

# Update on APS-U MBA Lattice and Accelerator Physics



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Reporting for the APS-U MBA beam physics team

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# Outline

- Goals
- Lattice concept
- Choice of energy
- Collective effects: limitations and requirements
- Lattice design and evaluation
  - Nonlinear dynamics optimization
  - Errors and correction
  - Nonlinear dynamics evaluation
  - Injection and beam loss simulations
  - Bunch lengthening
  - Beam lifetime
- Predicted beam properties and operating parameters
- X-ray performance predictions
- Conclusions



# Lattice Design Goals

- Basic goal: practical hard x-ray source with lowest possible emittance
- Concrete goal:
  - ~100-fold brightness increase compared to APS today for 20 keV and above
  - Increased flux
- Scaling to APS parameters (40 sectors and 6 GeV) from...
  - MAX-IV<sup>1</sup> lattice implies 160 pm
  - SIRIUS<sup>2</sup> lattice implies 140 pm
  - ESRF-II<sup>3</sup> lattice implies 73 pm
- Other goals
  - Support 200 mA in as few as 48 bunches
  - Use existing injector
  - Beam lifetime of >7.5 hours
  - 4.8-m space for IDs
  - 19.5 keV critical energy for BMs

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

Beam energy

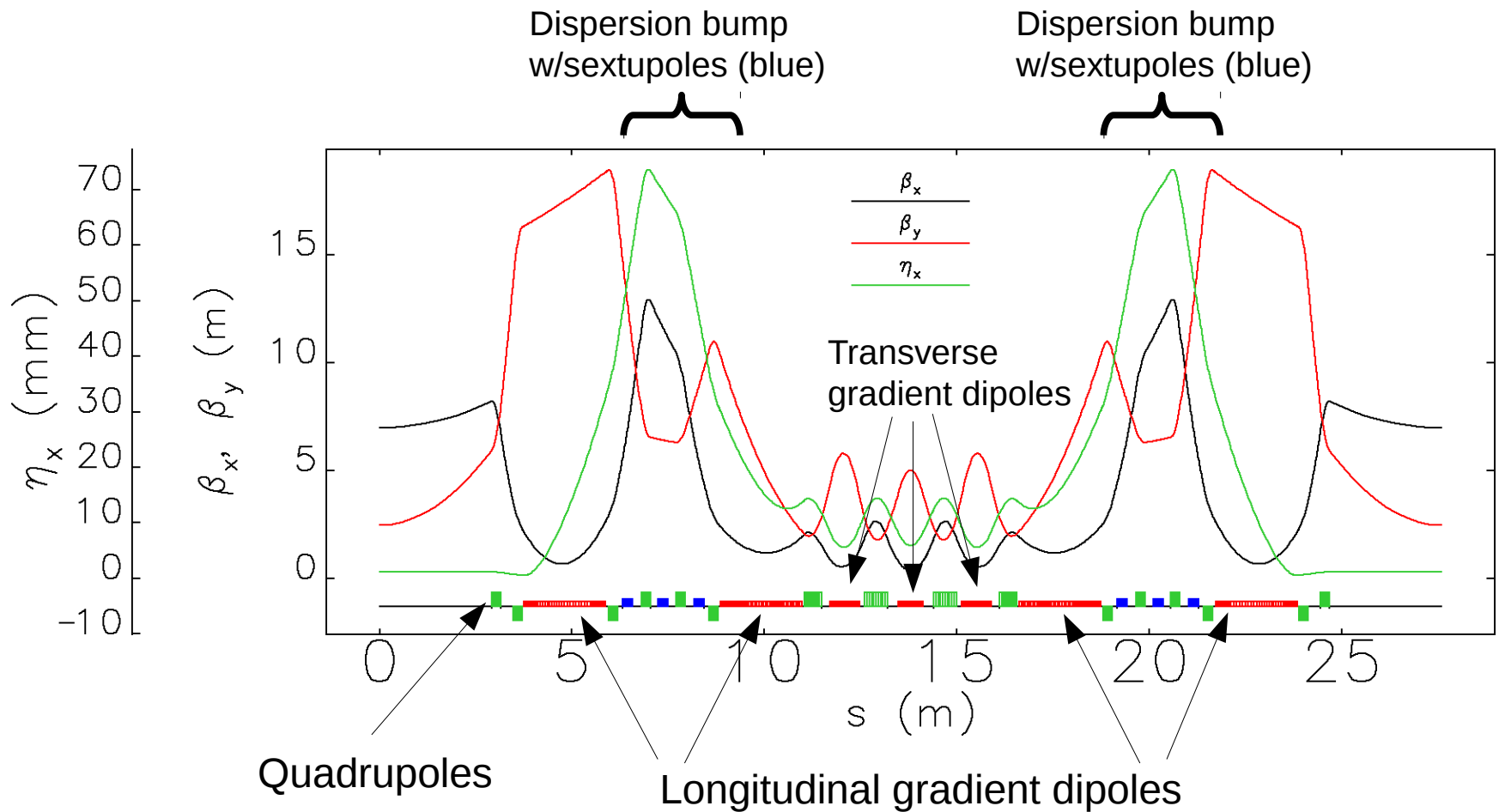
Number of sectors

J. Murphy, BNL-42333.  
See also M. Borland, <http://goo.gl/y6agiA>.

1: S. Leemann *et al.*, PRSTAB 120701 (2009).  
2: L. Liu *et al.*, IPAC13, 1874.  
3: L. Farvacque *et al.*, IPAC13, 79.



# Hybrid 7BA Lattice Concept<sup>1</sup>

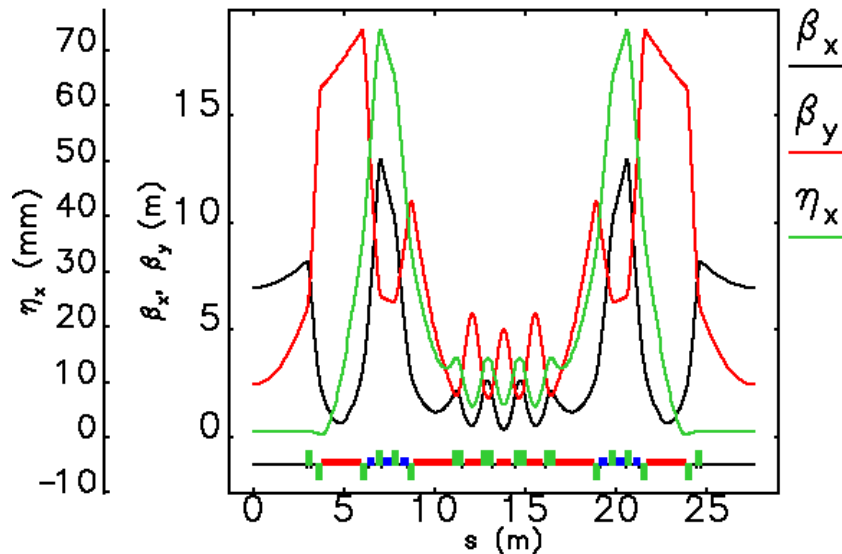
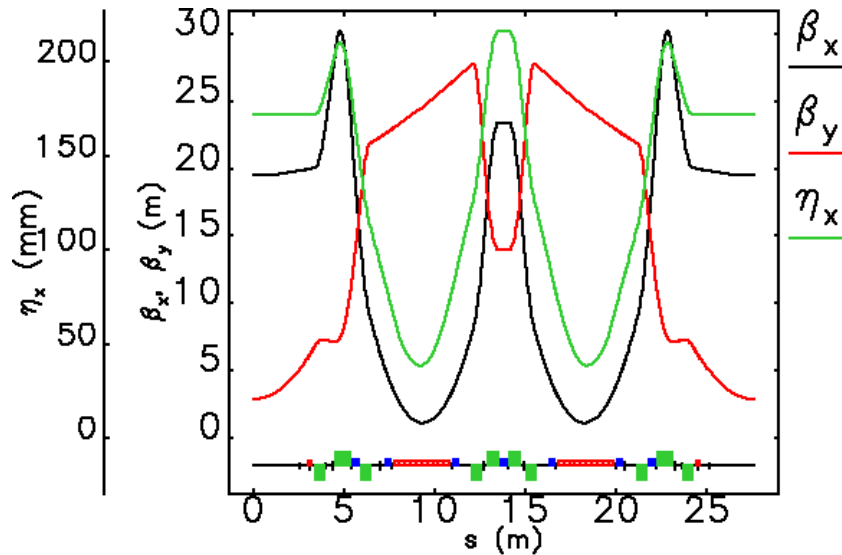


- Phase advance of  $\Delta\phi_x = 3\pi$  and  $\Delta\phi_y = \pi$  between corresponding sextupoles chosen to cancel geometrical sextupole kicks
- Thick, interleaved sextupoles  $\rightarrow$  cancellation isn't perfect

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



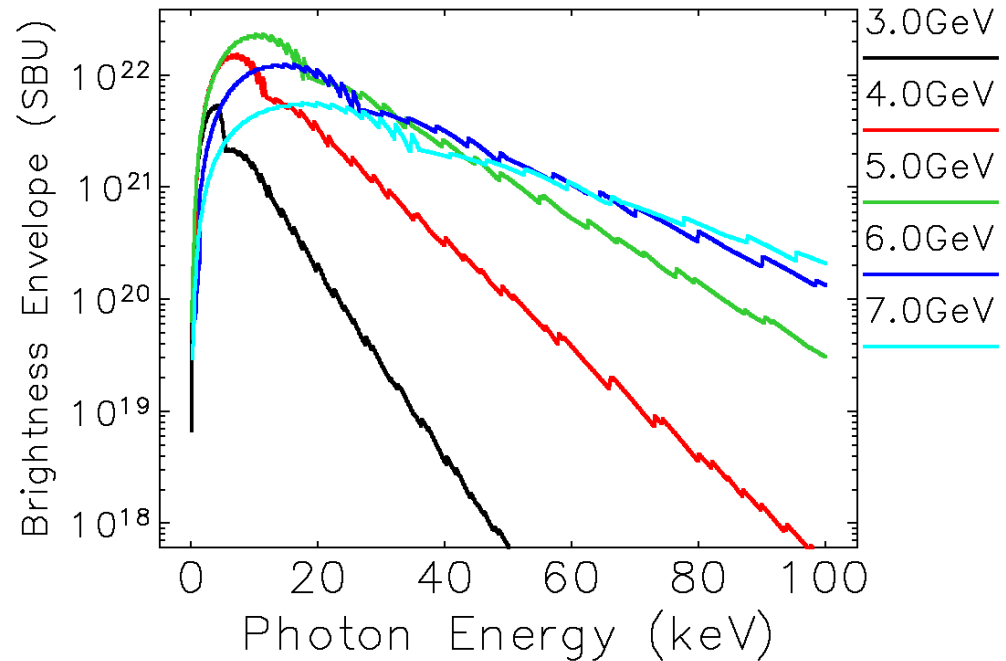
# Lattice Properties Compared to APS Today



	APS	MBA	
<b>Betatron motion</b>			
$\nu_x$	36.205	95.125	
$\nu_y$	19.272	36.122	
$\xi_{x,nat}$	-90.340	-138.580	
$\xi_{y,nat}$	-43.319	-108.477	
<b>Lattice functions</b>			
Maximum $\beta_x$	30.2	12.9	m
Maximum $\beta_y$	27.8	18.9	m
Maximum $\eta_x$	0.216	0.074	m
Average $\beta_x$	13.2	4.2	m
Average $\beta_y$	15.9	7.8	m
Average $\eta_x$	0.148	0.028	m
<b>Radiation-integral-related quantities</b>			
Beam energy	7	6	GeV
Natural emittance	2527.5	66.9	pm
Energy spread	0.095	0.096	%
Horizontal damping time	9.7	12.1	ms
Vertical damping time	9.7	19.5	ms
Longitudinal damping time	4.8	14.1	ms
Energy loss per turn	5.34	2.27	MeV
<b>ID Straight Sections</b>			
$\beta_x$	19.5	7.0	m
$\eta_x$	171.88	1.11	mm
$\beta_y$	2.9	2.4	m
$\epsilon_{x,eff}$	3142.7	67.0	pm
<b>Miscellaneous parameters</b>			
Momentum compaction	$2.84 \times 10^{-4}$	$5.66 \times 10^{-5}$	
Damping partition $J_x$	1.00	1.61	
Damping partition $J_y$	1.00	1.00	
Damping partition $J_\delta$	2.00	1.39	

# Choice of Beam Energy

- The question of beam energy is complex
  - E.g., Lower energy → lower natural emittance, higher average current, and easier magnets, but increased intrabeam scattering, shorter lifetime, lower single-bunch current, and more difficult undulators for hard x-rays
- We studied scaling of the nominal APS-U lattice including rf-power-limited beam current
  - Minimum emittance and energy spread (IBS included) between 4.5-5.5 GeV
  - For 324-bunch mode, ~2-fold increase in Touschek lifetime at 6 GeV vs 5 GeV
  - 5-6 GeV optimum for brightness
- 6 GeV is our working energy
  - Better hard x-ray performance
  - Longer lifetime
  - Higher single-bunch current



3.7-m long SCUs, 9mm magnetic gap, and HHL front ends.  $SBU = \text{ph/s/mm}^2/\text{mrad}^2/0.1\%BW$



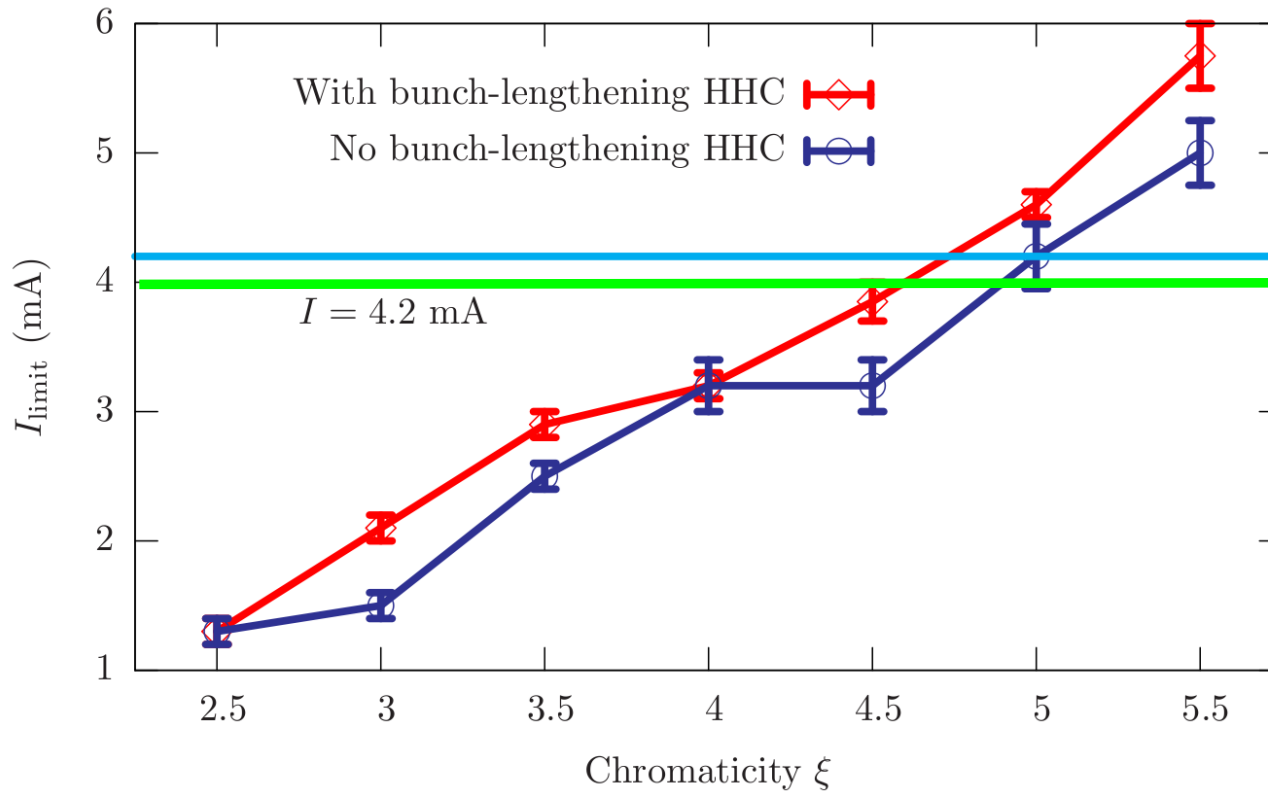
# Collective effects in storage rings

- Impedances/wakefields characterize how electrons interact in the ring
  - Geometric wakefields are generated by changes in the vacuum chamber cross section
  - Resistive wall wakefield is due to the finite conductivity of chamber walls
- Wakefields give rise to collective phenomena that can lead to rf heating of the vacuum chamber, changes in the electron beam distribution, and instabilities/beam loss
- Limitations imposed by collective effects can be simulated
  - Wakes computed by EM codes, e.g., GdfidL, ECHO2D
  - Track particles to determine stability limits with **elegant**

	<b>Short-term wakefields (single bunch, one turn)</b>	<b>Long-term wakefields (all bunches, many turns)</b>
<b>Longitudinal</b>	Heating of vacuum chamber Bunch lengthening Microwave instability	Heating of cavities Multi-bunch instability
<b>Transverse</b>	Source of orbit change Tune shift Transverse instabilities	Heating of cavities Multi-bunch instability



# Predicted single bunch limit vs chromaticity

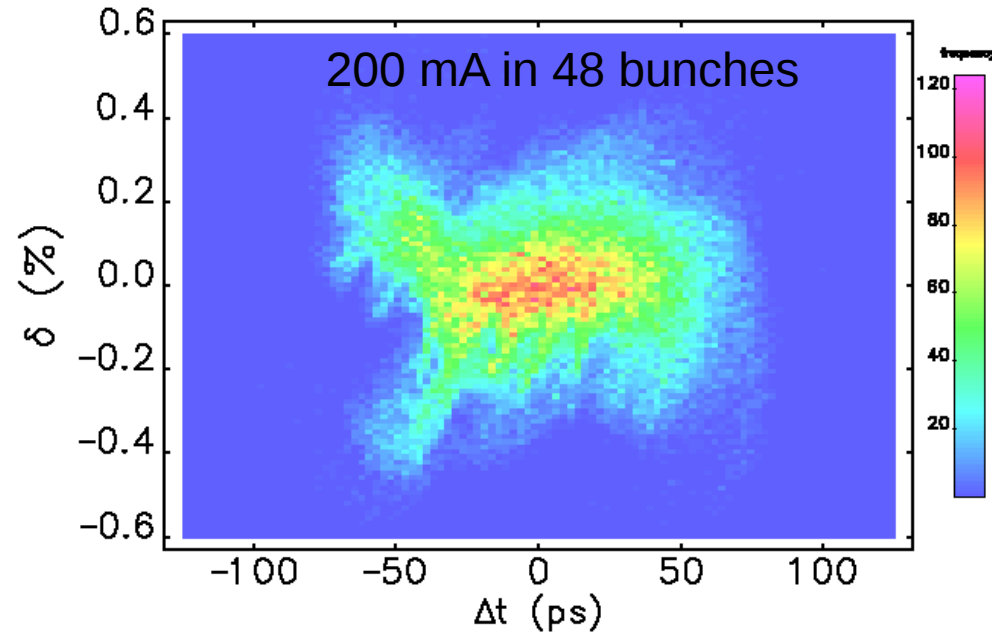


Chromaticity determines the spread in transverse oscillation frequency due to beam energy spread.

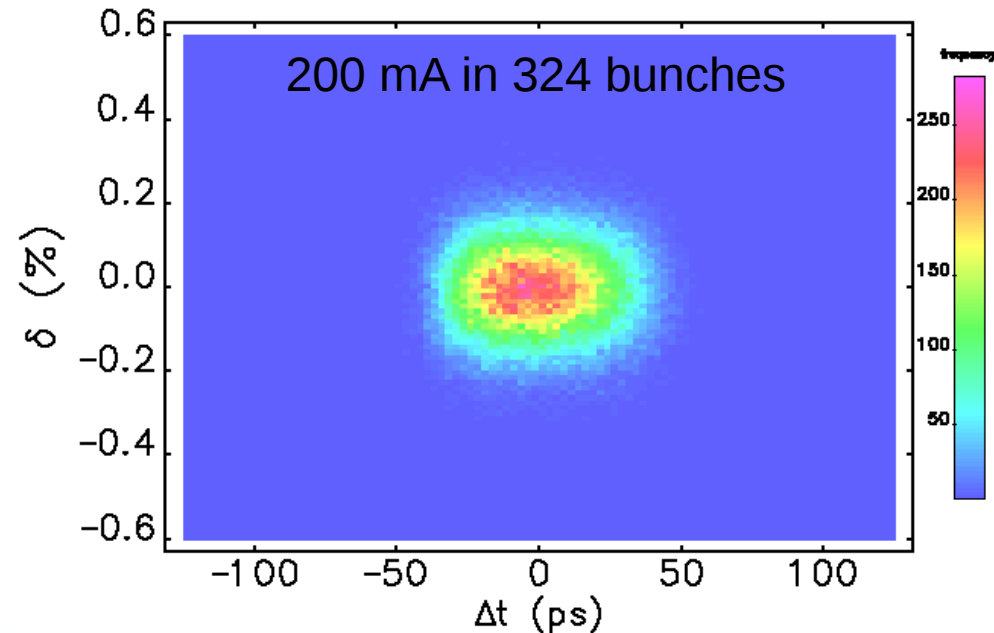
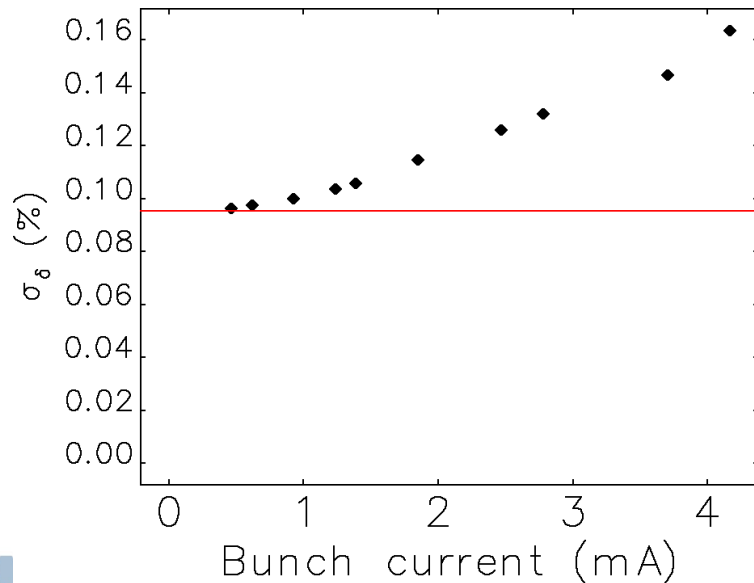
- 4.2 mA operation is possible if the chromaticity  $\xi \geq 5$  units
- There is not much headroom for uncertainties in design and in modeling
  - Look for ways to reduce impedance and increase margin.
  - Study including transverse feedback next on agenda.
  - Higher chromaticity lattices also under development.



# Longitudinal phase space impacted by impedance

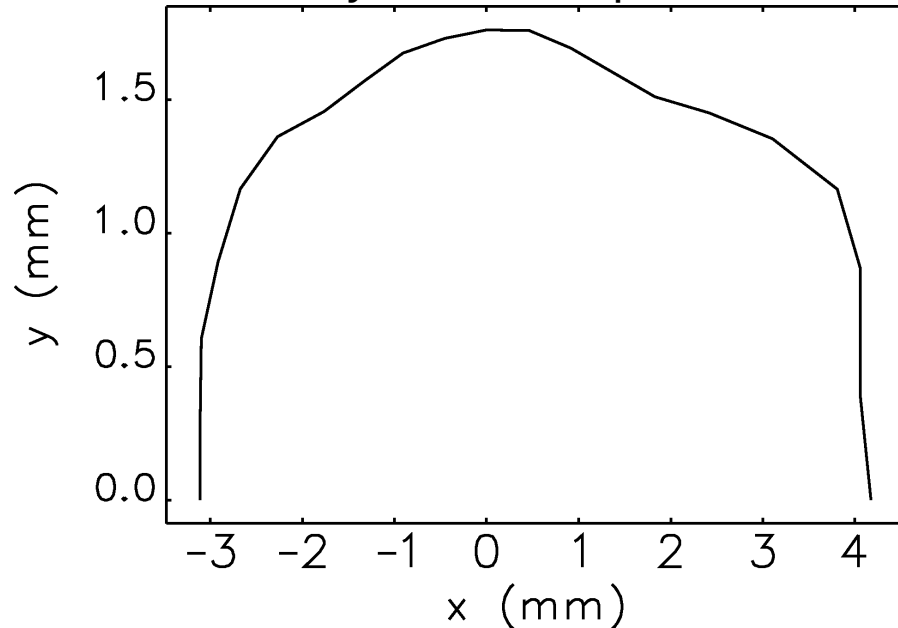


- Even when bunch is not lost, the impedance can have an effect
- The “microwave instability” stirs up the longitudinal phase space
- The threshold is at  $\sim 0.5$  mA/bunch
  - In APS, threshold is  $\sim 7$  mA/bunch
- Increased energy spread has a small impact on brightness

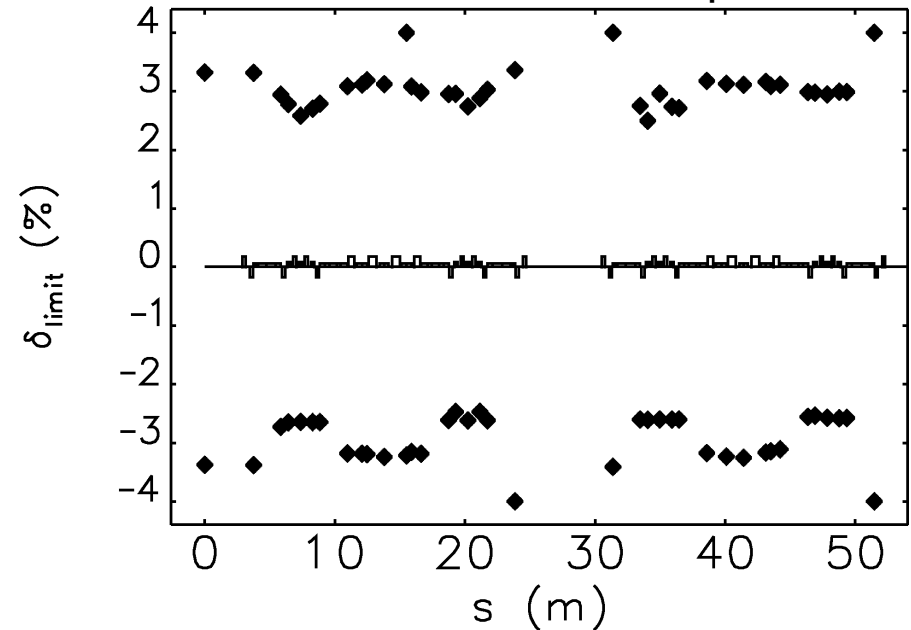


# Optimized Nonlinear Dynamics for $\xi=5$

Dynamic acceptance



Local momentum acceptance



- DA is area available for beam injection, determines elastic gas scattering lifetime
  - Comfortably exceeds  $\pm 2\text{mm}$  by  $\pm 0.6\text{mm}$  minimum requirement
  - For comparison, present APS DA is  $\sim 5\text{x}$  larger horizontally
- LMA shows extreme stable momentum kicks, determines Touschek and gas-bremsstrahlung lifetimes
  - LMA is comparable to present APS
  - Consistent with  $\sim 10\text{ h}$  Touschek lifetime in 324 bunch mode

# Magnet parameters compared to APS now

Magnet type	APS today		APS MBA	
	Maximum strength	Number	Maximum strength	Number
Pure dipole	0.6 T	80	-	0
Longitudinal gradient dipole	-	0	0.64 T	160
Transverse gradient dipole	-	0	0.6 T, 47 T/m	120
Quadrupole	21 T/m	400	82 T/m	640
Sextupole	730 T/m <sup>2</sup>	280	5600 T/m <sup>2</sup>	240
Skew quadrupoles (old/new)	0.36 T/ 0.41 T	20/40	0.25 T	160
DC steering per plane	~ 1150 $\mu$ rad	320	~ 300 $\mu$ rad	320
AC steering per plane	~ 770 $\mu$ rad	40	TBD	320

- Apertures must be much smaller to achieve needed strength
  - 80 mm bore diameter → 26 mm
- The number of magnets and power supplies is higher
  - Magnet cores: 1080 → 1320
  - Power supplies: 1344 → 2242

Thanks to L. Emery and J. Wang for some of these numbers.



# Commissioning Simulation

- 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

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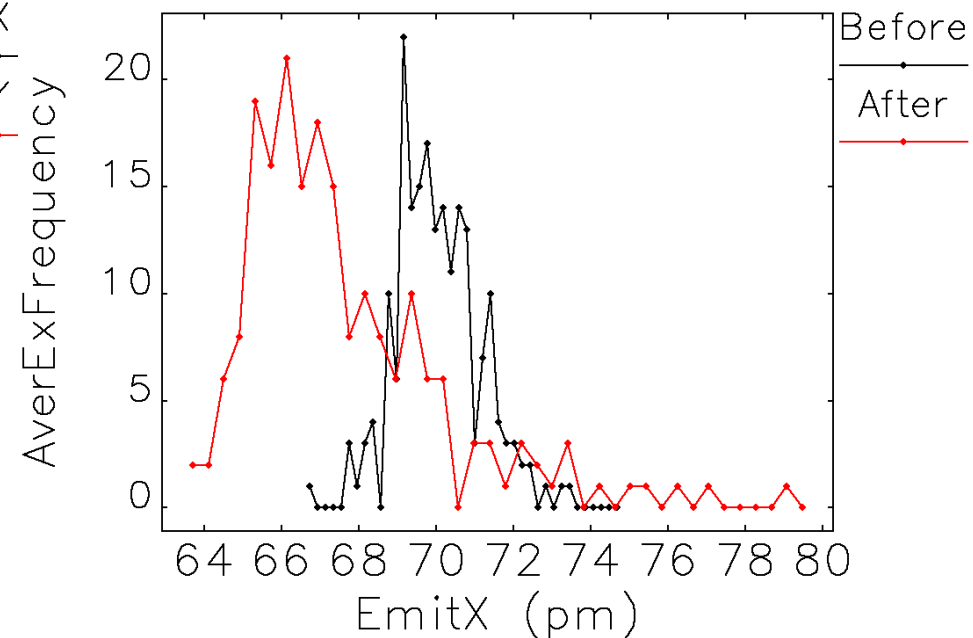
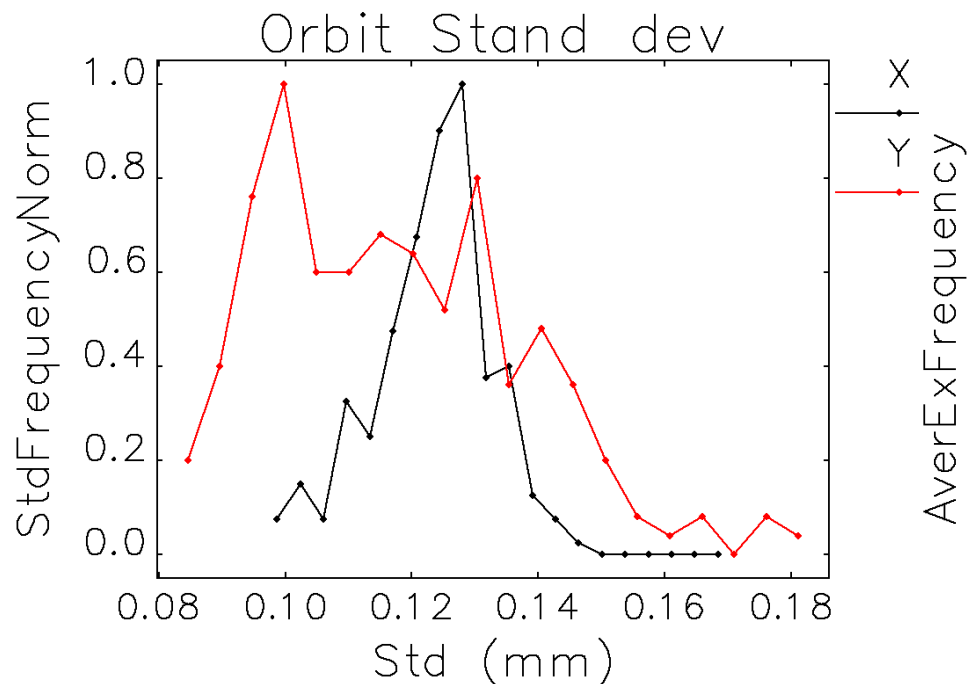
Girder misalignment	100 $\mu\text{m}$
Elements within girder	30 $\mu\text{m}$
Initial BPM offset errors	500 $\mu\text{m}$
Dipole fractional strength error	$1 \cdot 10^{-3}$
Quadrupole fractional strength error	$1 \cdot 10^{-3}$
Dipole tilt	$4 \cdot 10^{-4}$ rad
Quadrupole tilt	$4 \cdot 10^{-4}$ rad
Sextupole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

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

# Simulation results

- Procedure successfully completed in more than 98% of 200 cases
- Simulations indicate that small emittance is achievable
- Validates arrangement of BPMs and steering magnets, gives strength requirements for orbit correction
- Validates arrangement of skew quadrupoles and gives strength requirements for coupling correction
- Resulting configurations are used for nonlinear dynamics evaluation

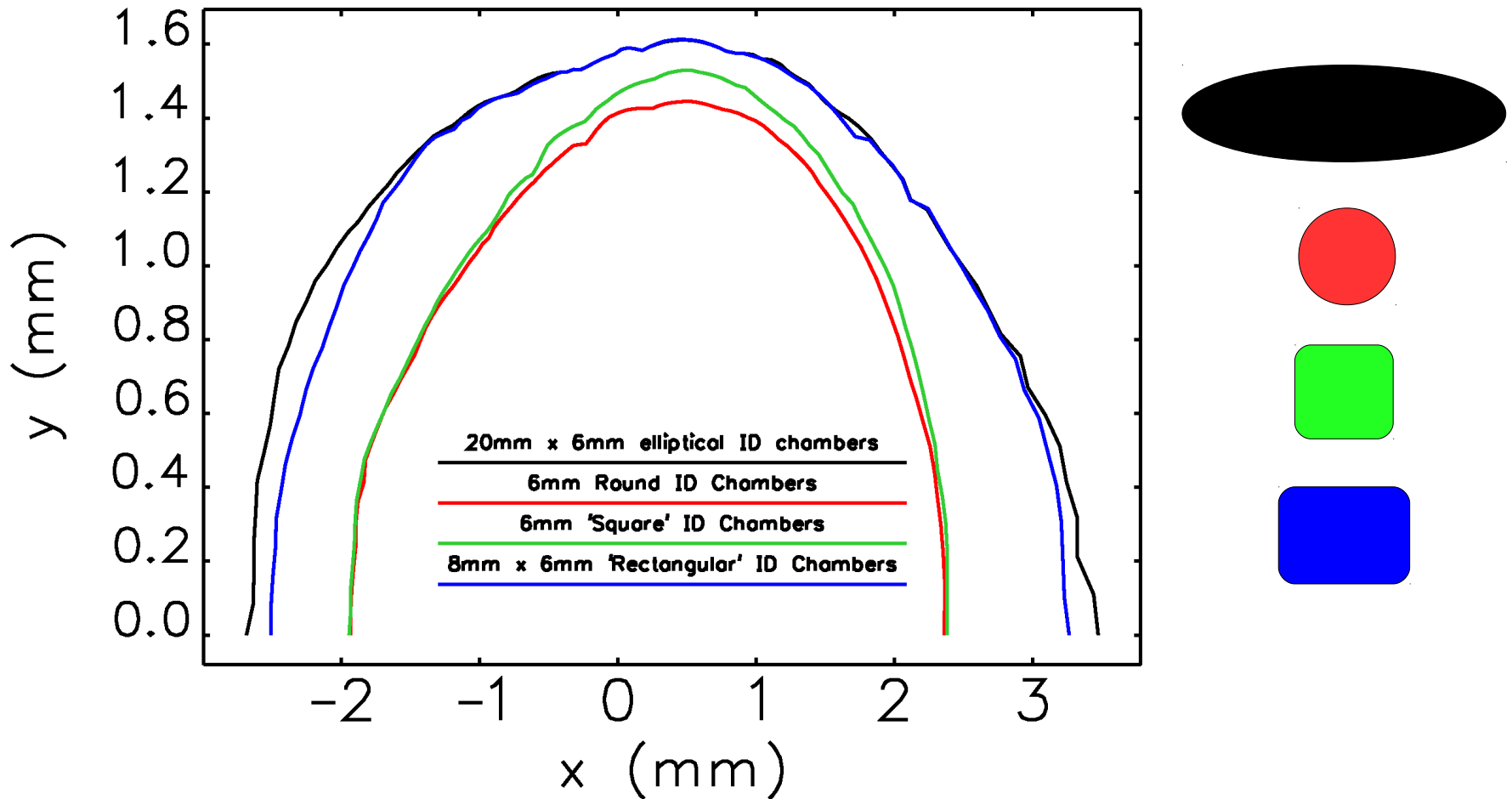


# Nonlinear Dynamics Evaluation

- Basic goal: test robustness of DA and LMA under various error ensembles
- Used 100 error ensembles from the commissioning simulation
  - These have most of the random errors we expect to encounter
- Multipole errors (imperfections in field patterns) need to be added
  - Systematic or allowed multipoles
    - These result from the finite width or non-ideal shape of the magnet poles
    - Data provided by magnetic modeling
  - Random or unallowed multipoles
    - These result from imperfections in machining, assembly, etc.
    - Data based on scaling NSLS-II measurements or theory
- We've also explored effects of
  - Insertion devices
  - Alternatives for ID apertures

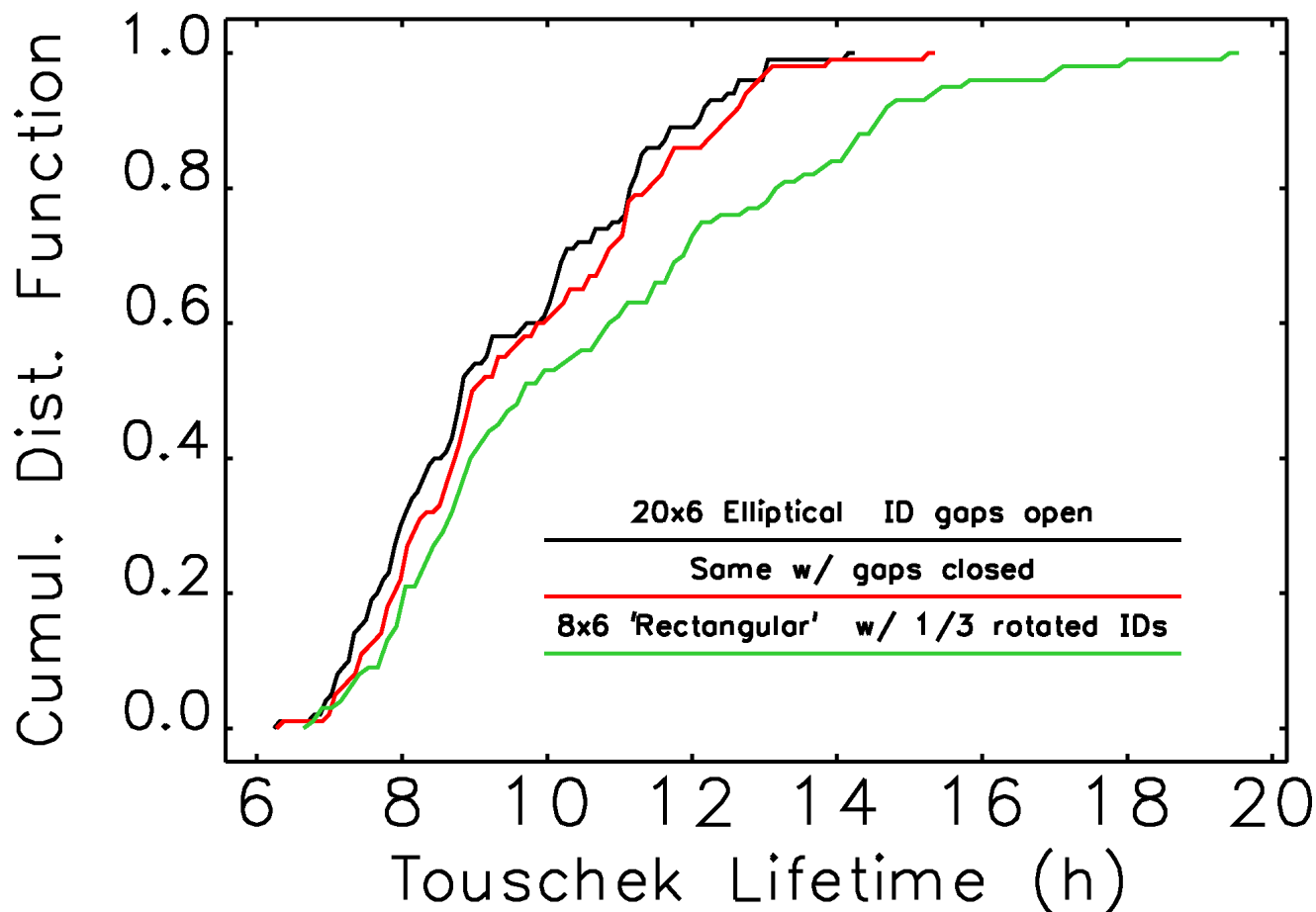


# 10<sup>th</sup>-Percentile DA w/ID Chambers



- Round 6 mm (ID) chambers in IDs have a significant impact
- Super-elliptical (n=6) 8mm x 6mm chambers have almost none
- No significant impact on lifetime in either case

# Lifetime Distribution with IDs



Results for 324 bunch, 200 mA, round beams with 50-ps rms bunch duration.

Use ID kickmaps from six types of APS and NSLS-II IDs

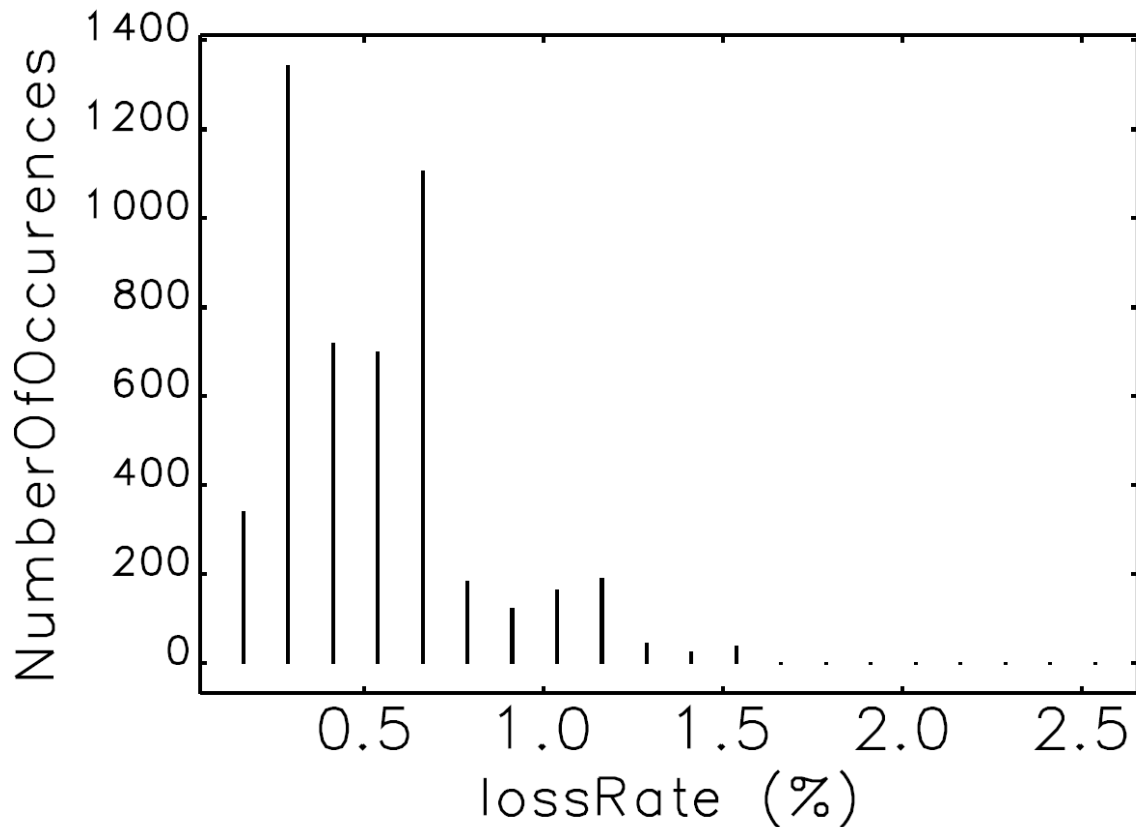
72, 2.4-m-long IDs included

- Horizontally-deflecting IDs have a small positive effect on lifetime
- Vertically-deflecting IDs have a clear positive effect
  - May be a clue to improving the lattice
- No significant impact on DA from IDs



# Injection Efficiency Simulations

- DA appears robust, but need to perform more literal simulations of injection
  - 100 static optical and multipole error ensembles, as above
  - Realistic beam distribution from booster, with optical errors
  - Injection trajectory errors and pulsed power supply jitter



This simulation uses the worst case from the 100 optical error ensembles, then adds BTS errors and jitter.

Even so, the expected loss rates are small.

Simulation by A. Xiao, ASD.

# Emittance Ratio

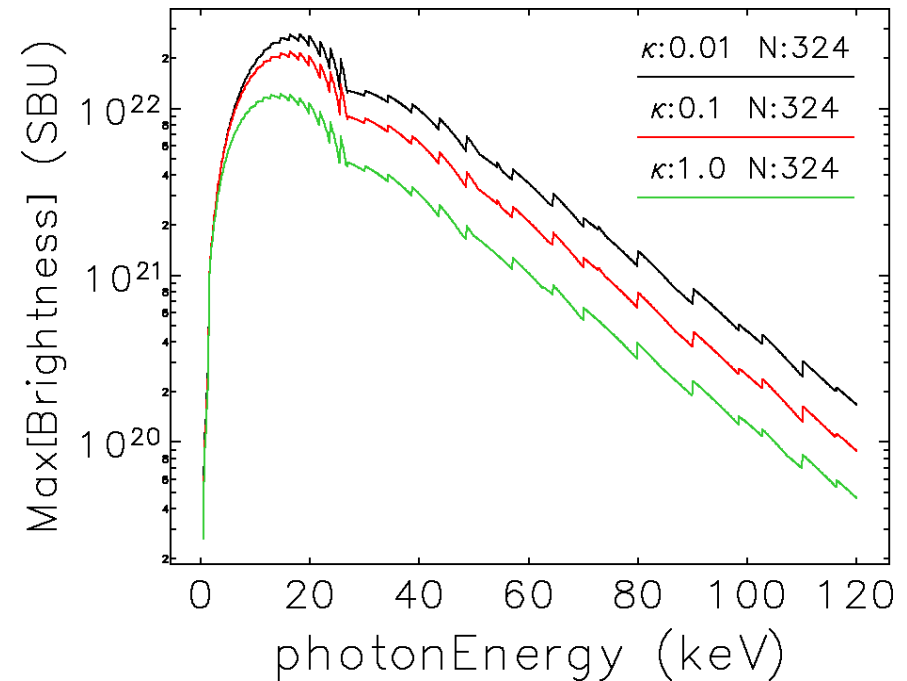
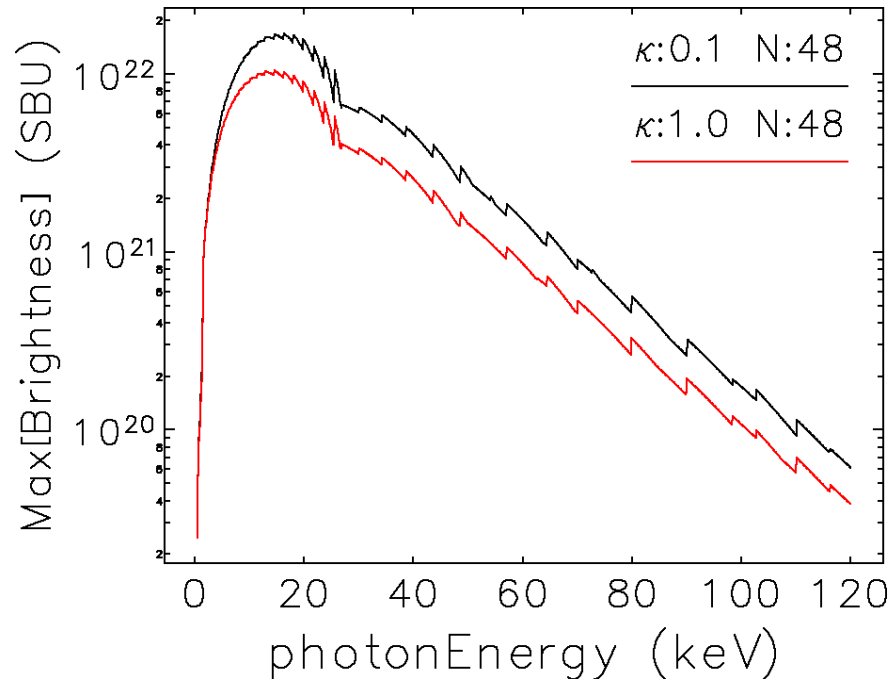
- Running with round beams is beneficial on several fronts

- Longer lifetime
- Less emittance blow-up from intrabeam scattering

- Because of IBS, small  $\kappa$  gives less emittance benefit than naively expected

- Benefit is particularly reduced for 48 bunches and high energy

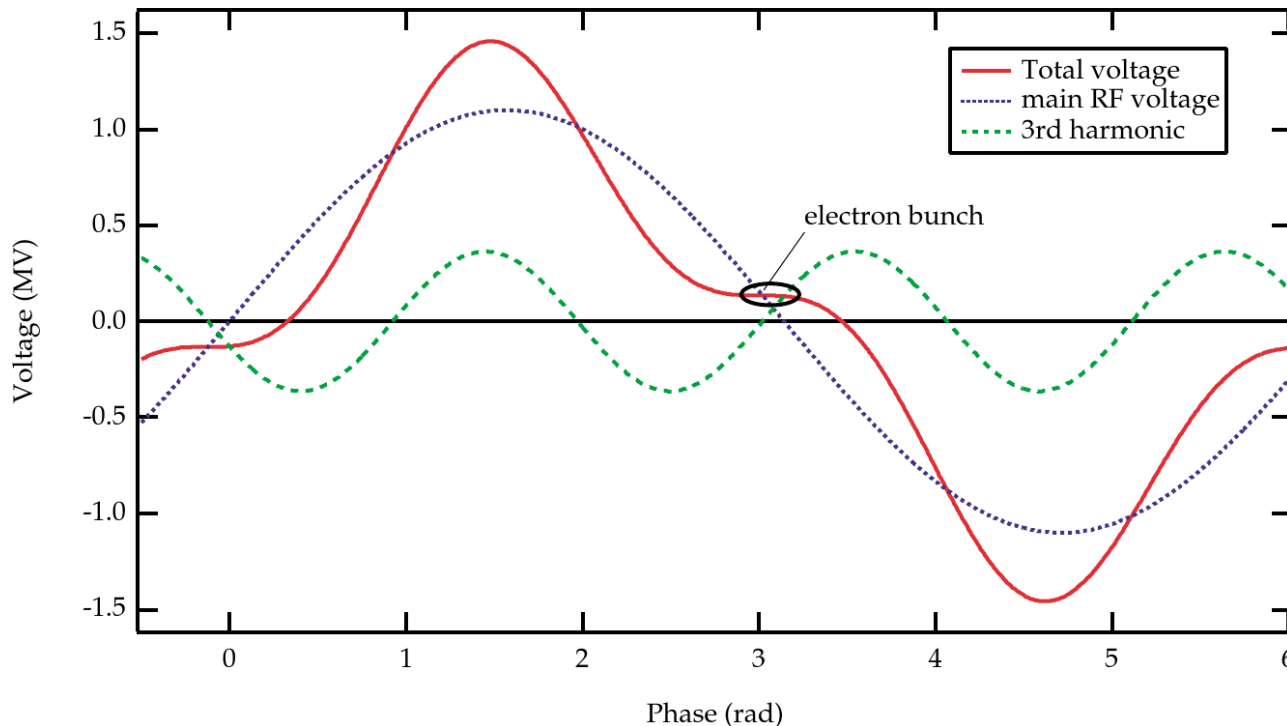
$$\mathcal{K} = \frac{\epsilon_y}{\epsilon_x}$$



Curves are envelopes for set of 3.7-m-long SCUs

# Bunch Lengthening Cavity

- Zero-current natural length is  $\sim 12.5$  ps
- Lengthens to 20-35 ps with longitudinal impedance
- Want even longer bunches for improved lifetime, control of IBS
  - Use Higher Harmonic Cavity (HHC) to further lengthen bunch

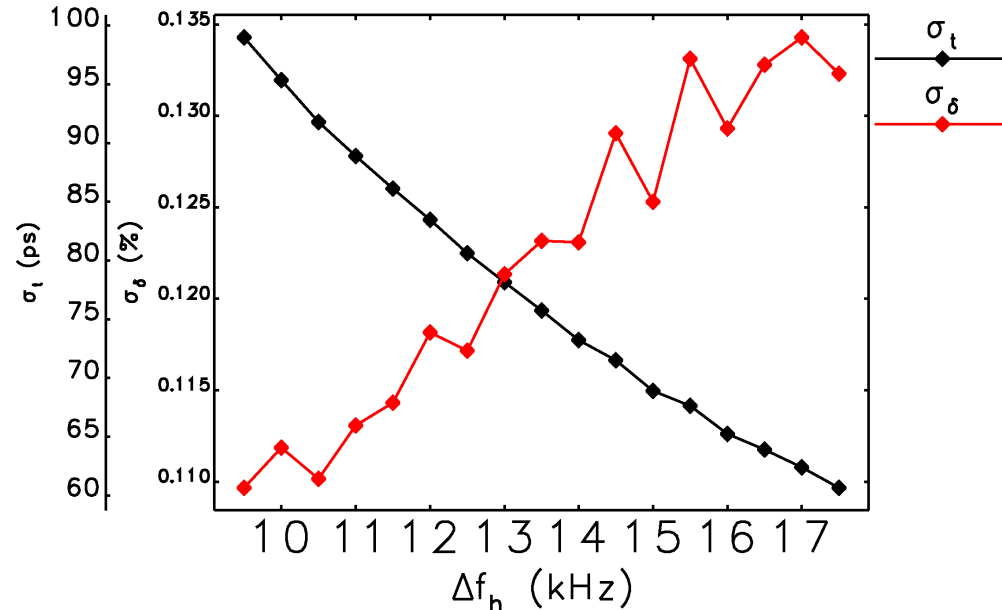


From J. M. Byrd and M. Georgsson, PRST-AB 4, 030701 (2001).



# Beam Dynamics with HHC

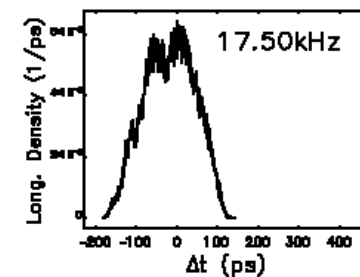
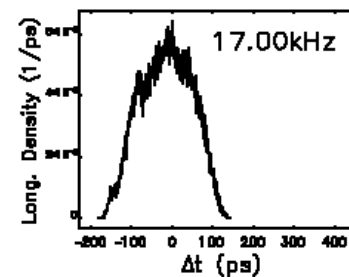
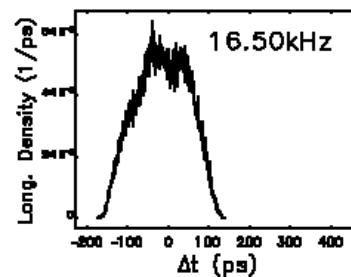
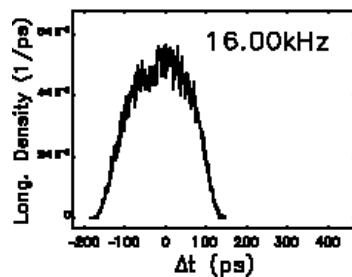
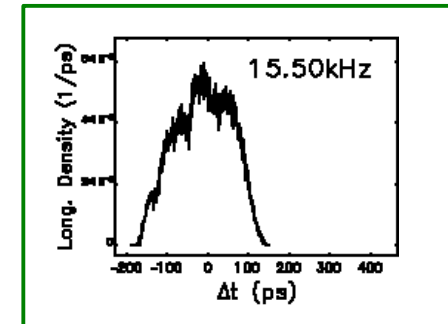
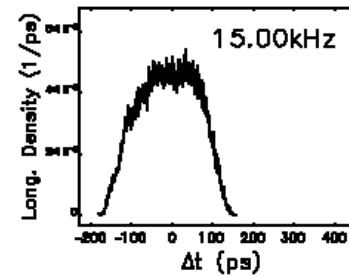
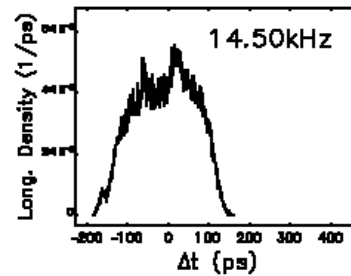
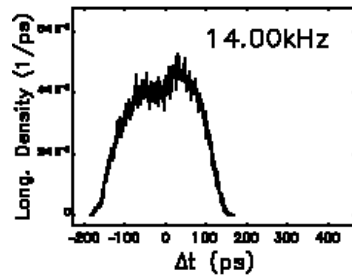
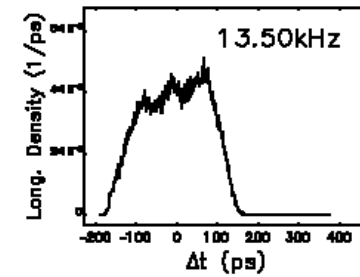
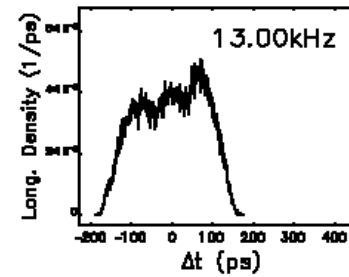
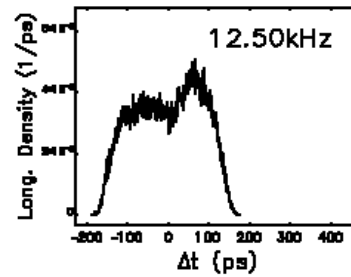
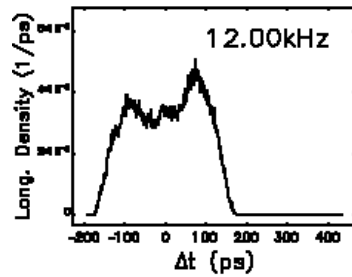
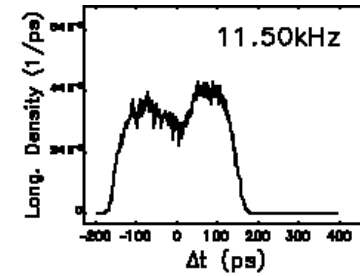
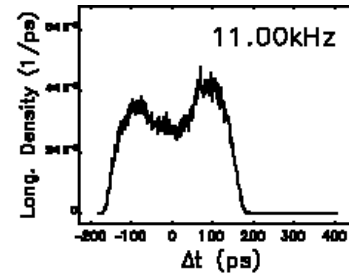
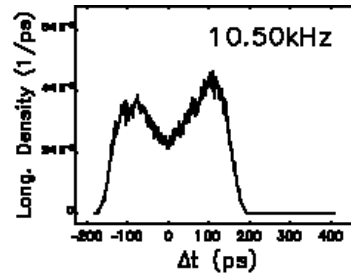
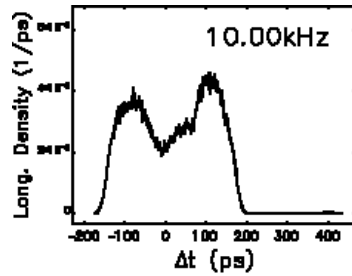
- Unlike main APS rf systems, the HHC will be “passive”
  - The cavity fields are excited by the beam itself
- How much field is induced depends on
  - Cavity loaded Q factor
  - Detuning from harmonic condition
- Situation is made more complex by
  - Inherent destabilizing effect of HHC on bunch centroid
  - Longitudinal impedance
- We've used simulation to study a passive HHC
  - Variation of loaded Q and detuning
  - Effect of filling from zero
  - Effect of ID gap changes
  - Effect of bunch population variation
  - Hybrid mode
  - Effect of kicking out a bunch



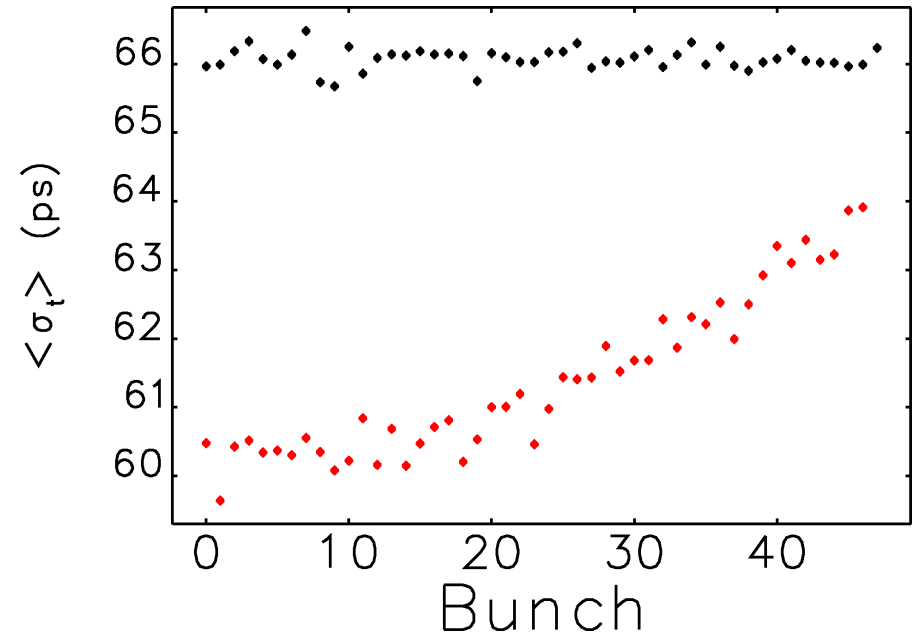
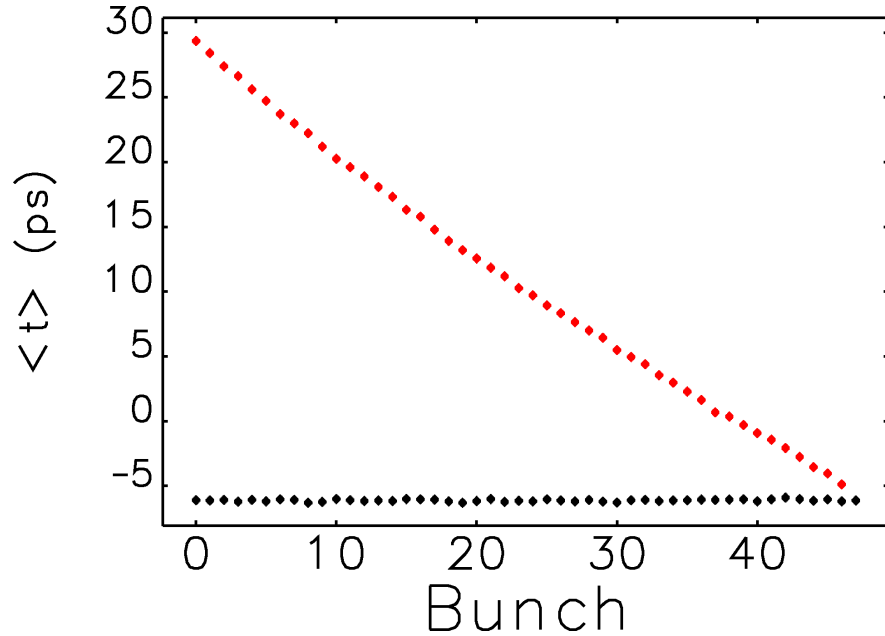
Simulation shows potential for significant bunch lengthening and partial suppression of microwave instability.

Cavity simulated is 4<sup>th</sup> harmonic of 352 MHz.

# Snapshots of Longitudinal Density



# Effect of lost bunch (48 bunches, minus 1)

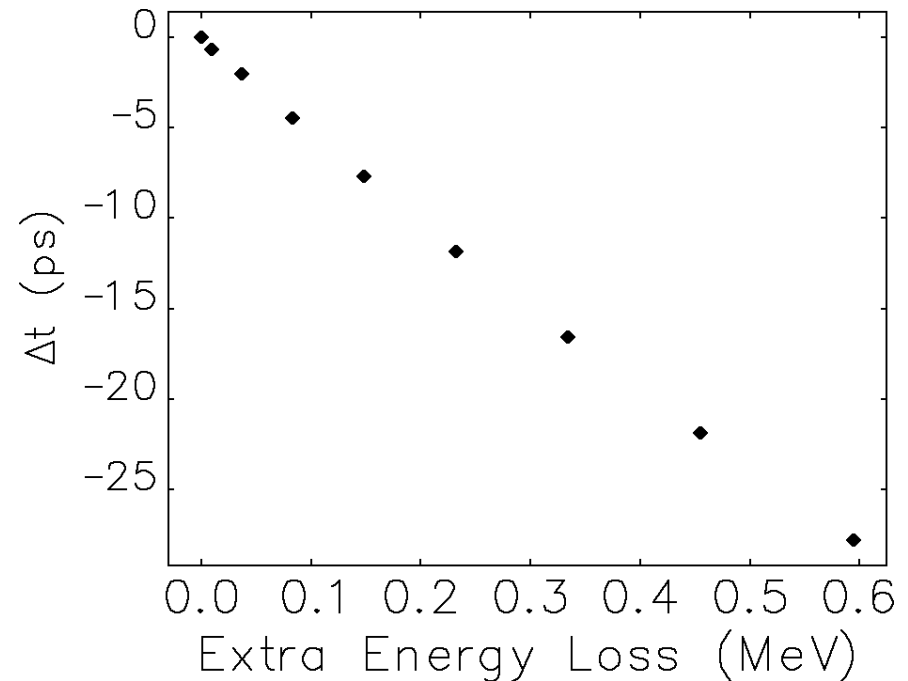
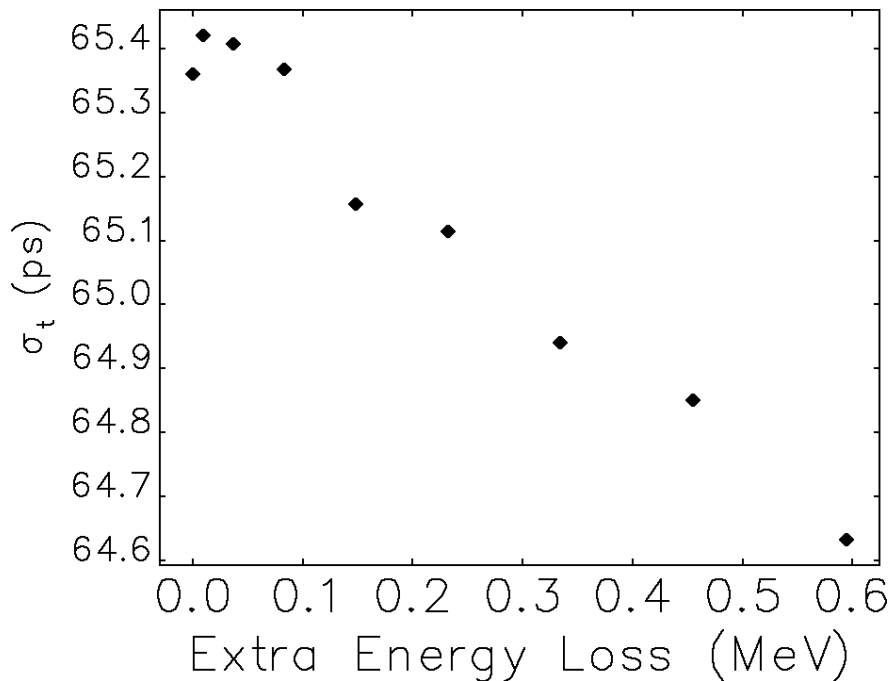


- Simulated kicking out of last bunch in 48-bunch fill, then return to equilibrium
  - No particle loss was observed
- Variation in the bunch centroid is a significant fraction of the bunch length
  - Could be a problem for some users
- Variation in bunch length is perhaps less of an issue
  - Will affect the lifetime, but presumably not much



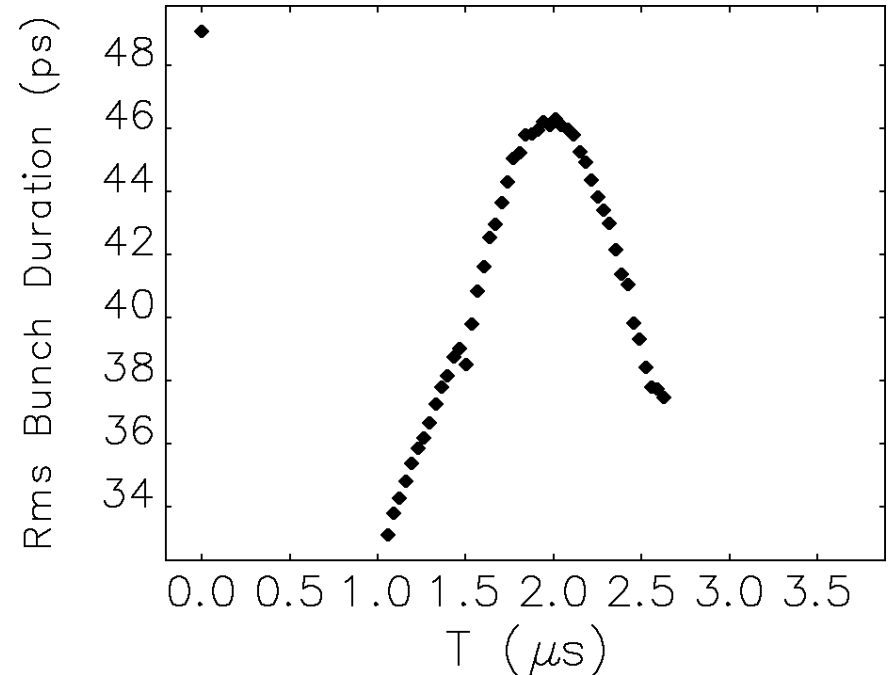
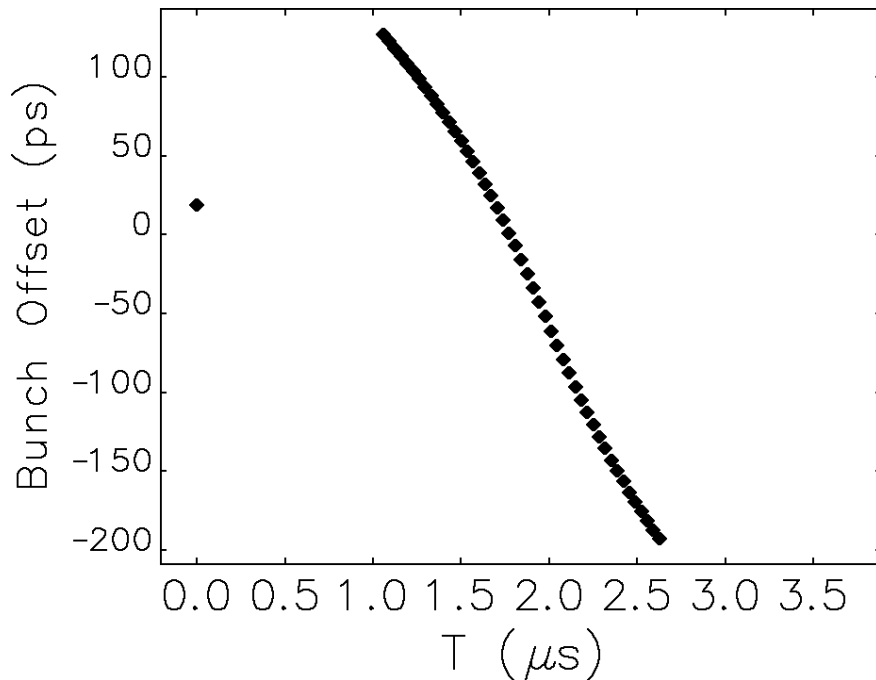
# Effect of ID gap variation

- Changing the energy loss per turn forces changes in power, phase, and detuning for the rf systems
- Simulations assume that a feed-forward system is used that has ID gaps as inputs
  - Little change in the bunch duration, but noticeable changes in timing
  - Required speed of ID-to-rf-system data transmission needs thought
- Methods of compensating timing shift are being discussed



# Possible hybrid mode

- We looked at a hybrid mode with 1 isolated bunch out of 48
  - 2  $\mu\text{s}$  gap around the isolated bunch
  - 12 bucket spacing of the 47 bunches
- Significant variation in arrival time
- Bunch lengthening is not very effective
- The outlook is pessimistic for this mode
  - Will continue to explore other possibilities



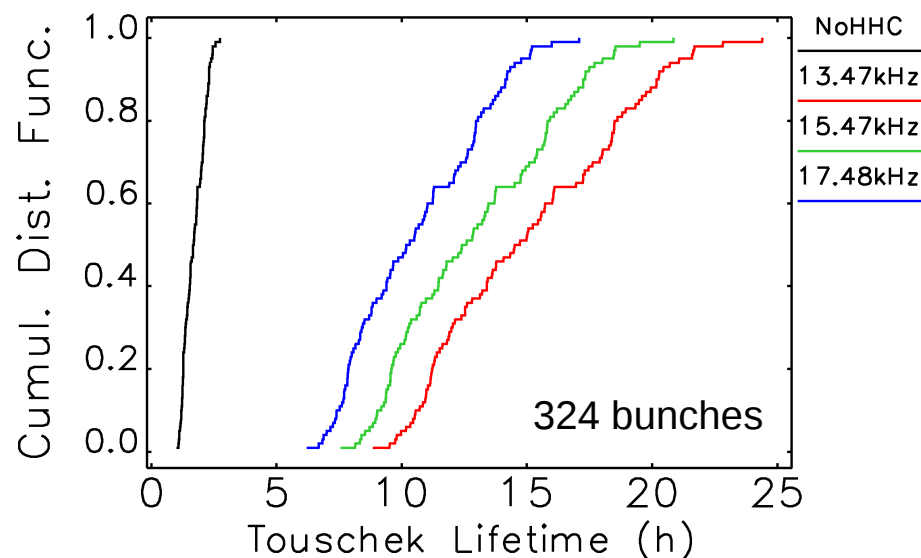
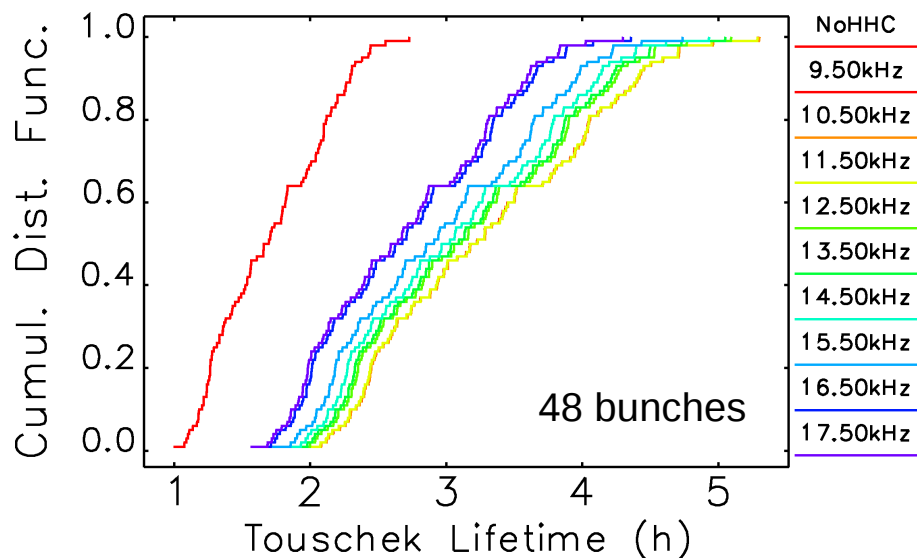


# Lifetime Analysis

- Two dominant lifetime effects are Touschek and gas scattering
  - Of these, Touschek is typically the most important
- Above analysis of Touschek lifetime made some assumptions
  - Notional bunch lengthening to 50-ps rms, gaussian shape
  - Emittance increase from IBS computed from this base
- Using results of tracking with HHC, can improve Touschek lifetime estimates
  - Use the computed longitudinal profiles rather than gaussian assumption
  - Combine the effects of microwave instability and intrabeam scattering in quasi-self-consistent fashion
- We also use particle tracking to provide data for gas scattering lifetime calculations
  - DA is used to provide aperture for elastic scattering
  - LMA is used to provide aperture for bremsstrahlung scattering
- In both cases, we get statistical distributions of lifetimes using the error ensembles

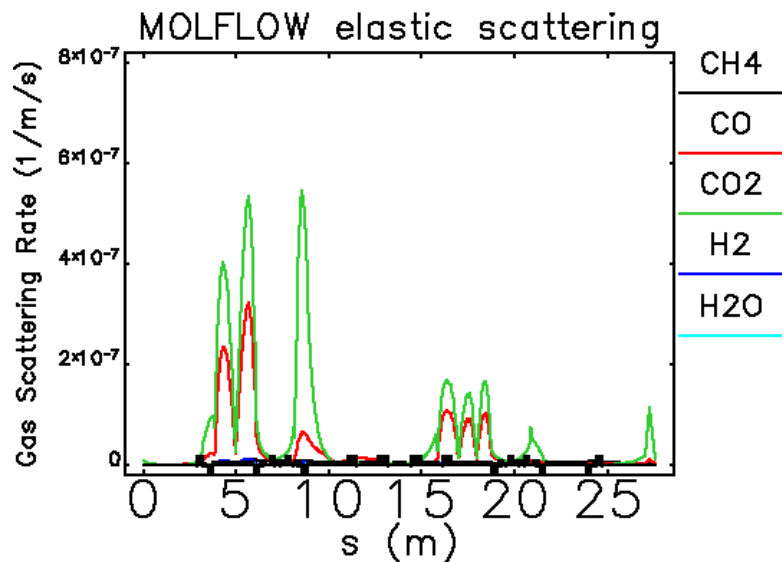
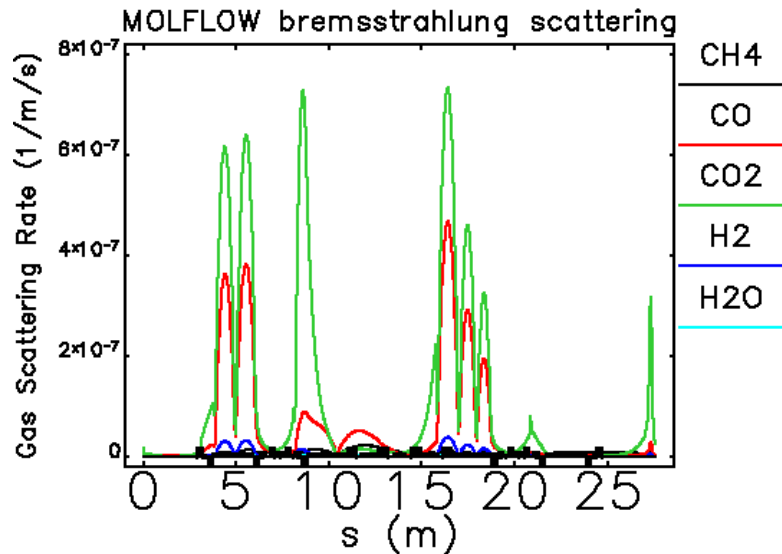


# Touschek Lifetime Distributions



- In both cases, have 200 mA,  $Q_L=600k$ ,  $\kappa \approx 1$
- For 48 bunches, get factor of 1.7 for 15.5 kHz detuning
  - Bunch is already significantly lengthened by the ring impedance
  - Do not reach the desired 7.5 h value
- For 324 bunches, get factor of 3.7 for 15.5 kHz detuning
- Some additional benefit from pushing to lower detuning
  - Have to watch for double-bunching, higher coupler power
  - Use 15.5 kHz for subsequent calculations

# Gas scattering lifetimes



- Computed from species-specific pressure profiles from MOLFLOW/SYNRAD (B. Stillwell, J. Carter)
  - Calculations give pressure profiles after 100 A\*h of operation
- For elastic scattering, use 100 DAs from tracking
  - Lifetime:  $104.9 \pm 0.6$  h
- For bremsstrahlung scattering, use 100 LMAs from tracking
  - Lifetime:  $54.3 \pm 0.8$
- Total gas scattering lifetime 35.8 h
- Separate calculation with VACCALC gives 32.5 h
- Use the lowest number to be conservative

# Summary of Parameters at ID Source Points

$\kappa$	$\sigma_t$ ps	$\epsilon_x$ pm	$\epsilon_y$ pm	$\sigma_x$ $\mu\text{m}$	$\sigma'_x$ $\mu\text{rad}$	$\sigma_y$ $\mu\text{m}$	$\sigma'_y$ $\mu\text{rad}$	$\sigma_\delta$ $10^{-4}$	10 <sup>th</sup> percentile $\tau$ h	$\Delta T_{\text{inj}}$ s	50 <sup>th</sup> percentile $\tau$ h	$\Delta T_{\text{inj}}$ s
$N_b = 48$		$f_b = 13.0\text{MHz}$			$Q_b = 15.3\text{nC}$							
0.98	67	46.8	45.9	18.1	2.6	10.6	4.3	$1.35 \times 10^1$	1.93	14.4	2.62	19.7
0.10	67	80.9	8.1	23.8	3.4	4.5	1.8	$1.39 \times 10^1$	1.10	8.3	1.44	10.8
$N_b = 324$		$f_b = 88.0\text{MHz}$			$Q_b = 2.3\text{nC}$							
0.98	55	43.0	42.2	17.4	2.5	10.2	4.2	9.63	7.07	7.9	8.98	10.0
0.10	55	67.9	6.8	21.8	3.1	4.1	1.7	9.77	4.20	4.7	5.30	5.9

- Injection intervals are workable with existing injector
  - Each injection followed by a ~40ms brightness dip (1 bunch)
- Median lifetime does not meet 7.5h goal except for 324 bunch mode with  $\kappa=1$ 
  - Further optimization of the HHC parameters, lattice should help some
  - Additional supplemental shielding likely needed, TBD
- Simulations will be used to produce loss maps for Touschek and gas scattering
  - Based on these, supplemental shielding scheme will be developed
  - Addition of collimators will also be studied



# Summary of Parameters at 3PW Source Points

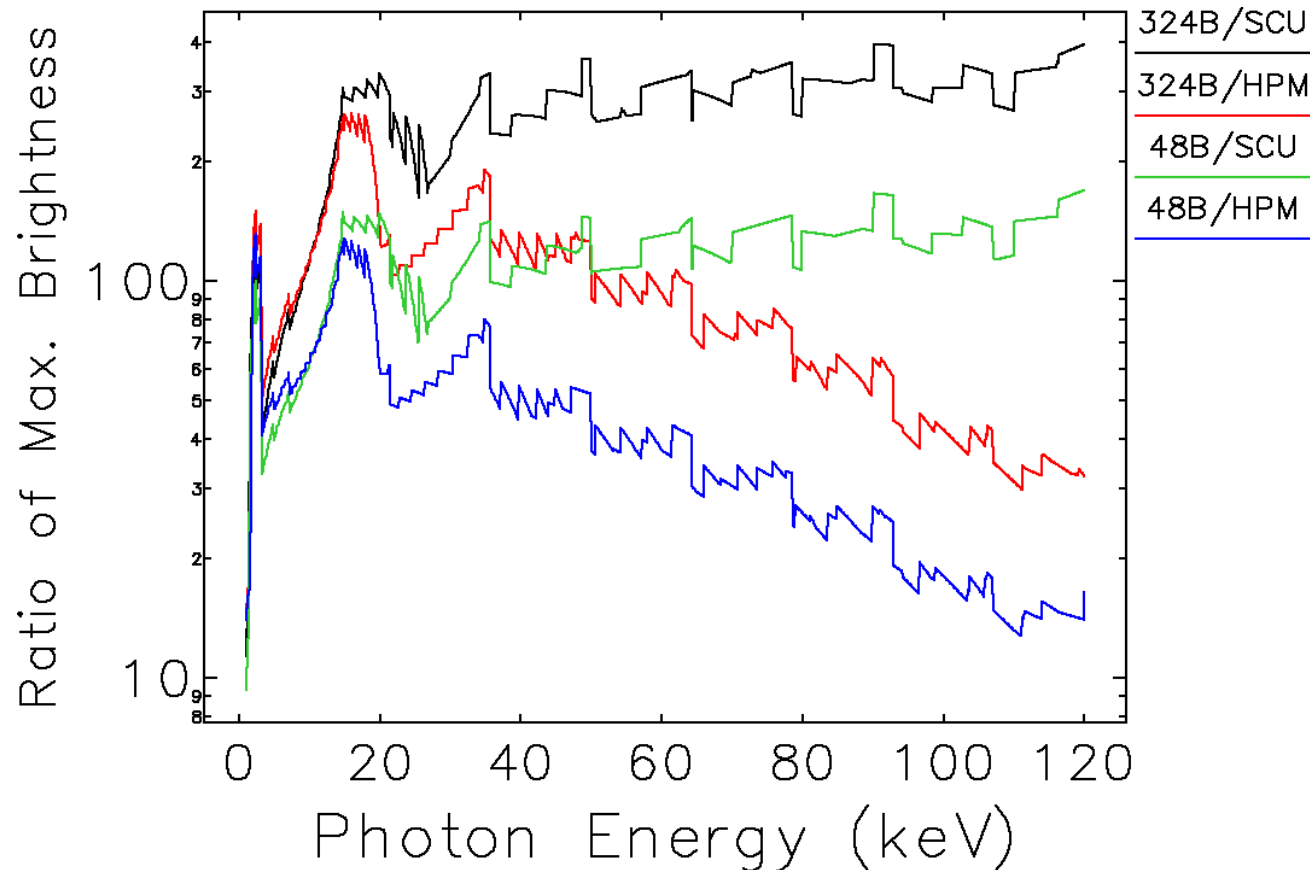
$\kappa$	$\sigma_t$	$\epsilon_x$	$\epsilon_y$	$\beta_x$	$\beta_y$	$\eta_x$	$\sigma_x$	$\sigma'_x$	$\sigma_y$	$\sigma'_y$	$\sigma_\delta$
	ps	pm	pm	m	m	m	$\mu\text{m}$	$\mu\text{rad}$	$\mu\text{m}$	$\mu\text{rad}$	$10^{-4}$
$N_b = 48$		$f_b = 13.0\text{MHz}$				$Q_b = 15.3\text{nC}$					
0.98	67	46.8	45.9	1.2	3.0	0.010	15.9	6.2	11.8	3.9	$1.35 \times 10^1$
0.10	67	80.9	8.1	1.2	3.0	0.010	17.4	8.1	5.0	1.6	$1.39 \times 10^1$
$N_b = 324$		$f_b = 88.0\text{MHz}$				$Q_b = 2.3\text{nC}$					
0.98	55	43.0	42.2	1.2	3.0	0.010	12.3	5.9	11.3	3.7	9.63
0.10	55	67.9	6.8	1.2	3.0	0.010	13.6	7.4	4.6	1.5	9.77

- Three pole wigglers are preferred for generating hard x-rays for BM lines
  - Fields in excess of 1T appear possible<sup>1</sup>
- Require 0.82 T dipole field to give 19.5 keV critical energy
  - Not feasible given that these dipoles also have large gradients
  - Not consistent with smallest emittance
- In principle, radiation from the M3 and M4 dipoles could be used
  - 13.2 and 14.5 keV critical energy, respectively

1: M. Abliz, private communication.

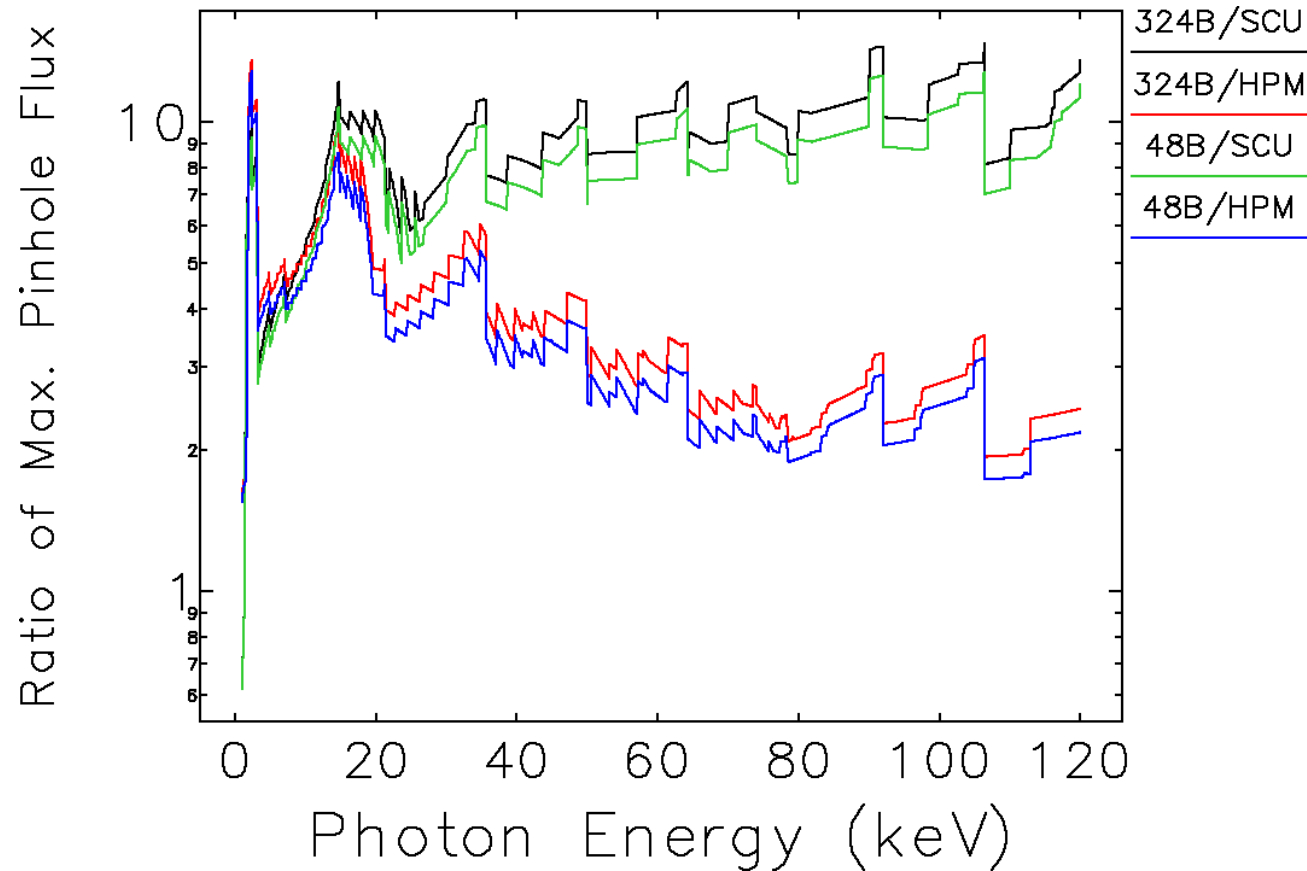


# X-ray Brightness Compared to APS Today



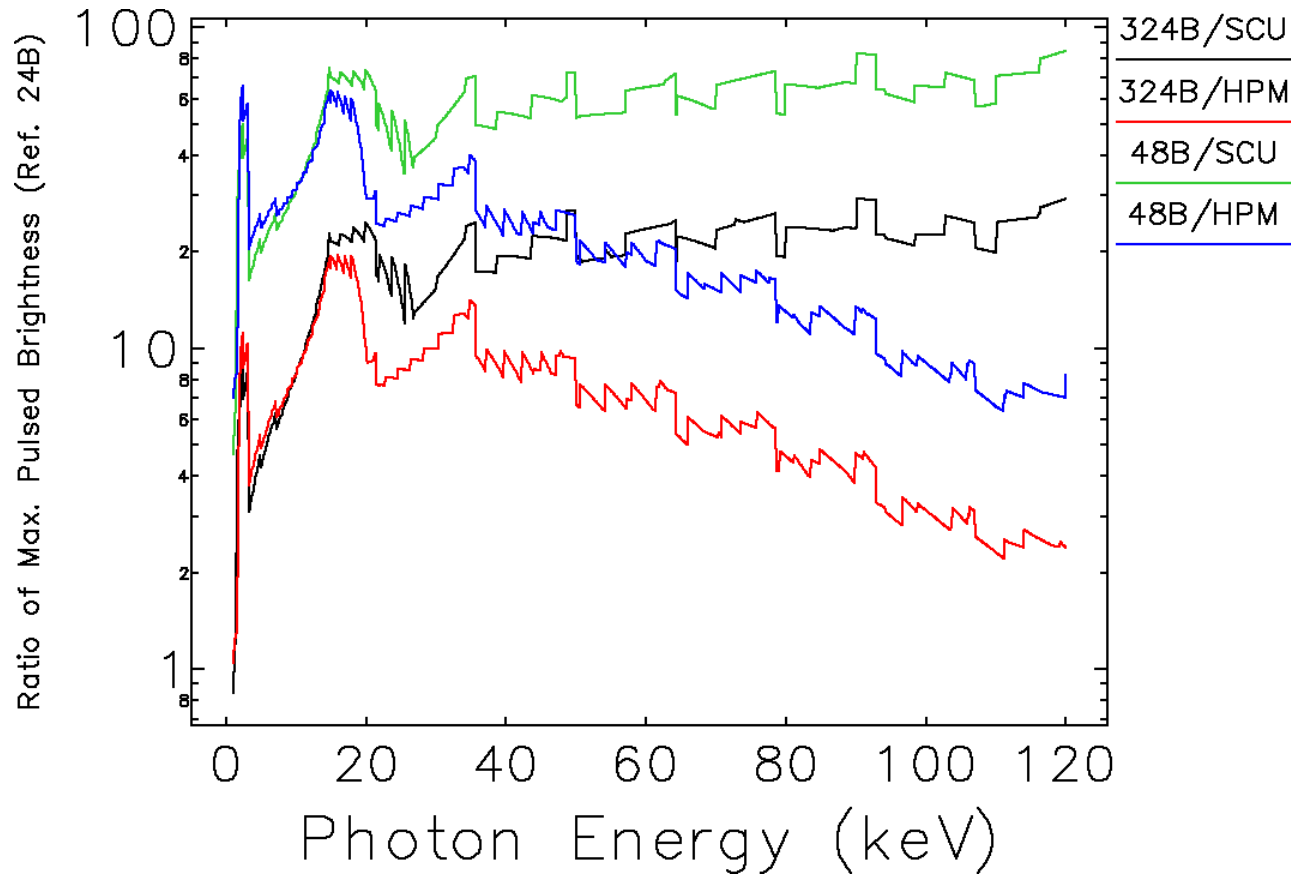
- Used  $\kappa=1$  for 48B and  $\kappa=0.1$  for 324B
- Assumed magnetic gap of 9 mm for 4.8-m HPM and 3.7-m SCU devices in APS-U
- Assumed APS High Heat Load (HHL) front end limits on power, power density
- Goal of 100-fold increase for  $>20$  keV is met

# X-ray Flux Compared to APS Today



- Conditions same as previous
- Used 0.5 mm by 0.5 mm pinhole at 30 m
- Increases of up 10-fold for hard x-rays

# X-ray Pulsed Brightness Compared to APS Today



- Conditions same as previous
- Comparison is to APS 24-bunch mode
- Increases of 40-80 fold for hard x-rays





# APS-U ID Optimizer

- A web page is available that helps identify the best IDs for a particular application

<http://goo.gl/lhzX5y>

- Includes
  - Single-period permanent magnet devices
  - Two- and three-way revolvers
  - Superconducting undulators
- Knows K-edges of elements through Uranium
- Comparison to existing ring also provided

Lattice:  3PW-V6

Beam current (mA):  200  400

Front end type:  Canted  HHL  VHHL  EHHL

Optimization quantity:  Brightness  Spectral flux density  Spectral flux

Maximum HPM ID length (m):  None  2.4  4.8

Maximum SCU magnetic length:  None  1.5  2.0  2.5  3.0  3.5  4.0

Undulator type:  HPM  Revolver2  Revolver3  SCU

Magnetic gap (mm):  9.0

Periods to consider:  Existing  All

0.5mm period increments:  Yes  No

Minimum, maximum period (mm):

Optimize:  Band Ave.  Band Min.  Band Max.  Few Dips

Ranks to include:

Default plot range (keV):

Reference:  None  U17.0  U17.5  U18.0  U18.5  U19.0  U19.5  U20.0  U20.5  U21.0  U21.5  U22.0  U22.5  U23.0  U23.5  U24.0  U24.5  U25.0  U25.5  U26.0  U26.5  U27.0  U27.5  U28.0  U28.5  U29.0  U29.5  U30.0  U30.5  U31.0  U31.5  U32.0  U32.5  U33.0  U33.5

K Edges:  H/1  He/2  Li/3  Be/4  B/5  C/6  N/7  O/8  F/9  Ne/10  Na/11  Mg/12  Al/13  Si/14  P/15  S/16  Cl/17  Ar/18  K/19  Ca/20  Sc/21  Ti/22  V/23  Cr/24  Mn/25  Fe/26  Co/27  Ni/28  Cu/29  Zn/30  Ga/31  Ge/32  As/33  Se/34  Br/35  Kr/36  Rb/37  Sr/38  Y/39  Zr/40  Nb/41  Mo/42  Tc/43  Ru/44  Rh/45  Pd/46  Ag/47  Cd/48  In/49  Sn/50  Sb/51  Te/52  I/53  Xe/54  Cs/55  Ba/56  La/57  Ce/58  Pr/59  Nd/60  Pm/61  Sm/62  Eu/63  Gd/64  Tb/65  Dy/66  Ho/67  Er/68  Tm/69  Yb/70  Lu/71  Hf/72  Ta/73  W/74  Re/75  Os/76  Ir/77  Pt/78  Au/79  Hg/80  Tl/81  Pb/82  Bi/83  Po/84  At/85  Rn/86  Fr/87  Ra/88  Ac/89  Th/90  Pa/91  U/92

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Band 0	Enable: <input checked="" type="radio"/> Yes <input type="radio"/> No	Low, High (keV): <input type="text" value="3.3"/> <input type="text" value="33.0"/>
Band 1	Enable: <input type="radio"/> Yes <input checked="" type="radio"/> No	Low, High (keV): <input type="text" value="0"/> <input type="text" value="0"/>
Band 2	Enable: <input type="radio"/> Yes <input checked="" type="radio"/> No	Low, High (keV): <input type="text" value="0"/> <input type="text" value="0"/>
Band 3	Enable: <input type="radio"/> Yes <input checked="" type="radio"/> No	Low, High (keV): <input type="text" value="0"/> <input type="text" value="0"/>
Band 4	Enable: <input type="radio"/> Yes <input checked="" type="radio"/> No	Low, High (keV): <input type="text" value="0"/> <input type="text" value="0"/>
Band 5	Enable: <input type="radio"/> Yes <input checked="" type="radio"/> No	Low, High (keV): <input type="text" value="0"/> <input type="text" value="0"/>

# Conclusion

- 67-pm lattice design consistent with engineering constraints delivers ~100-fold increase in brightness for hard x-ray
  - 6 GeV appears to be close to the optimum for x-ray performance
- A 48-bunch, 200-mA mode appears workable based on evolving model of the ring impedance
- Nonlinear dynamics fairly robust in the presence of errors and ID effects
  - Compatible with 8mm x 6mm ID chamber gaps assuming on-axis injection
  - Compatible with vertically-deflecting devices
- Intrabeam scattering has modest effect on brightness
- Passive bunch-lengthening cavity works well for 48- and 324-bunch modes
  - Detailed Touschek lifetime calculations confirm the beneficial effect
- Detailed gas scattering lifetime calculations performed based on tracking and vacuum system simulations
  - Being used to iterate vacuum system design with engineers
- Beam lifetime not as long as desired
  - Study of loss patterns, collimation, and supplemental shielding to be undertaken
- Exploring promising ideas for even smaller emittance<sup>1,2</sup>

1 A. Streun, NIMA 737 (2014) 148

2 Y.-P. Sun, priv. communication.



# Acknowledgments

- APS-U MBA Beam Physics Team

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

- Early version of H7BA lattice used data provided by ESRF
- Many of the simulations used the Blues cluster at Argonne's Laboratory Computing Resources Center

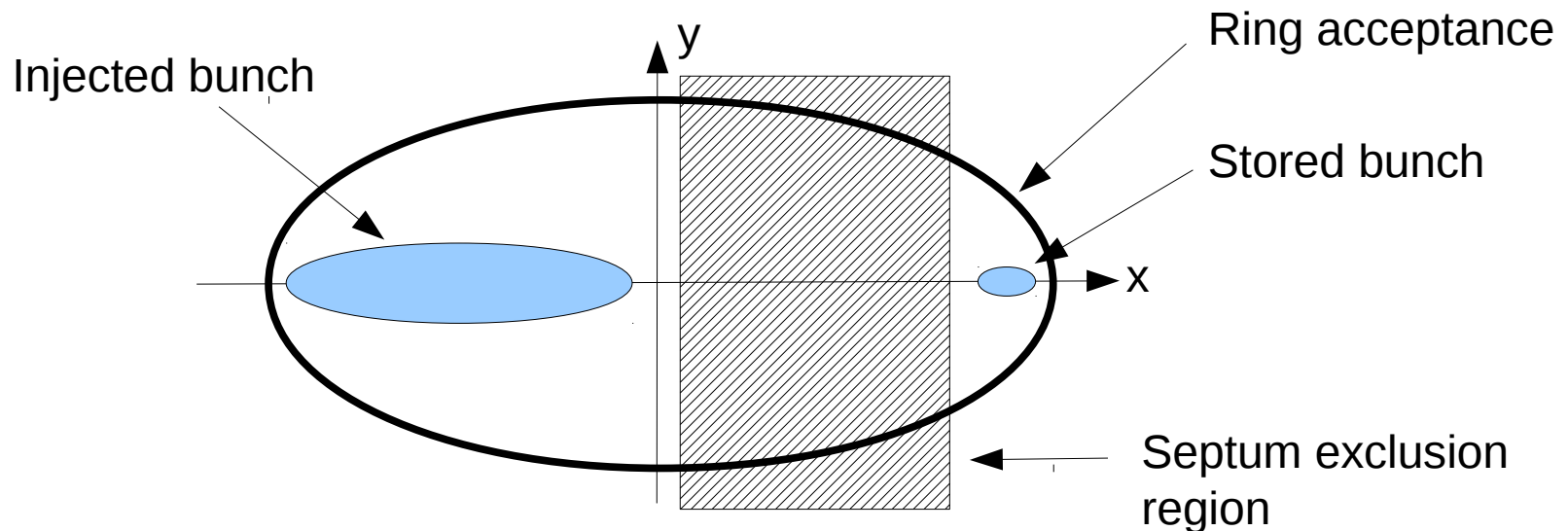


# Backup Slides



# Beam Injection Methods

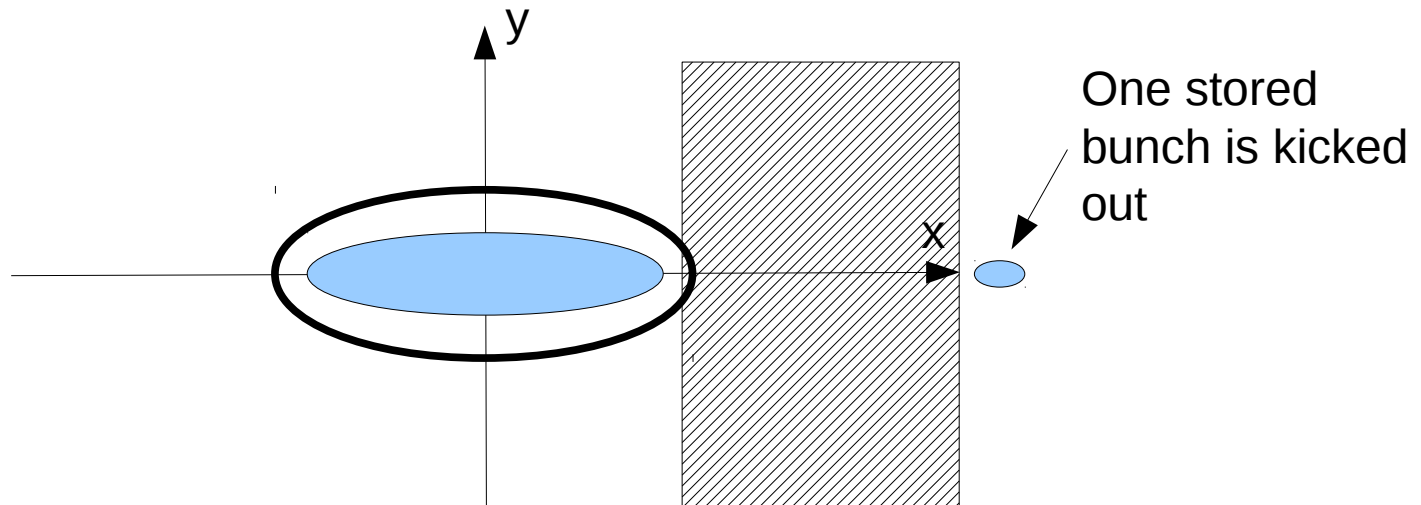
- All existing storage rings operate with accumulation-based injection
  - Each injector shot coalesces with existing store bunch via radiation damping
  - Lattice dynamic acceptance (DA) must accommodate
    - Injected beam size ( $\sim 2\text{-}4\text{mm}$  for  $\pm 3\sigma$ )
    - Stored beam size ( $< 0.5\text{mm}$  for  $\pm 5\sigma$ )
    - Distance between the two beams for septum and margin ( $2\text{-}3\text{ mm}$ )
  - Top-up is based on accumulation



This “open bump” accumulation scheme permits smaller DA, but stored beam gets rattled. Closed bump scheme requires  $\sim 2\text{x}$  larger DA.

# Beam Injection Methods

- On-axis “swap-out” injection is an alternative
  - Each injector shot replaces an existing stored bunch
  - DA must accommodate only the injected beam size
- Swap-out seems advantageous on balance
  - Smaller horizontal physical apertures possible in IDs
  - Emittance can be pushed to smaller values
  - Less disturbance to stored beam
  - Nonlinear dynamics optimization can emphasize lifetime instead of DA
  - Single-bunch current limited by injector capability
  - Maximum number of bunches limited by fast kicker technology to 324
  - Need an in-ring beam dump that is appropriately shielded



# Bunch Swap

