ILBIM Team : I Love Beam Injection Matching

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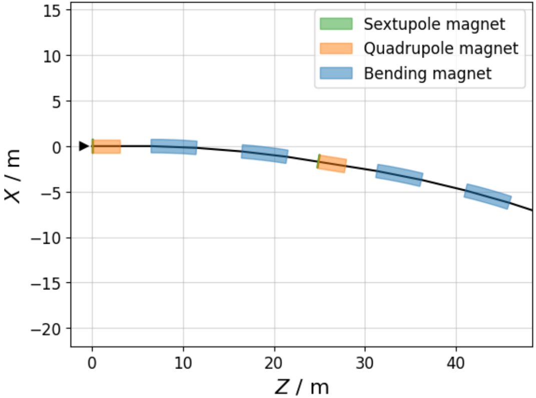
Outlines

Introduction

Problem situation

- Protons with a momentum of 20 GeV/c in a ring with circumference of 1000m
- Normalized beam emittance $\epsilon_n = 2.0\mu m$
- Chromaticity corrected to 0 by thin sextupole magnets



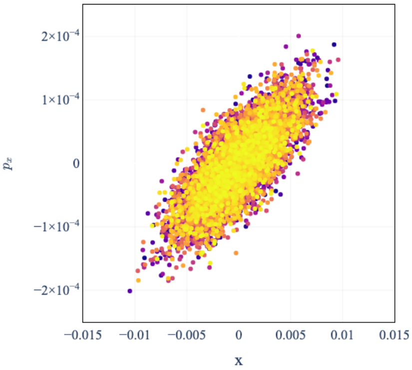
Beam injected with a horizontal error of $\Delta x = 1mm$

Matched beam

- Normalized beam distribution has to be statistically invariant under rotation

- RMS emittance computed with the correlation matrix:

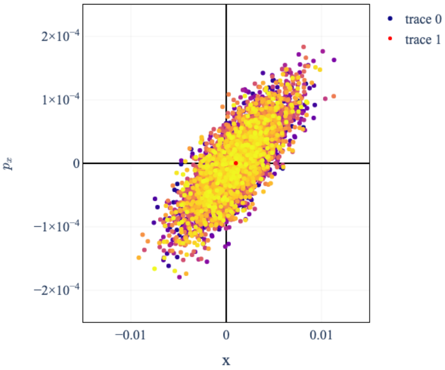
$$\epsilon_{\text{RMS}} = \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle x x' \rangle^2}$$



Unmatched Beam

- Broke rotation invariance
- Injection transverse errors :
  - Error in septum angle
  - Non perfect closure of the closed orbit bump
  - Steering errors from previous accelerator

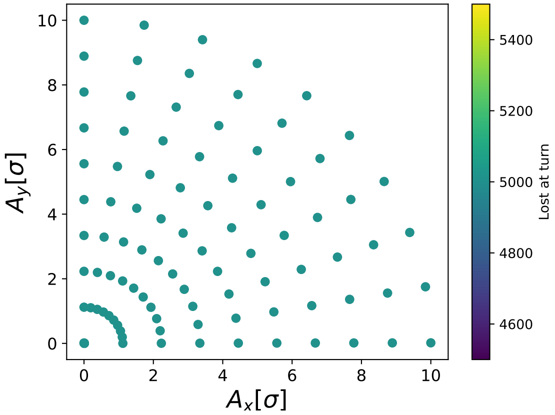
  $\rightarrow$ Leads to emittance blow-up through filamentation due to the non-linear effects (detuning with amplitude)
- Plot of the horizontal beam phase space at every turn at a fixed position $\rightarrow$ Not observing filamentation as quadrupolar error is not strong enough



Preliminary studies

Dynamical aperture study

- Study of the dynamical aperture to assess stability of beam
- Generate a polar distribution of particles and track it for 5000 turns.
- Very good stability for the first 1000s turns



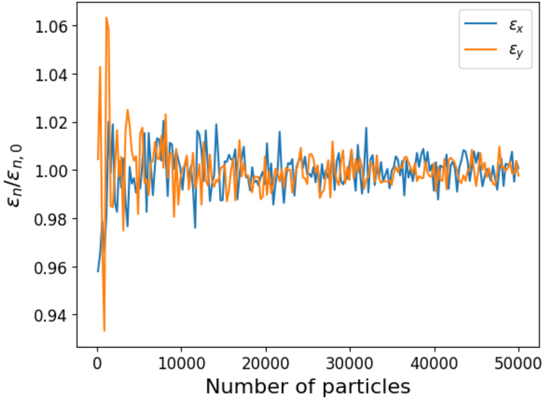
Choosing the number of particles

To fix the number of simulated particles:

- Start with a matched Gaussian distribution
- Vary the number of particles and compute the ratio between beam and target emittance

$$r = \gamma\beta\epsilon_{beam}/\epsilon_{\mathrm{n,target}}$$

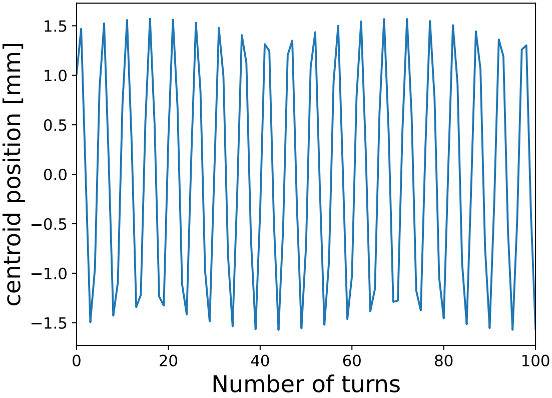
- Number of particles is chosen when convergence is achieved, here N = 10'000



Injection error from initial horizontal displacement

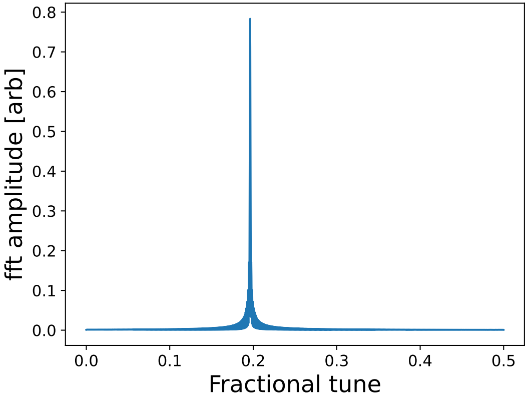
Horizontal displacement effect on the beam centroid (1)

- Displaced initial beam by $\Delta x = 1\text{mm}$
- Plotted horizontal beam centroid at every turn
- Oscillations of beam centroid with envelope modulation
- Small beta beating due to small quadrupolar component



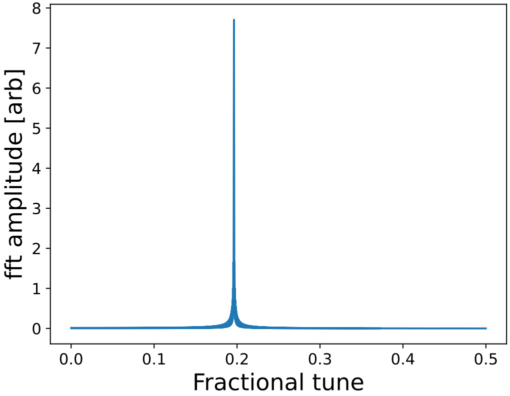
Horizontal displacement effect on the beam centroid (2)

- Doing a FFT of the centroid position oscillation over 2000 turns
- Frequency of centroid oscillation at the fractional tune : $1 - Q_{x,twiss} = 0.196$
- Quadrupolar component too small to be seen in the spectra with initial displacement of $\Delta x = 1$mm



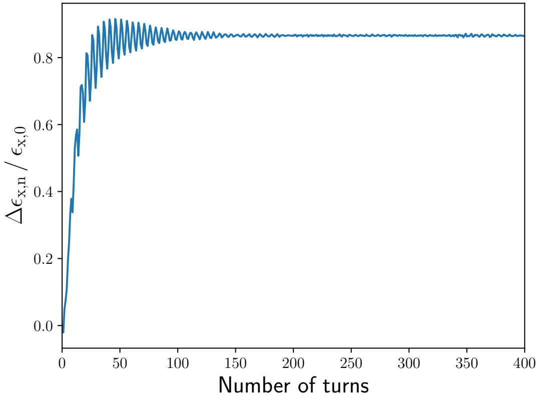
Horizontal displacement effect on the beam centroid (3)

- Increased displacement to $\Delta x = 5\text{mm}$
- Doing a FFT of the centroid position oscillation over 2000 turns
- Frequency of centroid oscillation at the fractional tune : $1 - Q_{x,twiss} = 0.196$
- Quadrupolar component still too small to be seen in the spectra



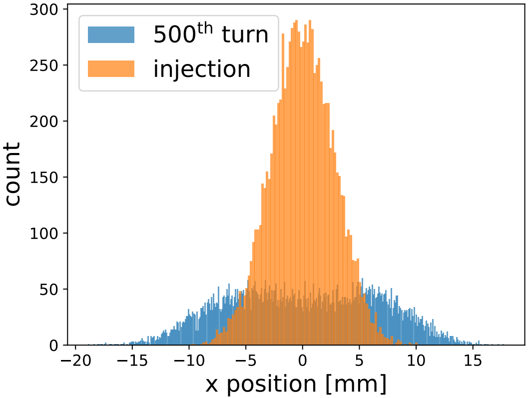
Horizontal displacement effect on evolution of emittance

- Mismatches at injection creates emittance growth
- Plot of the evolution of horizontal emittance per number of turns
- 80% of emittance increase in less than 100 turns



Horizontal displacement effect on evolution of beam envelope

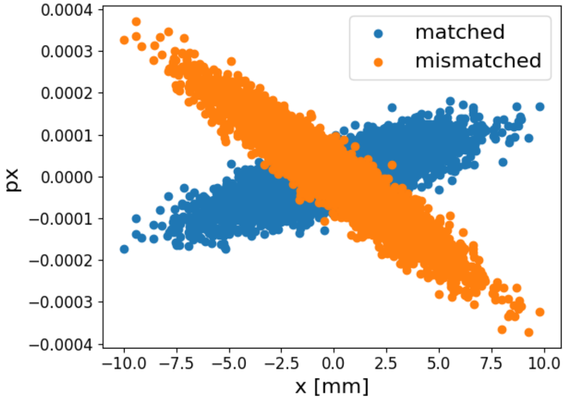
- Errors introduced by horizontal displacement Δx
- Plot of the initial beam profile and after 500 turns
- Emittance growth clearly observable from beam profile



Injection errors with initial mismatched beam

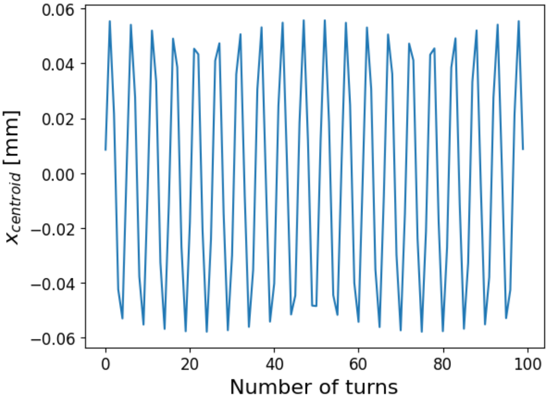
Mismatching the beam

- Initialize mismatched beam with centered distribution
- Mismatched twiss function by rotation in phase space of −50mrad



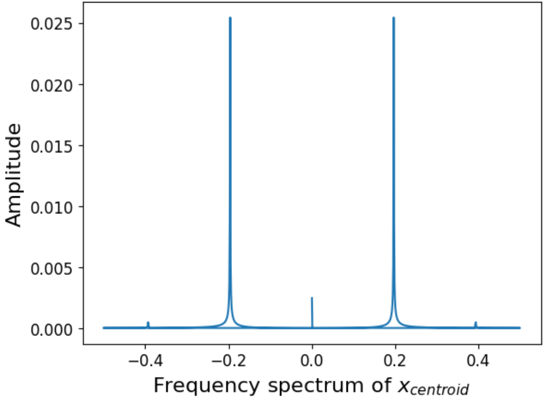
Beam centroid oscillation (1)

- Oscillation with modulated amplitude as for the horizontal displacement case
- Modulation of amplitude higher than for horizontal displacement case
- Expect to see two harmonics in FFT



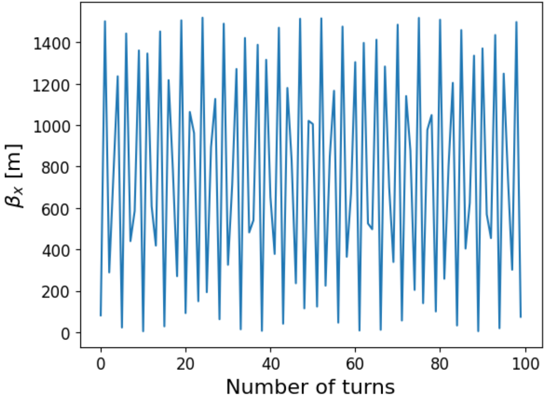
Beam centroid oscillation (2)

- FFT of horizontal beam centroid position
- β-beating oscillations at twice the frequency of centroid oscillations



β-beating

- Oscillations can also be seen on the β_x function of the particle distribution
- Computed from the correlation matrix of the beam

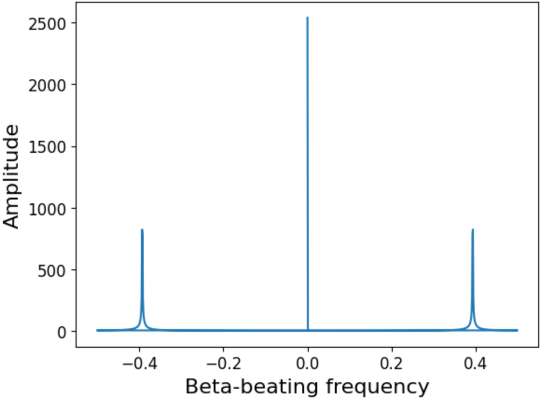


β-beating (2)

- Oscillations can also be seen on the β_x function of the particle distribution
- Frequency of oscillation at twice the tune (the beam centroid oscillation frequency)
- For a quadrupole field (gradient) error at S_0 [2]:

$$\frac{\Delta\beta}{\beta}(s) = \frac{\beta_m - \beta_0}{\beta_0} = \frac{\Delta k L \beta_0 \cos\left(2\pi Q - 2|\mu(s)\right)}{2\sin\left(2\pi Q\right)}$$

Δk the gradient error, L the length of the magnet, Q the tune, μ the phase advance.

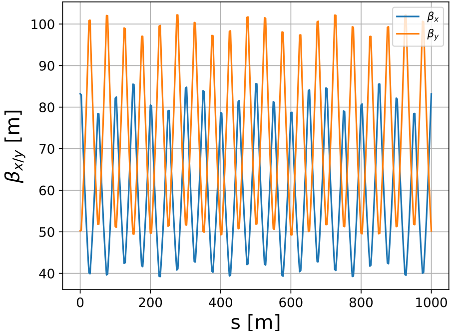


β quadrupole strength error

Beam injection Oscillations due to quadrupole strength error (1)

- Start with matched beam but introduce an error $k = 0.001\text{m}^{-2}$ to quadrupole strength

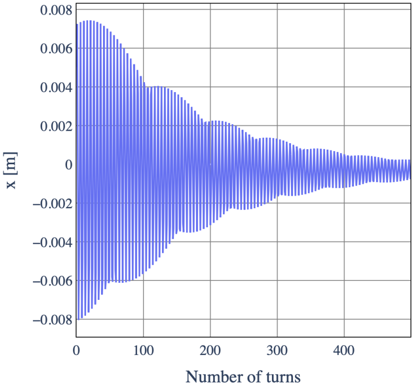
- Similar centroid oscillations as for beam mismatch with dipolar and quadrupolar errors



Increasing the sextupole strength

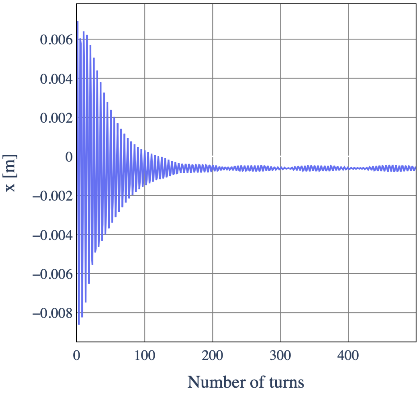
Increasing sextupole strength

- To be able to see more filamentation, increased sextupole strength
- Increase in feed-down quadrupolar error in sextupoles
- Plot of the horizontal centroid of the beam at fixed point in the lattice in function of the number of turns

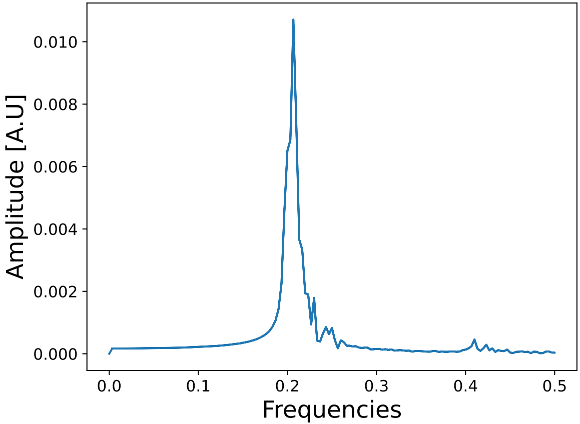


Increasing even more sextupole strength

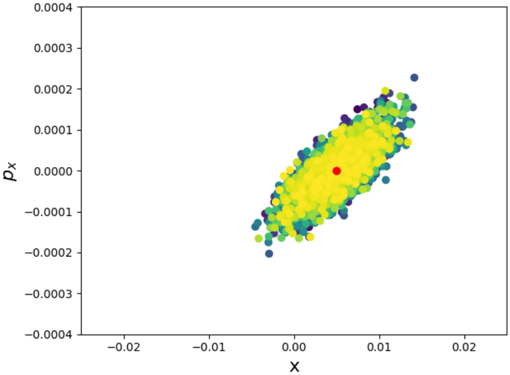
- Increased even more the sextupole strength
- Plot of the horizontal centroid of the beam at fixed point in the lattice in function of the number of turns



FFT of centroid oscillation



Unmatched beam evolution with stronger sextupolar strength



Conclusion

Conclusion

Observed beam injection oscillations in multiple cases:

- Horizontal displacement error $\Delta x = 1$mm and $\Delta x = 5$mm
- Mismatch in twiss parameters between beam and lattice at injection
- Increasing the non linearities by ramping up the sextupoles strength for an initial horizontal displacement

Thank you for your attention

References

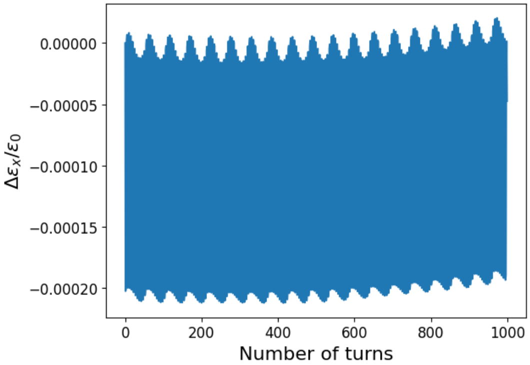
[1] Chiara Bracco. "Beam Injection, Extraction and Transfer". In: 2017. URL: https://indico.cern.ch/event/451905/contributions/2159032/.

[2] Giulio Morpurgo and Jukka Klem. "A method to measure the beta-beating in a 90 degrees phase advance lattice". In: 2000. URL: https://api.semanticscholar.org/CorpusID:85527168.

[3] .*CAS - CERN Accelerator School Second general accelerator physics school: Aarhus, Denmark 15 - 26 Sep 1986. CAS - CERN Accelerator School : Accelerator Physics*. CERN. Geneva: CERN, 1987. DOI: 10.5170/CERN-1987-010. URL: https://cds.cern.ch/record/181071.

Evolution of emittance due to a mismatched beam

- See an emittance growth as for horizontal beam displacement error
- Plot of the relative evolution of emittance $\Delta\epsilon$ w.r.t initial emittance ϵ_0
- Oscillation frequency $= 2Q_x$ (beam envelope oscillation)



Impact of transverse errors

- **Dipole error:** Deflection of the beam from the ideal path. A field error at s_k deflects the beam an angle θ. In the x-plane, the displacement of the beam center line is:

$$\Delta x = M_{12}\theta$$

  with M the transformation matrix from s_k to s_m.

- **Quadrupole field error:**
  - β-beat: Variation of the betatron function around the ring .

For a quadrupole field (gradient) error at S_0 [2]:

$$\frac{\Delta\beta}{\beta}(s) = \frac{\beta_m - \beta_0}{\beta_0} = \frac{\Delta k L \beta_0 \cos\left(2\pi Q - 2|\mu(s) - \mu_0|\right)}{2\sin\left(2\pi Q\right)},$$

Δk the gradient error, L the length of the magnet, Q the tune, μ the phase advance.