# Transverse stability during momentum slip-stacking: initial investigation

C. Zannini, H. Bartosik, E. Métral, G. Rumolo

Acknowledgments: T. Argyropoulos, N. Biancacci, G. Iadarola

# Overview

- Introduction
- Slip stacking parameters
  - Orbit and its effect on impedance
- Initial PyHEADTAIL simulations
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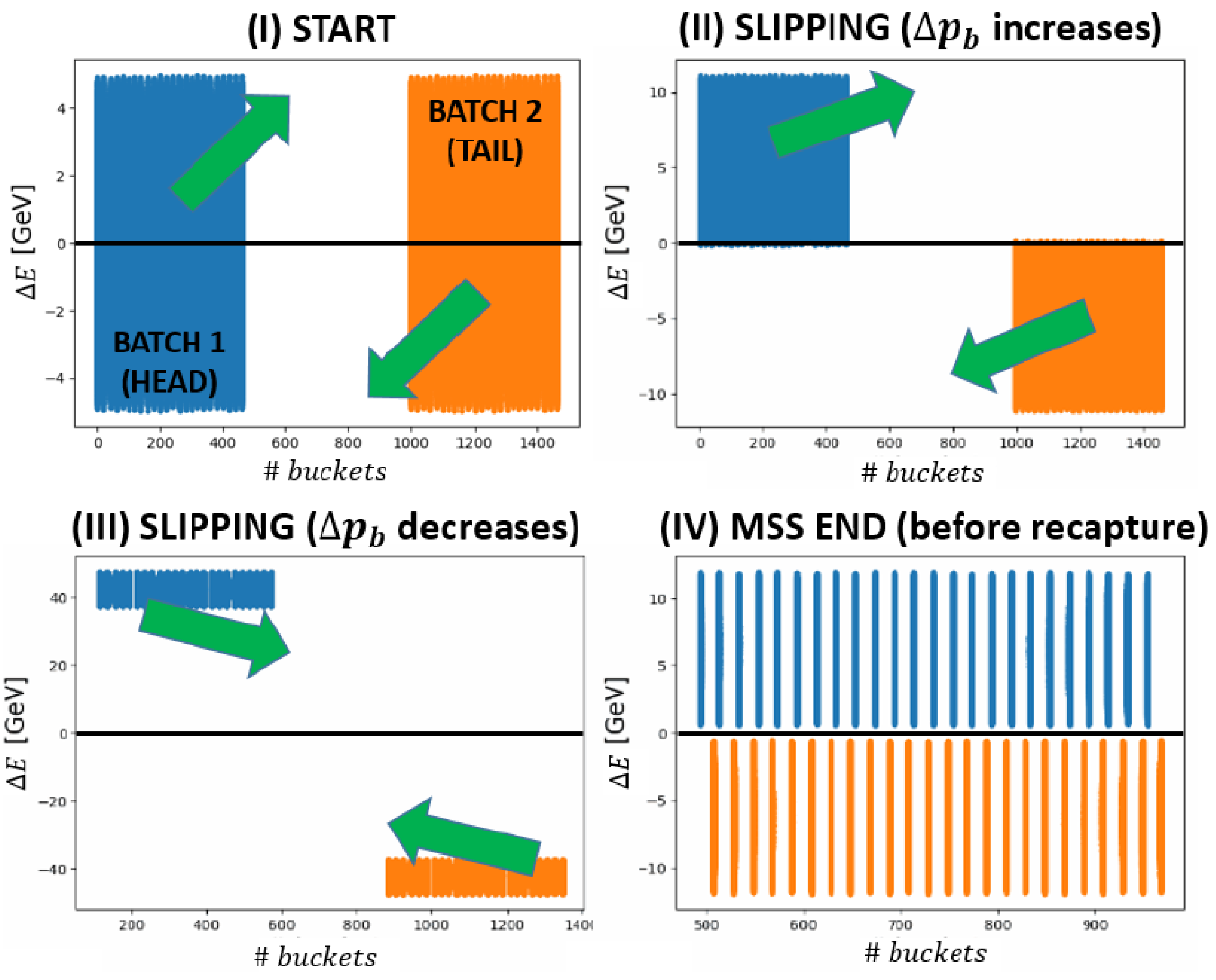
# Introduction

- Two SPS batches of 100 ns bunch spacing will be interleaved at an intermediate energy plateau (300 Z GeV) reducing the bunch spacing to 50 ns




D. Quartullo, T. Argyropoulos, A. Lasheen. *Momentum slip-stacking simulations for CERN SPS ION beam with collective effects*, HB 2018

# Introduction

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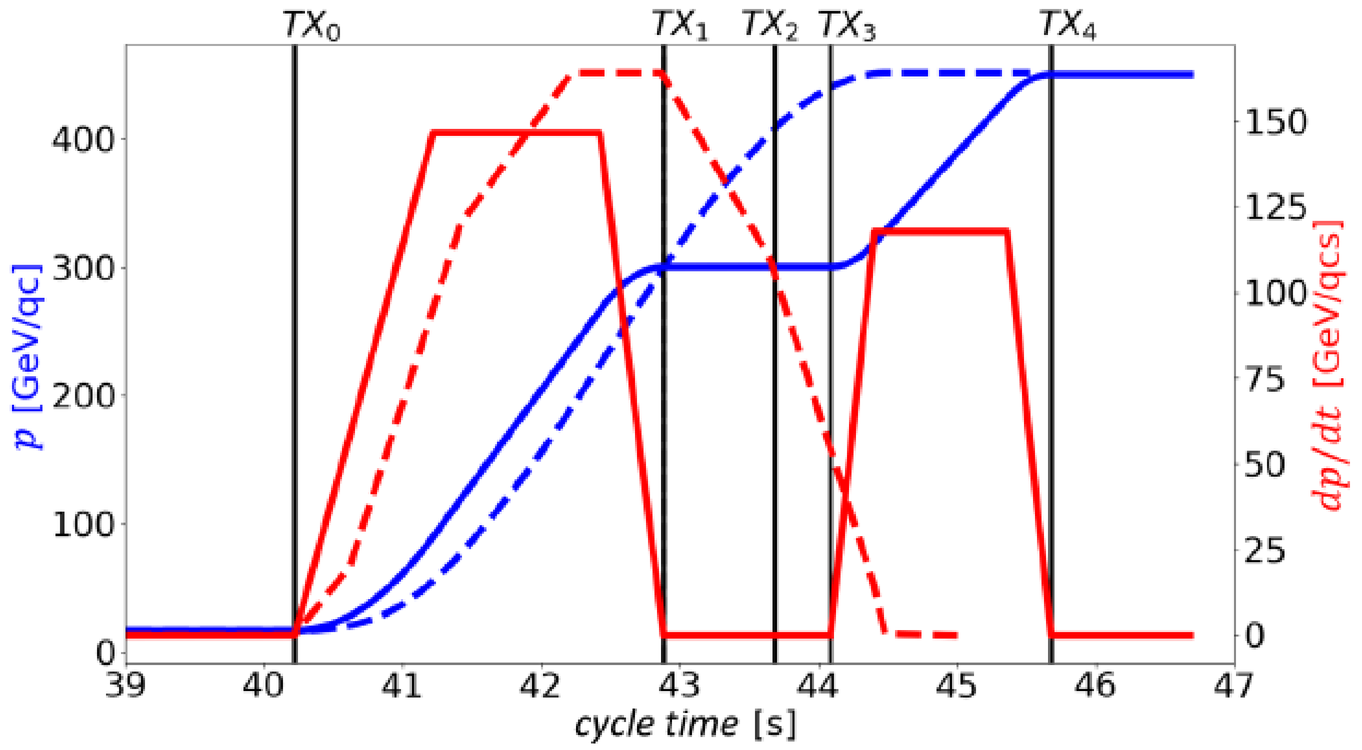


Operational (dashed) and slip stacking (continuous) momentum program

D. Quartullo, T. Argyropoulos, A. Lasheen. *Momentum slip-stacking simulations for CERN SPS ION beam with collective effects*, HB 2018

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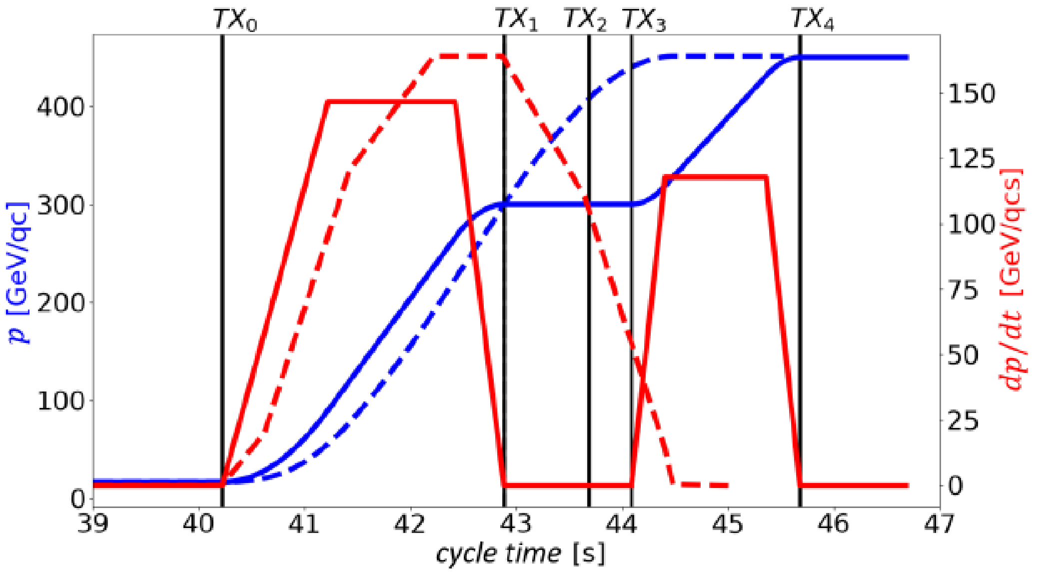
# Slip-stacking parameters



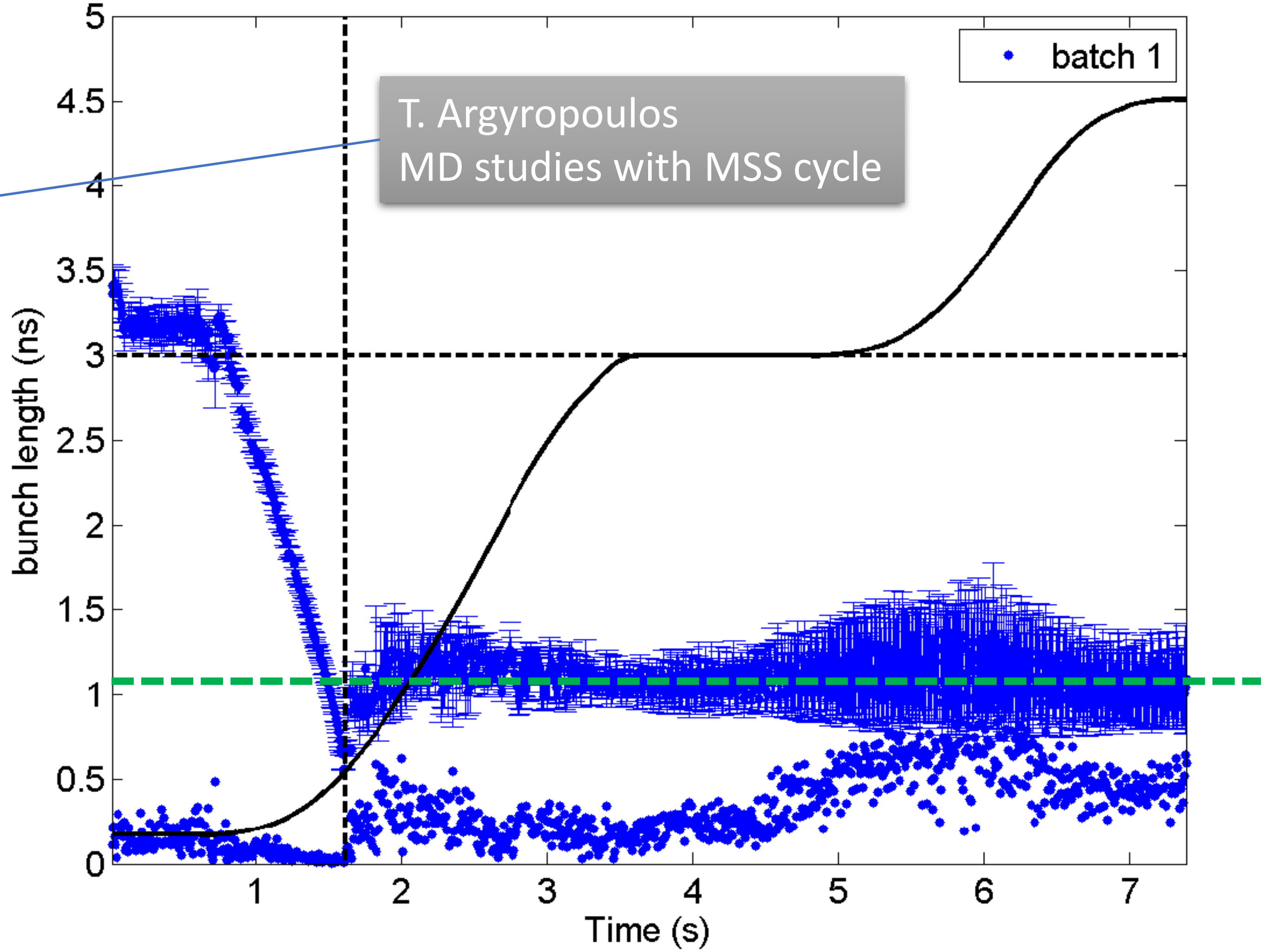

- Pb82+ p=300 ZGeV/c
- Momentum Slip-Stacking (MSS) takes about 0.8 s
- Head to head distance between batches is 1000 buckets just before MSS ($TX_1$) and 10 buckets at the end of MSS ($TX_2$)
  - During MSS $f_{RFb1} + f_{RFb2} = 2\ f_{RF}$ ; $f_{RFb1} = f_{RF} + \Delta$; $f_{RFb2} = f_{RF} - \Delta$;
    - $\Delta_{max}$ = 1kHz; Vrf1=Vrf2
  - At $TX_2$ $f_{RFb1} = f_{RFb2} = f_{RF}$

Independent LLRF control will be available only after LS2 (each cavity will be equipped with individual controllers)

D. Quartullo, T. Argyropoulos, A. Lasheen. *Momentum slip-stacking simulations for CERN SPS ION beam with collective effects*, HB 2018

# MSS parameters: bunch length and intensity

Bunch during slip stacking between 1.0 ns and 1.5 ns




| SPS extraction | $N_{ions}$ /bunch | # Bunches |
|---|---|---|
| LIU-ions/HL-LHC | $2.0 \times 10^8$ | 56 |
| Achieved (2018) | $2.3 \times 10^8$ | 42 |

H. Bartosik et al. *Recent beam performance achievements with the Pb-ion beam in the SPS for LHC physics runs*, IPAC19 proceedings

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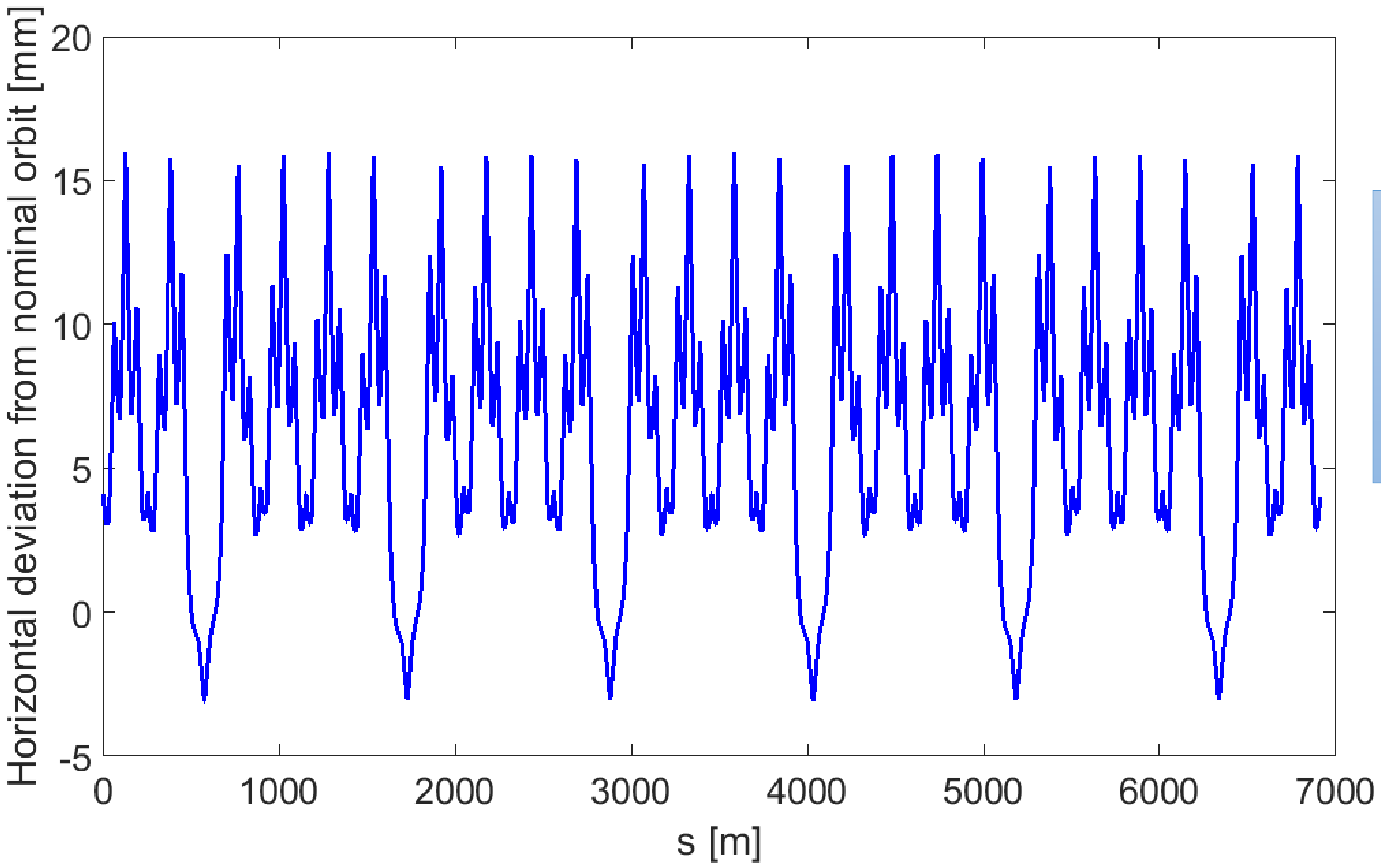
# MSS parameters: the orbit

- Slip-stacking momentum program received from T. Argyropoulos
  - Nominal option: acting on both batches symmetrically
  - Alternative option: acting only on one batch keeping the same momentum difference between the two batches (this will double the deviation from the nominal orbit)

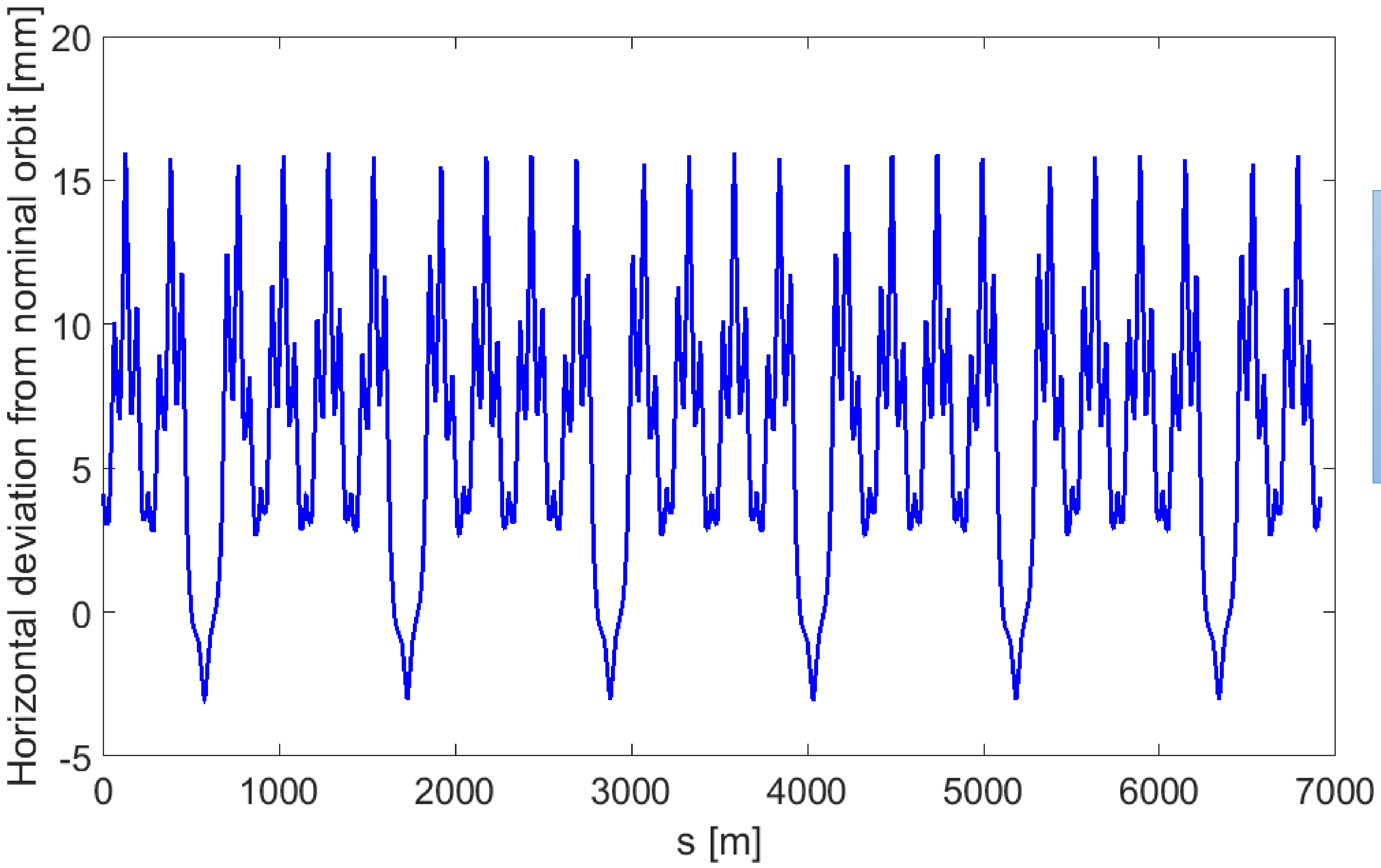
- By using the Q26 dispersion model and the slip stacking momentum program the maximum orbit deviation has been computed along the machine

# MSS parameters: the orbit




**This is the deviation in the case of the nominal option. In case only 1 batch will be moved we could expect a double deviation from the nominal orbit**

# MSS parameters: the orbit

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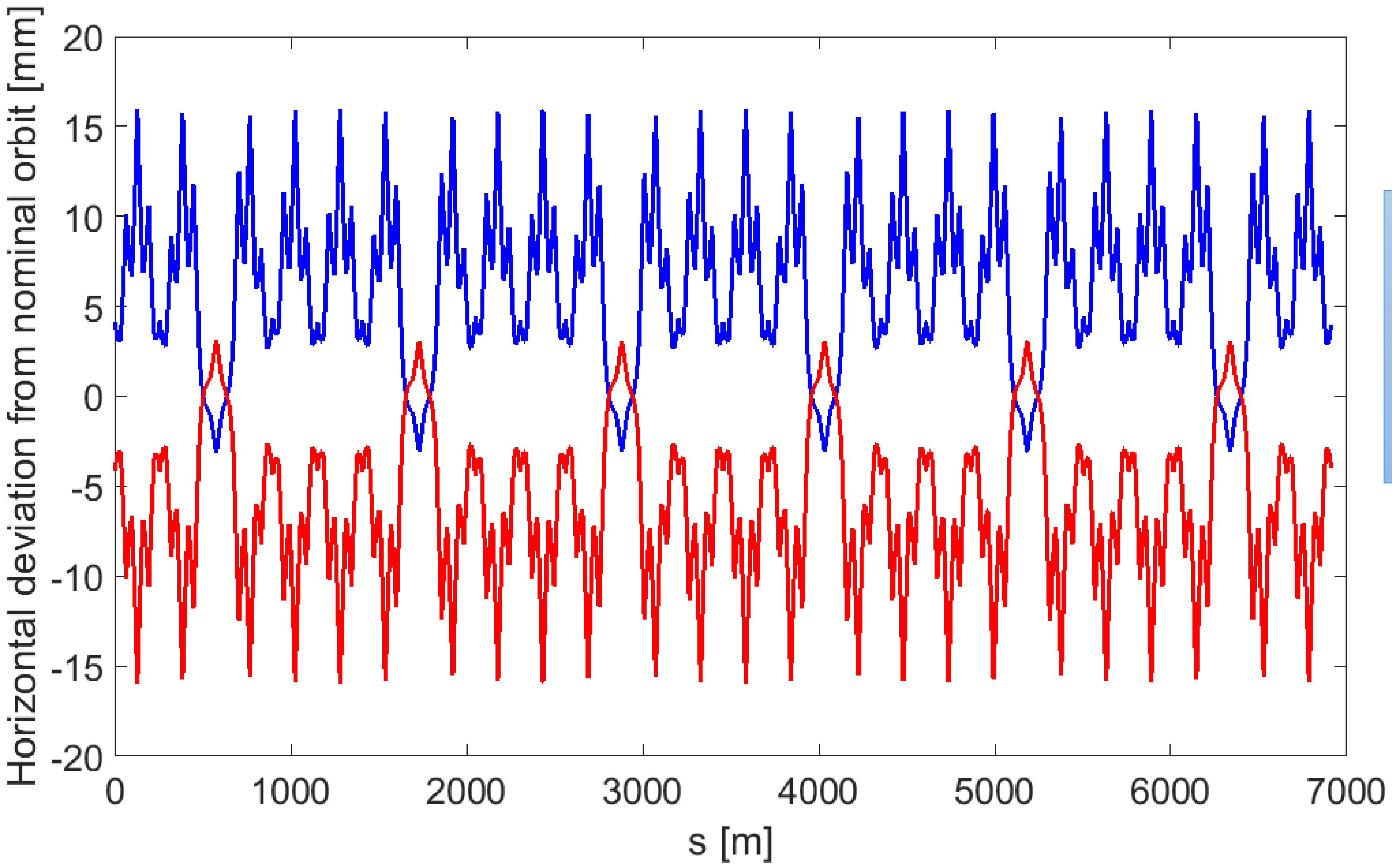


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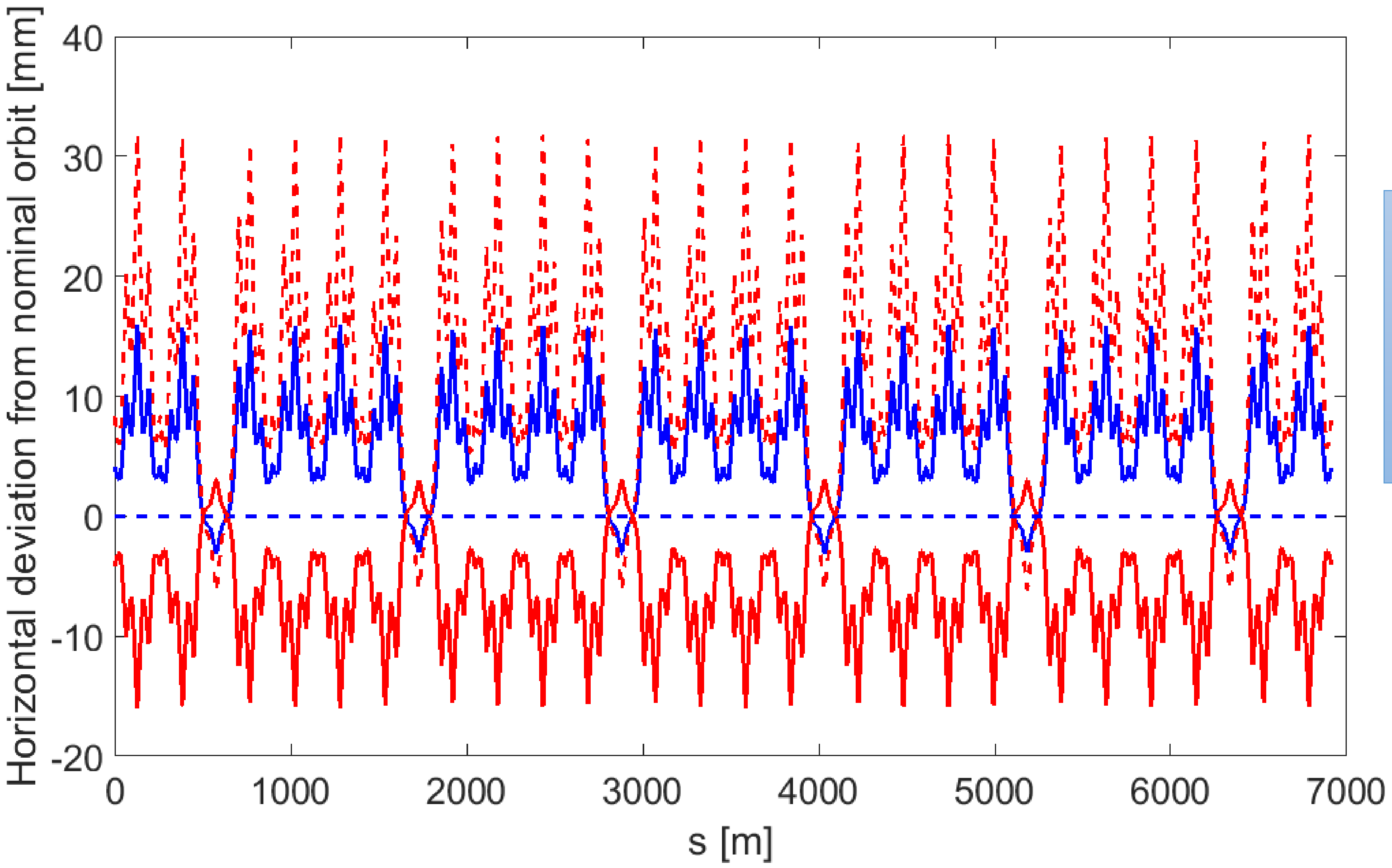
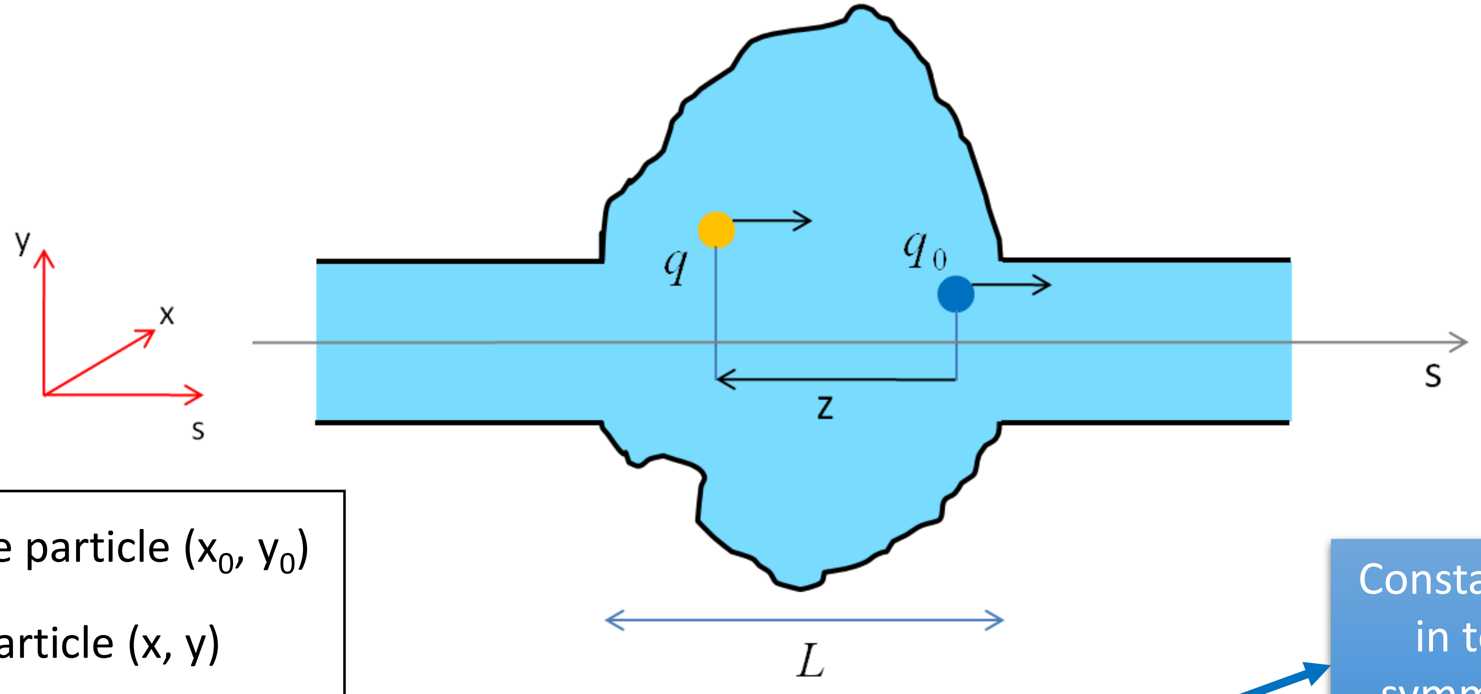



**This is the deviation in the case of the nominal option.** **In case only 1 batch will be moved we could expect a double deviation from the nominal orbit**

Which is the impact of the orbit deviation on beam coupling impedance?

# Effect of orbit deviation on the beam coupling impedance: the constant term




- source particle ($x_0$, $y_0$)
- test particle (x, y)

Constant term is also present in top-bottom left-right symmetric structures if the beam is off-centre

Transverse Impedance

$$Z_x(f) = a_x(f) + Z_x^{\mathrm{driv}}(f)\, x_0 + Z_x^{\mathrm{det}}(f)\, x$$
$$Z_y(f) = a_y(f) + Z_y^{\mathrm{driv}}(f)\, y_0 + Z_y^{\mathrm{det}}(f)\, y$$

$$a_x a_y = 0$$

C. Zannini, K. Li, G. Rumolo. EFFECTS OF AN ASYMMETRIC CHAMBER ON THE BEAM COUPLING IMPEDANCE. IPAC12 proceedings.

# Effect of orbit deviation on the beam coupling impedance: coupling terms

S. Heifets, A. Wagner, B. Zotter.
*Generalized Impedances and Wakes in Asymmetric structures*

**Generalized expansion of transverse wake/impedance at the first order**

$$
\begin{aligned}
W_x(s) &= c_{10} + x_0 c_{11} + 2x c_{20} - y_0 d_{11} - 2y d_{20} \\
W_y(s) &= -d_{10} - x_0 d_{11} - 2x d_{20} - y_0 \bar{c}_{11} - 2y c_{20}
\end{aligned}
$$

Constant terms

Coupling terms

## Wall impedance: coupling terms

up to 0.1% of linear uncoupled term

(grey) $W_x = k_{x1}\,x + k_{xy1}\,y$

up to 2% of linear term

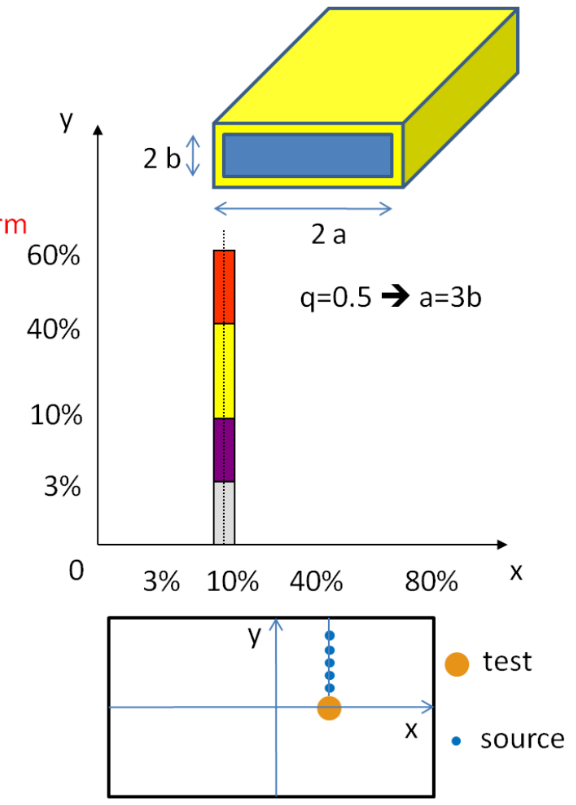
(purple) $W_x = k_{x1}\,x + k_{xy1}\,y + k_{xy2}\,y^2 + k_{xy3}\,y^3$

up to 30% of linear term

(yellow) $W_x = k_{x1}\,x + k_{xy1}\,y + k_{xy2}\,y^2 + k_{xy3}\,y^3$

up to 75% of linear term

(red) $W_x = k_{x1}\,x + k_{xy1}\,y + k_{xy2}\,y^2 + k_{xy3}\,y^3$



# Effect of orbit deviation on the beam coupling impedance: nonlinear terms

**Wall impedance: nonlinear terms**

(blue) $W_y = k_{y1}\, y$

up to 1% of linear term

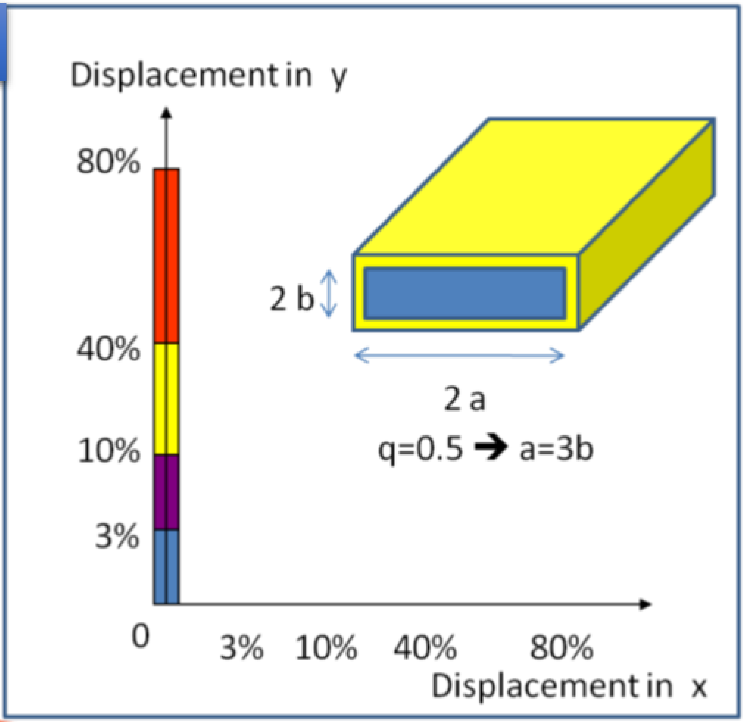
(purple) $W_y = k_{y1}\, y + k_{y2}\, y^2 + k_{y3}\, y^3 + k_{y4}\, y^4$

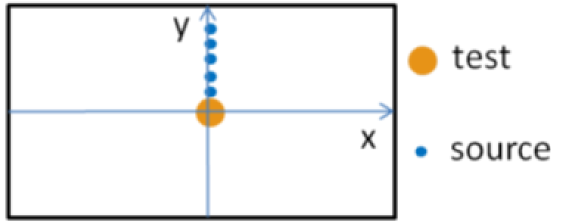
up to 5% of linear term

(yellow) $W_y = k_{y1}\, y + k_{y2}\, y^2 + k_{y3}\, y^3 + k_{y4}\, y^4$

up to 30% of linear term

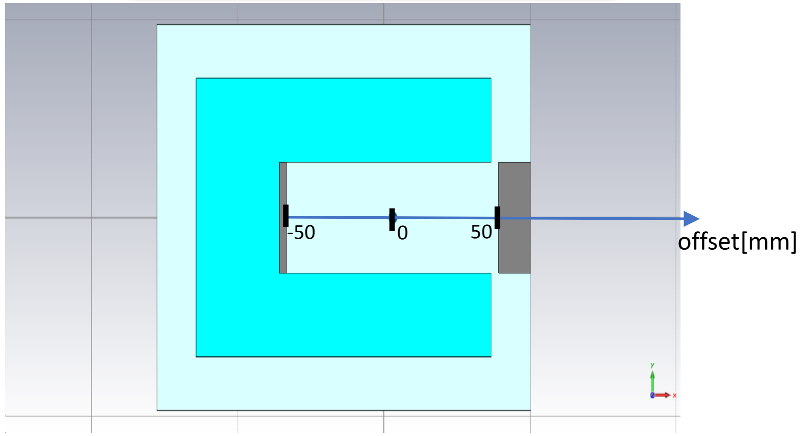
(red) $W_y = k_{y1}\, y + k_{y2}\, y^2 + k_{y3}\, y^3 + k_{y4}\, y^4 + k_{y5}\, y^5 + k_{y6}\, y^6$

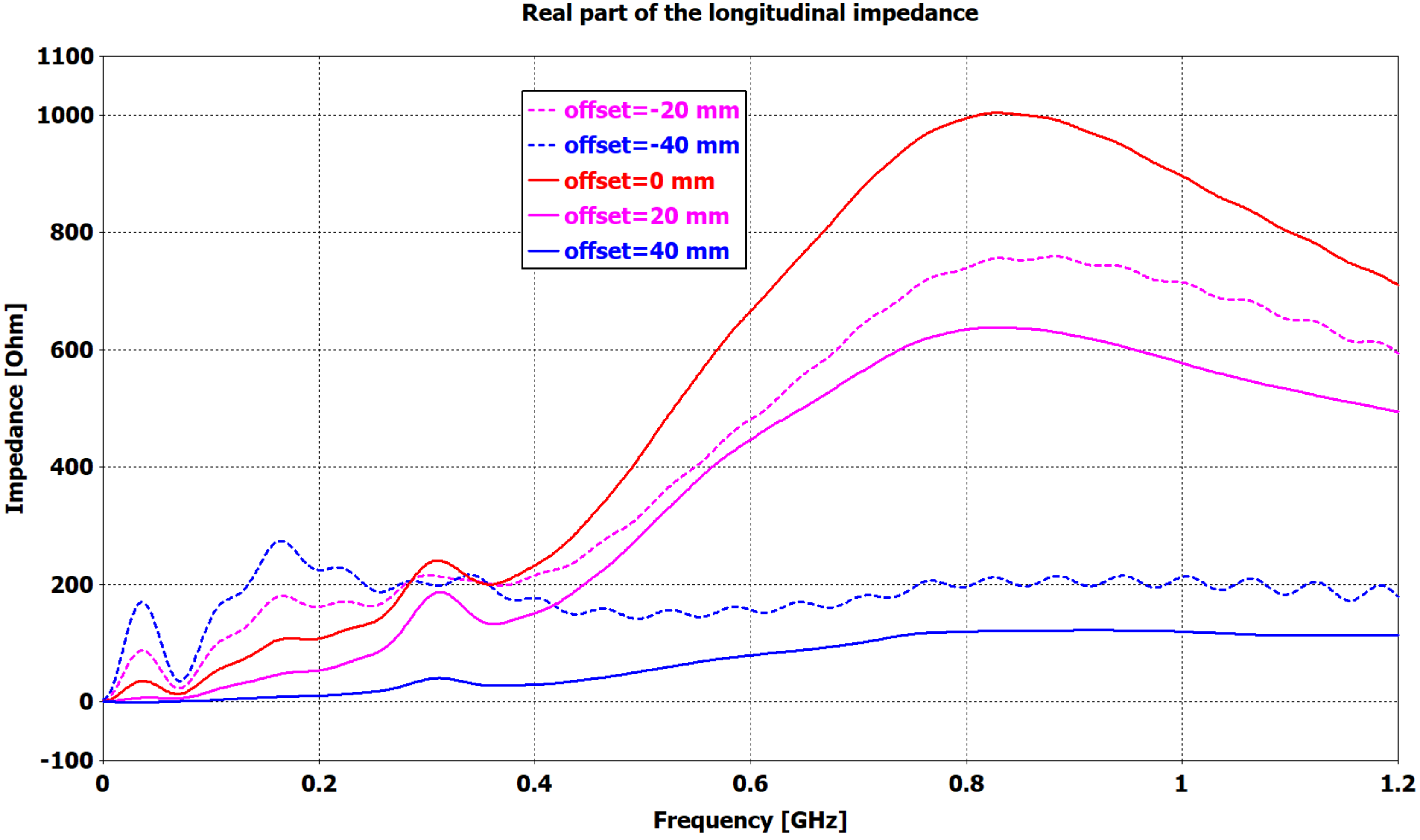


# Effect of orbit deviation on the beam coupling impedance: longitudinal impedance

Kicker impedance:
Example of the MKP-S

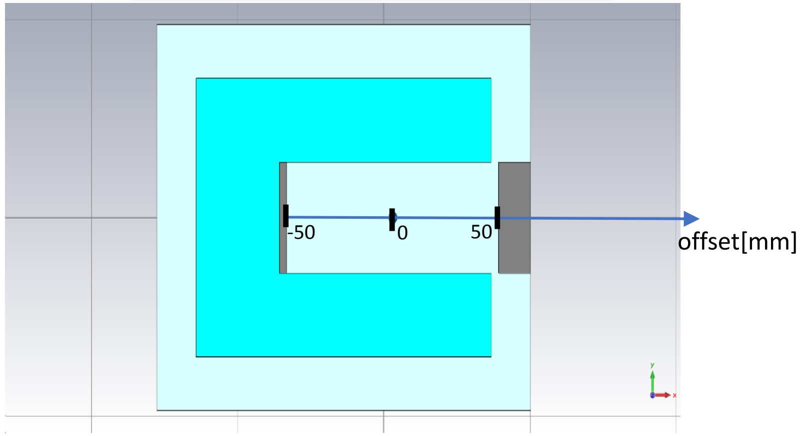


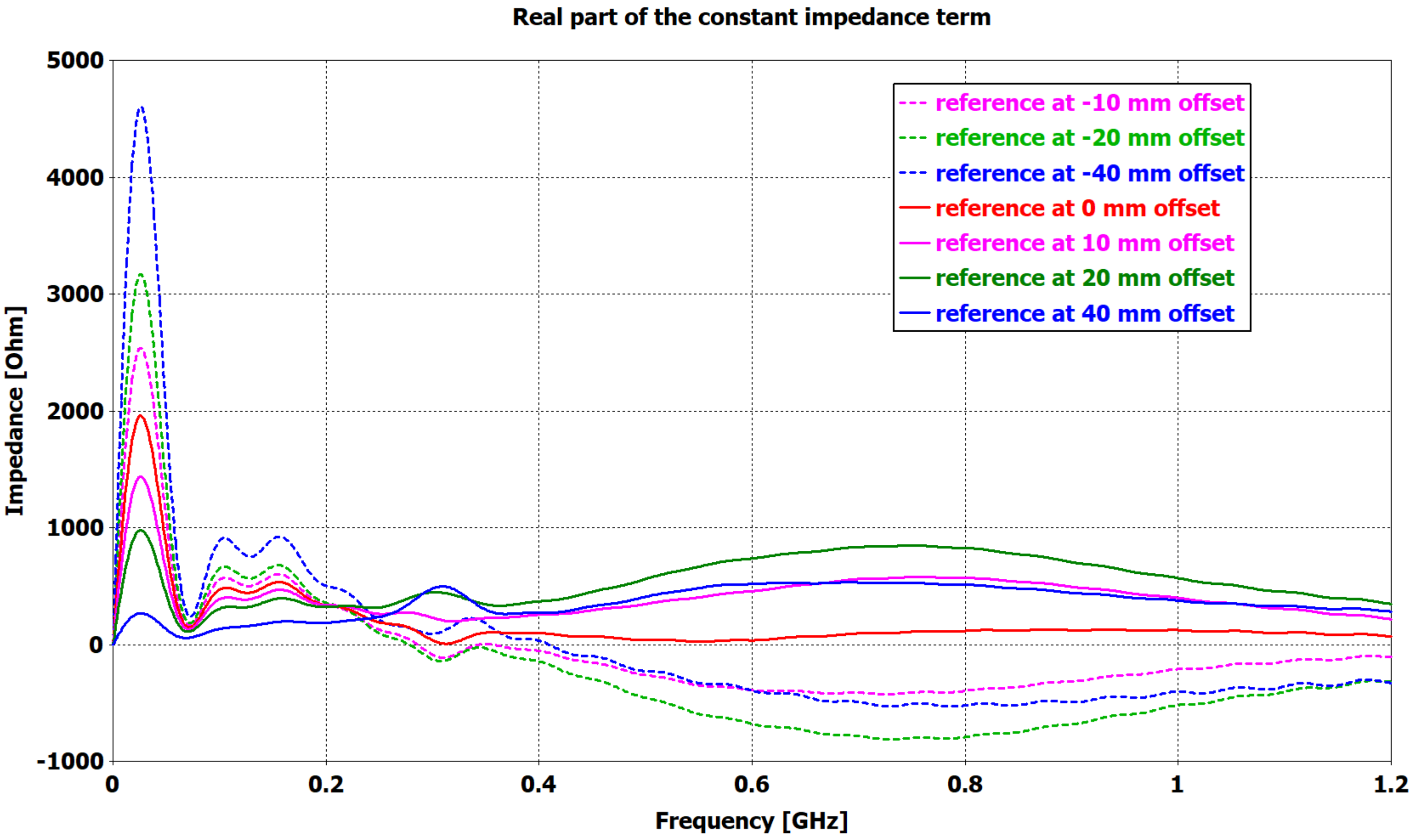

Slight increase of the impedance at low frequency when approaching the inner (HV) conductor. Impedance reduces on the full spectrum moving toward the outer (ground) conductor

# Effect of orbit deviation on the beam coupling impedance: constant term

Kicker impedance:
Example of the MKP-S

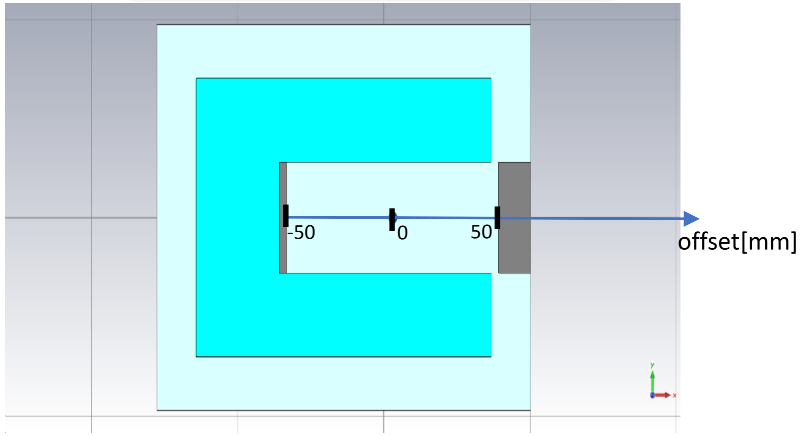



Orbit deviation is expected to have a significant impact on the constant term

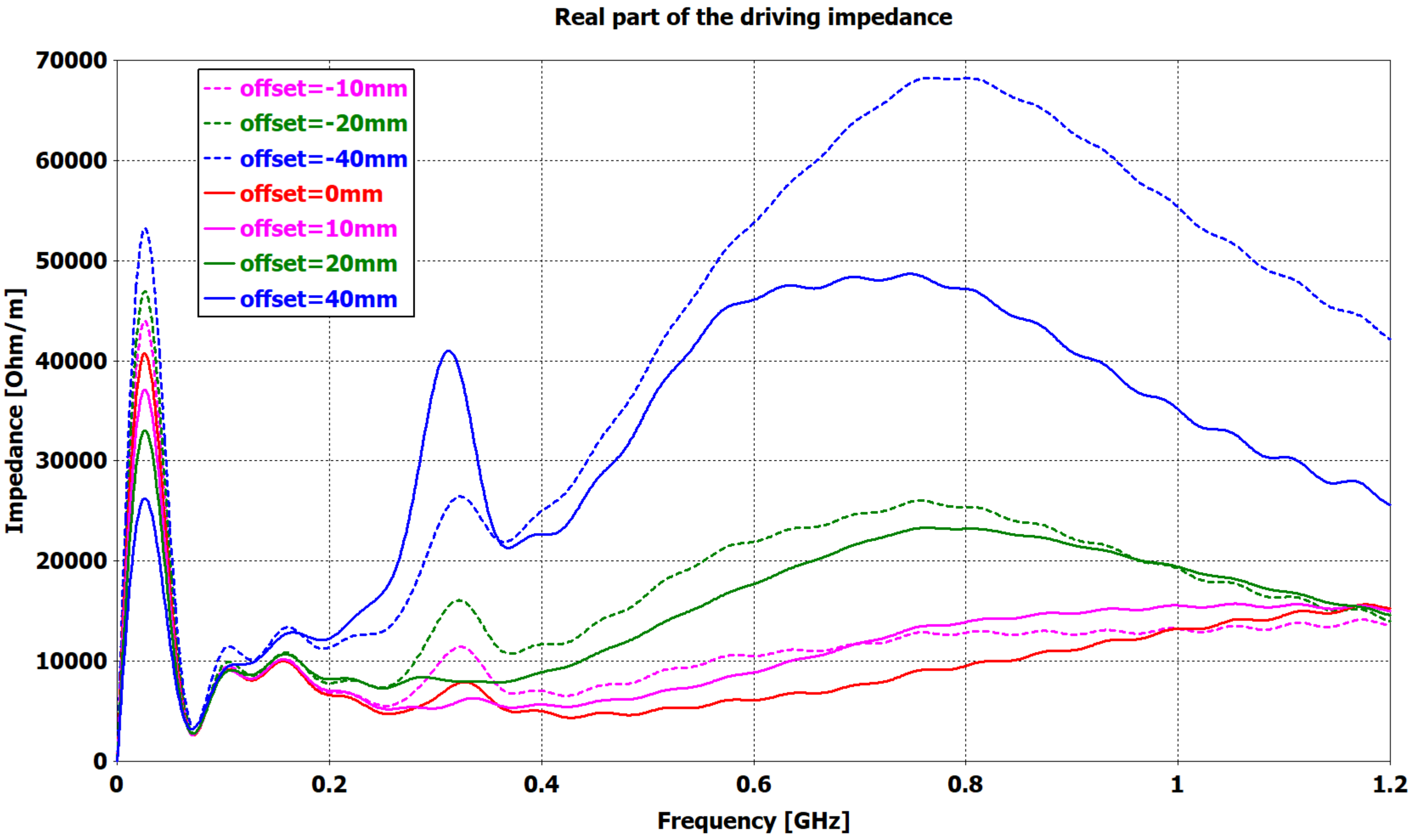


# Effect of orbit deviation on the beam coupling impedance: driving impedance

Kicker impedance:
Example of the MKP-S

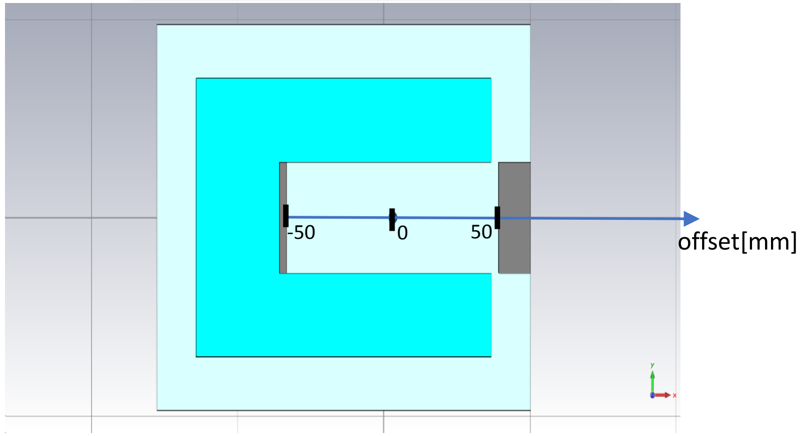



Orbit deviation is expected to cause a significant increase of the transverse driving beam coupling impedance

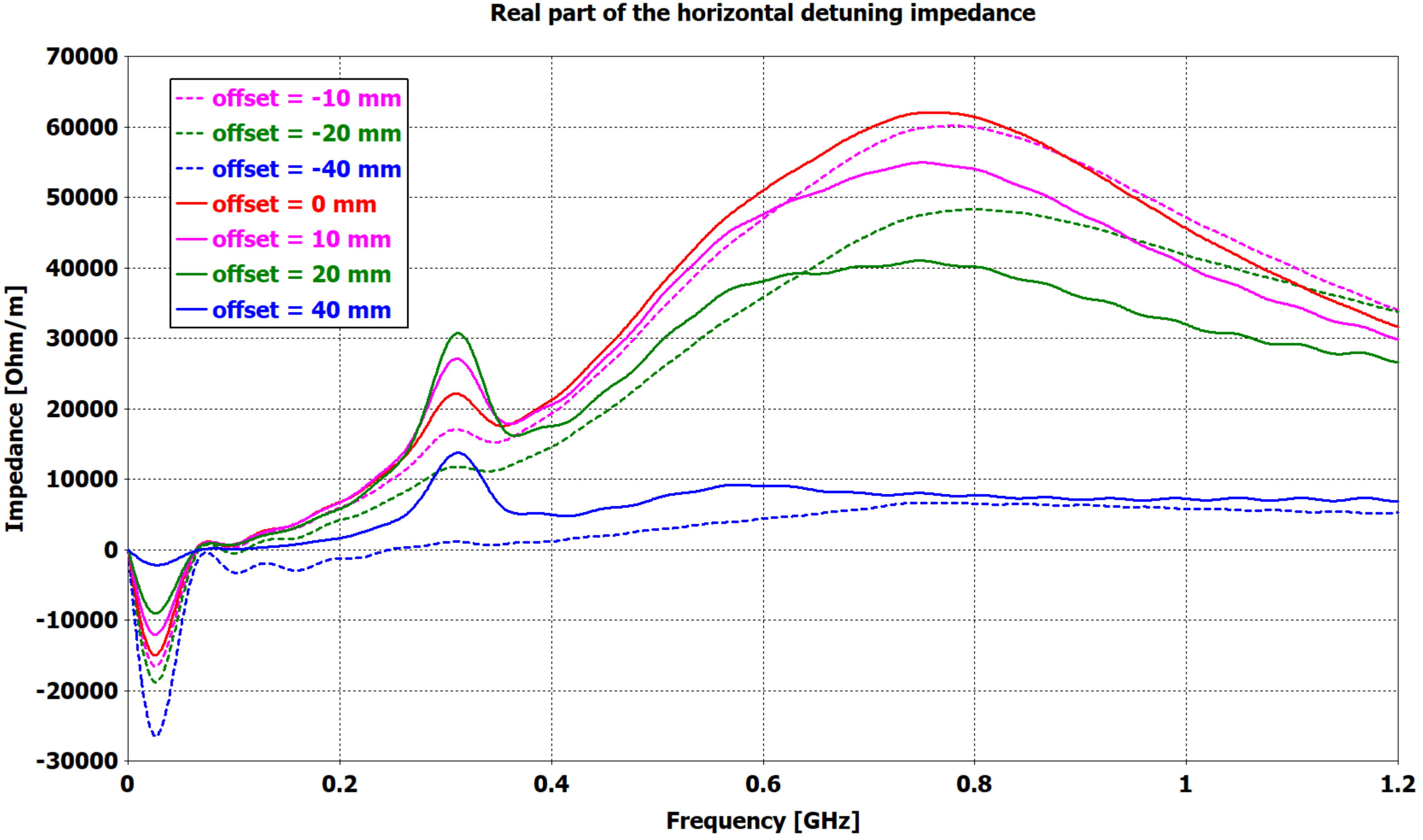


# Effect of orbit deviation on the beam coupling impedance: detuning impedance

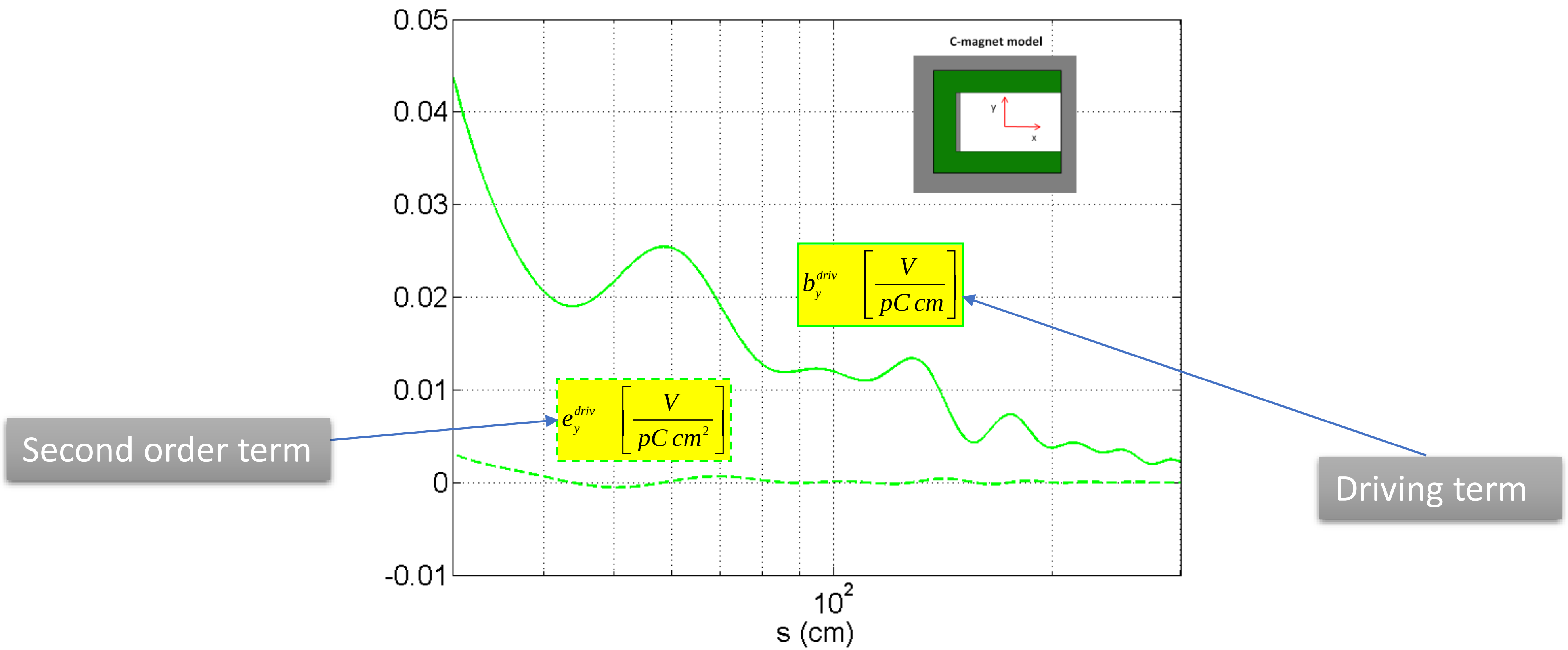
Kicker impedance:
Example of the MKP-S




Orbit deviation is not expected to cause a significant increase of the transverse detuning beam coupling impedance

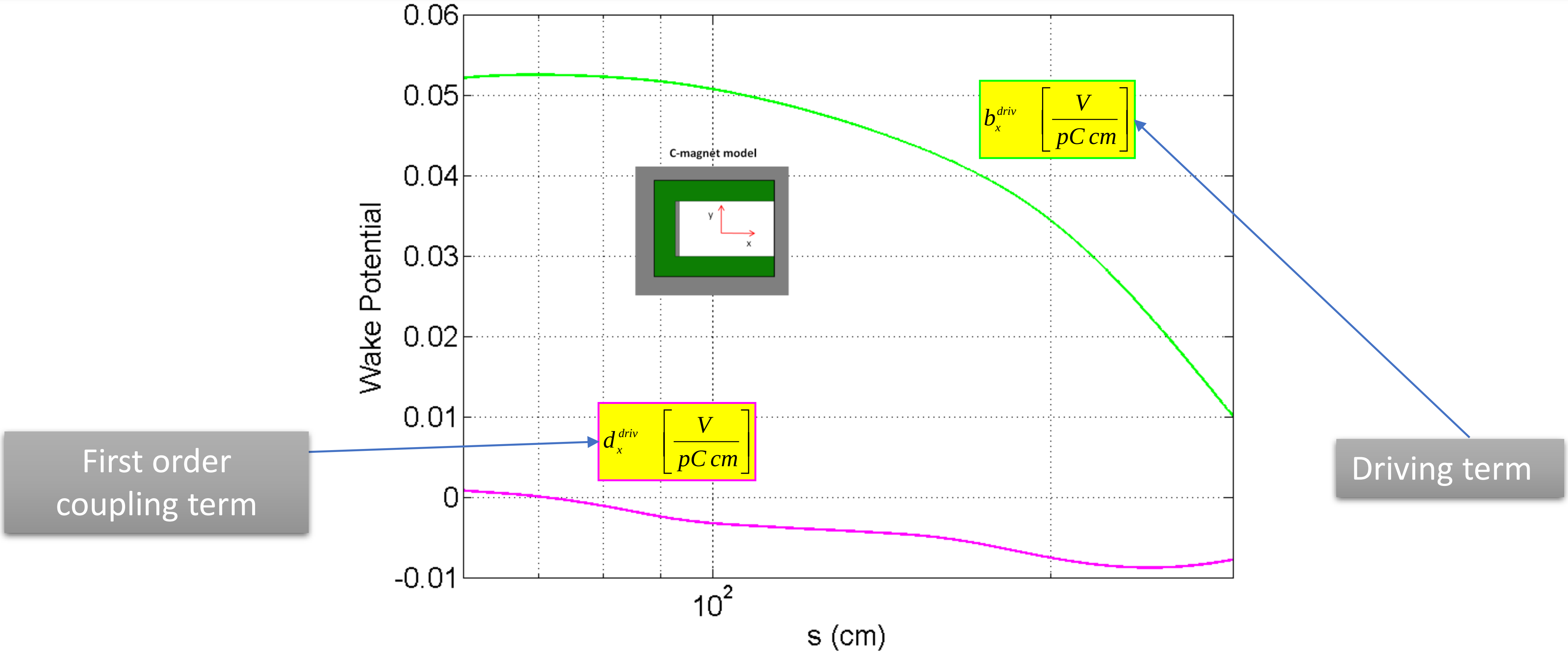


# Effect of orbit deviation on the beam coupling impedance: nonlinear and coupling term




C. Zannini and G. Rumolo The transverse wake components. Presented at the 6th HDWG meeting in May 2011

# Effect of orbit deviation on the beam coupling impedance: nonlinear and coupling term

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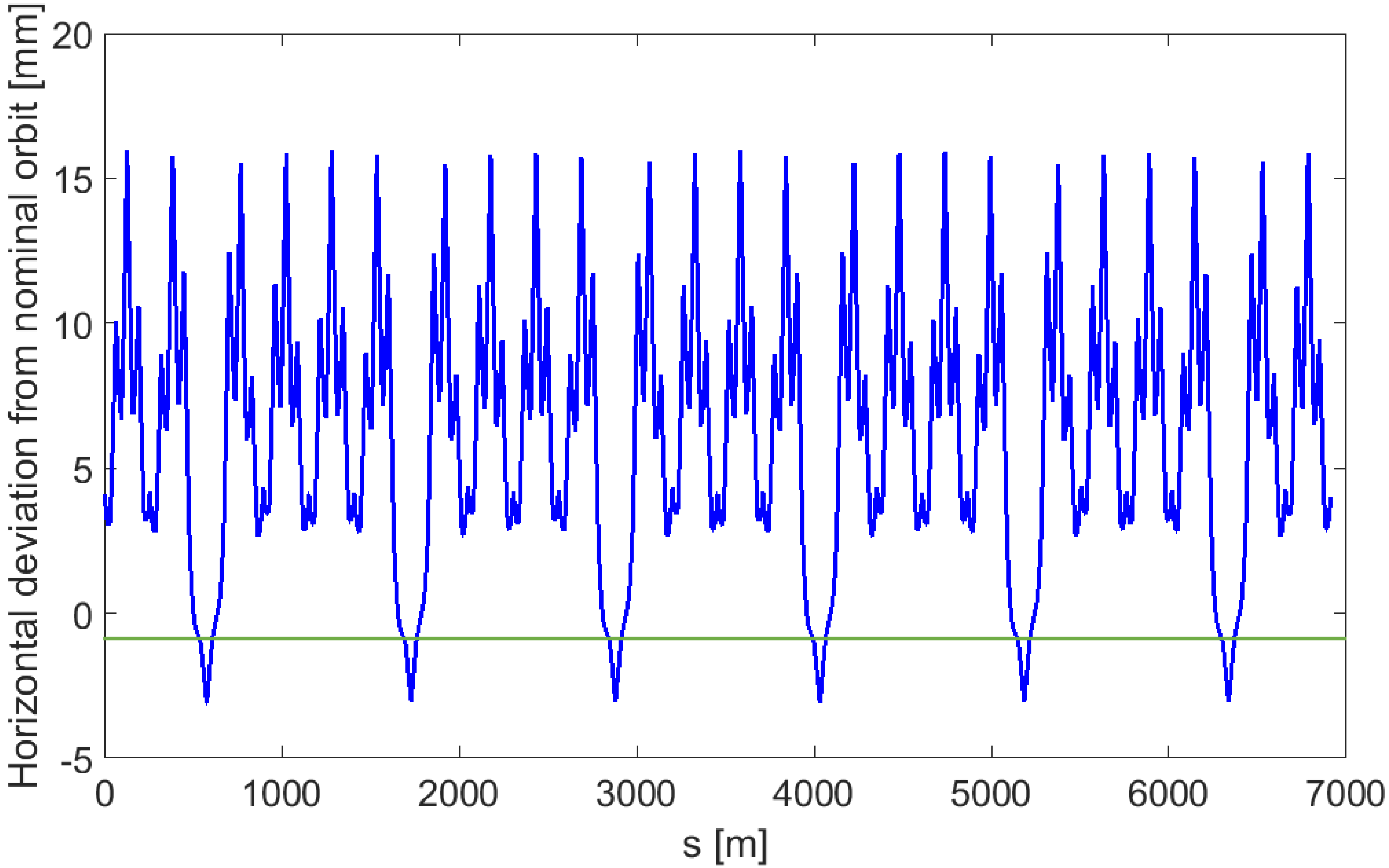
The nonlinear and coupling terms seem to be negligible in HEADTAIL simulations

# Effect of orbit deviation on the beam coupling impedance




Dispersion in the kicker location is about 20 times smaller than peak dispersion

The displacement will be negligible (in the order of 1 mm in the nominal option)

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# Initial PyHEADTAIL transverse stability simulations

- Neglecting the change of impedance due to orbit deviation
- Scan of the batch spacing and bunch spacing that will be experienced during slip-stacking (each configuration is simulated for 40k turns)
  - very pessimistic approach
- Estimation of the intensity thresholds

# Initial PyHEADTAIL transverse stability simulations

- Impedance model: wall and kickers
- Simulated beam (56 bunches: 2 batches (4 x 7))
- Initial Gaussian distribution ($\sigma$ = 0.08-0.12 m)
- Set tune (Qx=26.30, Qy=26.25)
- Q26 optics
- p=300 ZGeV/c ($\gamma$=127)
- Transverse emittance 2.0 µm
- Nonlinear synchrotron motion
- Double RF system ($V_{RF800}$/ $V_{RF200}$ = 0.1)
- Chromaticity (0.2 $\xi$ units in both planes)
- Nonlinear chromaticity up to the third order
- Damper off

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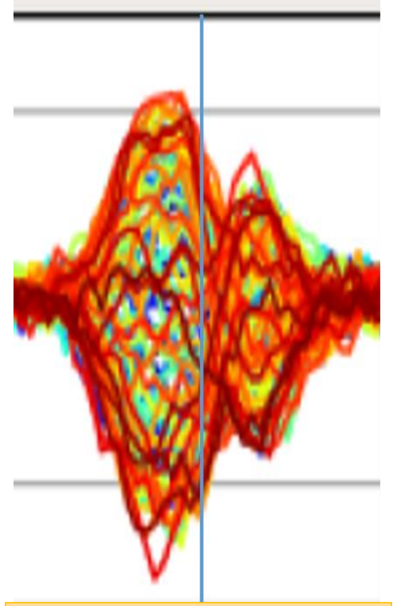
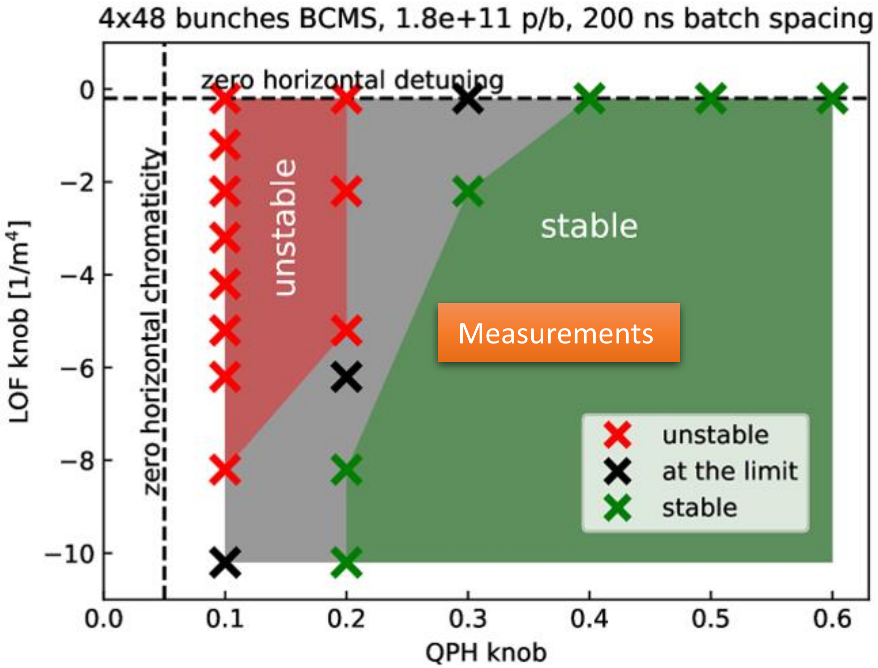
# Simulation parameters: impedance model

| MD observations |
|---|
| Stable with 1 batch at 2e11 ppb |
| Unstable with 4 batches at 2e11 ppb with BS = 200ns |
| Instability behaviour along the batches |
| Stabilization with batch spacing >500 ns |
| Instability threshold at about 1.8e11 ppb |
| Stabilization at horizontal chroma of about 0.6 |
| Behaviour with chroma and octupoles |

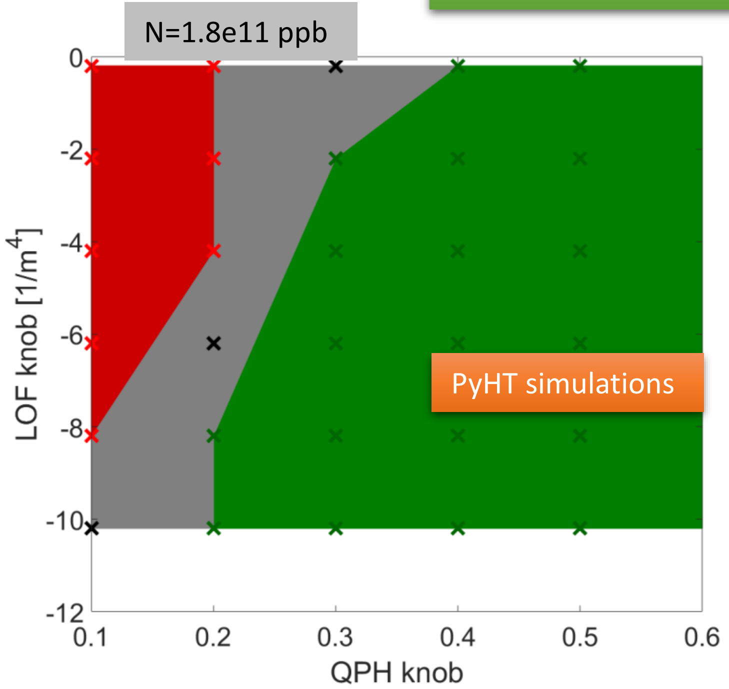
## Measurements

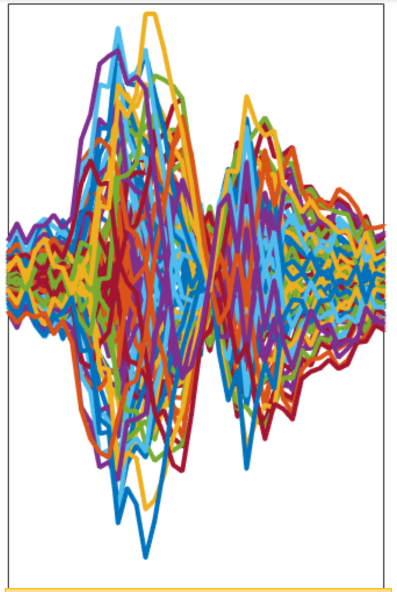


ξ = 0.2, LOF = -2.2



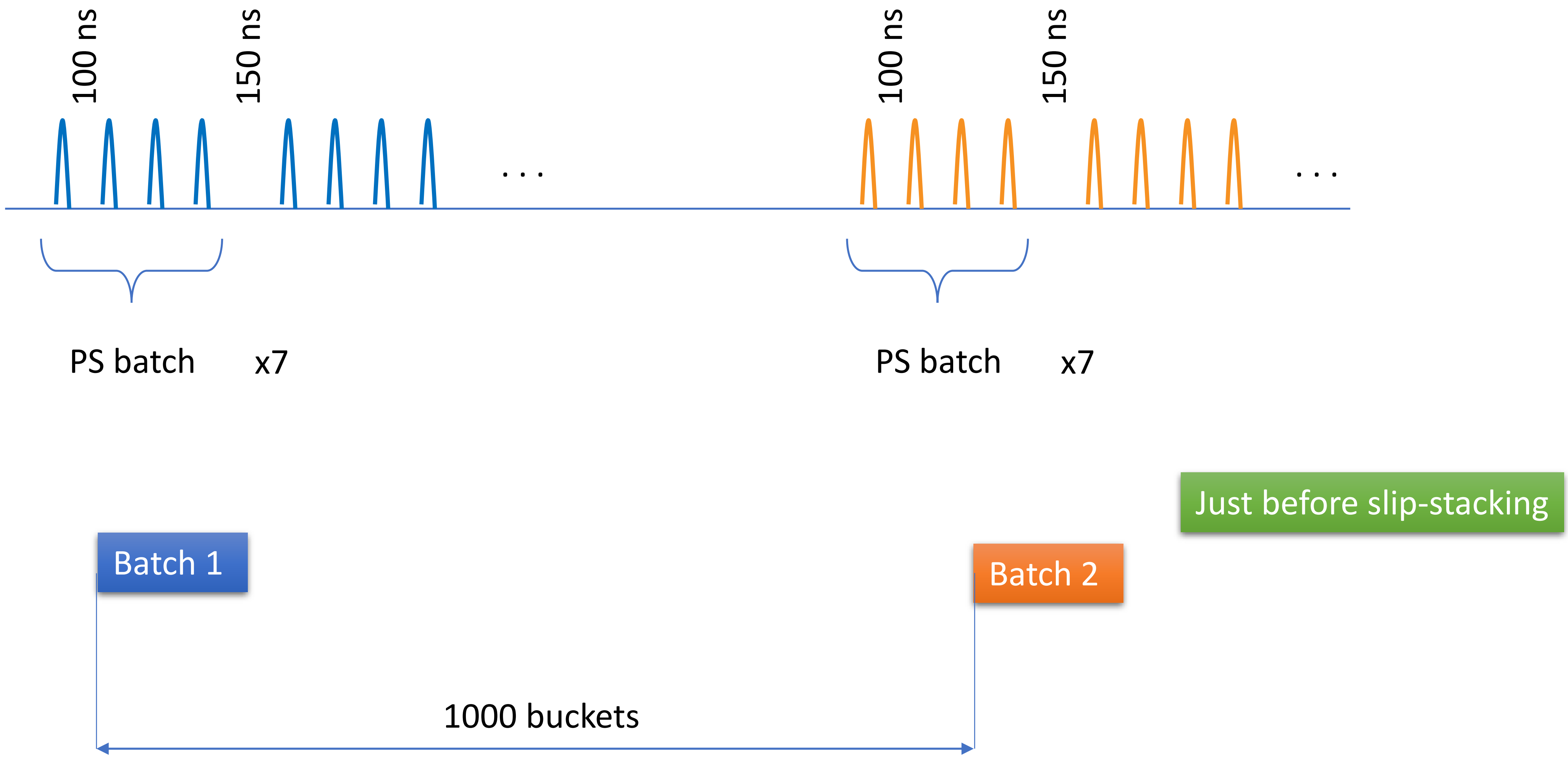

## PyHEADTAIL simulations



ξ = 0.2, LOF = -2.2

# Simulation parameters: beam



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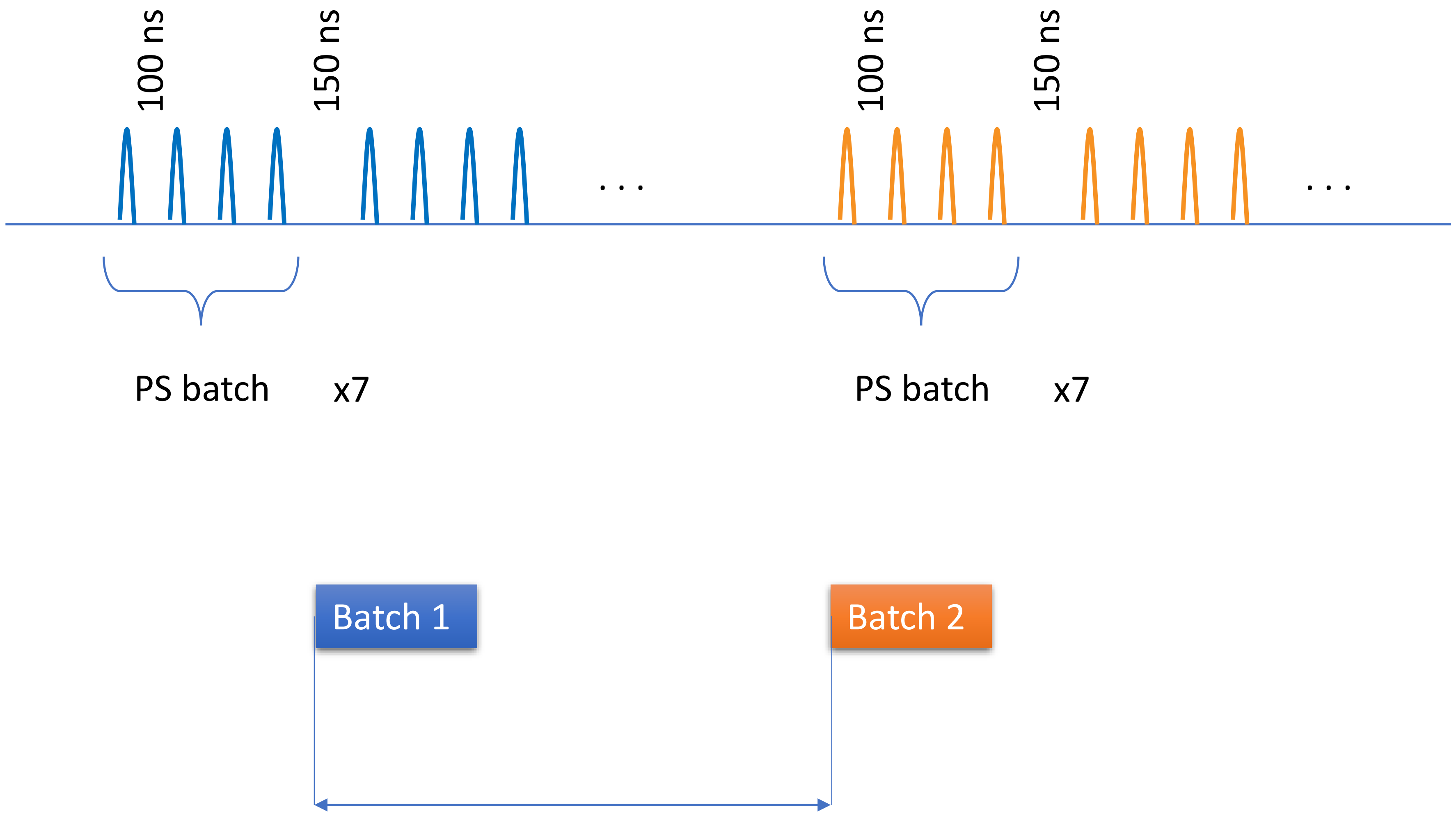

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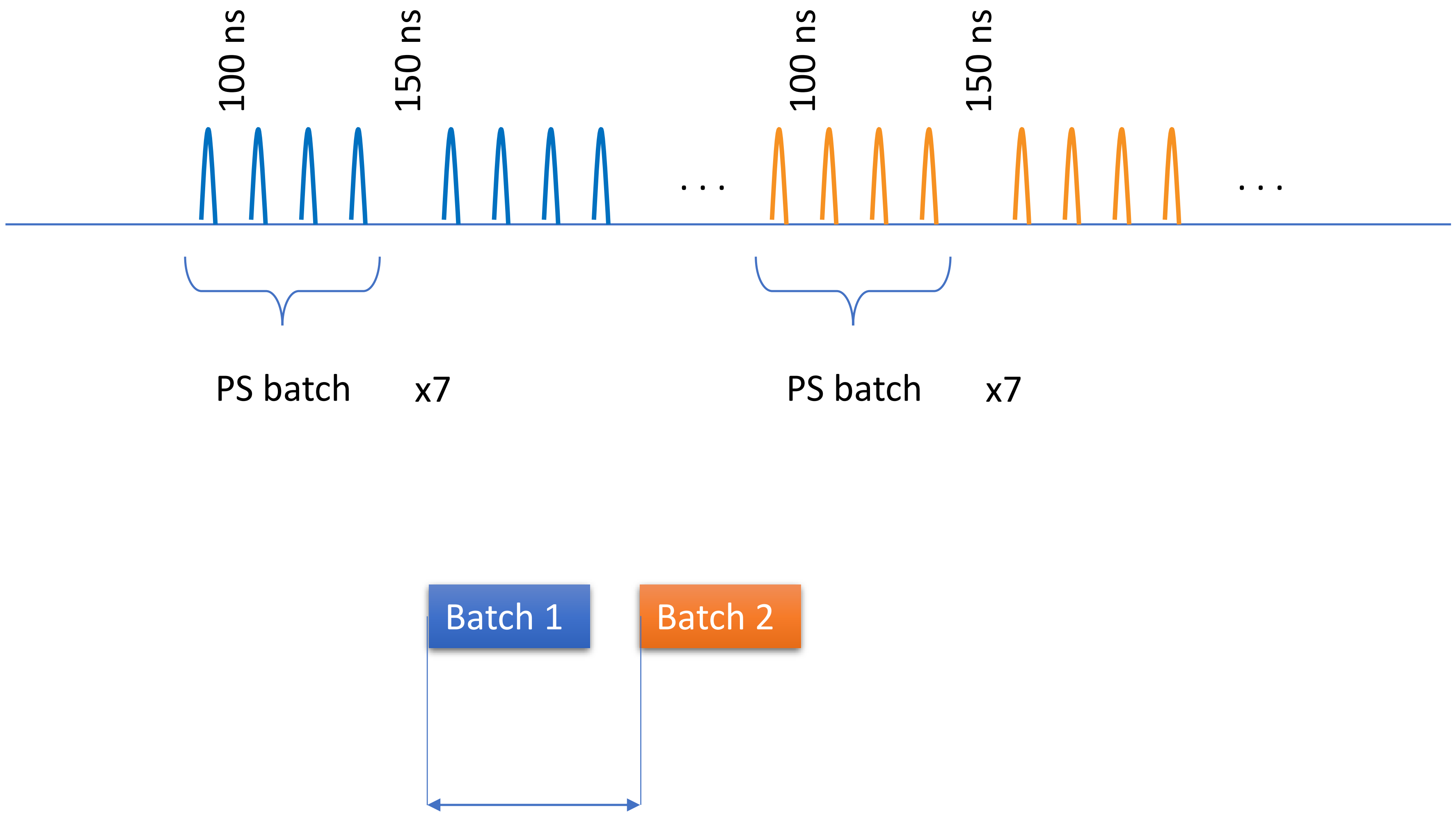

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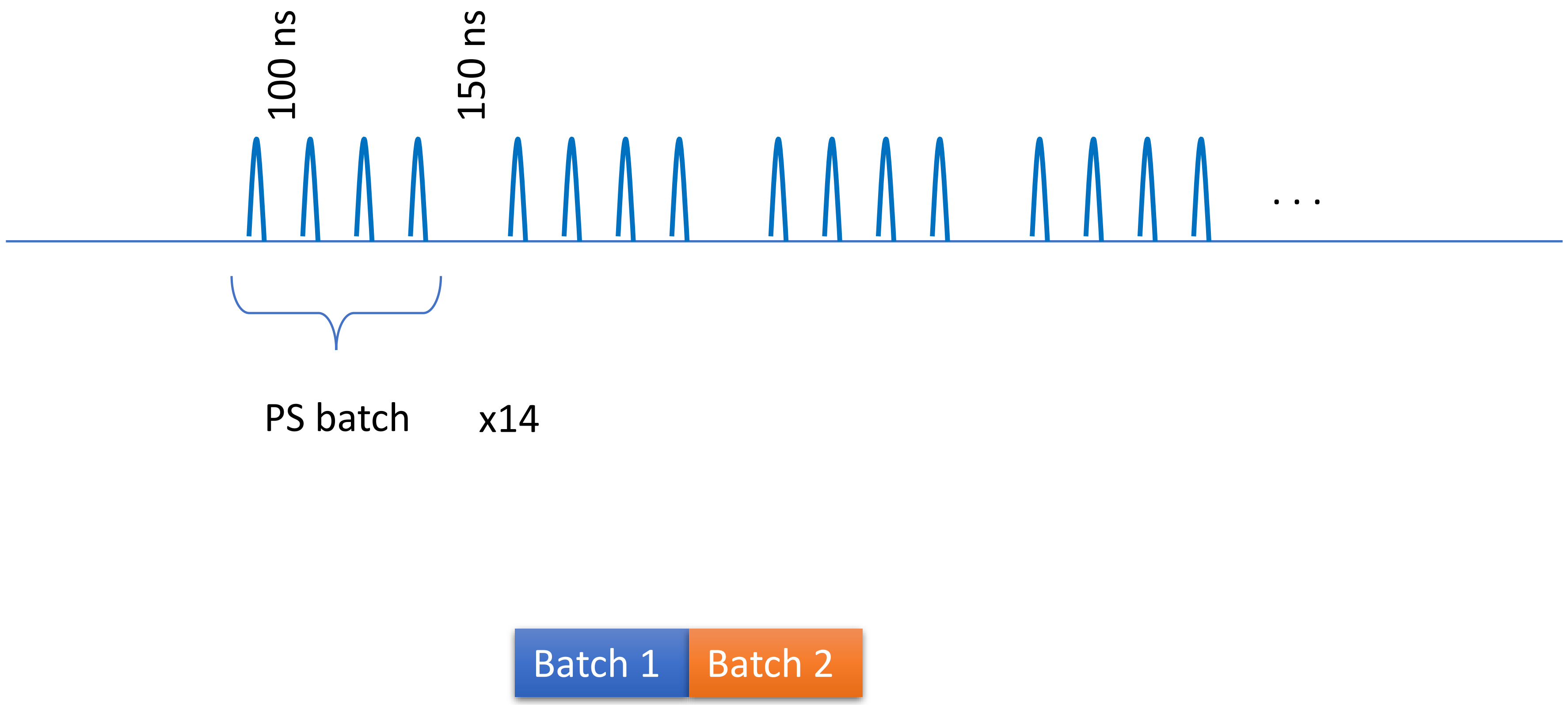

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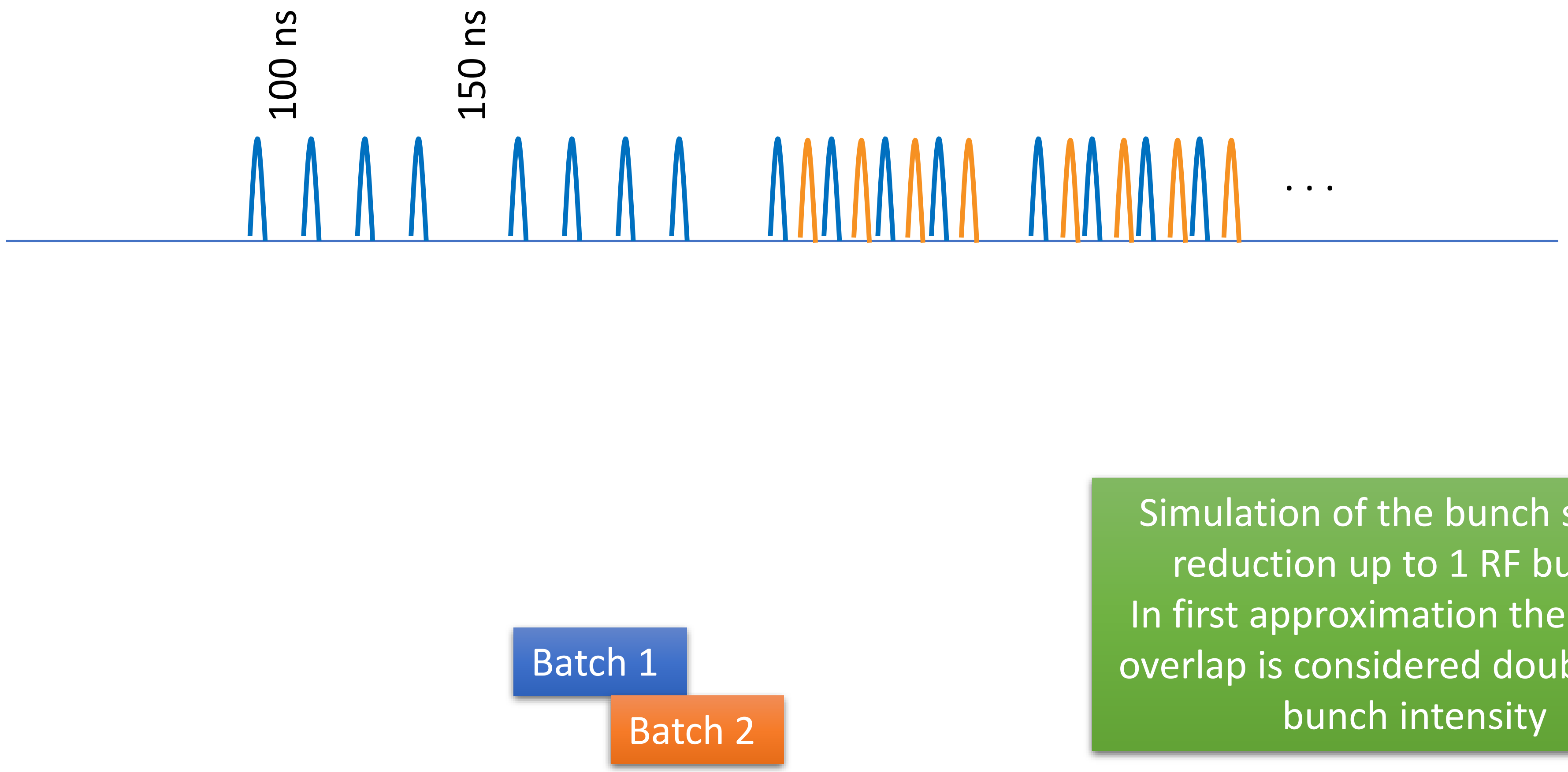
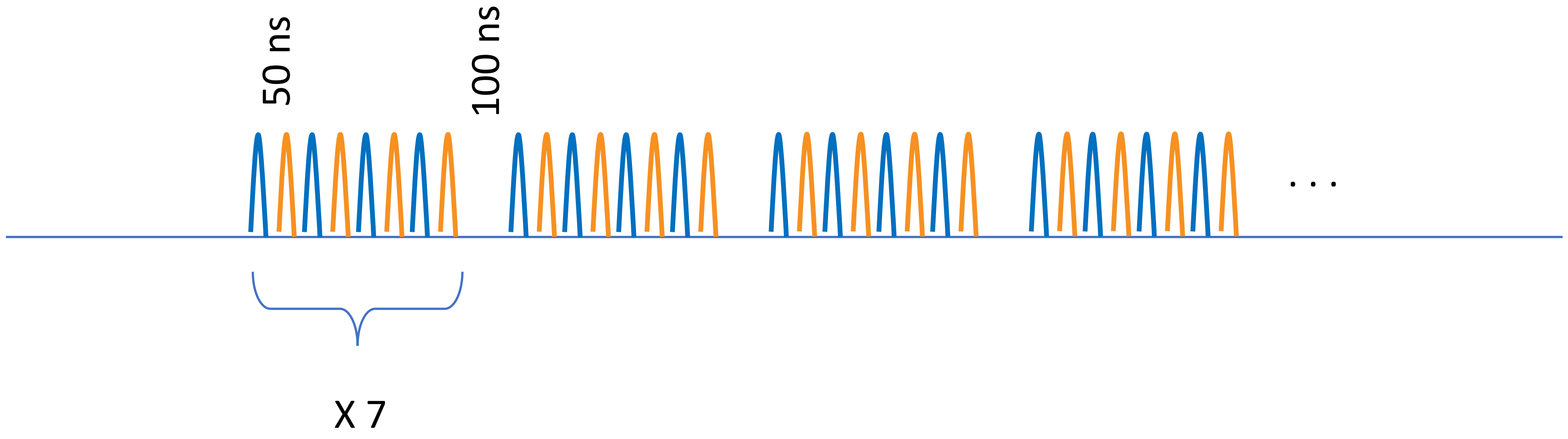



Simulation of the bunch spacing reduction up to 1 RF bucket.
In first approximation the perfect overlap is considered doubling the bunch intensity

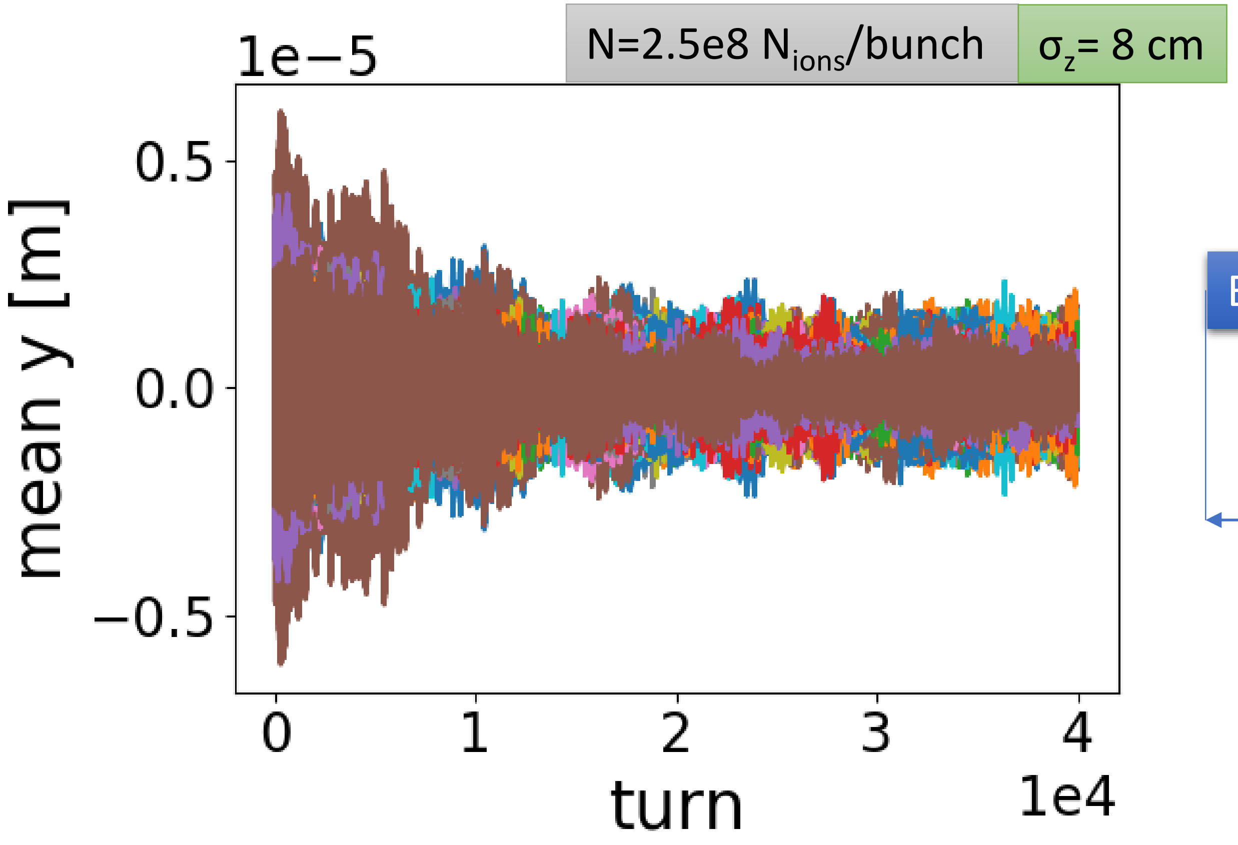
# Simulation parameters: beam

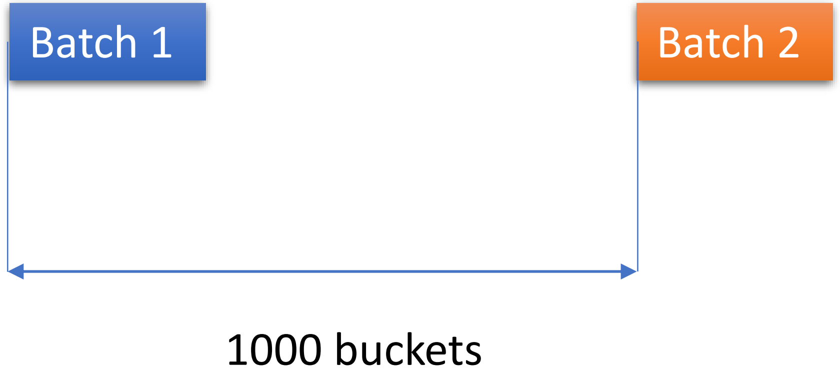




End of slip stacking head to head distance between batches is 10 RF buckets

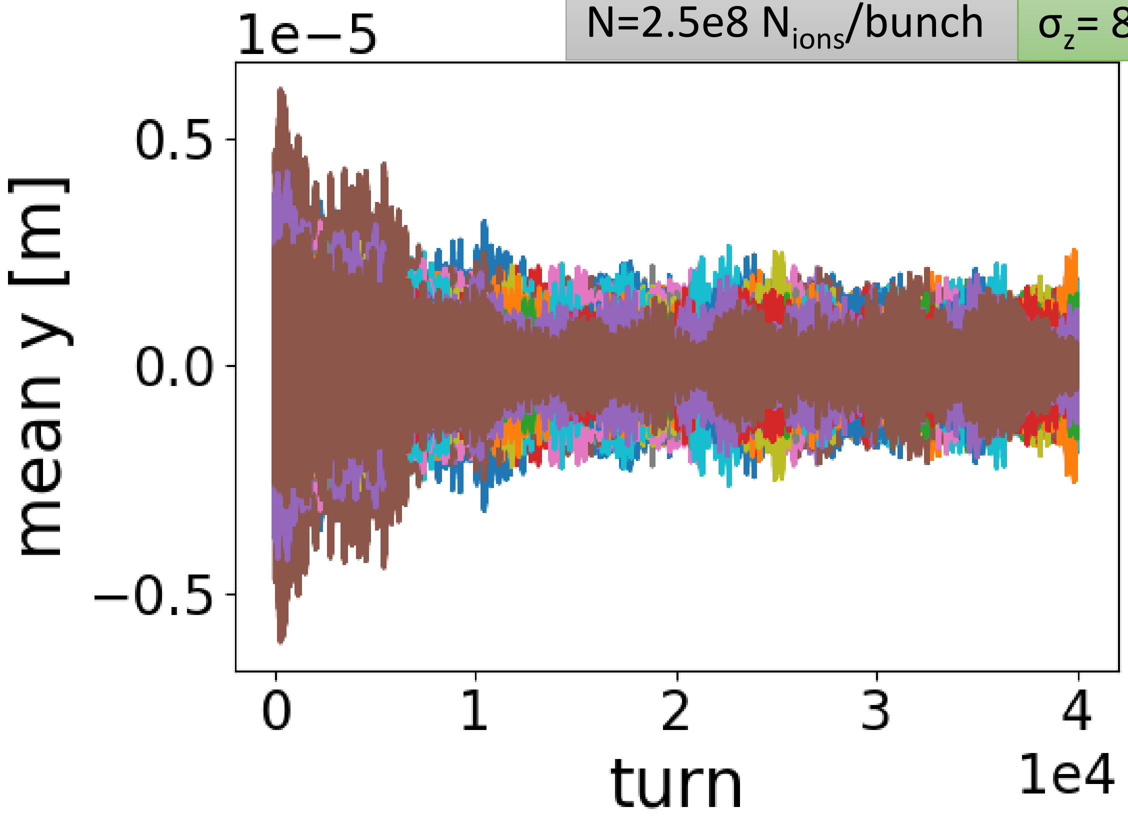
# Simulation results



# Simulation results

N=2.5e8 $N_{ions}$/bunch | $\sigma_z$= 8 cm




Batch 1 | Batch 2

# Simulation results

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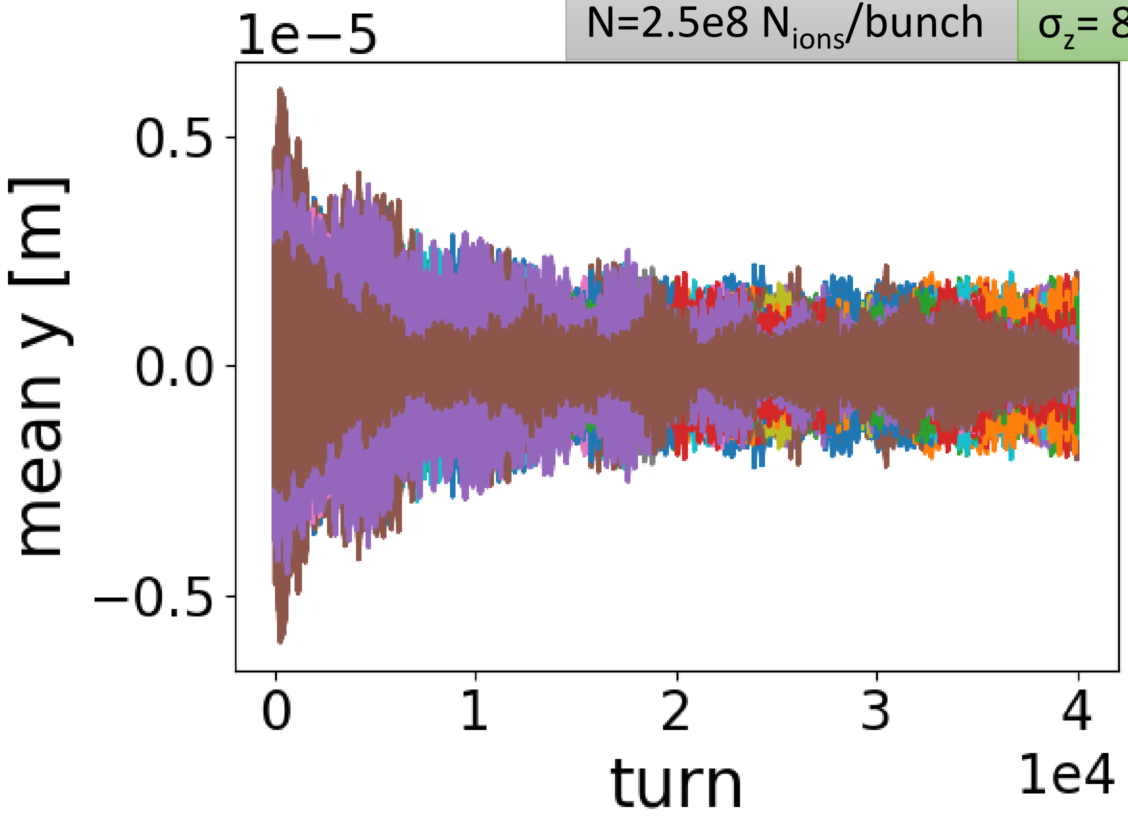


Batch 1

Batch 2

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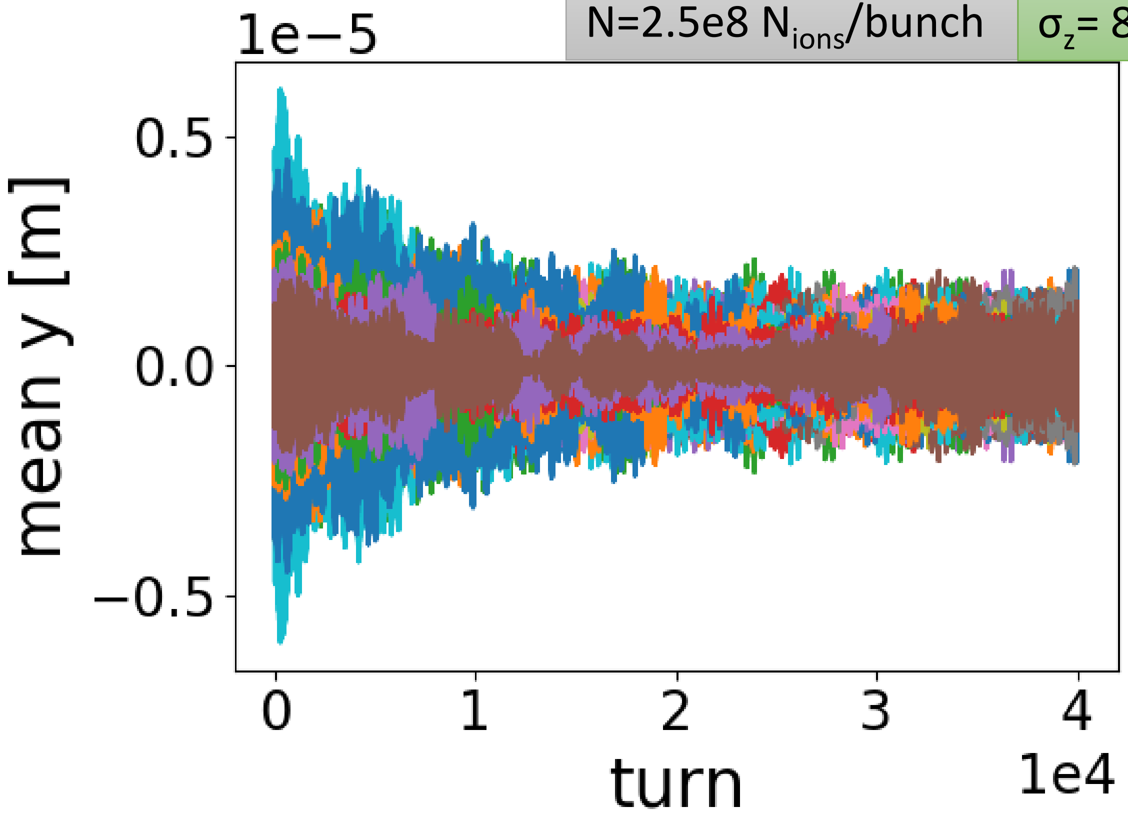



Batch 1

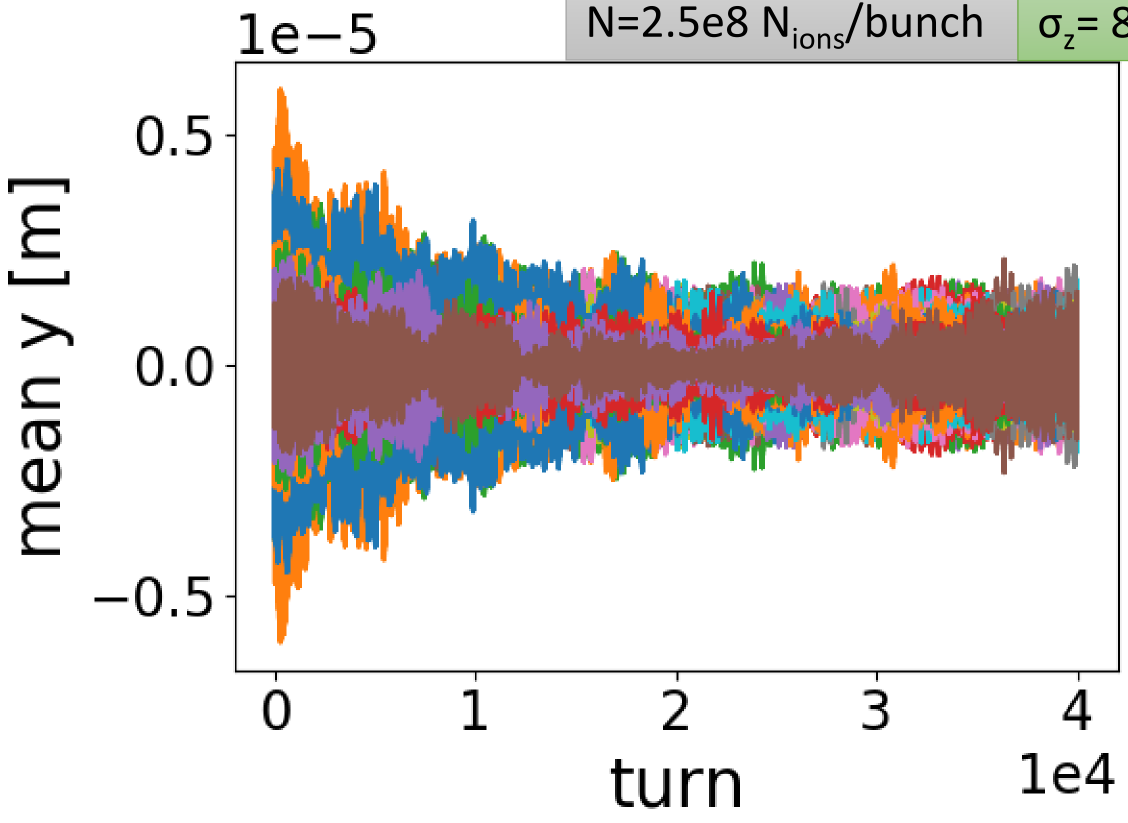
Batch 2

Bunch spacing 5 RF buckets

# Simulation results

N=2.5e8 $N_{ions}$/bunch

$\sigma_z$= 8 cm



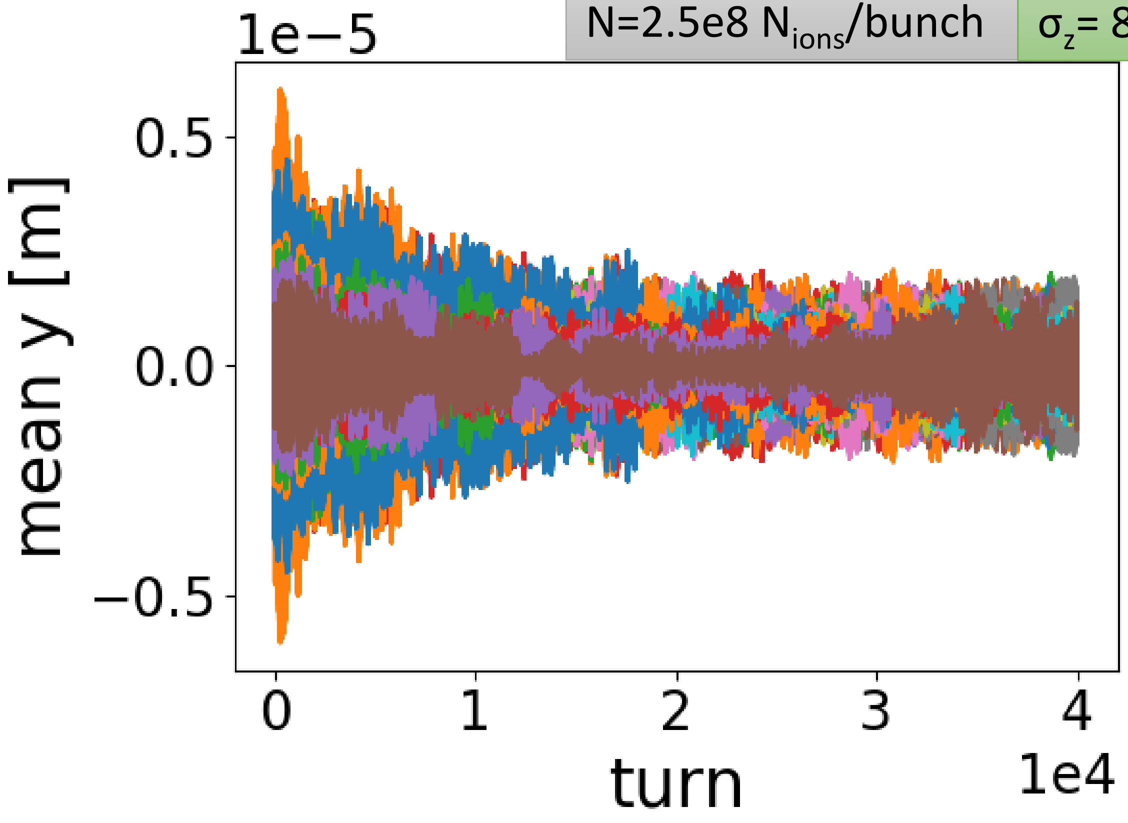

Batch 1

Batch 2

Bunch spacing 4 RF buckets

# Simulation results

N=2.5e8 $N_{ions}$/bunch | $\sigma_z$= 8 cm

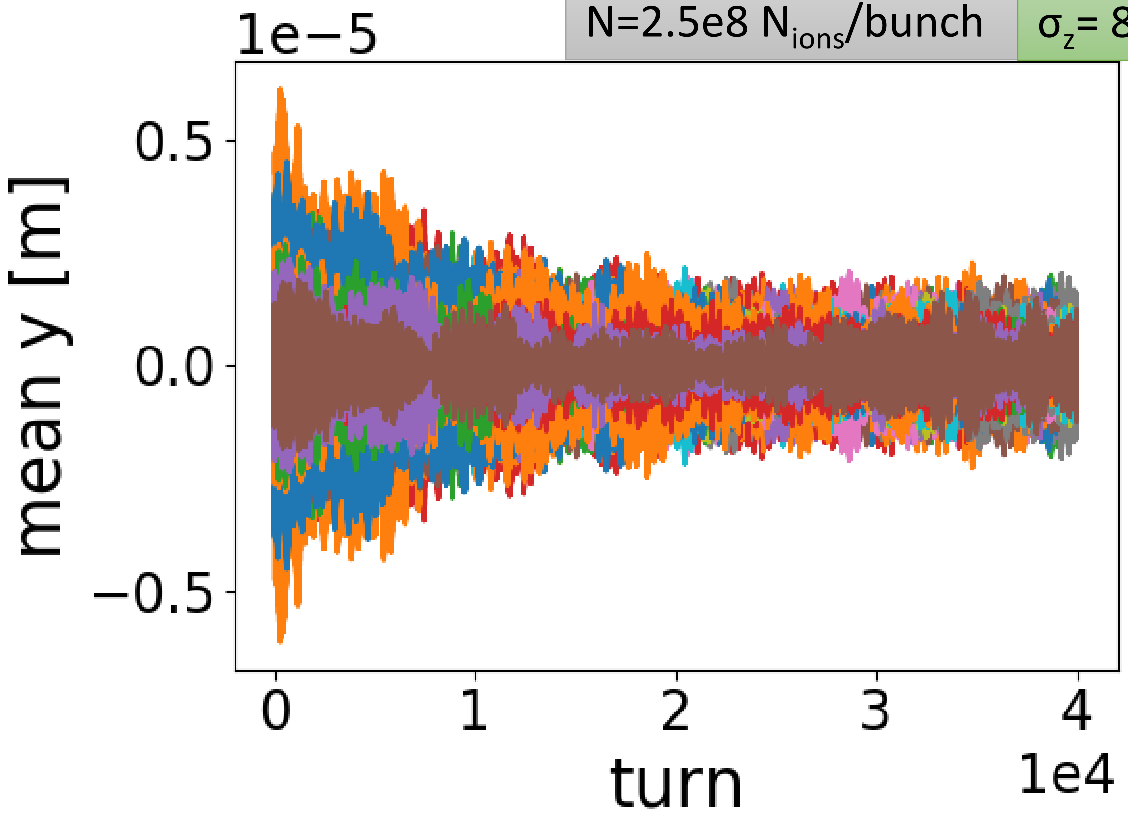



Batch 1

Batch 2

Bunch spacing 2 RF buckets

# Simulation results




N=2.5e8 $N_{ions}$/bunch

$\sigma_z$= 8 cm

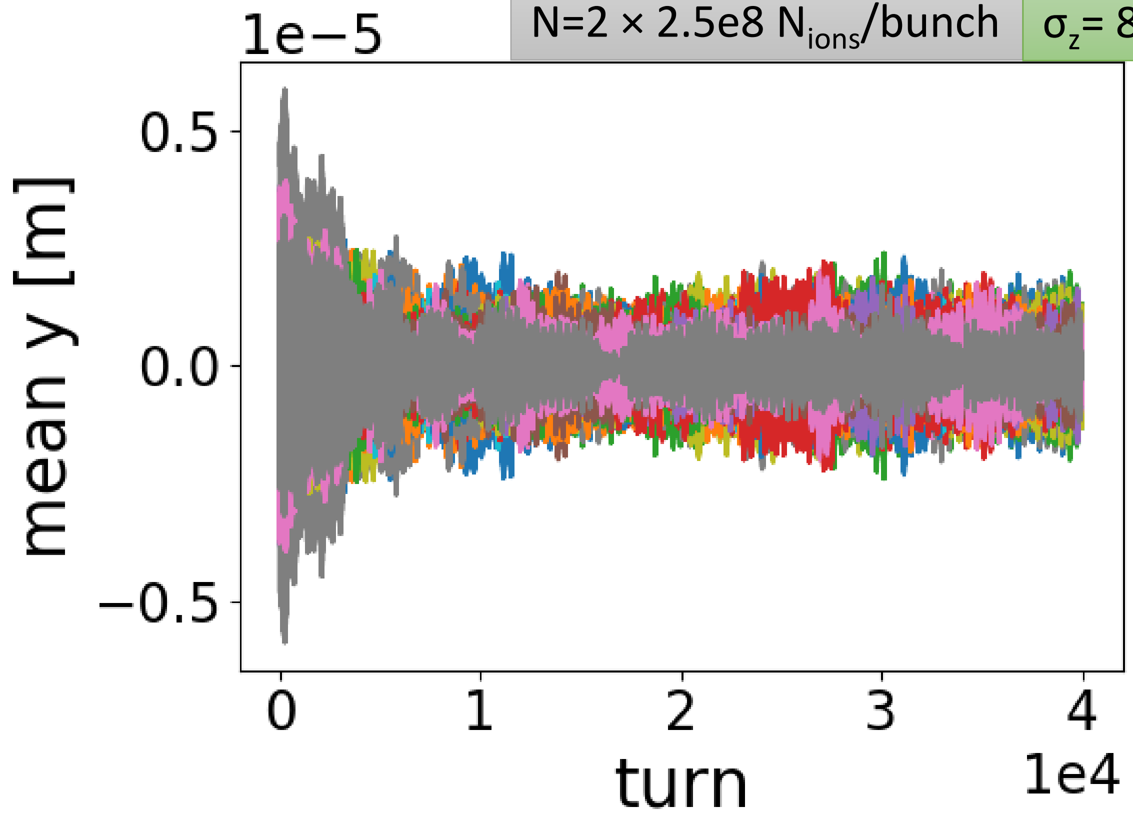
Batch 1

Batch 2

Bunch spacing 1 RF buckets

# Simulation results

N=2 × 2.5e8 $N_{ions}$/bunch | $\sigma_z$= 8 cm



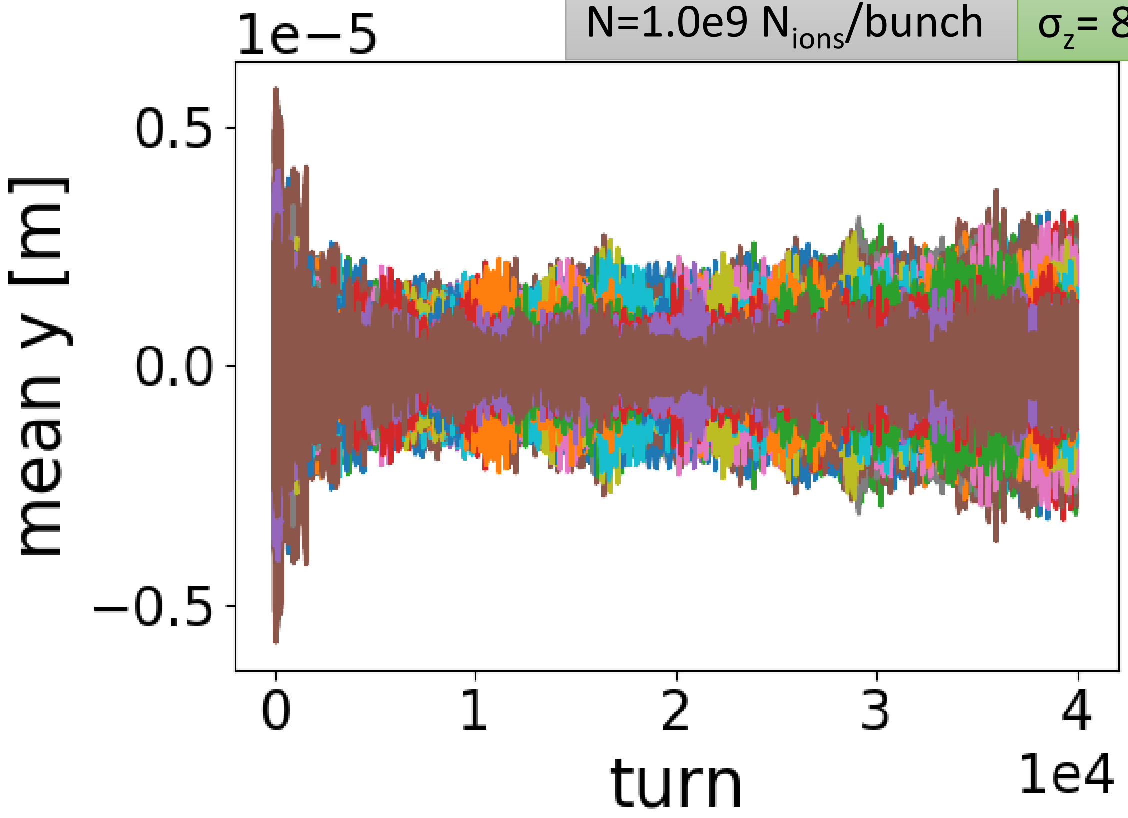

Batch 1

Batch 2

Bunch spacing 0 RF buckets

# Simulation results

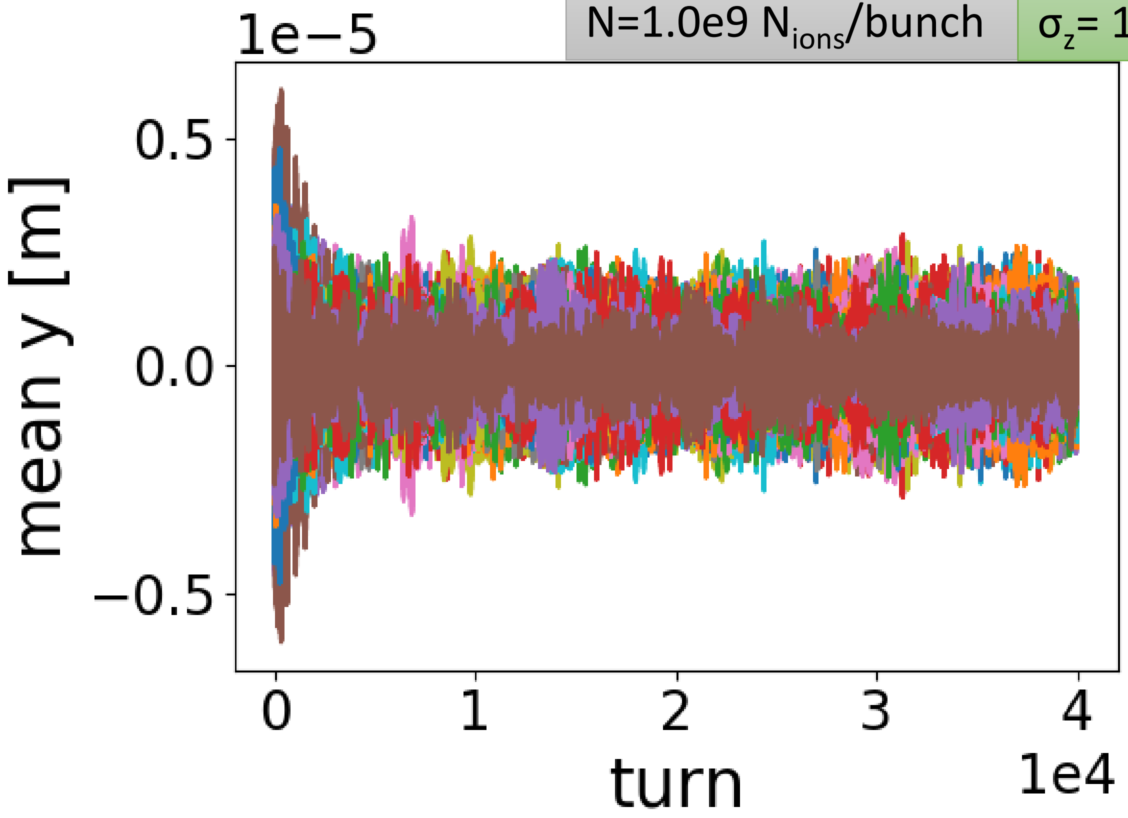
N=1.0e9 $N_{ions}$/bunch | $\sigma_z$= 8 cm




Batch 1 | Batch 2

# Simulation results

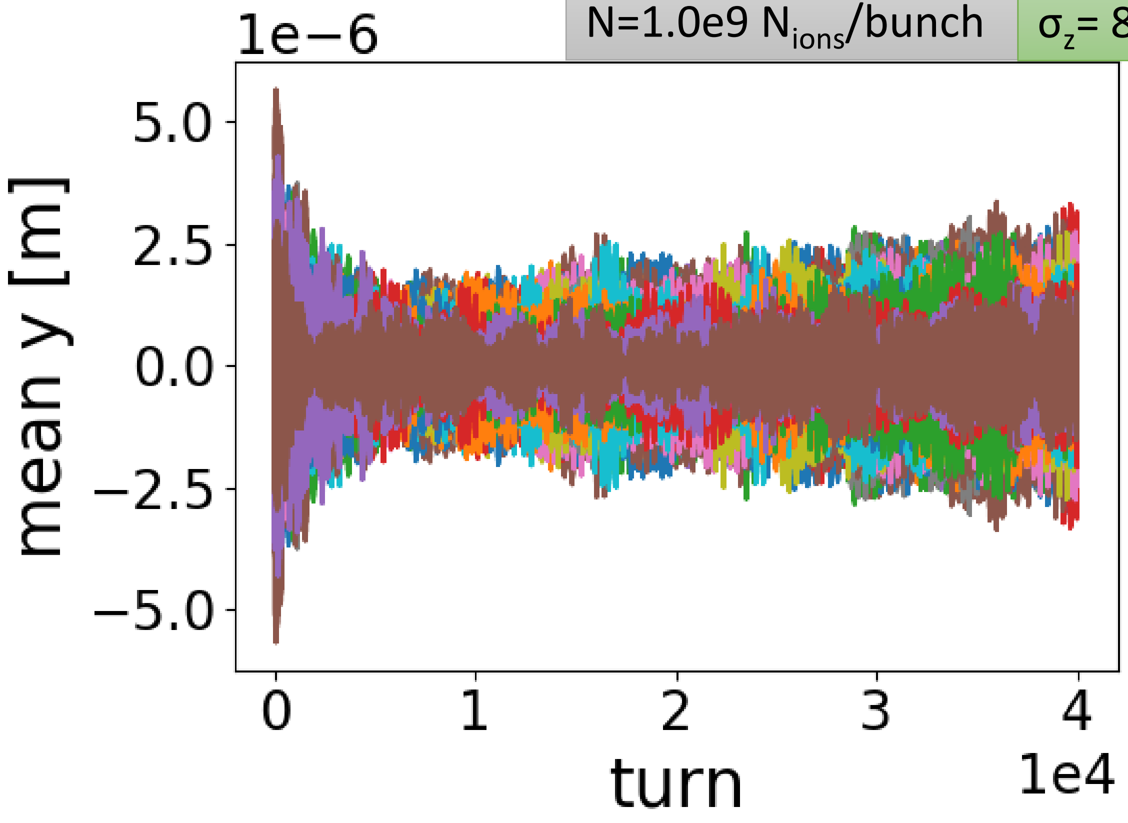
N=1.0e9 $N_{ions}$/bunch | $\sigma_z$= 10 cm




Batch 1 | Batch 2

# Simulation results

N=1.0e9 $N_{ions}$/bunch | $\sigma_z$= 8 cm




Batch 1

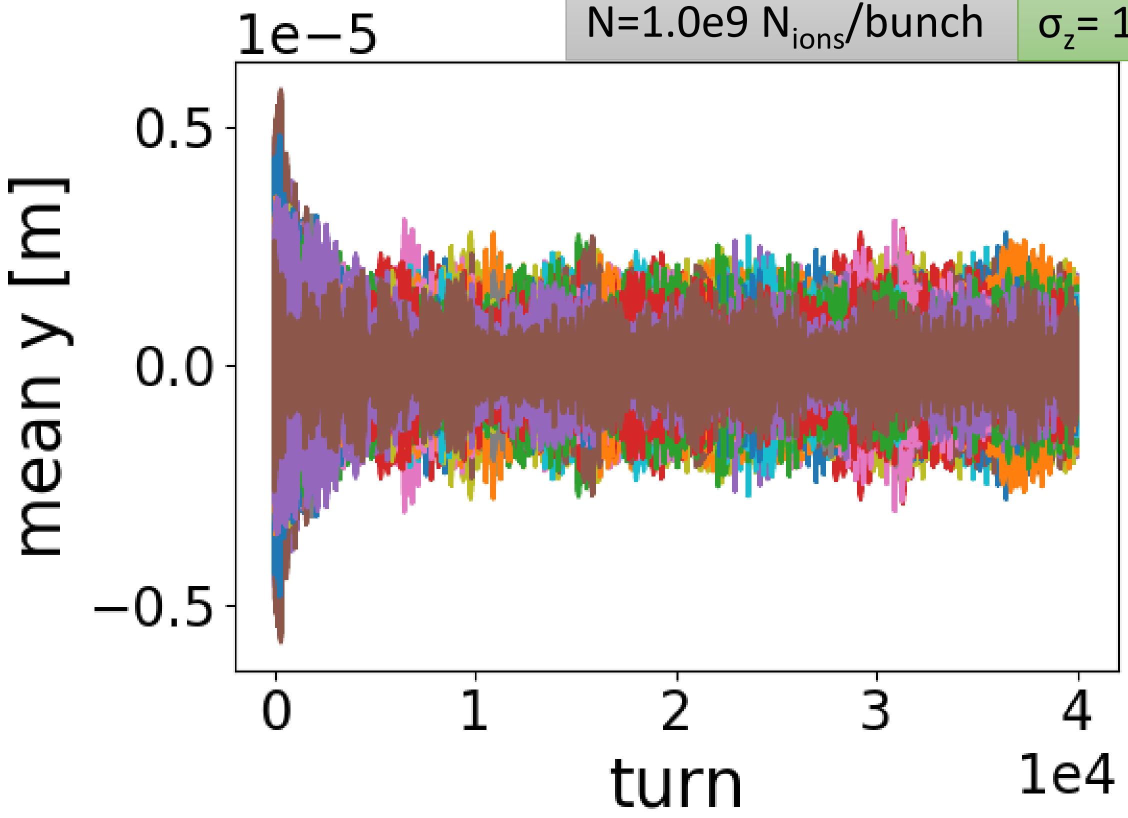
Batch 2

End of slip stacking head to head distance between batches is 10 RF buckets

# Simulation results

N=1.0e9 $N_{ions}$/bunch

$\sigma_z$= 10 cm



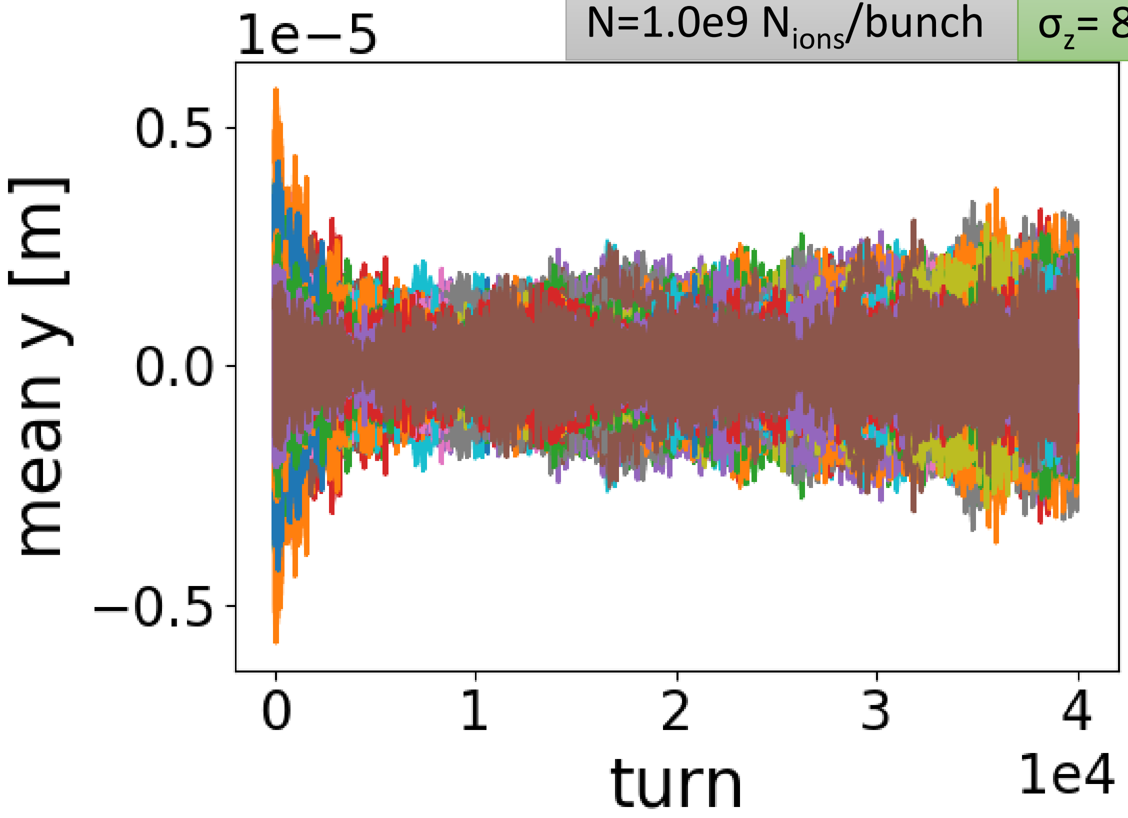

Batch 1

Batch 2

End of slip stacking head to head distance between batches is 10 RF buckets

# Simulation results

N=1.0e9 $N_{ions}$/bunch | $\sigma_z$= 8 cm




Batch 1

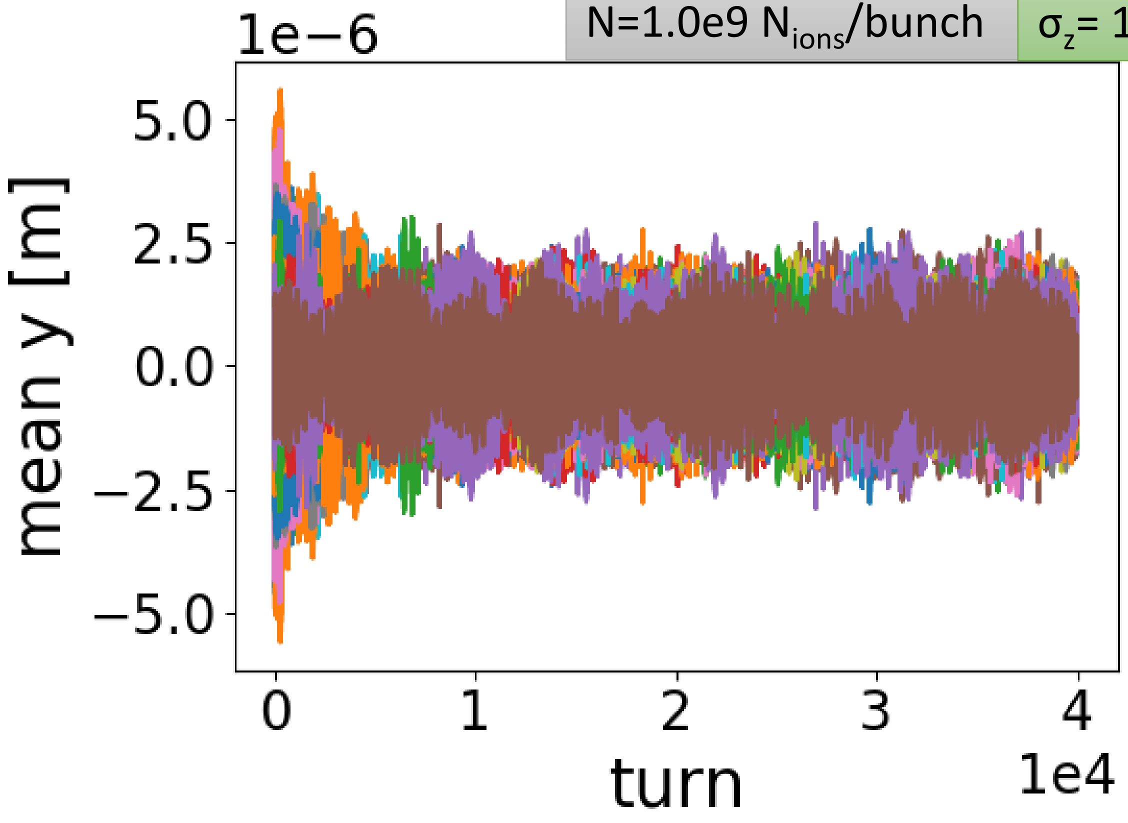
Batch 2

Bunch spacing 1 RF buckets

# Simulation results

N=1.0e9 $N_{ions}$/bunch

$\sigma_z$= 10 cm

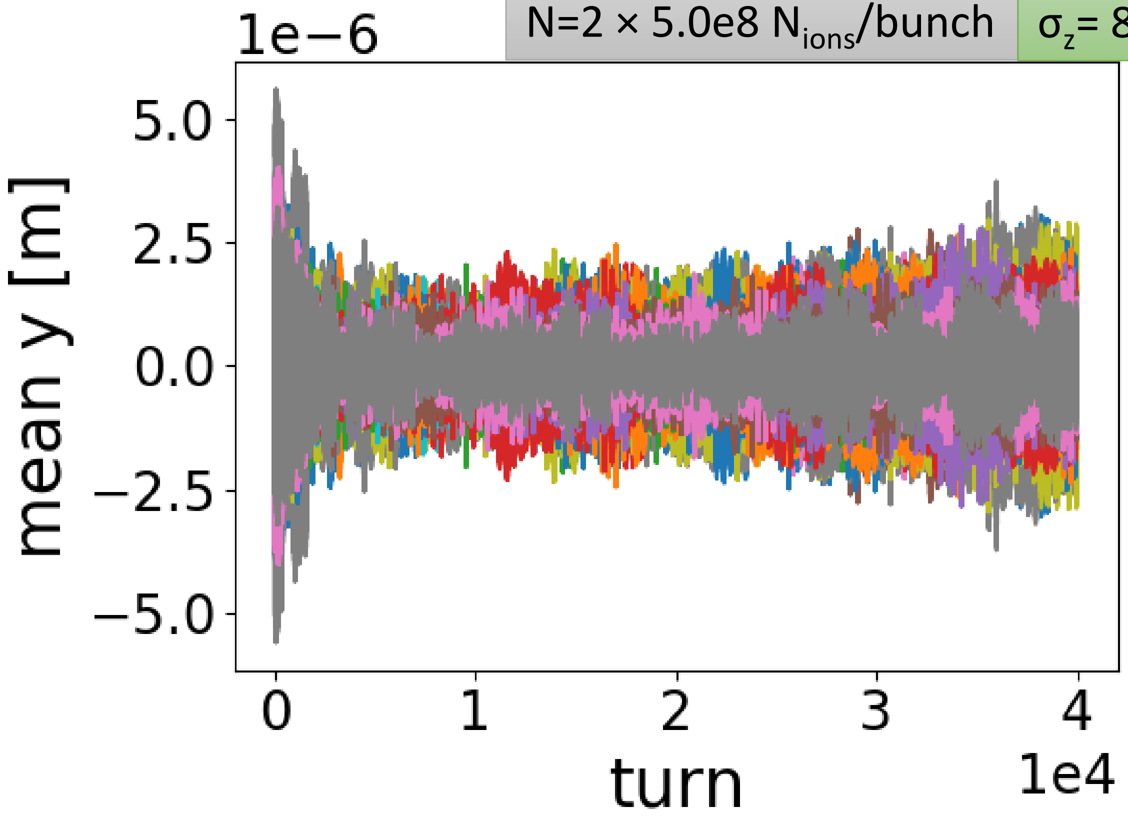



Batch 1

Batch 2

Bunch spacing 1 RF buckets

# Simulation results




N=2 × 5.0e8 $N_{ions}$/bunch

$\sigma_z$= 8 cm

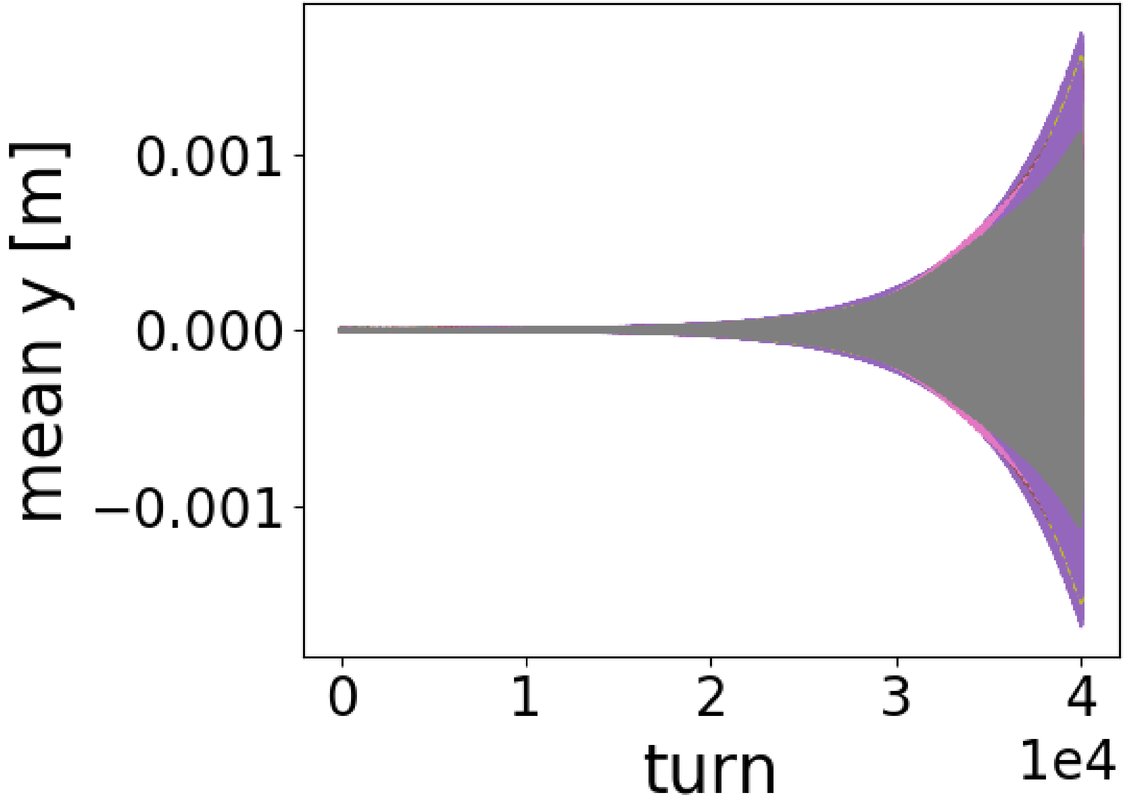
Batch 1

Batch 2

Bunch spacing 0 RF buckets

# Simulation results

N=2 × 1.0e9 $N_{ions}$/bunch | $\sigma_z$= 8 cm



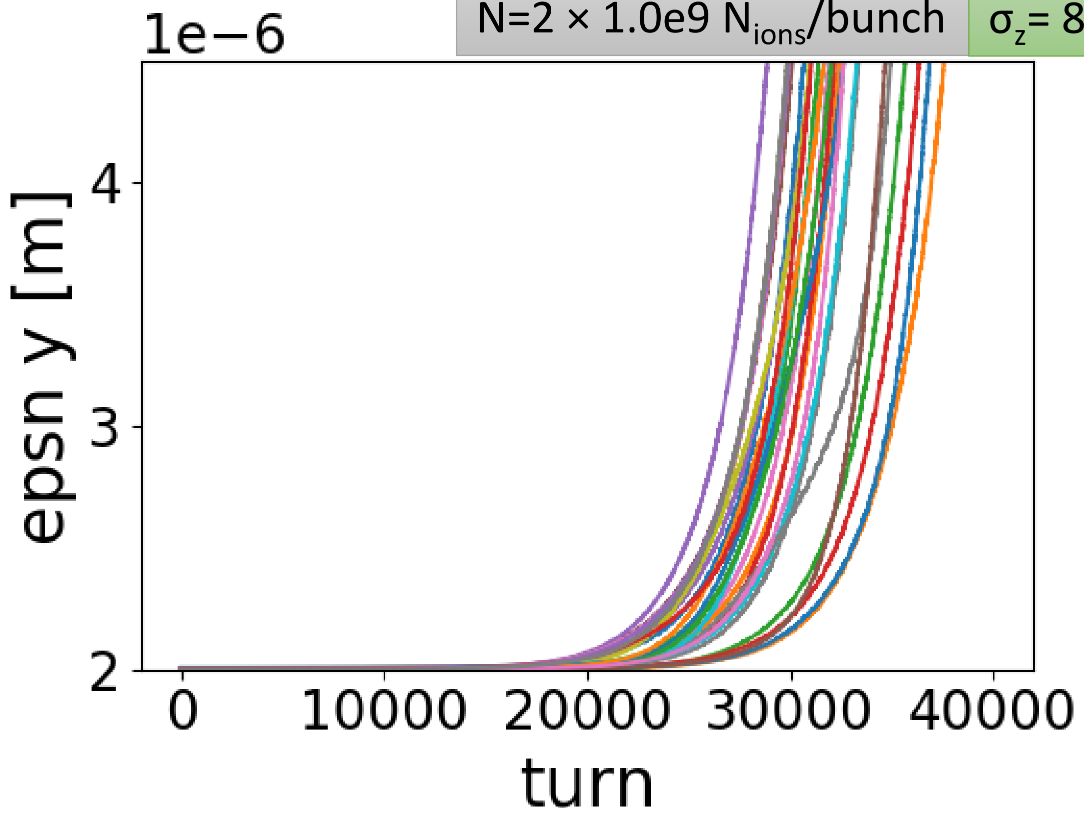

Batch 1

Batch 2

Bunch spacing 0 RF buckets

# Simulation results

N=2 × 1.0e9 $N_{ions}$/bunch | $\sigma_z$= 8 cm



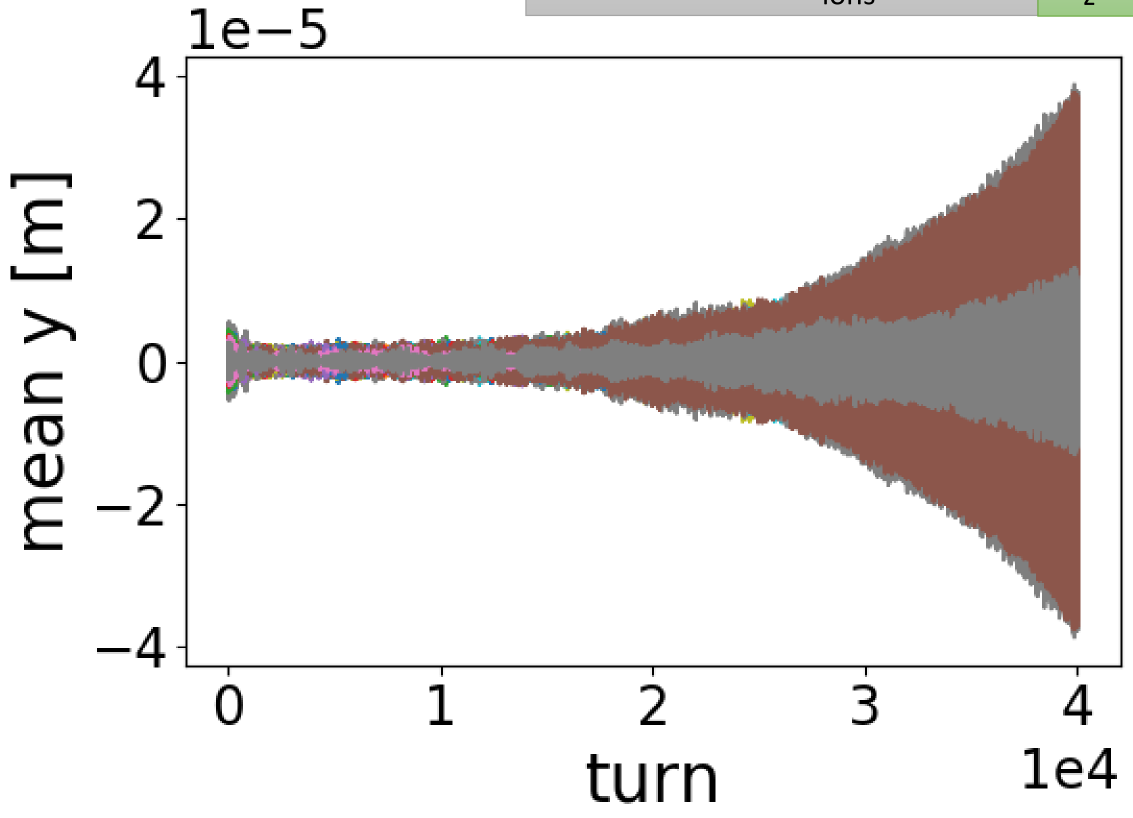

Batch 1

Batch 2

Bunch spacing 0 RF buckets

# Simulation results

N=2 × 1.0e9 $N_{ions}$/bunch | $\sigma_z$= 10 cm



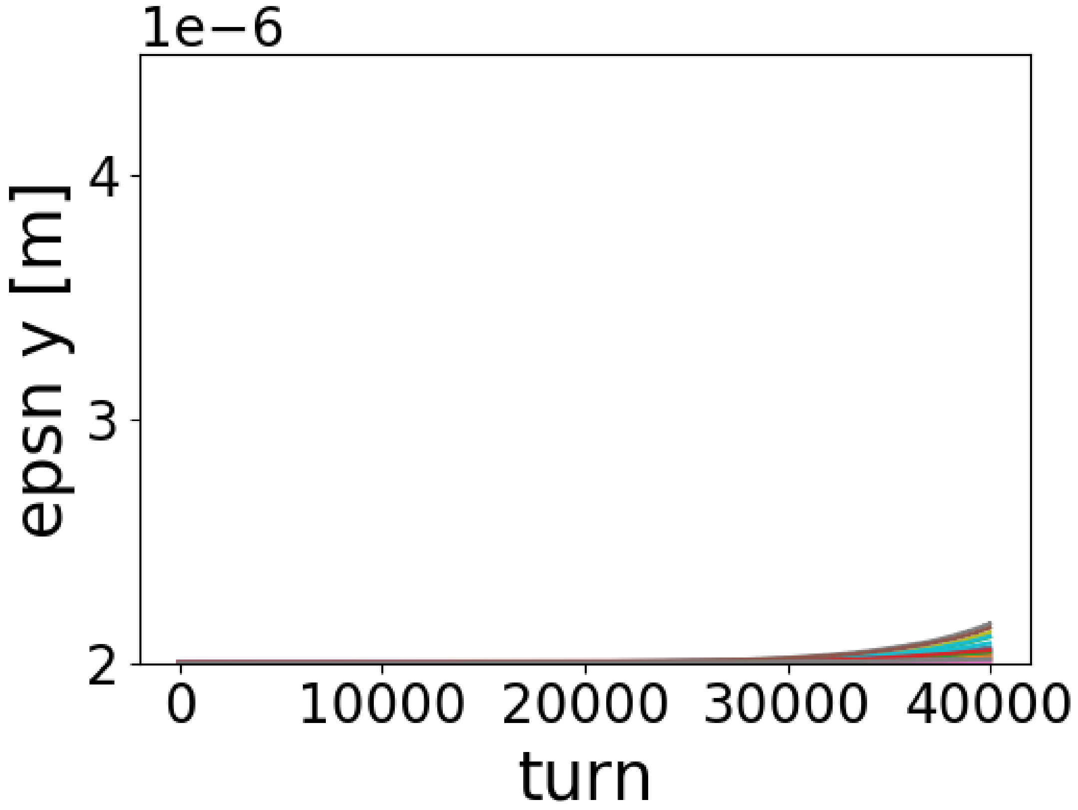

Batch 1

Batch 2

Bunch spacing 0 RF buckets

# Simulation results

N=2 × 1.0e9 $N_{ions}$/bunch | $\sigma_z$= 10 cm



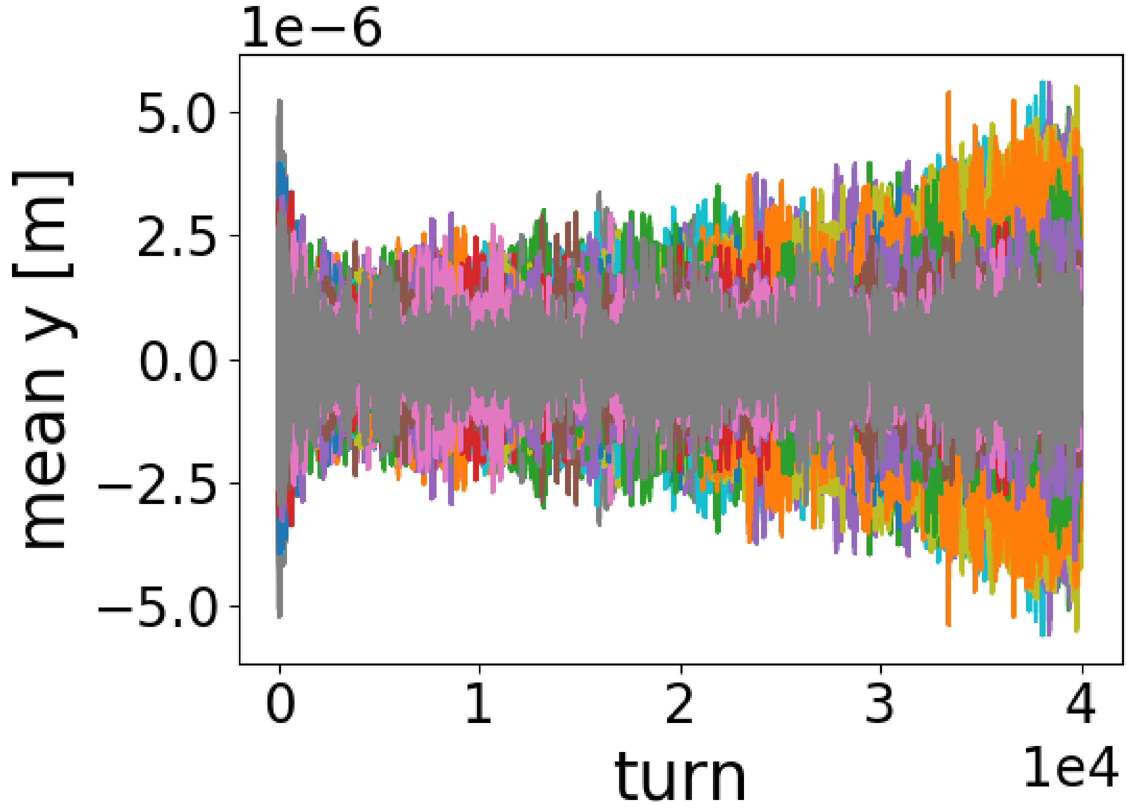

Batch 1

Batch 2

Bunch spacing 0 RF buckets

# Simulation results

N=2 × 1.0e9 $N_{ions}$/bunch | $\sigma_z$= 12 cm



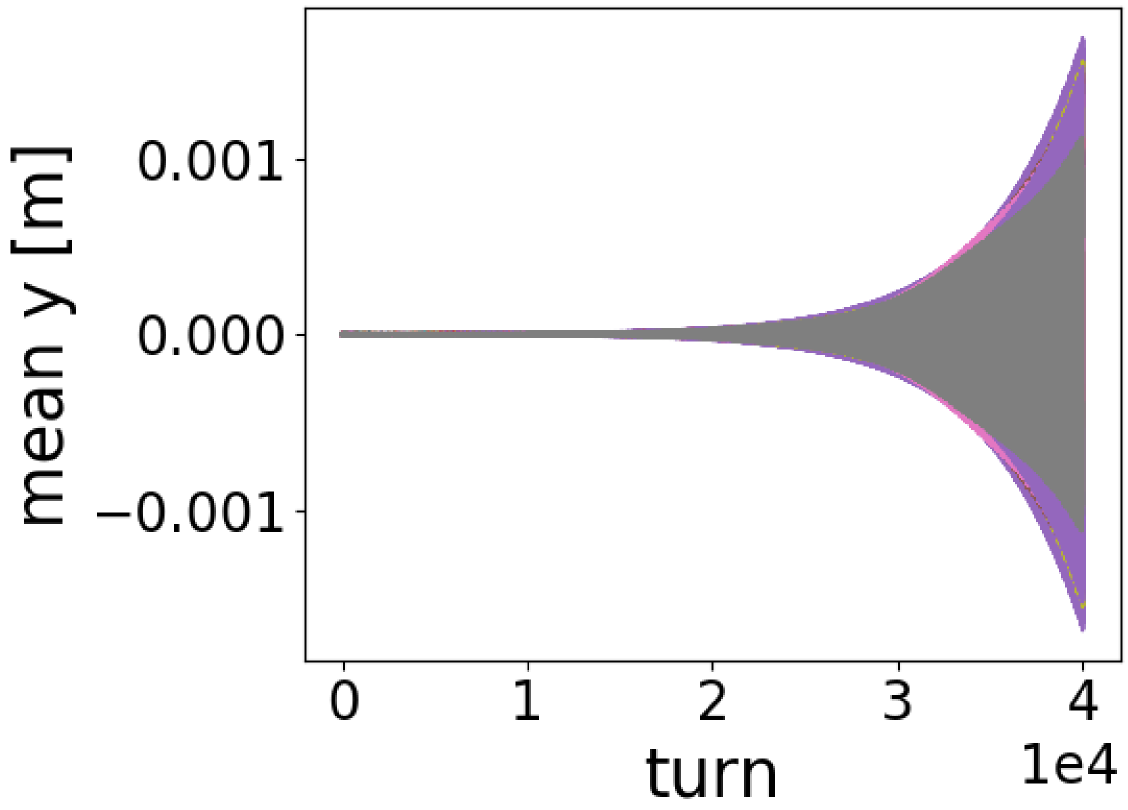

Batch 1

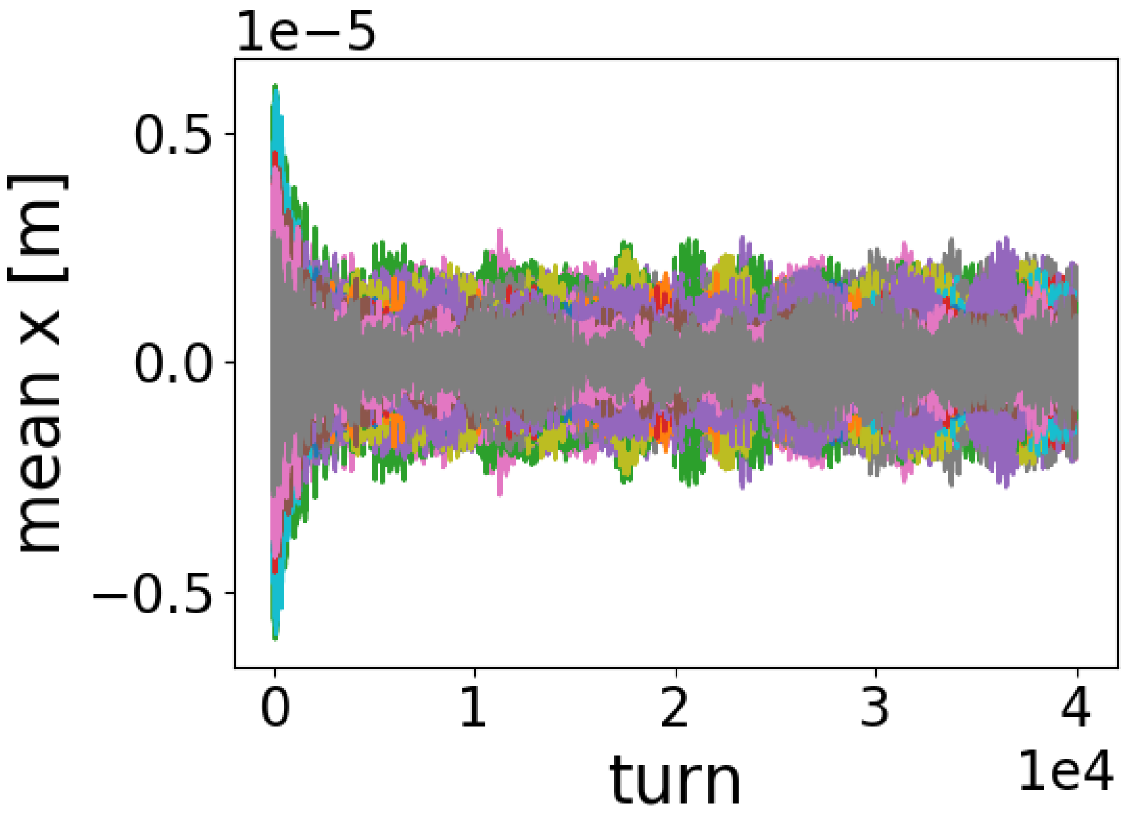
Batch 2

Bunch spacing 0 RF buckets

# Simulation results

| N=2 × 1.0e9 $N_{ions}$/bunch | $\sigma_z$= 8 cm |
|---|---|



# Overview

- Introduction
- Slip stacking parameters
  - Orbit and its effect on impedance
- Initial PyHEADTAIL simulations
- Summary

# Summary and next steps

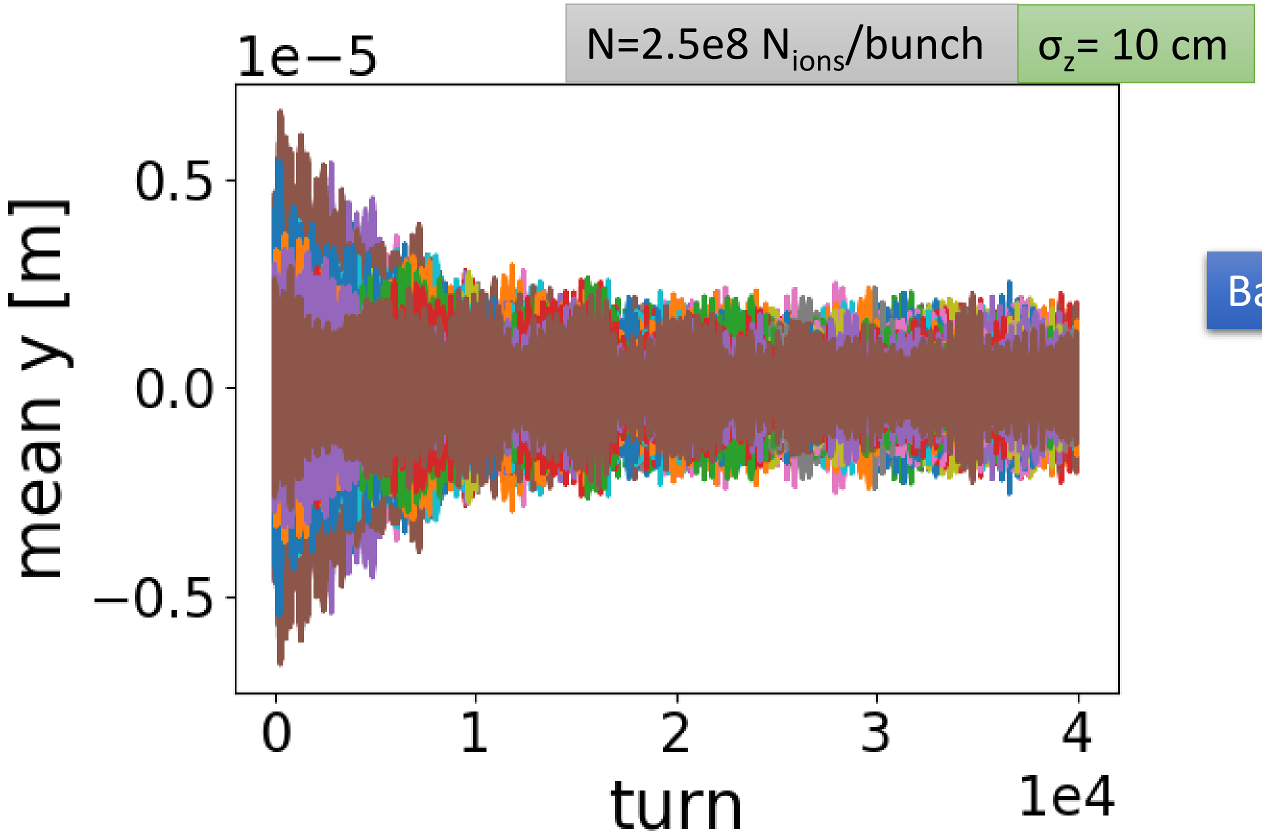
- The orbit deviation during MSS has been estimated
- The effect of orbit deviation on the beam coupling impedance has been investigated
- By using the present SPS multi-bunch model PyHEADTAIL simulations have been performed
  - Scan of the batch spacing and bunch spacing that will be experienced during slip-stacking simulating each configuration for 40k turns (very pessimistic)
    - Instability are observed only for intensity N=2 × 1.0e9 $N_{ions}$/bunch (2 x 4 times larger than nominal) and for short bunches ($\sigma_z$= 8 cm)
- Update the wall impedance model including the orbit deviation effect
- Include the constant term in the PyHEADTAIL simulations
- Include HOM from cavities and the low frequency resonances due to coupling with circuits (low frequency resonances could play an important role since we run without damper).

# Thank you for your attention

# References

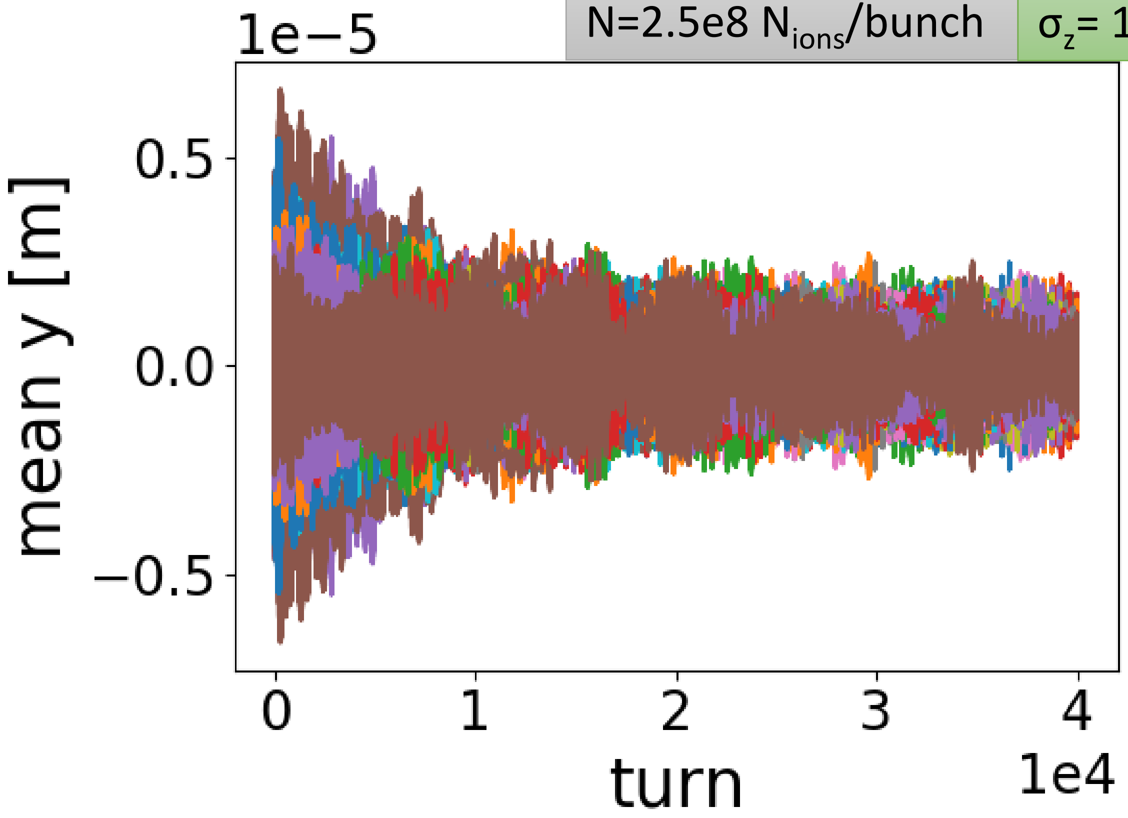

- D. Quartullo, T. Argyropoulos, A. Lasheen. *Momentum slip-stacking simulations for CERN SPS ION beam with collective effects*, HB 2018.
- T. Argyropoulos et al. *Momentum slip-stacking in CERN SPS for the ION beams*, IPAC 2019.
- H. Bartosik et al. *Recent beam performance achievements with the Pb-ion beam in the SPS for LHC physics runs*, IPAC 2019
- S. Heifets, A. Wagner, B. Zotter. *Generalized Impedances and Wakes in Asymmetric structures,* SLAC/AP-110, 1998.
- C. Zannini and G. Rumolo The transverse wake components. Presented at the 6th HDWG meeting in May 2011

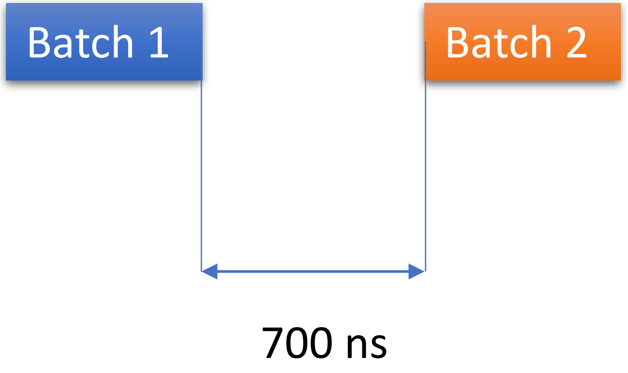
# Simulation results




# Simulation results

N=2.5e8 $N_{ions}$/bunch | $\sigma_z$= 10 cm

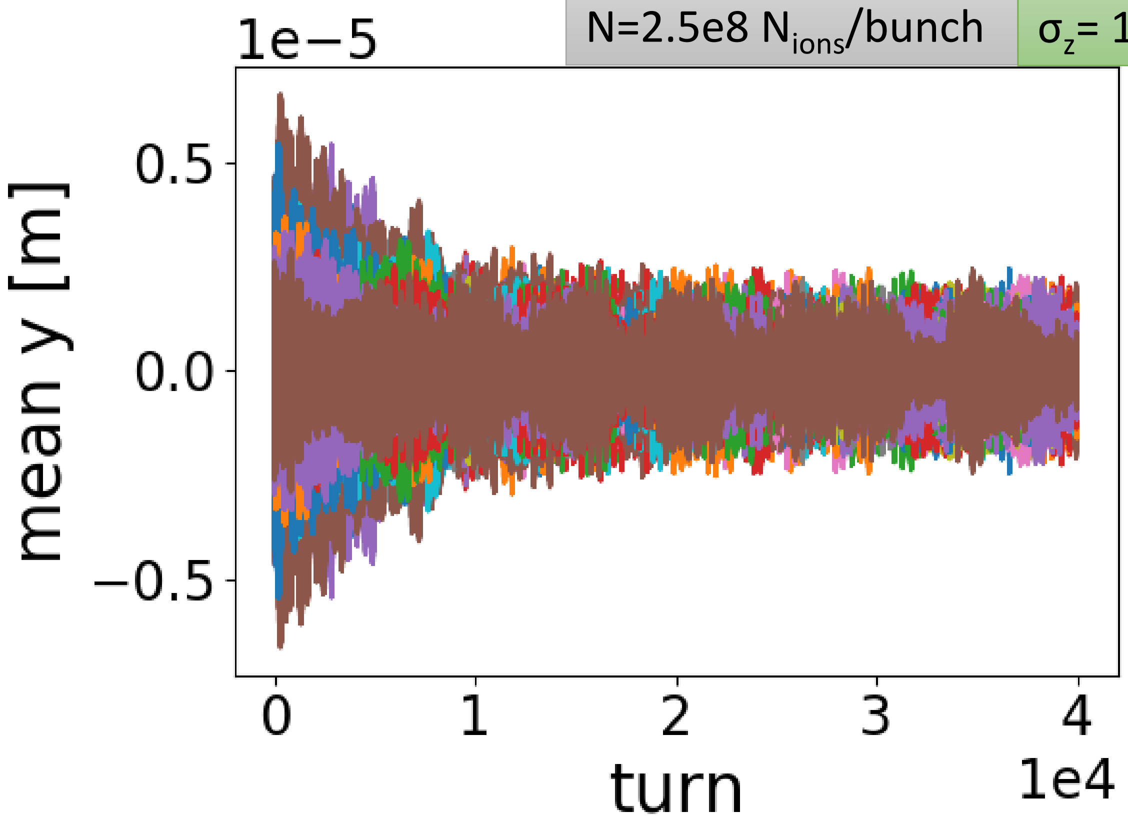


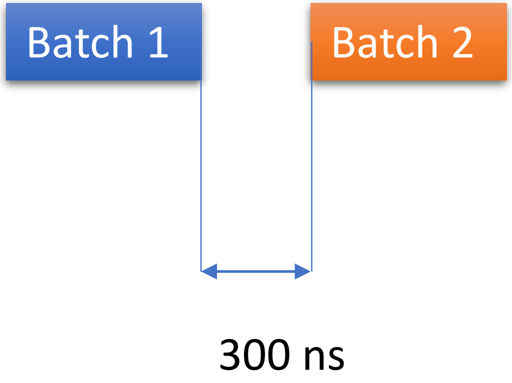



# Simulation results

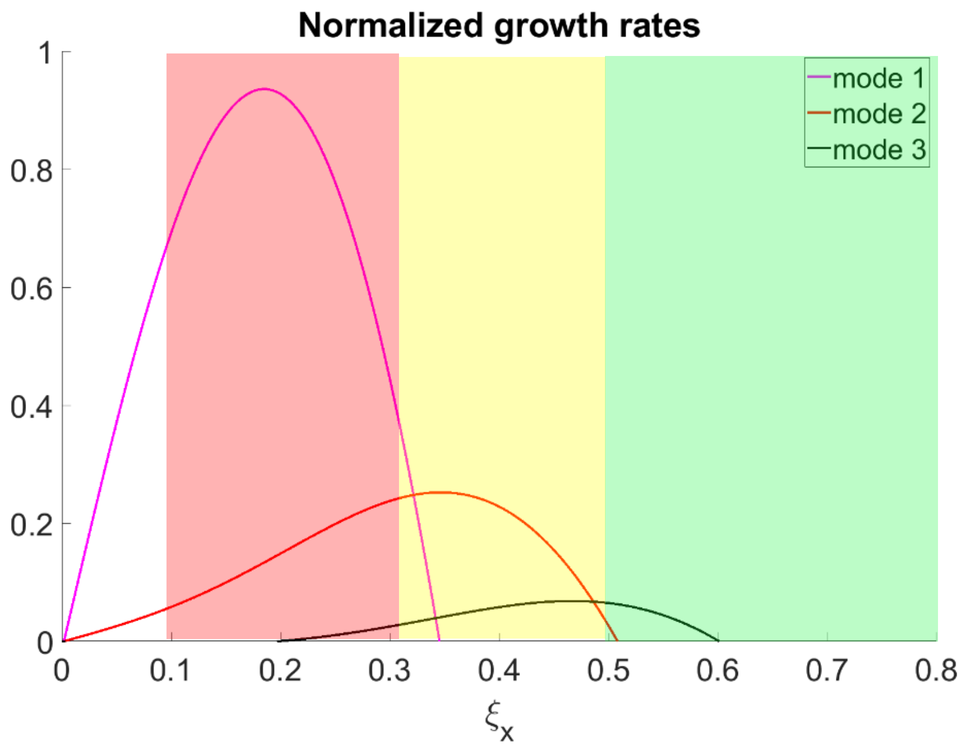
N=2.5e8 $N_{ions}$/bunch

$\sigma_z$= 10 cm



# Simulation parameters: impedance model




| MDs observations | |
|---|---|
| **Chromaticity** | **Beam Stability** |
| ξ=0.1 | Unstable mode1 |
| ξ=0.2 | Unstable mode1 |
| ξ=0.3 | Unstable mode1-2 |
| ξ=0.4 | Unstable mode2 |
| ξ=0.5 | Unstable mode2-3 |
| ξ=0.6 | Stable |

Instability behaviour with chromaticity reproduced with the SPS impedance model
Impedance source: combination of kicker and wall impedance

# Simulation results

N=2e9 $N_{ions}$/bunch | $\sigma_z$= 8 cm | Batch 1 | Batch 2 | Bunch spacing 0 RF buckets