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SLS booster emittance exchange

Advanced Low Emittance Rings Technology workshop, 11-07-2019

Outline

- Motivation
- Emittance redistribution
- SLS booster overview
- Measurements
  - Coupling
  - Tune along ramp
  - Emittance exchange
- Damping effects
- Outlook
- Summary

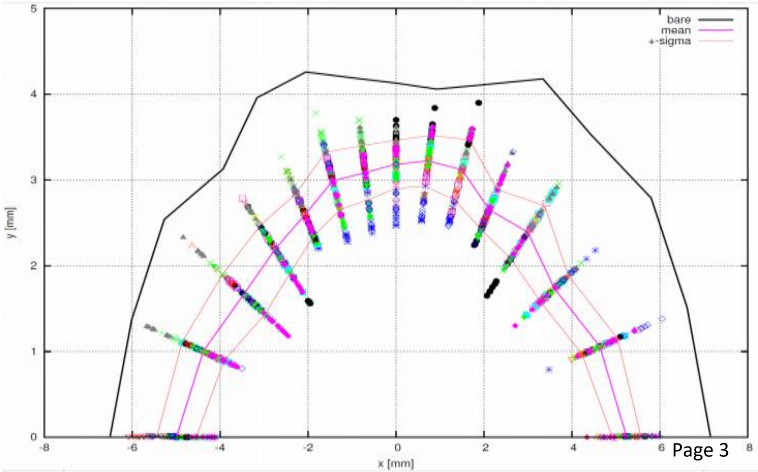
Motivation

- The new generation of storage ring-based light sources are be based on Multi-Bend Achromat (MBA) lattices with very strong focusing and low dispersion achieving < 250 pm·rad horizontal emittance.

- A common consequence is a rather limited dynamic aperture of typically ~5-10 mm.
  - SLS 2.0 CDR: **5 mm** dynamic aperture when including errors for $\beta_x = 3.5\text{m}$

- Existing 3th generation storage ring often inject using horizontal off-axis injections
  - Low dynamic aperture of new rings makes this challenging!
  - Upgrade projects often reuse injector complex!
    (Boosters w. $\epsilon_x > 50\text{nm·rad}$)

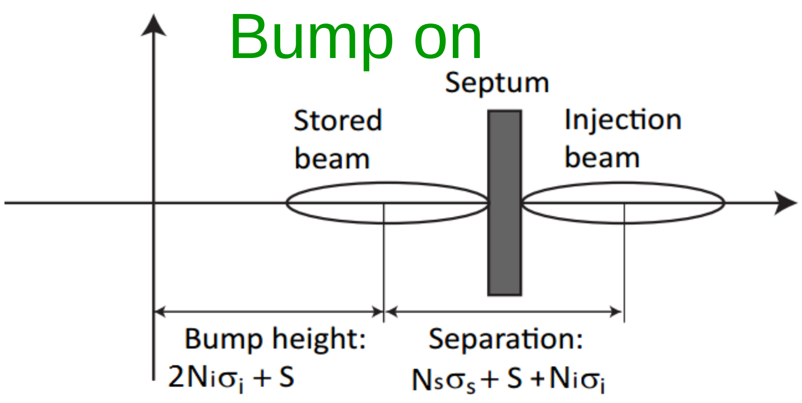
- New on-axis injection schemes under development
  - Technology not mature yet…
  - Off-axis still pursued as a „safe“ choice:
    we know how to do it!

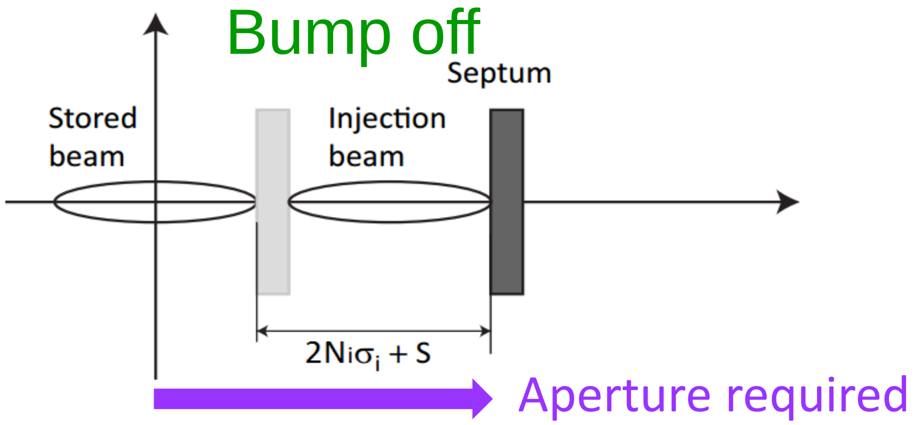


Motivation

- Several tricks can be used to improve off-axis injection efficiency or give safety margin
  - High-β region for injection
  - „Anti-septum“
  - **See previous talk by M. Aiba**

- Booster and transfer line initiatives
  - Reduction or Redistribution of booster emittances





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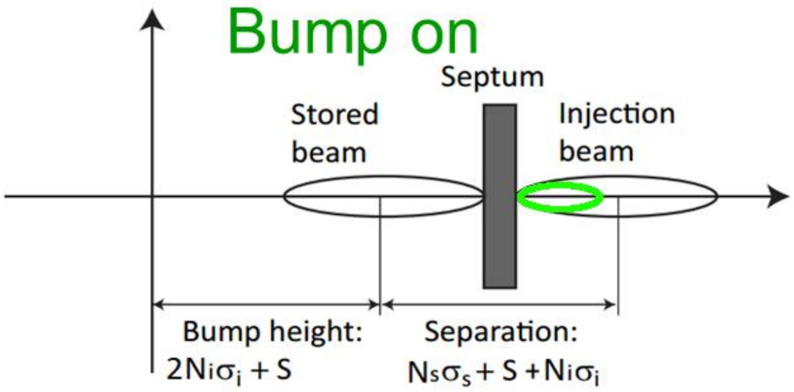
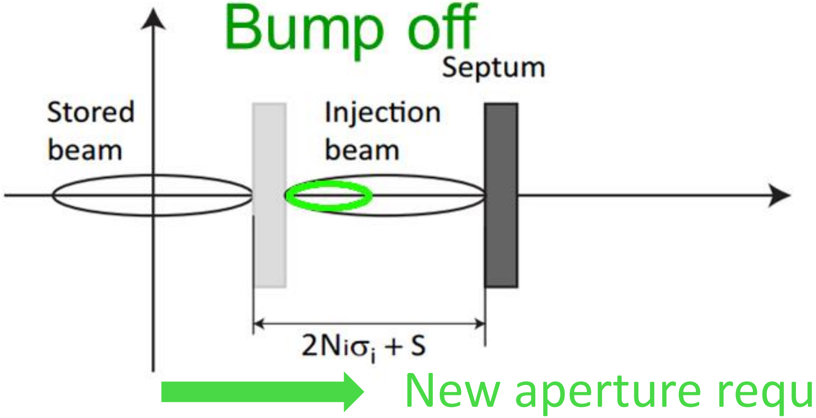




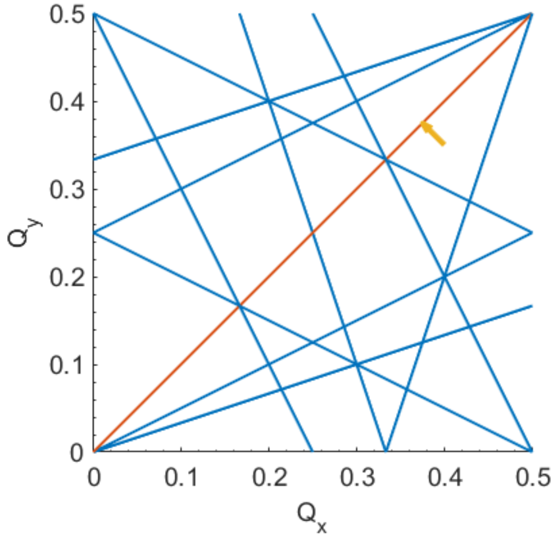
New aperture required!

Emittance redistribution: sharing

- The transverse emittances can be redistributed by using the nonzero coupling of the machine
- **Round beam** is achieved by moving tunes to the coupling difference resonance: $Q_x - Q_y - \ell = 0$

$$\epsilon_x = \epsilon_y = \frac{J_x J_y}{J_x + J_y} \epsilon_{x,0}$$

- Leads typically to a ≈50% reduction of horizontal emittance
- ESRF Booster: From 120/5 nm·rad to 60/60 nm·rad!
- Vertical dynamic aperture is plentiful
  - Move all horizontal emittance to the vertical plane!



Emittance redistribution: exchange

- A complete exchange of transverse emittances can be achieved by ***crossing*** the coupling resonance
  - Observed at the Proton Synchrotron (2001)

$$\epsilon_x = \epsilon_{x,0} + \frac{|C|^2}{\Delta^2 + |C|^2 + \Delta\sqrt{\Delta^2 + |C|^2}} \frac{\epsilon_{y,0} - \epsilon_{x,0}}{2}$$

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1. When Δ decreases, ϵ_x decreases, ϵ_y increases
2. When $\Delta = 0$, $\epsilon_x = \epsilon_y = \frac{\epsilon_{x,0}+\epsilon_{y,0}}{2}$
3. When Δ increases on the other side of the resonance

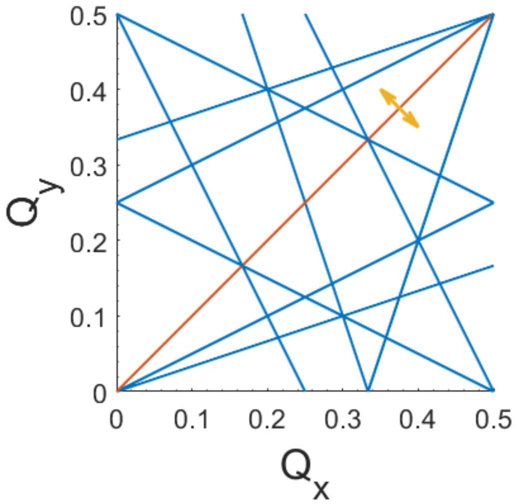
$$-\Delta \gg |C| \ : \quad \epsilon_x \rightarrow \epsilon_{y,0} \qquad \epsilon_y \rightarrow \epsilon_{x,0}$$

Δ: betatron tune separation $Q_x - Q_y - \ell$
$|C|$: coupling coefficient

WEOAA01 Proceedings of IPAC2016, Busan, Korea

TRANSVERSE EMITTANCE EXCHANGE FOR IMPROVED INJECTION EFFICIENCY *

P. Kuske[†] and F. Kramer, Helmholtz-Zentrum Berlin, Berlin, Germany



- Goal: Cross the coupling resonance quickly and extract immediately after!
- How: Rapid modification of quadrupole family ramp

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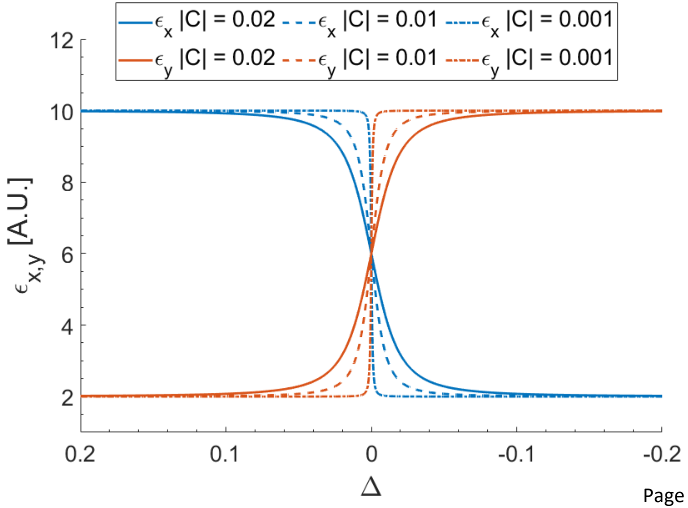

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SLS booster: overview

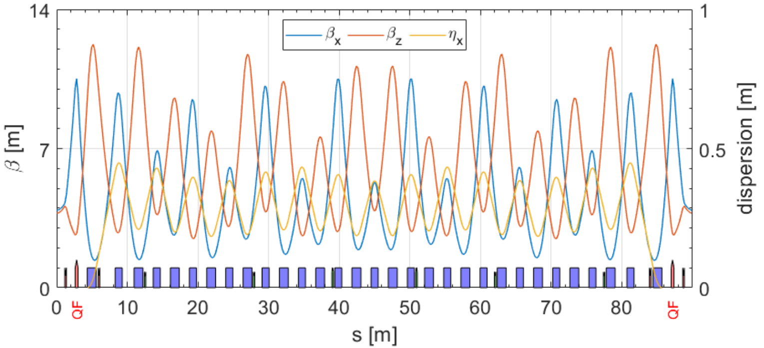
Highlights

- First booster built specifically for top-up operation
- Mounted on inner wall of Storage Ring tunnel
  - ≈ same circumference as SR
- Low horizontal emittance
  - Vertical emittance probably ~2-3 nm.rad while minimum is 0.05
- Tune are relatively close

- Digital magnet power supply control
- Dipoles with quadrupole + sextupole components
  - Quadrupole families for dispersion and tune control
- Relatively weak and inexpensive magnets

- **Extremely flexible and easily controllable!**

Injection energy	0.1	GeV
Extraction energy	2.4	GeV
Circumference (m)	270.0	m
$\epsilon_{x,y}$	9.6 / 0.05	nm rad
$\nu_{x,y}$	12.41 / 8.38	...
Energy spread	7.5×10^{-4}	...
RF frequency (MHz)	500	MHz
Damping time at 3 GeV	11.4 / 18.5 / 13.4	ms
Revolution period	0.9	µs
Repetition rate	3.1	Hz

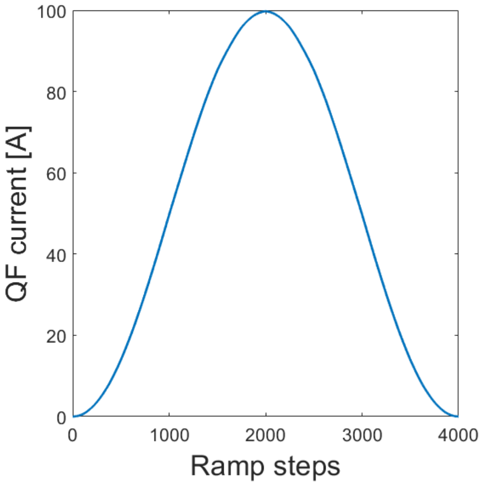


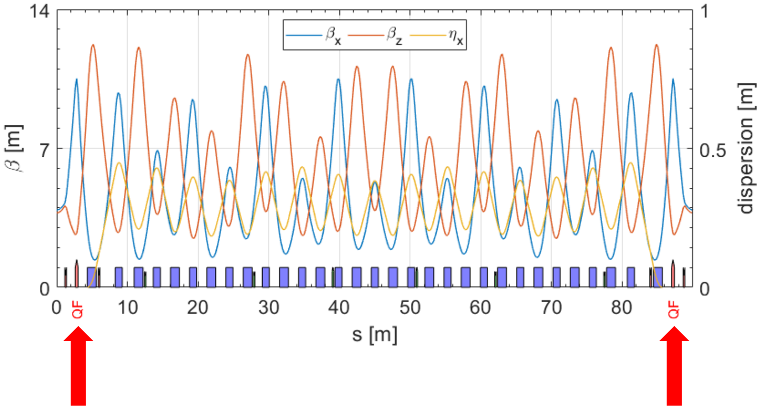
SLS booster: QF family

- Digitally controllable in 4000 steps along full ramp
  ≈ 88 turns / step ≈ 79 µs / step.
  - Quite nice resolution!

- Maximum current: 140 A

# magnets	6	…
Magnetic length	0.4	m
Max. gradient at 2.4 GeV	16	$T\,m^{-1}$
Max. current	140	A
Max. ramping speed	1600 / 1.44	$A\,s^{-1}$ / $mA\,turn^{-1}$
$\beta_{x,y}$	10.1 / 2.64	m
$\alpha_{x,y}$	-2.67 / 0.286	…
$\eta_{x,y}$	0 / 0	m



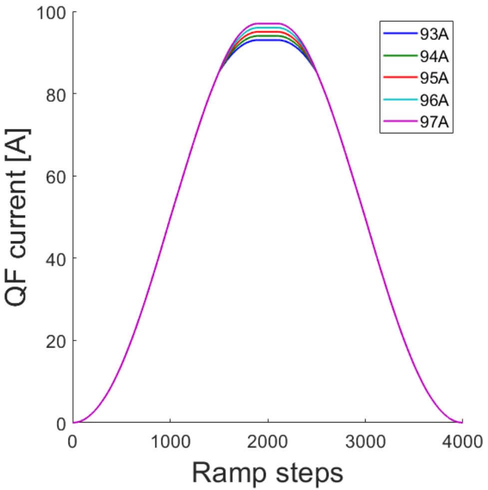


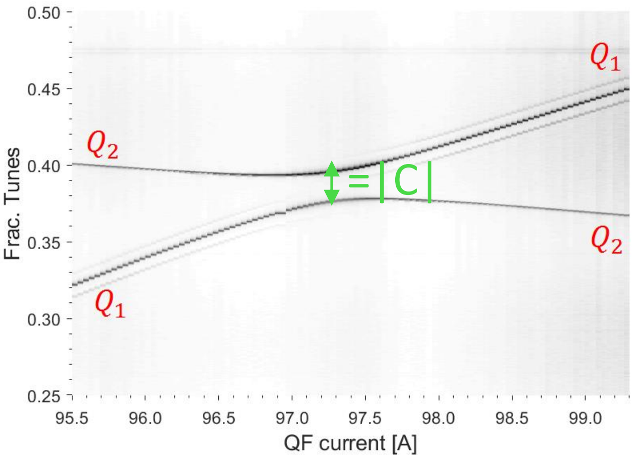
Closest Tune Approach measurements

- Coupling is measured using the Closest Tune Approach at the top of the ramp

$$Q_{1,2} = Q_{x,y} \mp \frac{1}{2}\Delta \pm \frac{1}{2}\sqrt{\Delta^2 + |C|^2} \qquad \Delta = Q_x - Q_y - \ell$$

- 'Natural' coupling is substantial:
  - |C| = 0.019
  - No need for additional skew quadrupoles

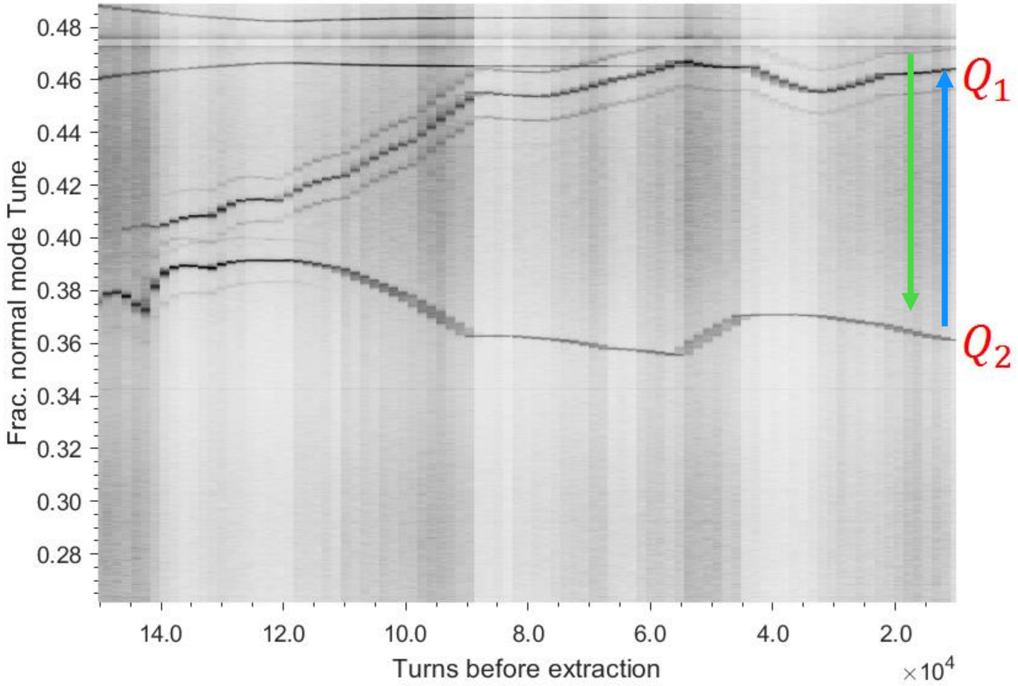




Tune along ramp

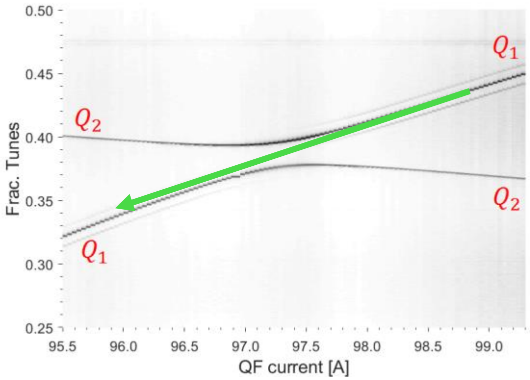
$$Q_{1,2} = Q_{x,y} \mp \frac{1}{2}\Delta \pm \frac{1}{2}\sqrt{\Delta^2 + |C|^2}$$

Waterfall plot of FFT of Turn-by-Turn BPM data



Goals:

- Cross the coupling resonance quickly to achieve the emittance exchange
- Extract beam shortly after to avoid damping
- $I_{QF}: 98A \rightarrow 95A$



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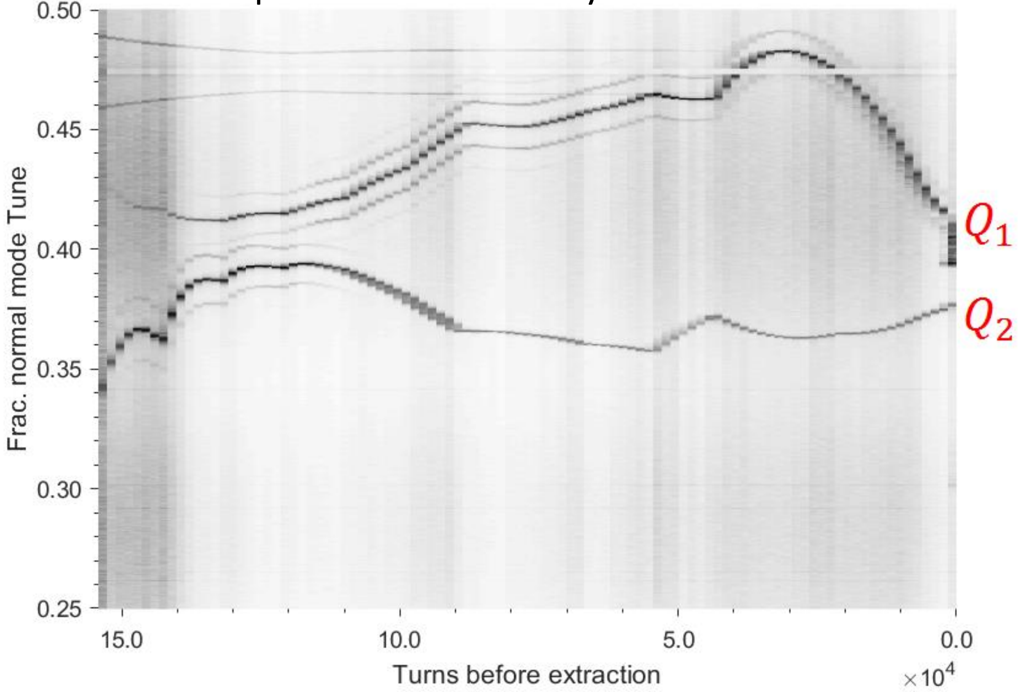

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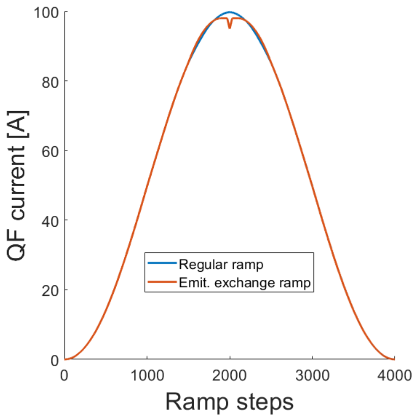

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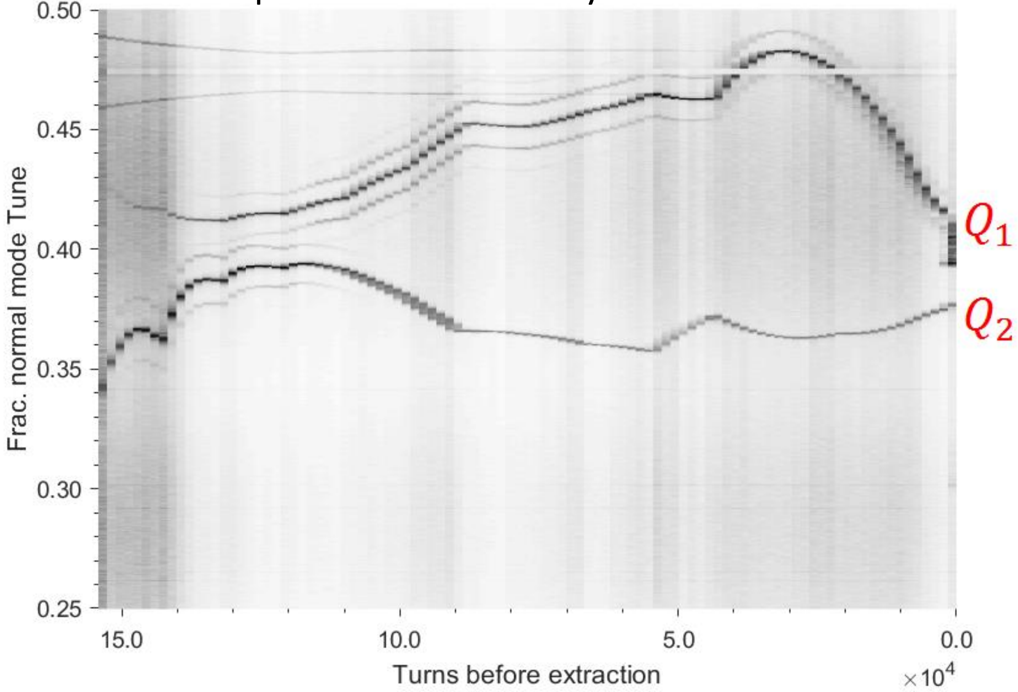

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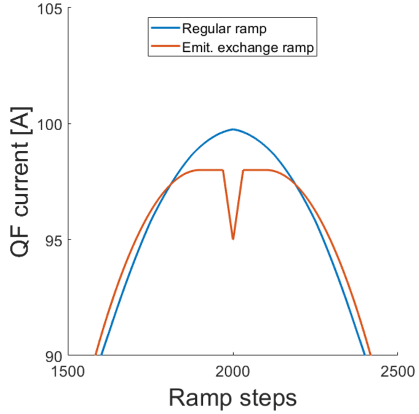


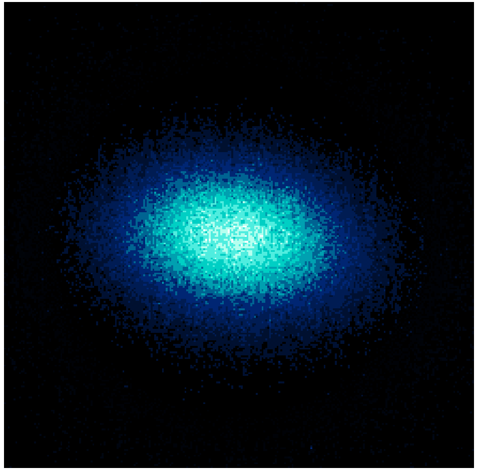
Results

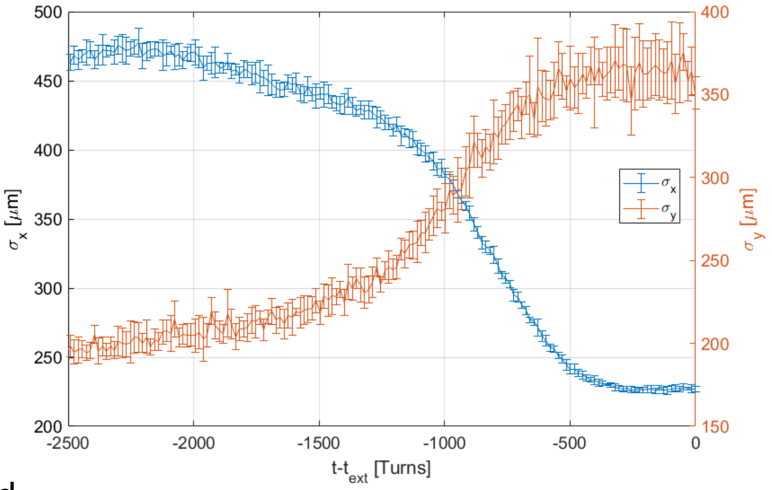
- Beam size measured on OTR in Booster-to-Ring transfer line

- Emittance Exchange process measured by extracting at earlier times over many ramp cycles

- Assuming β, η constant during quadrupole sweep

$$\epsilon_x = \frac{\epsilon_{x,0}}{4}, \qquad \epsilon_y = 3.6\epsilon_{y,0}$$





Not a "big" change but remember: $(\epsilon_x, \epsilon_y) \approx (10, 2.5)$ nm·rad

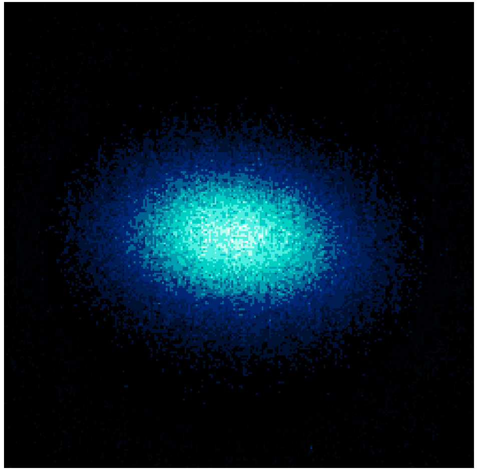
Results

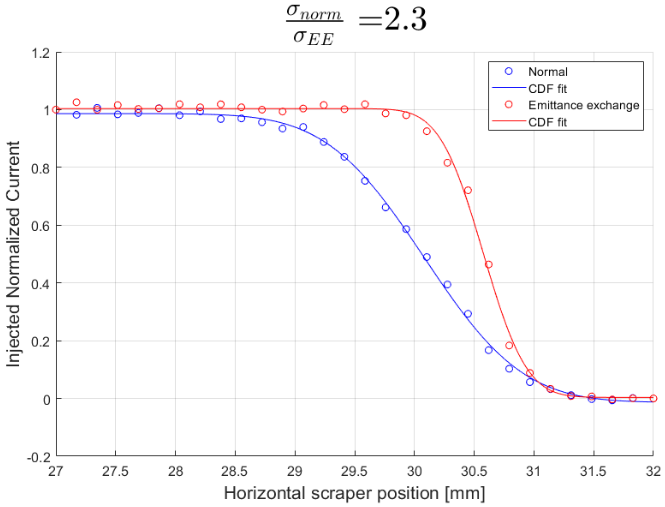
- Test of injections with limited aperture by inserting horizontal scraper

- Scraper can be inserted further without loss of charge when using emittance exchange

- Fitting Cumulative Distribution Function

$$\frac{\sigma_{normal}}{\sigma_{EE}} = 2.3$$





Emittance redistribution: Radiation damping

- Damping is a necessary evil for emittance exchange
  - Quadrupole power supplies must ‚beat' the damping

Rule of thumb (1):

$$t_{cross} \ll \tau_{x,y} \approx 5\text{-}15 \text{ ms}$$

- To gain maximum emittance exchange, the tune sweep must start and end far away from the resonance

Rule of thumb (2):

$$|\Delta_{start,\,finish}| \geq 3|C|$$

Our measurements:

$$\tau_x \approx 11 \text{ ms}, \quad t_{cross} \approx 2.5 \text{ ms}$$

$$\Delta_{start} \approx 2|C|, \quad \Delta_{end} \approx 4|C|$$

$$\epsilon_x = \epsilon_{x,0} + \frac{|C|^2}{\Delta^2 + |C|^2 + \Delta\sqrt{\Delta^2 + |C|^2}} \frac{\epsilon_{y,0} - \epsilon_{x,0}}{2}$$

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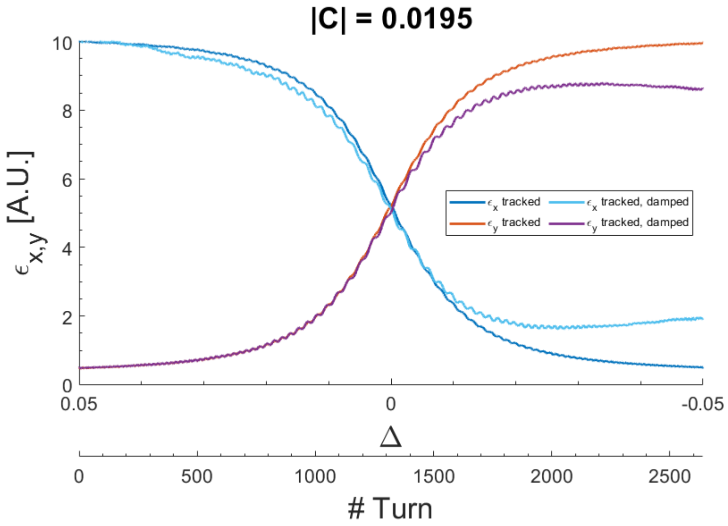

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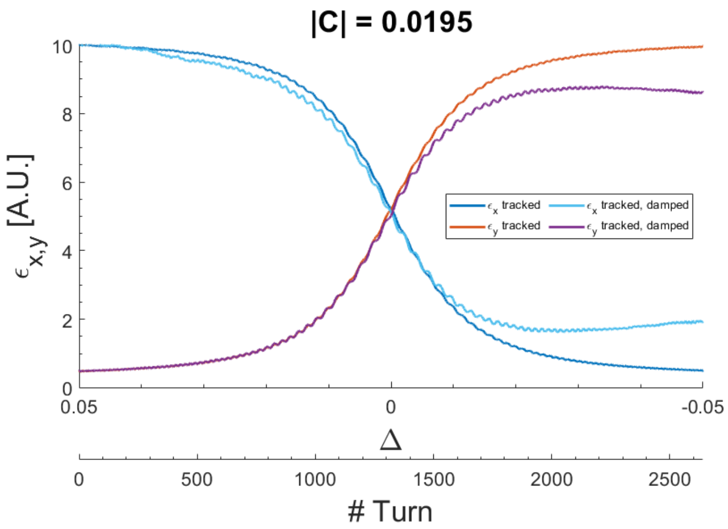
- Crossing time depends on ramping speed and the total tune shift:

$$t_{cross} = \Delta I \cdot v_{ramp}$$

$$= cal \cdot v_{ramp} \cdot \frac{4\pi|\Delta_{start} + \Delta_{\mathrm{end}}|}{\Sigma\beta_i \ell_i}$$

- Relief constraints on power supplies
  - Decrease |C|
  - BUT: smaller |C| needs longer crossing time to do the exchange adiabatically*

➔ Increased radiation damping



* See averaging of single particle emittance in: A. Franchi, E. Métral, R. Tomás, *“Emittance sharing and exchange driven by linear betatron coupling in circular accelerators”* eq. 20 & 21

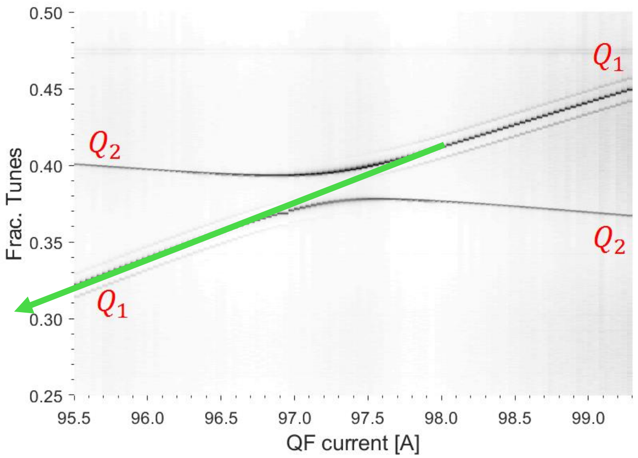
Improvements for future measurements

- Rule of thumb (2) was not fulfilled: $\Delta_{start} < 3|C|$
  - Starting point too close to resonance
  - Damping already plays a role decreasing efficiency of exchange

- Currently no reliable measurement of emittances
  - Betatronic and dispersive beam size contributions approximately equal

    ➔ standard quadrupole scans not useful
  - Attempts with multi-quad, multi-screen scans in progress

- Minimization of ϵ_y ➔ larger reduction of ϵ_x
  - Currently, $\epsilon_y \approx$ 2-3 nm·rad and we hope to get < 1 nm·rad
  - Orbit correction: currently only 2 BPMs in booster



Outlook

- Emittance exchange successfully tested: many future *and* existing facilities might apply this technique depending on their booster and injection scheme

- High-emittance (≥ 50 nm) boosters can have a significant relaxation of required horizontal acceptance, since vertical emittance is typically less than 5 nm
  - Large emittance does not imply longer crossing times

- Easy to implement:
  - Does (should) not require modifications of booster or transfer line hardware
  - Exploits ‘natural’ coupling of the machine

Summary

- Upgrade projects tend to reuse existing injector complex
- Small dynamic aperture make off-axis injections challenging
- The booster emittance can be redistributed through emittance exchange by coupling resonance crossing before extraction
- A factor 4 (3.6) decrease (increase) in horizontal (vertical) emittance achieved in SLS booster
  - Close to full exchange!
  - Can be useful for other existing and future facilities and (almost) immediately applied

Summary

Extra slides

Crossing speed dependency

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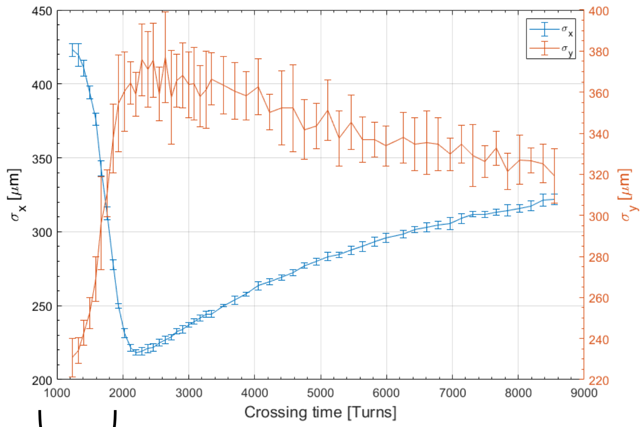
- Best exchange for the crossing $I_{QF} = 98A \rightarrow 95A$ with a “crossing time” of ≈2200 turns.

- Small machine coupling: Longer crossing time needed
  ➔Radiation damping becomes important
    ➔Additional coupling needed
      ➔Additional skew quadrupole needed



Power supply can’t follow

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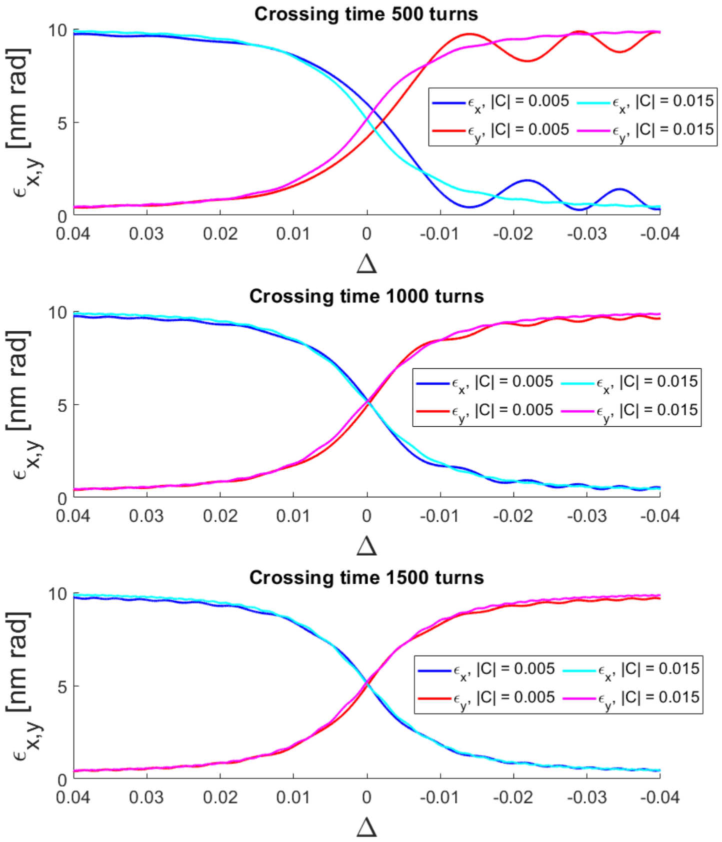
Crossing speed dependency

- Consequences of low coupling: mismatch of emittance
  - If coupling is small, then a longer crossing time is needed to do a proper emittance exchange without mismatch of the emittance.
  - If crossing time is too short, the emittance exchange becomes nonadiabatic.
  - If crossing time is too long, radiation damping & quantum excitation will play a role.
  - Skew quadrupoles might be needed if coupling is too small.



Results

- Movie of measured beam profile
  - Emittance exchange is not very visible due to large dispersion at OTR monitor $(D_x, D_y) \approx (0.1, 0.1)$ m measured