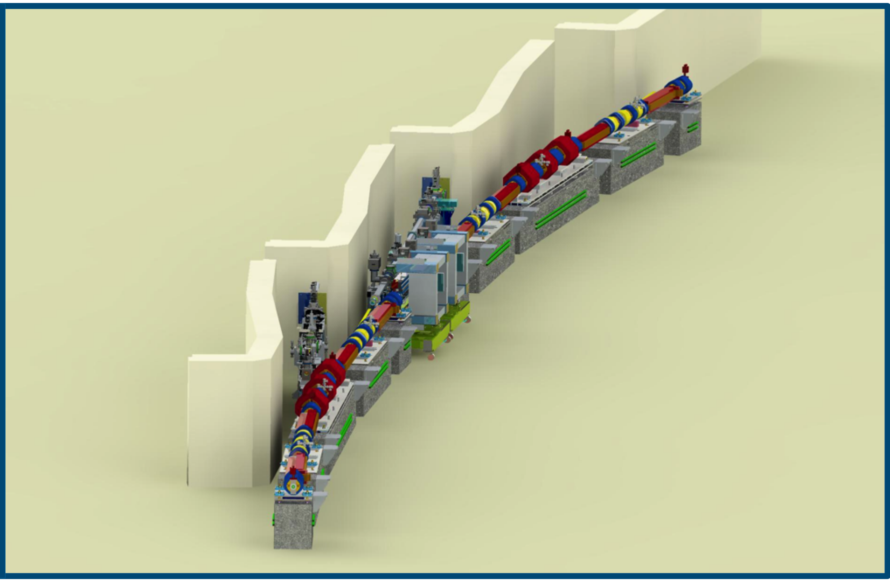
Lattice and Single-Particle Beam Dynamics for the APS Upgrade



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Presented by Ryan Lindberg on behalf of the
APS-U Beam Physics team

LER workshop
26-28 October, 2016

Outline

- Overview of APSU lattice design
- Commissioning simulation
- Nonlinear optimization
- Injection performance
- Beam loss and collimation

Lattice design goals and evaluation process

- Goals
  - Emittance less than 70 pm
  - 4.8 m free space for insertion devices
  - Support two operational modes at 200 mA
    - Timing mode – 48 bunches
    - High brightness mode – 324 bunches
  - Lifetime > 4.8 h at 200 mA and 6 GeV
    - Nominally obviate the need for supplemental shielding
- Development and evaluation process
  - Optimize lattice using tracking-based MOGA to maximize DA, Touschek lifetime
  - Perform commissioning simulation
  - Assess robustness of DA, Touschek lifetime, performance including
    - Harmonic cavity
    - Intra-beam scattering
    - Touschek lifetime
    - Gas scattering lifetime
    - Injection
    - Collective effects
- Compare lattices using scoring scheme

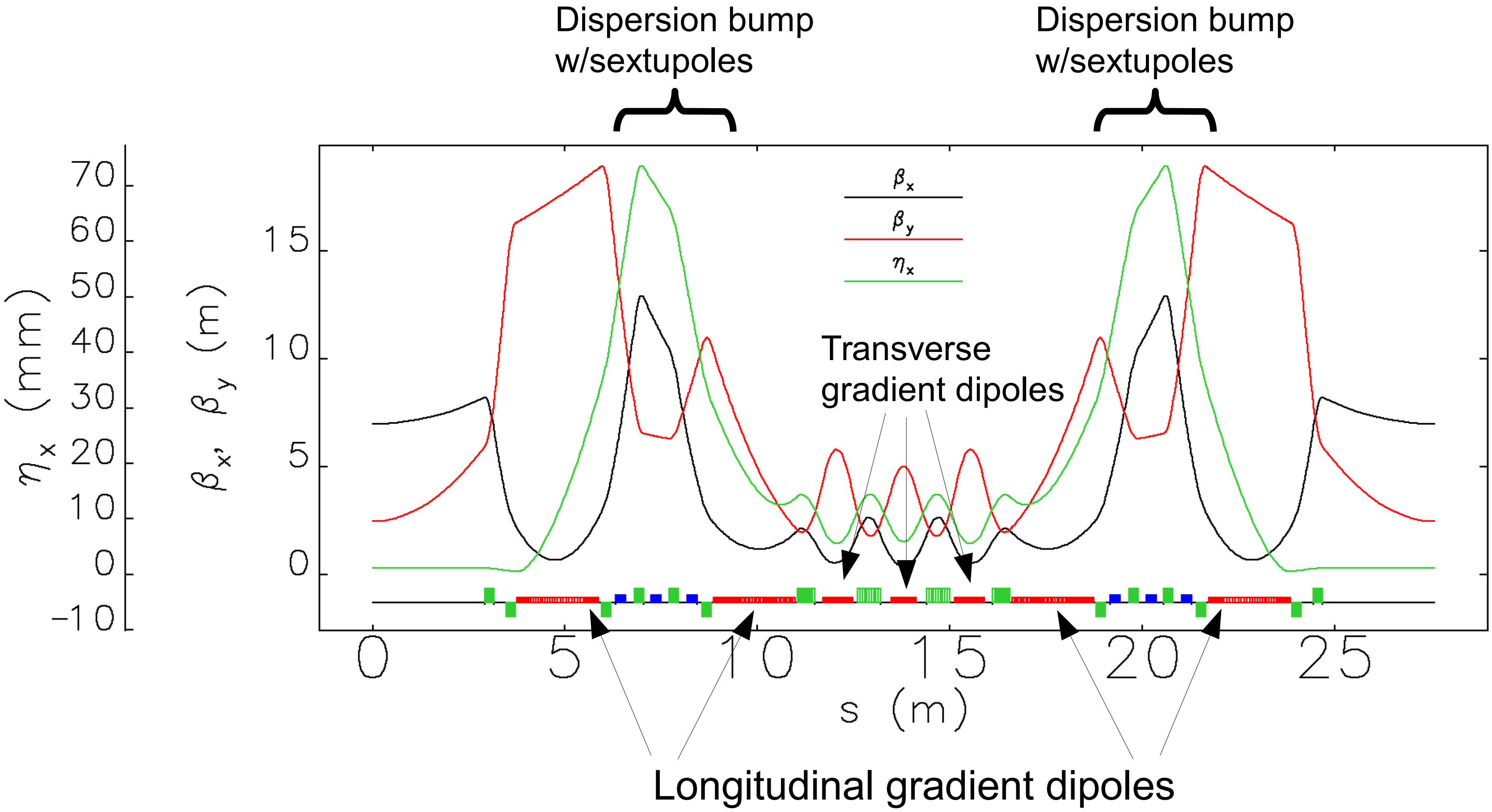
Items in blue will be touched on in this presentation.

Lattices studied for APS-U (Partial List)

1: L. Farvacque et al., IPAC13, 79.
2: M. Borland et al., IPAC2015,1776
3: J.P. Delahaye et al., PAC89, p. 1611.
4: A. Streun, NIM-A 737 (2014) , 148
5: M. Borland et al., NAPAC16, WEPOB01.

- All lattices are variants of a hybrid 7-bend achromat[1]
- 90-pm[2]
  - "Relaxed" emittance goal
  - Targets accumulation using conventional kicker technology
  - Compatible with swap-out injection
- 67-pm[2]
  - More demanding emittance goal
  - Optimized for swap-out injection with fast stripline kickers
  - Current "official" or "nominal" lattice
- 68-pm HB
  - Includes High-Beta insertion with goal of supporting accumulation
  - Derived from 67-pm lattice with special configuration in injection region
  - Not compatible with swap-out injection due to extra magnet in injection straight
- 41-pm RB[3,4,5]
  - Includes Reverse Bending magnets
  - Derived from 67-pm lattice
  - Optimized for swap-out injection with fast stripline kickers

Hybrid 7BA Lattice Concept[1]


Dispersion bump w/sextupoles

Dispersion bump w/sextupoles

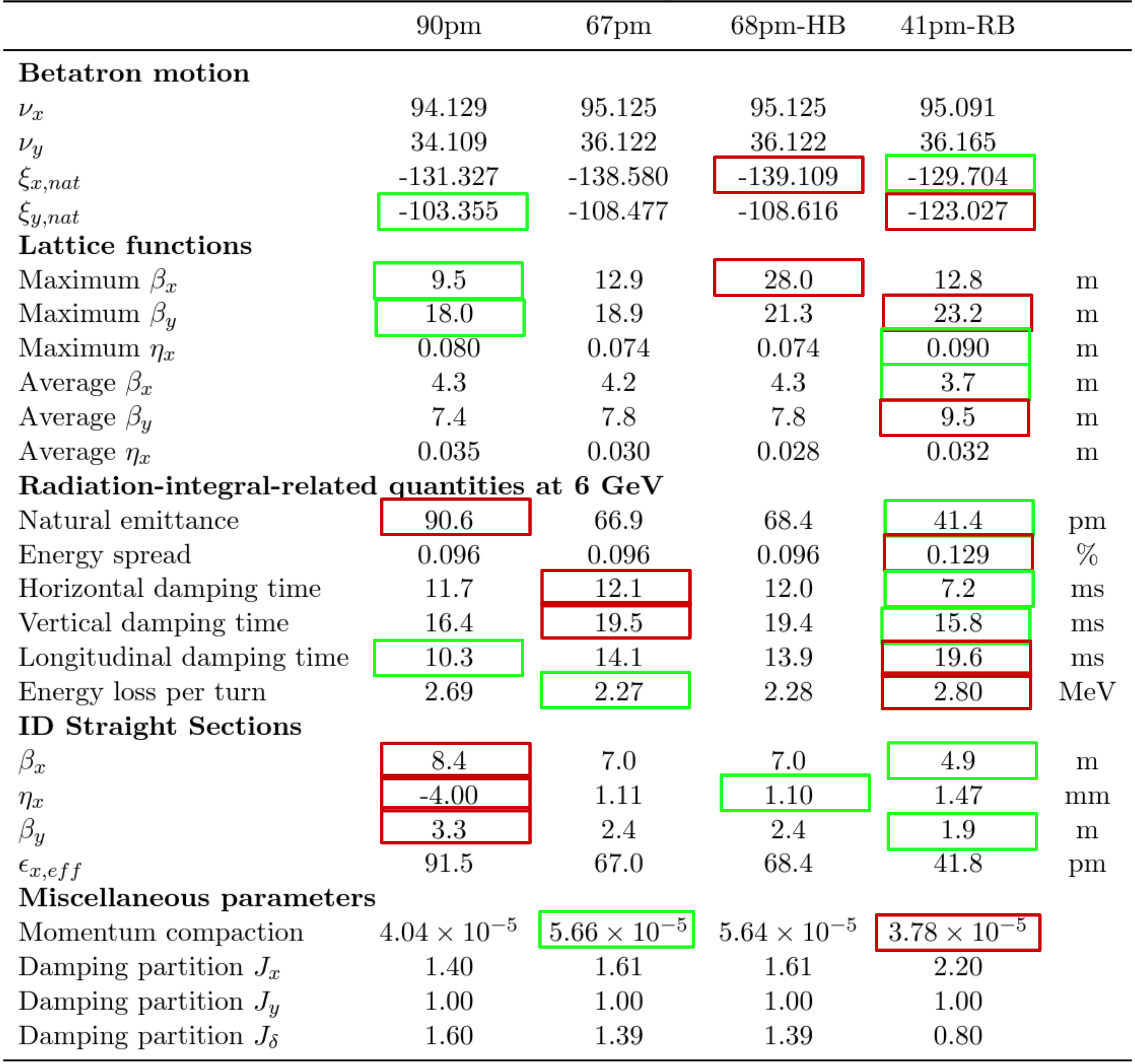
Transverse gradient dipoles

Longitudinal gradient dipoles

- Phase advance of $\Delta\varphi_x=3\pi$ and $\Delta\varphi_y=\pi$ between corresponding sextupoles chosen to cancel geometrical sextupole kicks
- Thick, interleaved sextupoles → cancellation isn't perfect

[1] L. Farvacque et al., IPAC13, 79.

Summary of main lattice parameters



	90pm	67pm	68pm-HB	41pm-RB	
Betatron motion					
ν_x	94.129	95.125	95.125	95.091	
ν_y	34.109	36.122	36.122	36.165	
$\xi_{x,nat}$	-131.327	-138.580	-139.109	-129.704	
$\xi_{y,nat}$	-103.355	-108.477	-108.616	-123.027	
Lattice functions					
Maximum β_x	9.5	12.9	28.0	12.8	m
Maximum β_y	18.0	18.9	21.3	23.2	m
Maximum η_x	0.080	0.074	0.074	0.090	m
Average β_x	4.3	4.2	4.3	3.7	m
Average β_y	7.4	7.8	7.8	9.5	m
Average η_x	0.035	0.030	0.028	0.032	m
Radiation-integral-related quantities at 6 GeV					
Natural emittance	90.6	66.9	68.4	41.4	pm
Energy spread	0.096	0.096	0.096	0.129	%
Horizontal damping time	11.7	12.1	12.0	7.2	ms
Vertical damping time	16.4	19.5	19.4	15.8	ms
Longitudinal damping time	10.3	14.1	13.9	19.6	ms
Energy loss per turn	2.69	2.27	2.28	2.80	MeV
ID Straight Sections					
β_x	8.4	7.0	7.0	4.9	m
η_x	-4.00	1.11	1.10	1.47	mm
β_y	3.3	2.4	2.4	1.9	m
$\epsilon_{x,eff}$	91.5	67.0	68.4	41.8	pm
Miscellaneous parameters					
Momentum compaction	4.04×10^{-5}	5.66×10^{-5}	5.64×10^{-5}	3.78×10^{-5}	
Damping partition J_x	1.40	1.61	1.61	2.20	
Damping partition J_y	1.00	1.00	1.00	1.00	
Damping partition J_δ	1.60	1.39	1.39	0.80	

Green:
Best value

Red:
Worst value

Integrated lattice evaluation

- Post-MOGA, lattices must be evaluated for robustness and performance[1,2]
- Commissioning and tolerances[3]
- DA/LMA tracking assesses robustness of nonlinear dynamics
  - Evaluate on linear difference resonance (round beam case)
  - 1000-turn tracking with multipole errors, statistical errors, commissioning corrections, apertures, main rf, harmonic rf, radiation damping
- Higher harmonic cavity (HHC) tracking[4]
  - Perform tracking with passive HHC and longitudinal impedance to determine longitudinal distribution
- Intra-beam scattering and Touschek lifetime
  - Uses distribution from HHC tracking, together with optics/LMA from tracking[5]
- Gas scattering lifetime
  - Uses species-specific pressure profiles, LMA/DA determined from tracking[6]
- Injection simulation[7]
  - More literal evaluation of adequacy of DA
- Collective effects[8,9,10]
  - Assess instability thresholds, injection issues, feedback requirements

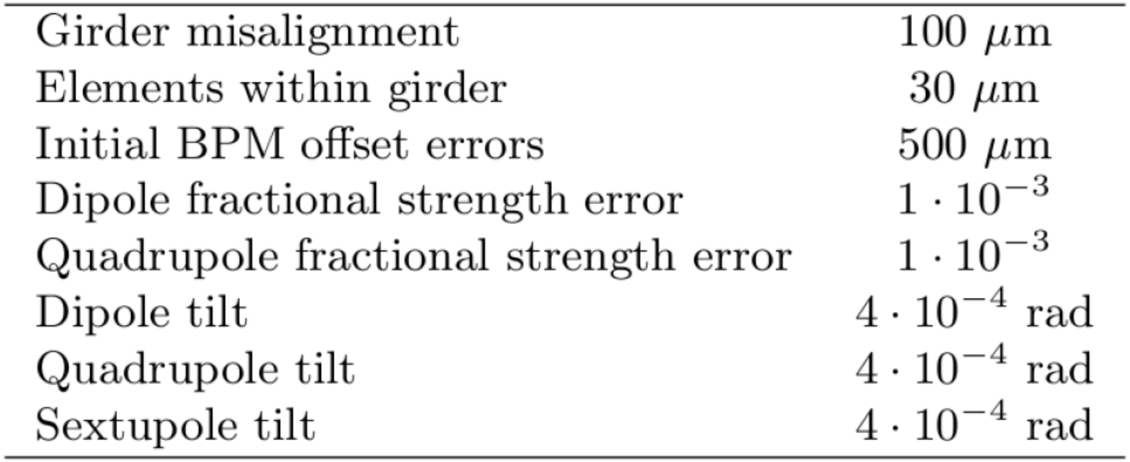
1: M. Borland et al., IPAC15, 1776.
2: M. Borland et al., NAPAC16, WEPOB01.
3: V. Sajaev et al., IPAC15, 553.
4: M. Borland et al., IPAC15, 543.
5: A. Xiao et al., IPAC15, 599.
6: M. Borland et al., IPAC15, 546.
7: A. Xiao et al., IPAC15, 1816.
8: R. Lindberg et al., IPAC15, 1825
9: R. Lindberg et al., NAPAC16, TUPJE077.
10: M. Borland et al., ICAP15, 61.

Commissioning simulation[1,2]

1: V. Sajaev et al., IPAC15, 553.
2: V. Sajaev, private communication

Performed a realistic simulation of commissioning steps, including

- Machine error generation (see table)
- Injection jitters added – 6D distribution
  - Obtained from APS operation and hardware measurement
- First-turn orbit correction based on particles transmission efficiency
- Find correct rf phase and rf frequency (a few tens of turns)
- First lattice correction using kick-based measured (a few tens of turns)
- BPM offset measurement
- Detail orbit and lattice correction



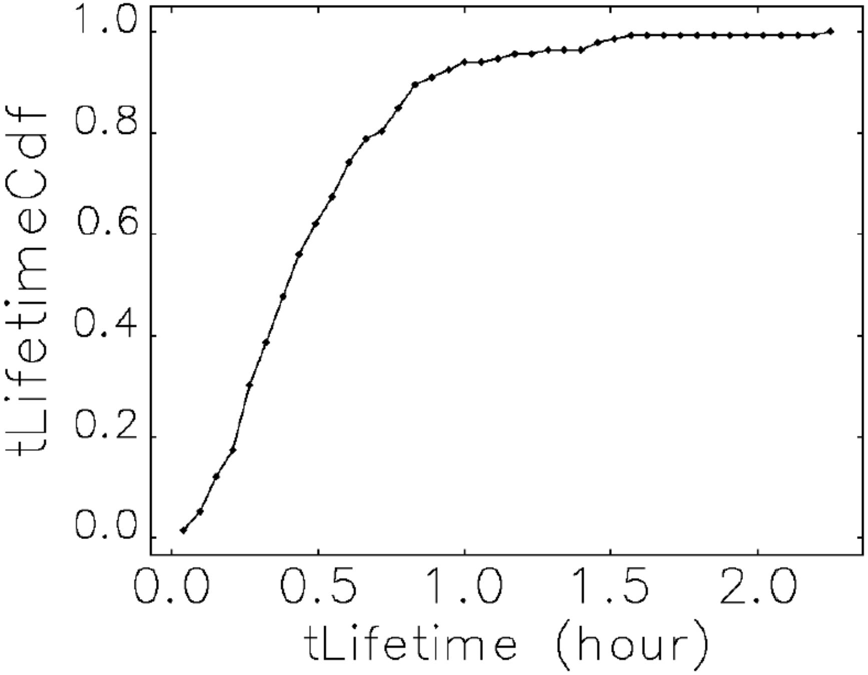
Girder misalignment	100 μm
Elements within girder	30 μm
Initial BPM offset errors	500 μm
Dipole fractional strength error	$1 \cdot 10^{-3}$
Quadrupole fractional strength error	$1 \cdot 10^{-3}$
Dipole tilt	$4 \cdot 10^{-4}$ rad
Quadrupole tilt	$4 \cdot 10^{-4}$ rad
Sextupole tilt	$4 \cdot 10^{-4}$ rad

These error levels appear readily achievable based on recent experience for NSLS-II

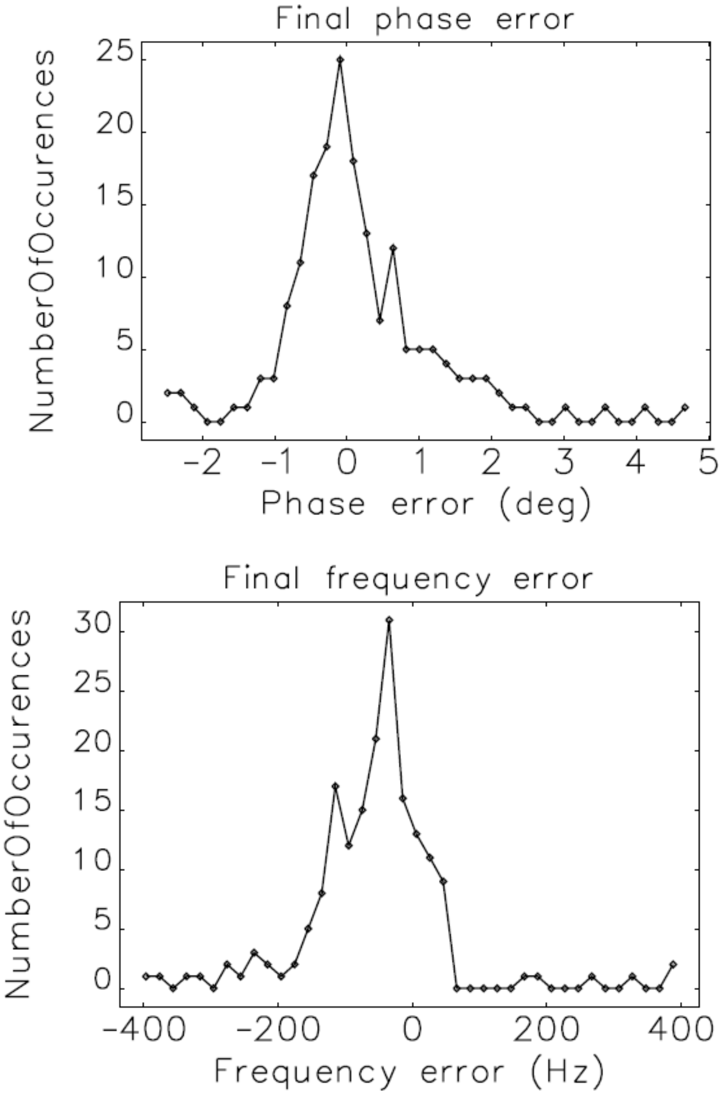
Commissioning simulation results

- Commissioning simulation is run for 200 error seeds
- Successful completion rate is ~98%

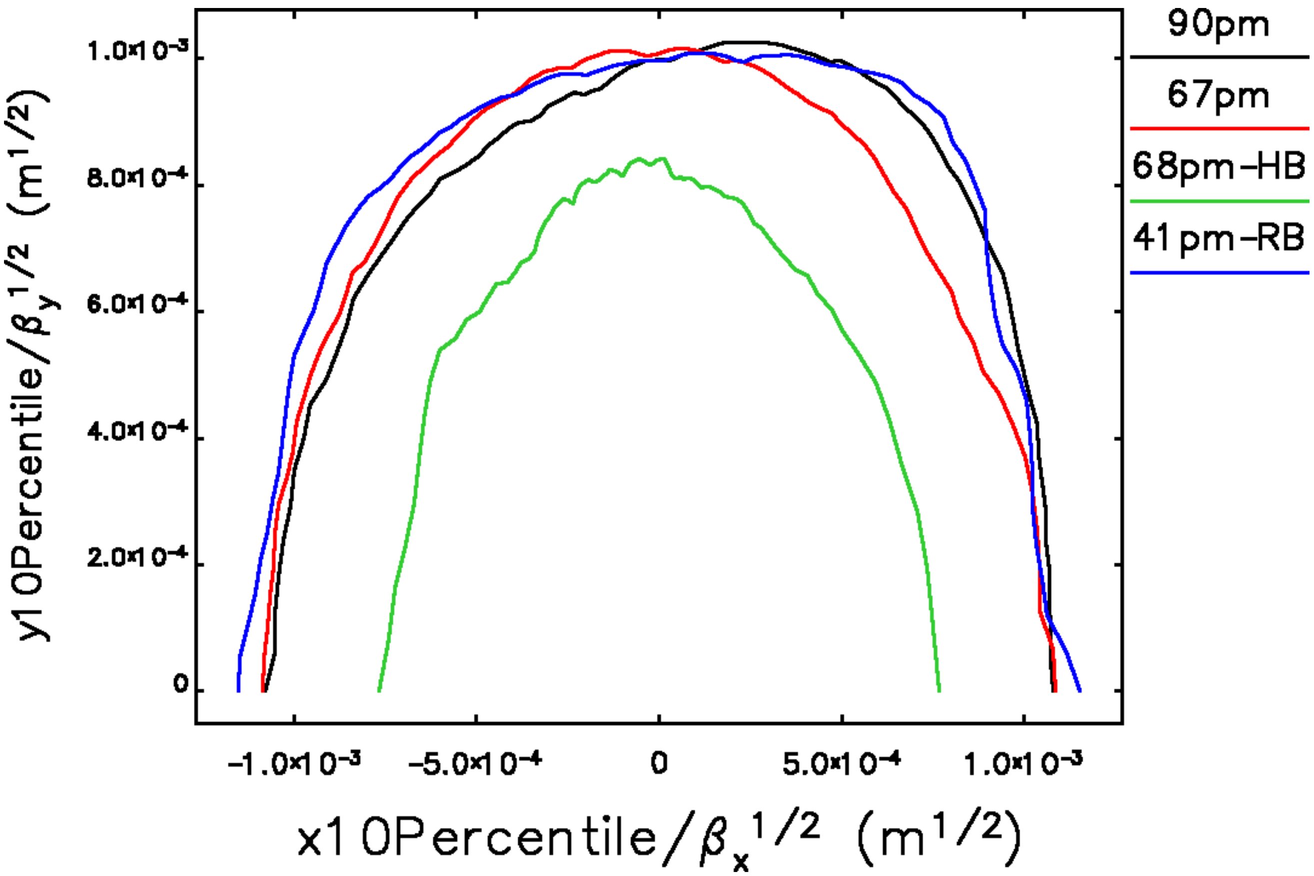
After initial lattice correction
(before BPM offset measurement)



After rf correction

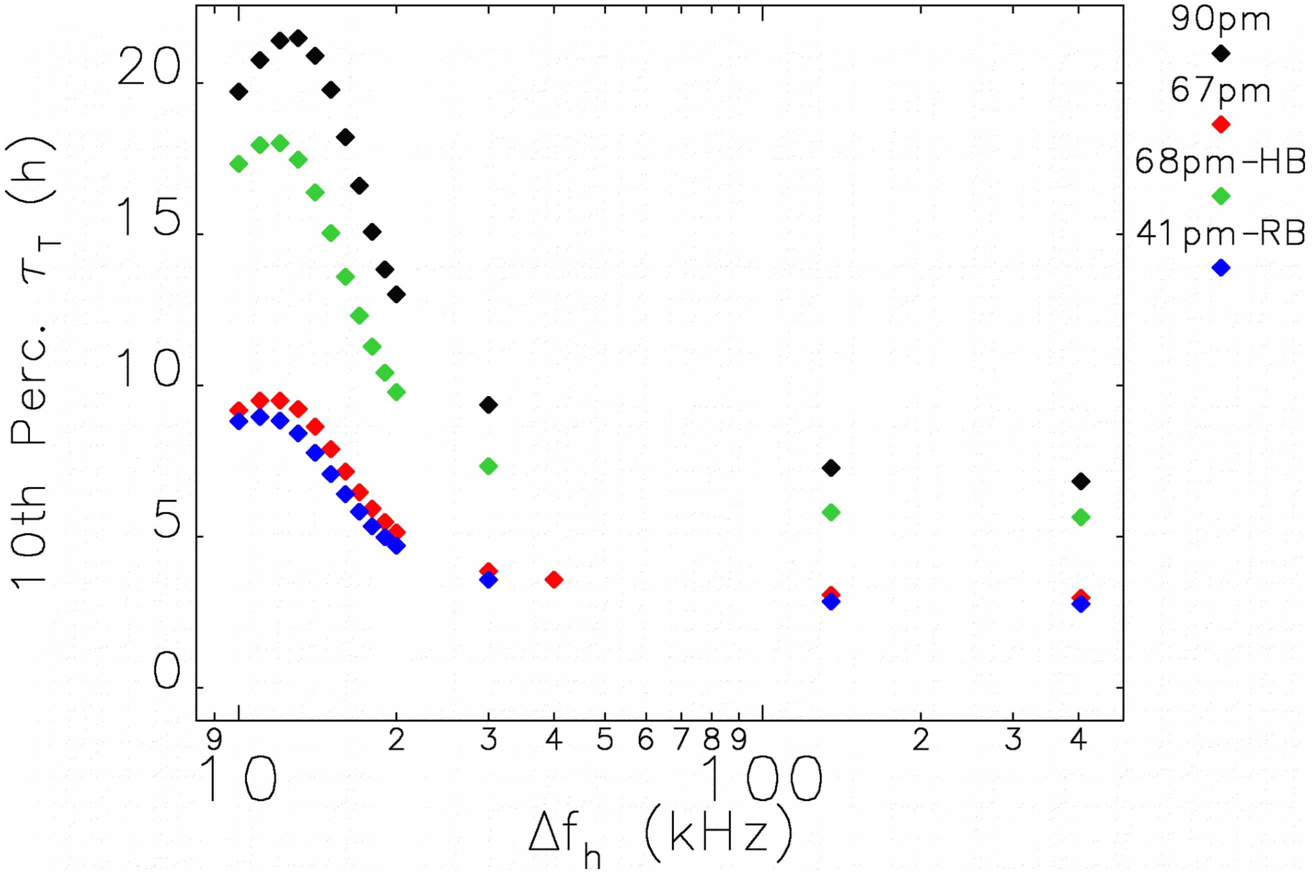


10^{th}-Percentile scaled dynamic acceptance comparison



- Curves are centered for easier comparison
- 68pm-HB lattice shows the worst performance
- Others are fairly similar

10th-Percentile Touschek lifetime for 200 mA in 324 bunches



- HHC improves lifetime about 3-fold
- 68pm-HB and 90pm lattice have much better Touschek lifetimes
- 67- and 41-pm lattices subsequently improved by ~60% at small expense to DA[1]

[1]: M. Borland et al., NAPAC16, WEPOB01.

Injection performance simulation[1]

1: A. Xiao, private communication.

- Booster beam: ε0=55 nm; σ_l = 50ps; $\Delta p/p_0$ =0.09%
- Use inflated injected beam size: εx – 80 nm; εy – 20 nm; σ_l - 100ps; $\Delta p/p_0$ – 0.12%, to include:
  - High charge effects
  - Various injection jitters
  - Optical function mismatch
- Simulate with 100 random sets of optical errors

Lattice	Ave. Beam Loss	Max Beam Loss	
67-pm	0.1%	3.7%	On-axis
41-pm RB	<0.1%	1.1%	
90-pm$^{(a)}$	0.45%	1.7%	Accumulation
90-pm$^{(b)}$	0.2%	2.8%	
68-pm HB$^{(b)}$	32.8%	61.1%	

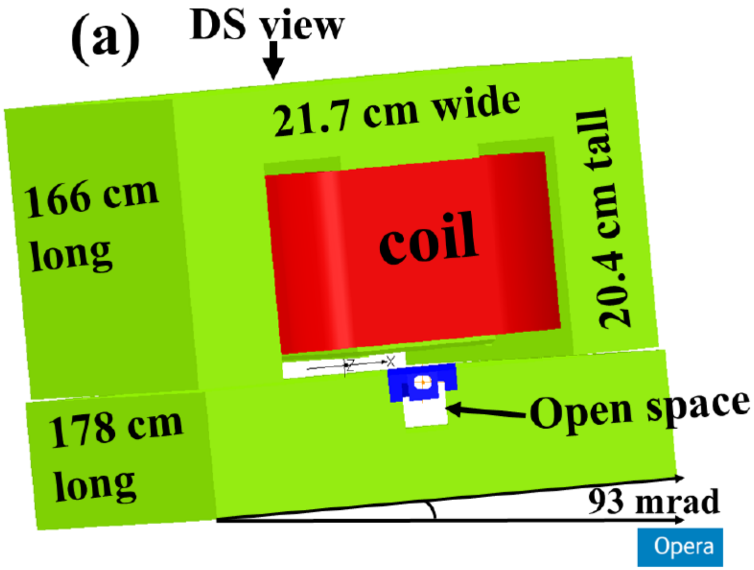
(a) With x-y emittance exchange at BTS line (ex=16nm, ey=60 nm)
(b) With fully coupled booster beam (ex=ey=40 nm)

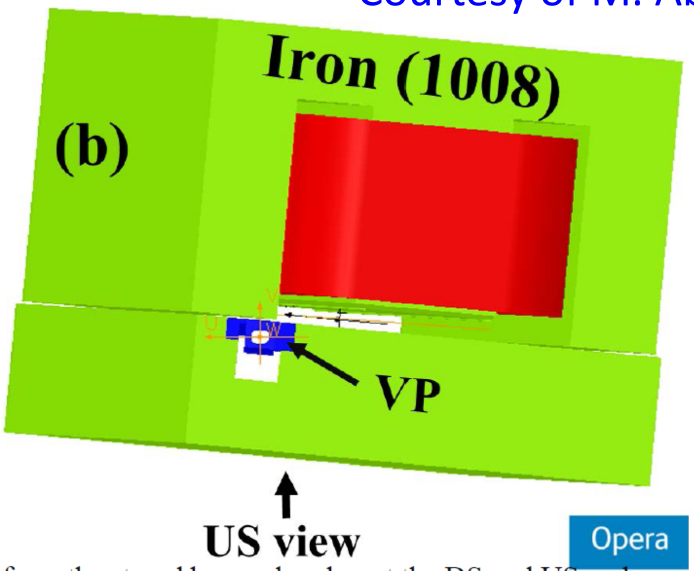
Development of Septum magnet[1]

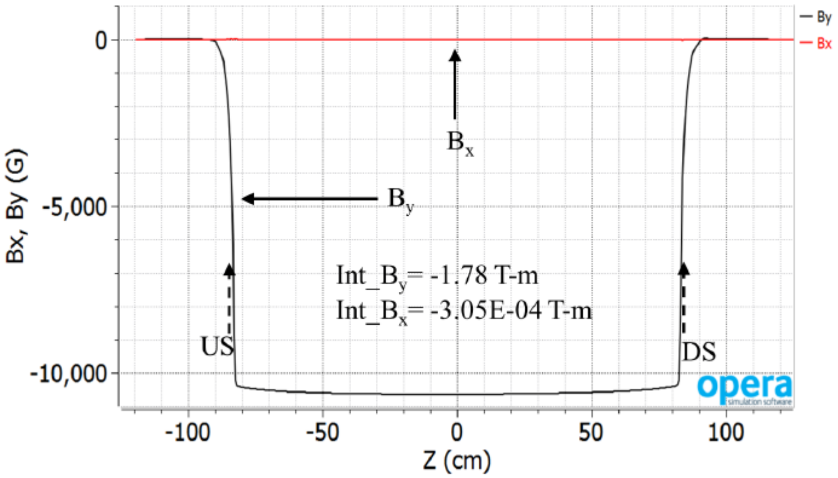
[1]: M. Abliz et al., THPOA63, NAPAC 2016

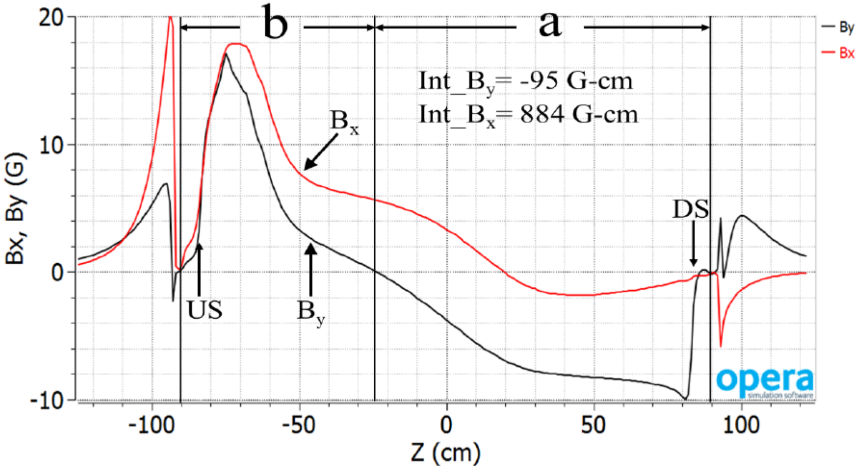
- 2 mm thick; average field 1 T; leakage field < 1000 G-cm (50 µrad)
- Design checked with tracking simulation

Courtesy of M. Abliz







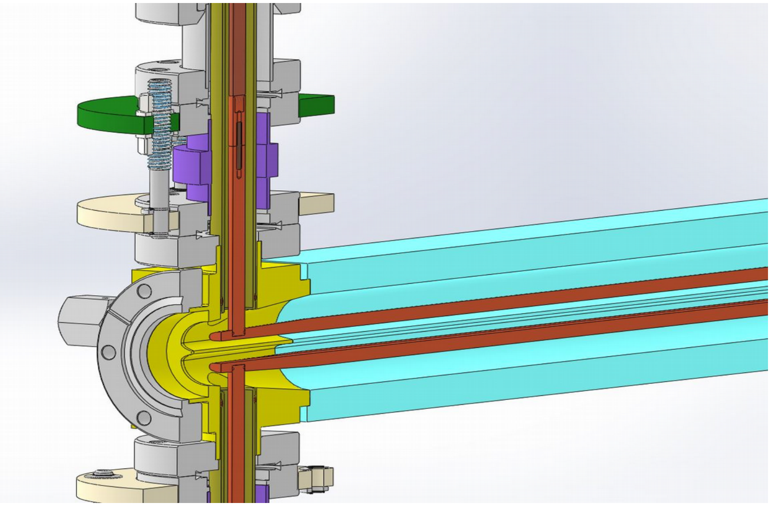


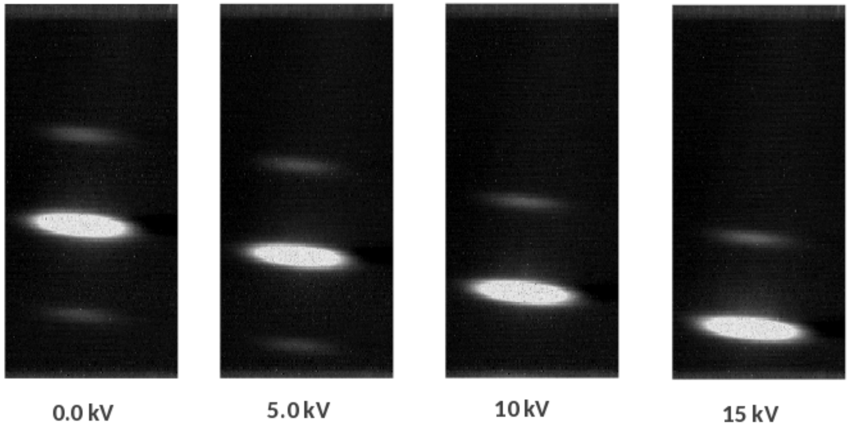
Development of Stripline kicker[1]

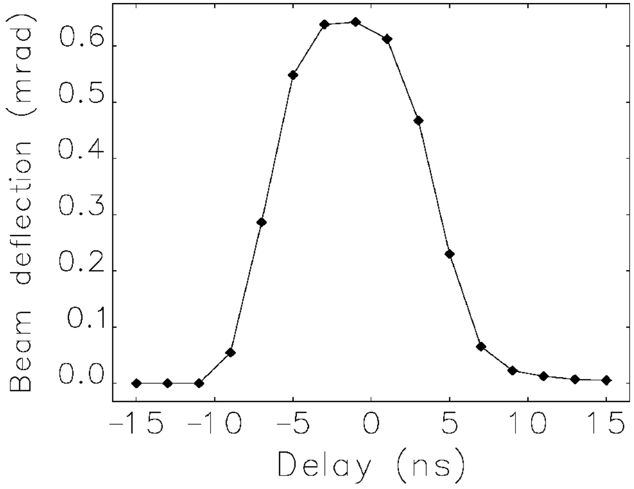
- 9 mm minimum gap; 1 mrad/m normalized kick angle
- 0.72 mrad @0.72 m
- Prototype installed to APS BTX line: 0.77 mrad at 15 kV; run up to 20 kV.

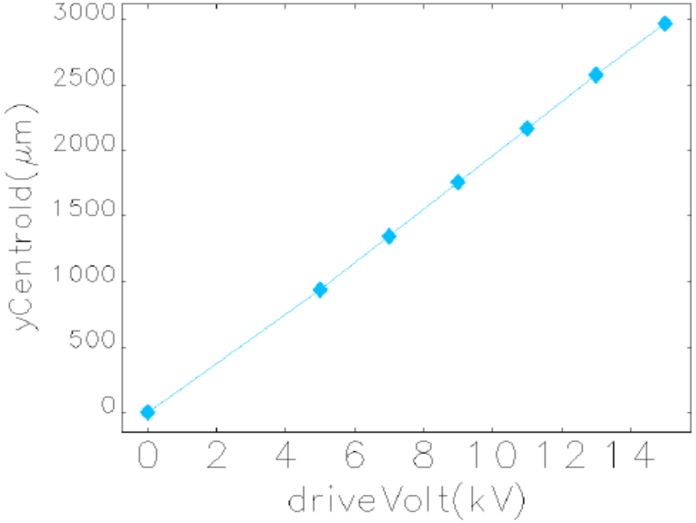
1: C. Yao et al., WEPOB24, NAPAC 2016

Courtesy of C. Yao









Beam loss and collimation[1]

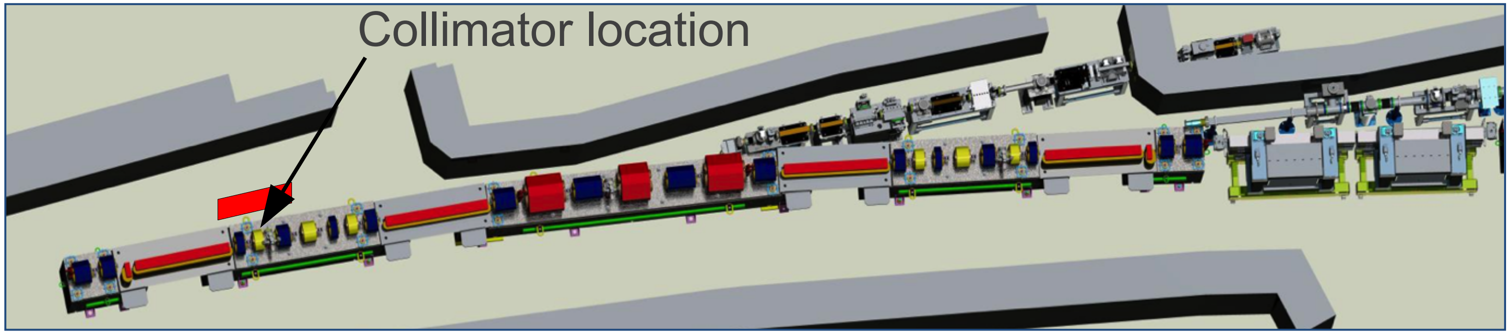
1: A. Xiao et al., WEPOB22, NAPAC 2016

- Injected beam loss
  - Loss Rate ~ 33 pA
    - Assuming 97% injection efficiency
    - Timing mode: injected bunch charge ~16.6 nC/shot at 15 s interval
  - Simulation study
    - Inflated injected beam size – accounting for effects of various jitters and injection errors
    - Uniform distributed particles associated with "weight" calculated from the Gaussian distribution – fast and accurate simulation
- Touschek beam loss
  - Loss rate ~ 102 pA - timing mode, average Touschek lifetime ~ 2h
  - Monte Carlo simulation – generate randomly scattered particles
- Gas scattering effect
  - Average lifetime: ~10h@100Ah to ~60h@1000 Ah
  - Loss rate: ~20 pA to 3 pA
  - No detail simulation yet
- Simulation study: two optical error sets from commissioning simulation
  - Case I – calculated Touschek lifetime 2.09 h
  - Case II – calculated Touschek lifetime 1.26 h

Aperture limitation and collimator configuration

- Nominal arc vacuum chamber: 11/11 mm radius (round)
- Nominal ID chamber: 10/3 mm radius (elliptical)
- Narrow ID chamber
  - Type I (8): 4/3 mm radius (n=6 super elliptical)
  - Type 2 (2): 4/4 mm radius (round)
- Collimators (6): size varies 4.7 mm – 5.7 mm
  - High dispersion, high beta area
  - 5 in zone F (no ratchet door for beamline front-end access, heavily shielded)
  - 1 in sector 20 (close to ratchet door)

Courtesy of B. Turner

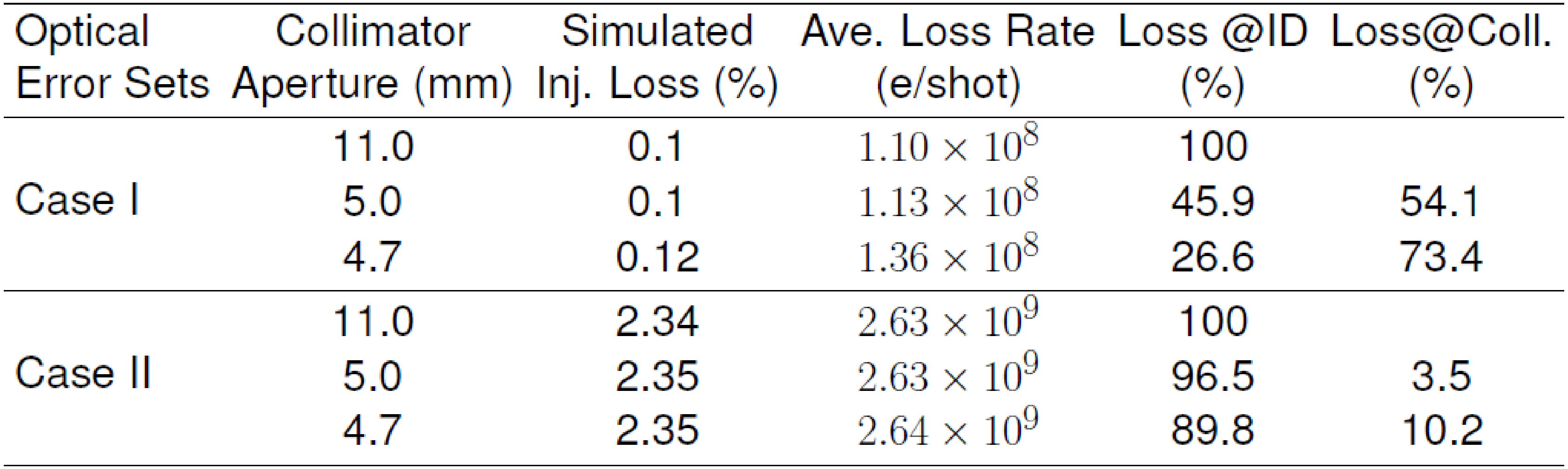


Summary of simulated Touschek lifetime and loss distribution

Optical Error Sets	Collimator Aperture (mm)	Calculated Lifetime (h)	Simulated Lifetime (h)	Losses @ID (%)	Losses @Collimator (%)	Losses @Other (%)
Case I	5.7	2.09	2.65	43.2	41.9	14.9
	5.4		2.65	27.1	63.1	9.8
	5.0		2.63	11.2	85.6	3.2
	4.7		2.61	4.0	93.4	2.6
Case II	5.7	1.26	1.16	48.7	35.2	16.1
	5.4		1.17	32.9	54.1	13.0
	5.0		1.17	14.2	79.1	6.7
	4.7		1.17	5.8	92.0	2.2

- Simulation shows up to ~30% difference between the calculated (hard edge MA) and simulated beam lifetime (fuzzy edge MA)
- Good collimation with 4.7 mm collimator size
- No obvious beam lifetime reduction

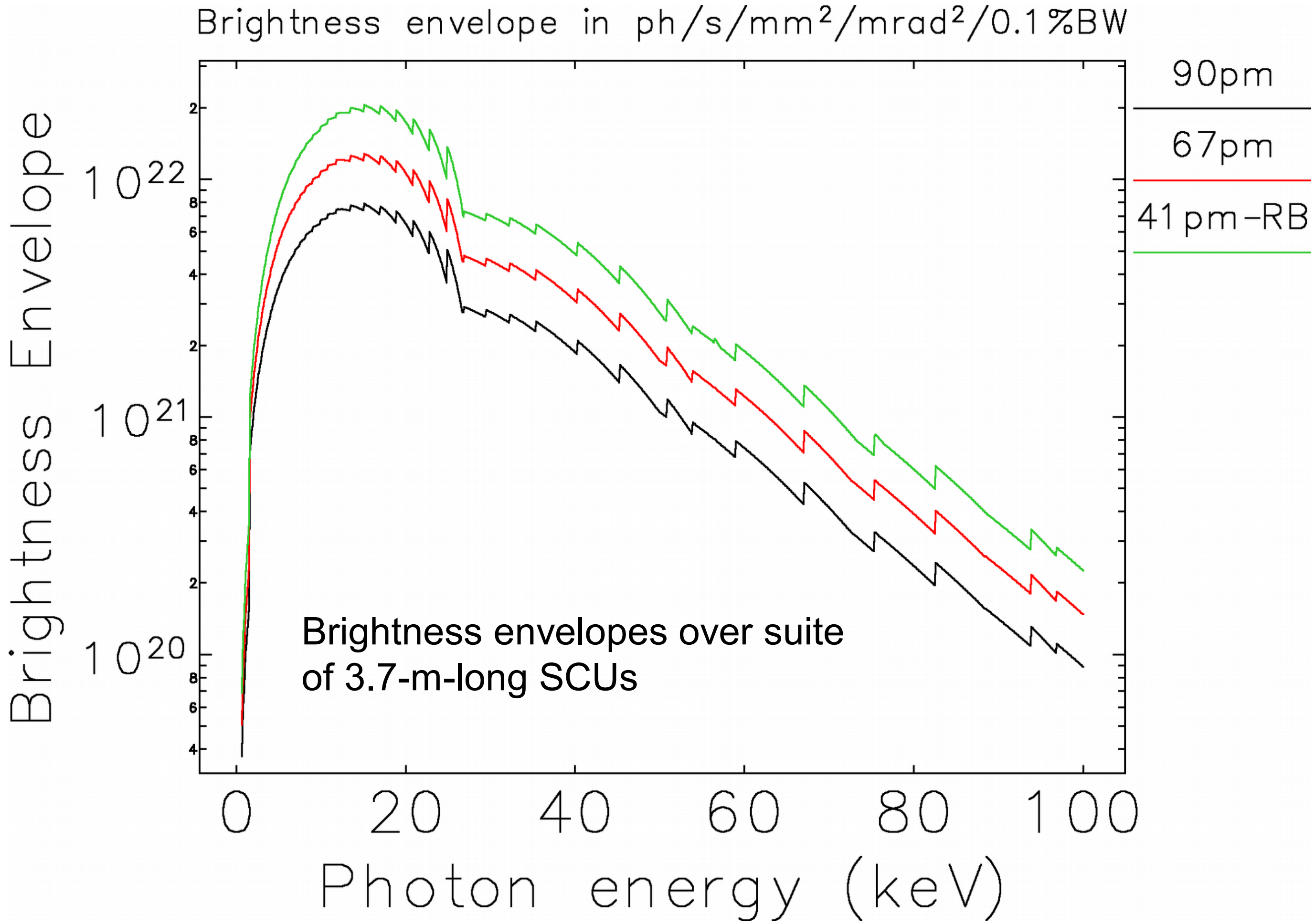
Summary of simulated injected beam loss distribution



Optical Error Sets	Collimator Aperture (mm)	Simulated Inj. Loss (%)	Ave. Loss Rate (e/shot)	Loss @ID (%)	Loss@Coll. (%)
Case I	11.0	0.1	1.10×10^8	100	
	5.0	0.1	1.13×10^8	45.9	54.1
	4.7	0.12	1.36×10^8	26.6	73.4
Case II	11.0	2.34	2.63×10^9	100	
	5.0	2.35	2.63×10^9	96.5	3.5
	4.7	2.35	2.64×10^9	89.8	10.2

- Injected beam loss has a very different signature than Touschek losses
  - Losses from large betatron oscillation rather than a large momentum error
- 4.7 mm collimator doesn't have significant impact to injection performance
- Proposed collimator configuration doesn't provide good shielding for the ID straights
- The collimation effect becomes even worse when the simulated injection efficiency is low (Case II)

Brightness comparison for 324 bunch mode



Brightness envelopes over suite of 3.7-m-long SCUs

- 67-pm lattice is ~60% brighter than 90-pm lattice
- 41-pm lattice provides additional ~60% gain
- A roughly 2-fold improvement is possible with flat beams (κ=0.1)

Lattice comparison with scores (subsets)

Goals and performances	90pm	67pm	68pm-HB	41pm-RB
Emittance under 70pm	1	2	2	3
4.8m for IDs	3	2	2	2
200 mA in as few as 48 bunches	2	2	2	2
Beam lifetime	3	2	3	2
X-ray brightness	1	2	2	3
On-axis injection efficiency	3	3	1	3
Single bunch limit for on-axis injection	3	2	2	2
Transverse FB effort (single-bunch)	3	3	3	2
Longitudinal FB effort (multi-bunch)	1	1	1	1

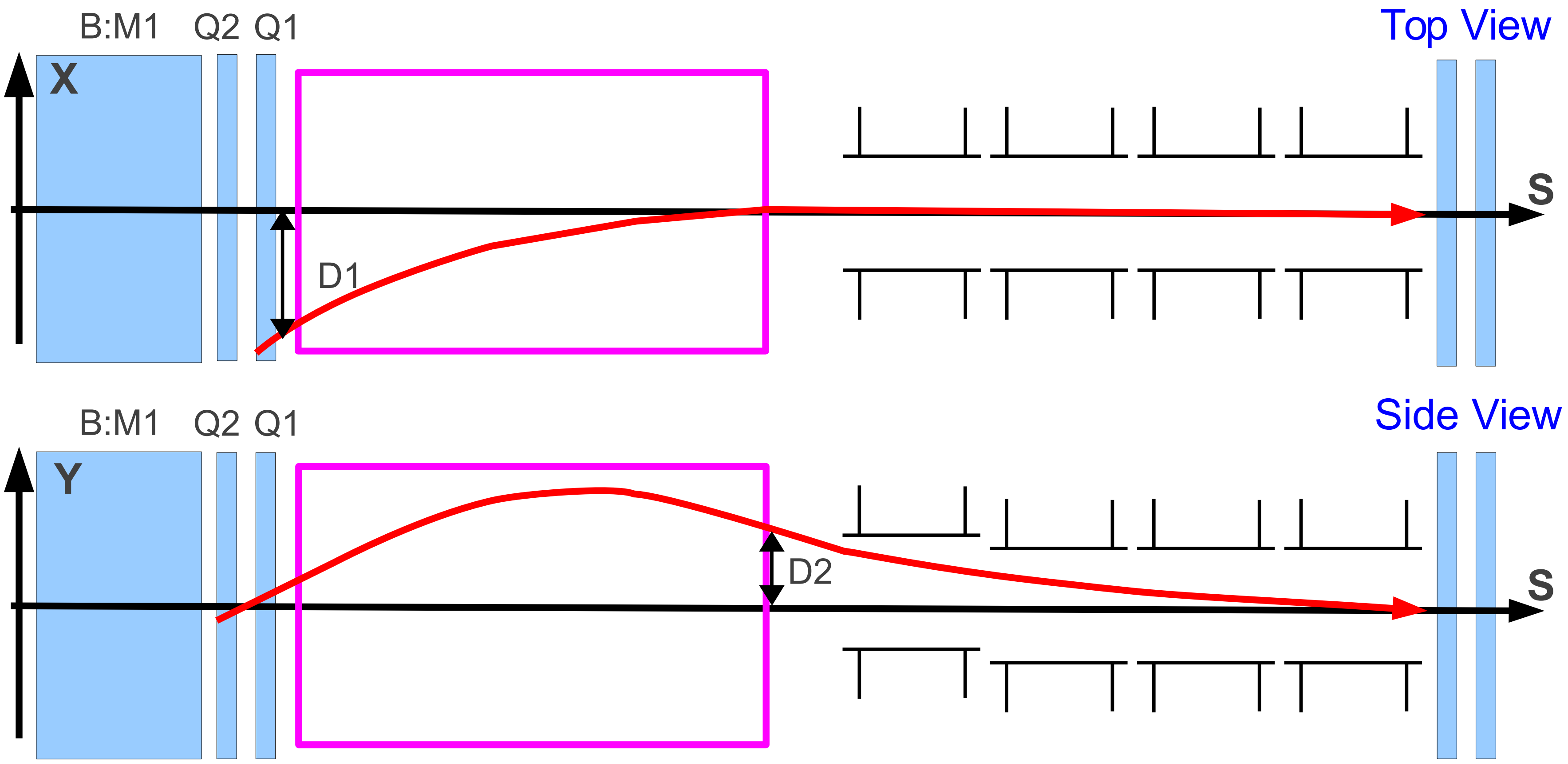
Commissioning and tolerances	90pm	67pm	68pm-HB	41pm-RB
First-turn trajectory correction	3	1	1	2
Orbit correction	3	2	2	2
Lattice correction	2	3	3	3
Corrector strengths	3	2	2	2
Noise sensitivity	3	2	2	1

Conclusions

- A lattice design has been developed that is consistent with engineering constraints and satisfies goals
  - ~100-fold increase in brightness for hard x-rays can be reached by both 67-pm and 41-pm reverse bend lattice
  - Scoring system is used for evaluation of candidate lattices
- Nonlinear dynamics evaluation shows lattices robust in the presence of errors, including commissioning simulation
- Injection is studied through
  - Detailed injection performance simulation including various errors
  - An innovative septum magnet design
  - A prototype of stripline kicker + FID pulser has been tested with beam
- Beam loss simulation and collimation system design is under the way
  - Results show a good collimation to Touschek beam loss without harming beam lifetime and injection efficiency
  - Injected beam loss depends on realistic machine errors and is difficult to collimate for small DA case
- Early version of H7BA lattice used file provided by ESRF
- Most of the simulations used the Blues cluster at Argonne's Laboratory Computing Resources Center

Thank you for your attention!

On-axis injection layout



- 🟦 Ring Magnet
- ▯ Lambertson (slightly tilt)
- — Stored Beam
- — Injected Beam
- ⊔ ⊓ Stripline Kickers

D1: beam separation at Q1: ~10 cm
D2: beam separation at septum: 5.5 mm