Injection into APS MBA Lattice

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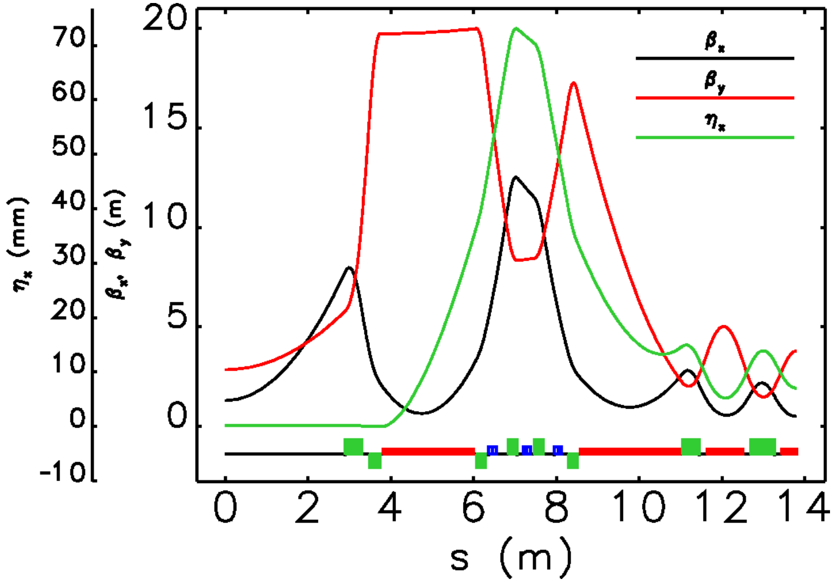
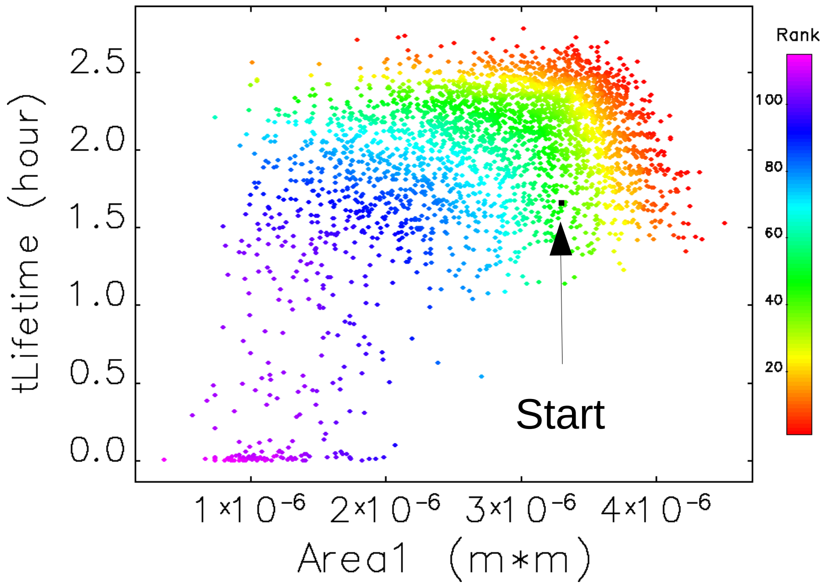
“Best” Solution from Optimization



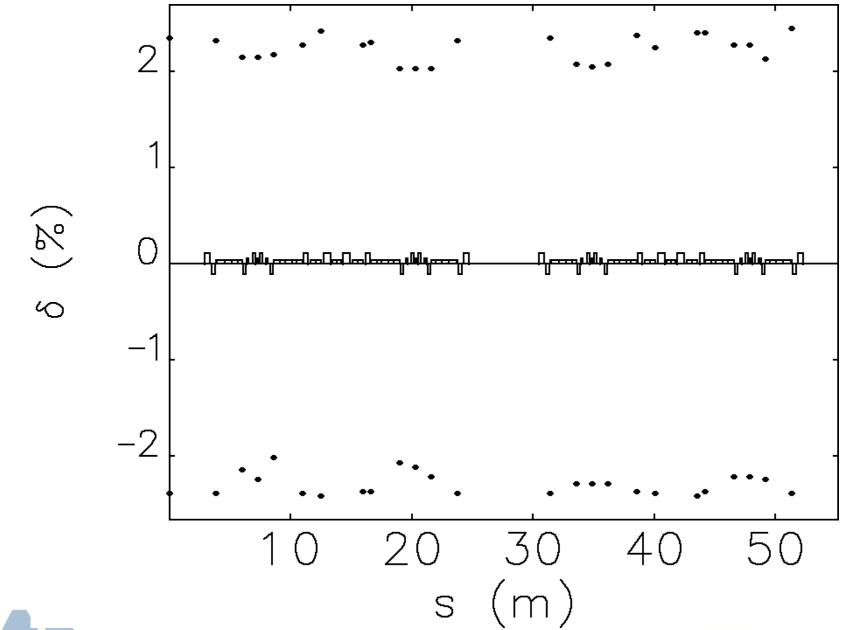
Betatron Tunes		
Horizontal	105.445	
Vertical	34.146	
Natural Chormaticicities		
Horizontal	-152	
Vertical	-127	
Lattice functions		
Maximum β_x	12.498	m
Maximum β_y	19.997	m
Maximum η_x	0.073	m
Average β_x	3.490	m
Average β_y	9.325	m
Average η_x	0.032	m

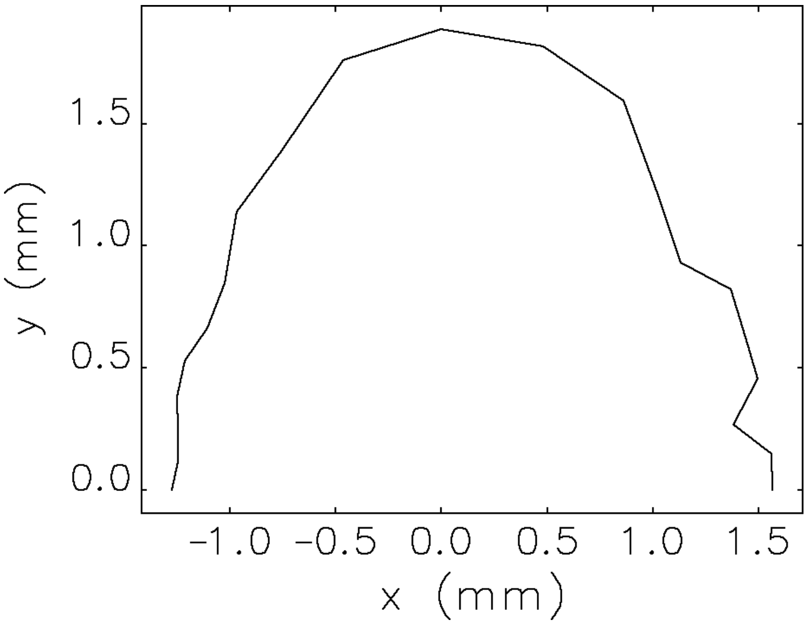
Radiation-integral-related quantities at 6 GeV		
Natural emittance	58.679	pm
Energy spread	0.094	%
Horizontal damping time	13.520	ms
Vertical damping time	21.342	ms
Longitudinal damping time	15.014	ms
Energy loss per turn	2.071	MeV
ID Straight Sections		
β_x	1.298	m
β_y	2.853	m
Miscellaneous parameters		
Circumference	1103.984694	m
Momentum compaction	6.131×10^{-5}	
Damping partition J_x	1.579	
Damping partition J_y	1.000	
Damping partition J_δ	1.421	

Best Solution from Optimization



- Touschek lifetime is computed with 10% coupling, 200 mA, 432 bunches, and 20 mm bunch length, which requires a harmonic cavity
- DA is only large enough for on-axis injection
- LMA is above 2%, similar to APS today





Swap-out Concept

- As noted, the DA is so small that only on-axis injection is possible
- Assuming we inject on-axis, DA requirements are greatly reduced
  - Large enough to accommodate injected beam without losses
    - Injected beam rms sizes are less than 300 microns
  - Large enough to give sufficient gas scattering lifetime
    - ~1mm is sufficient for a 30 hour lifetime
- On-axis injection implies a new mode called "swap-out"[1,2]
  - Stored bunch or bunch train is extracted and dumped
  - New bunch or bunch train is put in its place
  - Injector must supply sufficient charge in one shot to completely fill bunch or bunch train
- For APS MBA at 200 mA, captured charge must be
  - 2.3 nC/bunch in 324-bunch mode --- easy
  - 4.5 nC/bunch in 162-bunch mode --- seems workable with new rf ramp (C. Yao)
  - 15 nC/bunch in 48-bunch mode --- very challenging
- In addition to the injector requirements in 48-bunch mode, swap-out is challenging for kicker technology

1: M. Borland, "Can APS Compete with the Next Generation?" APS Retreat, May 2002.
2: L. Emery et al., Proc. PAC 2003, 256-258.

Swap-Out Algorithm

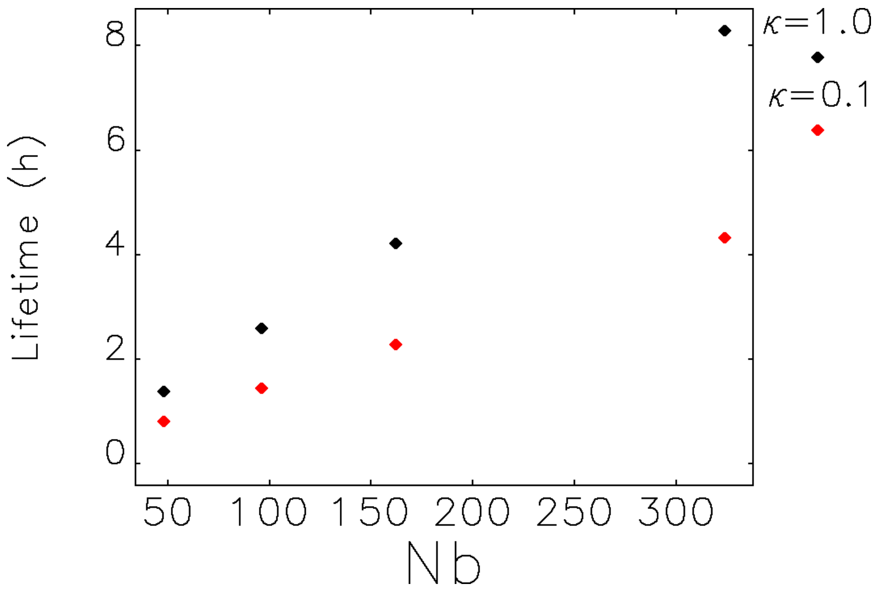
- Fill from zero by injecting at the maximum rate
  - If a shot is dropped (no current), repeat it
  - Stop when desired number of bunches are filled
- After filling, begin cycle of waiting and replacing individual bunches
- Wait time is

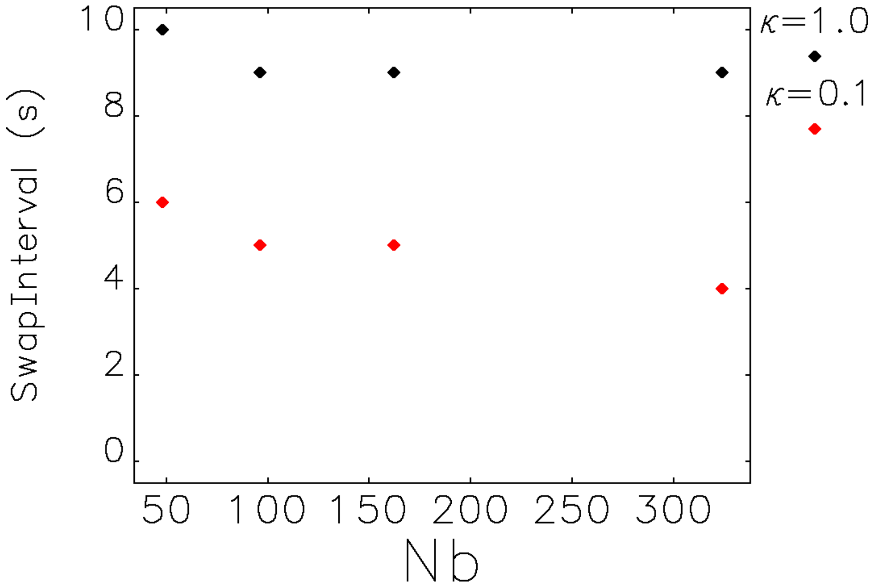
$$\Delta T_i = \frac{D\tau}{N_b}$$

  where D is the allowed fractional droop in bunch current, τ is the lifetime, and N_b the number of bunches
- If a shot is dropped, it is made up as soon as possible
  - I.e., if we extract the existing bunch but fail to inject the new bunch, we wait only sufficient time to prepare a new bunch
- For APS MBA
  - Assume average rate of charge capture into the ring is limited to 8 nA
    - E.g., 16 nC captured every 2 s, corresponding to 20 nC in PAR with 80% efficiency into the ring
  - Dropped shot is repeated after minimum N*0.5 s interval such that sufficient time is available to accumulate required charge in PAR

Swap-Out Algorithm

- Injection interval is determined by the beam lifetime, which is dominated by the Touschek lifetime
- Simulated Touschek lifetime (including effects of intrabeam scattering) is approximately proportional to N_b
  - Injection interval roughly depends only on emittance ratio κ
  - To be conservative, used the 10th-percentile predicted lifetime

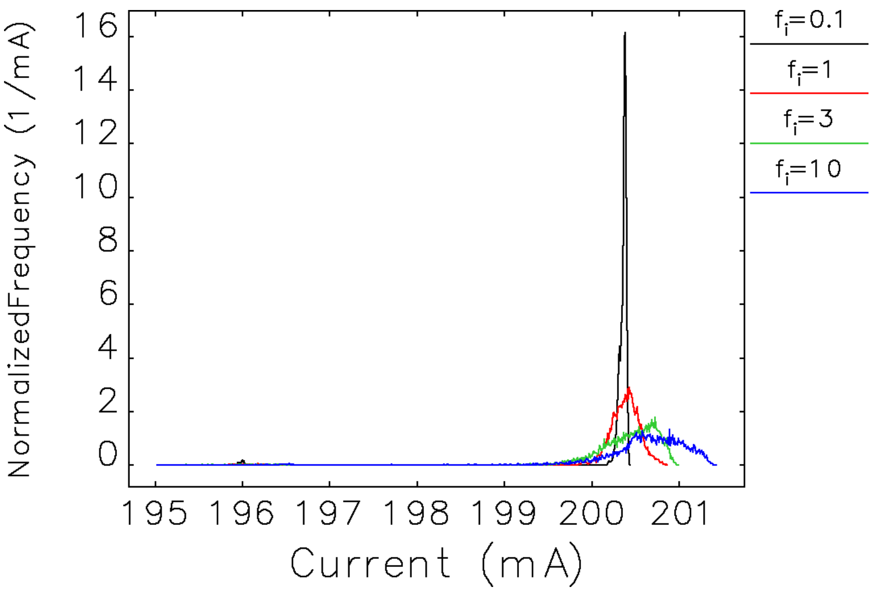




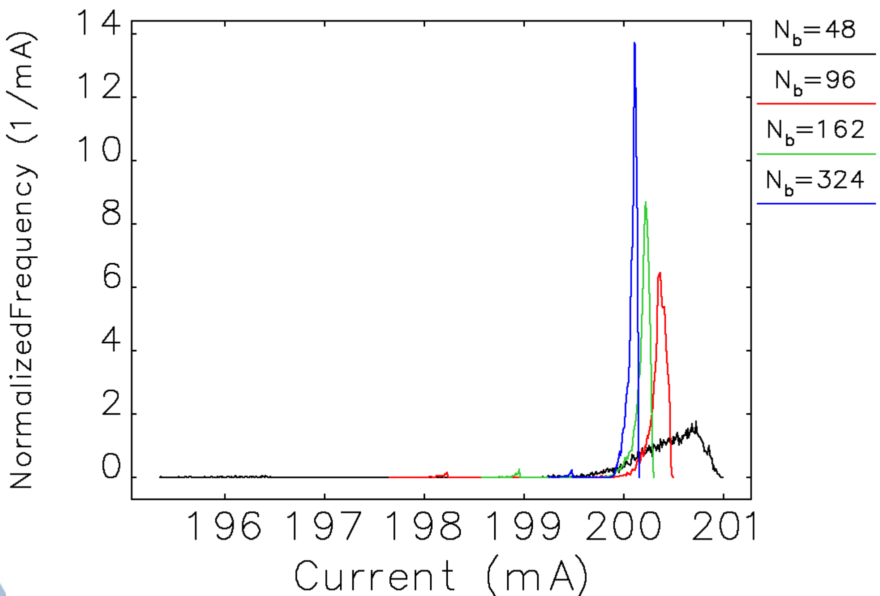
Swap-Out Simulations

- Simulated ~24 hours of swap out with various parameters
  - 200 mA in different numbers of bunches
  - Two different emittance ratios (0.1 and 1.0)
  - Lifetime derived from other simulation data for 20 mm bunch length
- Simulation includes realistic effects
  - Uniformly-distributed random variation in charge captured
    - Charge captured fluctuates about the average value needed (i.e., may fluctuate above or below requirement)
    - Characterized by parameter f_i, which gives the full fractional range of the variation
  - Possibility of randomly dropped shots (extraction but no injection)
    - Each shot has a 1% probability of being dropped
    - This includes make-up shots
- Analyzed simulation results to determine likely range of beam current as a function of various parameters

Swap-Out Simulation Results

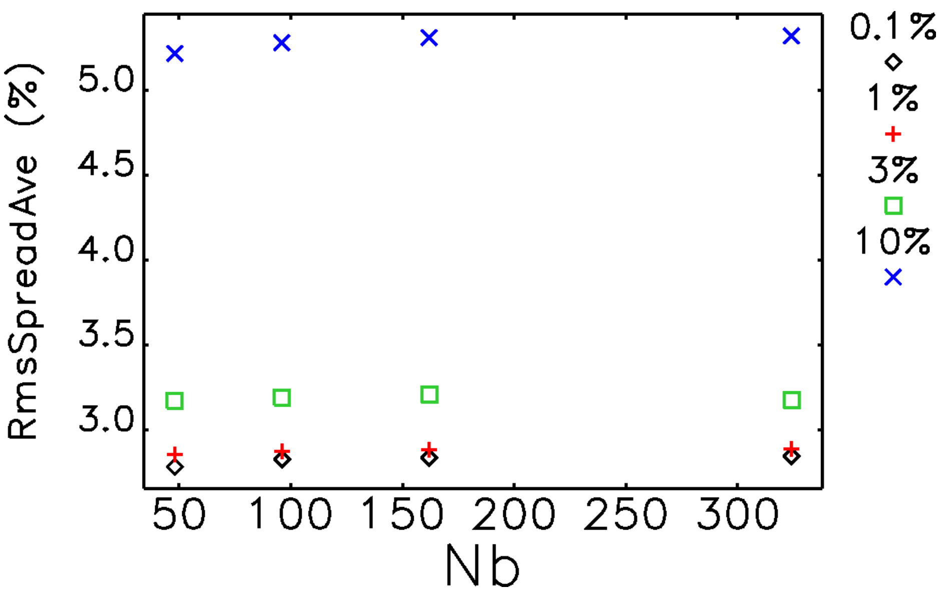


- Here we vary the randomness level for the captured charge
- Used 48 bunches, 100% emittance ratio, 1% drop-out rate
- In terms of average current variation, results look good

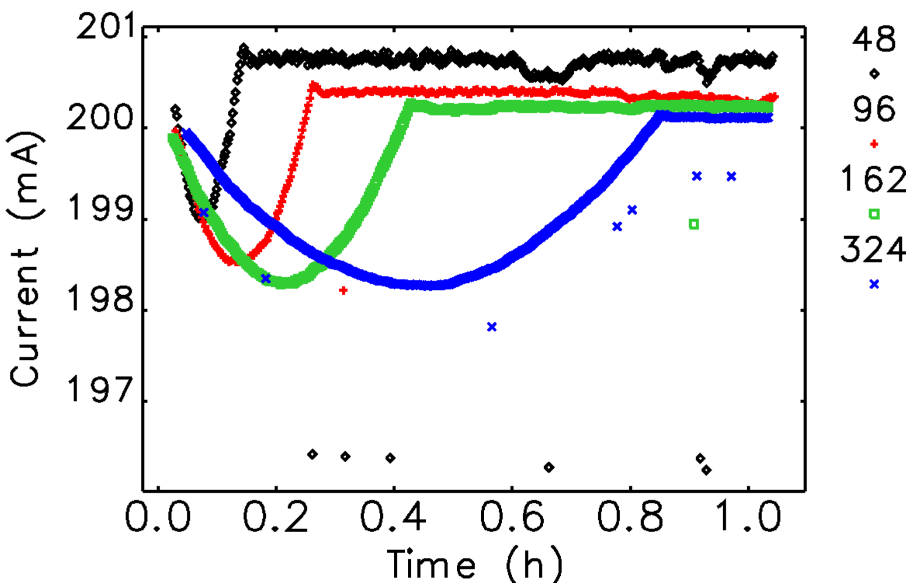


- Here we vary the number of bunches with 3% variation in captured charge
- Again, results are good for all cases

Swap-Out Simulation Results



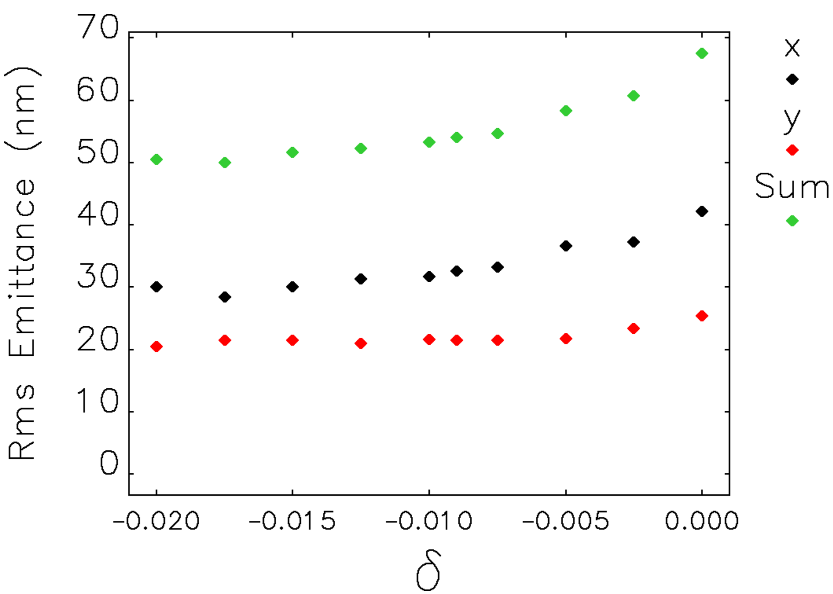
- Here we vary the randomness level for the captured charge, with κ=1 and 1% drop-out rate
- Rms variation in bunch current is generally well controlled

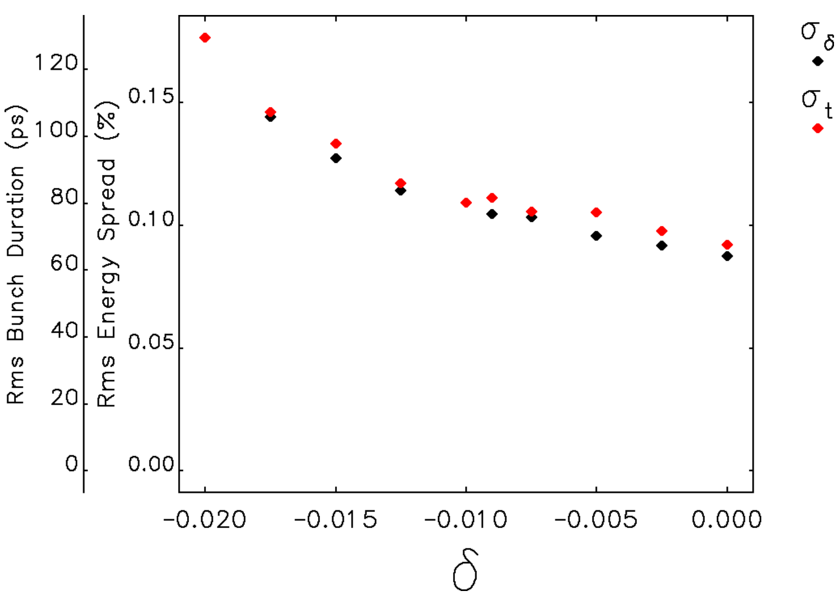


- Here we look at details of the beam current vs time following the fill from zero
- The transients result from evolution of the bunch pattern after changing from fast filling to the slower swap-out interval

Injection Tracking Simulations

- We performed tracking simulations of on-axis injection
  - Simulate rramping to 6 GeV in booster
  - Inject beam into ring with errors in lattice and injection trajectory
  - Look at capture efficiency
- Booster simulations were done as a function of momentum offset
  - Present value is -0.9% and was used for injection into the ring
  - Introduced a fictitious skew quadrupole to couple the emittances
    - Did not fully couple as this seemed to inflate the sum of the emittances

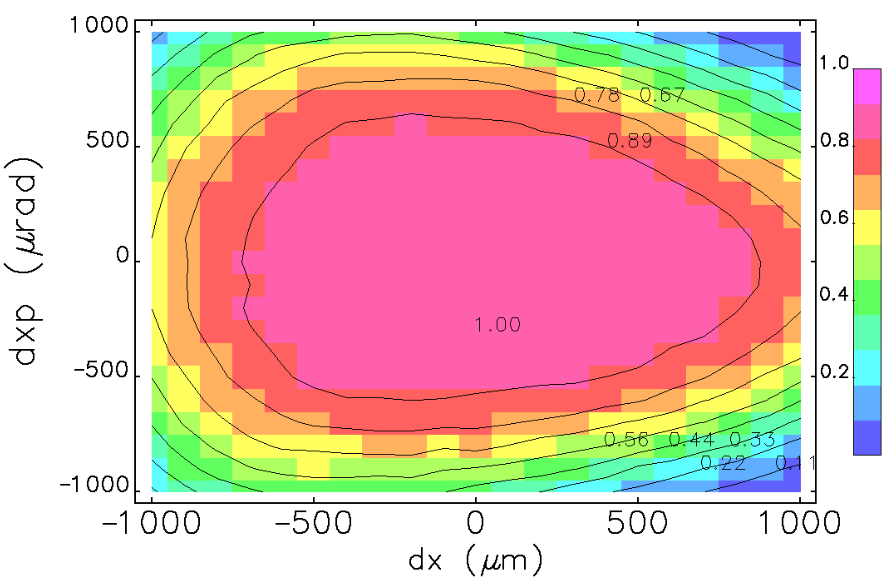




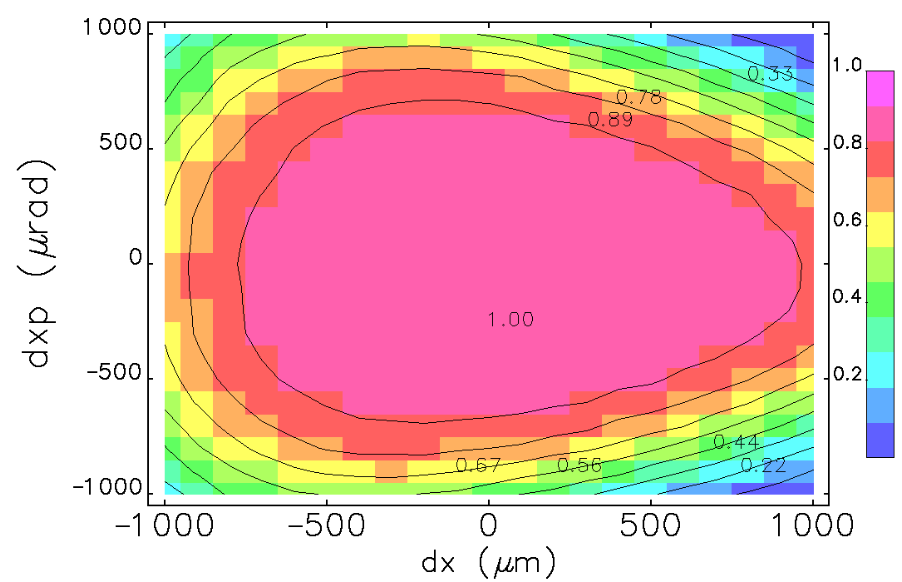
Injection Tracking Simulations

- Simulated 10 error ensembles for storage ring
  - Included 20mm ID round apertures in arcs, 20mm x 6mm ellipses in ID straights
- Tracked for 1500 turns (sufficient to determine capture fraction)
- Scanned x and x’ errors at center of injection straight
- Tolerances are determined with reference to 90% contours
  - About ±700 μm (rms size of beam is ~200 μm)
  - About ±500 μrad (rms divergence of beam is ~150 μrad)
    - Large compared to kicker strength of 3 mrad[1]

Contours of 10th percentile capture fraction



Contours of median capture fraction



[1] A. Xiao et al., Proc NA-PAC13, WEPSM13

Injection Transients

- Emittance transient will be seen following a swap-out event
  - Injected beam has much larger emittance than stored beam
  - Injected beam may have mismatch or trajectory error, leading to emittance growth from decoherence
  - Nearby bunches may be rattled by the injection kickers, leading to emittance growth from decoherence
- Requirements on the trajectory are described above
  - Amounts to a few percent stability of the kicker amplitude
  - Trade-offs possible among different components (e.g., mismatch vs trajectory)
- If we allow equal contributions from the new bunch and the rattled bunches, we find a tolerance of 250 µrad on the kicks to the rattled bunches
  - This is large compared to peak kick of ~3 mrad
  - Probably no need to make it this sloppy
- Full-beam emittance after injection and decoherence is

$$\epsilon_f(0) = \underbrace{\epsilon_s \frac{N_b - n_r - 1}{N_b}}_{\text{Undisturbed bunches}} + \underbrace{\frac{\epsilon_i (1 + f_i)}{N_b}}_{\text{Injected bunch}} + \underbrace{\frac{n_r}{N_b} \left(\epsilon_s + \frac{\beta_0 \Delta x_r'^2}{2} \right)}_{n_r \text{ rattled bunches}}$$

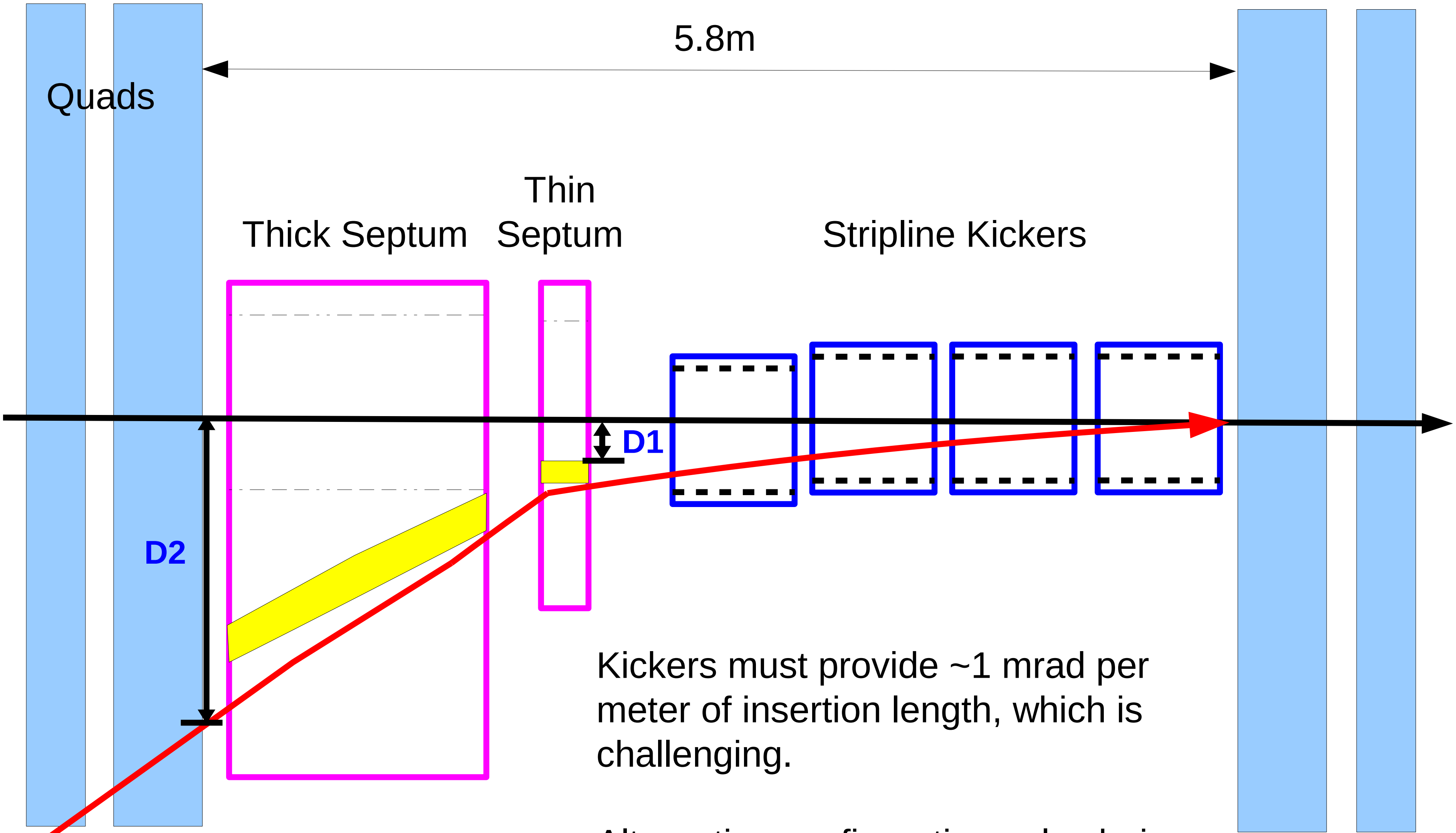
Injection Transients

- The emittance decays exponentially back to the equilibrium value with time constant $\tau_{x,y}/2$, where τ_x=13.5 ms and τ_y=21.3 ms
- Required time to get to 10% dilution is

$$t_w = \frac{\tau}{2} \ln \frac{1}{0.1 N_b} \left(\frac{\epsilon_i (1 + f_i)}{\epsilon_s} - 1 + \frac{n_r \beta_0 \Delta x_r'^2}{2\epsilon_s} \right)$$

	large coupling		small coupling		
	x	y	x	y	
injected beam emittance ϵ_i	30	20	45	5	nm
equilibrum emittance ϵ_s	40	20	40	20	pm
beta function β_0	1.3	2.9	1.3	2.9	m
injected beam decoherence factor $1 + f_i$	2	2	2	2	
number of bunches N_b	48	48	48	48	
number of rattled bunches n_r	2	2	2	2	
rattle amplitude $\Delta x_r'$	0.25	0.025	0.25	0.025	mrad
Full beam emittance after decoherence $\epsilon_f(0)$	3.0	0.89	3.6	0.27	nm
damping time τ	13.5	21.3	13.5	21.3	ms
$(\epsilon_f(0) - \epsilon_s)/\epsilon_s$	73.5	43.5	89.2	12.3	
acceptable increase fraction	0.1	0.1	0.1	0.1	
required wait time t_w	45	65	46	51	ms

Injection Layout (Extraction Similar)



Kickers must provide ~1 mrad per meter of insertion length, which is challenging.

Alternative configurations also being explored (e.g., LSS).

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Table 1: Main Parameters of Injection Element

Title	Description	Value				Unit
		Case 1A	Case 1B	Case 2A	Case 2B	
Stripline	Length	0.72	0.75	0.74	0.75	m
	Gap	9	9	9	9	mm
	Pulser Voltage	±15	±12.75	±15	±12.75	kV
	Kick Angle	0.72	0.6375	0.74	0.6375	mrad
	Δt_{0-top}	7.8	7.7	7.73	7.7	ns
	Δt_{top}	5.9	6.1	6.04	6.1	ns
	Δt_{top-0}	5.4	5.2	5.26	5.2	ns
Septum1	Length	1.32	0.95	1.89	1.5	m
	Thickness	5	5	5	5	mm
	Field Strength	1	1	1	1	T
	Angle	66	47.5	94.5	75	mrad
	Inner Aperture	4.5	4.5	4.5	4.5	mm
Septum2	Length	0.3	0.3	0.3	0.3	m
	Thickness	2	2	2	2	mm
	Field Strength	0.7	0.7	0.7	0.7	T
	Angle	10.5	10.5	10.5	10.5	mrad
	Inner Aperture	3.5	3.5	3.5	3.5	mm

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Acknowledgements

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