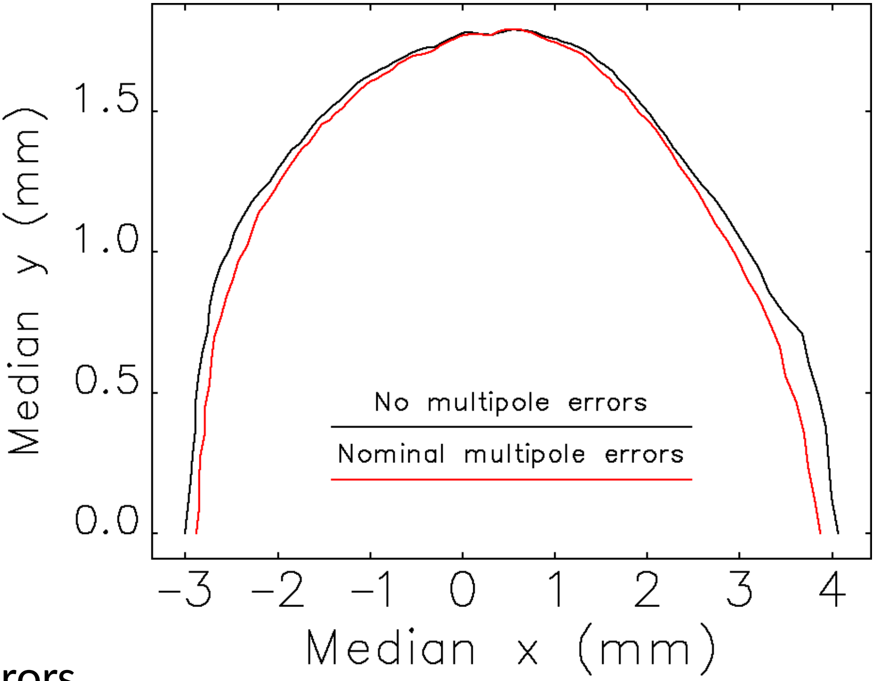
Two groups of magnets:

- S1/S3: < 3310 T/m^2
- S2: <4700 T/m^2

S1/S3 magnets will also include steering windings.

Present APS sextupoles are 0.25 m in length with strength of less than 500 T/m^2

Dynamic Acceptance

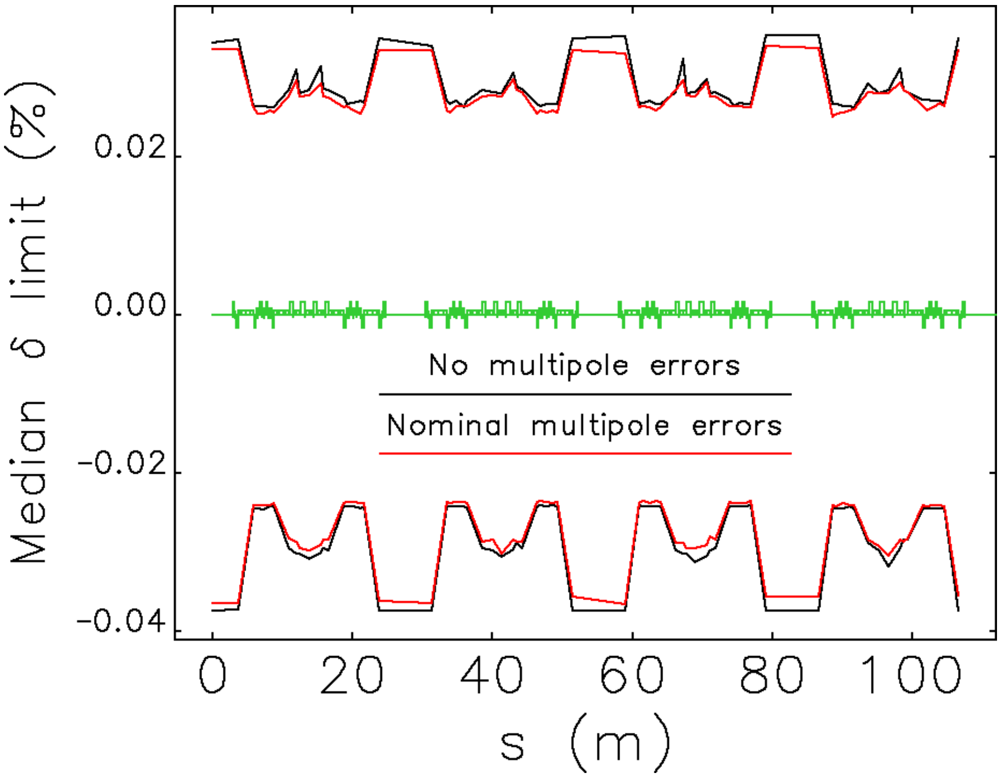


- DA was evaluated by 6D tracking with **elegant** for 1000 turns
- Included 100 ensembles of random errors and "commissioning" simulation[1]
- Included nominal multipole errors from
  - 3D magnet designs[2]
  - Scaling of NSLS-II measured results[3]
  - Estimates from Halbach's method[4]
  - See backup slide for more detail
- DA is only adequate for on-axis injection
- Relatively insensitive to most multipole errors
  - DA is very small, dominated by strong sextupoles
  - Most harmful error is unallowed multiples in quadrupoles
  - If attempting to achieve larger DA, better magnet quality would be needed
- Also developed[5] a higher-emittance lattice with DA sufficient for accumulation
  - Same errors have much greater impact on DA

1: V. Sajaev (ANL); 2: M. Jaski (ANL), V. Kashikin (FNAL); 3: A. Jain (BNL);
4: K. Halbach, NIM **74-1**, 147 (1969); 5: Y.P.Sun (ANL).

Local Momentum Acceptance

- LMA evaluated in same way as DA
- Also relatively insensitive to most multipole errors
  - Most harmful error is again unallowed multipoles in quadrupoles
- Earlier, we tried putting steering coils on all quadrupoles
  - Made LMA significantly worse
- Higher-emittance variant has similar but larger LMA compared to nominal design
  - Seems no more sensitive to errors than the nominal design



- This LMA is sufficient to get workable Touschek lifetime provided a bunch-lengthening cavity is used
  - Further improvement possible using octupoles[1,2]

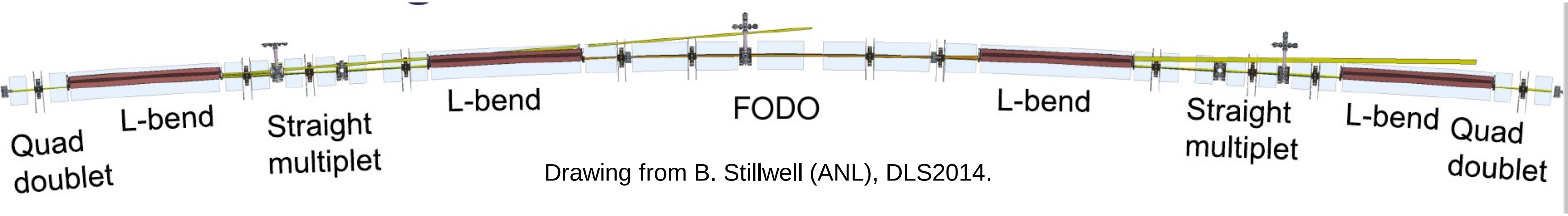
[1] P. Raimondi (ESRF); [2] Y.P.Sun (ANL)

“Magnet-Aware” Accelerator Design

- All accelerator design relies on a model of the magnet capabilities
  - Typically, just the maximum strength of the main components
  - First pass might just use estimates from hand calculations
- To quickly converge on a design, more is needed
- For APS, benefited from curves of maximum $B_n L$ vs L
  - This non-linear function was obtained from 3D magnet models
  - We derated the $B_n L(L)$ curves to allow explicit overhead for lattice flexibility and evolution
- Similarly, tracking-based optimization could benefit from
  - Early knowledge of magnet quality
  - Early inclusion of end effects
  - Typically, these are put in only after optimization as a check
- An open repository of magnet design information in a standardized format could be very useful jump-starting future accelerator designs

Other Magnet-Related Issues

- To save space, combining functions on many magnets
  - Strong gradient dipoles with ±5% gradient variation
  - Some quads (with low beta) have steering windings
  - Use eight-pole magnets for H/V steering plus skew quads[1]
- Need space between poles and between coils to extract photons
  - Particular problem for large rings since photon beams pass through many magnets
  - Limits K of undulator magnets, limits use of helical and vertically-deflecting devices



Drawing from B. Stillwell (ANL), DLS2014.

  - For APS upgrade, this has a significant impact on the magnets
    - Limits field quality in the sextupoles
    - Limits field quality and strength in the eight-poles

[1] A. Jain, C. Spataro (BNL)

Summary of Requirements for Magnets

- Significantly larger gradients and sextupole strengths
- Very strong, curved combined-function dipoles
  - Measurement and alignment not simple!
- Smaller bore diameters, e.g., 25 mm instead of 80 mm
  - Limited by vacuum system and impedance constraints
- Accommodation of photon channel imposes constrains on magnet quality, strength
- Closer spacing, e.g., as little as 50 mm instead of typ. >150 mm
- Combined functions on steering, skew quads, etc.
- Tighter alignment, e.g., 30 µm instead of 150 µm
- Early knowledge of detailed magnet properties can aid convergence of the design
- Field quality requirements not terribly difficult if swap-out is used
  - Will be somewhat harder with accumulation

Backup Slides

Tables of multipole errors used in simulations

Order	P1 10^{-4}	P2 10^{-4}	P3 10^{-4}	P4 10^{-4}	P5 10^{-4}
1	-3.5	-0.2	1.2	0.6	1.8
2	-7.5	11.5	3.0	1.3	-2.7
3	0.3	0.1	0.1	-0.0	-0.1
4	-2.0	-0.2	-0.5	-0.3	-0.2
5	-0.0	-0.0	-0.0	-0.0	-0.0
6	0.4	-0.1	-0.1	-0.0	-0.0
7	0.0	0.0	-0.0	0.0	-0.0
8	-0.1	-0.0	-0.0	0.0	0.0

M1 and M2 dipoles systematic normal multipole errors from 3D models

Order	Normal 10^{-4}
2	-8.0
3	-11.0
4	-11.0
5	-1.0
6	8.0
7	11.0
8	-5.0

M3 and M4 dipoles systematic multipole errors from 3D models

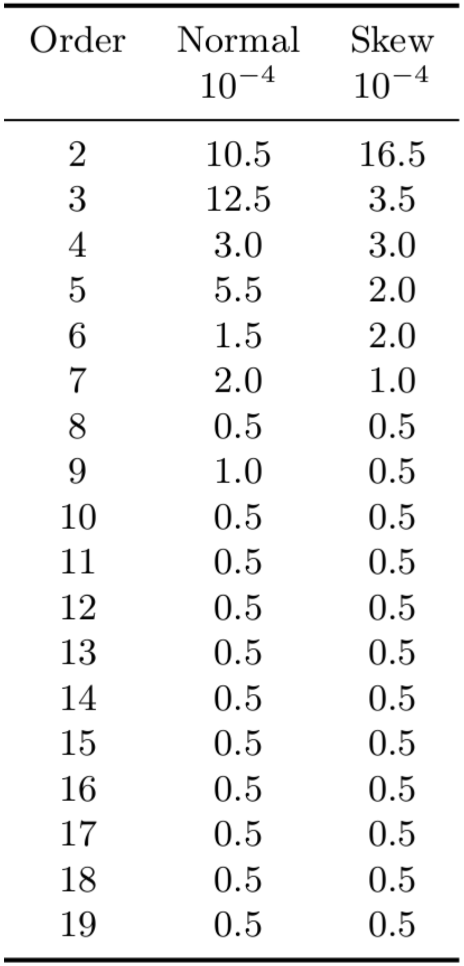
Reference radius: 10 mm

Tables of multipole errors used in simulations

Quadrupole systematic normal multipole errors (from 3D models)

Order	Q1-Q6 10^{-4}	Q7-Q8 10^{-4}
5	4.9	12.5
9	-4.2	-4.2
13	-2.5	-2.7
17	0.0	-0.1

Quadrupole random multiple errors (scaled from NSLS-II)



Order	Normal 10^{-4}	Skew 10^{-4}
2	10.5	16.5
3	12.5	3.5
4	3.0	3.0
5	5.5	2.0
6	1.5	2.0
7	2.0	1.0
8	0.5	0.5
9	1.0	0.5
10	0.5	0.5
11	0.5	0.5
12	0.5	0.5
13	0.5	0.5
14	0.5	0.5
15	0.5	0.5
16	0.5	0.5
17	0.5	0.5
18	0.5	0.5
19	0.5	0.5

Reference radius: 10 mm

Tables of multipole errors used in simulations

Sextupole systematic normal multipole errors (from 3D models)

Order	Normal 10^{-4}
8	-302.5
14	-13.2

These are large because the pole tips must be truncated to make room for the photon channel.

Sextupole random multiple errors (from Halbach theory)

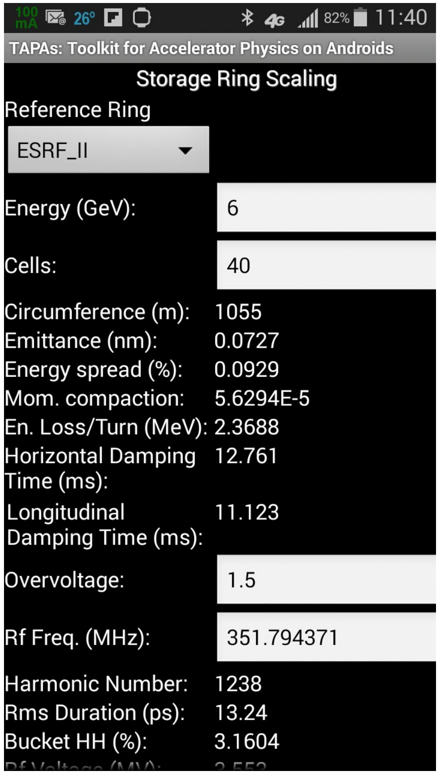
Order	Normal 10^{-4}	Skew 10^{-4}
1	0.0	0.0
2	0.0	0.0
3	8.9	8.9
4	9.1	5.5
5	4.5	0.9
6	2.6	1.8
7	0.7	0.7
8	0.8	0.3

Reference radius: 10 mm

Design Your Own Ring

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

Ring scaling

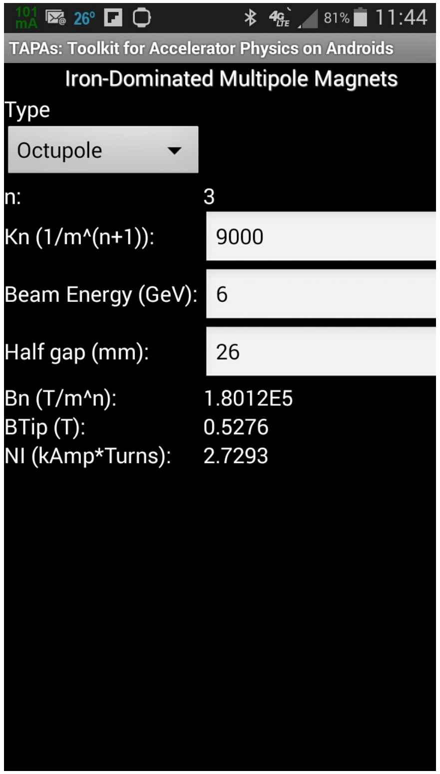


TAPAs: Toolkit for Accelerator Physics on Androids

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

Magnet estimation

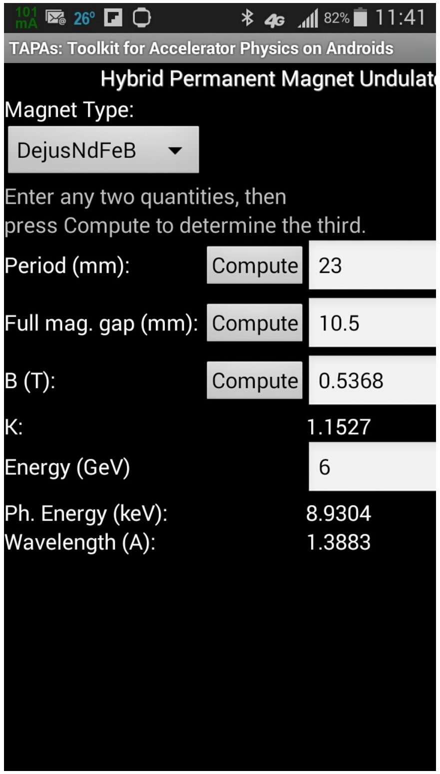


TAPAs: Toolkit for Accelerator Physics on Androids

Iron-Dominated Multipole Magnets

Type: Octupole
n: 3
Kn (1/m^(n+1)): 9000
Beam Energy (GeV): 6
Half gap (mm): 26
Bn (T/m^n): 1.8012E5
BTip (T): 0.5276
NI (kAmp*Turns): 2.7293

Undulator estimation



TAPAs: Toolkit for Accelerator Physics on Androids

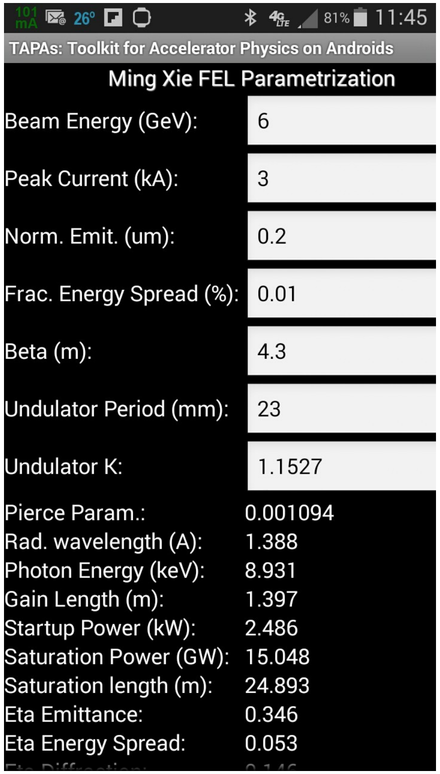
Hybrid Permanent Magnet Undulat

Magnet Type: DejusNdFeB

Enter any two quantities, then press Compute to determine the third.

Period (mm): 23
Full mag. gap (mm): 10.5
B (T): 0.5368
K: 1.1527
Energy (GeV): 6
Ph. Energy (keV): 8.9304
Wavelength (A): 1.3883

FEL estimation



TAPAs: Toolkit for Accelerator Physics on Androids

Ming Xie FEL Parametrization

Beam Energy (GeV): 6
Peak Current (kA): 3
Norm. Emit. (um): 0.2
Frac. Energy Spread (%): 0.01
Beta (m): 4.3
Undulator Period (mm): 23
Undulator K: 1.1527
Pierce Param.: 0.001094
Rad. wavelength (A): 1.388
Photon Energy (keV): 8.931
Gain Length (m): 1.397
Startup Power (kW): 2.486
Saturation Power (GW): 15.048
Saturation length (m): 24.893
Eta Emittance: 0.346
Eta Energy Spread: 0.053

M. Borland, PAC13, 1364-1366 (2013).