# Optimization of the multi-turn injection into rings with space charge

Christian Carli

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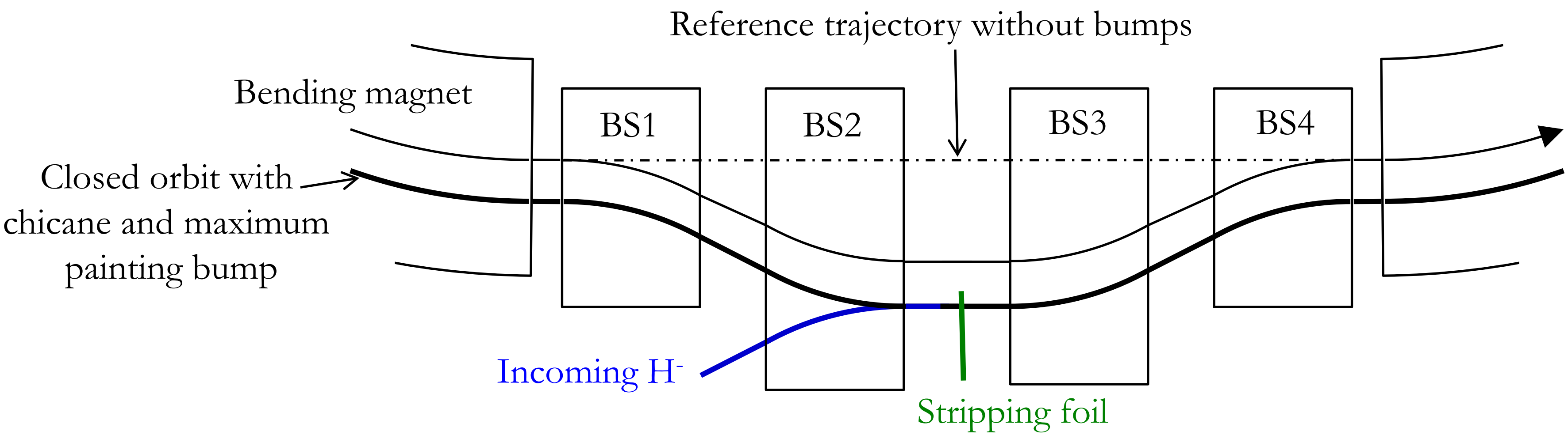
# Introduction

- Brief recap on multi-turn injection schemes
  - "Conventional" with stacking in phase space
    - Limited by Liouville theorem: distinct injected turns in distinct phase space regions
    - Mostly (e.g. CERN PS Booster) stacking in horizontal phase space, but stacking in longitudinal phase space or exploiting transverse and longitudinal phase space possible
    - High losses inherent to injection process
    - Rather limited for shaping distributions, high brightness of beam from Linac an issue
    - Not further considered in this presentation
  - Charge exchange injection
    - Not limited by Liouville theorem: distinct turns injected into same phase space regions
    - Strongly reduced losses (dominated by unstripped ions and scattering)
    - Larger number of turns (scattering in stripping foil still a limit) can be injected
    - Less demanding for Linac beam intensity and brightness
      => but for proton machine: generation $H^-$ more difficult for source)
      => lower Linac RF power requirements
    - Allows painting schemes to shape beam distributions for high brightness and intensity
      - Chopper required for longitudinal painting schemes (aiming for large bunching factors)
      - Transverse painting with orbit bumps and steering of incoming beam
    - Focus of the presentation

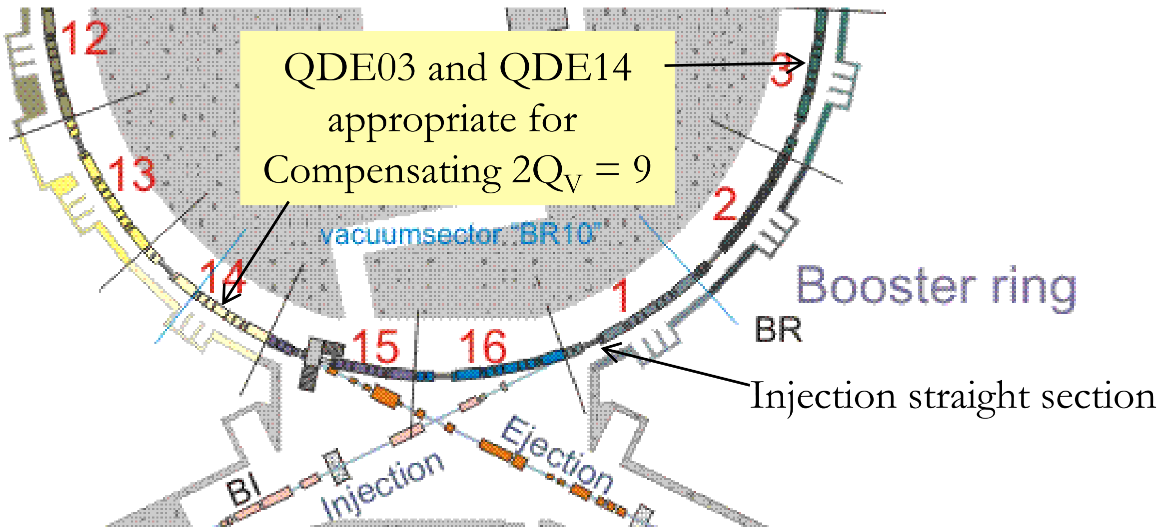
# Practical Aspects of Charge Exchange Injections - Injection chicane and induced perturbations




- Charge exchange injection with "chicane" (BS magnets) to merge incoming and circulating beam
  - In most cases superposition of painting bump and chicane bump
  - In principle one bump ("chicane" varying already during injection) sufficient as e.g. at FNAL
- Non-linear (multipolar components) may be a limitation
  - E.g. at SNS: complicated shape of magnetic field of chicane magnets with longitudinal component at the foil location (motivation explained later: magnetic field to strip excited $H^0$ and long. component to bring electrons away from foil)
  - magnets optimized such that effects (roughly) cancel
  - E.g. for CERN Booster: corrugated vacuum chamber and time varying multipolar components due to eddy currents studied at present to evaluate feasibility (ceramic chambers as fallback solution)

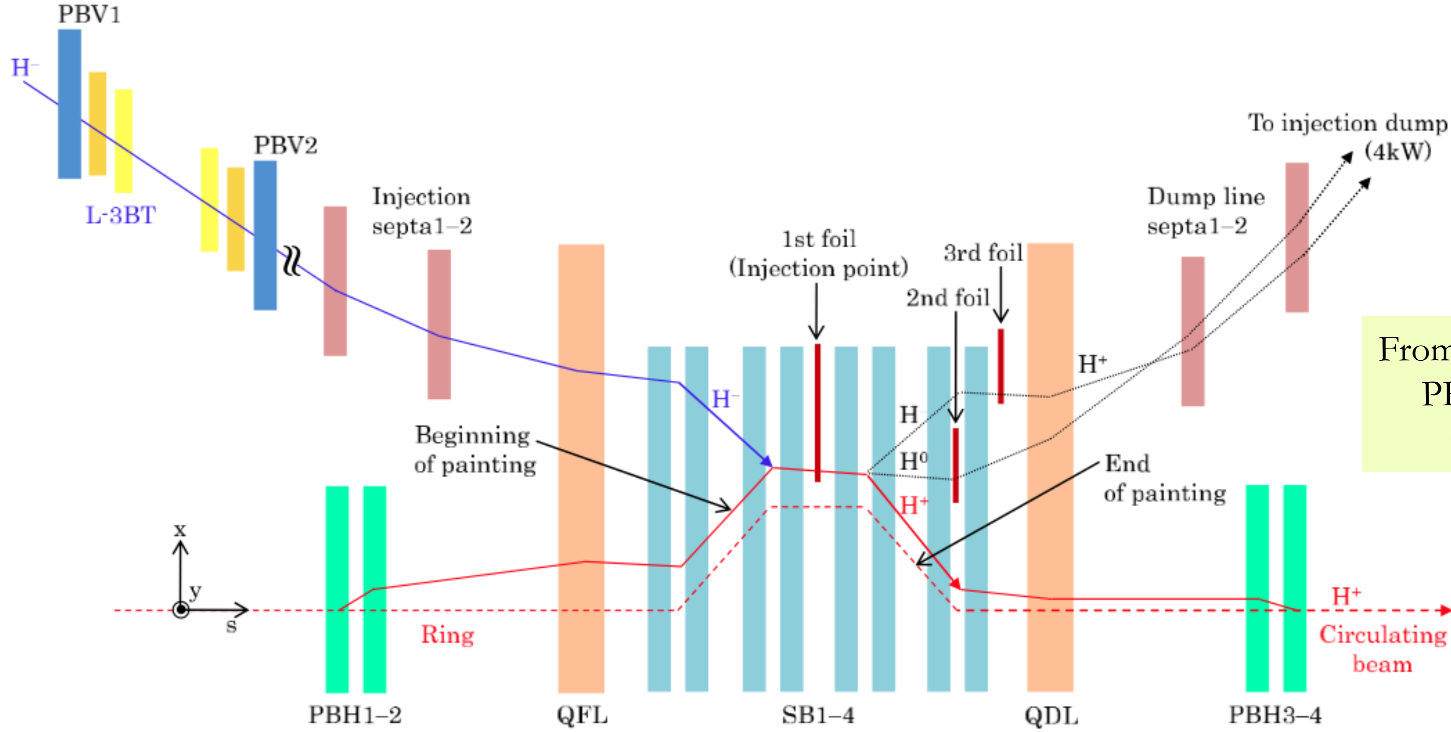
# Practical Aspects of Charge Exchange Injections - Injection chicane and induced perturbations

- Lattice perturbation by focusing due to chicane magnets is a potential performance limitations (e.g. at FNAL, thanks to F. Ostiguy for drawing our attention to this effect)
  - Make BS magnets as long as possible to reduce additional focusing and compensate lattice perturbations (as much as possible) by additional quadrupolar fields
  - "Active" compensation of perturbations due to chicane in the CERN Booster
    - Trims on QDE magnets (on additional windings …) in period 03 and 14 with appropriate phases for an effective compensation with large vertical β-functions (and small horizontal β's)




    - Slow chicane fall (say 5 ms) such that quad trim converter can follow programmed currents

# Practical Aspects of Charge Exchange Injections
# - Integration of a dump for un-stripped ions

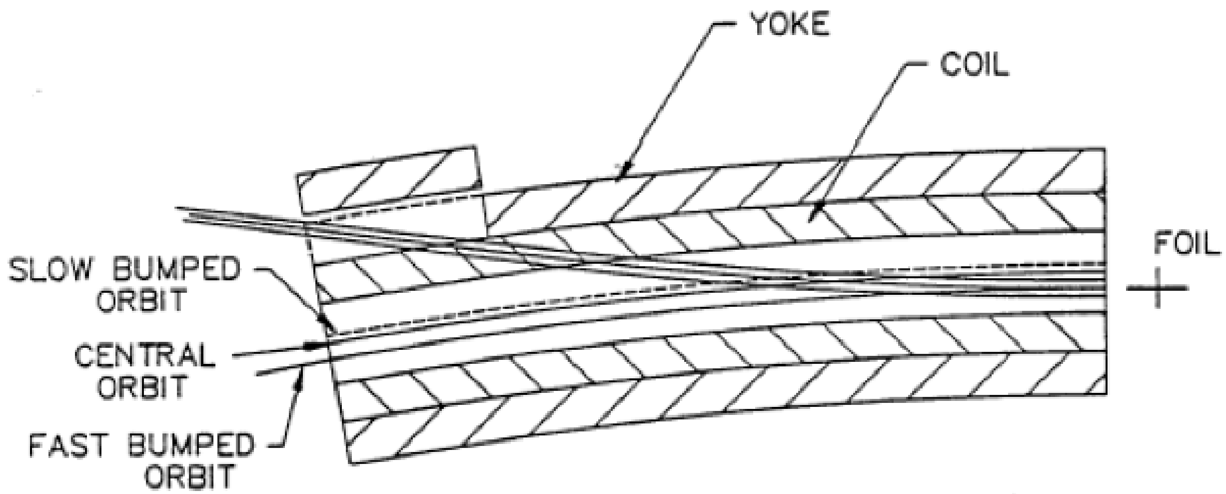



From: H. Hotchi et al., PRSTAB Vol. 15 040402 (2012)

Sketch of an $H^-$ charge exchange injection (J-Parc 3 GeV ring) with dump for unstripped ions

- Non-stripped ions (small fraction during regular operation, full intensity in case of broken foil) activate and possibly damage machine … potential intensity limitation
- Bring non-stripped ions in a controlled way to an external or internal (if space contraints do not allow guiding unstripped ions away from the machine as e.g. for the CERN PSB) dump
- Excited $H^0$ may be an issue solved by inserting foil into a region with relatively strong magnetic field (stripping highly excited $H^0$ within short distance, see work on SNS)

# Practical Aspects of Charge Exchange Injections
## - A simple scheme without chicane (main bends to merge beams)




- Usage of a lattice bend to merge incoming and circulating beam(example: BNL Booster)
  - Elegant solution – no need for chicane bump
  - Displaced yoke to create space for incoming beam – impact on field quality?
  - Painting bump
    - Weaker deflection than injection chicane magnets needed to move circulating beam from foil
    - Less perturbations for optics
  - More difficult (impossible) to integrate dumps for unstripped ions
    - Magnet damage close to charge exchange injection region
  - (Conventional multiturn injection for ions into BNL Booster in another section)

# Practical Aspects of Charge Exchange Injections

## - Issues related to foil damage and life-time

- Limited life-time and damage of foil may limit possible intensity (and brightness)
- Direct heating of the foil due to incoming $H^-$ and circulating p
  - Limit number of foil hits: choice of transverse painting parameter
  - Increase part of foil surface hit by beam: choice of transverse painting parameter, lattice with large betatron functions at foil (not favorable for blow-up due to scattering), …
  - Foil thickness: thinner foil enhances temperature decrease between injections (via radiation, more relevant for high repetition rate), but choice limited by stripping efficiency
- Electrons stripped from $H^-$ may hit foil several times or damage surrounding equipment
  - Encountered during SNS intensity ramp up
  - Cure: careful design (simulations) of magnetic fields and electron trajectories around the foil to safely dump stripped electrons
- … cure/mitigation of foil damage in general:
  - Efficient foil exchange mechanism
  - Use other methods, e.g. Laser, for stripping

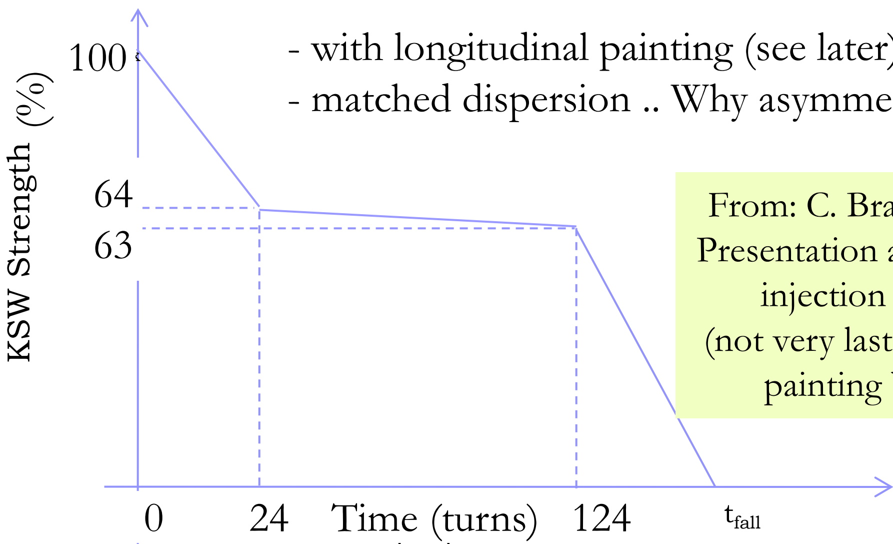
From: M. Plum et al., Proceedings of HB2010


SNS foil holder damaged (molten parts) by convey electrons

# Transverse Painting

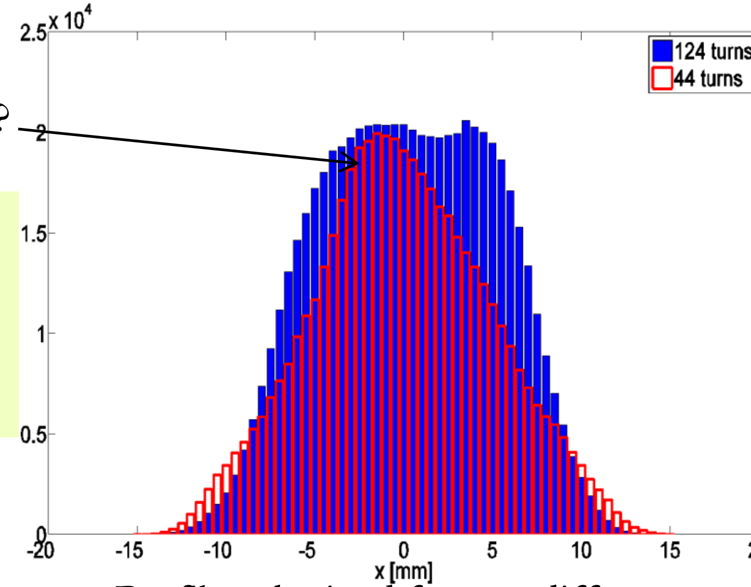
- Combination of orbit bump(s) and steering of incoming beam allows shaping transverse distribution

- with longitudinal painting (see later)
- matched dispersion .. Why asymmetric shape?




Time evolution of the horizontal painting bump

From: C. Bracco et al., Presentation at a PSB H⁻ injection review (not very last version of painting bump)



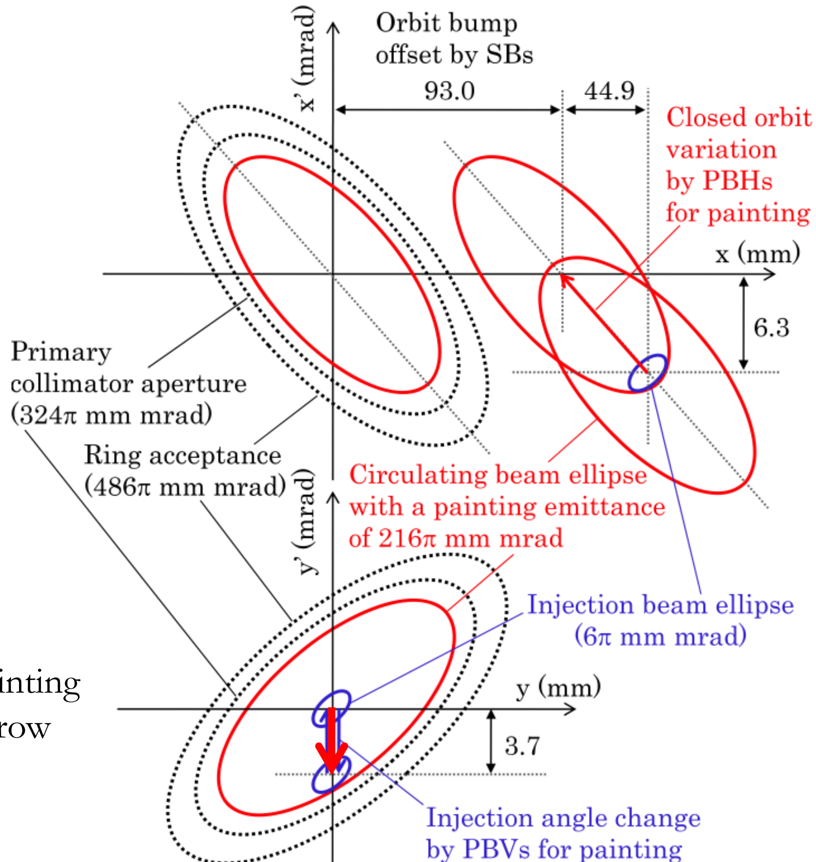

Profiles obtained for two different durations of the injection

- Simulations for the PS Booster by C. Bracco
  - At the beginning: incoming beam injected on closed orbit (small emittances)
  - Few turns injected with small betatron oscillation
  - Many turns injected with large betatron amplitudes
    - Flat transverse profile yielding small space charge tune shift (for given emittances)
    - Optimum for high brightness and intensity?
  - PS Booster: vertical emittance by steering and betatron mismatch – vertical painting discussed

# Transverse Painting

- Independent horizontal and vertical bump and/or injection steering
  - In principle possible to shape both horizontal and vertical beam distribution and correlation
- Correlated painting
  - Particles with small (large) hor. oscillation amplitudes have small (large) vertical amplitudes as well
    - "Square" shape of transverse beam distribution (in x-y) and high density at (transverse) beam center
    - Expect modest maximum beam brightness and intensity with large maximum space charge tune shift?

correlated painting with red arrow



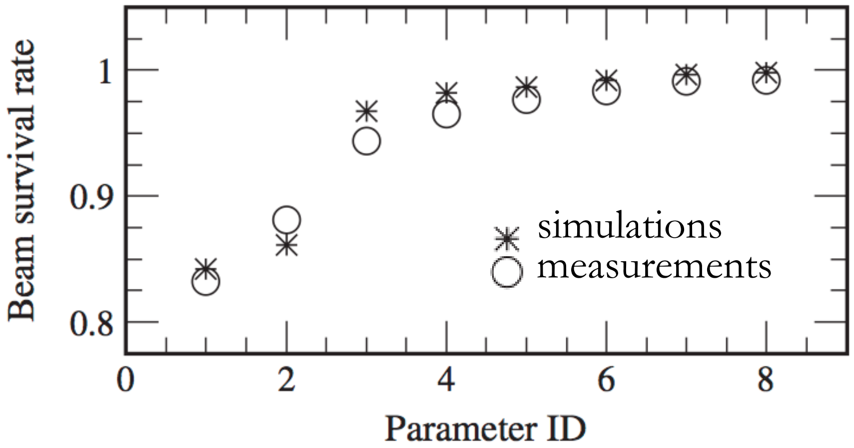

JPARC 3 GeV ring painting scheme:
- Horizontal: shift of closed orbit with painting bump
- Vertical: steering in injection line

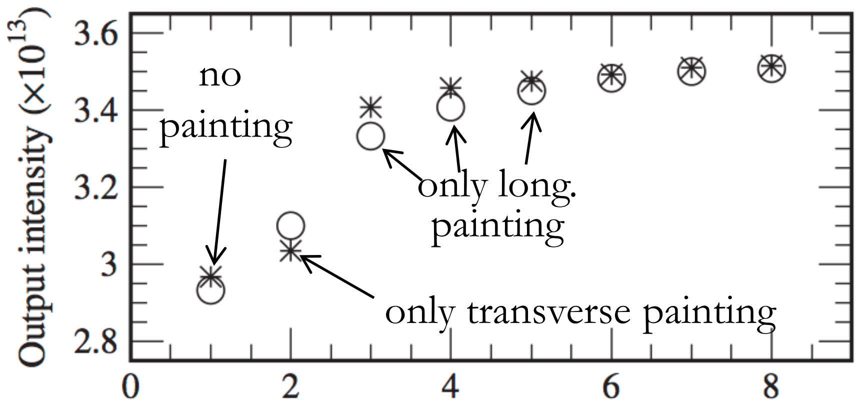
- Anti-correlated painting
  - Particles with small (large) horizontal oscillation amplitudes have large (small) vertical amplitudes
    - Lower density at center and, thus, lower direct space charge tune shift and higher intensity and brightness!?!
- Distribution somewhat close to KV with
  - Horizontal and vertical offset along a circle … should be best for direct space charge?

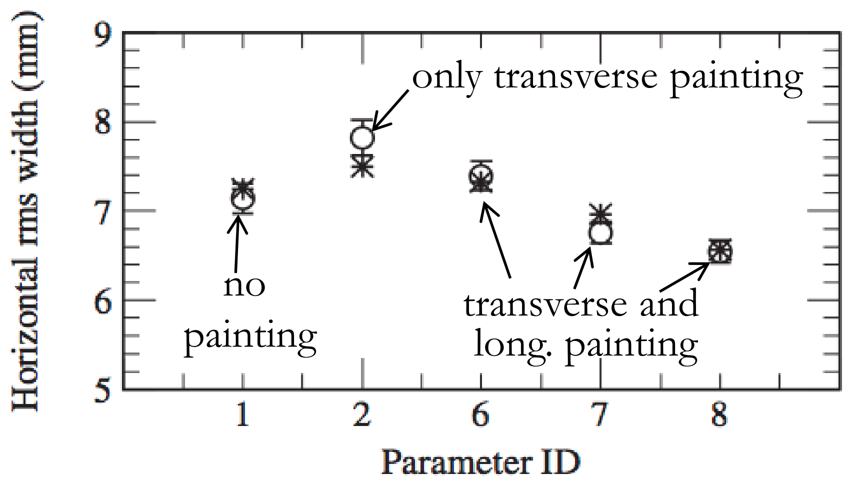
# Transverse Painting

- Study comparing various painting schemes for JPARC 3 GeV ring
  - Longitudinal painting (see next section)
  - Only correlated transverse painting

From: H. Hotchi et al., PRSTAB Vol. 15 040402 (2012)



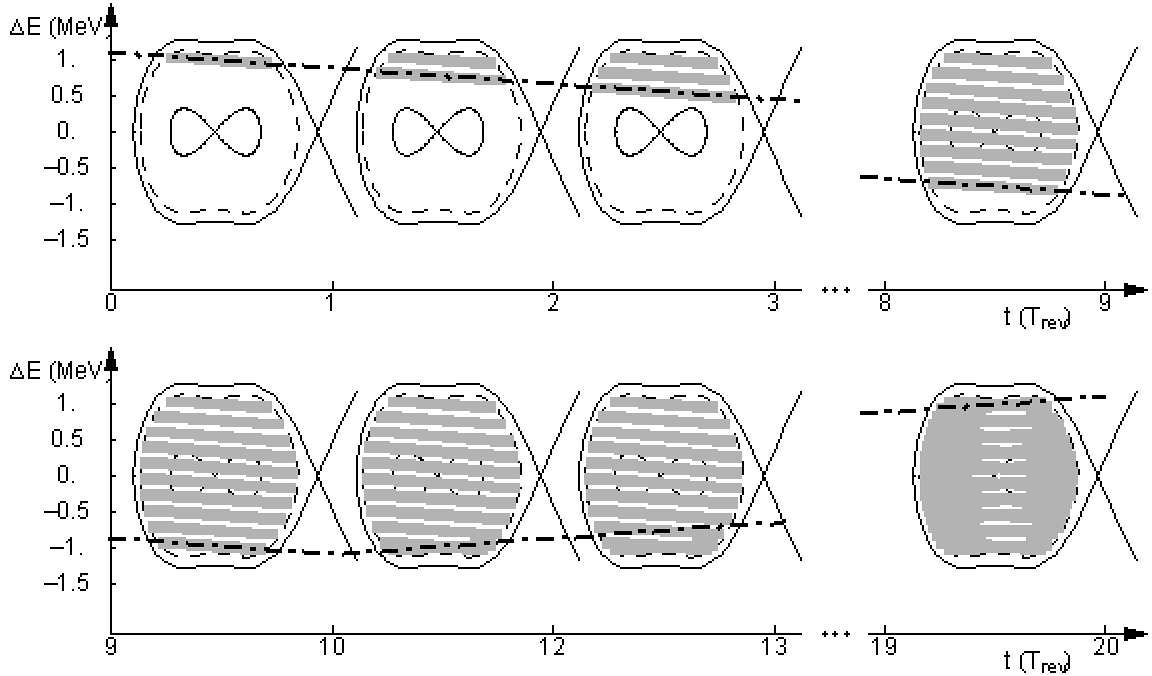

- Unclear whether correlated or uncorrelated transverse painting gives higher beam brightness and intensity (simulations seem to indicate that correlated painting is better)
  - Why does anti-correlated painting not allow higher brightness due to lower direct space charge tune shift?
- Longitudinal painting clearly improves possible brightness and intensity (next section)

# Longitudinal Painting - general considerations

- Aim: generate suitable longitudinal phase space density to
  - Maximize bunching factor (ratio between average beam current and peak current)
  - Minimize space charge tune shift (for fixed transverse beam parameters)
- Role of synchrotron motion and possible strategies
  - Significant synchrotron motion during injection process
    - Large RF voltages, high harmonics (RCS?), many injected turns
      e.g.: J-PARC 3 GeV ring
    - Strategy:
      - Use synchrotron motion to distribute particles over bucket … combined with energy offset or other schemes to avoid high density at the center
  - Little synchrotron motion during injection process
    - Small RF voltage, low harmonic, "few" injected turns
      e.g. scheme proposed for CERN Booster (>2018) with Linac4
    - Impossibility to exploit synchrotron motion to distribute particles over bucket
    - Strategies:
      - Fill bucket as well as possible with chopping and appropriate energy spread of incoming beam ("rectangular" shape in phase space of incoming beam does not match bucket)
      - "Active" painting scheme with Linac energy modulation

# Longitudinal Painting
## - "active" painting proposed for CERN Booster

- Low RF voltages and harmonic and, thus, little synchrotron motion even during longest injections
  - Double harmonic bucket to be filled homogeneously
  - Synchrotron motion cannot be exploited and is rather a perturbation
  - "Active" longitudinal painting with energy modulation generated by Linac4
  - (needed after Linac4 to CERN Booster connection around 2018)



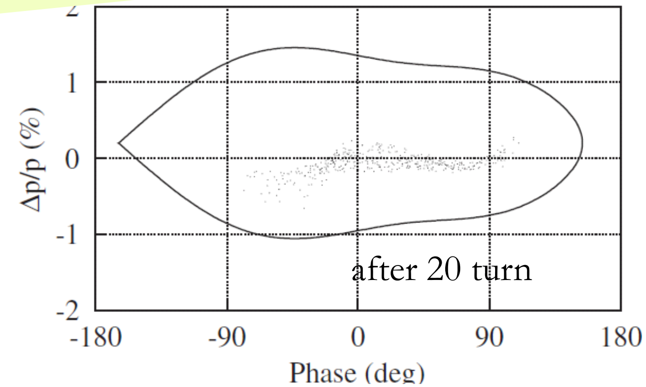

Sketch of the longitudinal painting scheme planned for the CERN Booster with Linac4 (energy modulation period doubled to 40 due to Linac4 RF power limitations)

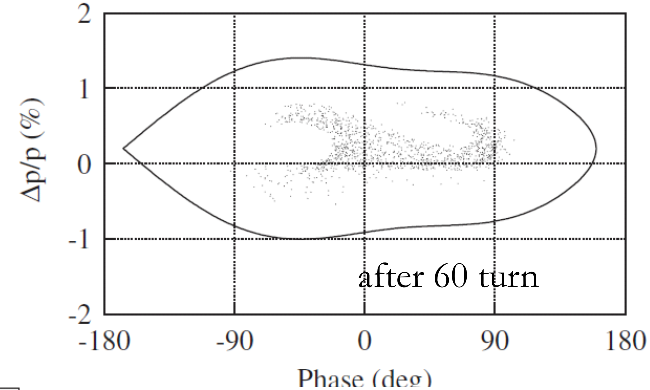
- Expected gain: about 10 % increase in bunching factor
- Consequences: need for Linac energy modulation and more complicated synchronization between the two machines

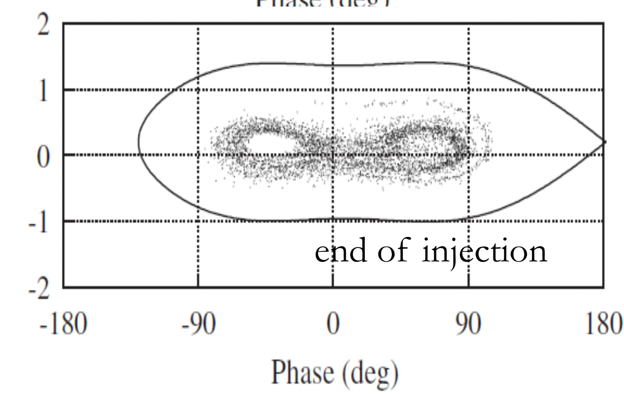
# Longitudinal Painting
# - JPARC 3 GeV ring scheme

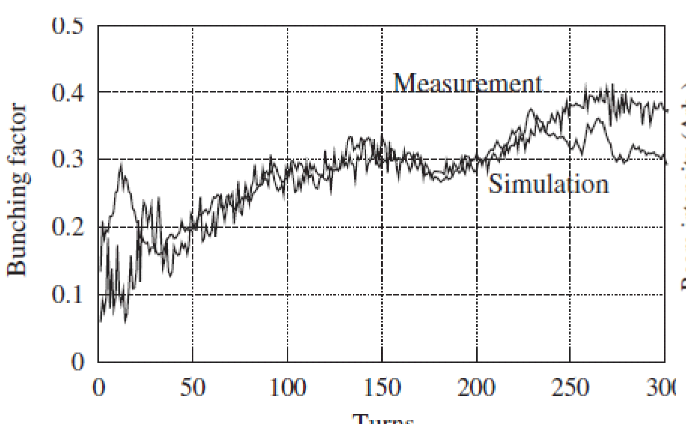
From: M. Yamamoto et al.
NIM A 621 (2010)
(many more simulation on different schemes)

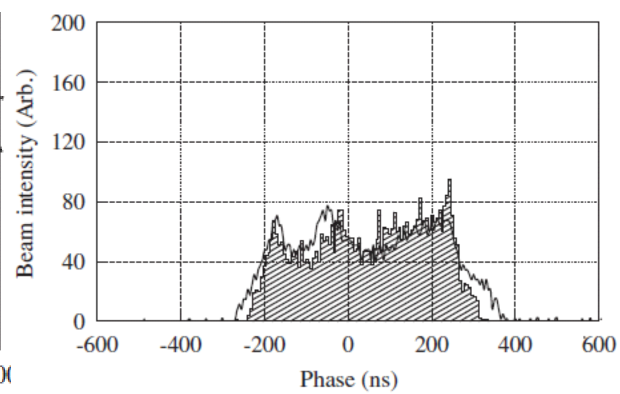
- Double harmonic system for flat buckets
- Injection of 234 turns with almost large RF voltage with harmonics 2 and 4 gives significant motion in longitudinal phase space during injection
- Many schemes with different 2nd harmonic voltage, energy offset, 2nd harmonic phase shift …. simulated
- Best results
  - Energy offset of Linac beam (synchronous particle moves by $\Delta p/p \approx \pm 10^{-3}$, bucket height $\Delta p/p \approx\geq \pm 1.1\ 10^{-3}$) of $\Delta p/p \approx -0.2\ 10^{-3}$
  - Modulation of phase between first and second harmonic (moves stable fixed point): 60 % for simulations in phase space plots, 80 % for comparison with measurement



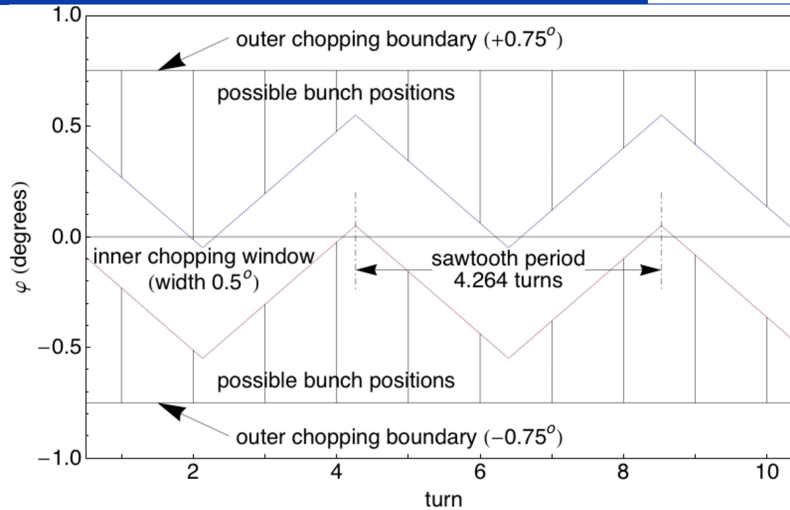



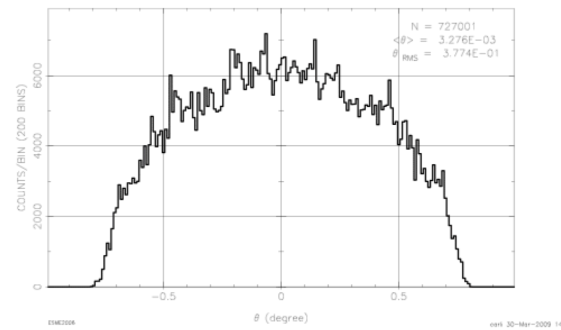



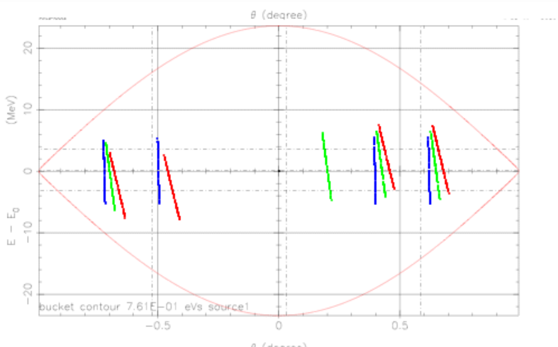



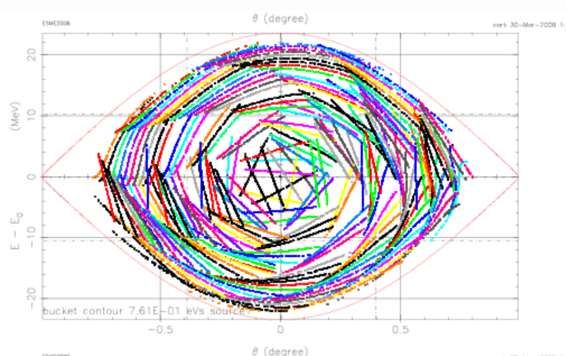
# Longitudinal Painting - A scheme for LHC bunches (as assumed at that time) for the CERN PS2 proposal

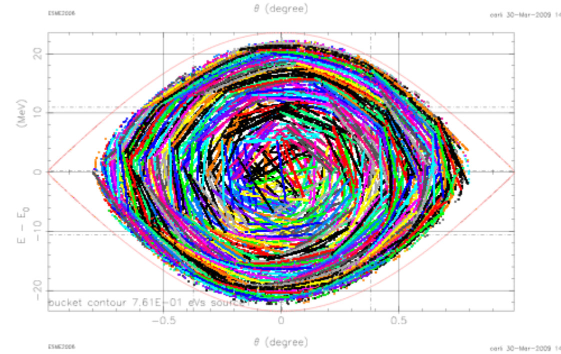
- Harmonics h=180 (bucket from -1° to +1°),
- Synchrotron oscillation period: ~ 60 turns
- Aim: lower density in center, smooth distribution
- Different schemes with energy offset, 2nd harmonics just for capture, energy modulation with fixed frequency cavities in injection line …
- Scheme giving excellent bunch shape,
  => but very demanding for chopping
  - remove Linac bunches outside bucket and in center with time varying inner window
  - No energy offset … after fill bucket within ~half a synchrotron oscillation



# Summary and Conclusion

- A few practical issues to be taken into account to avoid limitations not directly linked to direct space charge in design lattice
  - Perturbations due to injection hardware,
  - Proper dumping to avoid inacceptable activation
  - Protection of foil and surrounding against damage by different beams ($H^-$, protons electrons)
- Phase space painting
  - Possible with charge exchange injection
  - Many options to tailor longitudinal and transverse beam distributions with chopping and transverse painting schemes
  - Shaping of transverse distributions with orbit bumps and steering of injected beam
  - Longitudinal painting schemes aim at large bunching factors (average beam current divided by peak current) and depend on synchrotron motion during injection
- Optimum painting strategies
  - Not so obvious whether correlated or anti-correlated transverse painting allows higher brightness & intensity …. Why??
  - Increase of bunching factor by longitudinal increase possible intensity & brightness

- Thanks a lot to Gianluigi Arduini, Sarah Cousineau, Vincenzo Forte, Hideaki Hotchi, Jeff Holmes, Haixin Huang, Bettina Mikulec … for precious help