
CERN

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Simulation Studies on E-Cloud Single-Bunch Instabilities at the LHC

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Acknowledgements: L. Mether, K. Paraschou

Outline

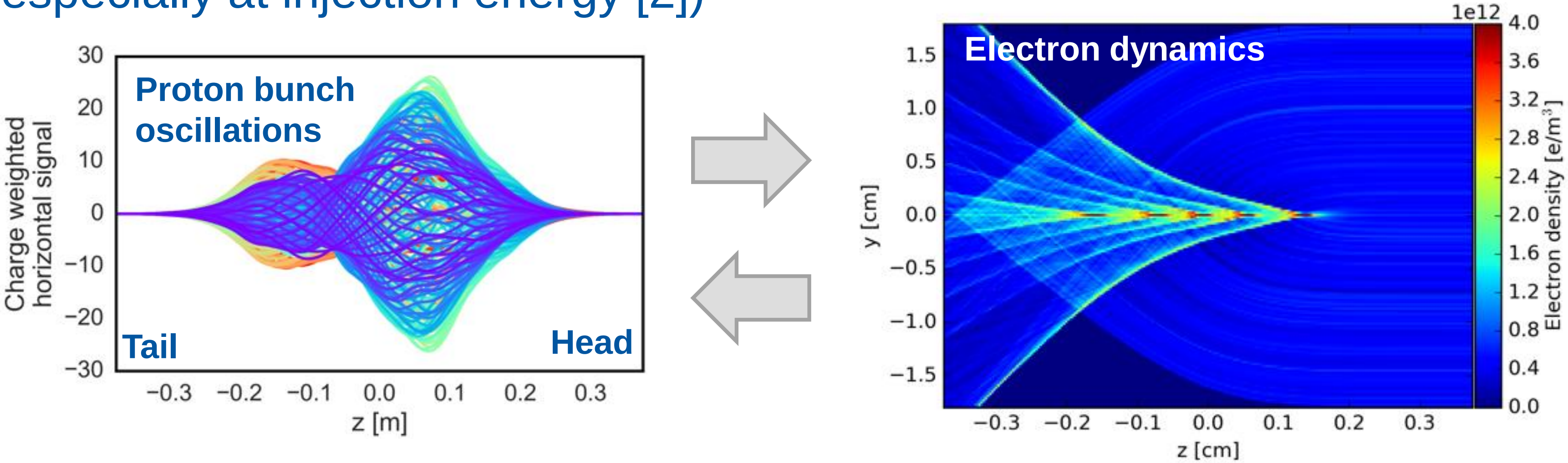
- Introduction
- Quadrupoles at Injection Energy
- Quadrupoles at Collision Energy
- Dipoles at Injection Energy
- Conclusions

Outline

- **Introduction**
  - Motivation
  - Simulation Parameters
- Quadrupoles at Injection Energy
- Quadrupoles at Collision Energy
- Dipoles at Injection Energy
- Conclusions

Introduction: Motivation

- During Run2 (2015-2018) the Large Hadron Collider (LHC) has been operated with the nominal bunch spacing of 25 ns
    - e-cloud develops in the beam chambers (heat loads measured on the beam screens of the superconducting magnets [1])
- The interaction of the circulating bunches with the e-cloud can trigger transverse head-tail instabilities (observed during LHC operation, especially at injection energy [2])

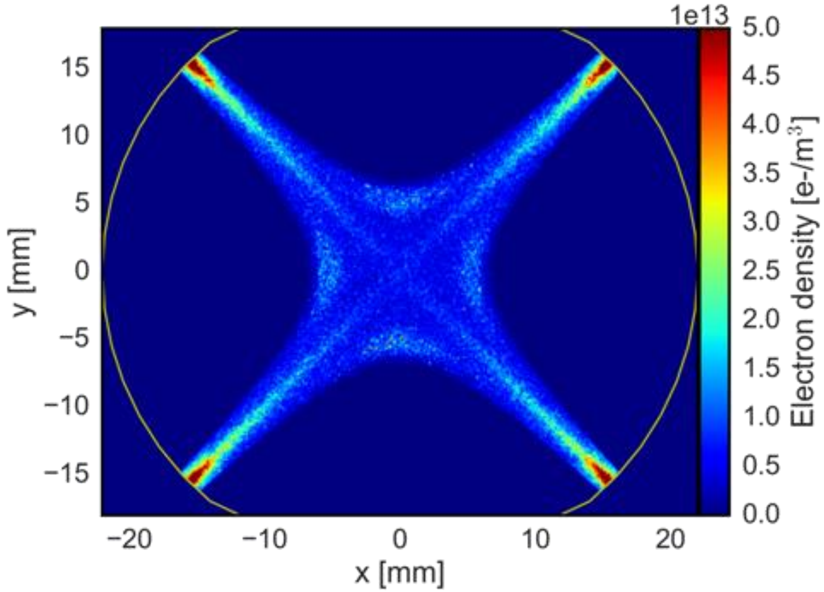


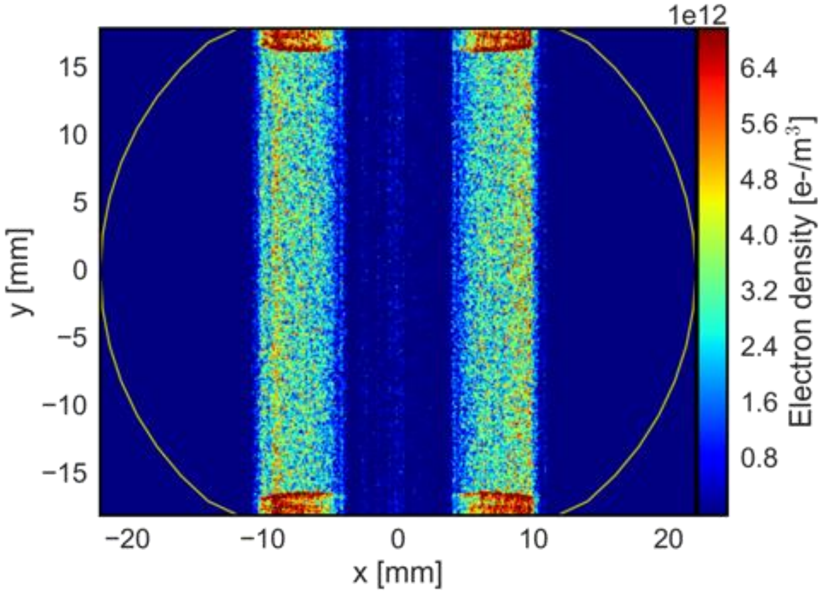
[1] G. Iadarola et al., "Analysis of the beam induced heat loads on the LHC arc beam screens during Run 2," CERN-ACC-NOTE-2017-0066, Dec 2017.

[2] X. Buffat et al., "Transverse instabilities," in Proc. 2019 Evian Workshop on LHC beam operation, Evian Les Bains, France, Jan 2019.

Introduction: Motivation

- For nominal bunch intensity electrons in the **arc quadrupoles** are expected to be the **strongest contributor** (quadrupolar field concentrates a large electron density at the beam location [3])





- For these reasons, particular attention is given to the study of instabilities driven by e-cloud in quadrupole magnets at injection energy
- Simulations for the dipoles were performed to check that they are not critical

[3] R. J. Macek et al., “Electron cloud generation and trapping in a quadrupole magnet at the Los Alamos proton storage ring,” Phys. Rev. Accel. Beams, vol. 11, no. 1, p. 010101, 2008.

Introduction: Motivation

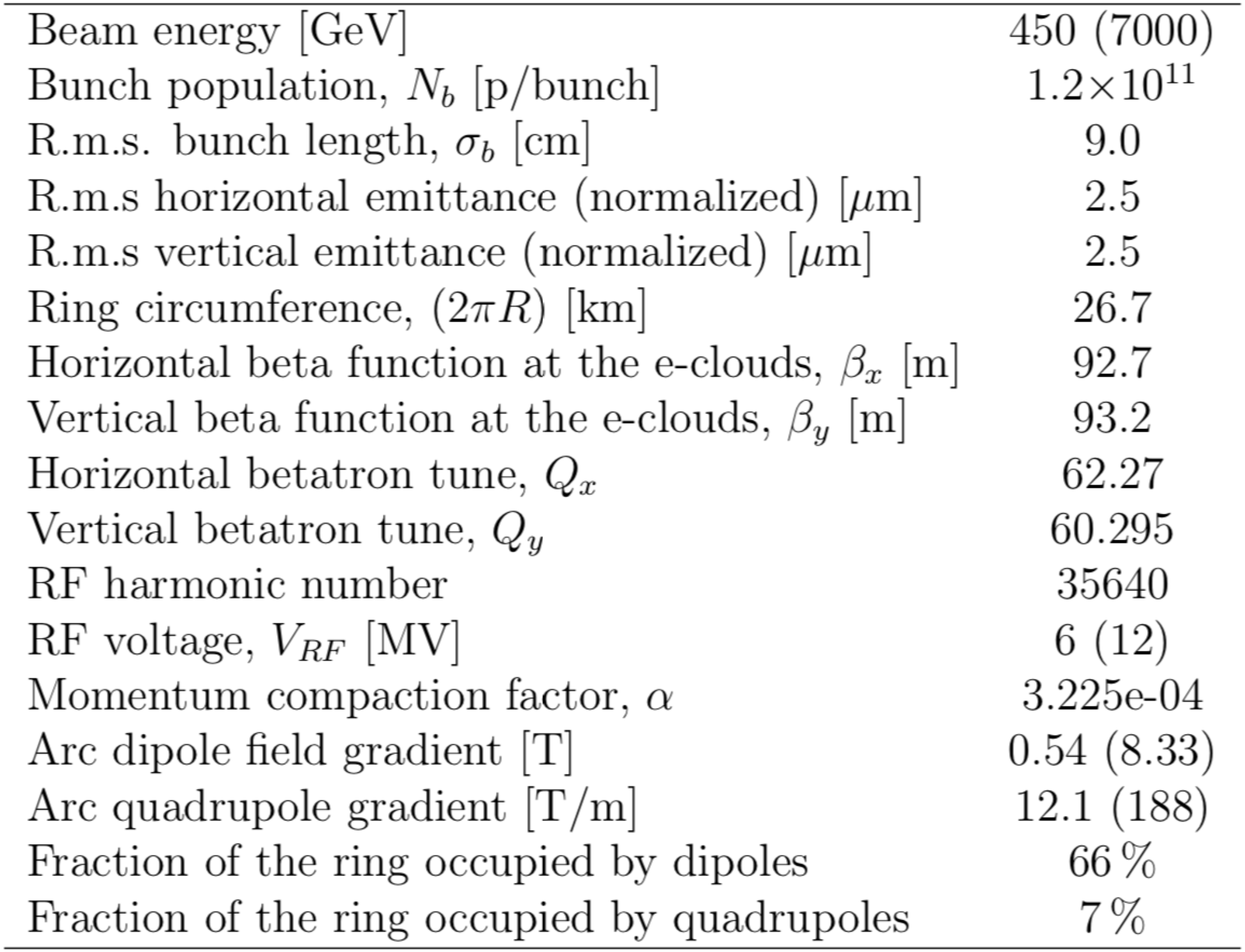
- We carried out a systematic study on these transverse instabilities and on their dependence on beam and machine configuration
  - based on macroparticle (MP) simulations performed with the PyECLOUD-PyHEADTAIL suite

- The simulations have significant requirements in terms of computing resources and time
  - performed on the High Performance Computing (HPC) cluster at INFN-CNAF (Bologna, Italy)

- The simulation results have also been used to benchmark a recently developed linearized approach for the study of e-cloud instability using the Vlasov method [4]

[4] G. Iadarola, L. Mether, N. Mounet, and L. Sabato, “Linearized method for the study of transverse instabilities driven by electron clouds,” Phys. Rev. Accel. Beams, vol. 23, p. 081002, Jul 2020.

Introduction: Simulation Parameters



Beam energy [GeV]	450 (7000)
Bunch population, N_b [p/bunch]	1.2×10^{11}
R.m.s. bunch length, σ_b [cm]	9.0
R.m.s horizontal emittance (normalized) [μm]	2.5
R.m.s vertical emittance (normalized) [μm]	2.5
Ring circumference, ($2\pi R$) [km]	26.7
Horizontal beta function at the e-clouds, β_x [m]	92.7
Vertical beta function at the e-clouds, β_y [m]	93.2
Horizontal betatron tune, Q_x	62.27
Vertical betatron tune, Q_y	60.295
RF harmonic number	35640
RF voltage, V_{RF} [MV]	6 (12)
Momentum compaction factor, α	3.225e-04
Arc dipole field gradient [T]	0.54 (8.33)
Arc quadrupole gradient [T/m]	12.1 (188)
Fraction of the ring occupied by dipoles	66 %
Fraction of the ring occupied by quadrupoles	7 %

For the parameters that differ between injection energy and collision energy the latter are indicated in parenthesis

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- **Quadrupoles at injection energy**
  - Convergence Studies
  - Bunch Length and RF voltage
  - Bunch Intensity
  - Transverse Emittance
  - Chromaticity and Damper
  - Octupoles
  - Frequency Analysis

- Quadrupoles at collision energy

- Dipoles at injection energy

- Conclusions

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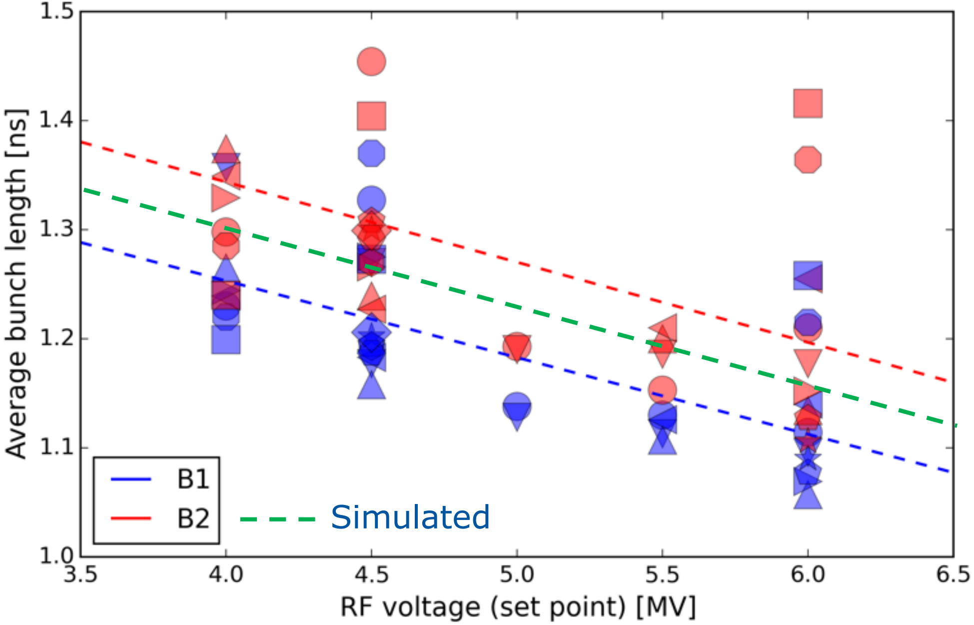
Quad at 450 GeV: Convergence Studies

- The possibility of **lowering the RF voltage at injection** is being considered to cope with RF power limitations
  - → An **extensive simulation study** has been conducted to address the impact on e-cloud driven instabilities
- In the simulations the **bunch length has been adapted to the RF voltage** following the **dependence measured at the LHC**
  - ○ In all simulations the longitudinal distribution is matched to the bucket

LHC measurements



H. Timko, presentation at LMC meeting, 5 Sep 2018

Quad at 450 GeV: Convergence Studies

Finding the numerical convergence for these simulations is not trivial

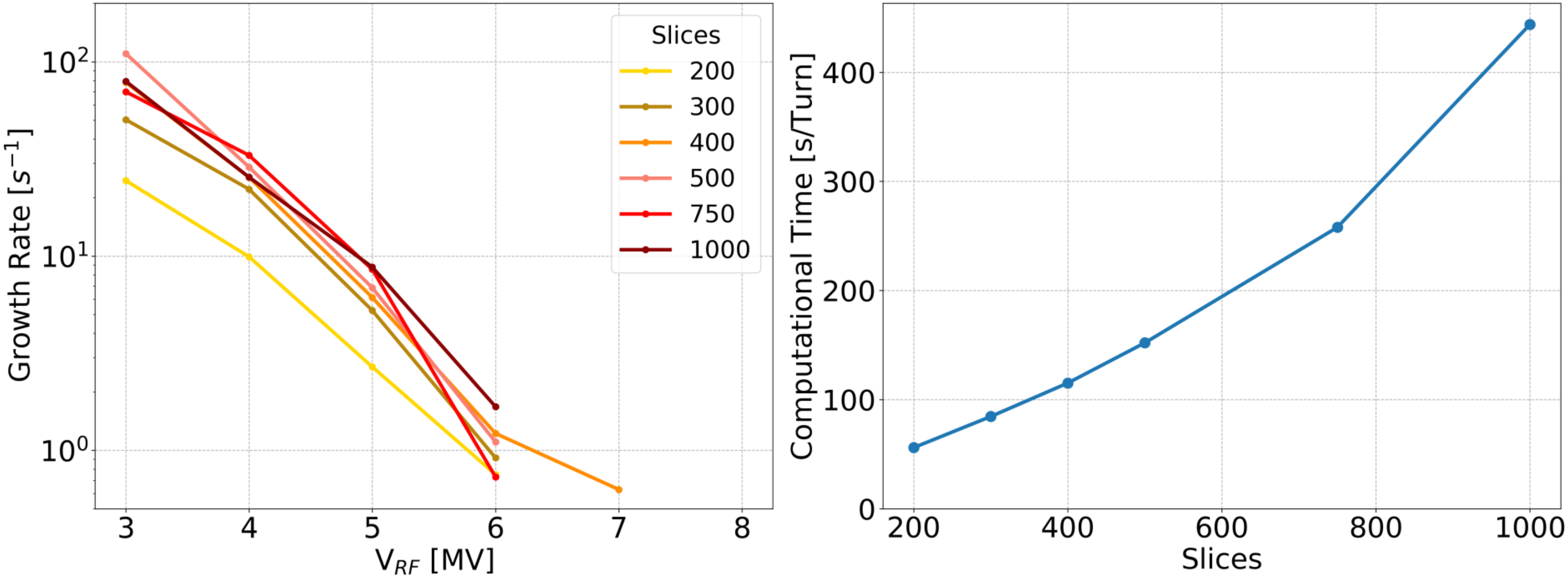
We performed an extensive study to find the correct numerical parameters:

1. the number of longitudinal slices along the bunch
2. the average number of MPs/slice used to model the proton bunch
3. the number of e-cloud interactions (kicks) along the ring
4. the number of MPs used to model the e-cloud at each interaction
5. the configuration of the transverse grids used to compute the fields generated by the beam and by the electrons through the PIC method [5])

[5] E. Belli**,** **“**PyPIC: the multigrid solver”, EC Meeting #32 – September 2, 2016

Quad at 450 GeV: Convergence Studies

Slices

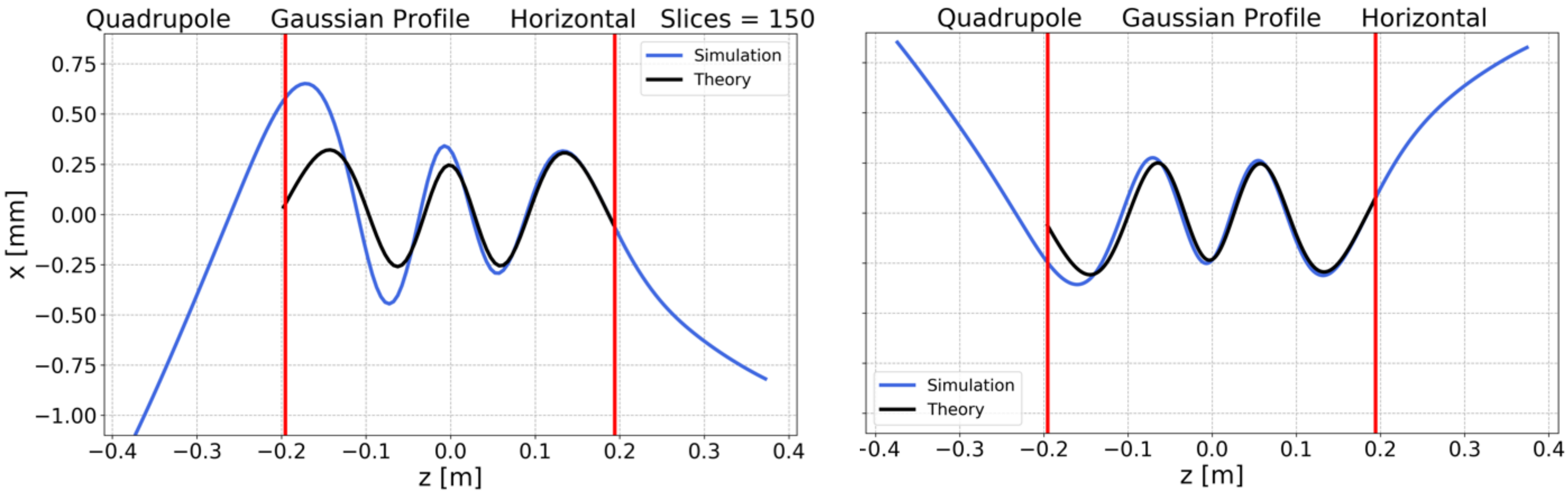


- numerical convergence is observed when the number of slices is larger than 300
- old setting 150 slices is not adequate
- the number of longitudinal slices has a strong impact on the required computational time

Quad at 450 GeV: Convergence Studies

To understand the origin of such requirements in terms of longitudinal slicing

- we analyzed the motion of individual electrons at small transverse amplitude [6]
- using a too small number of slices, the amplitude of the electron oscillation artificially increases along the bunch
- this effect is instead suppressed for a sufficiently large number of slices

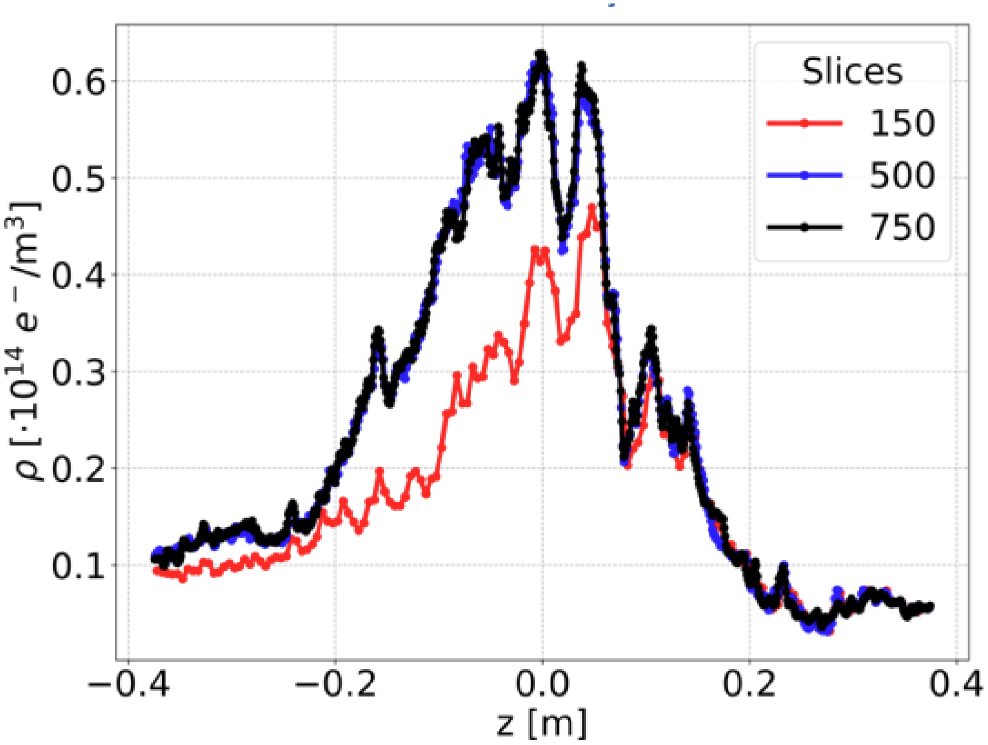


[6] L. Sabato, “Analysis of the electron motion within the Beam,” Presentation at the Electron Cloud Meeting, CERN, 22 February 2019.

Quad at 450 GeV: Convergence Studies

To understand the origin of such requirements in terms of longitudinal slicing

- when the number of slices is too small, the inaccurate modeling of the electron motion results in a reduced electron density at the beam location
- this effect tends to artificially stabilize the bunch



Quad at 450 GeV: Convergence Studies

Selected Numerical Parameters

Convergence scans performed on all numerical parameters allowed to identify the following configuration, useful for the future studies

Numerical Parameter	Chosen Value
Slices/bucket	500
MPs/Slice	2,500
Segments	8
e^- MPs	$5\text{x}10^5$
Transverse Grid	T_0 Internal grid coverage: 6.95 mm (10σ) Internal grid cell size: 0.139 mm (0.2σ) External grid cell size: 0.8 mm

More details in:

[7] L. Sabato, G. Iadarola, and L. Mether, “Numerical simulation studies on single-bunch instabilities driven by electron clouds at the LHC”, CERN-ACC-NOTE, to be published

Quad at 450 GeV: Convergence Studies

Summary

- 378 multi-core simulations
- Total computational time: ~ 32672 CPUcores*days
- It took months using the full CNAF cluster
- ~127 GB stored

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- Dipoles at injection energy

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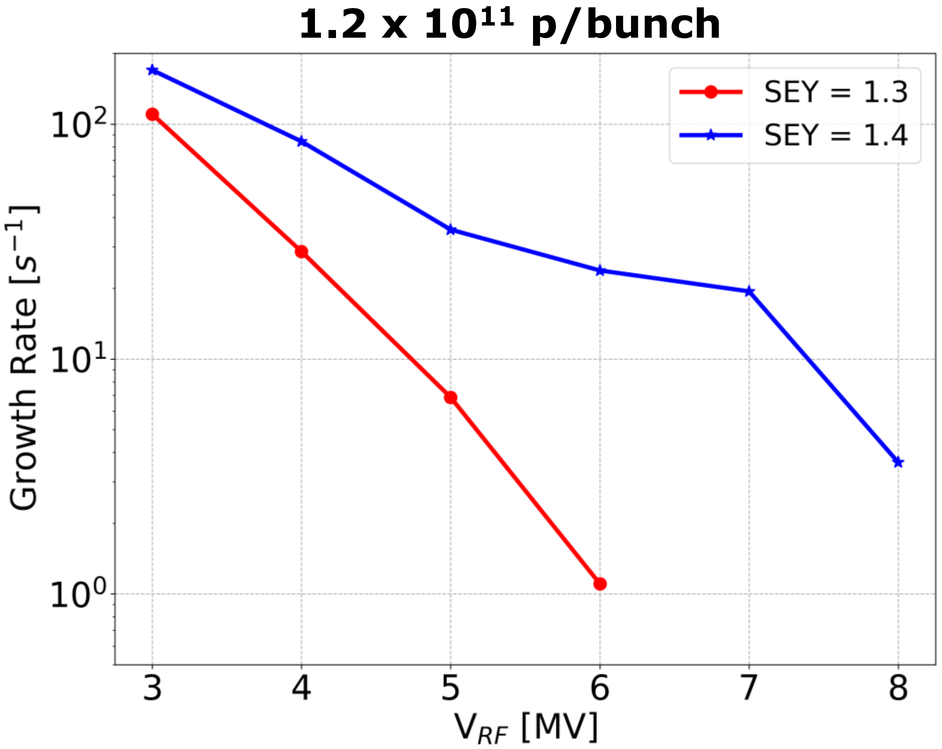
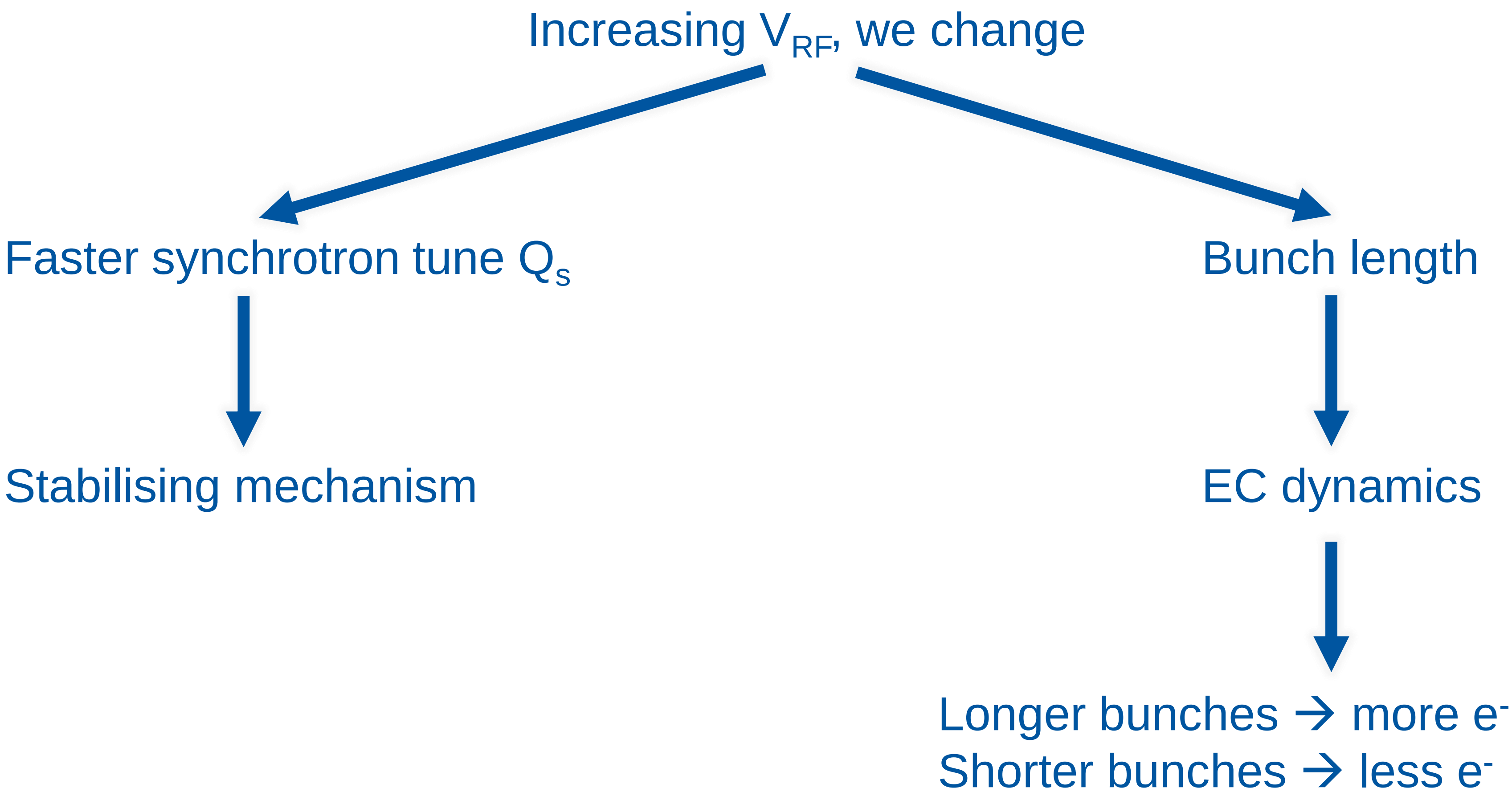
Quad at 450 GeV: Bunch Length and RF Voltage



- Increasing the SEY, the bunch is more unstable
- Increasing V_{RF} and decreasing the bunch length, the bunch is more stable

  → Which is dominant?

Quad at 450 GeV: Bunch Length and RF Voltage



Increasing V_{RF}, we change

Faster synchrotron tune Q_s

Stabilising mechanism

Bunch length

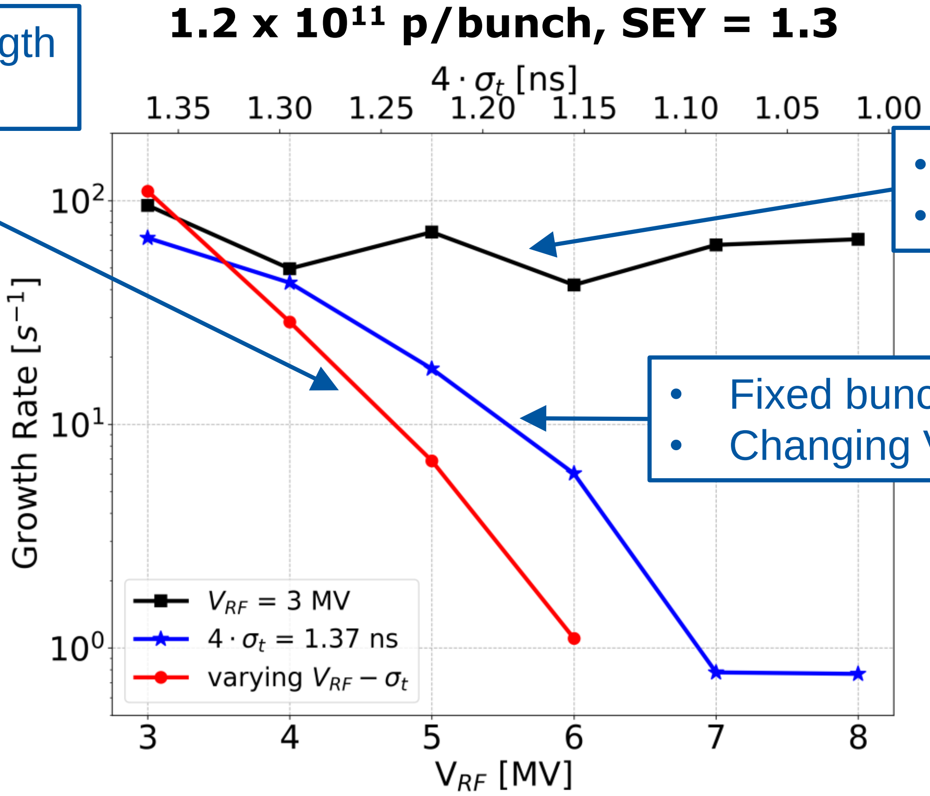
EC dynamics

Longer bunches → more e^-
Shorter bunches → less e^-

We study the two effects separately

Quad at 450 GeV: Bunch Length and RF Voltage

- Changing bunch length
- Changing V_{RF} (Q_s)



1.2×10^{11} p/bunch, SEY = 1.3

- Fixed V_{RF} (Q_s)
- Changing bunch length

- Fixed bunch length (same e^- pinch)
- Changing V_{RF} (Q_s)

→ the dominant stabilizing factor is the change of Q_s

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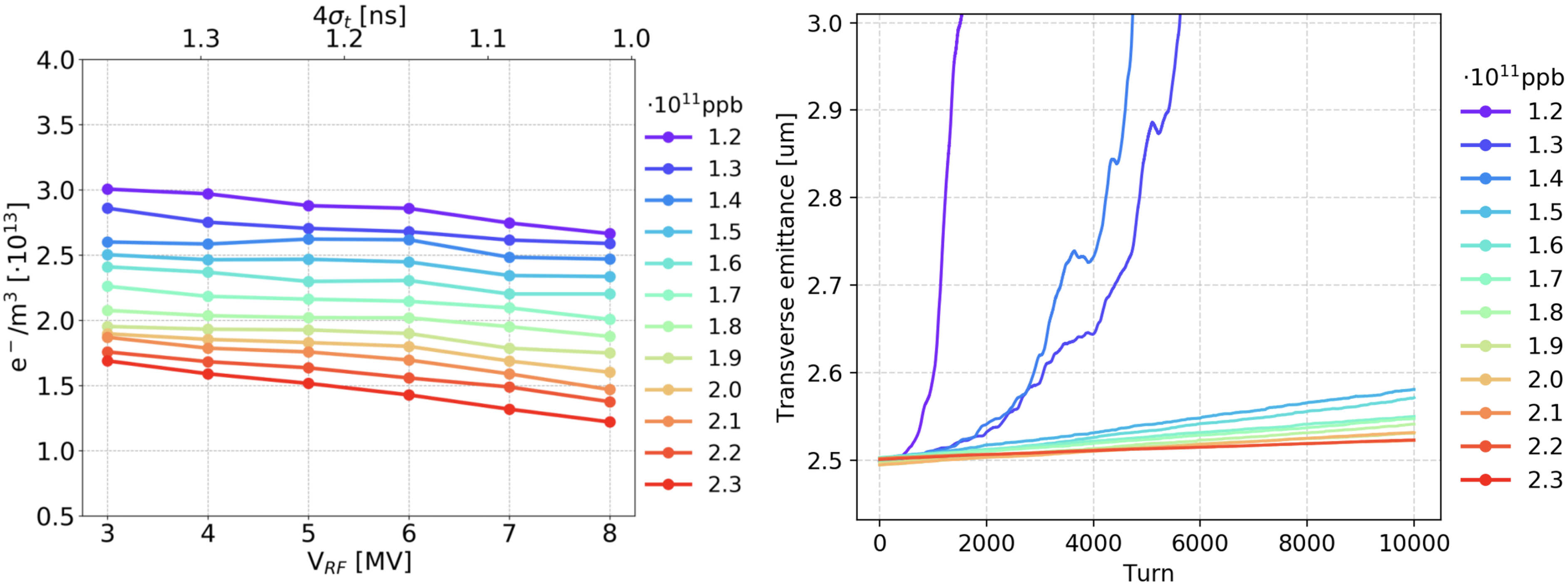
Quad at 450 GeV: Bunch Intensity



- The electron density close to the bunch, during the pinch, is significantly smaller for high intensity

- Over the simulated 10^4 turns, an instability could be observed only for the lowers values of the bunch intensity

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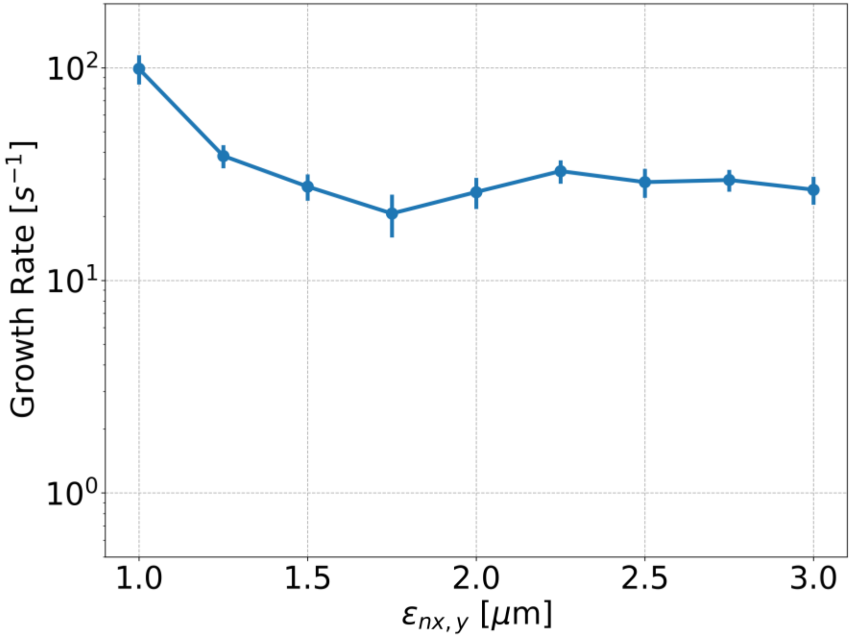
Quad at 450 GeV: Transverse Emittance

1.2×10^{11} p/bunch, SEY = 1.3, V_{RF} =6 MV



- The observed dependence is rather weak
- to distinguish the effect from statistical fluctuations due to the generation of the bunch distribution, we needed to simulate each case twenty times

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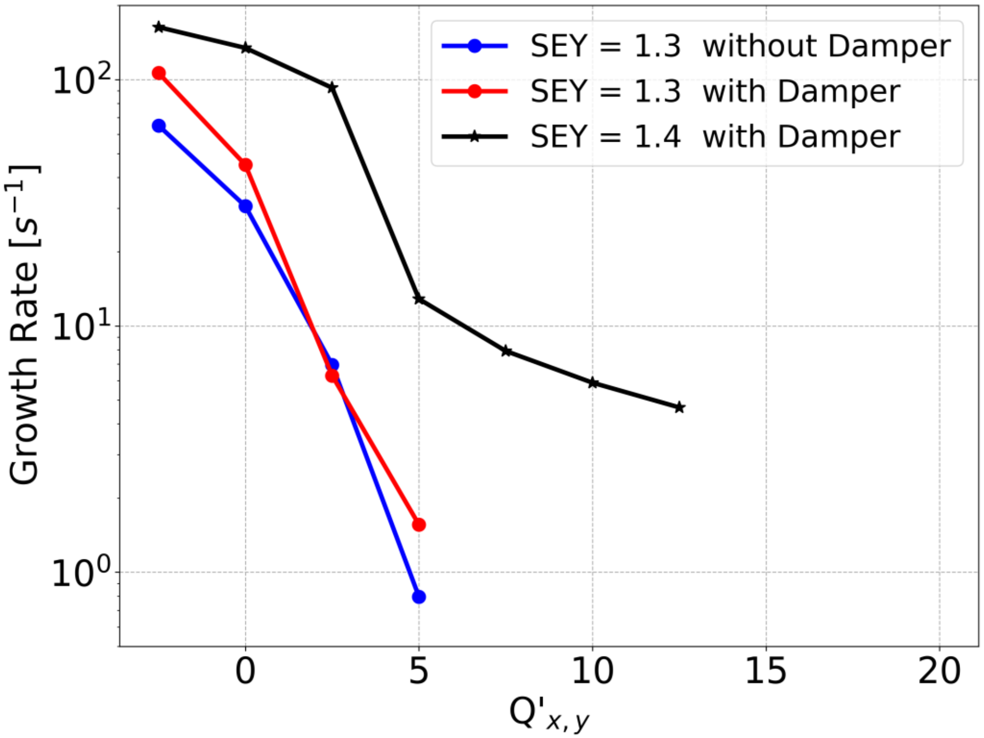
Quad at 450 GeV: Chromaticity and Damper



- 1.2 x 10^{11} p/bunch
- V_{RF} = 4 MV
- SEY = 1.3 – 1.4
- Feedback damping time is 10 turns

- The instability is **strongly mitigated** by increasing the **chromaticity** settings
- The **transverse feedback** is **mostly ineffective** → cannot damp **intra-bunch motion**

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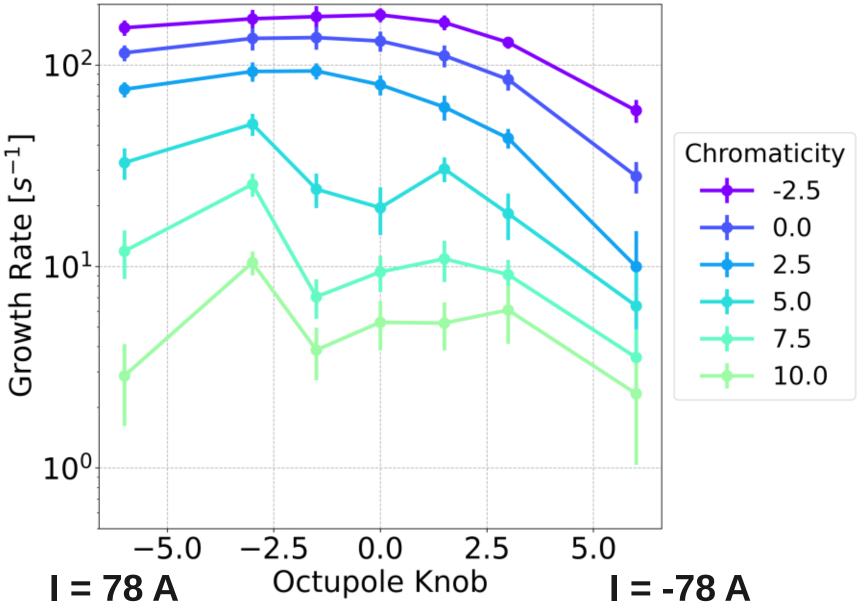
Quad at 450 GeV: Octupoles



1.2×10^{11} p/bunch
V_{RF} = 4 MV
SEY = 1.4
Damper = 10 turns

- For the case of LHC intensity the **octupole current** has also been scanned
  - → **less effective** compared to **chromaticity**
- To mitigate dependence on initial random seed (bunch MP coordinates) we repeat each simulation 20 times
- Reveals non-trivial dependence on octupole current for high chromaticity
  - → The dependence on the knob value is non monotonic
  - → Large values of the octupole knob tend to reduce the instability growth rate

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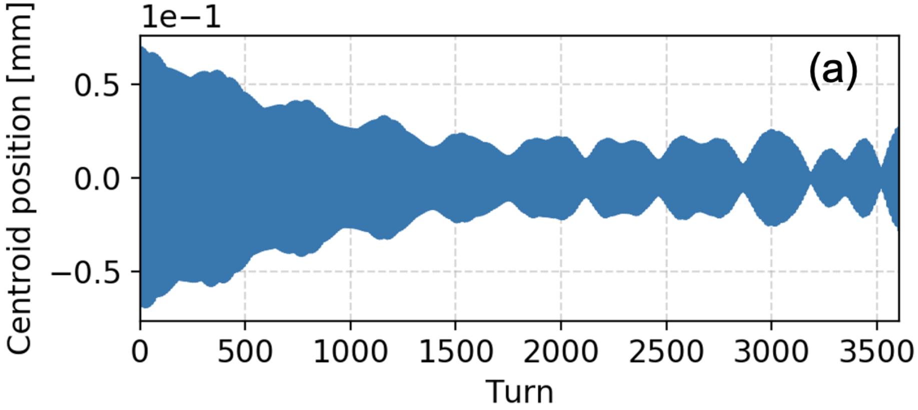
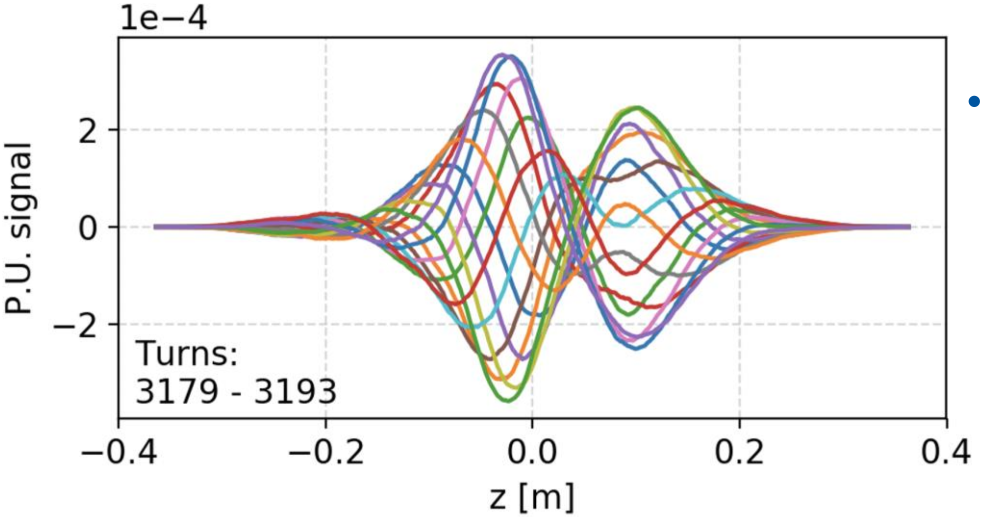
Quad at 450 GeV: Frequency Analysis

1.2 x 10^{11} p/bunch, SEY = 1.3, V_{RF} = 5 MV

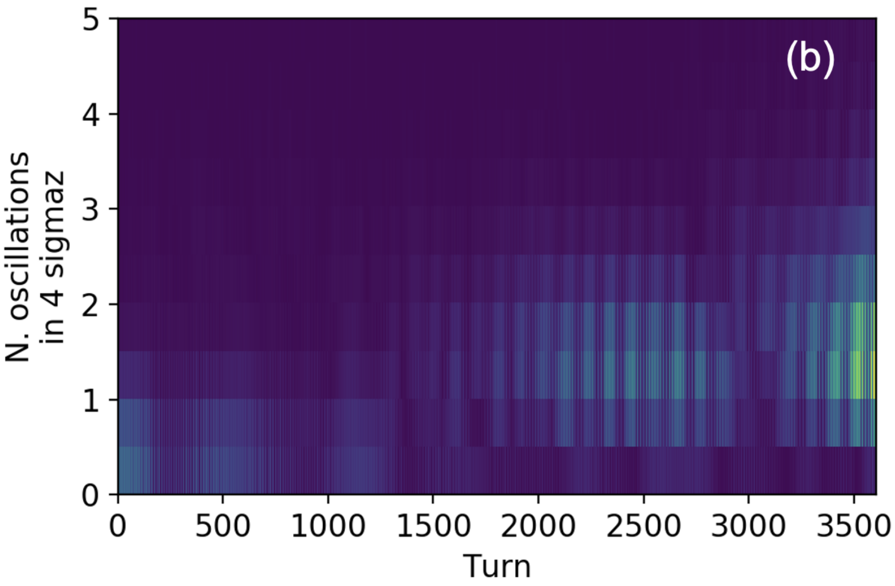


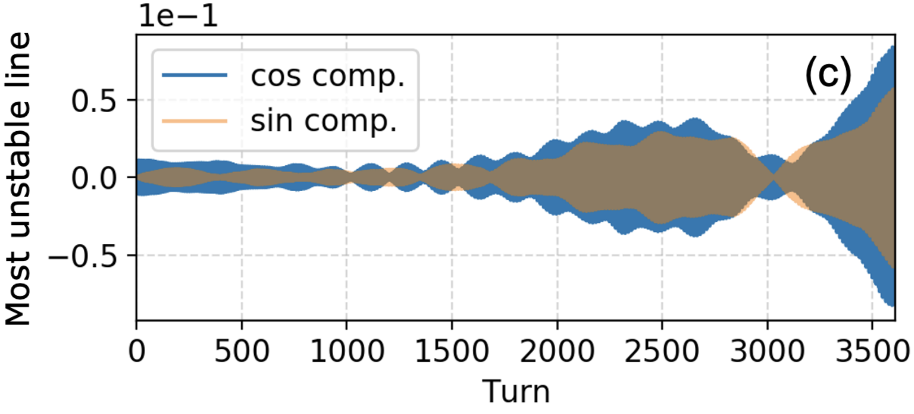
- The instabilities are often characterized by the absence of a clear growth in the motion of the bunch centroid



- The instabilities are instead revealed by the development of a strong intrabunch motion and by fast transverse emittance blow-up

Quad at 450 GeV: Frequency Analysis



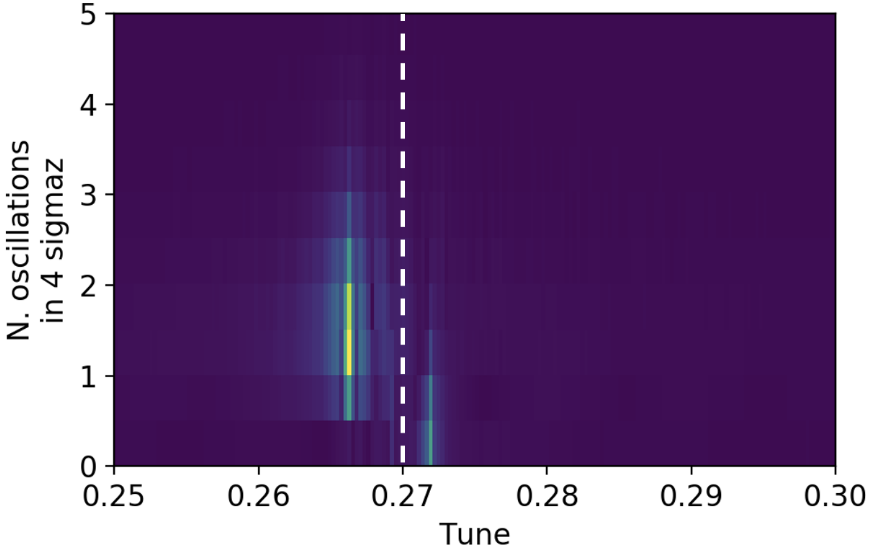


- Applying a Fourier transform to the position along the bunch at each turn:
  - the spectral line corresponding to a rigid oscillation of the bunch ($N_{osc} = 0$) shows indeed a decreasing amplitude
  - instead, an increase in amplitude is observed on other spectral lines ($0.5 < N_{osc} < 2.5$)

- In the time evolution of the sine and cosine components of the strongest spectral line, the development of the instability is clearly visible

Quad at 450 GeV: Frequency Analysis

By performing a double Fourier transform with respect to the intrabunch position and with respect to time, we obtain the 2D spectrum:

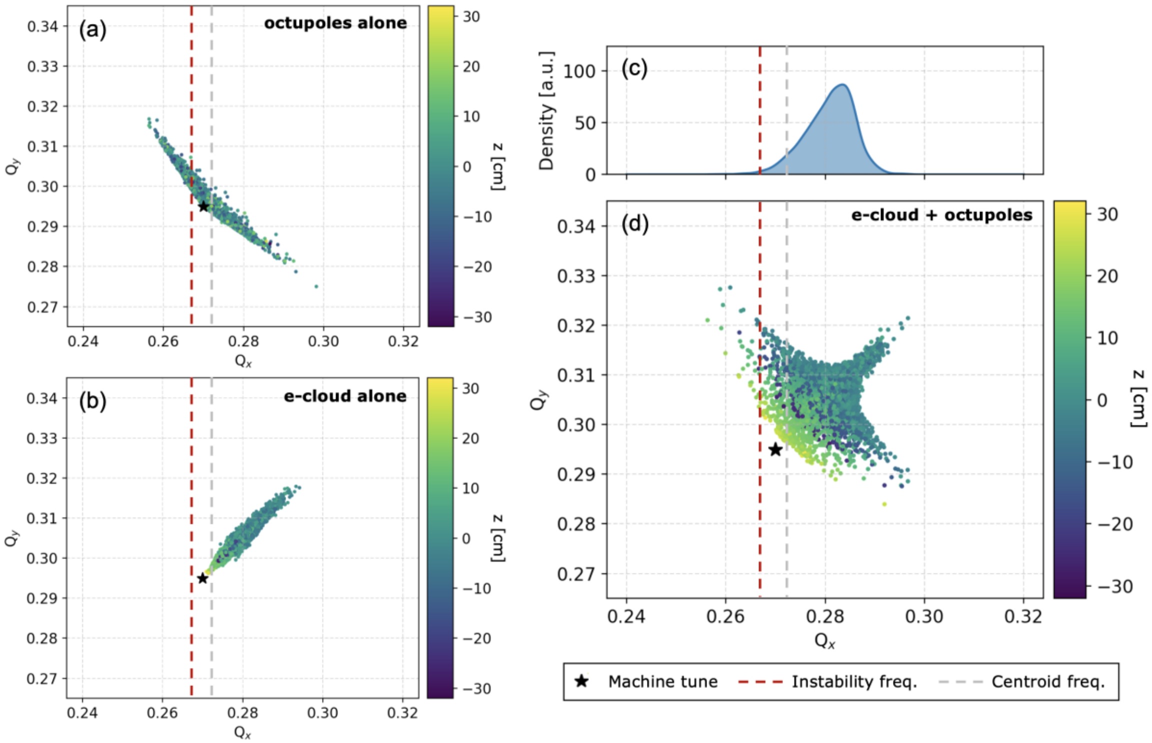


- The vertical dashed line indicates the unperturbed betatron tune
- A positive tune shift is observed on the rigid bunch line ($N_{osc} = 0$)
- The unstable lines ($0.5 < N_{osc} < 2.5$) show a negative tune shift
- Recent work based on a linearized model of the e-cloud has shown that the instability is generated by a Transverse Mode Coupling mechanism [4]

[4] G. Iadarola, L. Mether, N. Mounet, and L. Sabato, “Linearized method for the study of transverse instabilities driven by electron clouds,” Phys. Rev. Accel. Beams, vol. 23, p. 081002, Jul 2020.

Quad at 450 GeV: Frequency Analysis

Having identified the frequency of the unstable line is useful to explain why the octupoles are ineffective for suppressing the instability



- Octupoles alone: the tune spread overlaps with the unstable line
- e-cloud alone: positive detuning both in the horizontal and in the vertical plane

- Octupoles + e-cloud: due to the positive detuning introduced by the e-cloud, the particle density in the tune space at frequencies close to the unstable line is very low, rendering Landau damping ineffective

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- **Quadrupoles at Collision Energy**
- Dipoles at Injection Energy
- Conclusions and Future Developments

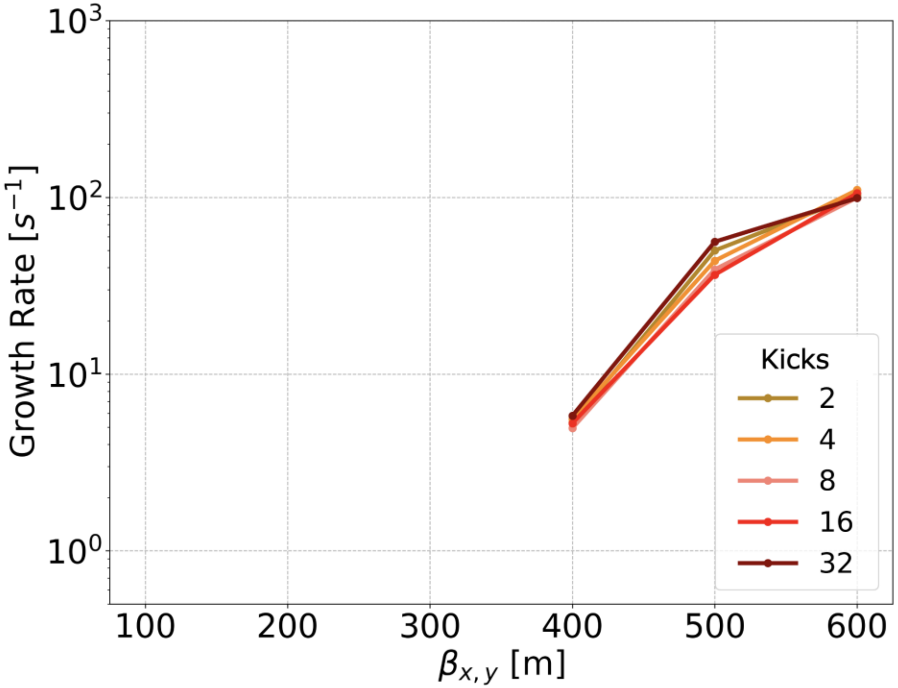
Quadrupoles at Collision Energy

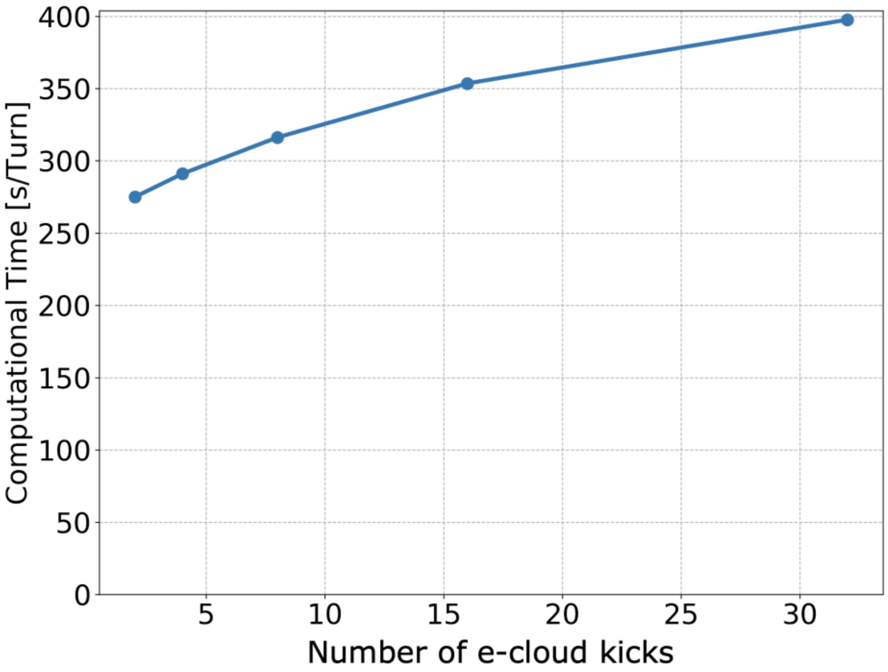
- From previous simulation studies, instabilities driven by e-cloud in the LHC are expected to be less critical at collision energy compared to injection energy [8]

- We have performed a set of convergence scans for this simulation scenario, studying in particular the dependence of the instability growth rate on the beta function at the e-cloud interactions (for simplicity the beam is assumed to be round at those locations)

[8] A. Romano, “Electron cloud formation in CERN particle accelerators and its impact on the beam dynamics,” Darmstadt, Tech. U. : 2018-04-30, 2018.

Quadrupoles at Collision Energy





- No instabilities are observed over the simulated 2×10^4 turns for values of the beta function below 400 m
- For all scenarios considered for LHC operations and for the HL-LHC upgrade the average beta function in the arcs is well below such a value

Quadrupoles at Collision Energy

Selected Numerical Parameters

Numerical Parameter	Chosen Value
Slices/bucket	750
MPs/Slice	2,500
Segments	4
e^- MPs	$5\mathrm{x}10^5$
Transverse Grid	T_0 Internal grid coverage: 10σ Internal grid cell size: 0.2σ External grid cell size: 0.8 mm

More details in:

[7] L. Sabato, G. Iadarola, and L. Mether, “Numerical simulation studies on single-bunch instabilities driven by electron clouds at the LHC”, CERN-ACC-NOTE, to be published

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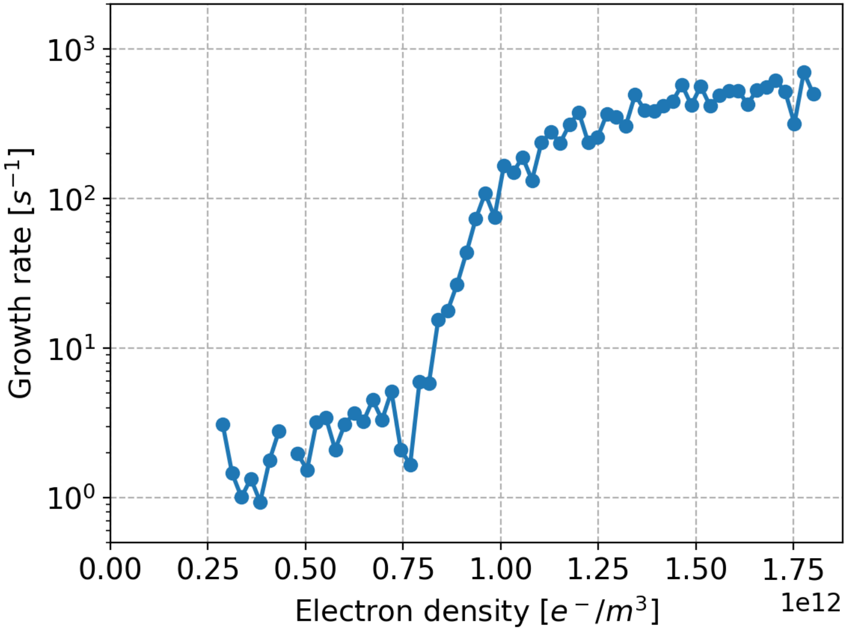
- **Dipoles at Injection Energy**
- Conclusions

Dipoles at Injection Energy



- No instability is observed for electron densities below 2.5×10^{12} e^-/m^3
- For densities 0.25×10^{12} e^-/m^3 - 0.75×10^{12} e^-/m^3: slow instability is observed
- For densities above 0.75×10^{12} e^-/m^3: a much stronger instability appears

- The electron densities predicted in the dipoles from buildup simulations are below 0.1×10^{12} e^-/m^3 (SEY < 1.4 and bunch intensity > 10^{11} p/bunch)
  - "dipole instabilities" are expected less critical compared to "quadrupole instabilities"
  - For bunch intensity < 10^{11} p/bunch, the electron density at the beam location can be higher and "dipole instabilities" are possible, as observed experimentally at LHC [9]

[9] A. Romano et al, "Electron cloud buildup driving spontaneous vertical instabilities of stored beams in the Large Hadron Collider," Phys. Rev. Accel. Beams, vol. 21, p. 061002, Jun 2018.

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- Quadrupoles at Collision Energy
- Dipoles at Injection Energy
- **Conclusions**

Conclusions

- Instabilities driven by e-cloud at the LHC have been studied by means of numerical simulations
- Particular care has been given to the study of instabilities due to the e-cloud in the quadrupole magnets at injection energy
  - The numerical parameters of the simulations have been defined through extensive convergence studies (useful guidelines for future simulation campaigns)
  - The stability properties have been studied in particular with respect to the RF voltage settings: the beam is more stable for higher voltage as a result of the faster synchrotron motion
  - Higher bunch intensity mitigates the instability: the electron density is lower
  - A bunch-by-bunch damper is unable to suppress the instability due to the presence of a strong intrabunch motion
  - Octupole magnets are ineffective: the detuning forces due to the e-cloud tend to move the tune spread away from the frequency of the observed unstable mode
  - The instability can be suppressed using large chromaticity settings

Conclusions

- Simulations have also been performed for instabilities driven by e-cloud in the quadrupoles at collision energy
  - confirm no instability is expected at collision energy in the operational conditions foreseen for LHC and HL-LHC

- Instabilities driven by e-cloud in dipole magnets at injection energy were also simulated
  - confirm that they are not expected to be critical for realistic values of the bunch intensity and of the SEY

Thanks for your attention

Spares

Introduction: Description of the Simulation Setup

- The bunch is modelled by a set of MPs
- Longitudinal and transverse beam dynamics are simulated using modules from the PyHEADTAIL code
- Smooth approximation (constant beta functions) is used for the transverse dynamics
- Longitudinal dynamics is lumped at a single location of the ring
- e-cloud is modelled by a set of thin interactions installed along the ring
  - at each interaction the electron dynamics is simulated using the PyECLOUD code, based on the bunch distribution provided by PyHEADTAIL
- The bunch is longitudinally sliced, each slice defining a time step for the simulation of the electron dynamics
- For each slice, the forces generated by the bunch and by the electrons are computed using the Particle In Cell (PIC) method to solve a 2D Poisson problem

Introduction: Description of the Simulation Setup

- The electric field generated by the beam and by the electron themselves is taken into account for the simulation of the electron motion, while the electric field generated by the electron distribution alone defines the transverse kicks applied on the bunch MPs at each e-cloud interaction
- e-cloud MPs at each interaction are initialized using the charge, position and momenta of MPs saved from PyECLOUD buildup simulations, performed with a rigid beam for the same scenario
- electron distribution from a single snapshot of the buildup simulation shows a significant numerical noise, due to the limited number of MPs.
    - it would introduce numerical artifacts in the corresponding instability simulation
    - the MP set used in the instability simulation is obtained by merging MP sets from several snapshots of the e-cloud at saturation, as obtained from the buildup simulation
    - left-right and top-bottom symmetry of the distribution is also enforced by mirroring the MP distribution

Introduction: Description of the Simulation Setup

- Parallel computing is regularly exploited by simulating different e-cloud interactions on different computing cores, using the PyPARIS parallelization layer
    - typically a number of cores equal to the number of e-cloud interactions is utilized

- Positions and statistical momenta of the bunch and of the slices are recorded by PyHEADTAIL at each revolution
- To characterize the instability, a Fourier transform is applied to the position along the bunch at each turn and the instability growth rate is measured by applying an exponential fit on the most unstable spectral line
- Based on the computational time, we had to limit the simulation time window to 20,000 turns, which allows detecting instabilities with growth rates in the order of 0.5 s^{-1} (corresponding to a risetime of two seconds) or faster.

Quad at Inj: Convergence Studies

Force interpolation

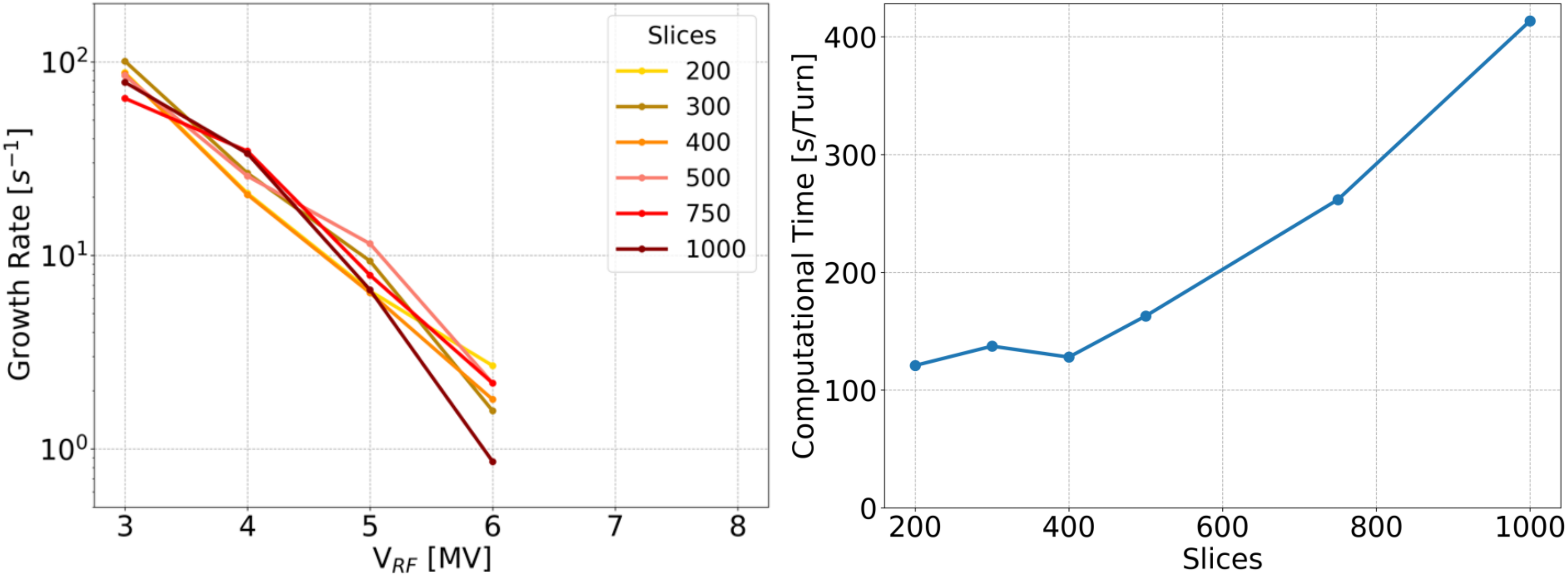
- In PyECLOUD each time-step is divided in a certain number of substeps in which the electric fields are kept constant
  - this is convenient to handle the very fast cyclotron motion of the electrons in the presence of strong magnetic fields
  - in instability simulations this is done based on the input parameter Dt_{REF} which defines the target size of these substeps

- Recently the possibility of updating also the electric fields at each substep has been introduced in PyECLOUD (as of version 8.3.0)

- This is done without performing the full PIC recalculation, but simply re-interpolating the field map at the new MP location at each substep

Quad at Inj: Convergence Studies

Force interpolation



- This is found to significantly improve the convergence properties, but implies some cost in terms of computing time, especially for small numbers of slices

Quad at Inj: Convergence Studies

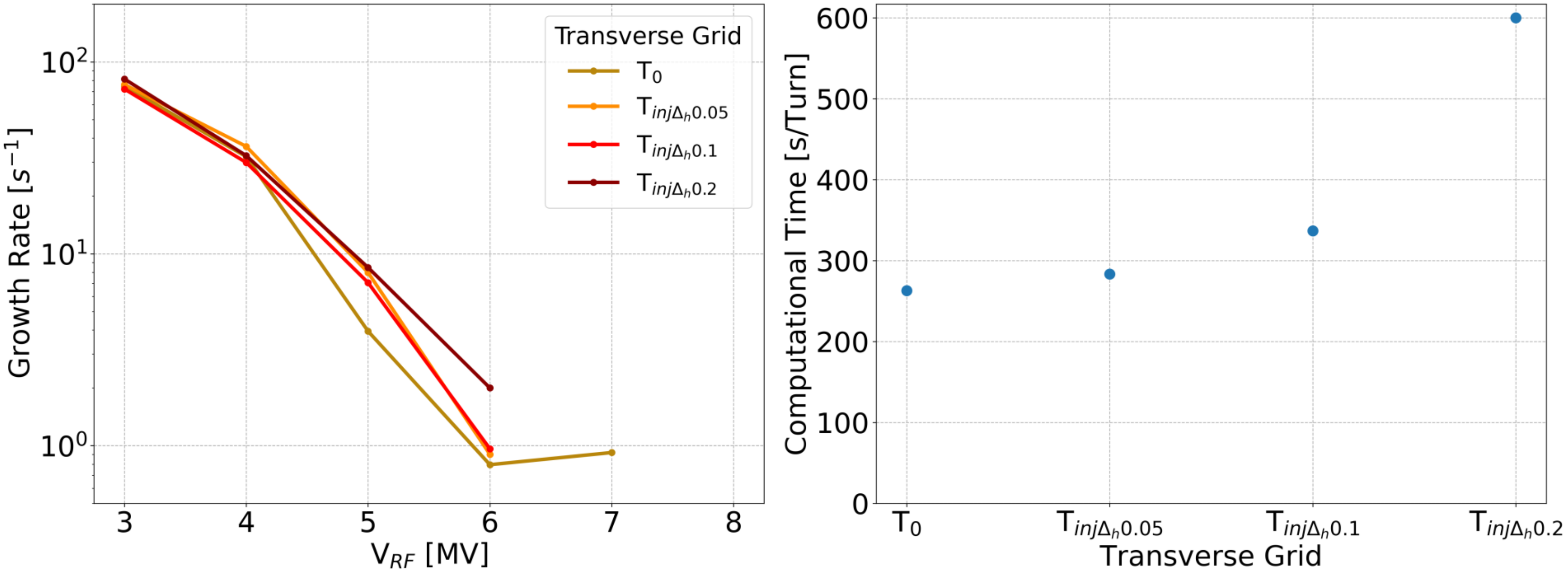
Strategy

Scan every numerical parameter, using conservative values for the other parameters:

- Slices = 750
- MPs/slice = 5,000
- Segments = 8
- e^- MPs = 500,000
- Transverse Grid: T_0

Quad at Inj: Convergence Studies

Transverse Grids

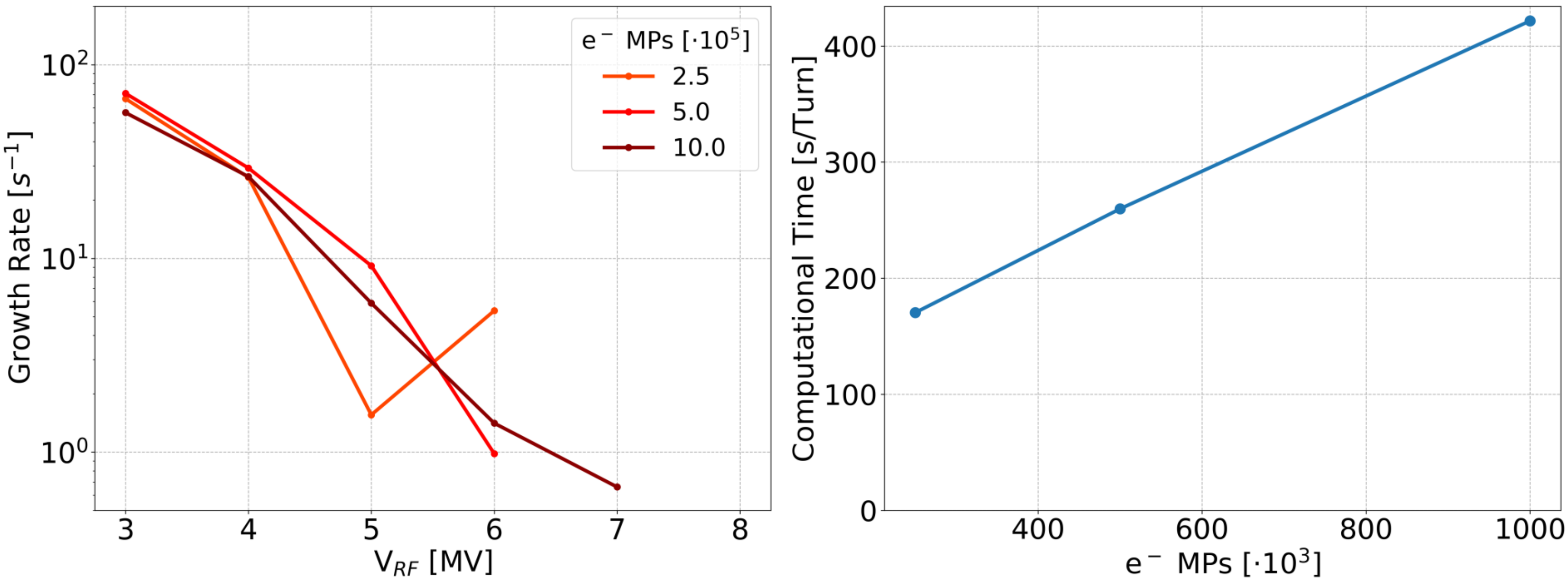


- The grid T_0, used in the past studies, is adequate

Parameter	T_0	T_{inj} $\Delta h=0.2\sigma$	T_{inj} $\Delta h=0.1\sigma$	T_{inj} $\Delta h=0.05\sigma$
Internal grid coverage [mm]	6.95 (10σ)	10.5 (15σ)	10.5 (15σ)	10.5 (15σ)
Internal grid cell size [mm]	0.139 (0.2σ)	0.139 (0.2σ)	0.0697 (0.1σ)	0.0349 (0.05σ)
External grid cell size [mm]	0.8	0.4	0.4	0.4

Quad at Inj: Convergence Studies

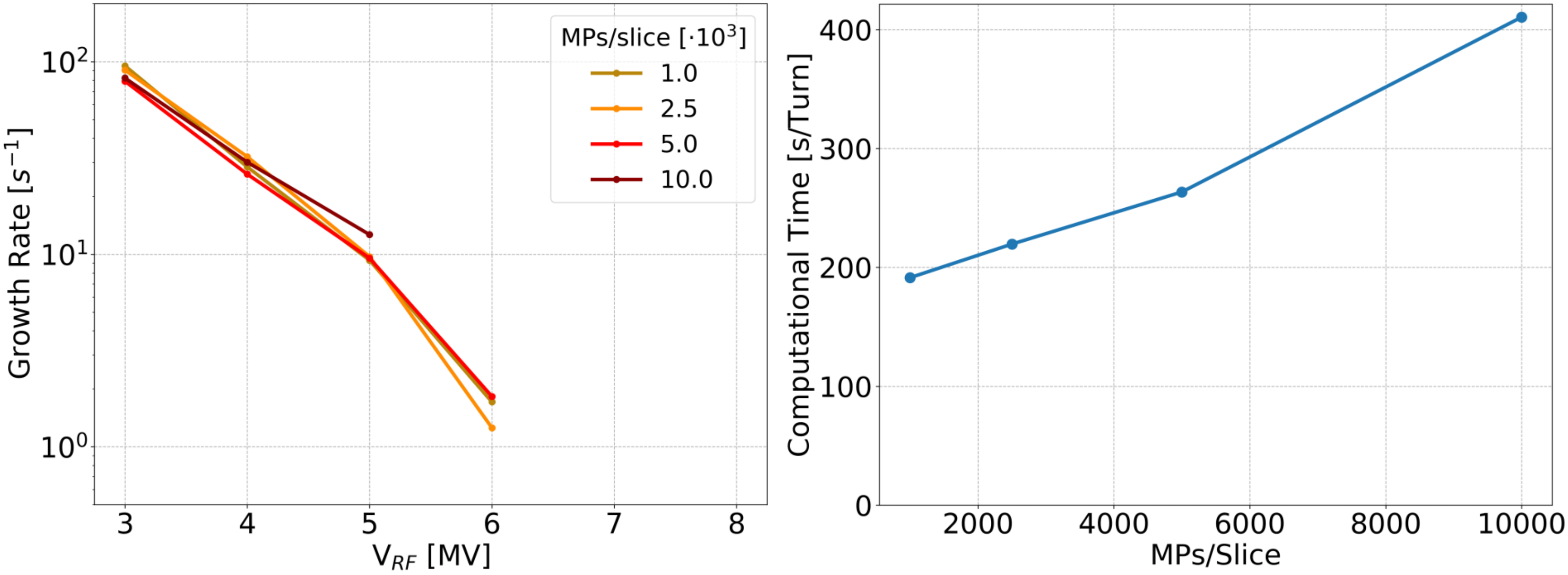
Electron MPs



- At least 5×10^5 MPs are required to achieve convergence

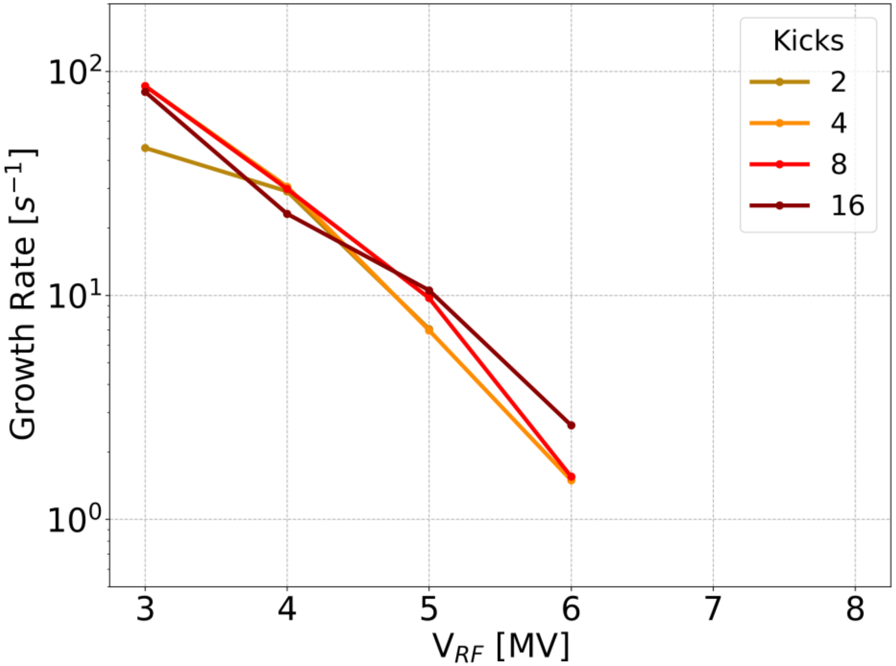
Quad at Inj: Convergence Studies

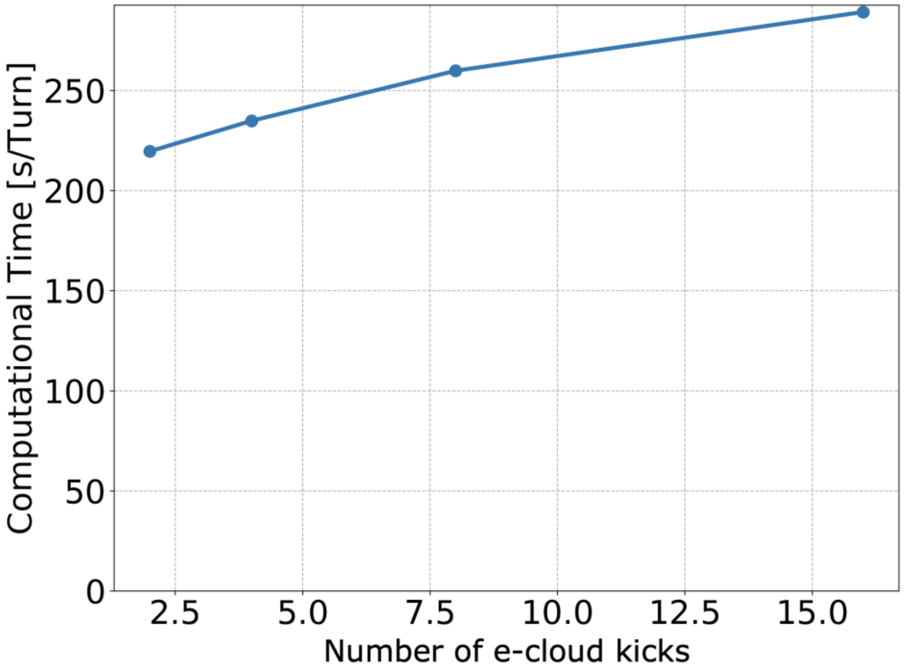
MPs per Slice



- Numerical convergence is achieved already for 10^3 MPs per slice

Quad at Inj: Convergence Studies

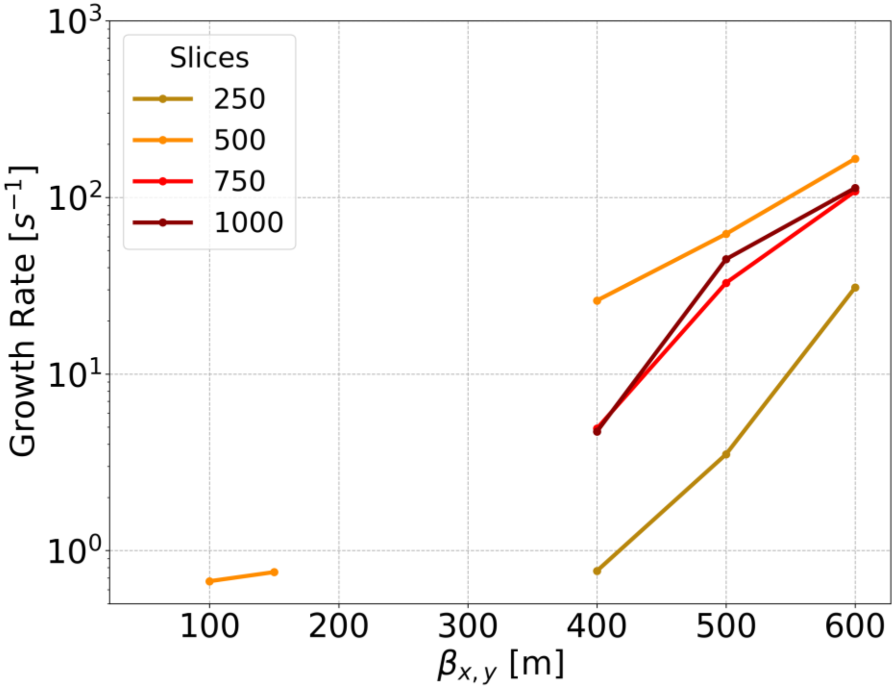


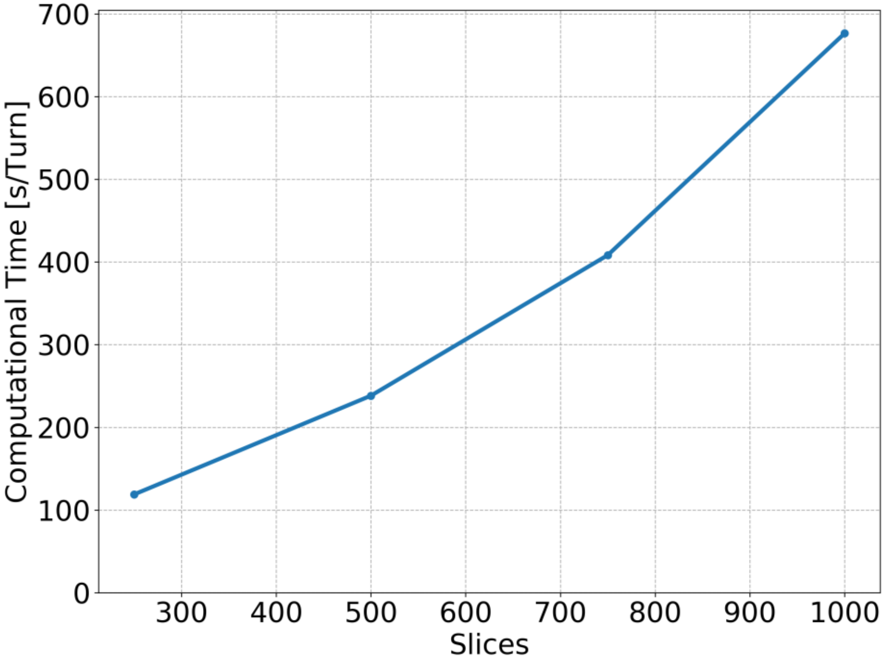


- Numerical convergence is obtained already with a small number of e-cloud interactions
- The number of CPU-cores used for the simulation is chosen equal to the number of e-cloud interactions
  - For this reason the corresponding increase in the computational time is relatively small and is in line with the expectation from the employed parallelization strategy [6]

[6] G. Iadarola, E. Belli, K. Li, L. Mether, A. Romano, and G. Rumolo, “Evolution of python tools for the simulation of electron cloud effects,” in Proc. 8th International Particle Accelerator Conference, Copenhagen, Denmark, May 2017. pp.THPAB043.

Quad at Col: Slices





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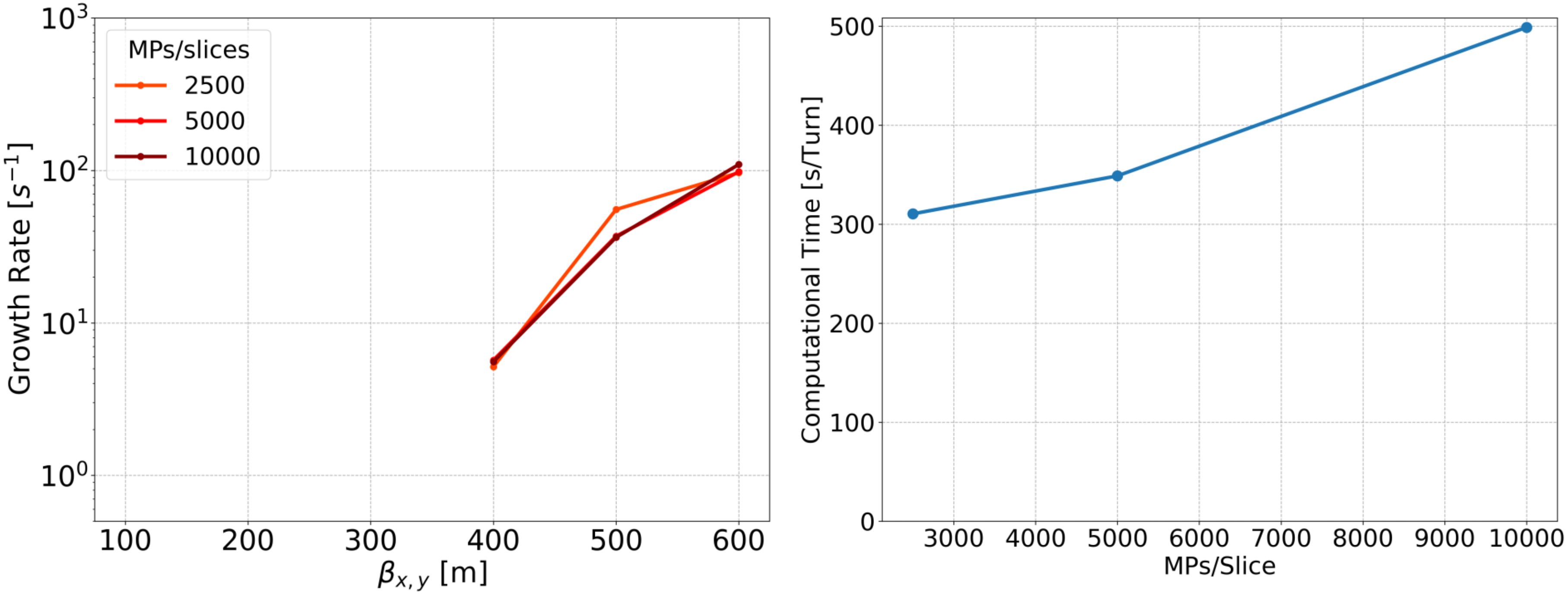
Quad at Col: MPs per Slices



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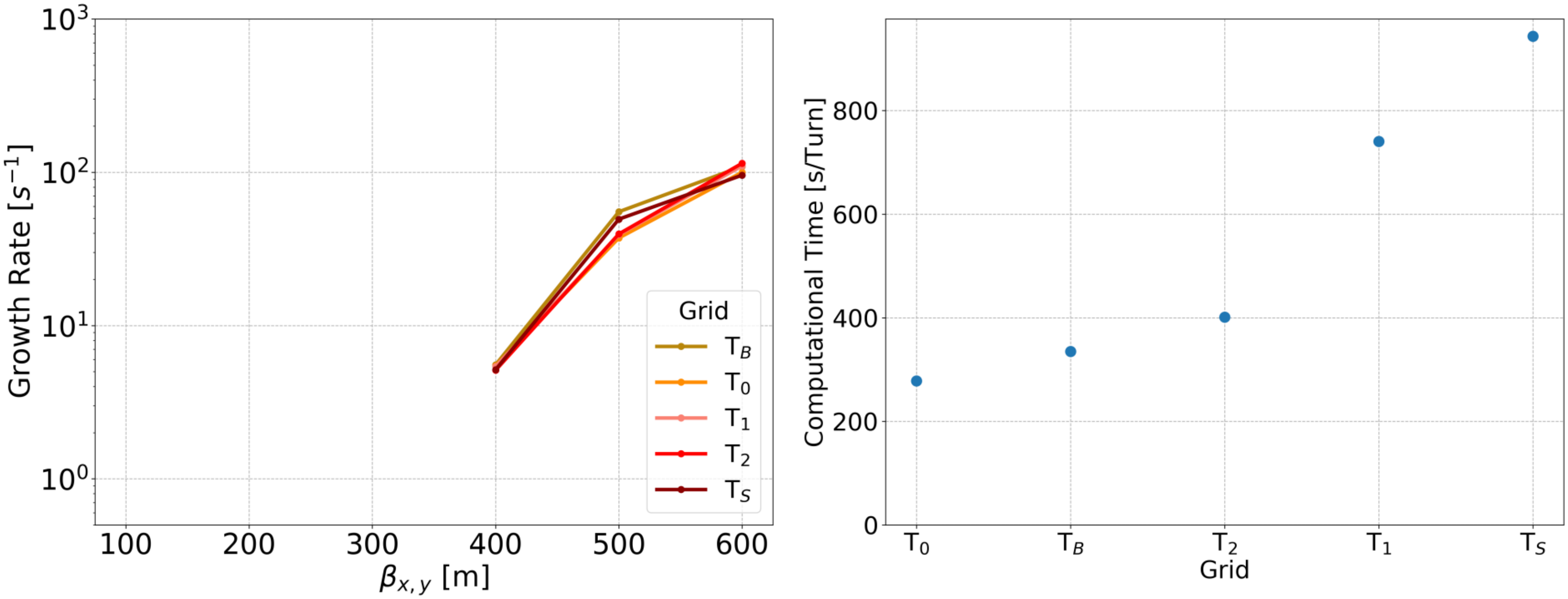
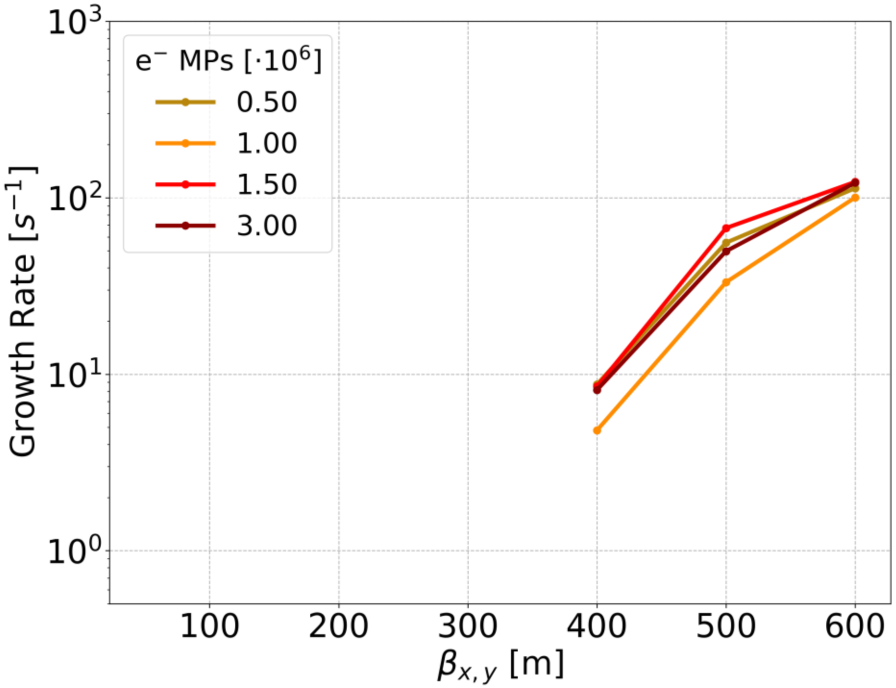
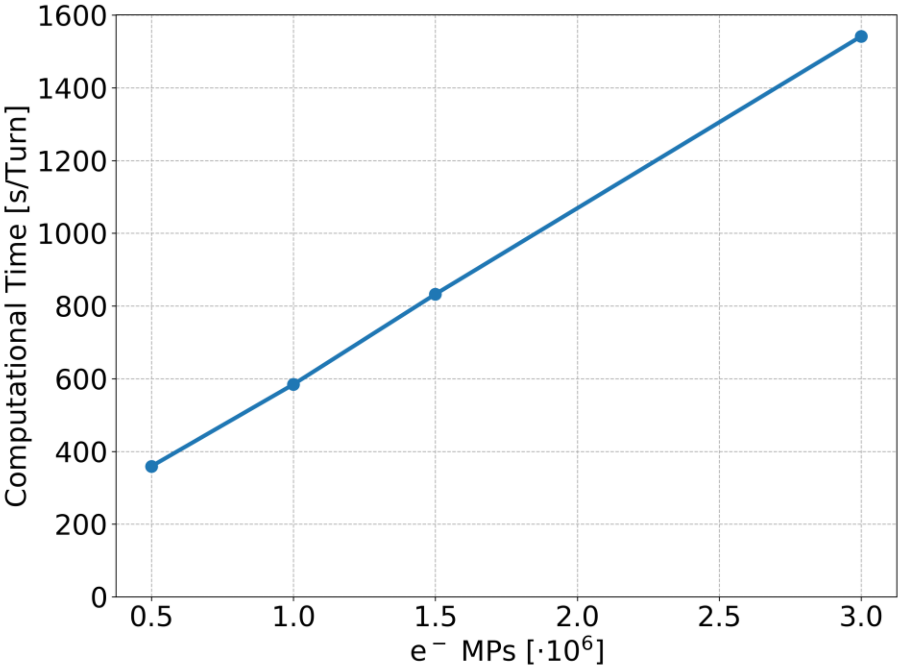
Quad at Col: Transverse Grids



	T_0	T_1	T_2	T_B	T_S
external grid cell size	$0.8\,\mathrm{mm}$	$0.4\,\mathrm{mm}$	$0.4\,\mathrm{mm}$	$0.8\,\mathrm{mm}$	$3.5\times10^{-5}\,\mathrm{mm}$
internal grid extension	$\pm10\,\sigma$	$\pm10\,\sigma$	$\pm10\,\sigma$	$\pm10\,\sigma_{\mathrm{max}}$	n.a.
internal grid cell size	$0.2\,\sigma$	$0.2\,\sigma$	$0.1\,\sigma$	$0.2\,\sigma_{\mathrm{min}}$	n.a.

Quad at Col: Electron MPs





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