Numerical tools for CC simulations and results in SPS

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Introduction

- **Crab Cavities (CC)** will help increase the luminosity of collisions in the HL-LHC.
- CCs are expected to induce emittance growth by noise introduced by the CC RF control.
- **Our goal** is to predict the impact of the CCs on the beam considering reduction in DA, losses and emittance growth.
- As CCs were never used with protons two prototype CCs were installed in the SPS in 2018.
- Therefore our studies and simulations so far are done for the **SPS** machine aiming later on to be extrapolated for HL-LHC .

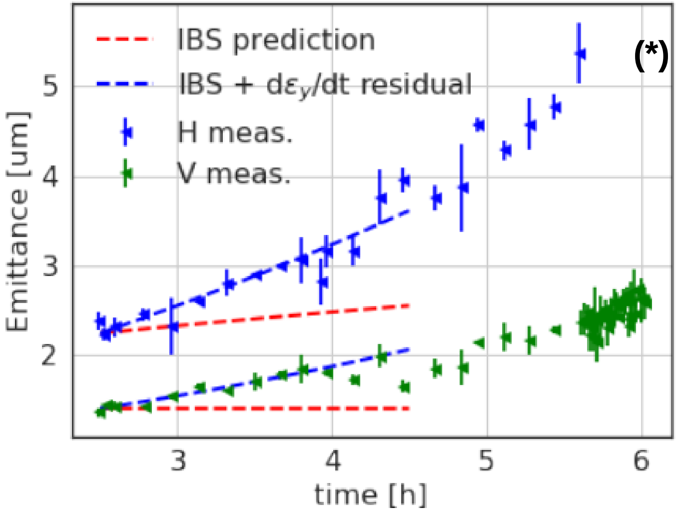
Motivation

- ☐ Emittance growth is already observed in SPS in coast (Fig 1) even without Crab Cavities. Some of the potential sources:
  - Vacuum
  - **Magnet non linearities**
  - **Power supply ripples**

- ☐ To understand the effect of CCs, the contribution of these effects should also be considered.

- ☐ **Preliminary results (using SixTrack) concerning (A) magnet non linearities, (B) power supply ripples and © CCs are presented here.**

Fig 1 : Emittance evolution in SPS in coast



(*)“"Emitance growth in coast in the SPS at CERN”, F.Antoniou

Methodology

- ❑ Simulations performed at 26GeV (injection) – stronger effects.
- ❑ DA studies:Initial distribution from SixDesk (polar grid) - Lifetime studies: **weighted Gaussian** distribution (800^2 particles)

• Weighted Gaussian distribution

- ❑ **Problem:** For our studies we want a detailed representation of the tails of our distribution – not possible with a 6D Gaussian distribution (very few number of particles in the tails).
- ❑ **Solution:** We use a 6D "uniform" distribution with weights.

  - Each particle has different weight according to its initial position.

  - Particles in the core of the distribution are more important than the particles in the tails.

  - The weights are computed from the p.d.f. of the Gaussian distribution.
- ❑ **How does it work?:** (more info at Sofia's presentation here)

  - We create a "uniform" distribution according to the parameters of the bunches and the optics values of SPS.

  - Tracking for 10e6 turns ~ 20sec in SPS

  - Post process analysis: assign the weights to the particles and include them at the computations. The weight of a particle is set to zero once it reaches the horizontal or vertical aperture.

List of contents

(A) Magnet non linearities

(B) Power supply ripples

(C) Tests with Crab Cavities

Magnet non linearities

We study magnet non linearities as:
1) They are a potential source of the natural emittance growth observed in SPS.
2) In order to study the emittance growth in the presence of other effects we need to use an SPS model which is close to the real conditions of the machine.

Contents:

1) Which multipole components do we include in the simulations?

2) Sanity check:
Can the chromatic behavior we obtain from MAD-X be reproduced with Sixtrack?

3) Impact on DA, Lifetime/Losses

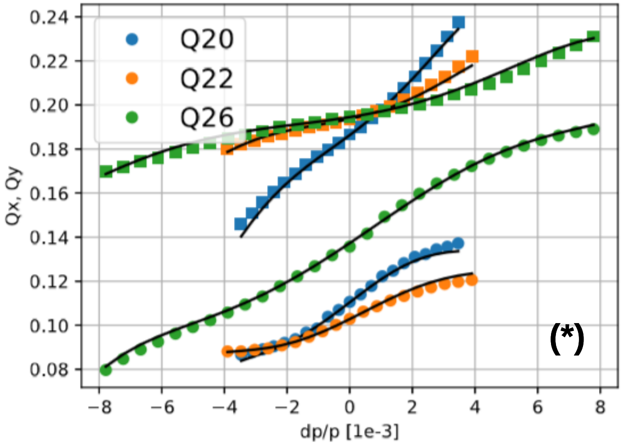
Mulitpole components

- One of the most important source of non-linearities in SPS are the **odd multipole components of the main dipole magnets.**
- The multipole errors of the SPS main magnets are unfortunately not available from magnetic measurements.
- Therefore a non-linear optics model of SPS has been established based on a fit of the measured non linear chromaticity.
  - The chromatic detuning was measured over a range of momentum deviation (dp/p).
  - The optics model is obtained by assigning systematic multipole components to the main lattice magnets in order to reproduce the chromatic properties of SPS. For the matching the SPS model in MAD-X was used

The values of b3 b5 and b7 that are obtained from this method, are the ones we assign in the main dipoles of SPS.

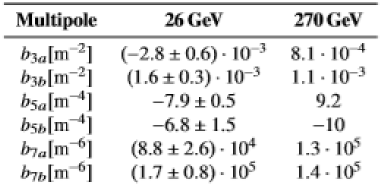
Fig 2:Sample of tune during a dp/p scan

Qx (dots) Qy(squares)



(*)"Studies of a New Optics With Intermediate Transition Energy as Alternative for High Intensity LHC Beams in the CERN SPS", M. Carlà (link here)

Multipole errors from SPS non linear model (*)



Multipole	26 GeV	270 GeV
$b_{3a}[\mathrm{m}^{-2}]$	$(-2.8 \pm 0.6) \cdot 10^{-3}$	$8.1 \cdot 10^{-4}$
$b_{3b}[\mathrm{m}^{-2}]$	$(1.6 \pm 0.3) \cdot 10^{-3}$	$1.1 \cdot 10^{-3}$
$b_{5a}[\mathrm{m}^{-4}]$	-7.9 ± 0.5	9.2
$b_{5b}[\mathrm{m}^{-4}]$	-6.8 ± 1.5	-10
$b_{7a}[\mathrm{m}^{-6}]$	$(8.8 \pm 2.6) \cdot 10^{4}$	$1.3 \cdot 10^{5}$
$b_{7b}[\mathrm{m}^{-6}]$	$(1.7 \pm 0.8) \cdot 10^{5}$	$1.4 \cdot 10^{5}$

Random multipole error

- ☐ However from this method we **cannot infer the magnet-to-magnet variation.**
- ☐ To reproduce better the real conditions in the machine **random errors** **(Gaussian distribution truncated at 3 sigma) are assigned** in the multipolar components mentioned before.

Random error applied:

$b_{n\_random} = b_n$*x%*tgaus(3),
where n = 3,5 or 7

Final value of a multipole component:

$b_{n\_new} = b_n + b_{n\_random} = b_n + b_n$*x%*tgaus(3),
where x the random error scaling factor

Random multipole error

- However from this method we **cannot infer the magnet-to-magnet variation.**
- To reproduce better the real conditions in the machine **random errors** **(Gaussian distribution truncated at 3 sigma) are assigned** in the multipolar components mentioned before.

Random error applied:

$\mathbf{b_{n\_random} = b_n*10\%*tgaus(3),}$

where n = 3,5 or 7

Final value of a multipole component:

$\mathbf{b_{n\_new} = b_n + b_{n\_random} = b_n + b_n*x\%*tgaus(3),}$

where x the random error scaling factor

Which is the optimal value of x?

- **Test impact on DA**

Magnet non linearities

Fig 3 :DA in the presence of multipole errors

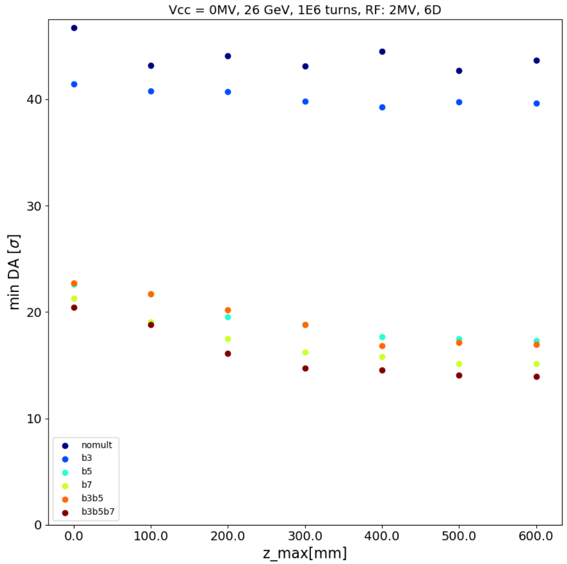
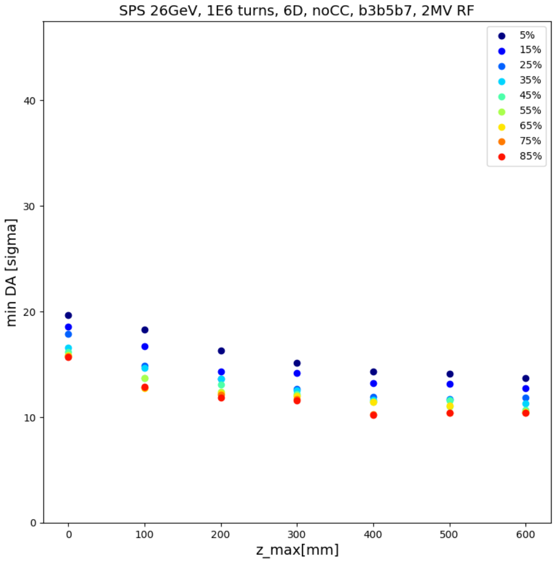


Fig 4 : DA depndence on z and multipole error random factor



We will work with the **random factor of 25%** on the values of b3, b5 and b7.

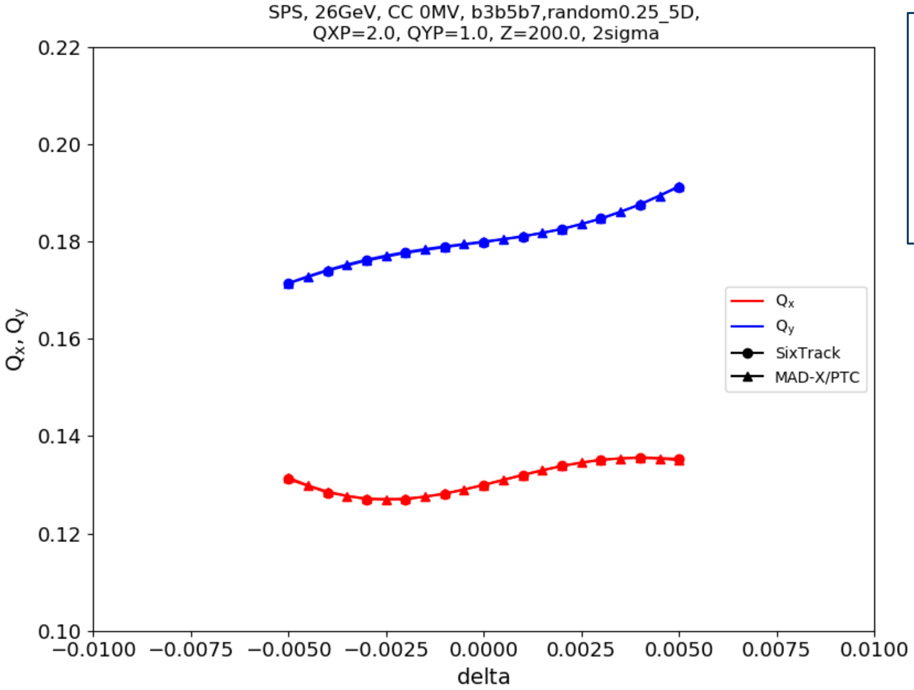
- Fig 2: Strong reduction in the DA in the presence of multipole components higher than b3.
- Fig 3: Further reduction with increased value of random error .
- However this reduction is **relatively small** regarding the values of the DA. Additionally the DA values do not even approach the physical aperture of SPS (6σ).
- Therefore we are allowed to choose a bit arbitrary with which value we will keep working.

Simulation Parameters

SPS + b3b5b7+ x%
26 GeV
6D → RFs “ON” V_RF = 2MV
QPX= 2.0 , QPY = 1.0
CC = 0MV
10e6 turns

Chromatic behavior Sixtrack vs MAD-X

Fig 5 : Chromatic behavior SixTrack vs MAD-X



Simulation Parameters

SPS + b3b5b7+ 25%
26 GeV
5D → frozen motion in longitudinal plane
QPX= 2.0 , QPY = 1.0
CC = 0MV

Plot information

MAD-X plot: Done with PTC
SixTrack plot : Corresponds to a particle at longitudinal position z = 200 mm and 2σ betatron amplitude. *

- The chromatic behavior from MAD-X is reproduced with SixTrack.

- The assignment of the random errors at the multipole components seems as expected.
- **This is the SPS model we use for the simulations.**
- **SPS + b3b5b7 +25%, QXP= 2.0, QPY = 1.0**

Impact on Losses – Emittance growth

How do we calculate the emittance?

$$\epsilon = \sqrt{\langle (x - x_{CO})^2\rangle \langle (p_x - p_{x_{CO}})^2\rangle - \langle (x - x_{CO})(p_x - p_{x_{CO}})\rangle^2}$$

$$x(\delta_p) = x|_{\delta_p=0} + \cancel{\eta_x \delta_p} + \eta_x^{(2)} \delta_p^2 + \ldots..$$

$$p_x(\delta_p) = p_x|_{\delta_p=0} + \cancel{\eta_{p_x} \delta_p} + \eta_{p_x}^{(2)} \delta_p^2 + \ldots..$$

By subtracting the dispersion we don't have dependence on the δp

- This equation is valid only for uncoupled motion
- In our studies we have **linear** coupling between the horizontal and the longitudinal plane due to the dispersion.
- In order to use this equation we need to "decouple" the motion.
- We can easily "decouple" the motion by **subtracting the dispersive contribution from the coordinates of each particle.**

What do we consider "losses"?

- In losses we include the particles that are lost during the tracking and the ones that do not satisfy the aperture limitations in the H either the V plane (5σx, 5σy) .

Impact on Losses – Emittance growth

Fig 6 : Emittance growth in the presence of different multipole components

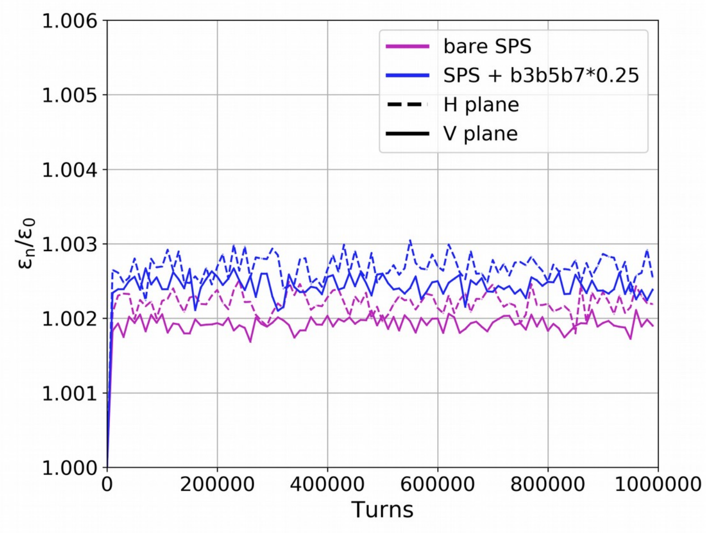
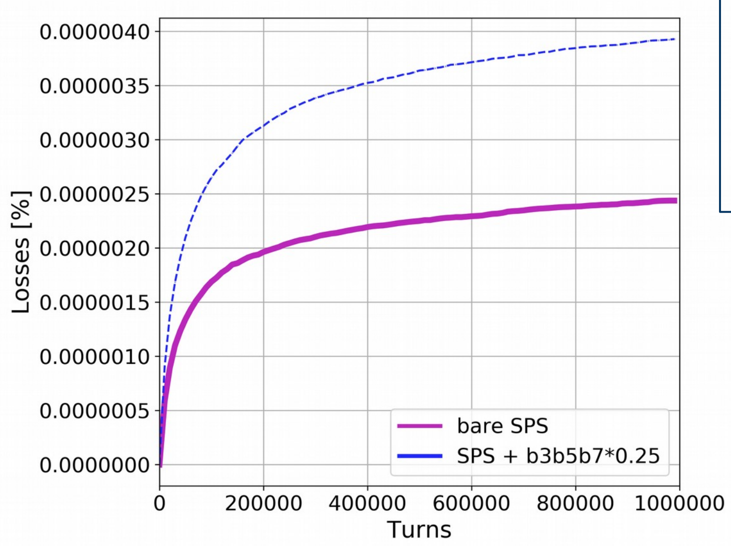


Fig7 :Losses in the presence of different multipole components



Simulation Parameters

SPS + b3b5b7+ 25%
26 GeV
V_RF = 2MV
QPX= 2.0 , QPY = 1.0
CC = 0MV
10^6 turns

- Emittance values are similar in both planes as expected.
- There is a small increase in the losses and emittance values in the presence of the multipole components.

However the impact of the magnet non linearities in both emittance values and losses is **negligible.**

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(A) Magnet non linearities

(B) Power supply ripples

(C) Tests with Crab Cavities

Power supply ripples

1) What kind of ripple do we include in the simulations?

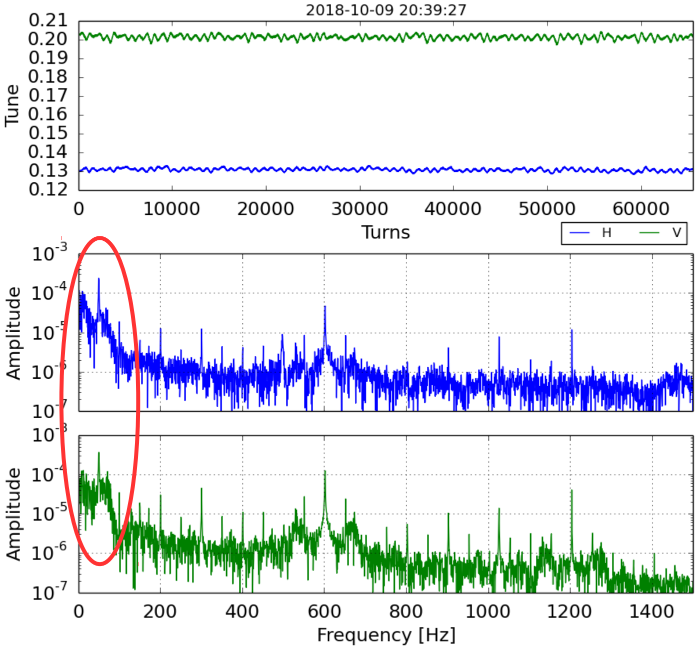
2) Impact on DA, Lifetime/Losses

Power supply ripples

What kind of ripple to we use?

We assign at all the **main QFs** ripple of **50Hz** that results to **tune shift 5e-3** (in the H plane)**.**

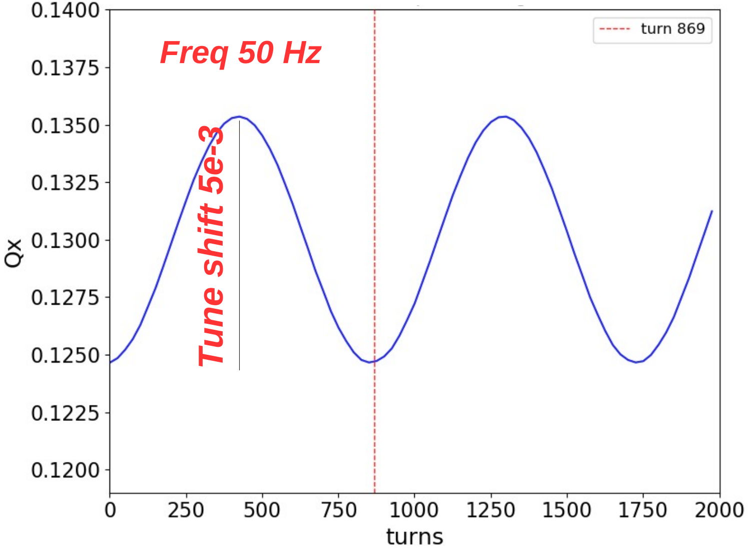
Fig 8: Example of SPS tune ripple



Test for correct implementation of the ripples

- Figures below show the tune modulation for in H and V plane, when we apply a ripple in **every** main QF.
- We track a particle with initial z=0 for 2000 turns. Using NAFF the tune value is calculated for each turn using a sliding window of 25 turns.

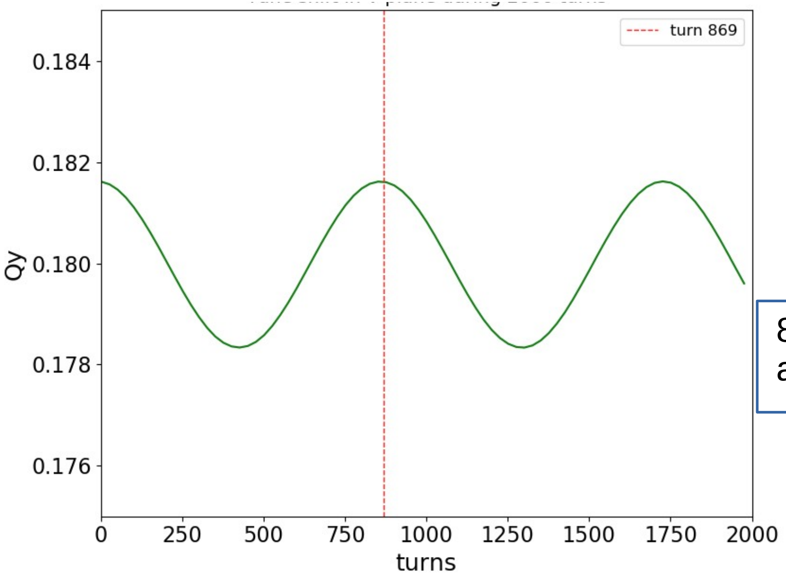
Fig 9: Tune shift in the H plane



Freq 50 Hz

Tune shift 5e-3

Fig 10: Tune shift in the V plane



Simulation Parameters

Bare SPS machine
26 GeV, VRF = 2MV
QPX=2.0, QPY = 1.0
CC = 0MV
Ripple in **all main** QF
50Hz (869 turns)
tune shift 5e-3

869 turns correspond at 50Hz in SPS

Ripples are implemented correctly.

- The tune shift in the V plane (Fig 10) is smaller than in the H plane → expected as at QFs $\beta_x > \beta_y$

Impact on Emittance - Losses

Simulation Parameters

26 GeV, VRF = 2MV
QPX=2.0, QPY = 1.0
1MV per CC
B3b5b7*0.25
Ripple of 50Hz, 5e-3
Tune shift

Fig 11 : Emittance growth in the presence of different multipole components and ripples

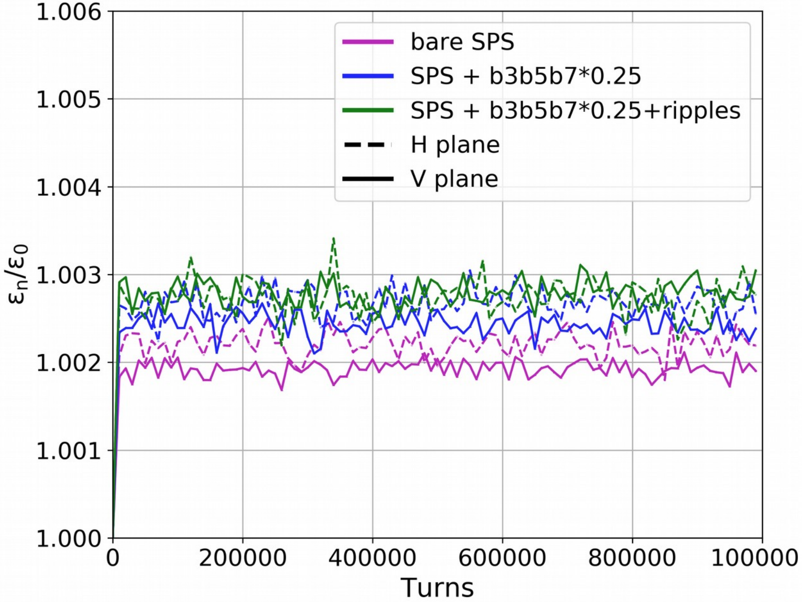
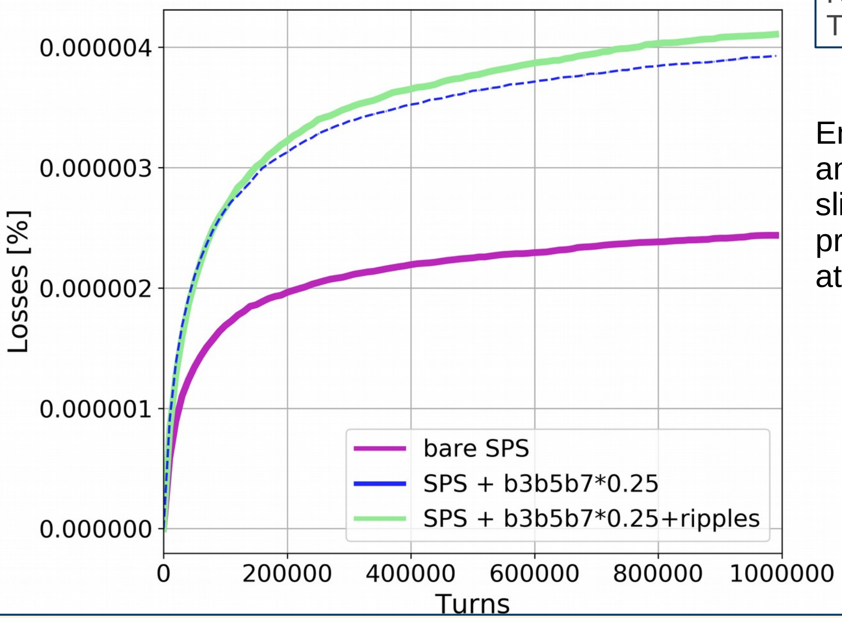


Fig 12 : Losses in the presence of different multipole components and ripples



Emittance values and losses are slightly bigger in the presence of ripples at 50 Hz

The impact of the ripple at 50Hz in both emittance values and losses is **negligible.**

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Crab Cavities

1) What are the settings of Crab Cavities do we include in these tests?

2) Emittance calculation in the presence of CCs

3) Impact on DA, Lifetime/Losses

Crab Cavities

- We add in the SPS lattice **two Crab Cavities** in the location where they are installed in SPS for the 2018 tests.
- **1MV per CC** → The kick is strong enough to have observable effect. 2MV is too big and it is not realistic as never both o the CC operate at 2MV. **$\varphi_{CC1}=\varphi_{CC2}=0^{o}$**
- **26 GeV** : At the injection energy the effect is larger.
- The **voltage at the CCs is ramped up** to the maximum value of 1MV after **300 turns** – if not : emittance blow up.

Fig 13:Initial distribution

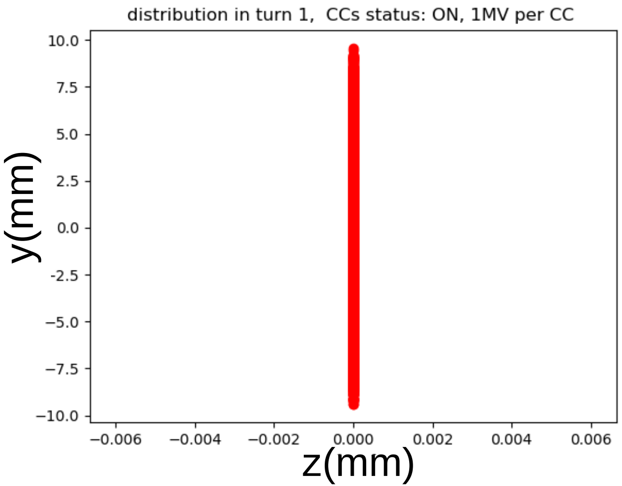


Fig 14:**CCs “OFF”,** after 40k turns, s =0

No correlation between V and longitudinal

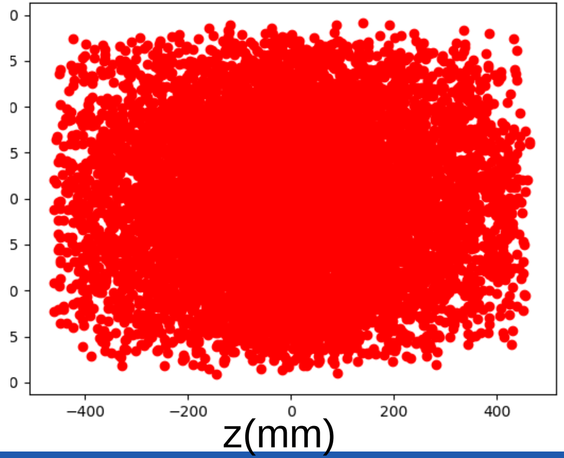
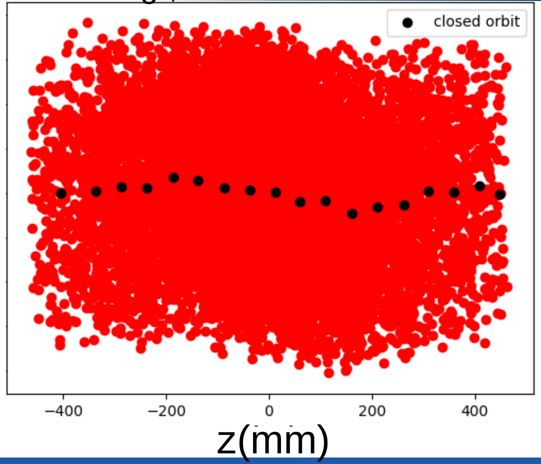


Fig 15:**CCs “ON”,** after 40k turns, s=0

Typical shape of distribution after “crabbing”, **deformed V CO with s**



Emittance calculation in the presence of CCs

- The Crab Cavities introduce an **additional coupling** between the longitudinal and the vertical plane.

$$\Delta p_y = -\frac{qV}{E} sin(\frac{\omega z}{c} + \phi)$$

- Not considering this coupling during the emittance calculation leads to “wrong” values, much bigger than the real ones.

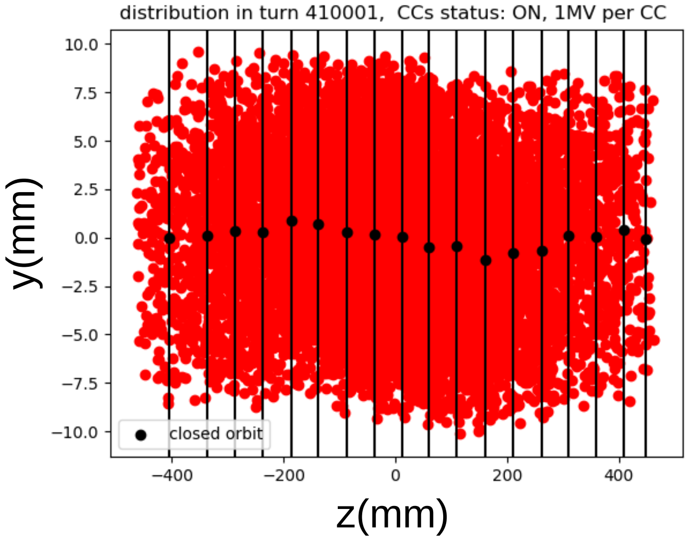
$$\epsilon = \sqrt{\langle(x - x_{CO})^2\rangle\langle(p_x - p_{x_{CO}})^2\rangle - \langle(x - x_{CO})(p_x - p_{x_{CO}})\rangle^2}$$

- **How do we “treat”** this additional coupling?

We subtract the V closed orbit of each longitudinal slice.

  - Slice the beam in longitudinal slices (50 slices)
  - Find the x,xp,y,yp of the mean of each slice
  - Subtract them from the coordinates of the rest of the particles in that slice.

Fig 16: Longitudinal slices of the particle distribution



Impact on Emittance - Losses

Simulation Parameters

SPS + b3b5b7*0.25
26 GeV, 6D
QPX=2.0, QPY = 1.0
1MV per CC
Rump up 300 turns
$\varphi_{CC1}=\varphi_{CC2}= 0$

Fig 17 : Emittance growth in the presence of CCs

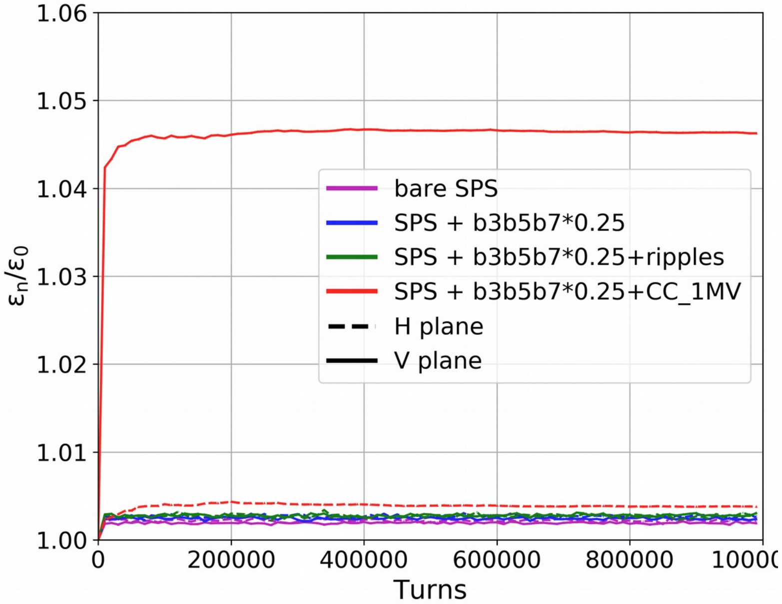
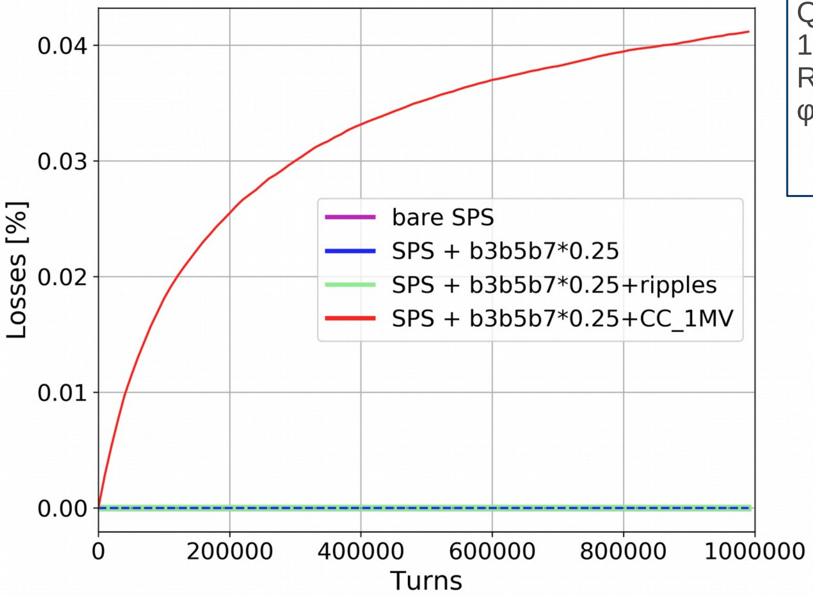


Fig 18 : Losses in the presence of CCs



- In the presence of the CCs the losses increase by a factor of 10^4.
- The V emittance values are clearly bigger in the presence of the CCs. The H emittance values is also bigger.

Bigger values are expected , due to the high voltage, 1MV per CC, and the low energy, 26GeV.

Impact on Emittance - Losses

Simulation Parameters

SPS + b3b5b7*0.25
26 GeV, 6D
QPX=2.0, QPY = 1.0
1MV per CC
Rump up 300 turns
$\varphi_{CC1}=\varphi_{CC2}= 0$

Fig 17 : Emittance growth in the presence of CCs

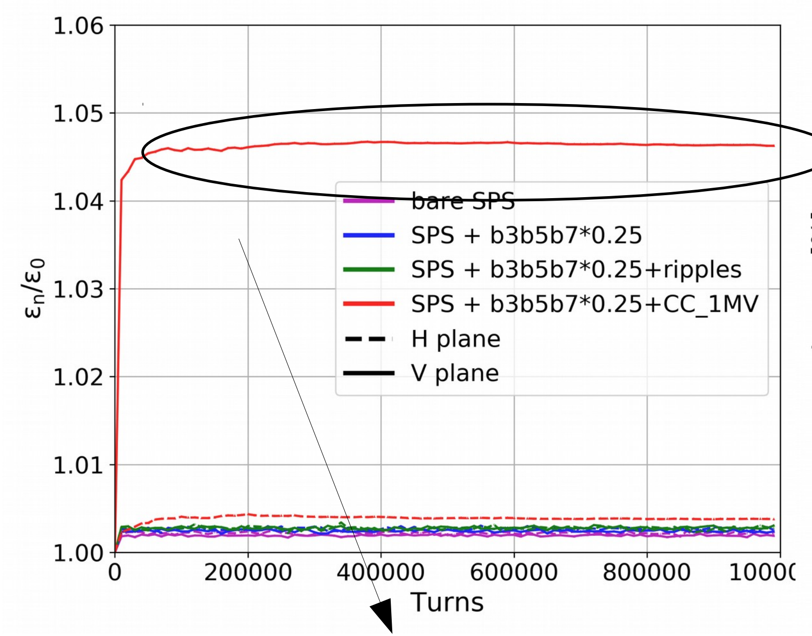
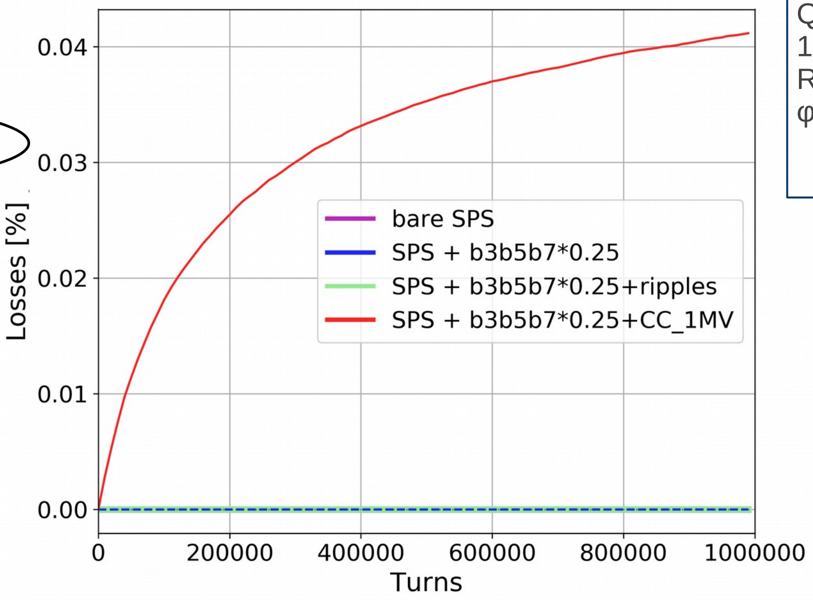


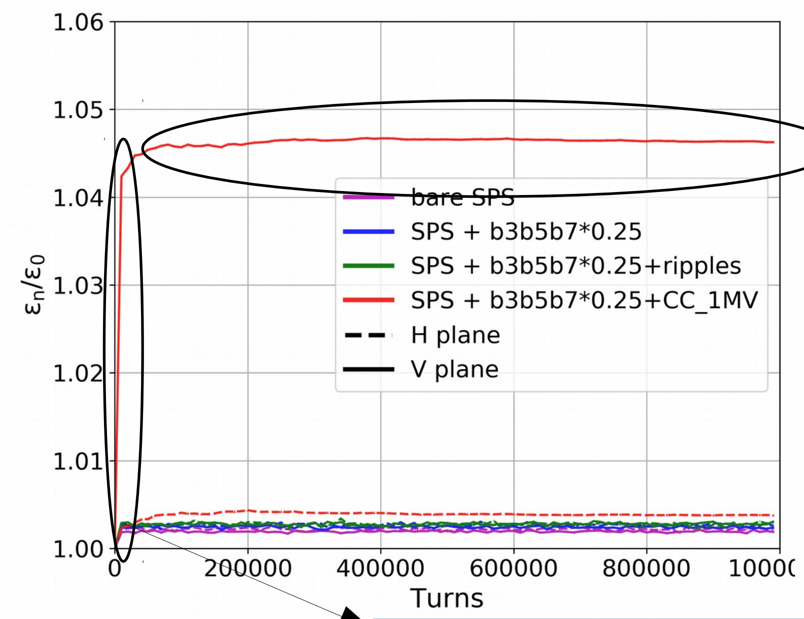
Fig 18 : Losses in the presence of CCs



We don't observe emittance growth for this CC settings during the first 10^6 turns → 20 seconds.

Impact on Emittance - Losses

Fig 17 : Emittance growth in the presence of CCs



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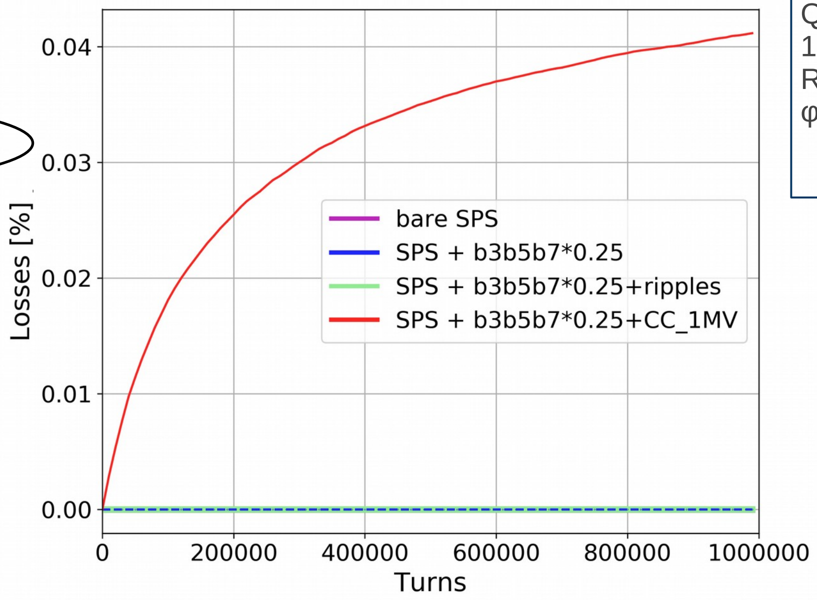

Simulation Parameters

SPS + b3b5b7*0.25
26 GeV, 6D
QPX=2.0, QPY = 1.0
1MV per CC
Rump up 300 turns
$\varphi_{CC1}=\varphi_{CC2}= 0$

This is not emittance growth , CCs rump up.

We don’t observe (settings during the first 10^6 turns → 20 seconds.

Conclusions

- The SPS model we will use is:
  SPS + b3b5b7 +25%, QXP= 2.0, QPY = 1.0
- The impact of the multipole components and the ripple at 50Hz on the losses and emittance evolution is **negligible**.
- In the presence of CCs the losses are increased by a factor of 10^4. However they are considered **negligible**.
- In the presence of CCs we observe higher emittance values, which is expected due to the high voltage, 1MV per CC, and the low energy, 26GeV. No emittance growth observed during the first 20 seconds.

Next Steps

- Investigate the impact of ripples at higher frequencies and close to the betatron frequency.