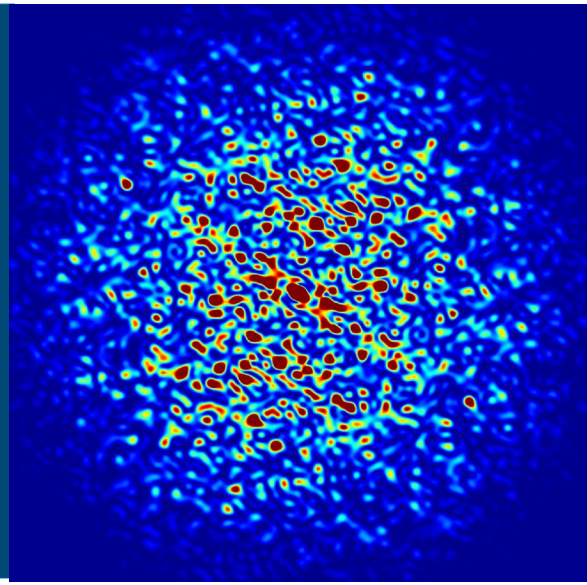
Challenges of on-axis swap-out injection for fourth-generation storage ring light sources



Michael Borland, Ryan Lindberg, Vadim Sajaev, Seungwhan Shin, Yipeng Sun, Aimin Xiao

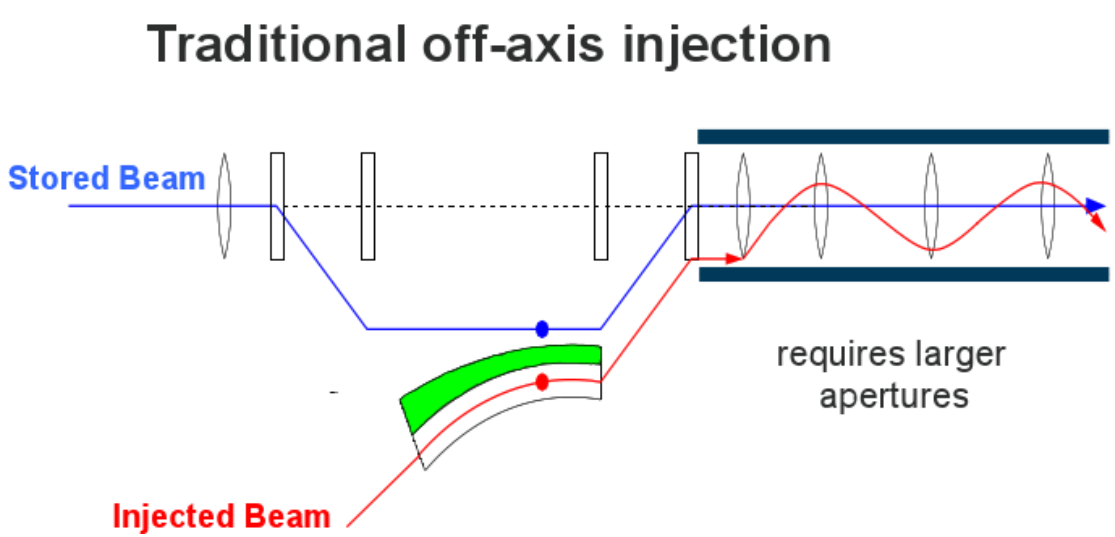
2nd RULε Topical Workshop on Injection and Injection Systems
April 1, 2019

Outline

- Advantages of on-axis injection over accumulation
- APS-U swap-out scheme
- Kicker requirements
- Beam damage risks and solutions
- Injector requirements and options
- Conclusions

On-axis swap-out takes over where top-up left off

- Lower emittance strongly correlated with reduced lifetime and injection aperture[1]
- Top-up operation[2,3] helped 3rd -generation light sources maximize performance
  - Accommodates shorter lifetime, gives higher average current
  - Small amounts of charge added to circulating bunches as they decay
- Swap-out[4,5] accommodates drastically reduced injection aperture



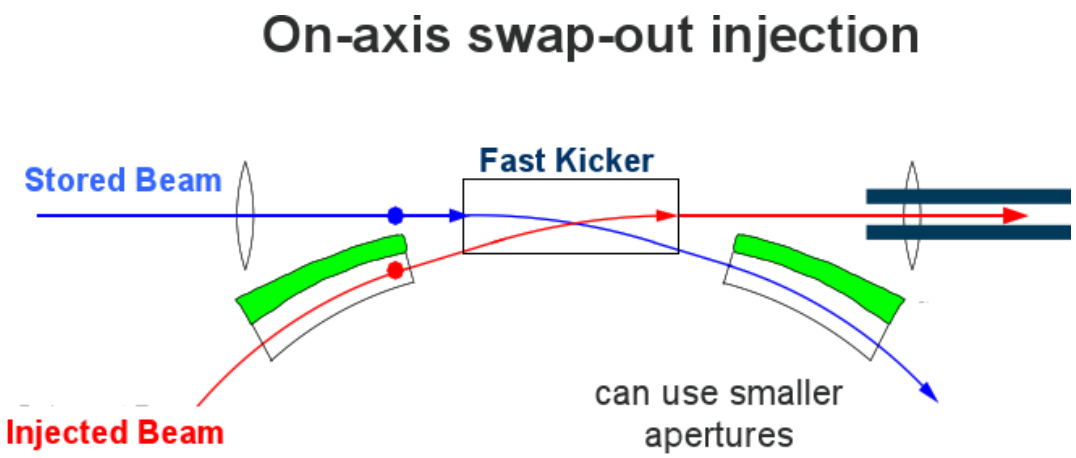


Diagram courtesy C. Steier (ALS).

1: M. Borland et al., JSR 21, 912 (2014).
2: S. Nakamura, EPAC90, 472.
3: L. Emery et al., PAC99, 200.
4: R. Abela et al., EPAC 92, 486.
5: L. Emery et al., PAC03, 256.

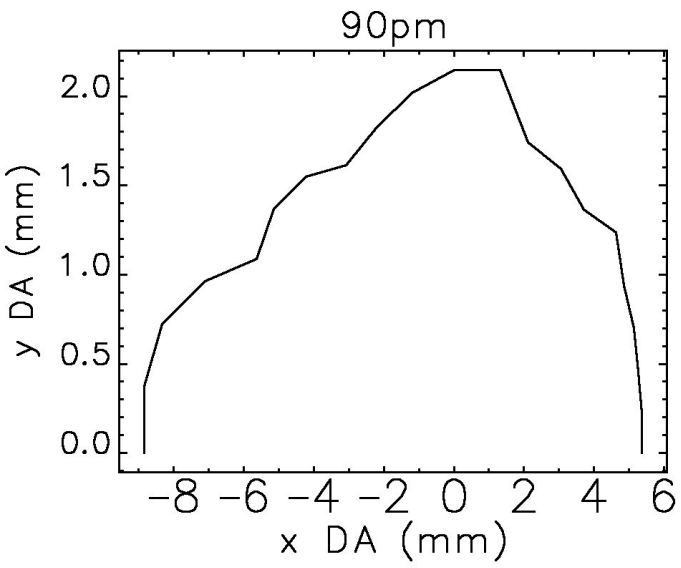
On-axis injection supports higher brightness

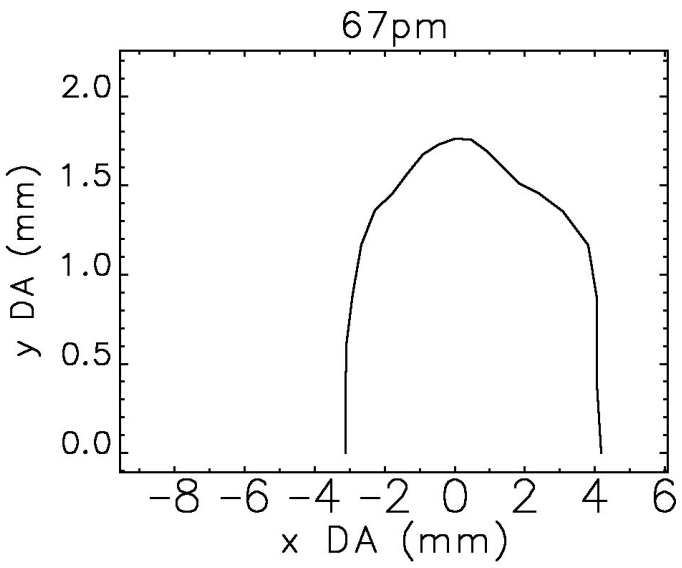
- Major challenge for 4GSRs is nonlinear dynamics
  - Need adequate DA for high-efficiency injection, long elastic gas scattering lifetime
  - Need adequate LMA for long Touschek and inelastic gas scattering lifetimes
- With on-axis injection, can tolerate much smaller DA
  - Allows pushing to lower emittance lattice
  - Allows emphasizing Touschek lifetime over DA
  - Can accommodate injector with larger emittance

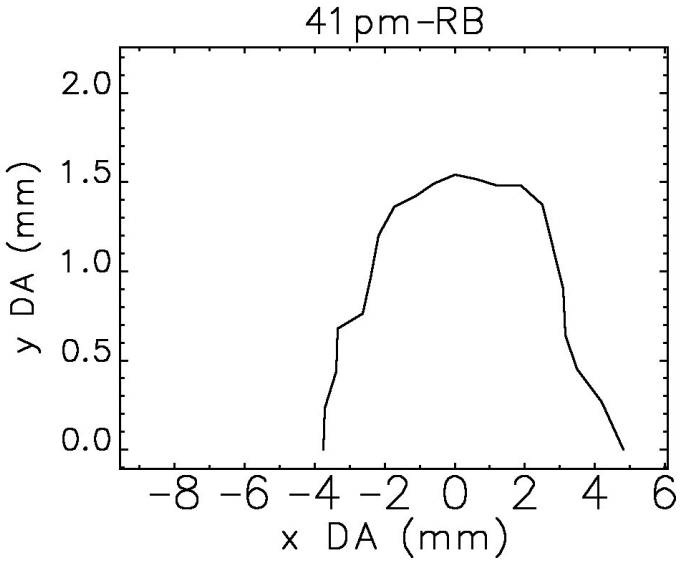
"If you can accumulate, you haven't pushed the lattice hard enough."
— R. Hettel

Low emittance lattices have small DA

- Lattices show considerable variation in DA in spite of similar beta functions at injection point
- All lattices optimized with MOGA-based[1,2] approach emphasizing DA and Touschek lifetime
- 90-pm lattice[3] would allow accumulation
- Others[4,5] work on-axis with ~0.6mm x ~0.2mm rms beam size from booster

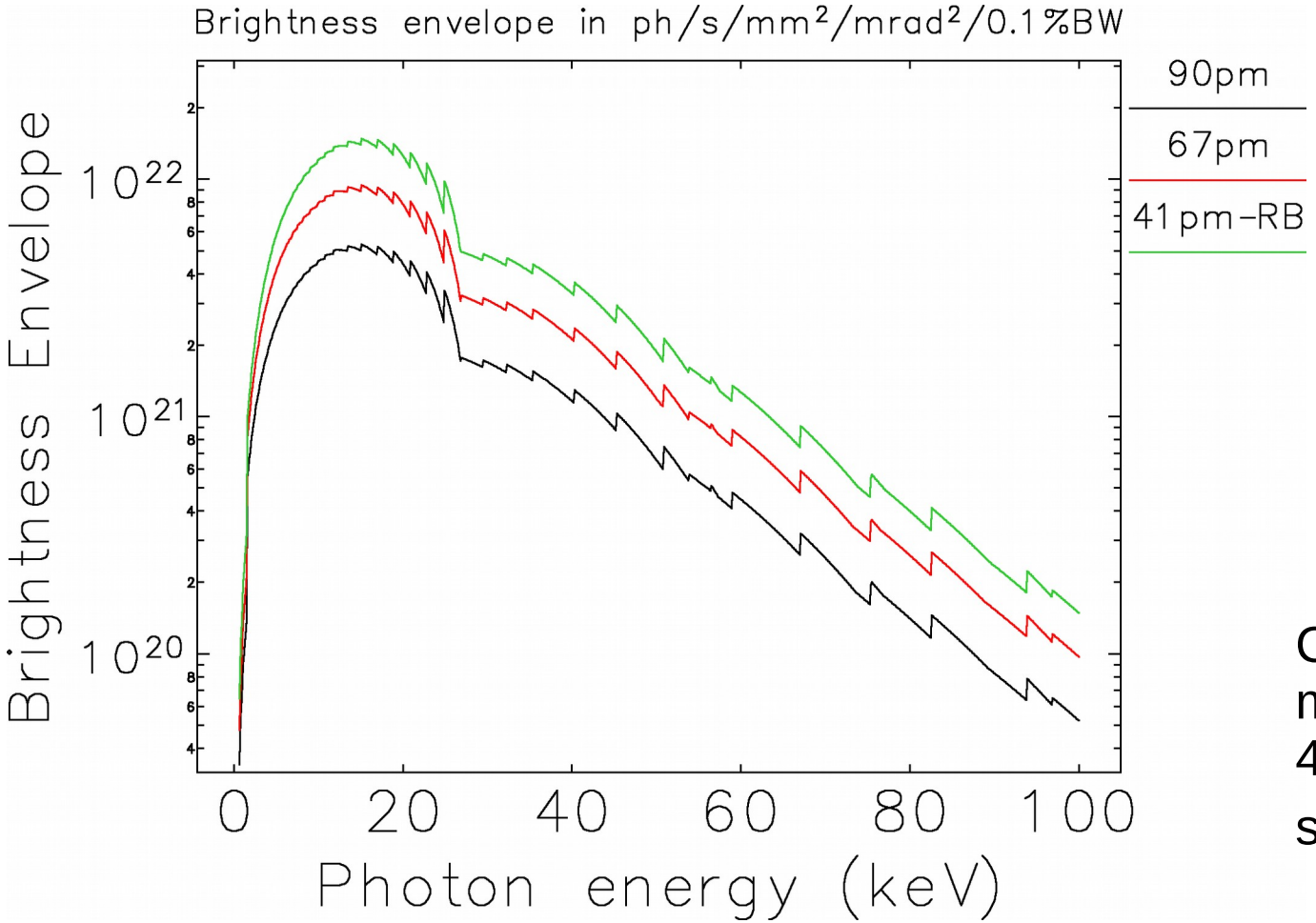






1: N. Srinivas et al., Evol Computing 2, 221 (1995).
2: M. Borland et al., ANL/APS/LS-319 (2010).
3: Y. Sun et al., NAPAC16, 920.
4: M. Borland et al., IPAC15, 1776.
5: M. Borland et al., NAPAC16, 877.

APS-U brightness benefits from abandoning accumulation



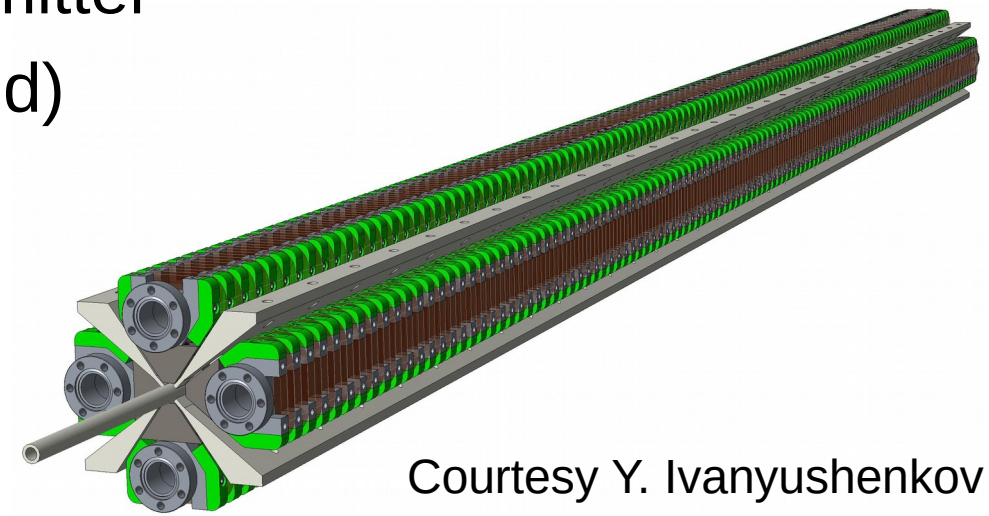
- 67-pm lattice is ~2x brighter than 90-pm
- 42-pm lattice is ~50% brighter than 67-pm
- Lattices in 20-30pm range explored, but became unworkable

Curves are envelopes for set of 3.7-m-long SCUs [1], assuming 200 mA in 48 bunches with $\varepsilon_x=\varepsilon_y$. Intrabeam scattering is included.

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

On-axis injection supports unusual IDs

- In addition to small DA, want to accommodate smaller physical apertures
  - Smaller bore accelerator magnets are smaller, cheaper, stronger
  - IDs with small horizontal aperture can be accommodated without breaking lattice symmetry
- APS-U will accommodate a new device called SCAPE[1]: Super Conducting Arbitrarily Polarized Emitter
  - To achieve the required 10-mm (round) magnetic gap, chamber has a 6-mm inner diameter
  - Two devices will be installed in a ~4.8-m APS-U straight section

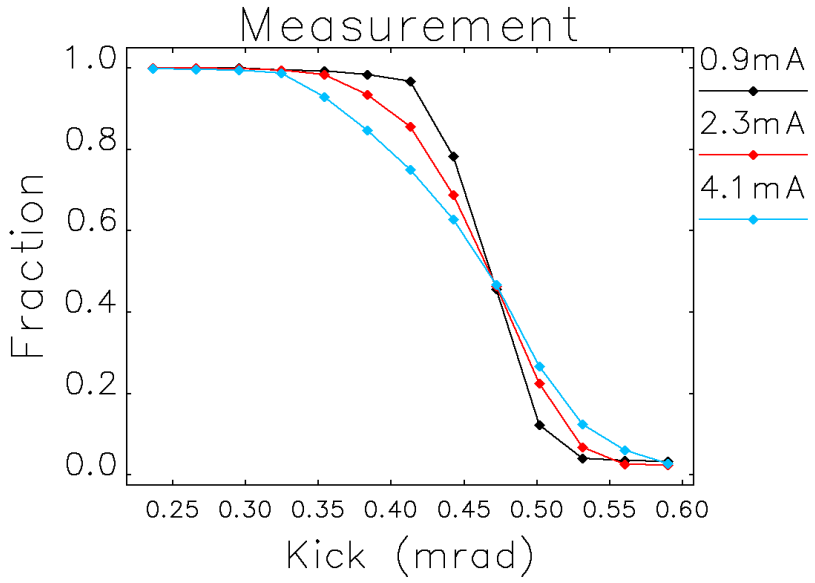


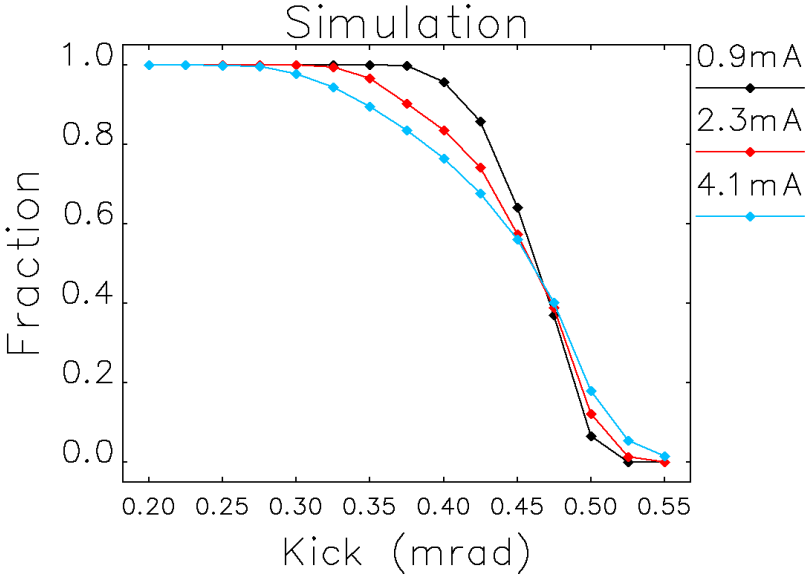
Courtesy Y. Ivanyushenkov

Y. Ivanyushenkov et al., IPAC17, 1596.

On-axis injection reduces high-charge issues at injection

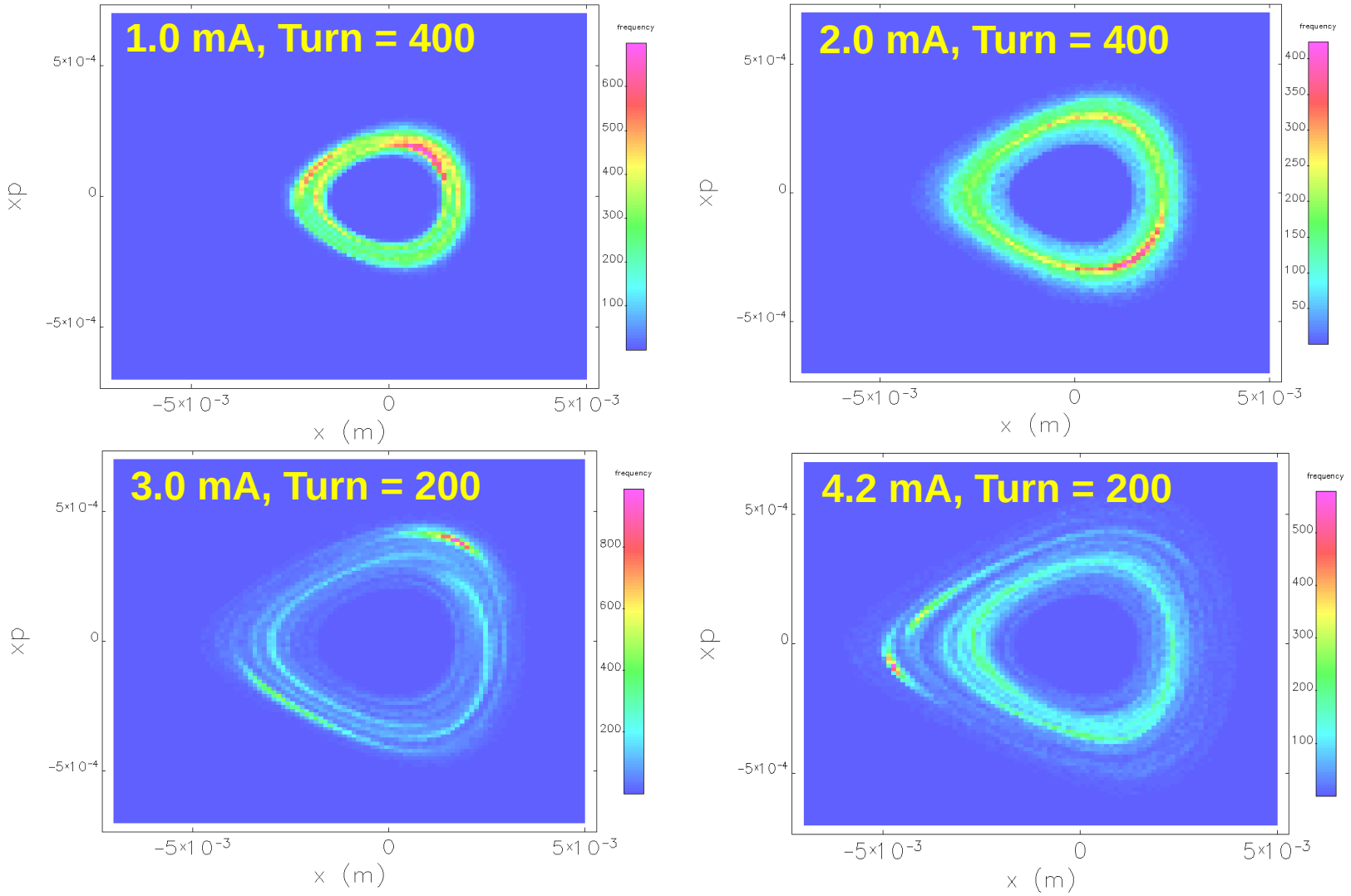
- APS and APS-U emphasize timing operation with 15 nC/bunch
  - APS operates ~60% of the time in 24-bunch, 100-mA mode
  - APS-U will operate in 48-bunch, 200-mA mode
- Effective DA for APS depends on bunch charge[1]
  - Mechanism appears to be filamentation driven by wakefields, which rapidly inflates the emittance of high-charge kicked bunches
- On-axis injection mitigates this by minimizing centroid oscillations





1. V. Sajaev, et al., PRAB **22**, 032802 (2019).

APS-U 90-pm lattice would suffer from this effect[1]



- With SCAPE device (r=3mm), we'd be limited to less than 2 mA/bunch
- Even twice that aperture would *just* give us 4.2 mA
- Simulations do not include effect of x-y coupling or errors

1. R. Lindberg et al., NAPAC16, 901.

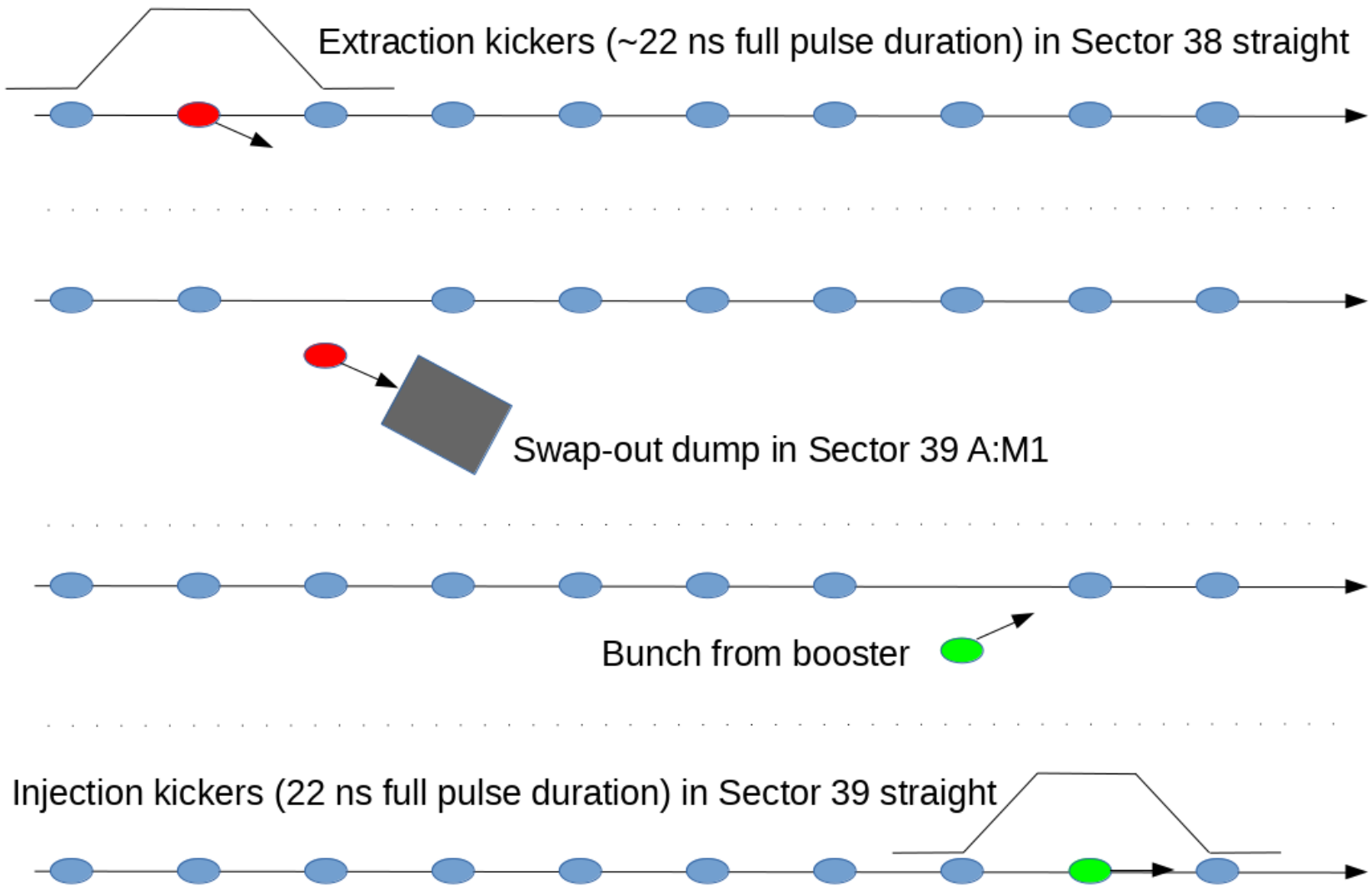
On-axis injection provides more flexibility with coupling

- Typically for accumulation, we avoid coupling large (~10mm) horizontal motion into vertical where we have small aperture
- With on-axis injection, the major source for APS-U is from the booster emittance (~0.6 mm rms beam size)
- APS-U plans to operate on the linear difference resonance ν_x-ν_y=59
  - Increases the Touschek lifetime by giving $\varepsilon_x \approx \varepsilon_y$
  - Avoids pointless battle with intrabeam scattering

N_b	Charge nC	κ	ϵ_x pm	ϵ_y pm	σ_δ %	$\tau_{10^{th}}$ h	ΔT_{inj} s	$\tau_{50^{th}}$ h	ΔT_{inj} s
48	15.34	0.99	31.9	31.6	0.145	3.7	28.0	4.0	30.3
324	2.27	0.99	29.8	29.5	0.136	15.0	16.7	16.1	17.9
324	2.27	0.13	41.7	5.6	0.138	7.3	8.1	9.1	10.1

APS-U swap-out scheme[1] is conceptually simple

- APS-U scheme uses an internal dump inside one of the long dipole magnets
- Dipole magnet provides radiation shielding
- Reduces number of magnets needed (e.g., no extraction septum or transport line)
- Tail kicks from extraction and injection kickers partially cancel ($\Delta\varphi_y$=325˚)
- Rf system doesn't experience a significant transient



1. A. Xiao et al., PAC13, 1076.

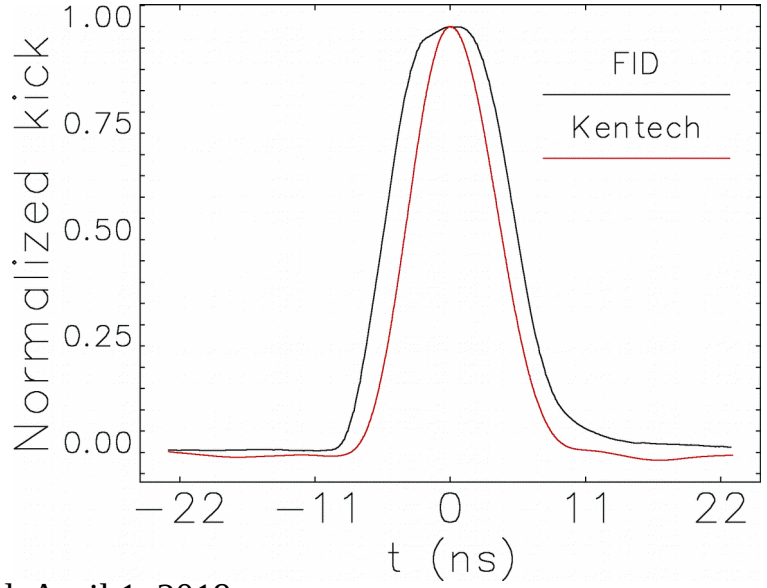
Kicker tails need careful consideration

- APS-U has two nominal fill modes
  - 324-bunches, 200 mA: 11-ns bunch spacing (with ion gaps)
  - 48-bunches, 200 mA: 76.7-ns bunch spacing
- May also want unusual patterns, e.g.,
  - 24 doublets, 200 mA: 11- and 76.7-ns spacing
  - Hybrid mode
- How much kick can the stored bunches tolerate from kicker tails without loss?
  - With a vertical DA of ~1.5 mm at β=2.2 m, the angular acceptance is ~0.7 mrad, which is ~25% of the 2.6-mrad injection kick
  - This seems very relaxed...

Separate extraction kickers give more margin, flexibility

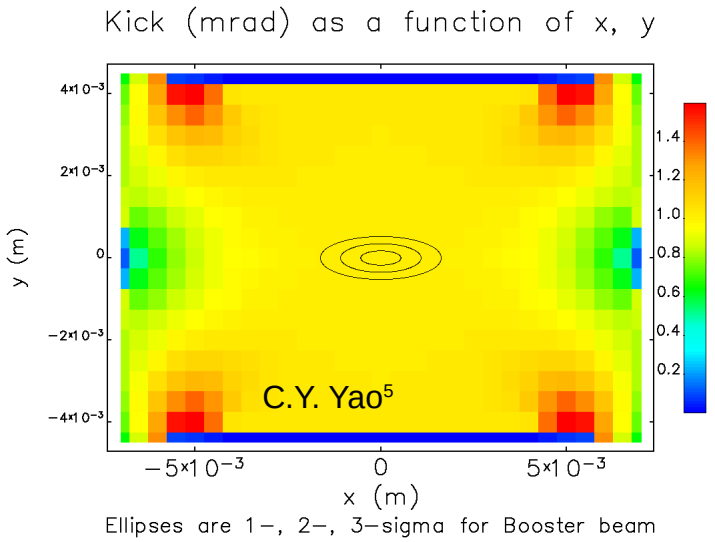
- Did element-by-element tracking with errors and collective effects
  - For 11-ns spacing, bunch charge is low, can tolerate ~15% tails
  - For 77-ns spacing, bunch charge is high, but tails should have fallen off
- Unusual patterns (e.g., 24 doublets) would require 8% tails at 11 ns
  - This is challenging for one of the pulser options
- Need also to allow for differences among multiple pulsers, jitter
- Having separate extraction kickers is more conservative

Pattern	Minimum spacing	Bunch charge	Kick aperture
	ns	nC	mrad
324-bunch with gaps	11.4	4.6	0.4
72-bunch	51.1	10.2	0.3
48-bunch	76.7	15.3	0.2



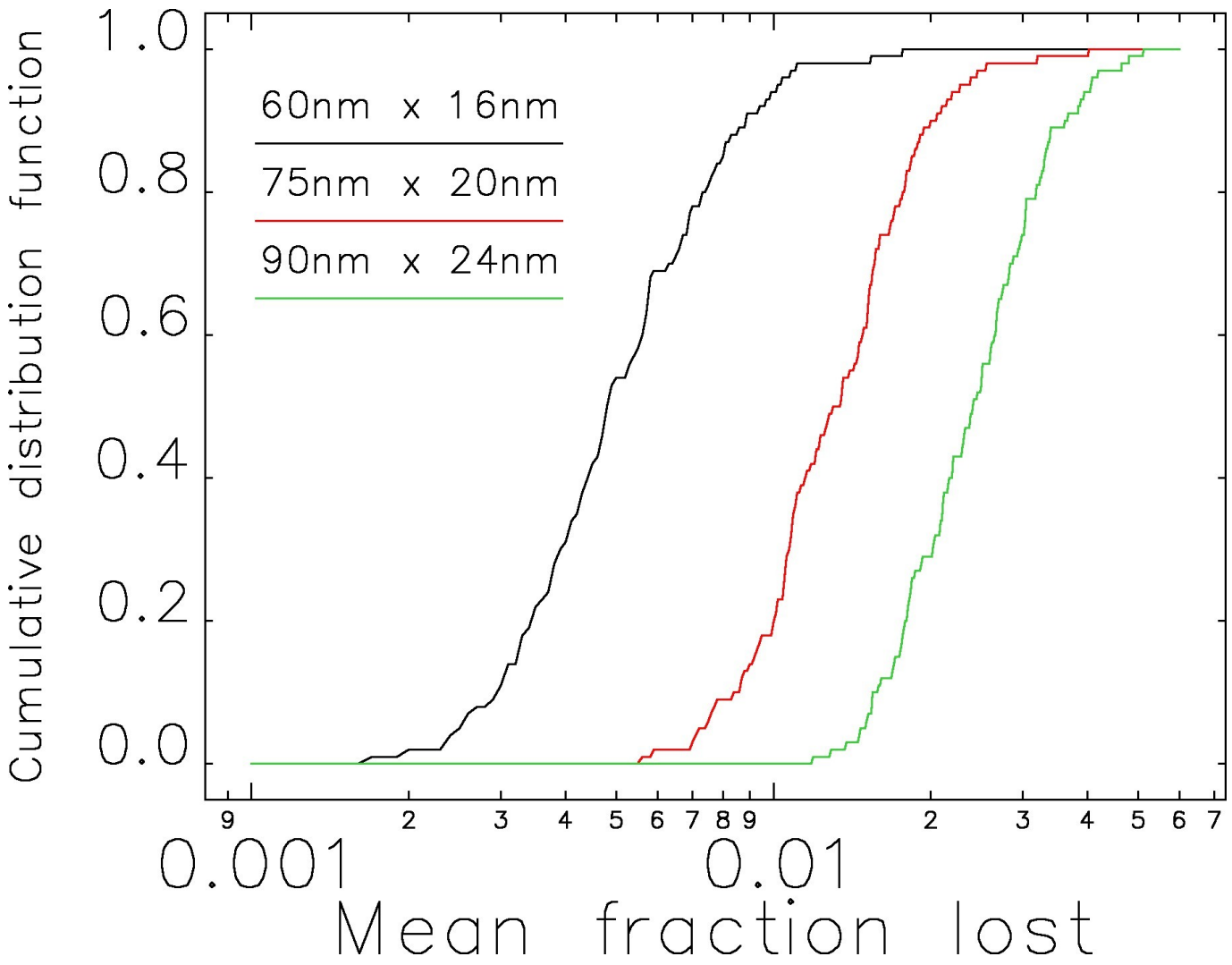
Modeling injection allows including many effects

- Ring errors as per commissioning ensembles[1]
- 2D deflection map for striplines
- Booster errors
  - Rms orbit errors of 100 um in each plane[2]
  - Rms energy error of 0.1%[3]
  - 50 ps rms phase error relative to master clock
- Magnet errors
  - Booster and Lamberston septum jitter of 0.01%[2]
  - Measured kicker rms timing jitter of 100 ps and rms amplitude jitter of 0.2%[4]
  - Quadrupole strength errors to give 5% rms beta errors in BTS upstream of first vertical bend
- Ring rf jitter of 50 ps



1: V. Sajaev et al., IPAC15, 553.
2: C. Yao measurements, with safety factor of 10.
3: L. Emery measurements, with safety factor of 10.
4: J. Wang, measurements on FID pulser.
5: C. Yao et al., IPAC15, 3286.

Injection efficiency high, but sensitive to increased emittance



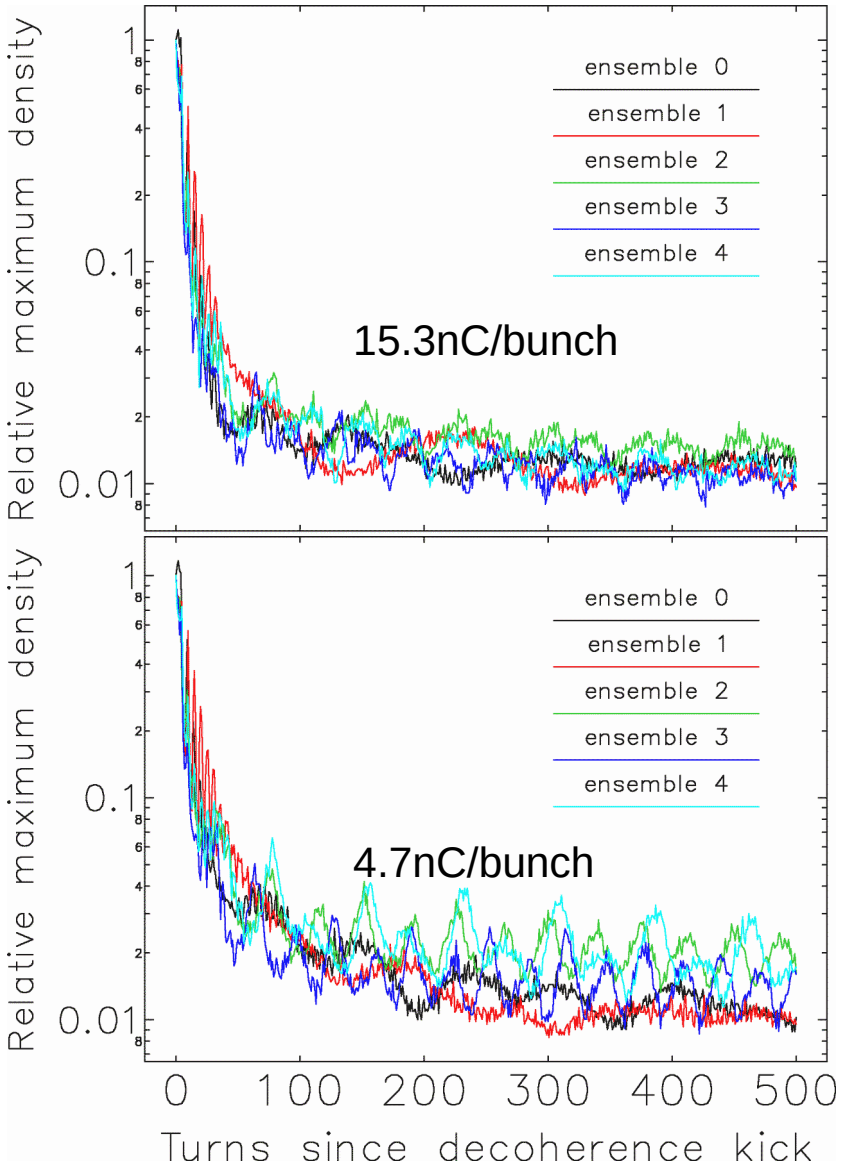
- Nominal emittance requirement from booster is $\varepsilon_x \leq 60$nm and $\varepsilon_y \leq 16$nm
- Not considered challenging for booster at moderate charge
- Emittance may increase in high-charge mode, but not seen in tracking studies (J. Calvey)
- A ~25% increase in emittance seems tolerable

Extraction of stored bunches can be hazardous

- In APS-U, 15 nC bunch hits the internal swap-out dump with rms beam size of 6.5 μm by 24.5 μm
  - Using the collisional stopping power[1], dose is ~3 MGy (1Gy=1J/kg)
  - Surface melting/sublimation predicted for all common materials[2]
    - E.g., for aluminum, the surface temperature rise is ~3600 K
- This could be a show-stopper: drilling into the swap-out dump is not going to work long-term
- Extracting the beam to an external dump is an obvious “solution”
  - Allows blowing up the beam size with quadrupoles
  - Problem: beam may hit something (e.g., septum, vacuum chamber) if a kicker malfunctions or is incorrectly configured

1. physics.nist.gov/PhysRefData/Star/Text/ESTAR.html
2: M. Borland et al., IPAC18, 1494.

Decoherence can prevent damage to components



- Decoherence following a 100 μrad pre-kick significantly reduces energy density within less than 100 turns
- Model includes element-by-element tracking and single-bunch collective effects
  - For high charge (critical case), impedance enhances decoherence
  - For low charge (less relevant), emittance beating slightly reduces effectiveness
  - In all cases, required ~10-fold dilution is readily obtained
- APS-U approach requires pre-kicker to fire before each swap out of a bunch
- We'll also incorporate the pre-kicker into our slow beam abort system

Swap-out makes heavy demands on the injector

- Swap-out necessarily makes higher demands on the injector than top-up
  - Top-up: add small amount of charge to replace what was lost
  - Swap-out: discard a bunch (or train) and inject a full-charge replacement
- Typically we want to regulate the stored current to C~0.1% or so
- Injection interval is at minimum

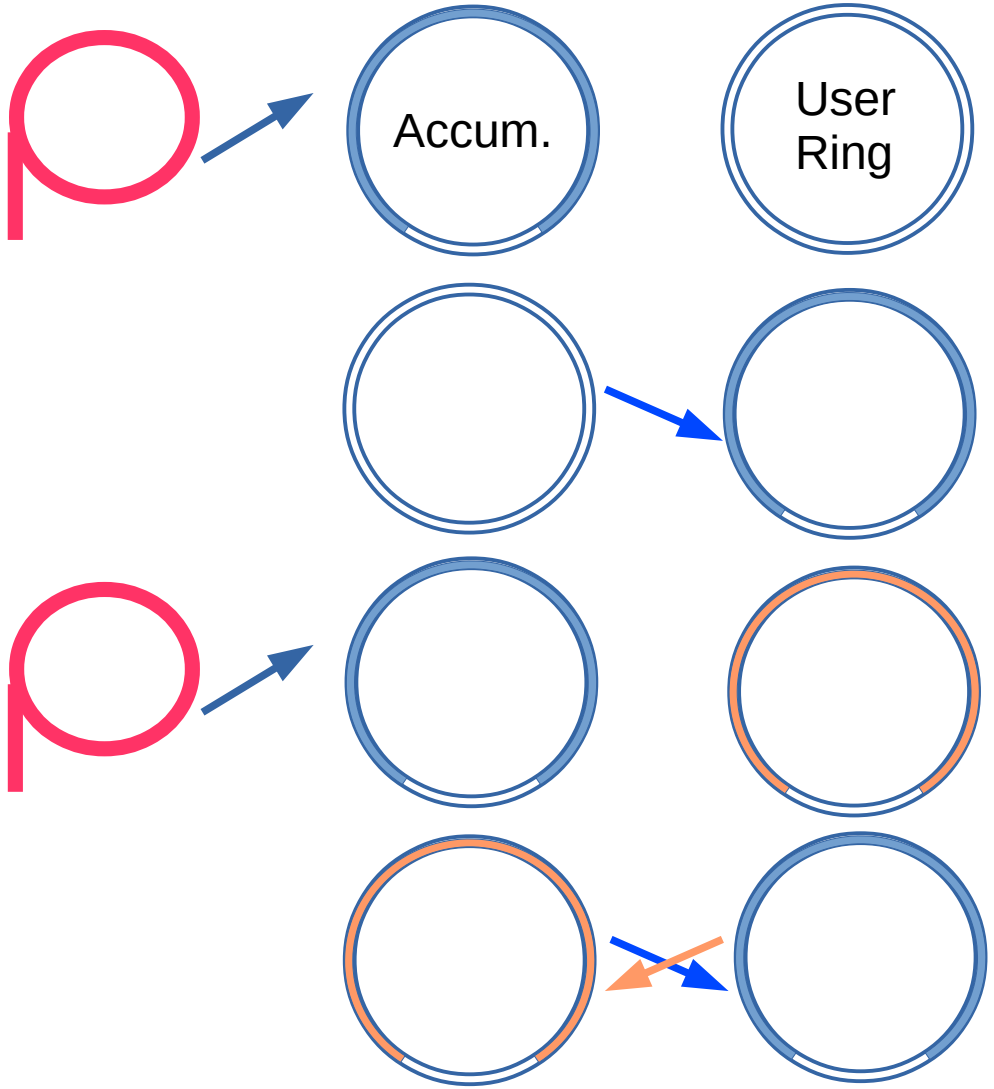
$$\Delta T = \tau C$$

- E.g, for 48-bunch mode with 3 hr lifetime we'd inject every ~23s
  - Top-up: injector supplies one 1.7 nC bunch every 23 s
  - Swap-out: injector supplies one 18 nC bunch every 23 s

Several solutions for injector requirements

- Low-energy accumulator upstream of the booster can accumulate linac pulses
  - This is the APS-U solution since we already have an accumulator (J. Calvey's talk)
- High-energy accumulator
  - High-energy accumulator downstream of the booster can accumulate booster pulses
  - This is a more expensive solution but reduces collective effects, allows lower emittance injected beam
- Recycler
  - This is like a high-energy accumulator, but captures extracted beam from the ring
  - ALS-U and IHEP are using variants of this idea

Swap-out using an accumulator/recycler[1]



Fill accumulator from linac/booster.

Transfer on-axis from accumulator to UR.

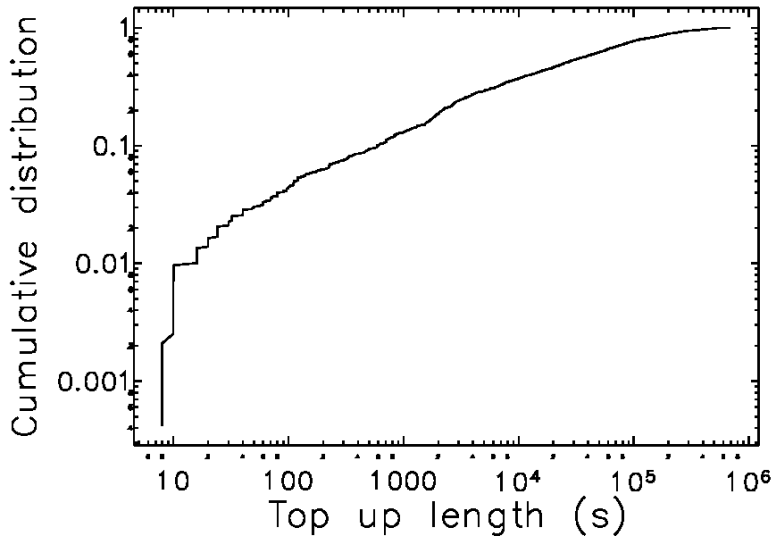
Fill accumulator, use top-up to maintain fill.

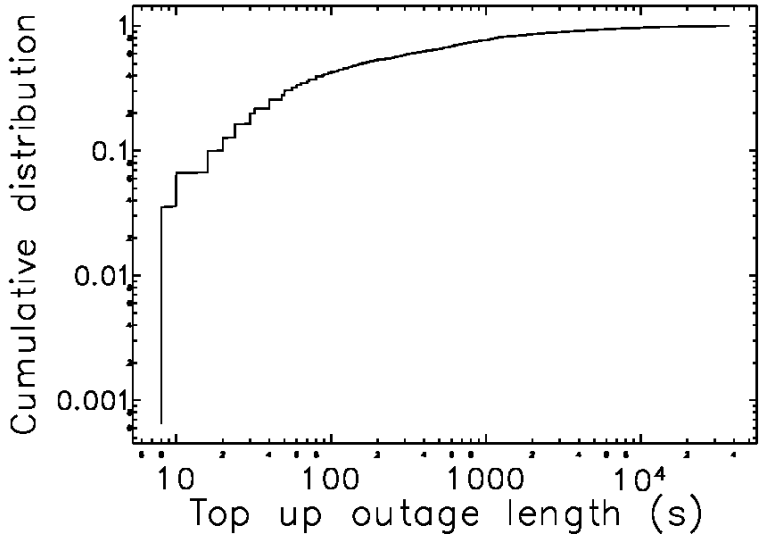
Swap beams when UR beam decays too far.
Repeat from last step.
Must decohere beams before swapping to ensure nothing gets destroyed.

1: L. Emery et al, PAC 2003, 256-258 (2003).

APS injector has known reliability for top-up

- As in top-up, facilities using swap-out require high reliability from their injectors
  - APS presently does a top-up shot every 2 minutes
  - APS-U will do a swap every 8-30 seconds
- Analysis of APS statistics gives distribution of durations of continuous top-up and top-up outages
- We can use this to model how injector reliability will impact APS-U operation

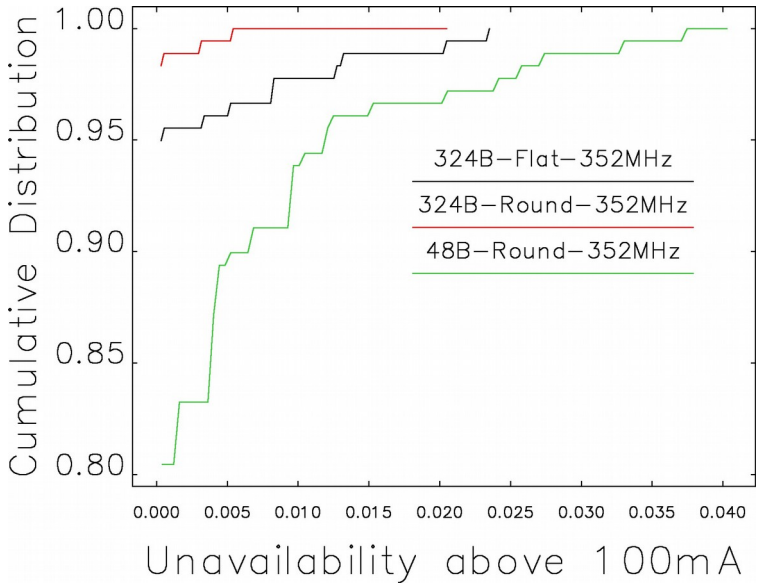


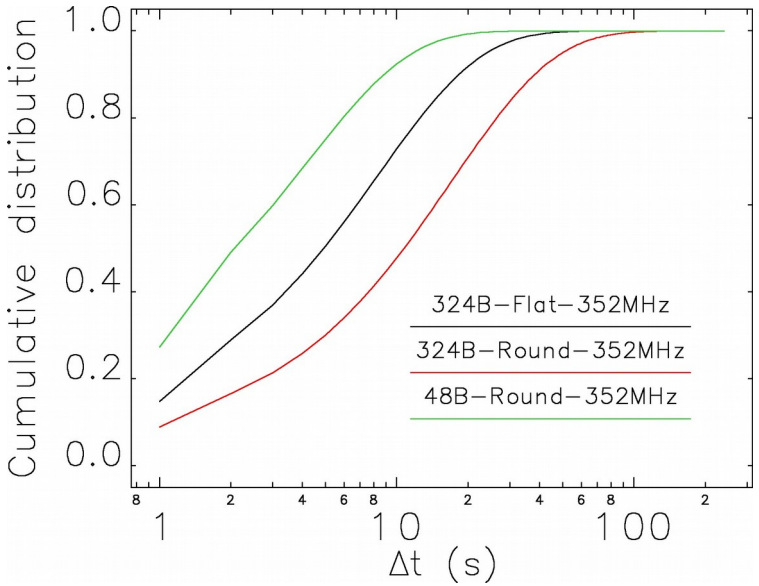


1: M. Borland, NAPAC16, 881.

Injector reliability shouldn't significantly impact APS-U

- APS has 3% unavailability, almost entirely due to storage ring systems
- For APS-U, modeled six years of operation at 5200 h/yr, assuming the ring never had a fault
- Assumed 50% drop in current (below 100mA) was “downtime”
  - Even in 48-bunch mode (shortest lifetime), 95% chance that contribution of injector is <1.5% unavailability per week
- Included a 1% dropped shot rate and 3% rms charge jitter
  - As a result, we must sometimes re-inject immediately after a failed/weak shot
- Since injector was built 25 years ago, we need to upgrade/maintain systems to ensure continued reliability





Conclusions

- Swap-out injection supports higher brightness
  - Nonlinear dynamics can emphasize lifetime over DA
  - DA need only be larger than the incoming beam phase space
  - Insertion devices with small horizontal and vertical gaps
  - Fully-coupled beams to improve lifetime, suppress intrabeam scattering
- If a separate accumulator is available, can still support high bunch current
  - In APS-U case, we already had a low-energy accumulator ring
  - Swap-out helps raise bunch intensity limits by reducing residual betatron oscillations
- APS-U gained a factor of ~3 in brightness using swap-out instead of accumulation
- Kicker and injector requirements are challenging, but achievable

Acknowledgments

- APS-U Beam Physics Team includes
  T. Berenc, A. Blednykh (BNL), M. Borland, J. Byrd, J. Calvey, J. Carwardine, G. Decker, J. Dooling, L. Emery, K. Harkay, S. Henderson (TJNAF), R. Hettel, J. Kerby, S. Kim, R. Lindberg, B. Micklich, V. Sajaev, M. Sangroula (MIT), N. Sereno, Y.P. Sun, D. Teytelman (Dimtel), U. Wienands, K. Wootton, A. Xiao, C.Y. Yao, A. Zholents
- Simulation codes
  - Serial and parallel versions of ELEGANT[1,2] and related tools[3]
  - Wakefields: ECHO[4], GdfidL[5]
  - Other: TAPAs[6]
- Computations used ANL's Blues and Bebop clusters, ASD's Weed cluster
- ESRF generously shared an early version of their H7BA lattice

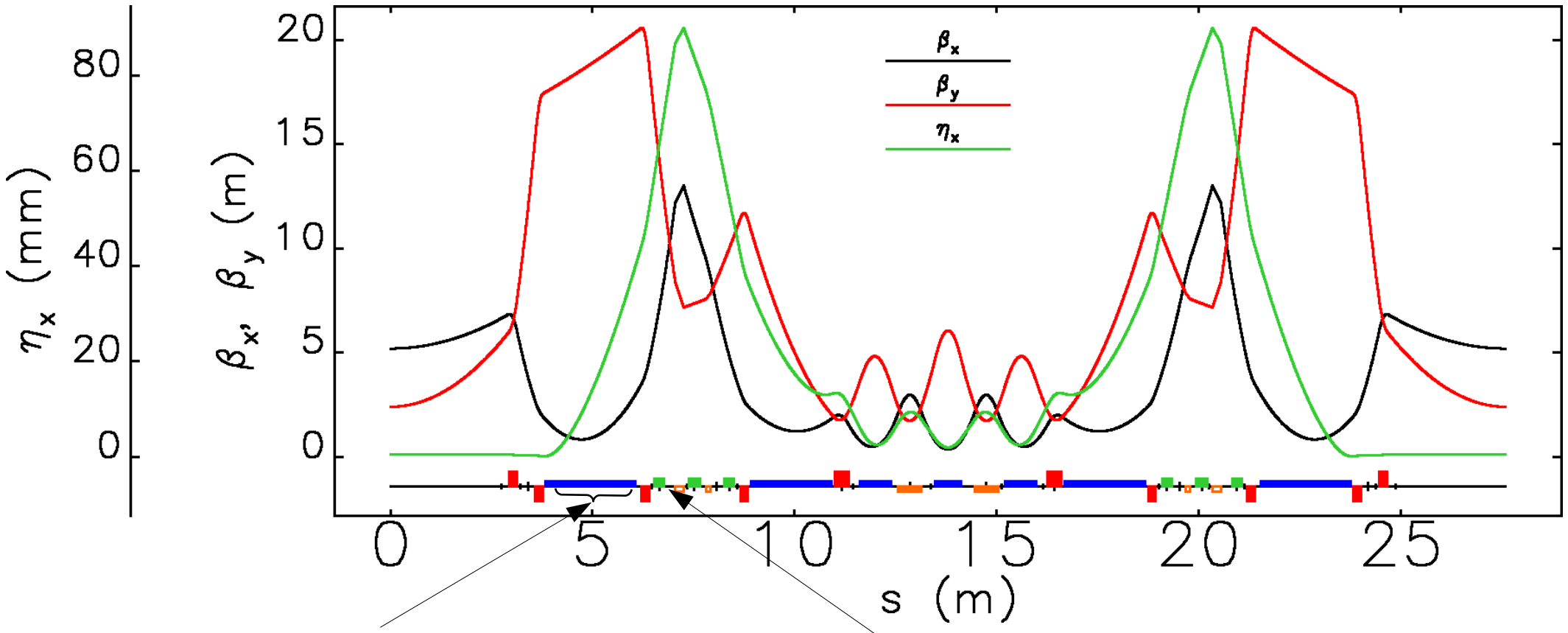
1: M. Borland, LS-287.
2: Y. Wang et al., AIP Conf. Proc 877.
3: M. Borland et al., IPAC2003.
4: I. A. Zogorodnov et al, PRSTAB 8, 042001.
5: W. Bruns.
6: M. Borland, NAPAC16, 625.

Backup Slides

Injection modeling provides more direct check than DA

- Having large DA compared to injected beam size gives some assurance, but better to model injection directly
- Expect losses to be low, so track uniformly-distributed particles with gaussian weights
  - Provides greater sensitivity to small losses with manageable number of particles
- Four stages
  - Generate 30 “bunches” with uniform distribution, gaussian weights
  - Track each from booster, through BTS and into ring, with errors
  - Track bunches together for 1000 turns in ring for each of the 100 commissioning ensembles
  - Separate using particle IDs to recover per-bunch results

Collimation locations take advantage of lattice functions



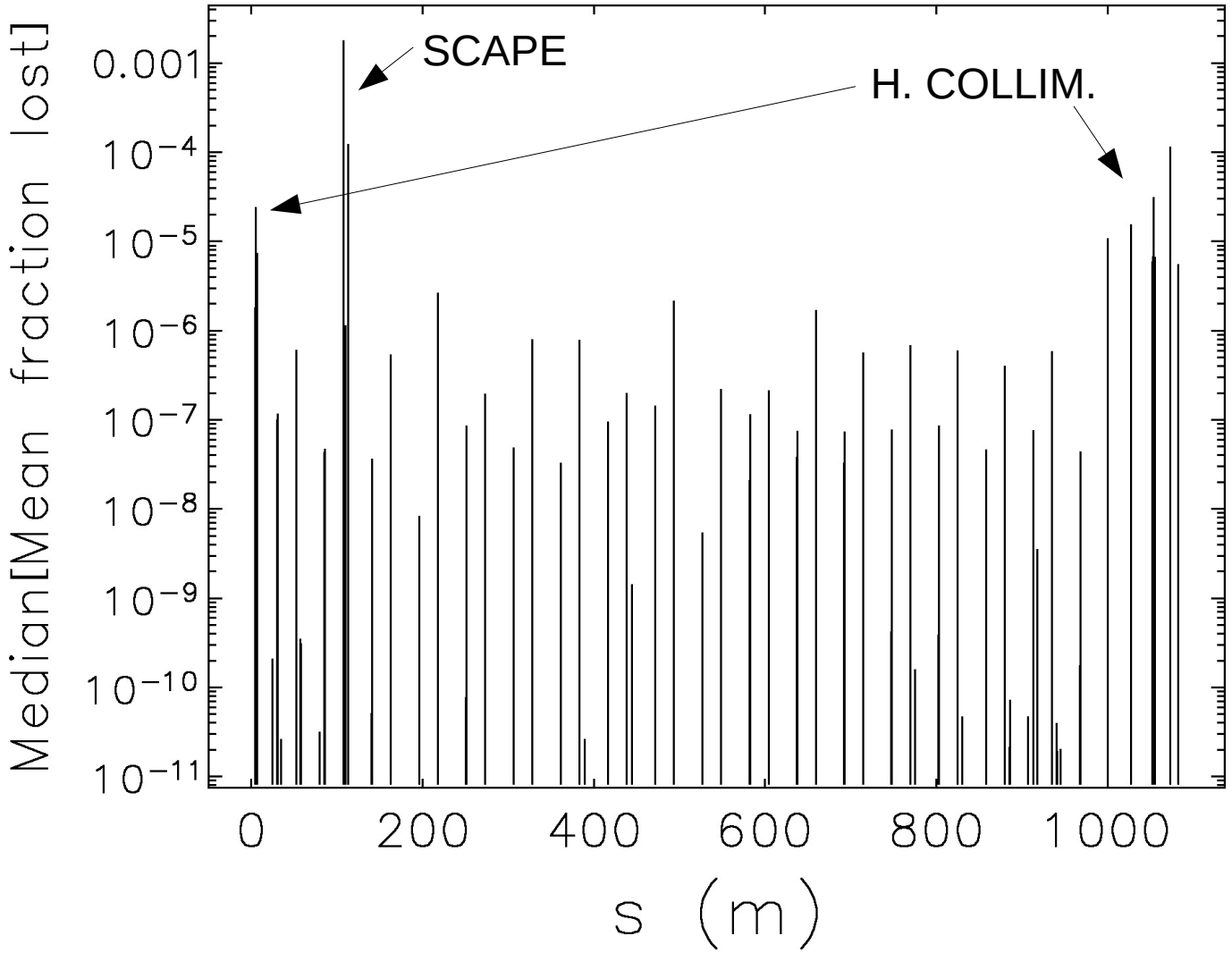
Vertical collimator or swap-out dump:

- Localizes injection and elastic scattering losses
- Two locations: S39A:M1, S01A:M1
- S39A:M1 is swap-out dump

Horizontal collimator and whole-beam dump

- Localizes Touschek and inelastic gas scattering losses
- Five locations (sectors 37, 38, 39, 40, 1) with existing enhanced shielding

Simulations provide distribution of injection losses



Injected beam emittance: 60nm x 16nm

- Unfortunately, difficult to protect the SCAPE (r=3mm) from injection losses
- The two vertical collimators seem to have little effect
  - Adding more was also ineffective
  - Reducing vertical collimator apertures mostly just increases losses at the collimators