On-axis injection into small dynamic aperture

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On-Axis (Swap-Out) injection for Future Storage Ring

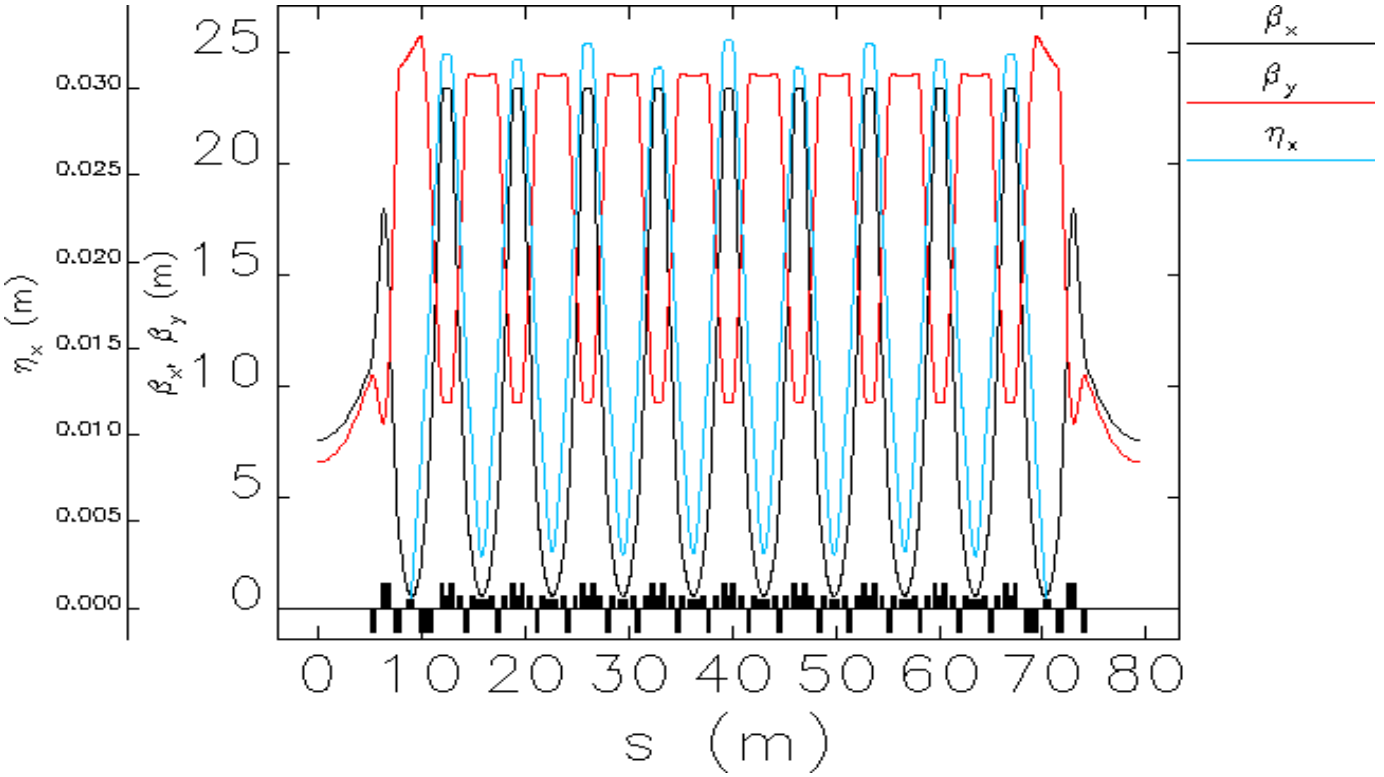
- Future rings with lower emittance will have smaller aperture (e.g. USR7)
- We assume that bunch trains can be replaced with new bunch trains from a booster (or linac)
- Injection will be done on-axis because transverse space is not large enough for a septum
- Aside on USR7 (slides from Borland) follows

7-GeV, 40-Sector Ultimate Storage Ring: USR7

Quantity	Value	Unit
Energy	7	GeV
Circumference	3.16	km
Natural emittance (no IBS)	0.030	nm
Energy spread	0.079	%
Maximum ID length	8	m
Number of dipoles	10	per sector
Horizontal/vertical tune	183.1/36.1	
Horizontal/vertical chromaticity	-495/-166	
Energy loss	3.6	MeV/turn
Beta functions (x/y) at ID	7.58/6.56	m

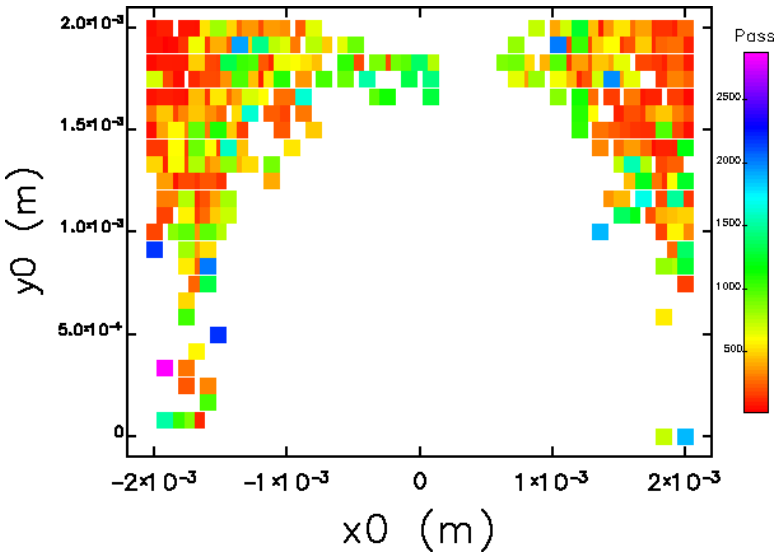
- Similar to Tsumaki and Kumagai (2006), but
  - Larger circumference (3.16 vs 2 km)
  - Higher energy (7 vs 6 GeV) to make hard x-rays easier
  - More sectors (40 vs 32)
  - Longer straight sections (10 vs ~5m)

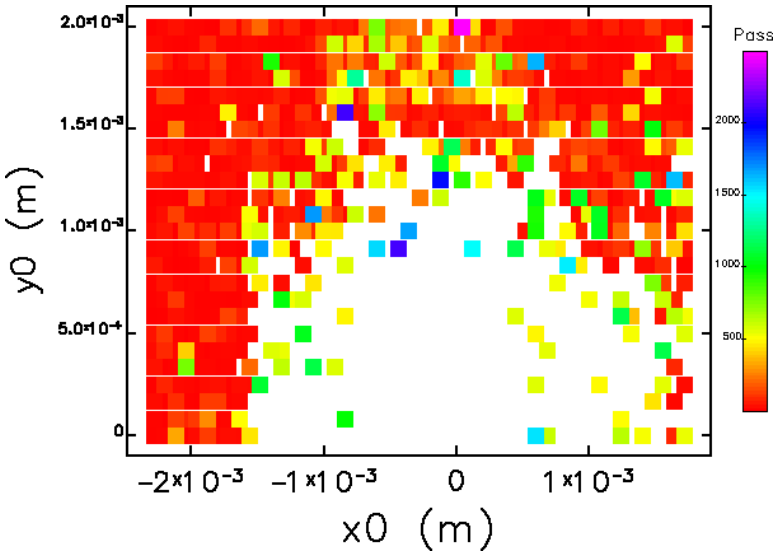
Lattice Functions

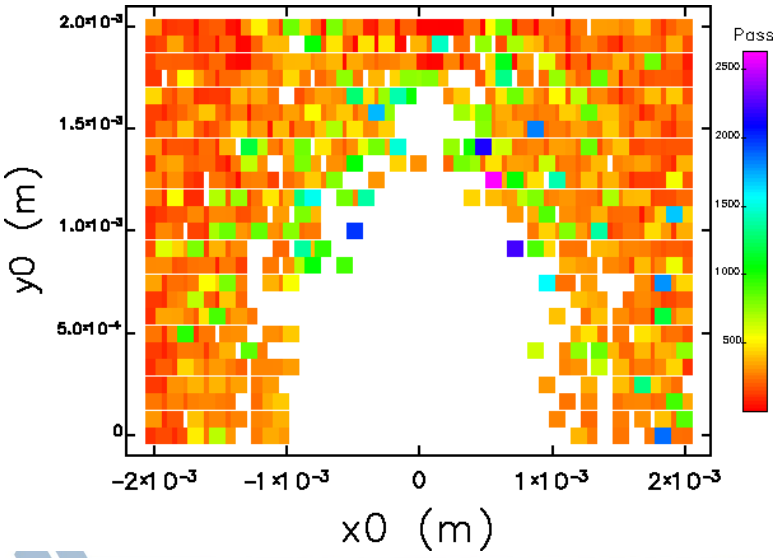


- Uses conventional magnets with workable strengths
- For 200 mA in 4000 bunches, emittance is 16 pm in both planes with full coupling (and IBS of course)
- With ten 4-m-long PETRA III damping wigglers, drops to 11 pm

Dynamic Aperture of USR7





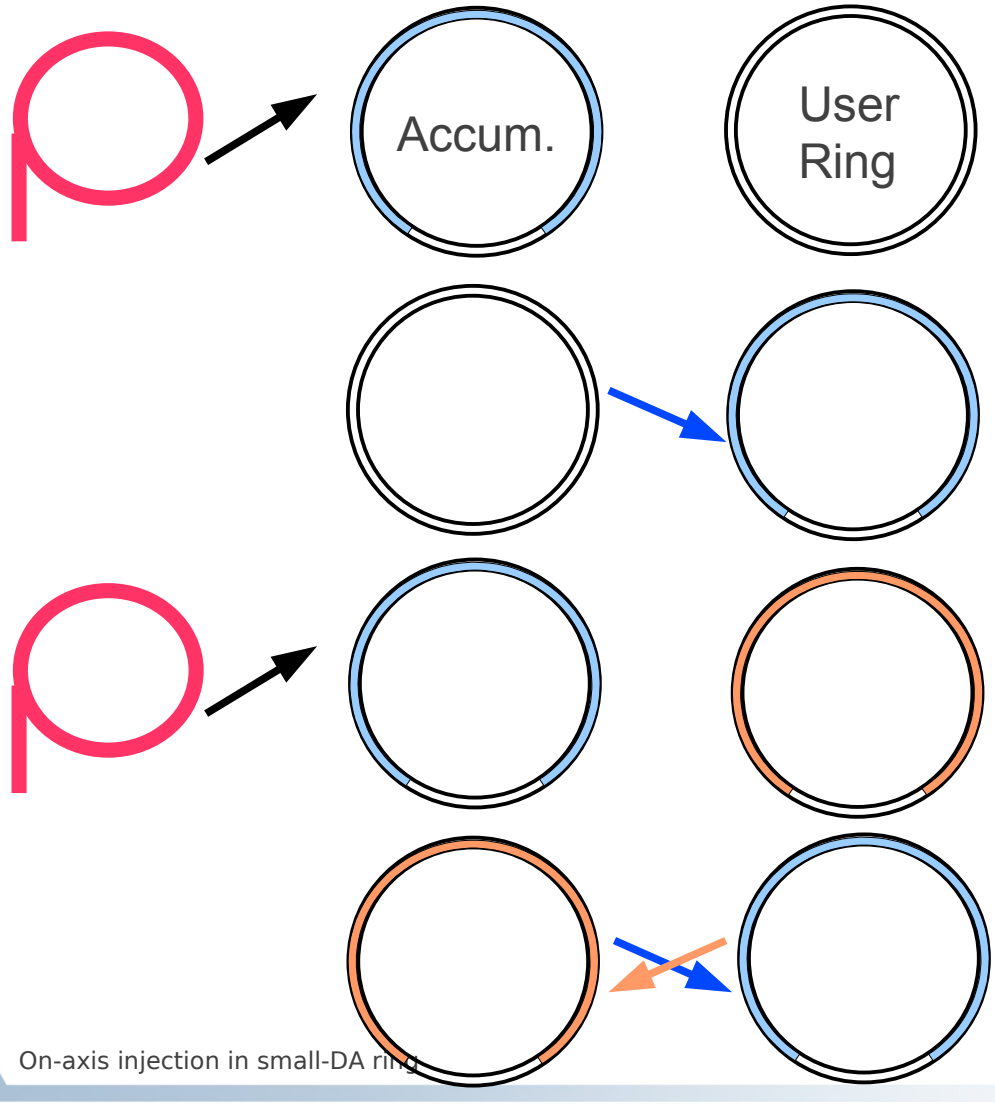


- Nonlinear elements tuned using genetic optimization technique
- 4000-turn tracking with damping and synchrotron oscillations
- Dynamic aperture is small, but very large compared to ~10 μm beam size
- Momentum aperture about ±2%
  - 2 hour Touschek lifetime

Bunch Replacement Modes

- Several possible modes
  - Full beam replacement in one shot
  - Bunch train replacement
  - Individual bunch replacement using fast kickers
- Allows us to operate on the coupling resonance
  - Provide round beams (for users)
  - Reduce intrabeam scattering (for lifetime)
- Several possible injectors
  - Booster + Accumulator ring
  - Low-emittance booster
  - Full-energy linac.

Booster and Accumulator Ring



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. Repeat from last step.

Booster and Accumulator

- Accumulation ring (AR) and user ring (UR) would occupy the same tunnel to reduce cost
- AR design easier than UR design
  - No user straight sections
  - May have comparable emittance and still allow accumulation
  - Damping wigglers in AR could be SR sources
- Need not swap the entire beam from ring-to-ring
  - Swapping a bunch train reduces transients seen by users and AR/UR systems
  - Would require increased swapping frequency
  - Would reduce need for a long kicker flat-top.

Low-Emittance Booster and no Accumulator

- Swap out bunch trains
  - Kick out a train while injecting a new train
  - Decide which train is depleted
  - Trains (just like bunches in regular top-up) will have a distribution of charge
- Swap out single bunches
  - Requires flat-top booster and very fast kickers of few ns
- Extracted beam must be dumped, increasing radiation

Low-Emittance Booster (con't)

- A large-circumference booster emittance can be close to that of the ring (e.g., SLS booster)
  - Optics is “easy” since there are no user straights
  - Can occupy the same tunnel as the user ring to reduce cost
  - Can fill bunch trains at few Hz repetition rates
- This has advantages over accumulator concept
  - Booster emittance is lower since we needn't accumulate in it
  - Less costly since accumulator still needs booster to fill it

Linac

- In principle, could fill the ring in one shot or using trains
  - Single-shot filling promises better bunch pattern stability
  - Single-shot filling would result in a large emittance transient
- Probably not the optimum choice
  - Emittance would be ~70 nm-rad for a typical ~0.5 nC bunch
  - Short bunches are not desirable
  - Long linac requires a separate tunnel, driving up cost
  - Linac structures, rf systems more costly and less reliable than booster
  - Full energy extracted beam must be dumped
    - Could perhaps use the linac to decelerate the extracted beam

Bunch Pattern and Fill Rate

- If we inject bunch trains, the fractional droop in intensity among trains is

$$D \approx \frac{\Delta T_{inj}}{\tau} N_{trains}$$

- The required injector current is

$$I_{inj} \approx \frac{I_{ring} L_{ring}}{c \tau D}$$

- We probably want D<0.1
- We are considering a very large ring (3.16 km) with up to 200 mA
- For 4000-bunch beam, 200 trains, 20 bunches per train, and 2 hour lifetime
  - Inject a bunch train every 3.6 s
  - 3 nA average current from the injector (APS injector: 4 nA)
  - Each train has 11 nC (APS injector: 3 nC/bunch).

Study injection on-axis? This sounds trivial.

- On-axis injection is normally easy
  - Linac beams into booster
  - Booster beams into storage ring (in machine studies)
- Boosters and present storage rings have very large dynamic apertures compared to beam size.
- What if we built a ring with 2-mm DA, but we couldn't inject into it on-axis, as planned?

So what could go wrong with on-axis injection?

- This question reminds me of the difficulty of injecting in new lattices, even on-axis
- Drifts in injection beam centroids that were tolerable before (energy, transverse plane)
- Tails in distribution of Booster beam
- Drift in SR tune or energy
- Beta matching
- Effect of 100% coupling
- Can we perform standard beam dynamics measurement in low-DA conditions, i.e. response matrix measurements?

Simulate low-DA on Established Rings

- Modify in a simple way an operating lattice
  - Worsen the sextupole configuration (say, turn off one)
  - Move tunes closer to a linear resonance (say integer)
    - We selected this change
  - Move in a scraper
  - Change coupling
- Hopefully a well-characterized reference lattice implies that the derivative lattice can be as well
  - Tunes, lifetime
  - Orbit control should still be possible
  - Agreement with simulations
    - DA, MA
  - Loss distribution at apertures
  - All a challenge for good lattices to begin with!

Work so far at APS (a few hours of machine studies over last two weeks)

- Lower the tunes closer to integer
  - (36.17, 19.22) to (36.05, 19.06)
    - Assume that DA depends smoothly on tunes
    - No simulations were done (yet)
  - Both tunes needed to be lowered for smaller DA
  - Run orbit correction, and establish equilibrium orbit to inject into later
- To characterize, always need to fill ring with reference lattice, then ramp the quadrupoles to “bad” lattice
  - Modified some tools to ramp back and forth for injection
- Measure DA in h-plane: kicker angle at which 50% of beam is lost in one pulse.
  - Measured 4 mm aperture (reduction from ~13 mm)
  - Note that SigmaX of booster is about 1 mm
  - MA not measured

Work so far (cont'd)

- Set-up on-axis injection with kickers
  - In “single-turn” mode we adjust last two kickers until trajectory is straight, i.e. line up trajectory with equilibrium orbit obtained earlier.
  - Same tool used for new lattices and start-ups.
- Characterize on-axis capture
  - Loss locations, coordinates at loss points, variation with time, shot-to-shot variation, sensitivity to various settings [not done]
  - With not much time to “optimize” or to understand we had very low capture of 10% for the 4 mm DA
- Will continue studies (at low priority)