Beam Physics Update

Michael Borland
on behalf of APS-U Beam Physics Team

October 27, 2016

Acknowledgments

- APS-U beam physics team includes

  T. Berenc, A. Blednykh, M. Borland, J. Calvey, G. Decker, J. Dooling, L. Emery, K. Harkay, S. Kim, R. Lindberg, V. Sajaev, R. Soliday, M. Sangroula, U. Wienands, A. Xiao, Y.-P. Sun, C.-Y. Yao, A. Zholents, ...

- Many simulations relied on the Blues cluster at Argonne's Laboratory Computing Resource Center

Outline

- Lattice options
- Challenges
- Pushing brightness further
- Bunch lengthening options and benefits
- Beam properties
- Conclusions

Lattice Options

- All lattices are based on the Hybrid Seven Bend Achromat (H7BA) concept from ESRF [1]
- Three options under recent consideration

	today	90pm	67pm	41pm	units
Values in ID Straight Sections					
Energy	7.0	6.0	6.0	6.0	GeV
β_x	19.5	8.4	7.0	4.9	m
η_x	171.85	-4.00	1.11	1.47	mm
β_y	2.9	3.3	2.4	1.9	m
$\epsilon_{x,eff}$	3129.4	91.5	67.0	41.8	m
Energy spread	0.096	0.096	0.096	0.129	%

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

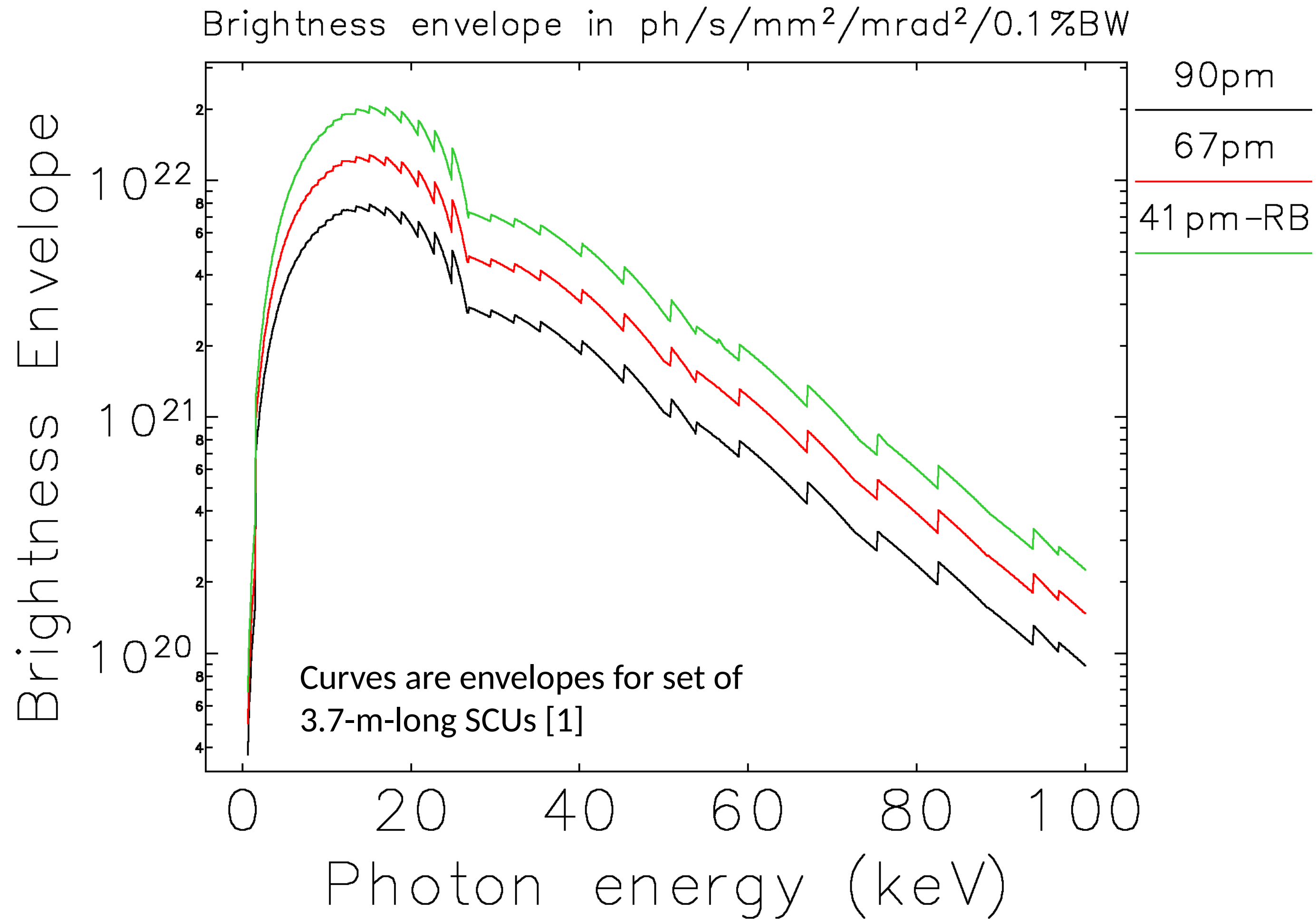
High-Level Lattice Comparison

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

- 90-pm lattice eliminated due to lower brightness
- 41pm-RB lattice seems likely to be the final selection
  - Better positioned relative to international competition
  - Not significantly harder or more expensive than 67-pm lattice

1: Y. Sun et al., NAPAC16, WEPOB14.
2: M. Borland et al., IPAC15, p.1776.
3:M. Borland et al., NAPAC16, WEPOB01.

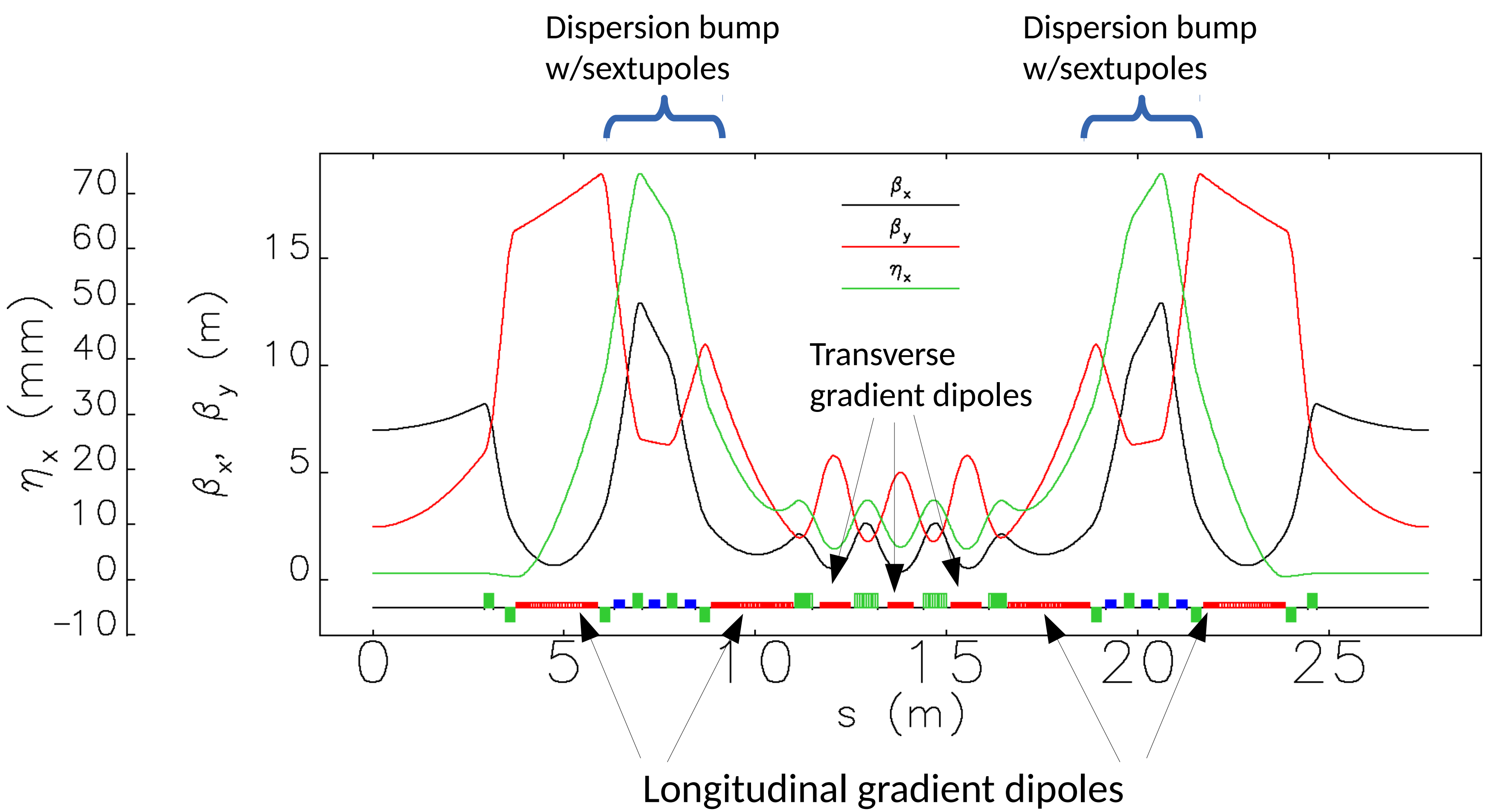
Brightness comparison for 324 bunch mode



- These are "round"-beam calculations (more later)
- 67-pm lattice is ~60% brighter than 90-pm
- 41-pm lattice is ~60% brighter than 67-pm

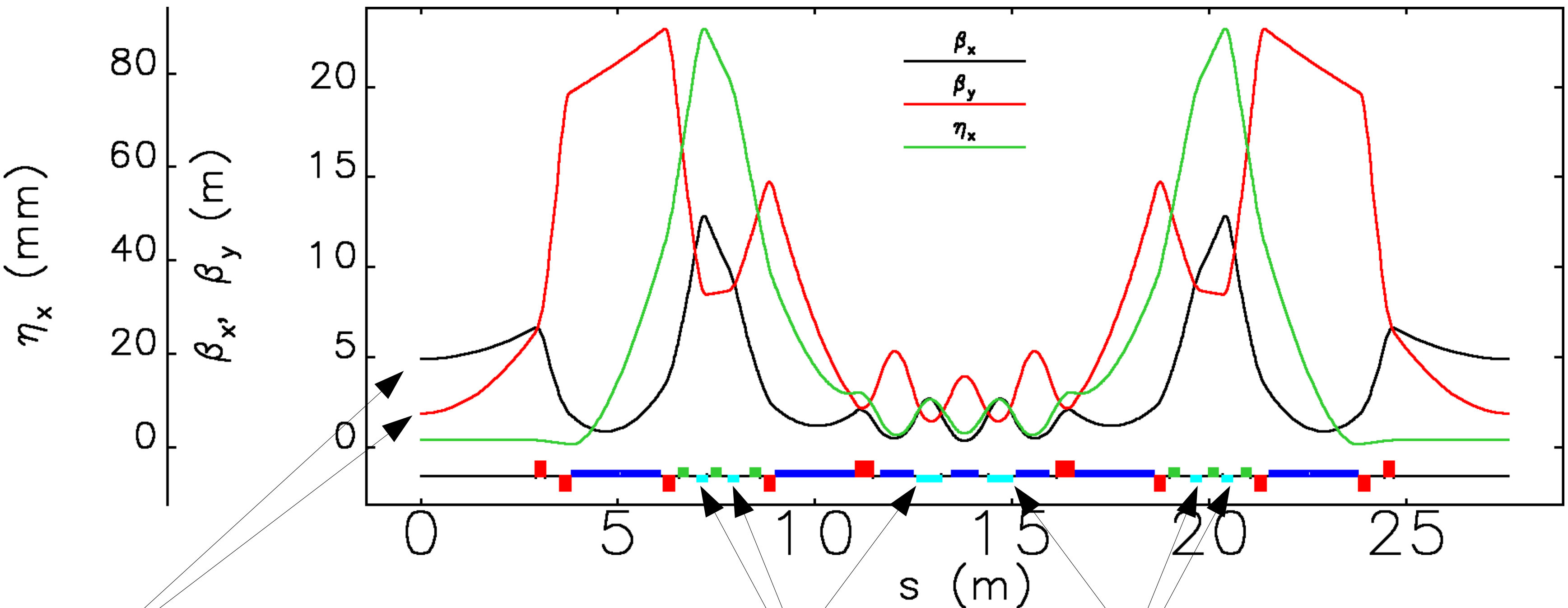
1: S.H. Kim, NIM A 546, p. 604 (2005).

67-pm lattice



41-pm RB lattice

- Synchrotron radiation power 24% higher: more damping
- Damping repartitioned to favor emittance
  - Lower emittance, but higher energy spread



Improved beta functions

Reverse bends

Reverse bends

Challenges

- Injection acceptance
  - 90-pm has sufficient acceptance for bunch accumulation
  - In the others, can only inject on axis
  - Quest for brightness pushes us to use swap-out injection [1,2]

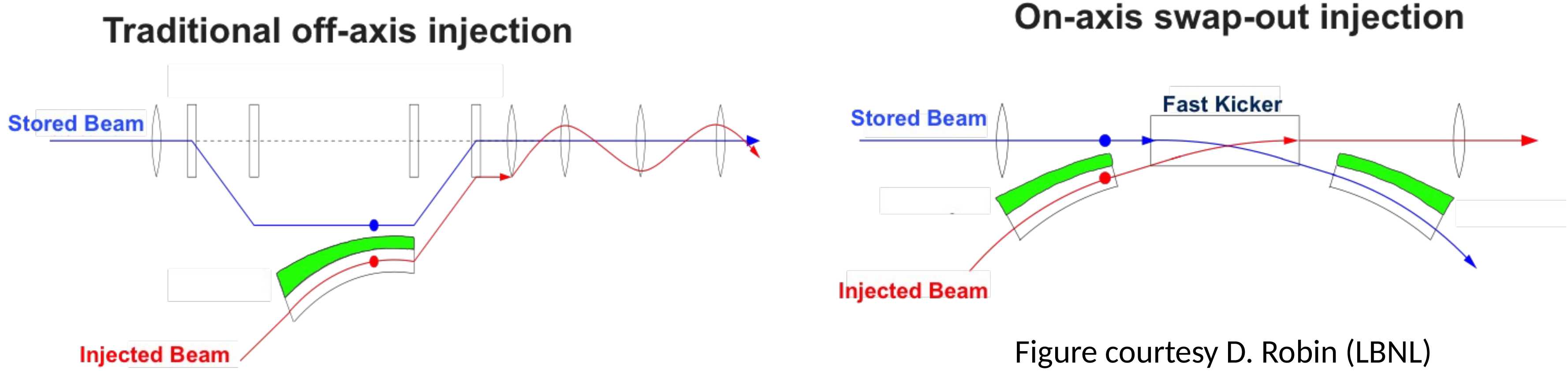


Figure courtesy D. Robin (LBNL)

Lattice	Ave. Beam Loss	Max. Beam Loss
67-pm	1%	3.7%
41-pm RB	<1%	1.1%

Results from A. Xiao, DOE CD-3b Review, 2016.

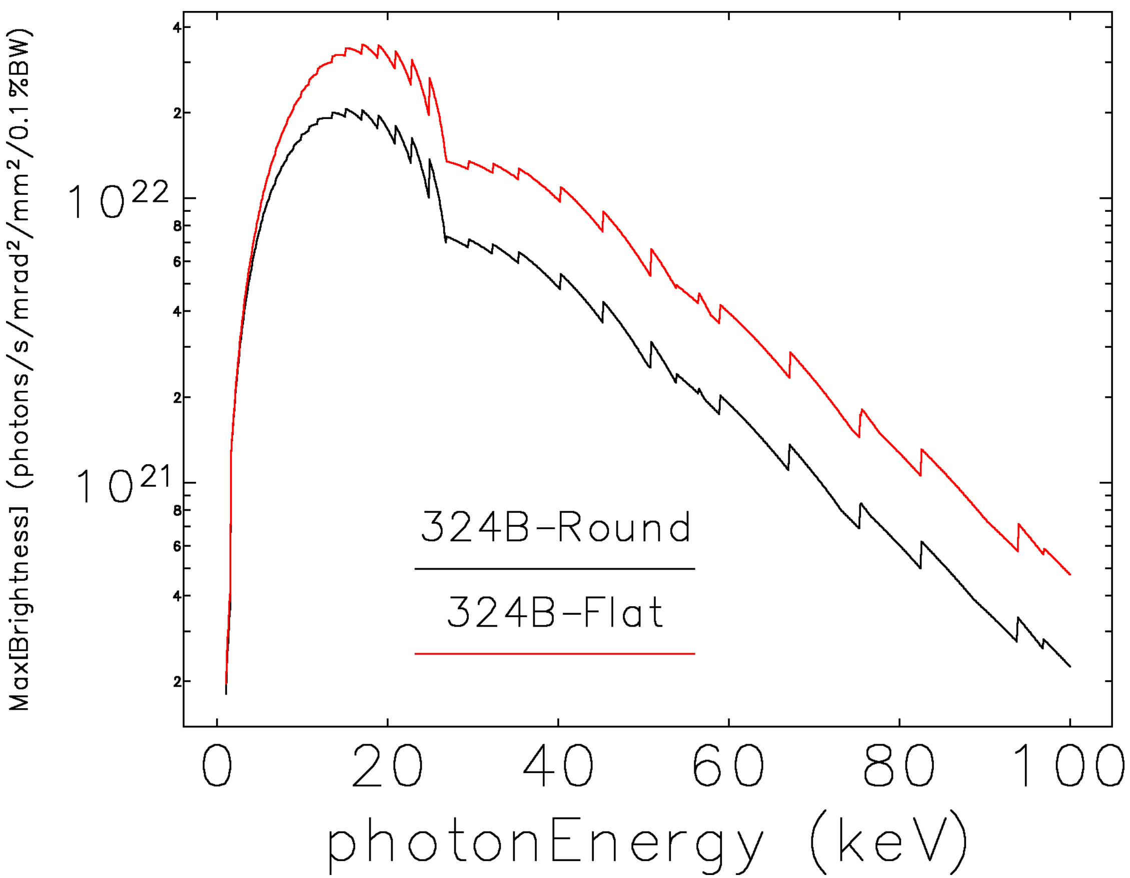
1: R. Abela et al., EPAC92, p. 486.
2: L. Emery et al., PAC03, p. 256.

Challenges

- Injection acceptance
  - 90-pm has sufficient acceptance for bunch accumulation
  - In the others, can only inject on axis
  - Quest for brightness pushes us to use swap-out injection
- Collective stability [1,2]
  - All lattices can stably store 200 mA in 48 bunches
  - 90-pm lattice shows injection instability, can't get there
  - This again pushes us to use swap-out operation
- Lifetime
  - Lifetime goal is 4.8 h, to nominally avoid supplemental shielding
  - Challenges arise with flat beams or 48-bunch mode
- Ion trapping [3]
  - Challenges arise with round beams in 324-bunch mode

1: R. Lindberg et al., IPAC15, 1822.
2: R. Lindberg et al., NAPAC16, WEPOB08.
3: J. Calvey, AOP-TN-2016-044.

Increasing brightness with flat beams



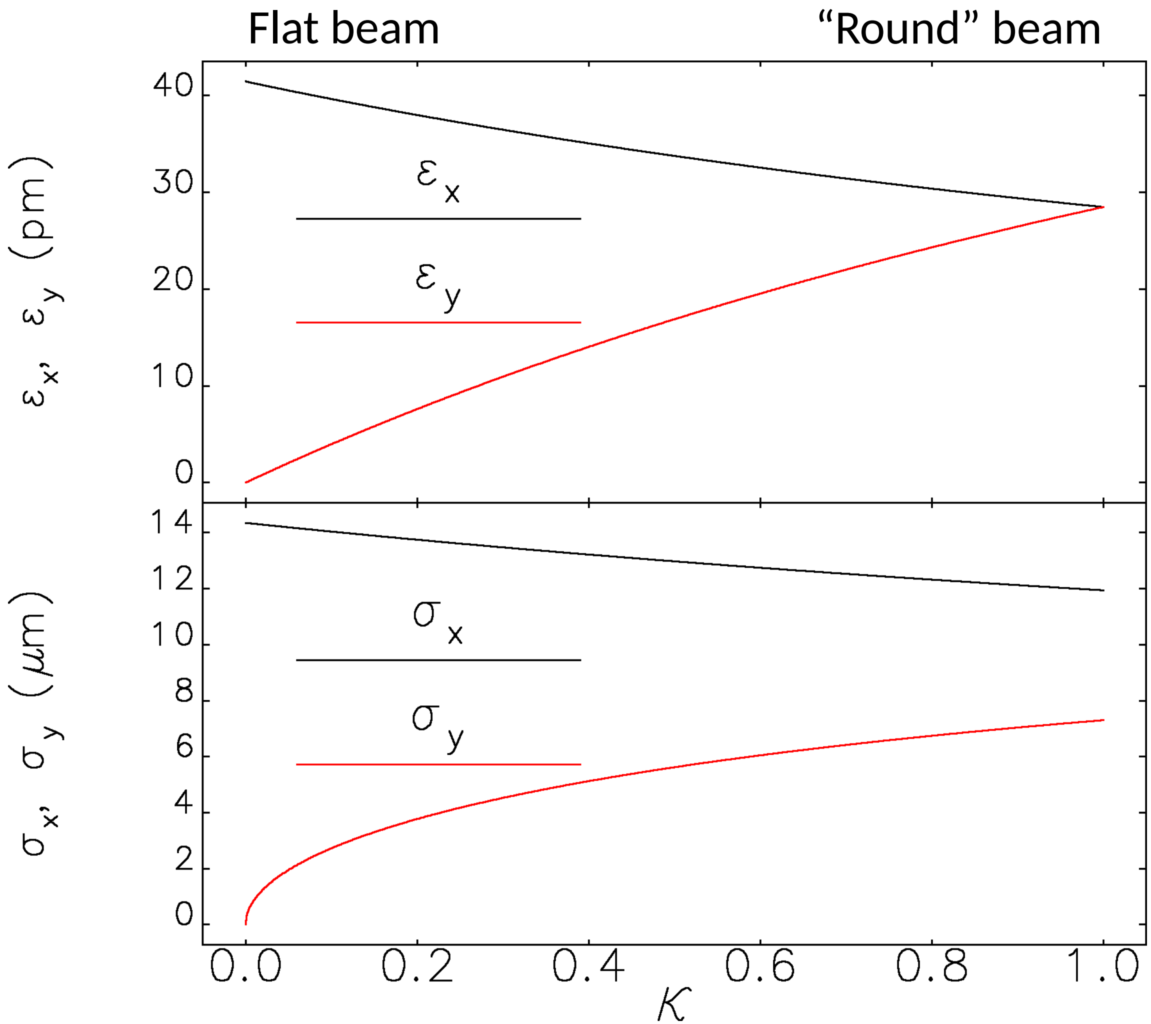
- Running with "flat" beams boosts the brightness
- Can give ~2-fold increase for APS-U compared to round beams
- In reality, x-ray optics may mask the effect
- Still, many present-day light sources run with vertical emittance of 4pm or less

Envelopes over suite of 3.7-m-long SCUs

"Round": $\varepsilon_y = \varepsilon_x$

"Flat": $\varepsilon_y = \varepsilon_x / 10$

Emittance ratio variation at zero charge



~~$$\epsilon_x = \frac{\epsilon_0}{1+\kappa}$$~~

$$\epsilon_x = \frac{\epsilon_0}{1+\frac{\kappa}{J_x}}$$

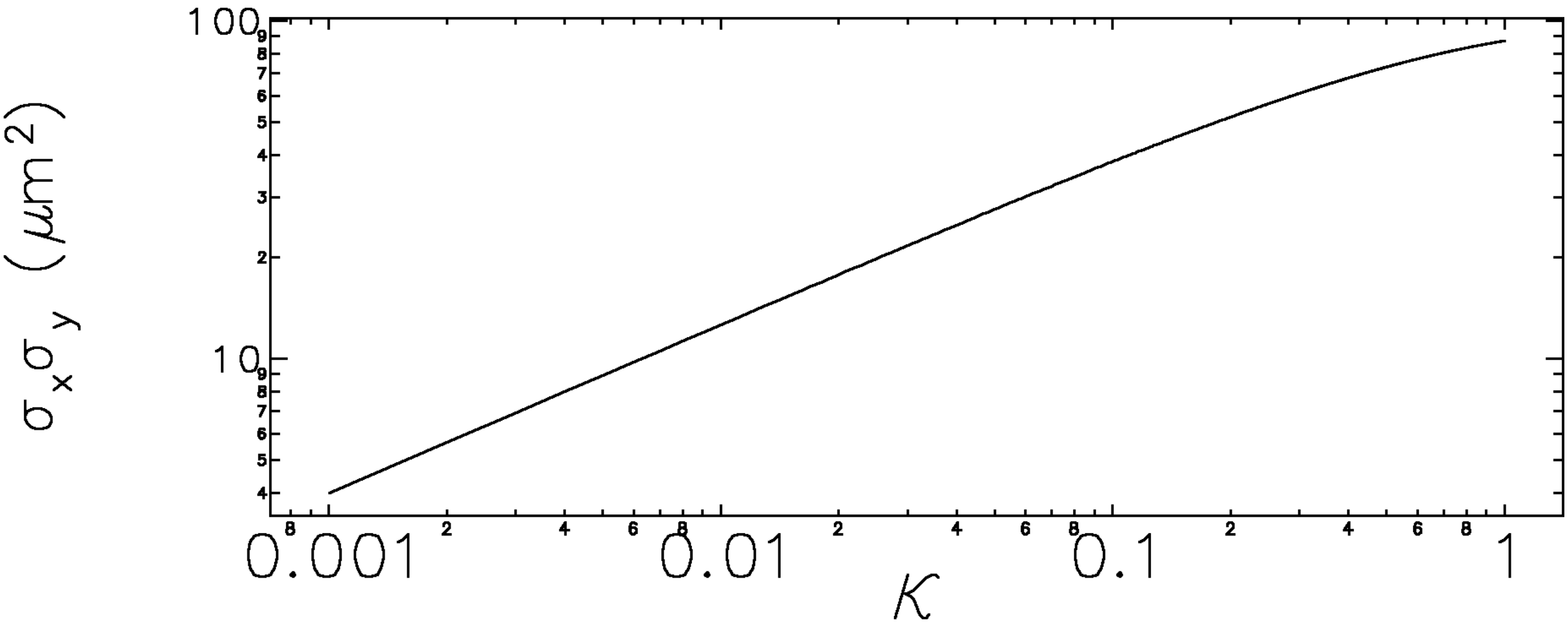
$$\epsilon_y = \kappa\epsilon_x$$

R. Lindberg, AOP-TN-2014-020.

For 41-pm, lattice we have

$$J_x \approx 2.20$$

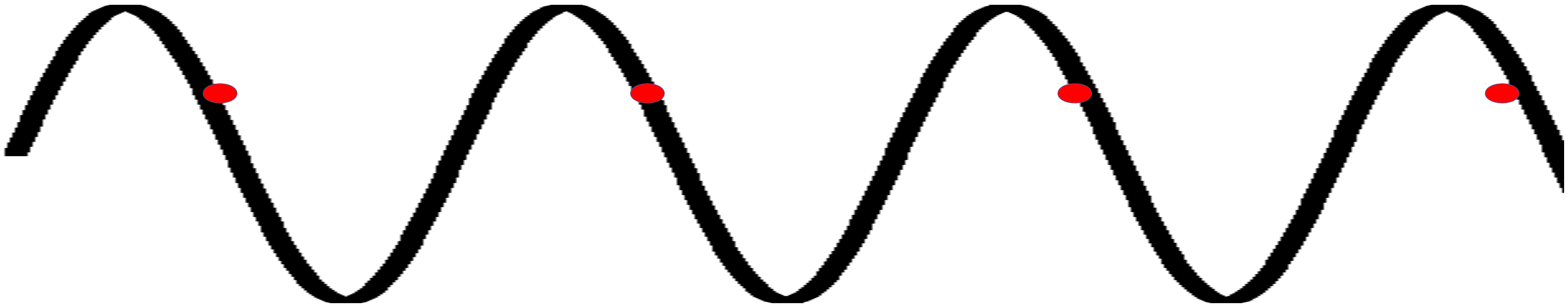
Bunch volume vs emittance ratio



- Bunch volume ~$\sigma_x \sigma_y \sigma_z$, goes down rapidly for flatter beams
- Hence, flat beams → higher bunch density → shorter lifetime, emittance growth
- Mitigating strategies
  - – Use "round" beams
  - ✗ Reduce beam current and thus flux
  - ✔ Make the bunch longer (larger σ_z)

Longitudinal Dynamics 101

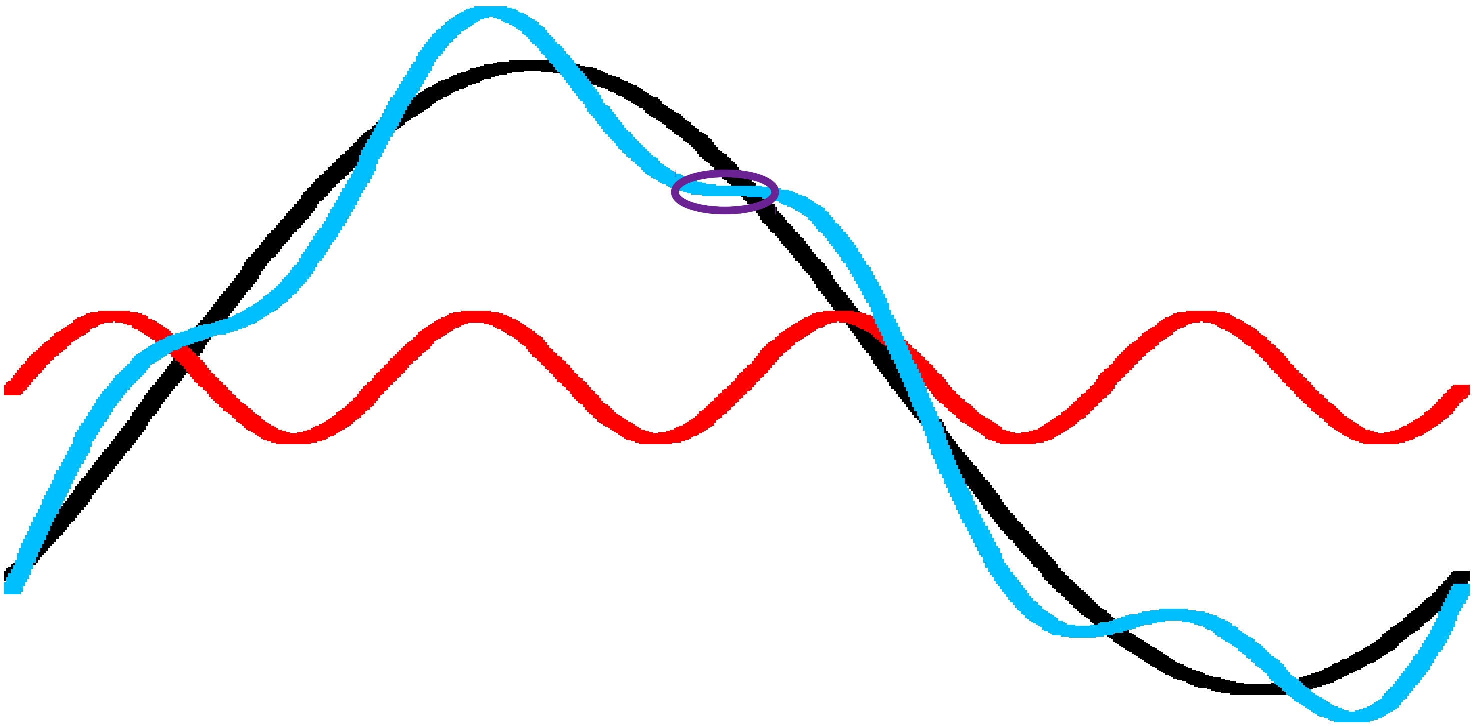
- Storage rings use radio frequency ("rf") systems to restore energy that the beam loses to synchrotron radiation
- Sinusoidal variation of the voltage focuses the beam longitudinally
  - Allows storing beam in bunches
  - Combination of rf voltage, frequency, and lattice properties defines a nominal bunch duration



- The slope of the voltage determines the bunch duration
- To make bunches longer, we can
  - Add a second, higher harmonic frequency to synthesize a flatter waveform, and/or
  - Build new rf cavities working at a lower frequency

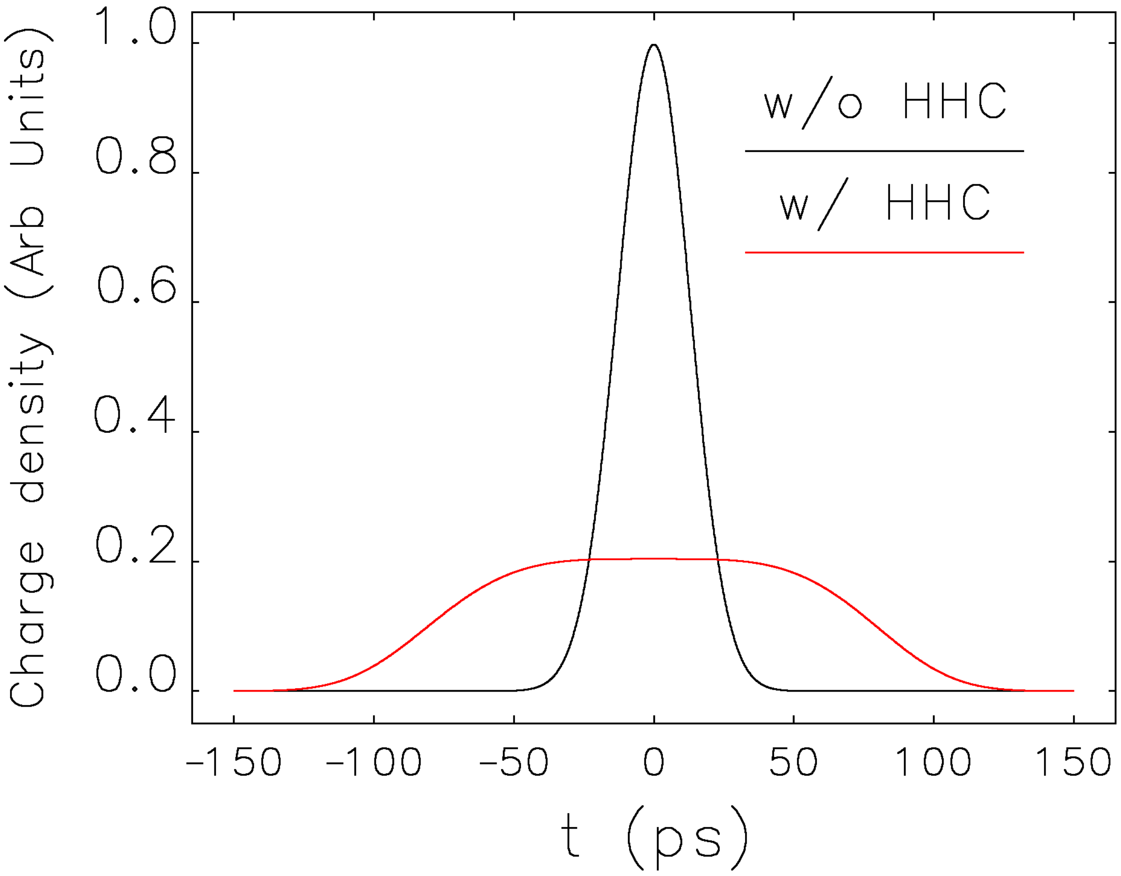
Higher Harmonic Cavity

- For APS-U, plan a 4th-harmonic bunch lengthening cavity
- This will nominally lengthen the bunch by a factor of 4



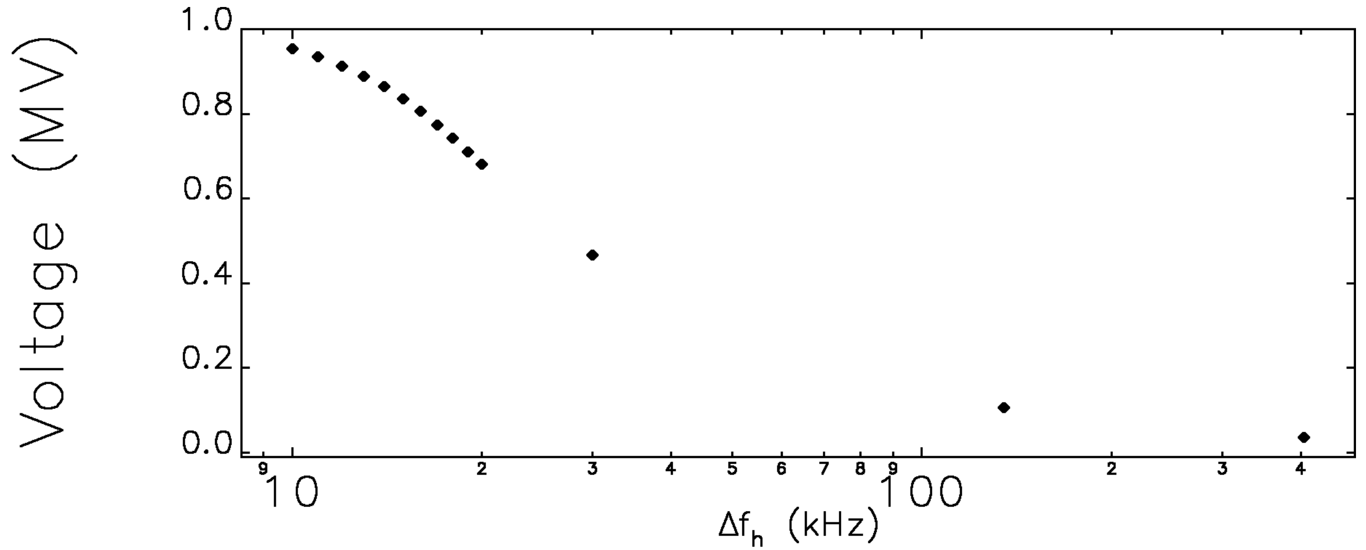
Higher Harmonic Cavity

- For APS-U, plan a 4th-harmonic bunch lengthening cavity
- This will nominally lengthen the bunch by a factor of 4
- Naively expect 4-fold improvement in lifetime



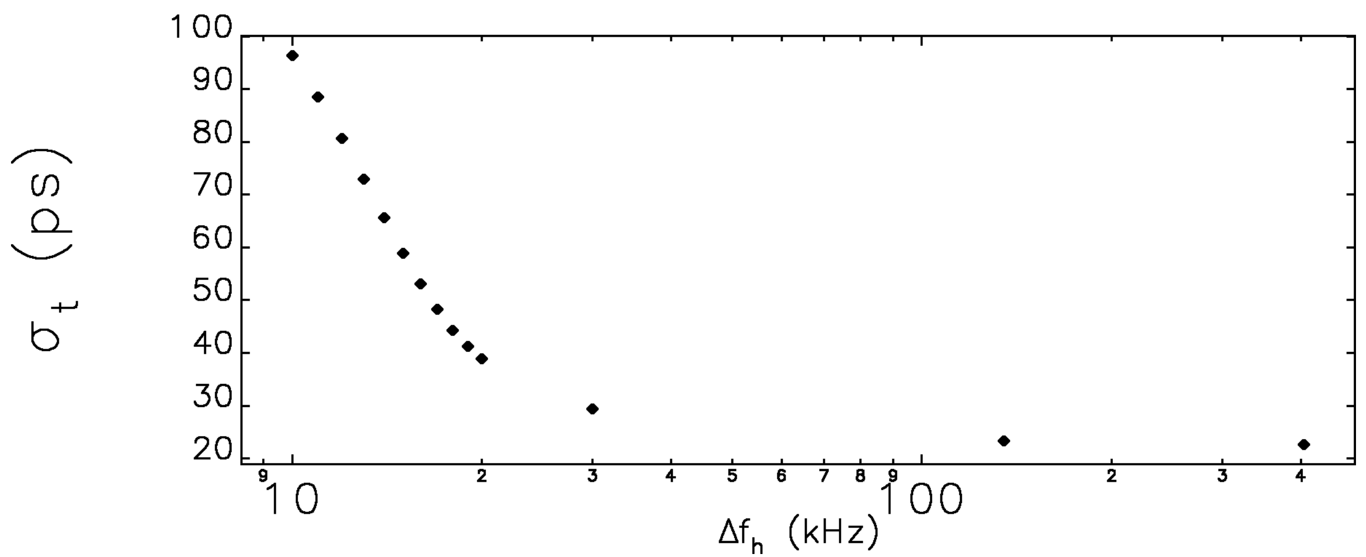
Idealized bunch shapes in the absence of collective effects.

Harmonic Cavity Tuning



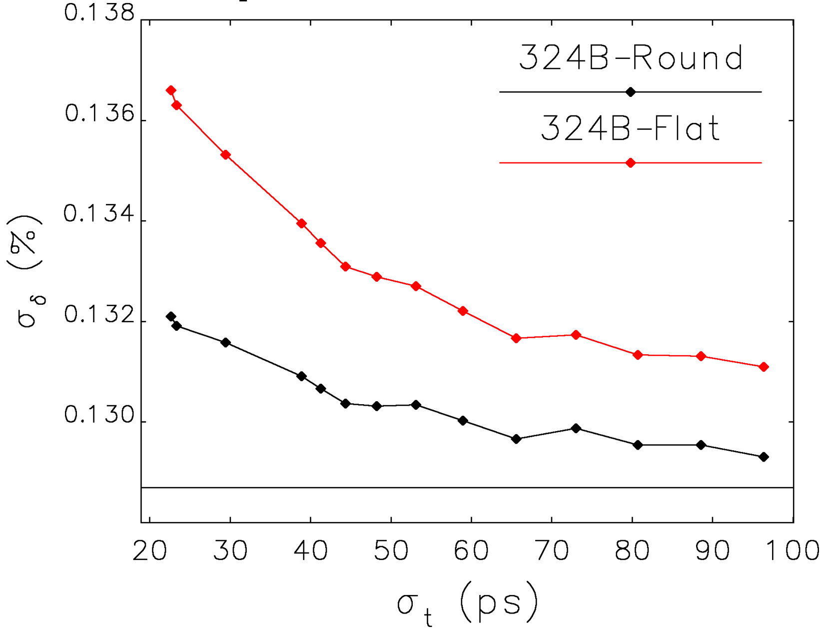
Harmonic cavity
is beam-driven

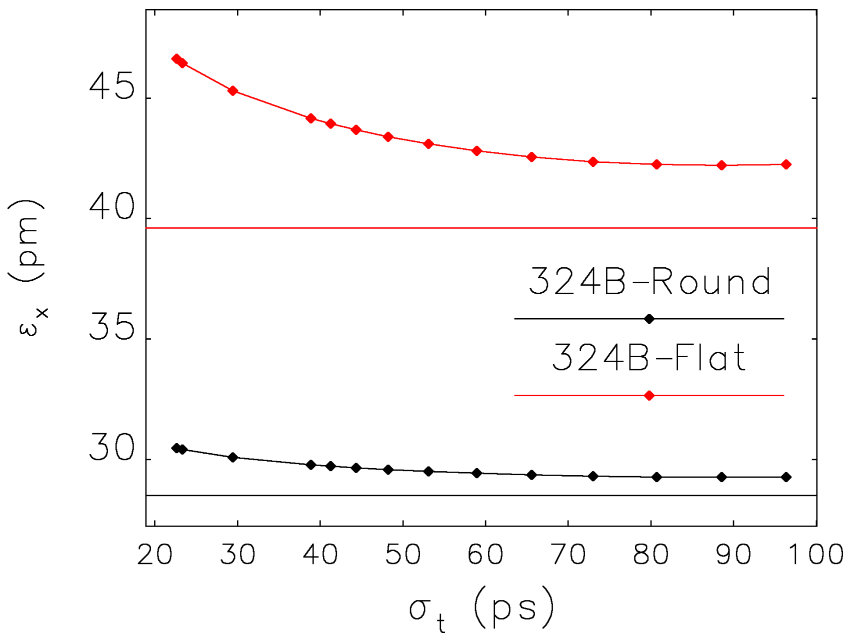
Voltage build-up
is determined
by how much it
is “detuned” from
the exact harmonic

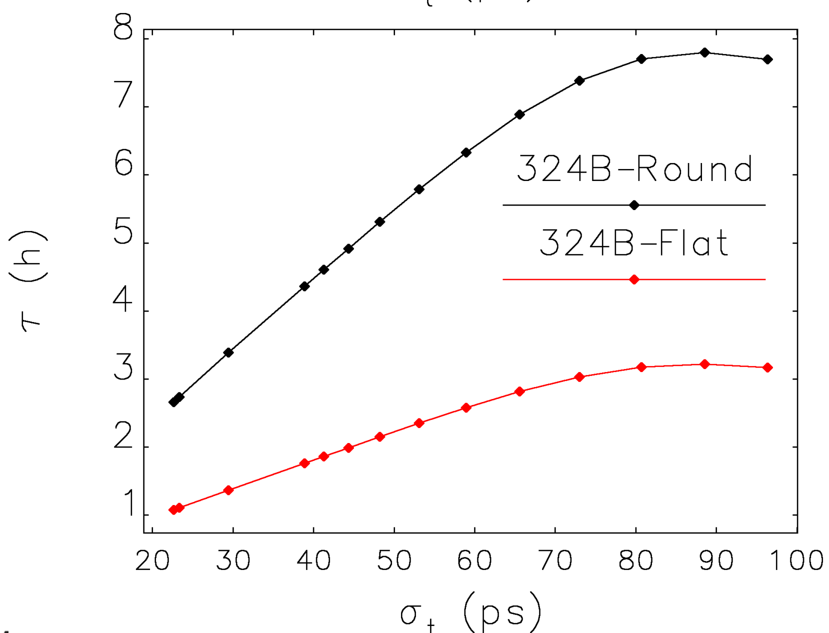


Less detuning→
Higher voltage→
Longer bunches
(up to a point)

324B parameters, lifetime vs bunch duration







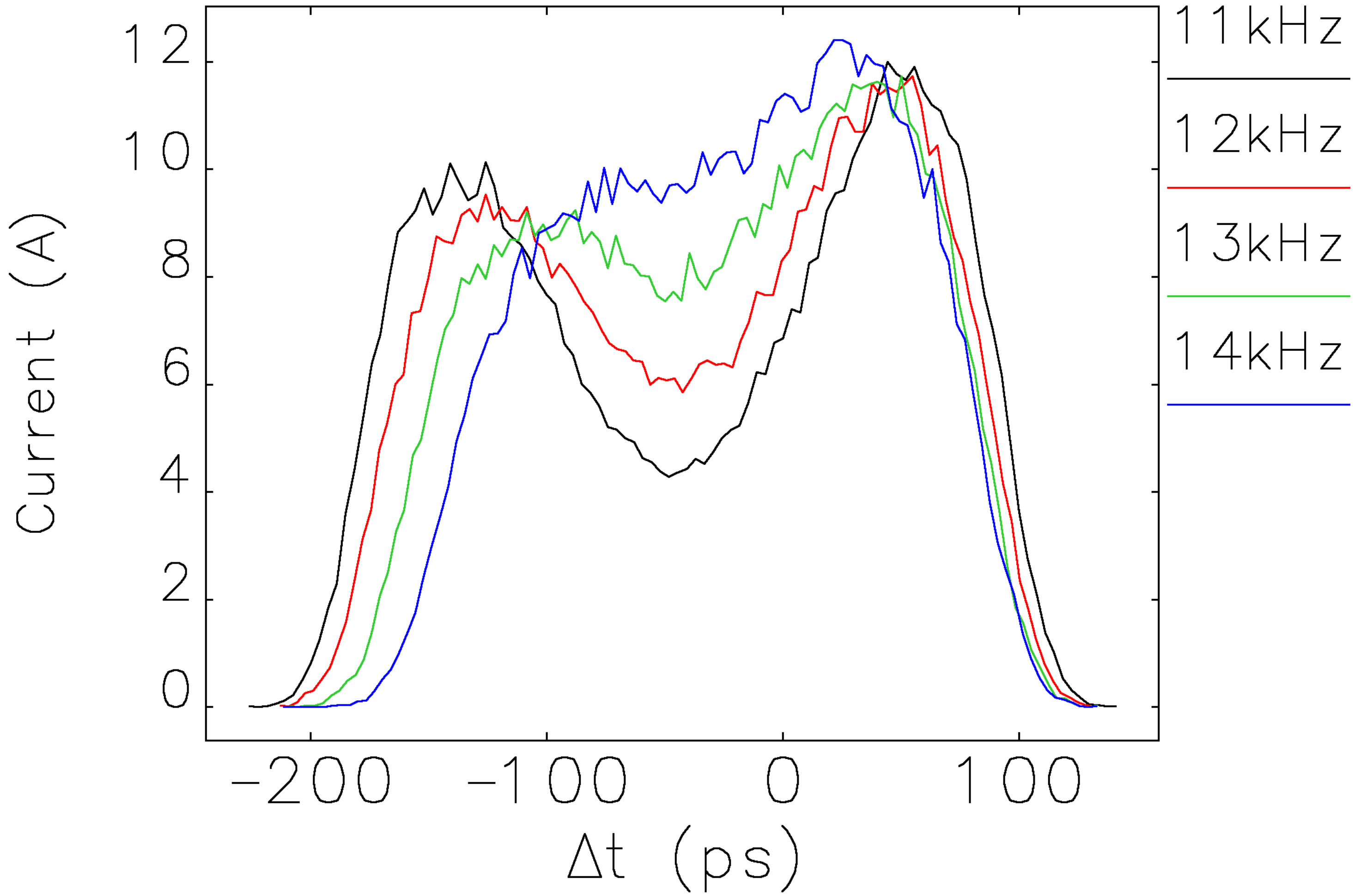
- Bunch duration is varied by varying the HHC detuning
- Flat beam case shows slightly more elevated energy spread
- Zero-current x emittances are 28.5 pm (round) and 39.6 pm (flat)
  - Growth is 3% for round beam vs 7% for flat beam
- <u>Lifetime drops 2.5-fold for flat beam</u>

Lifetime calculations

- Lifetimes shown include two contributions
  - Touschek scattering: hard electron-electron scattering within a bunch
  - Gas scattering after 1000 A*h of dose (~1 year of operation)
- Values arrived at through complex simulations [1,2]
  - Simulation of commissioning for 100 possible actual machines [3]
  - Simulation of dynamic and momentum acceptances for each
  - Calculation of gas scattering lifetime from DA, MA, pressure profiles [4]
  - Calculation of Touschek lifetime, including [5]
    - Particle tracking simulation to determine bunch shape [6]
    - Intrabeam scattering contribution to emittance, energy spread
- We get 100 lifetime values, but show the 10^{th} percentile
- Hence, we will eventually probably have longer lifetime than shown
  - By luck (90% chance)
  - As we learn gradually to correct residual errors
  - As we learn to better optimize nonlinear dynamics

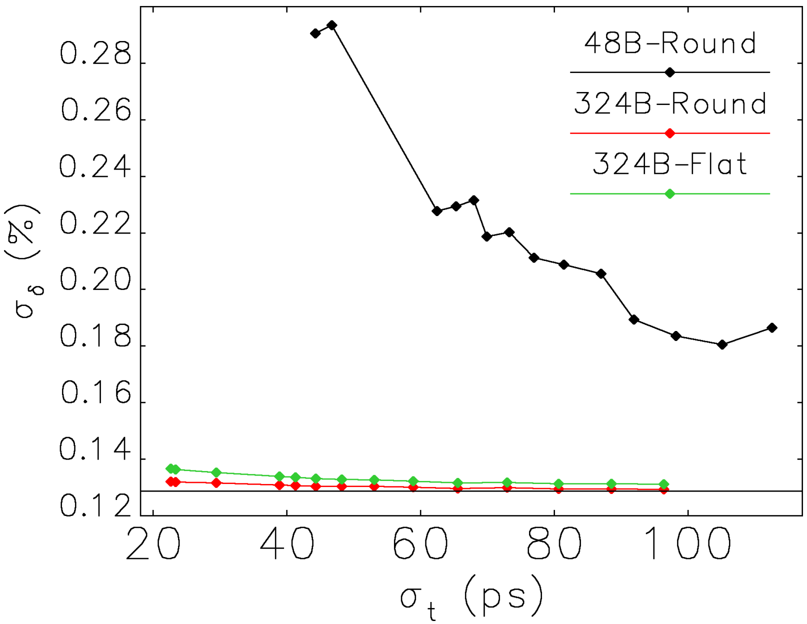
1: M. Borland et al., IPAC15, p. 1776.
2: M. Borland et al., NAPAC16, WEPOB01.
3: V. Sajaev et al., IPAC15, p. 553.
4: M. Borland et al., IPAC15, p. 546.
5: A. Xiao et al., IPAC15, p. 559.
6. M. Borland et al., IPAC15, p. 543.

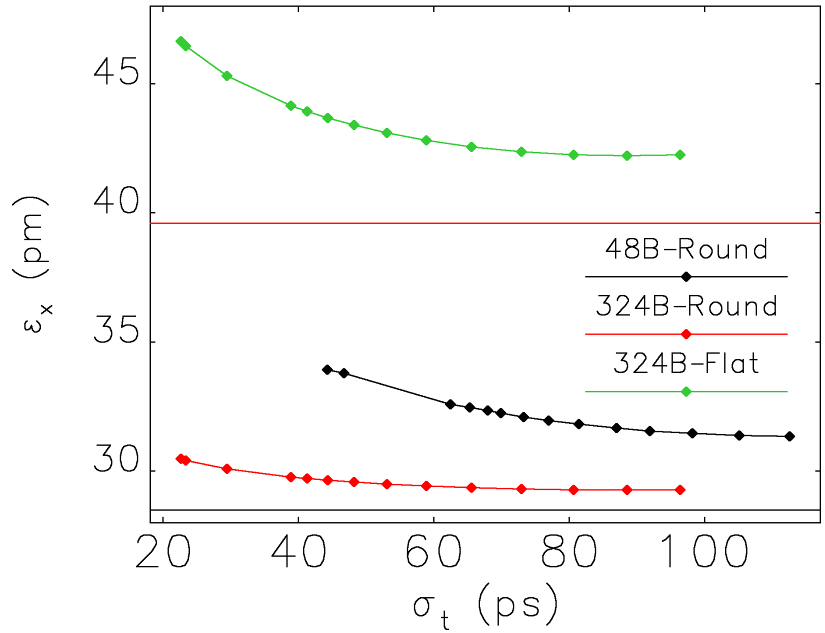
324B bunch shape

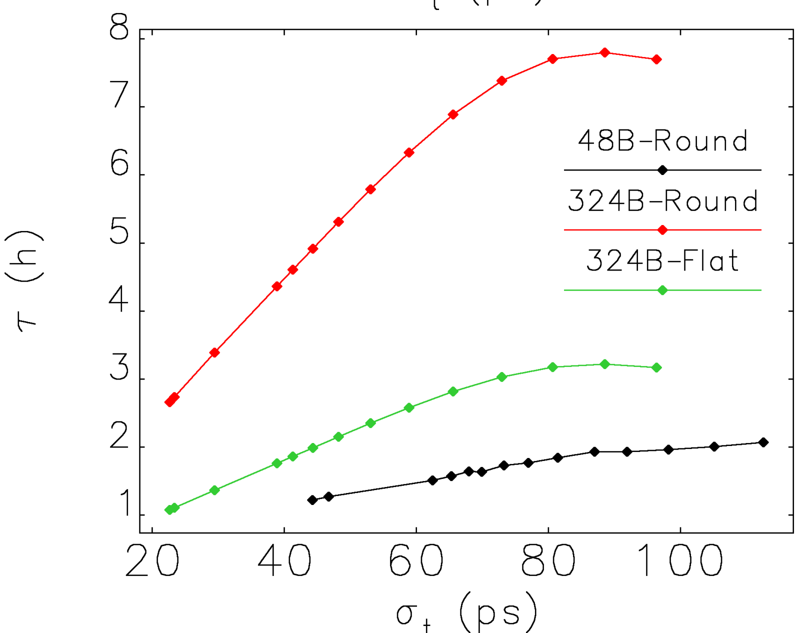


- HHC detuning of 11 kHz maximizes the lifetime, bunch is “split”
- Detuning of 14 kHz gives ~15% lower lifetime, bunch is “normal”

48B parameters, lifetime vs bunch duration

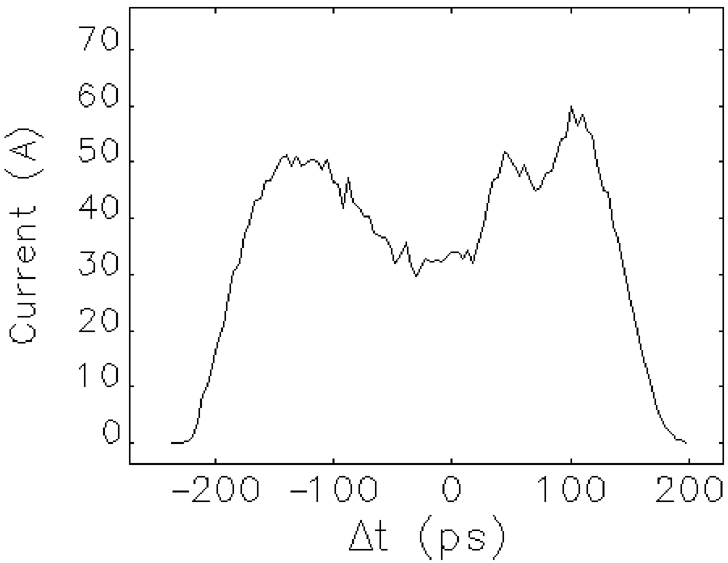




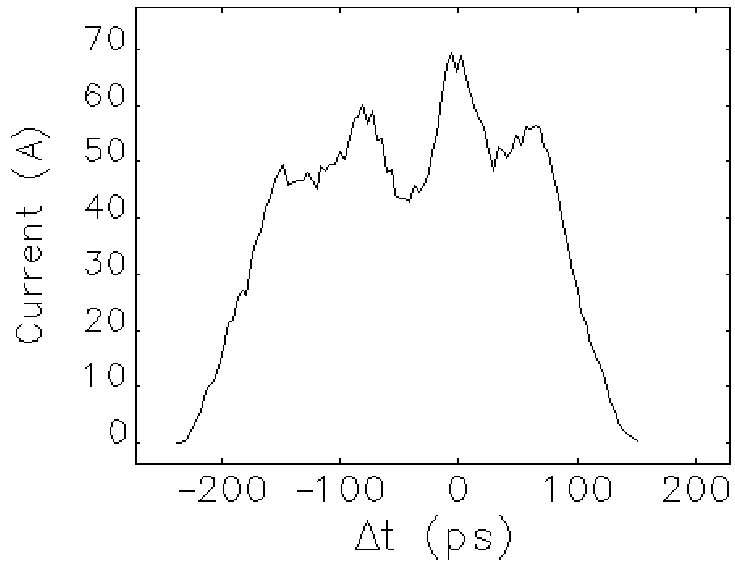


- Energy spread dramatically inflated by collective instability
- Emittance somewhat inflated compared to 324B mode
- Lifetime much shorter for 48-bunch mode
  - Recent nonlinear dynamics adjustments give ~60% improvement
  - Flat beams untenable in any case

48B bunch shapes



9kHz detuning (maximum lifetime)

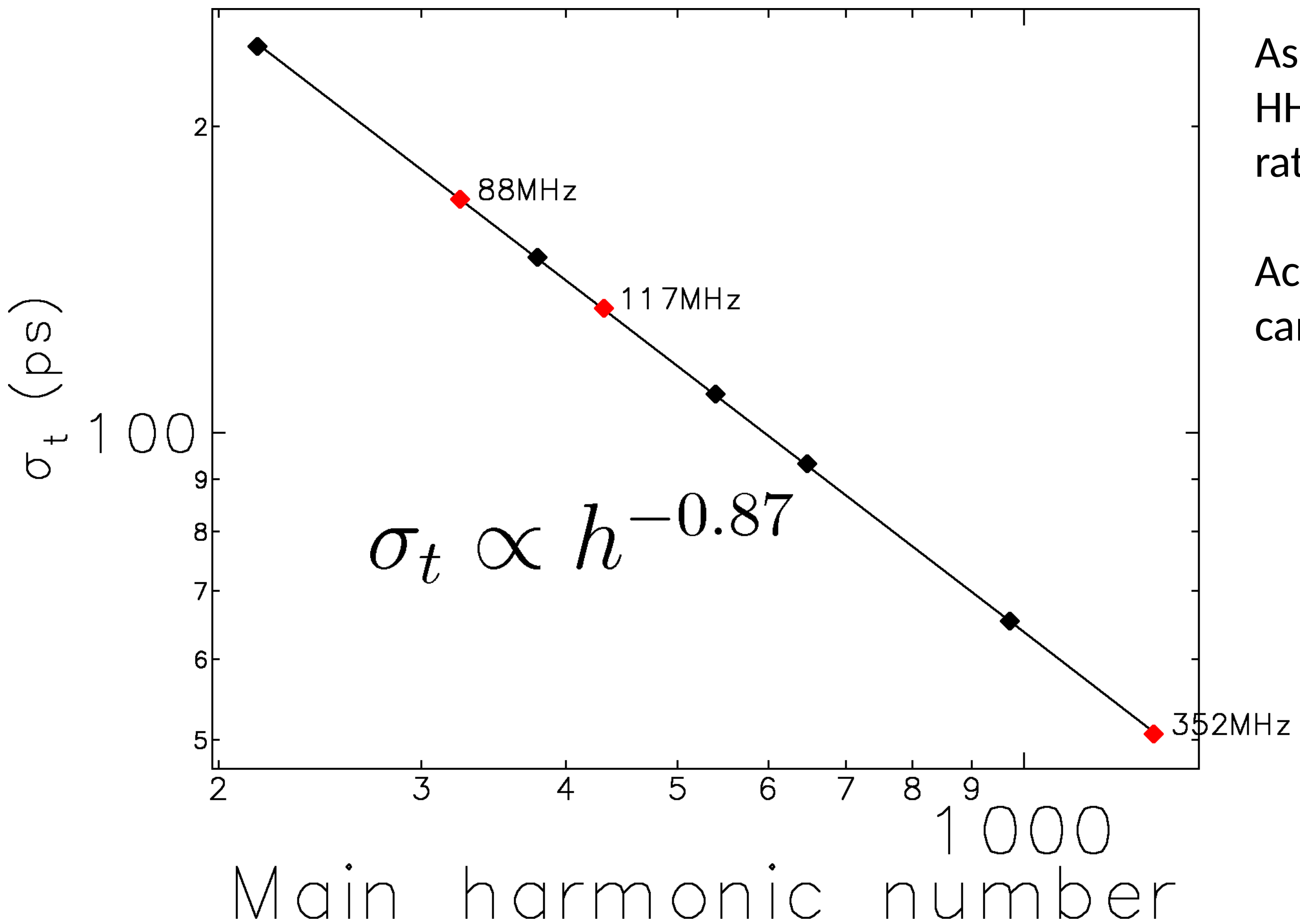


12kHz detuning (10% shorter lifetime)

- Beam is very active due to microwave instability
- Energy spectrum is also noisy
- Each bunch will be slightly different even for the same current
- Hybrid bunch is similar in APS today

Rf frequency scaling

- Using low-frequency rf would provide further bunch lengthening
- Must still be combined with an HHC



Assuming "ideal" HHC with harmonic ratio of 4.

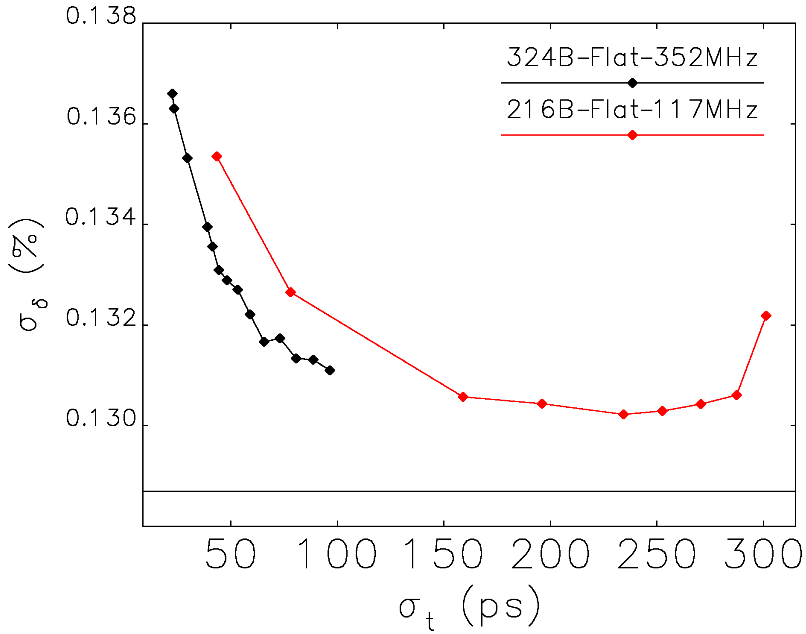
Actual bunch lengths can be longer.

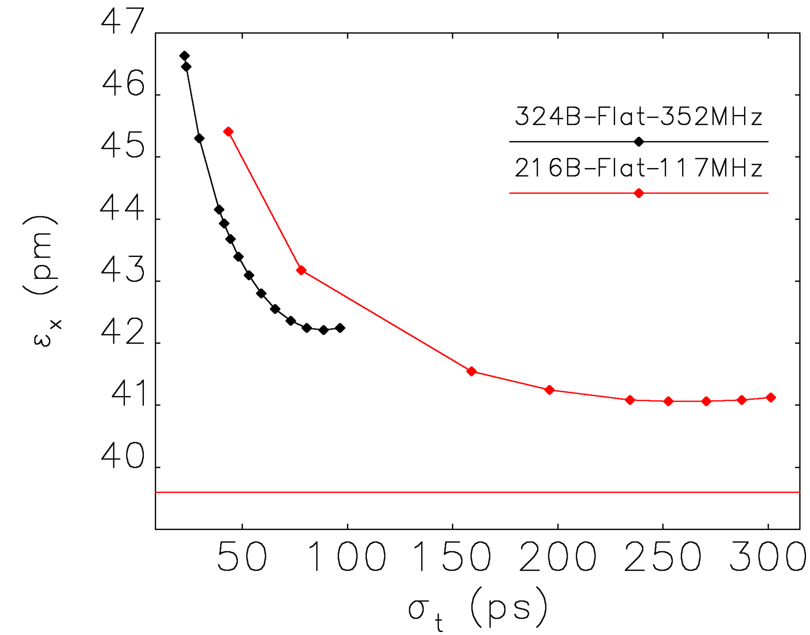
Low-frequency rf options

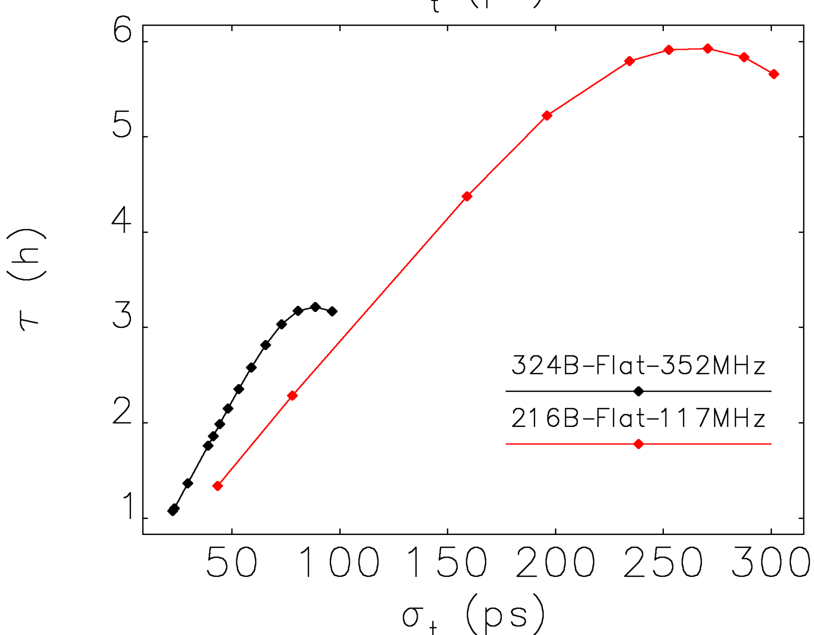
1. Keep a few existing 352 MHz cavities as harmonic cavities
   - New cavities could be 88 MHz or 117 MHz
   - 117 MHz
     - Allows 48- and 216-bunch modes, but not 324
     - Attractive for space reasons
   - 88 MHz
     - Allows 54- and 324-bunch modes, but not 48
2. Start from scratch with all new cavities, e.g.,
   - 130 MHz, giving 48- and 240-bunch modes
     - Better bunch pattern options, smaller cavities, but higher cost
   - 91 MHz, giving 48- and 336-bunch modes
     - Best bunch pattern options, but higher cost and space requirements

Cost and schedule risk are significant concerns with all options.

Low-frequency rf, many-bunch mode

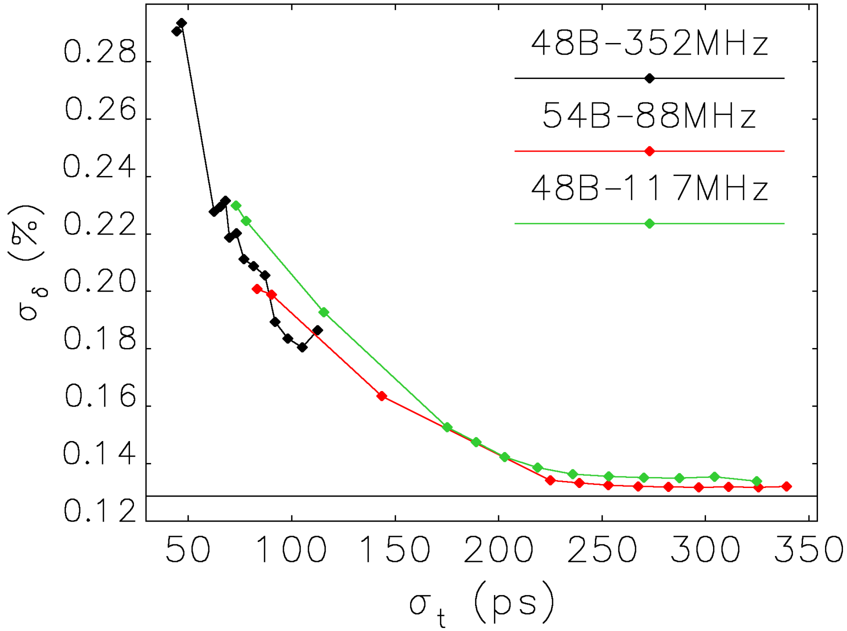


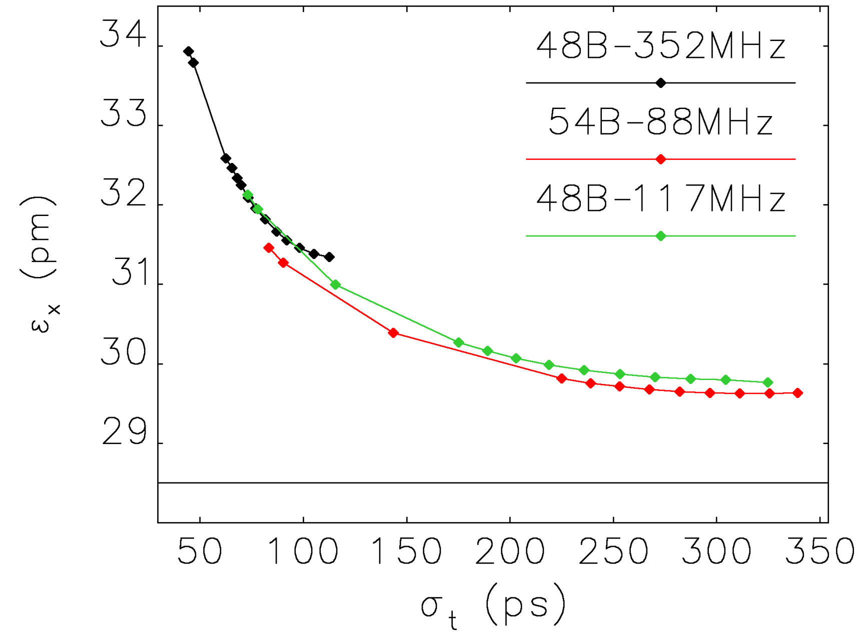


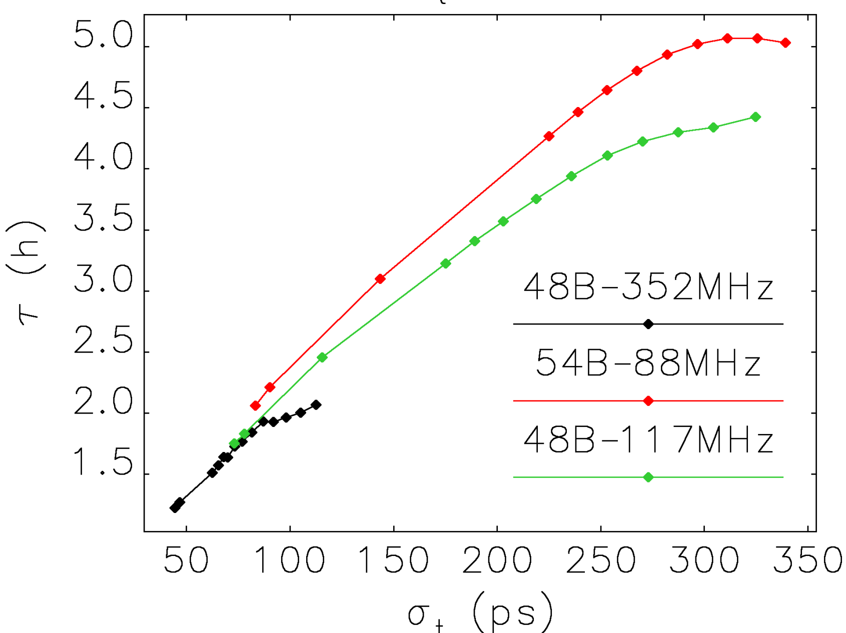


- Using low-frequency rf (e.g., 117 MHz) increases bunch volume by lengthening the bunch
  - Some suppression of IBS
  - Improves lifetime ~2-fold
- Issues:
  - With 117 MHz, can't run 324 bunches, which reduces gains

Low-frequency rf, timing mode

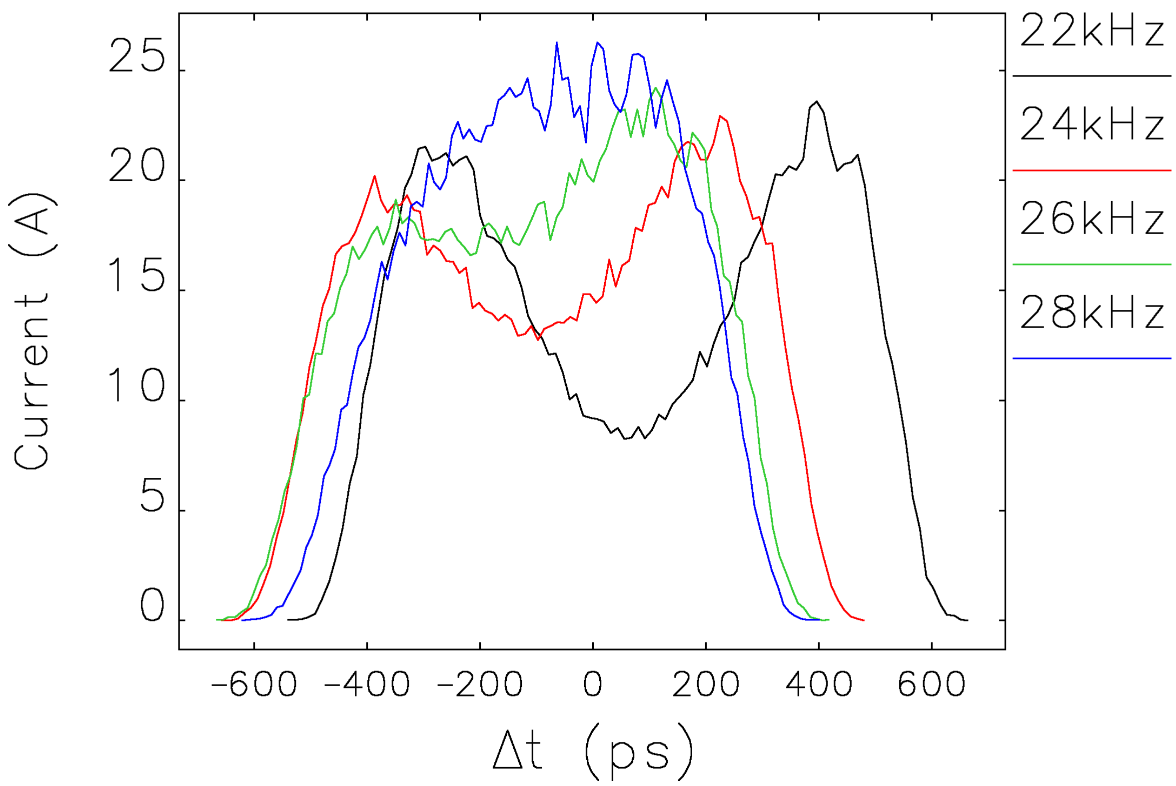






- Much lower energy spread
  - Microwave instability suppressed
- Also improvement in emittance
- Lifetime more than doubles

Bunch shapes for timing mode



- Beam is very quiet compared to previous case
- Can tune for more “normal” profile at expense of lifetime

Ion trapping

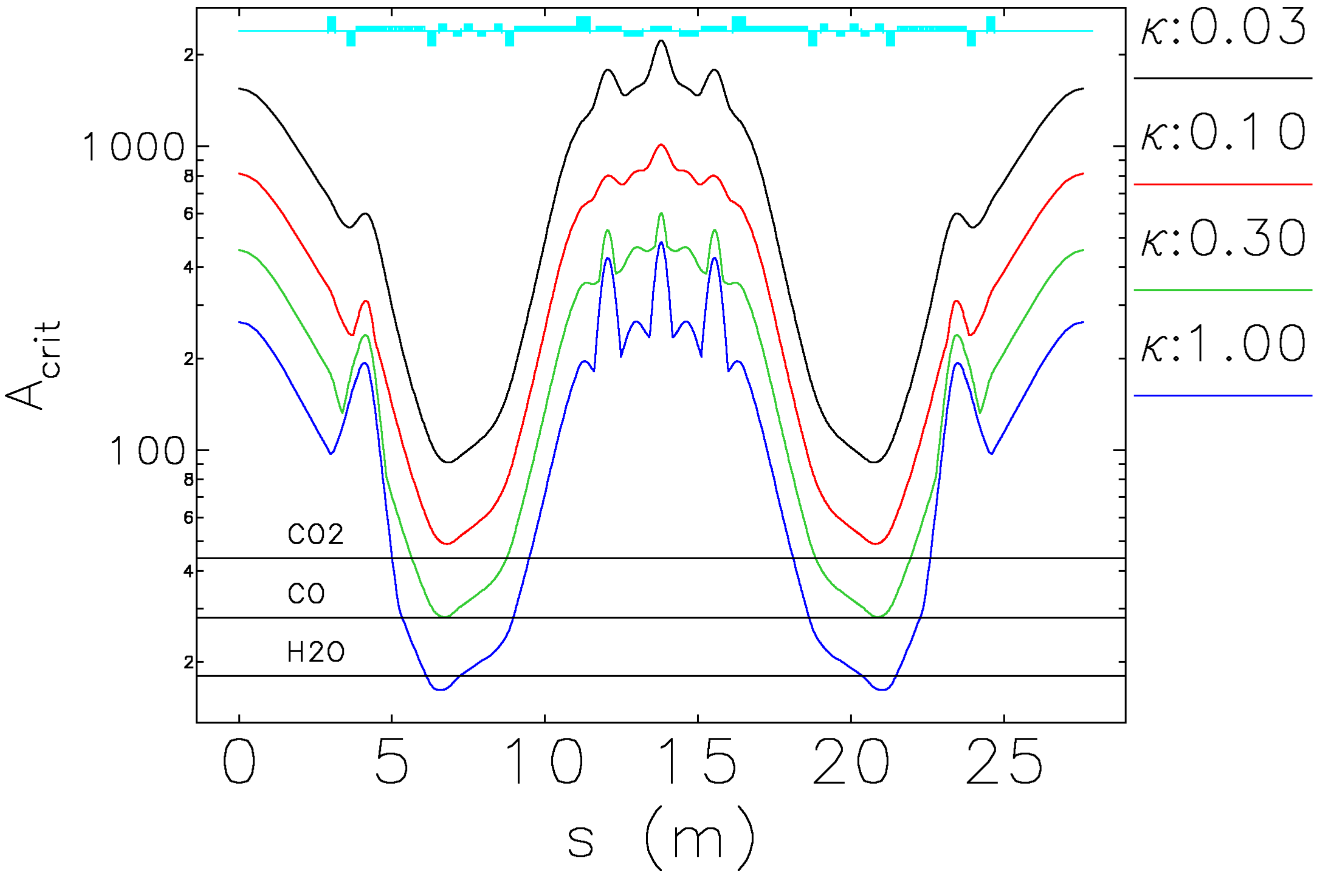
- Electron beams have the potential to trap ions
  - Ions can cause beam motion, emittance growth, beam loss
- Ions with atomic mass heavier than a critical value may be trapped [1]

$$A_{crit}(s) = \frac{N_e r_p S_b}{2\min(\sigma_x(s),\sigma_y(s))(\sigma_x(s)+\sigma_y(s))}$$

- We can increase the critical value by
  - Decrease beam size(s), e.g., make κ small
  - Increase distance S_b between bunches
    - Fewer bunches and/or gaps in the bunch train
  - Increase bunch charge eN_e
- All of these make the lifetime shorter

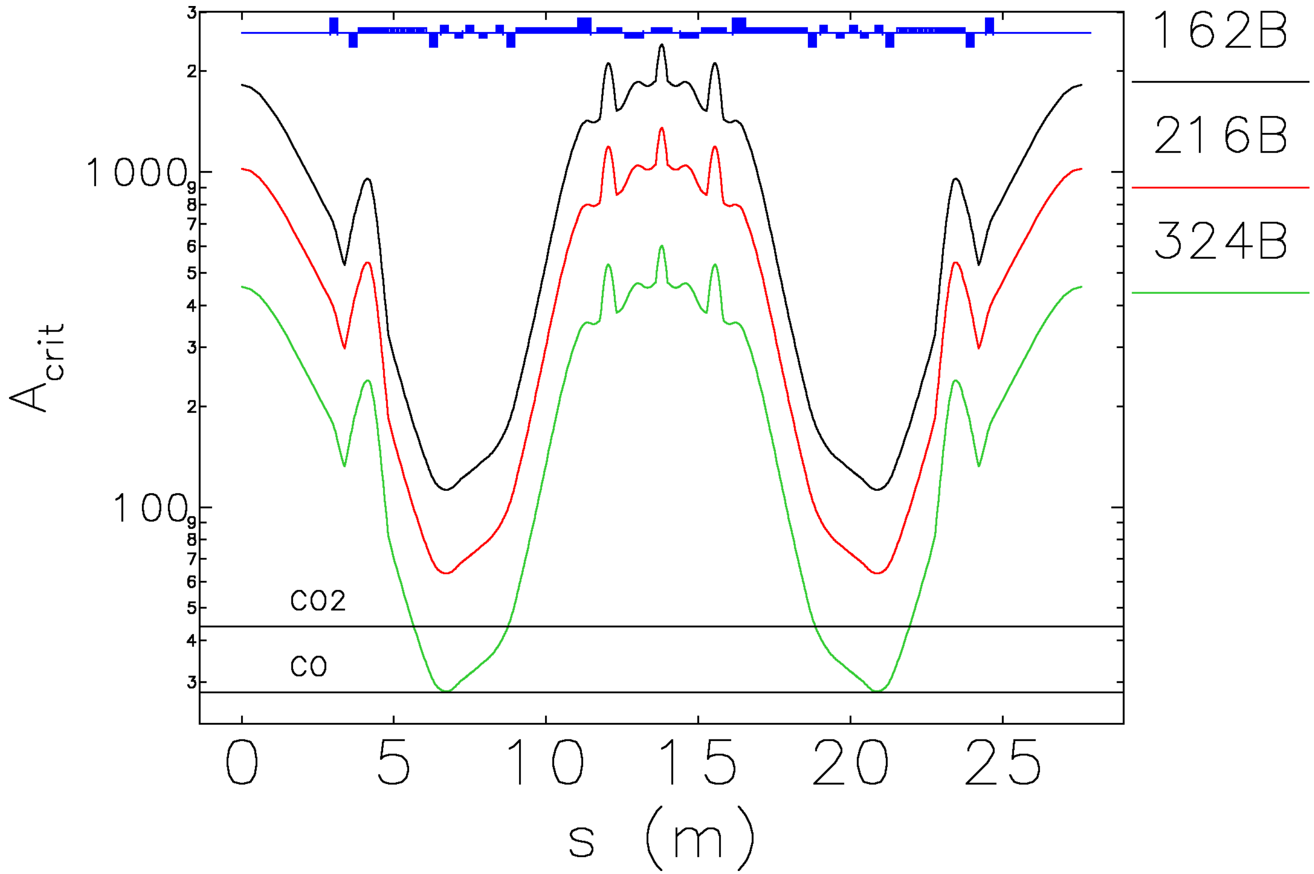
1: Y. Baconnier et al., Tech. Rep. CERN/SPS/80-2 (1980).

Ion trapping for 324B mode



- Round beams appear to trap H_2O, CO, and CO_2
- Flat beams make this much less likely

Ion trapping for various fill modes, κ=0.3



- Introducing gaps in the bunch train can also be effective
- In either case, the lifetime is reduced to various degrees

Beam parameters for lifetime-maximizing bunch length, many-bunch mode

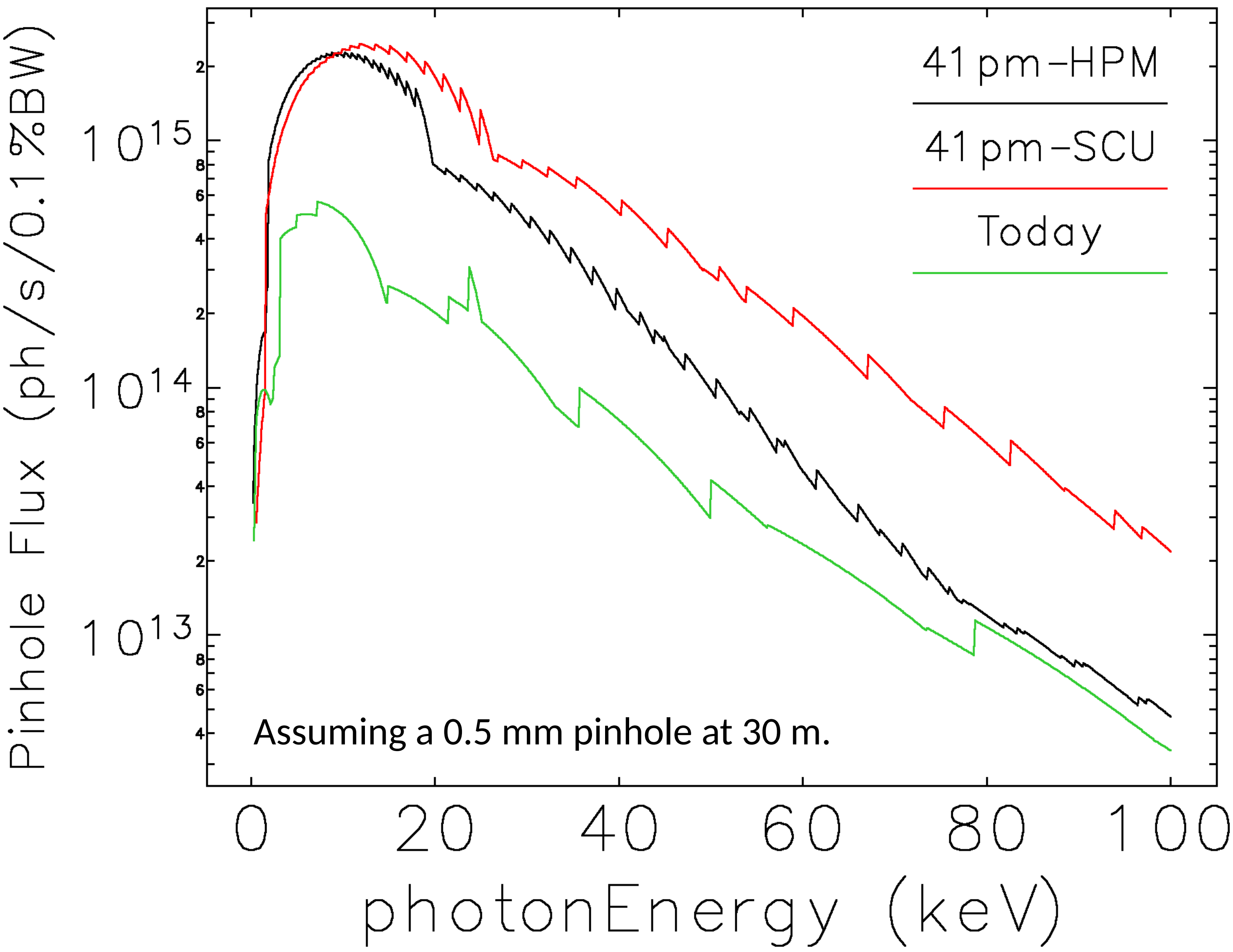
Insertion device beamlines

κ	σ_t	ϵ_x	ϵ_y	β_x	β_y	η_x	σ_x	σ'_x	$\langle xx' \rangle$	σ_y	σ'_y	$\langle yy' \rangle$	σ_δ	$\tau_{10^{th}}$	ΔT_{inj}
	ps	pm	pm	m	m	mm	μm	μrad	μmμrad	μm	μrad	μmμrad	10^{-4}	h	s
324B-352MHz															
0.10	89	42.2	4.2	4.9	1.9	1.466	14.5	2.9	-0.0	2.8	1.5	0.0	1.31×10^1	3.21	3.6
0.99	89	29.3	29.0	4.9	1.9	1.466	12.1	2.4	-0.0	7.4	3.9	0.0	1.30×10^1	7.75	8.6
216B-117MHz															
0.10	271	41.1	4.1	4.9	1.9	1.466	14.3	2.9	-0.0	2.8	1.5	0.0	1.30×10^1	5.89	9.8
0.99	271	29.0	28.7	4.9	1.9	1.466	12.1	2.4	-0.0	7.3	3.9	0.0	1.29×10^1	13.42	22.4

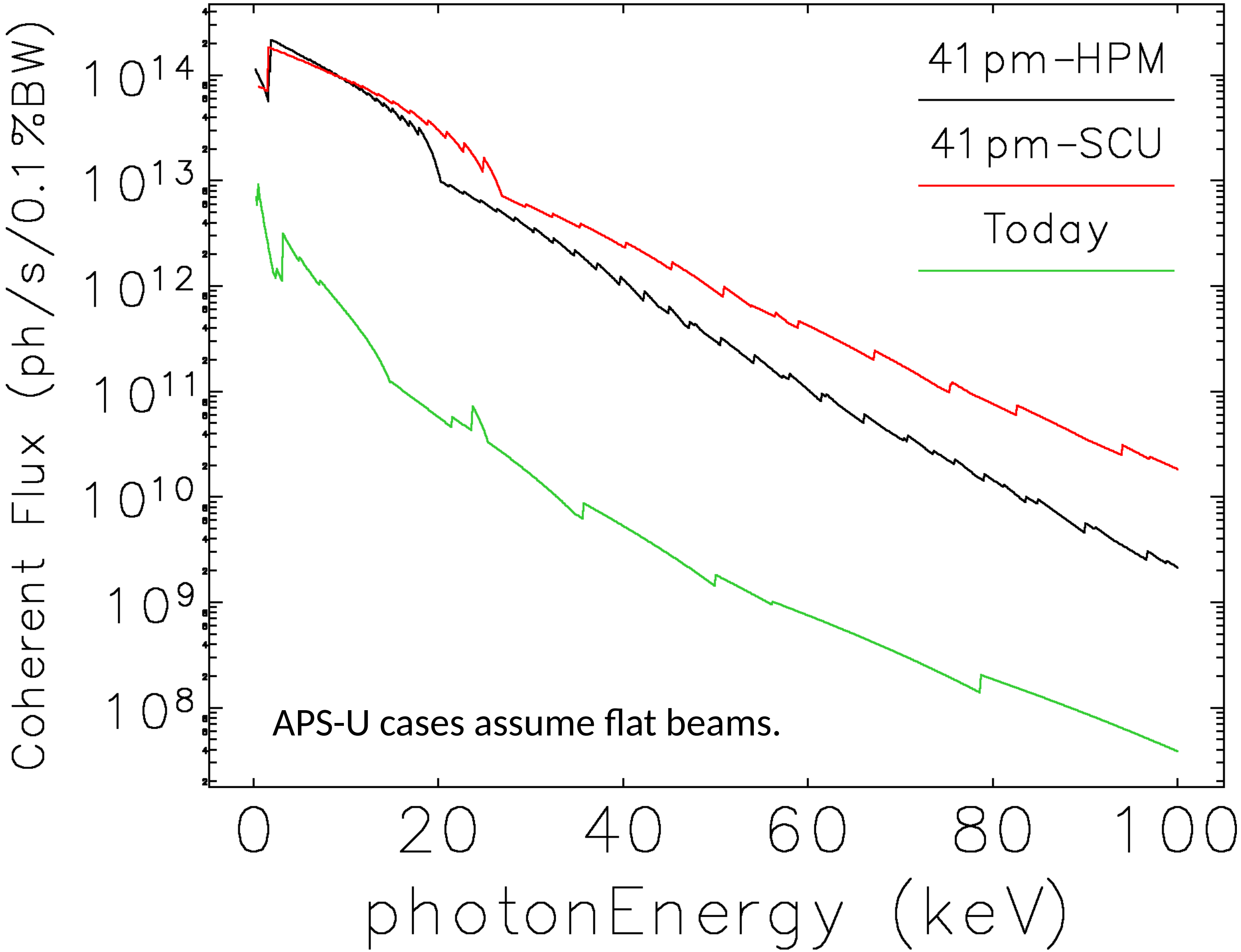
Wiggler beamlines

κ	σ_t	ϵ_x	ϵ_y	β_x	β_y	η_x	σ_x	σ'_x	$\langle xx' \rangle$	σ_y	σ'_y	$\langle yy' \rangle$	σ_δ	$\tau_{10^{th}}$	ΔT_{inj}
	ps	pm	pm	m	m	mm	μm	μrad	μmμrad	μm	μrad	μmμrad	10^{-4}	h	s
324B-352MHz															
0.10	89	42.2	4.2	1.2	2.4	6.712	11.4	20.9	228.5	3.2	3.2	-9.1	1.31×10^1	3.21	3.6
0.99	89	29.3	29.0	1.2	2.4	6.712	10.6	19.5	199.4	8.3	8.4	-63.3	1.30×10^1	7.75	8.6
216B-117MHz															
0.10	271	41.1	4.1	1.2	2.4	6.712	11.3	20.8	224.3	3.1	3.1	-8.9	1.30×10^1	5.89	9.8
0.99	271	29.0	28.7	1.2	2.4	6.712	10.6	19.5	198.7	8.3	8.3	-62.7	1.29×10^1	13.42	22.4

324B Mode Pinhole Flux Comparison



324B Mode Coherent Flux Comparison



Beam parameters for lifetime-maximizing bunch length, timing mode

Insertion device beamlines

κ	σ_t ps	ϵ_x pm	ϵ_y pm	β_x m	β_y m	η_x mm	σ_x μm	σ'_x μrad	$\langle xx' \rangle$ μmμrad	σ_y μm	σ'_y μrad	$\langle yy' \rangle$ μmμrad	σ_δ 10^{-4}	$\tau_{10^{th}}$ h	ΔT_{inj} s
54B-88MHz															
0.99	326	29.6	29.3	4.9	1.9	1.466	12.2	2.5	-0.0	7.4	4.0	0.0	1.32×10^1	5.05	33.6
48B-352MHz															
0.99	113	31.3	31.1	4.9	1.9	1.466	12.7	2.5	-0.0	7.6	4.1	0.0	1.86×10^1	2.07	15.5
48B-117MHz															
0.99	325	29.8	29.5	4.9	1.9	1.466	12.2	2.5	-0.0	7.4	4.0	0.0	1.34×10^1	4.41	33.1

Wiggler beamlines

κ	σ_t ps	ϵ_x pm	ϵ_y pm	β_x m	β_y m	η_x mm	σ_x μm	σ'_x μrad	$\langle xx' \rangle$ μmμrad	σ_y μm	σ'_y μrad	$\langle yy' \rangle$ μmμrad	σ_δ 10^{-4}	$\tau_{10^{th}}$ h	ΔT_{inj} s
54B-88MHz															
0.99	326	29.6	29.3	1.2	2.4	6.712	10.7	19.8	205.2	8.4	8.4	-64.1	1.32×10^1	5.05	33.6
48B-352MHz															
0.99	113	31.3	31.1	1.2	2.4	6.712	14.0	26.0	356.1	8.6	8.7	-67.8	1.86×10^1	2.07	15.5
48B-117MHz															
0.99	325	29.8	29.5	1.2	2.4	6.712	10.8	20.0	210.0	8.4	8.4	-64.4	1.34×10^1	4.41	33.1

Conclusions

- Lattice decision is planned soon
  - 90-pm lattice already eliminated
  - 67-pm and 41-pm lattices remain
- The 41-pm RB lattice is the leading contender
  - ~60% brightness improvement compared to the nominal lattice
  - Automated commissioning algorithm works just as well
  - Beam lifetime clearly workable in many-bunch mode, more challenging in timing modes
  - Swap-out injection required, simulations show high efficiency
  - Single-bunch instabilities slightly worse, but manageable

Conclusion

- Decision is also expected shortly on low-frequency rf option
- Offers many benefits
  - Significantly improved lifetime
  - Longitudinally quiet beam
    - More flexibility to shape the bunch distribution
  - Ability to run flat beams with reasonable lifetime
    - Higher brightness
    - Reduced risk of ion trapping
  - Replacement of legacy systems
- Unfortunately not cost- or risk-free