CERN

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Electron Cloud Stability: Single Bunch Effects

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Acknowledgements: L. Mether, K. Paraschou

Outline

- Introduction
- Convergence Studies
- Bunch Length and RF voltage
- Effect of SEY and Bunch Charge
- Chromaticity and Damper
- Octupoles
- Frequency Analysis
- Conclusions and Future Developments

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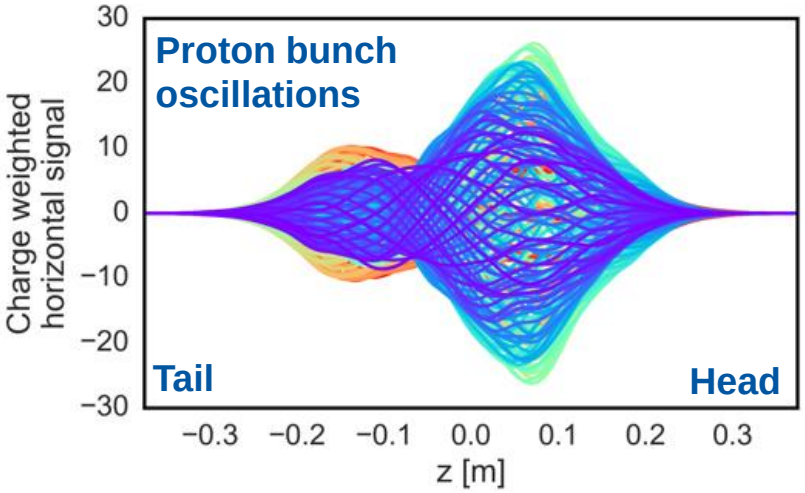
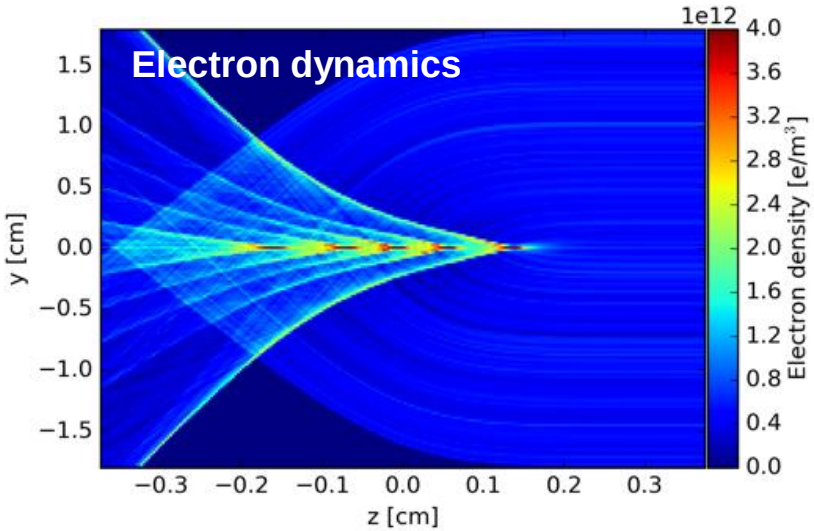
Introduction: Motivation

- The **electron motion** is fast enough to act as a **coupling mechanism** between the **head** and the **tail** of the bunch (dominated by electrons at the beam location)
  - **Stronger at injection energy** due to lower beam rigidity

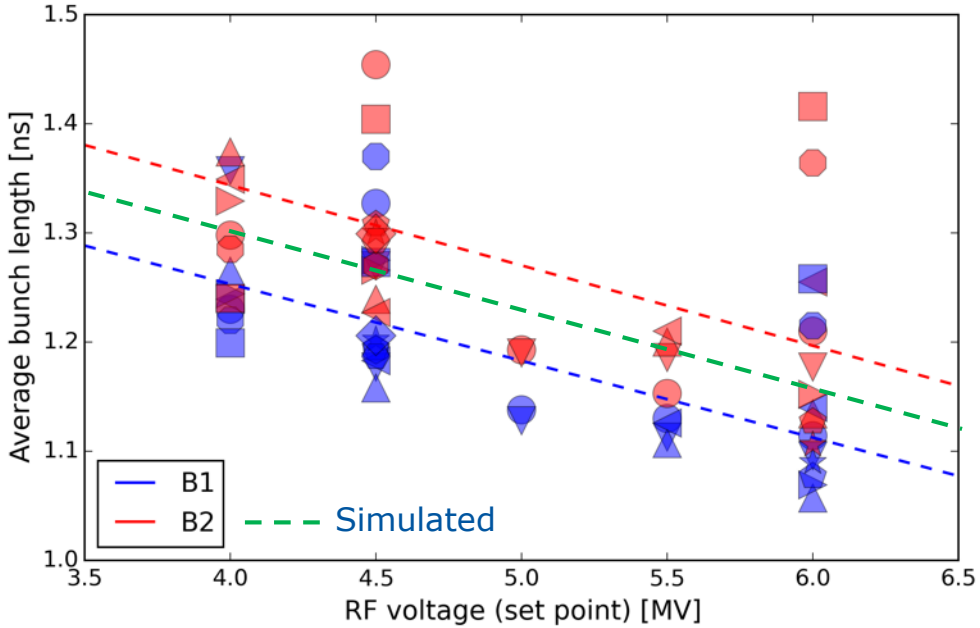




Introduction

- 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

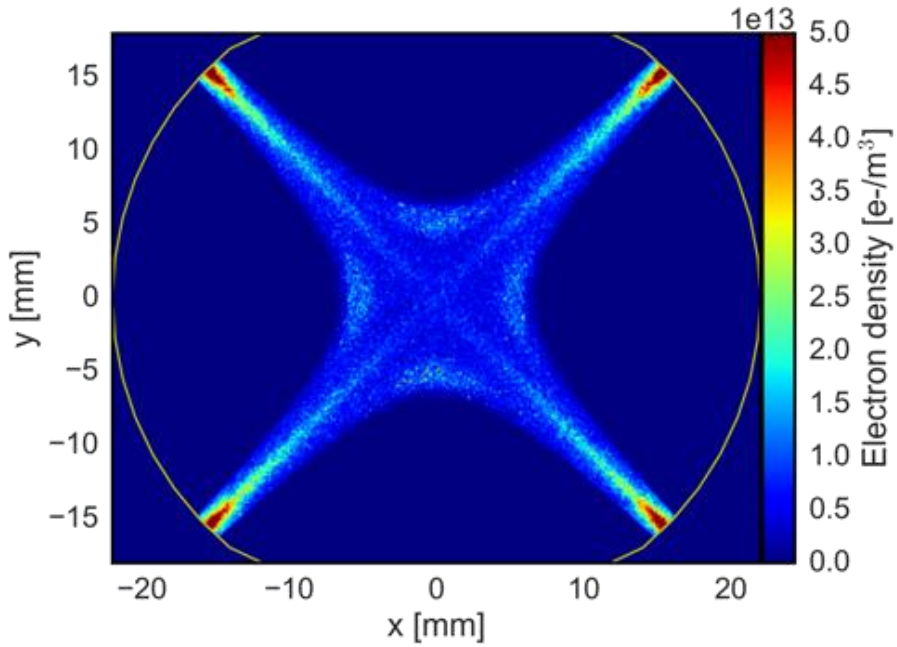
LHC measurements

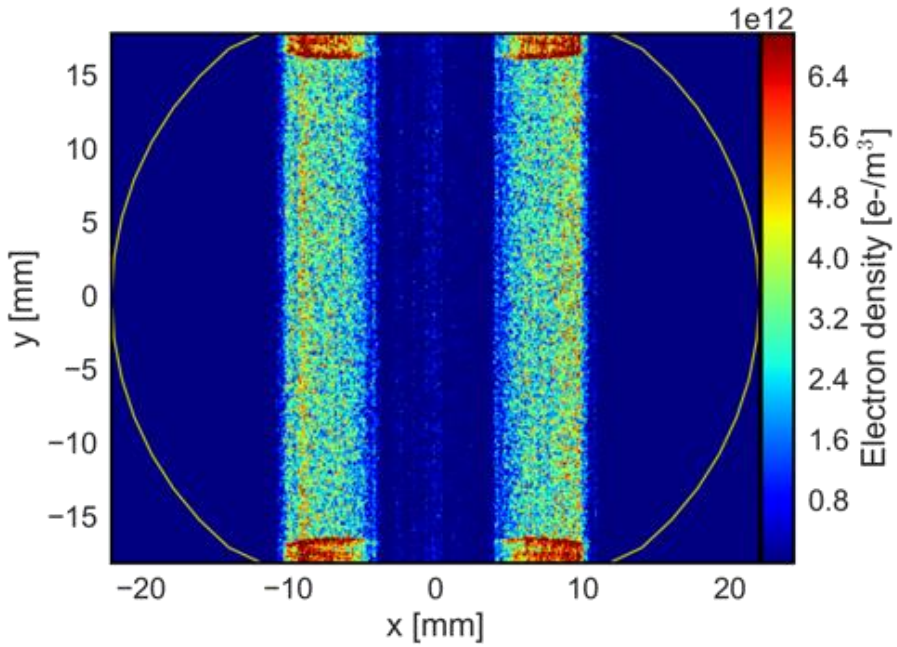


H. Timko, presentation at LMC meeting, 5 Sep 2018

Introduction

- Electrons in the **arc quadrupoles** are expected to be the **strongest contributor** (quadrupolar field concentrates a large electron density at the beam location)
  - Instabilities driven by **e-cloud in the quadrupoles** will be **considered in the following**



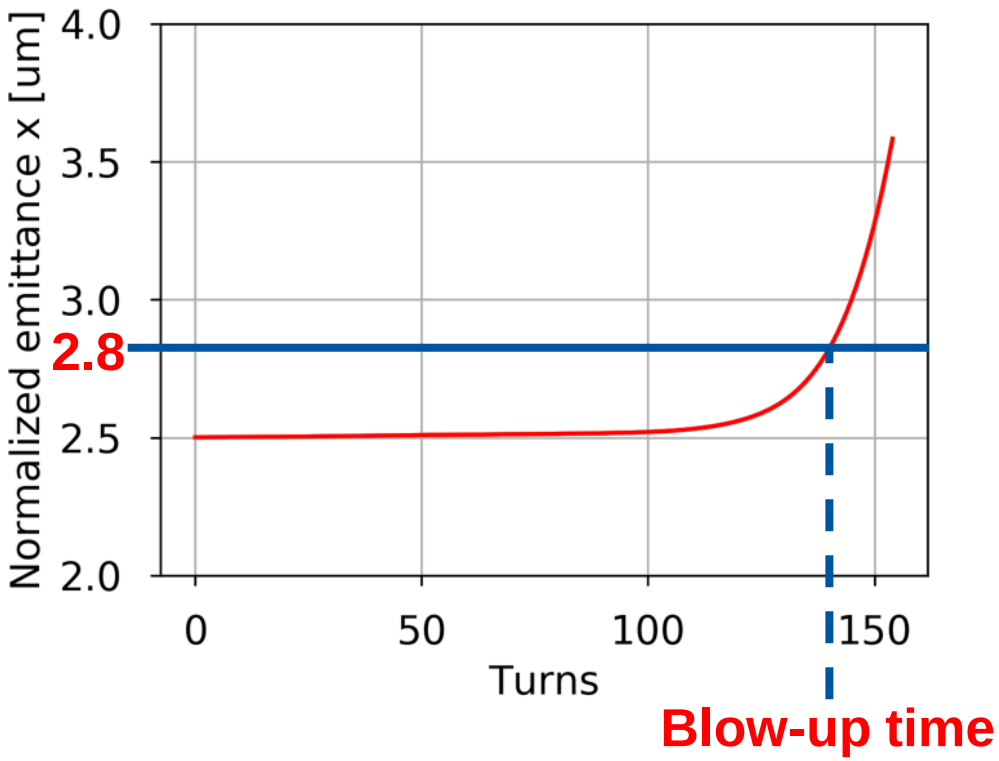


Introduction: Simulation Parameters

- $\varepsilon_{nx} = \varepsilon_{ny} = 2.5\ \mu m$
- $\beta_x = 92.7$ m and $\beta_y = 93.2$ m
- Energy: 450 GeV
- Magnetic Field (Arc Quadrupoles): 12.1 T/m
- Electron density: from build-up simulation
- SEY: 1.30 - 1.40
- Bunch Intensity: 1.2e11 - 2.3e11 protons per bunch
- Scan: $4\sigma_t$ (1.37 – 1.02 ns) / RF voltage (3 - 8 MV)

Introduction: Instability Study Observables

- Blow-up time: time required for observing an emittance blow-up of 12% (2.5 µm ➔ 2.8 µm)



- No EC kick on the vertical plane
- The maximum number of turns is fixed: 20,000

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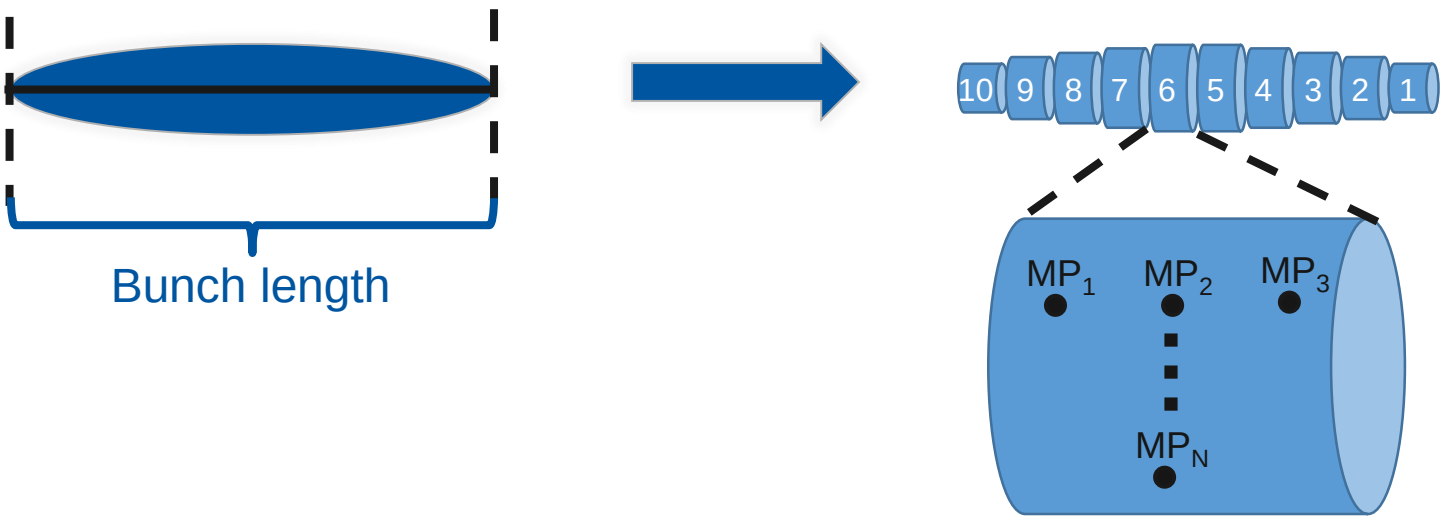
Convergence Studies

The motivation of these convergence studies is to find the lowest acceptable values for the numerical parameters:

1. number of slices of the bunch
2. number of MacroParticles (MPs) / slice
3. number of kicks (or segments) for each e^- cloud element
4. number of electron MPs for each kick
5. transverse grids (Multigrid **[1]**)



[1] E. Belli, "PyPIC: the multigrid solver", EC Meeting #32 – September 2, 2016

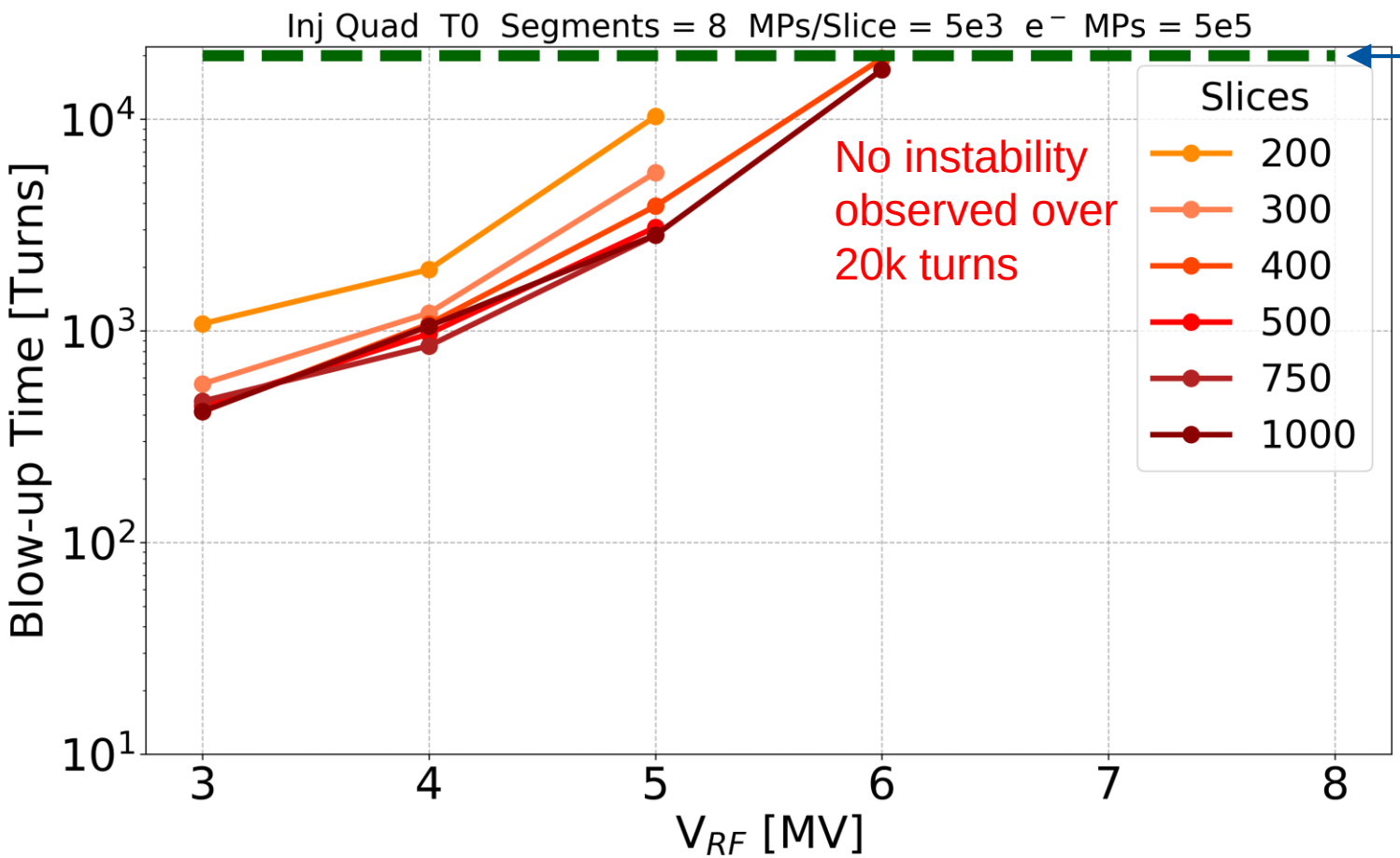
Convergence Studies

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

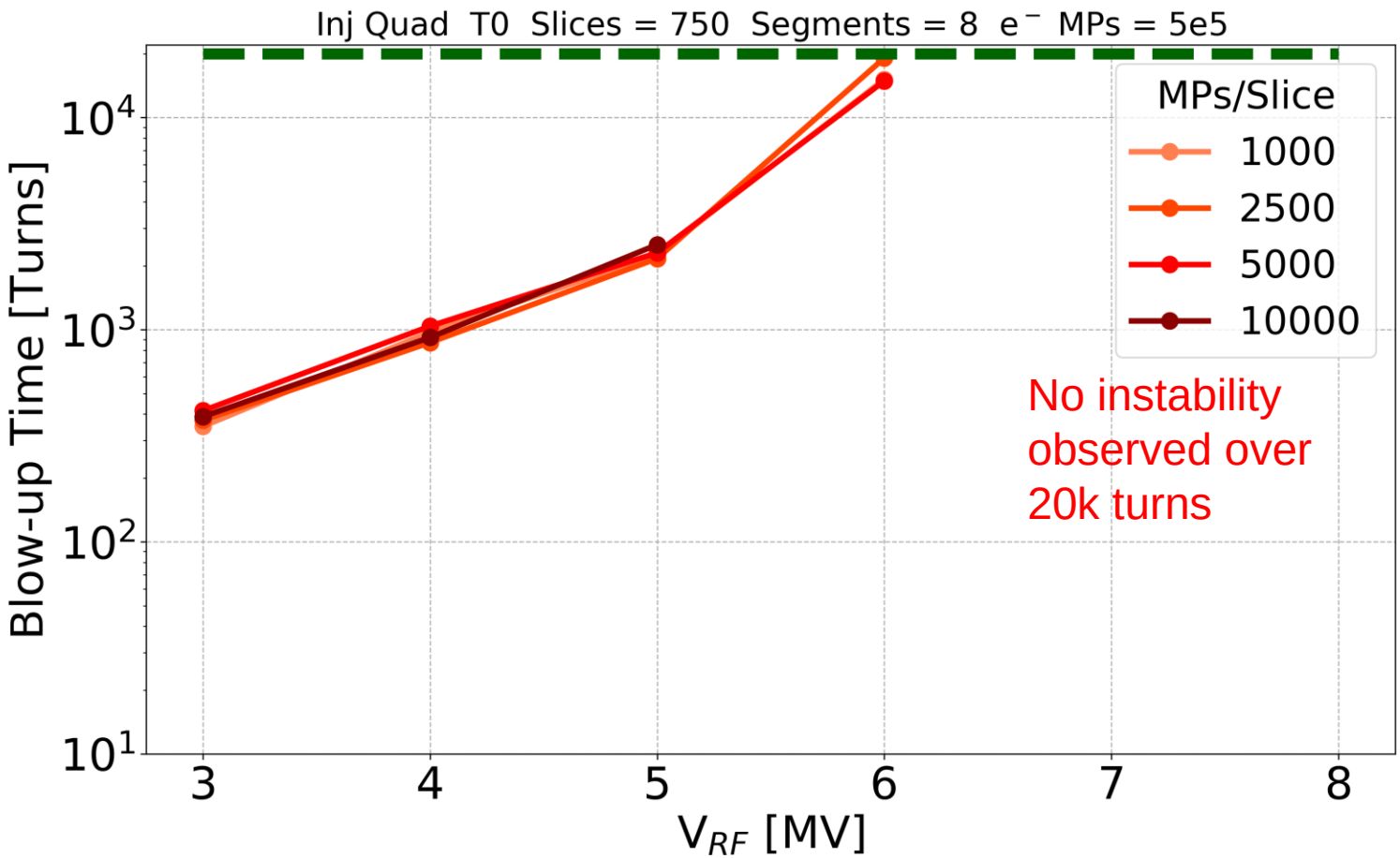
Convergence Studies: Slices



Simulated number of turns

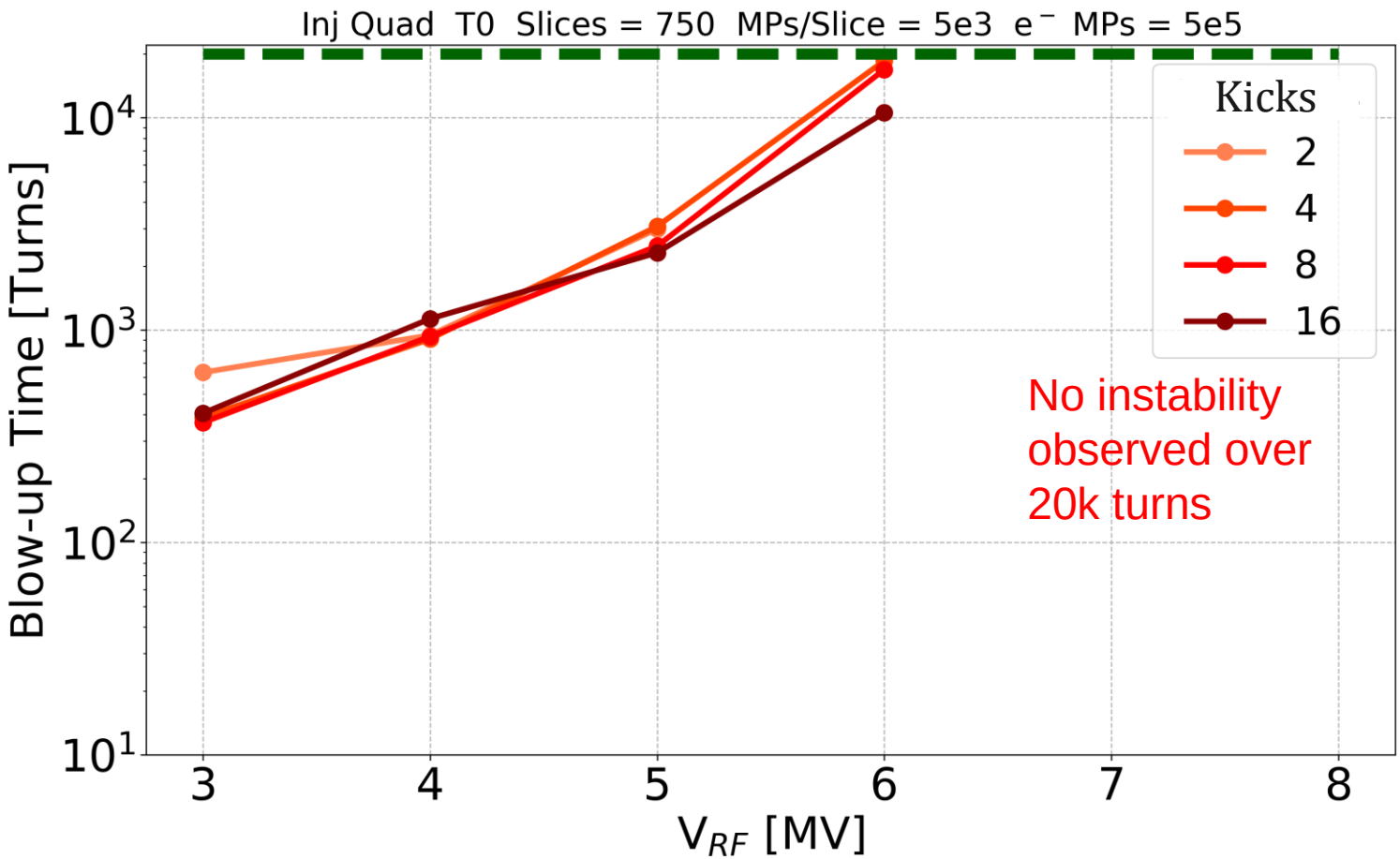
- Old setting 150 slices is not adequate
- 500 slices is chosen

Convergence Studies: MPs/Slice



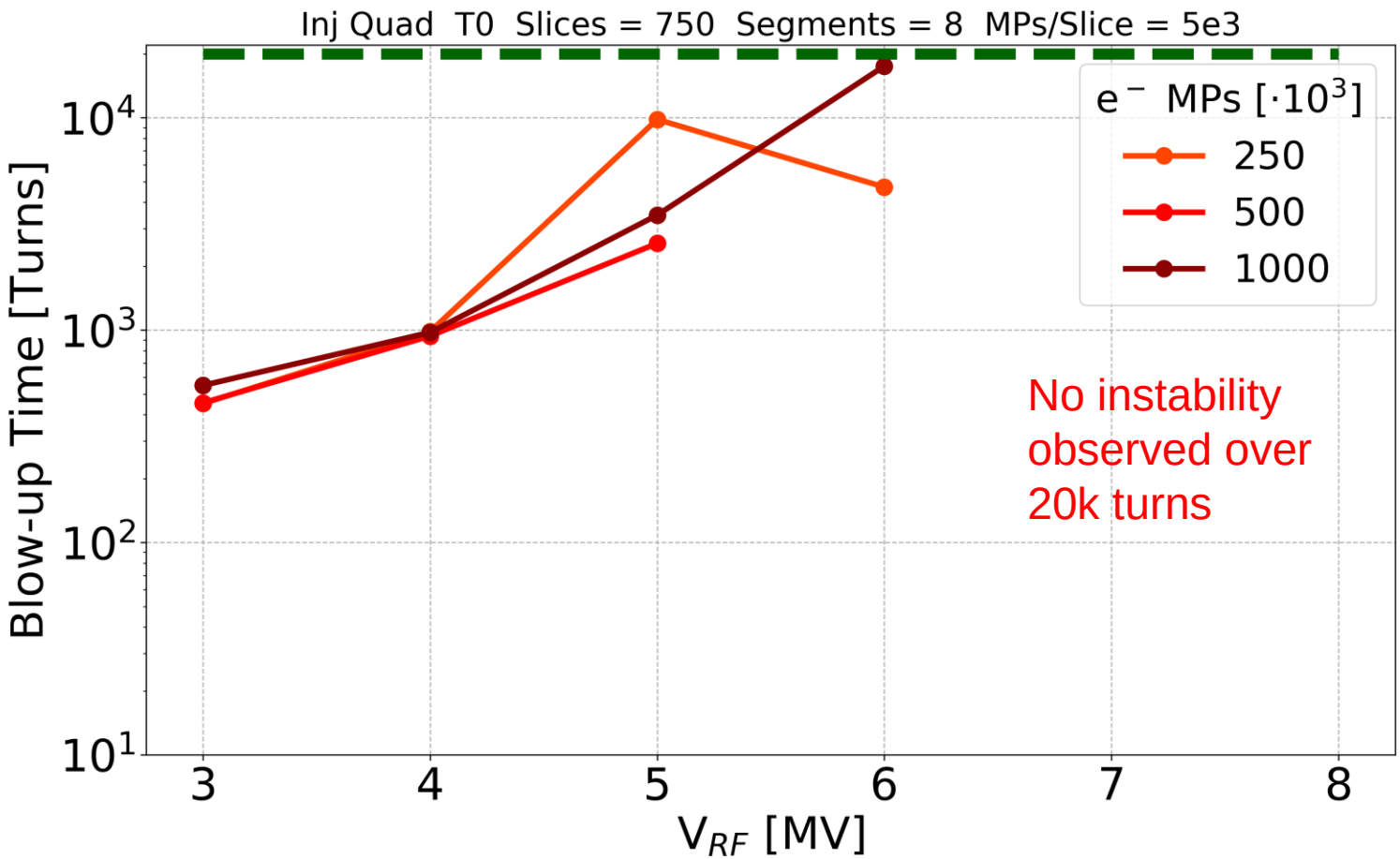
- 2,500 MPs/slice is chosen

Convergence Studies: Kicks



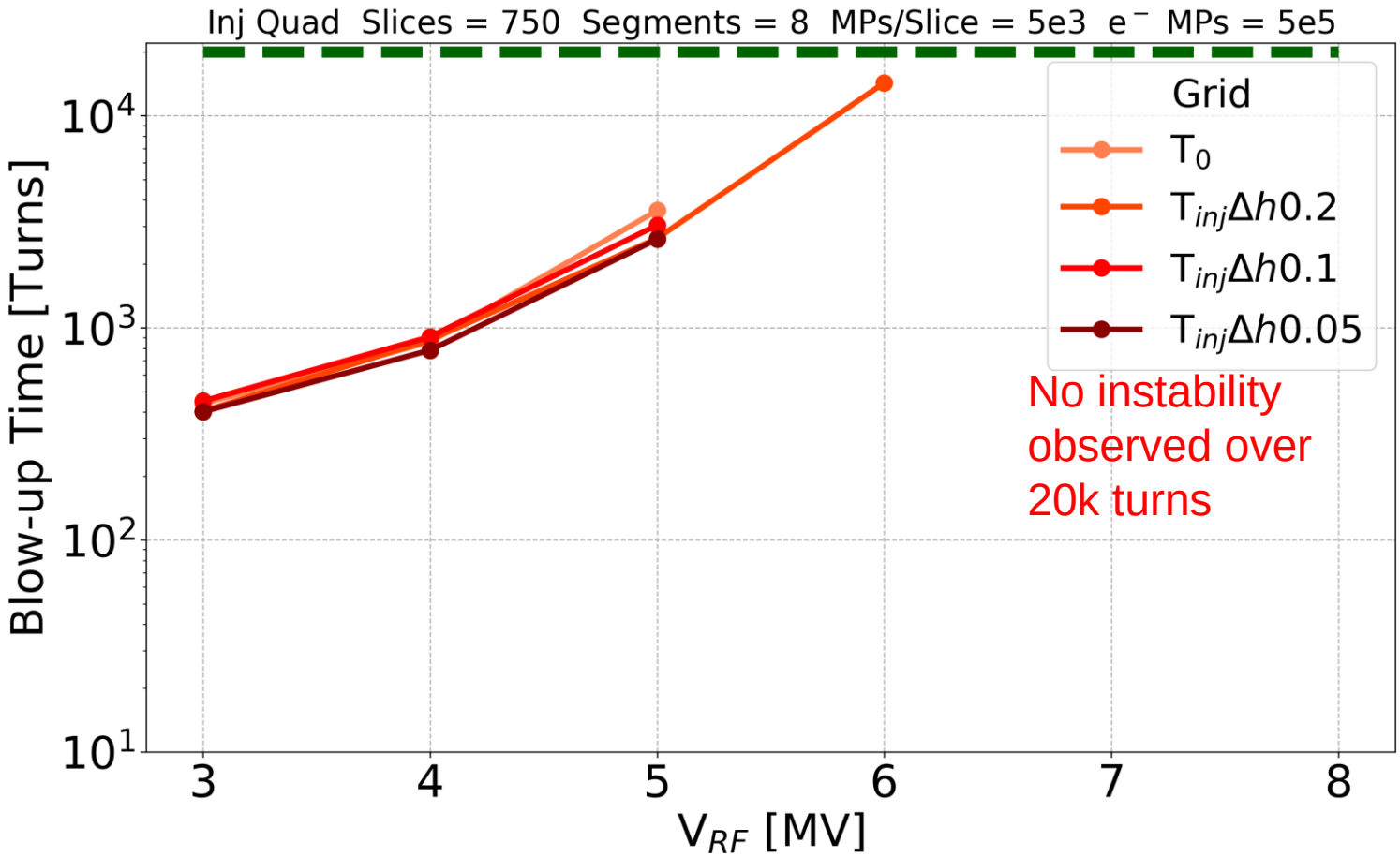
- 8 kicks is chosen

Convergence Studies: e^- MPs



- 500,000 e^- MPs is chosen

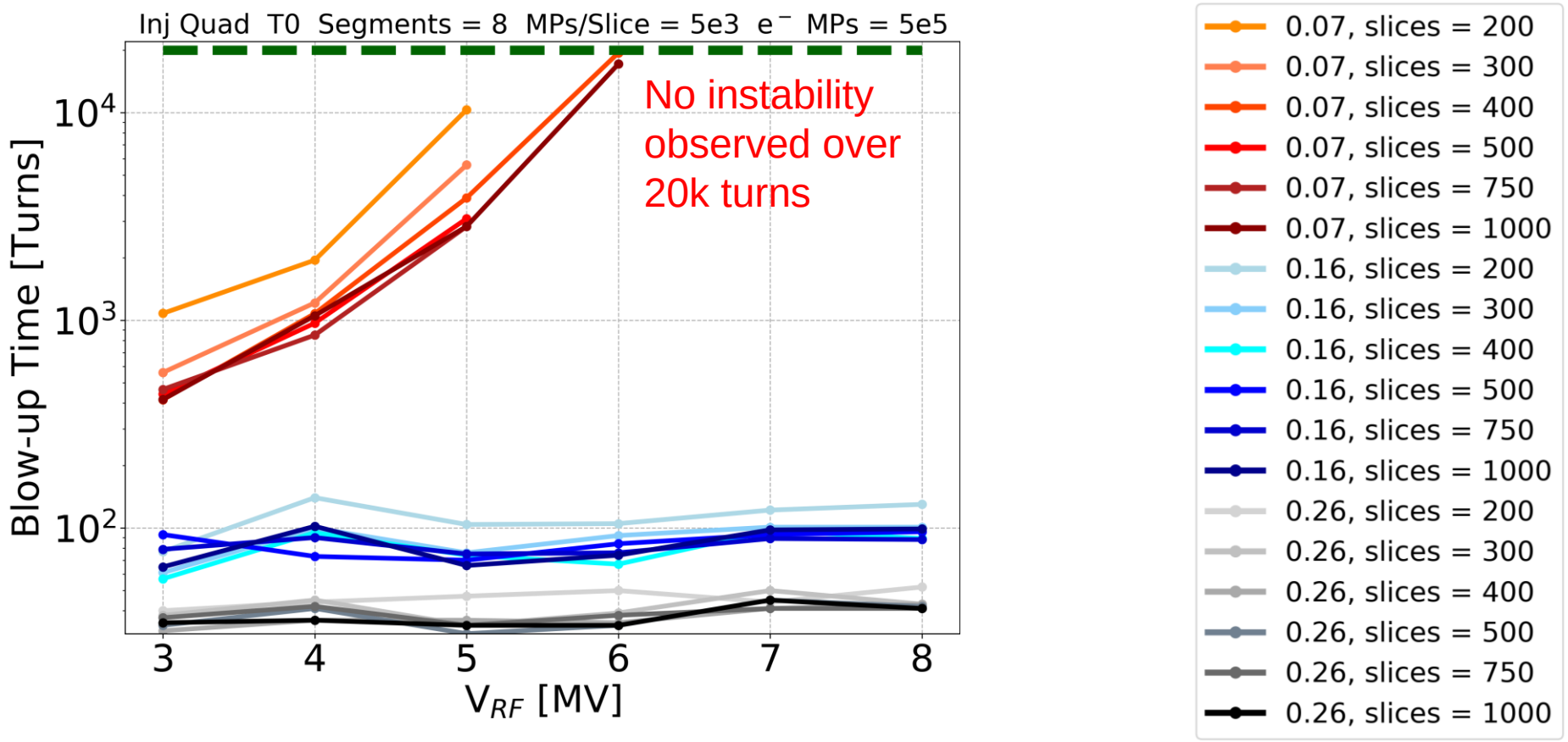
Convergence Studies: Transverse Grid



Still running (3)

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

Convergence Studies: 16% - 26%



- Scans of the length of the quadrupoles (equivalent to have stronger electron cloud kicks) for each numerical parameter
- They confirm the previous conclusions

Convergence Studies: Summary

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

Convergence Studies: Chosen Parameters

Numerical Parameter	Chosen Value
Slices/bucket	500
MPs/Slice	2,500
Segments	8
e^- MPs	5e5
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

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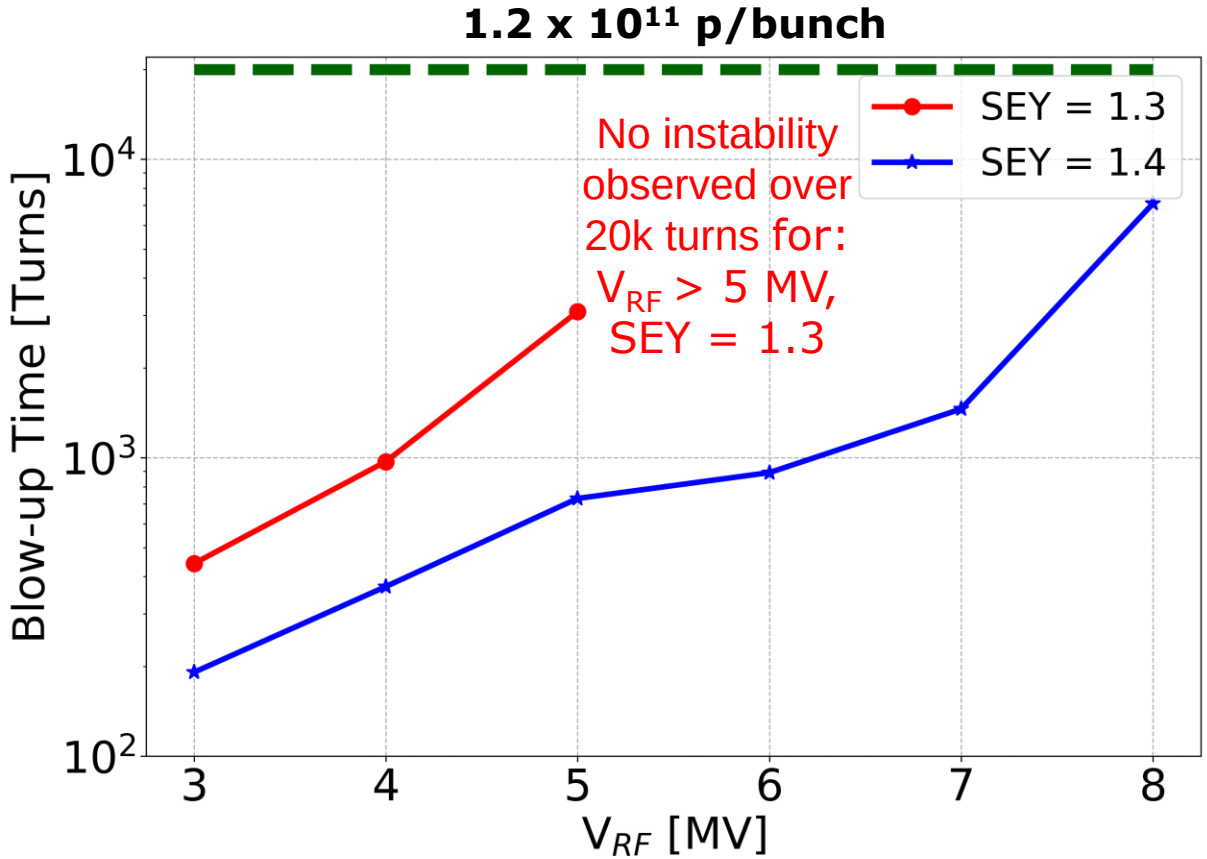
Bunch Length and RF voltage



- Increasing V_{RF} and decreasing the bunch length, the bunch is more stable
  → Which is dominant?

Bunch Length and RF voltage

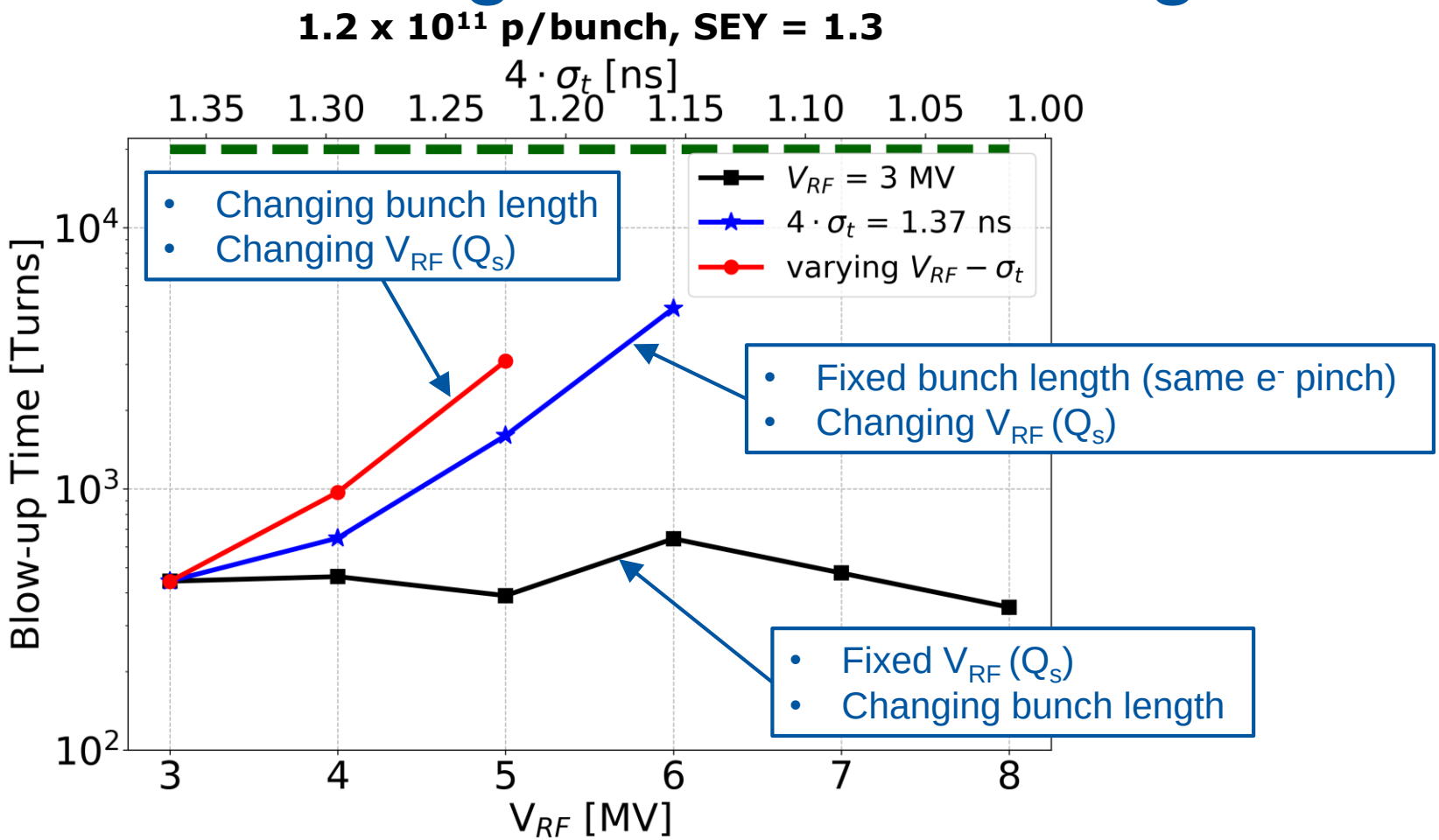
Increasing V_{RF}, we change

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

Bunch Length and RF voltage



→ the dominant stabilizing factor is the change of Q_s

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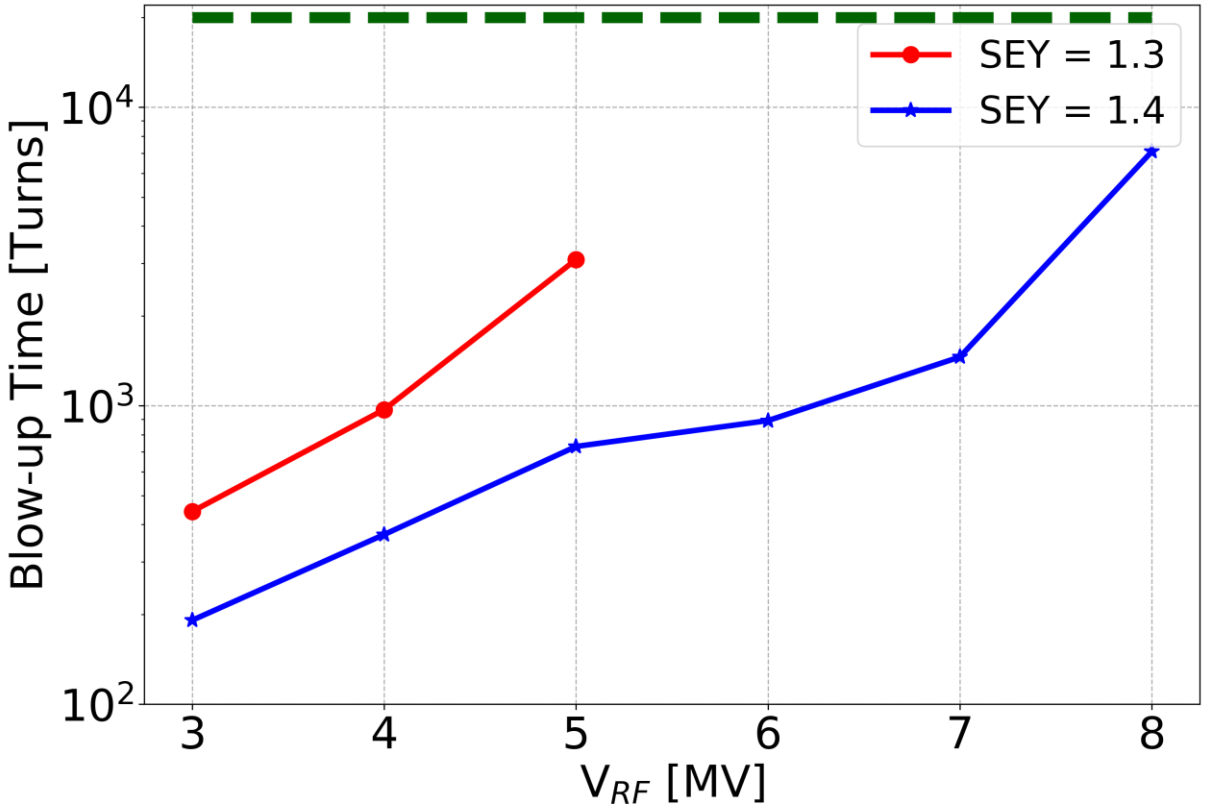
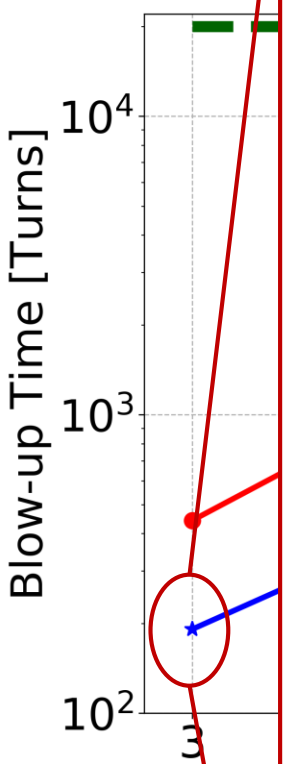
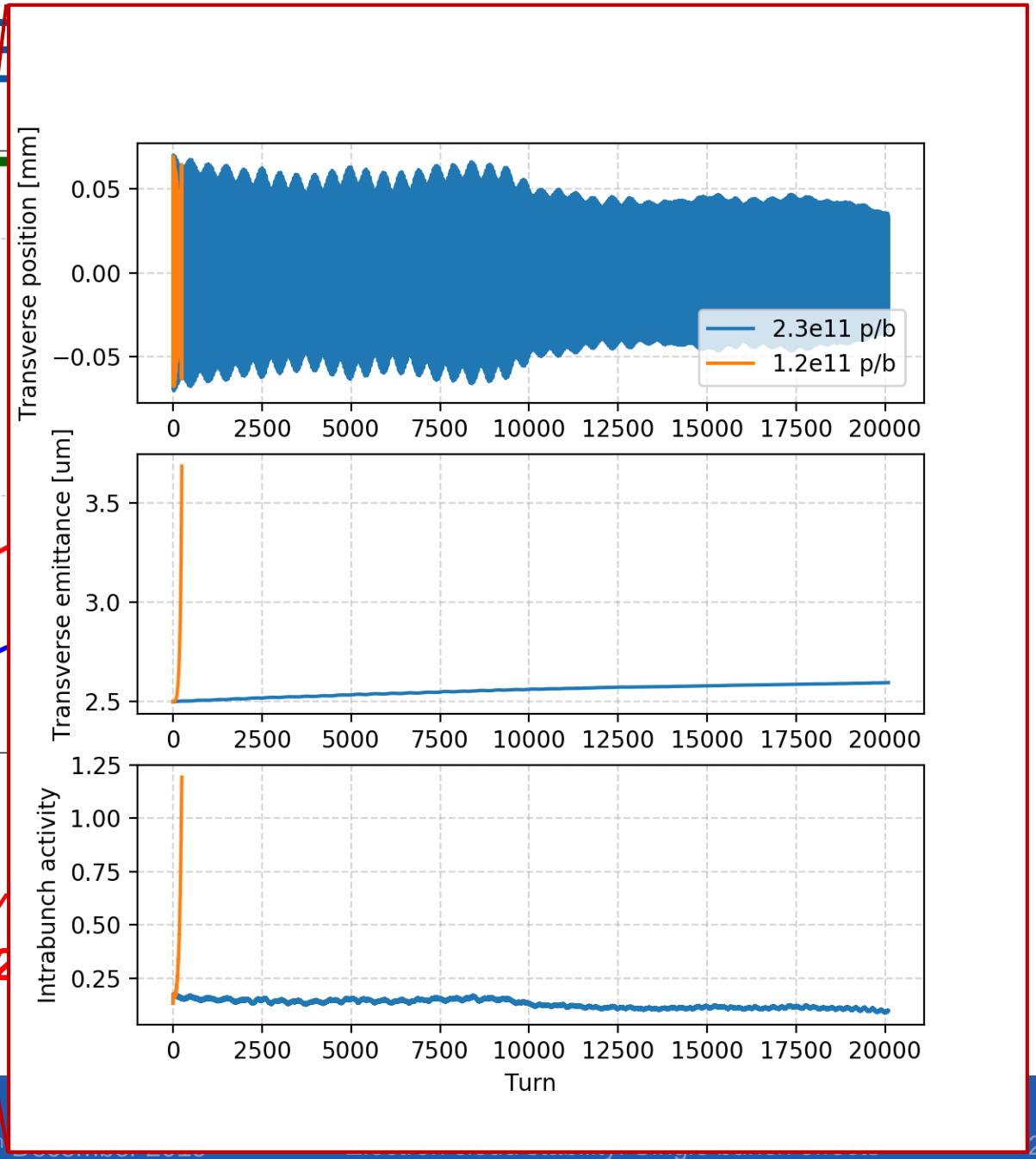
Effect of SEY and Bunch Charge



- Increasing the SEY, the bunch is more unstable
- **No instability for 2.3e^{11} ppb** in this entire range of parameters

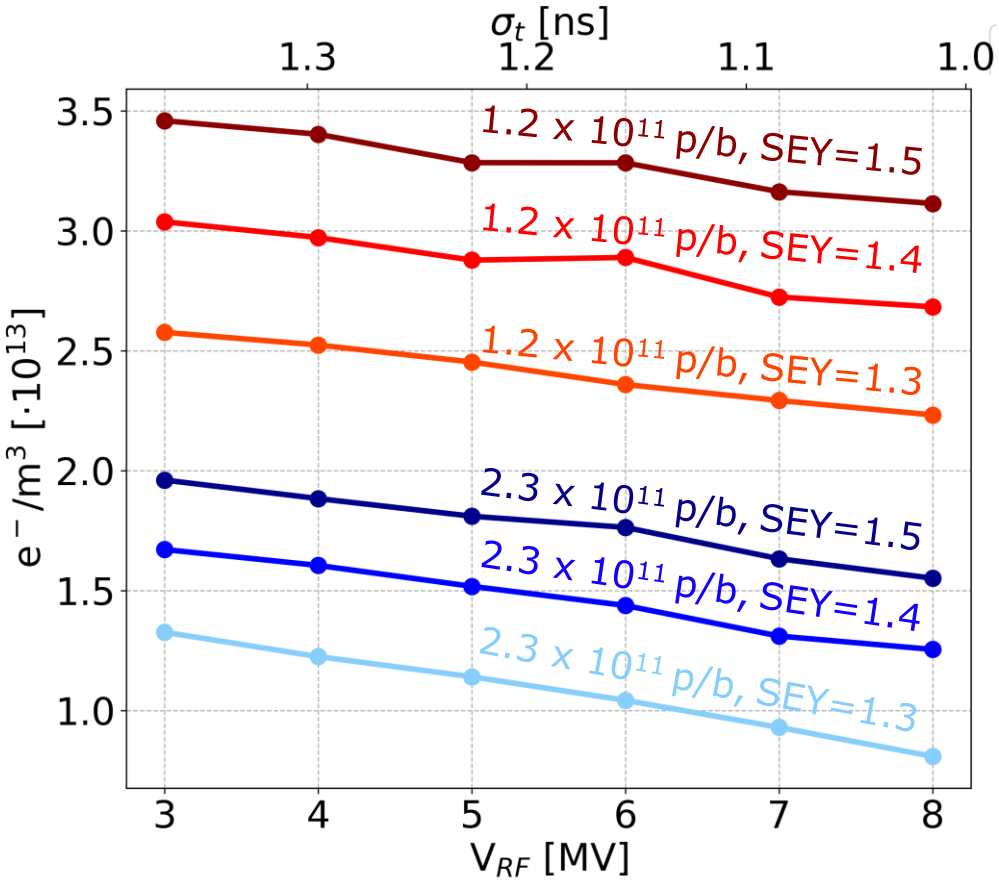
Effect of SE





- Increasing the SEY
- **No instability for 2**

Why no Instability at High Intensity?



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

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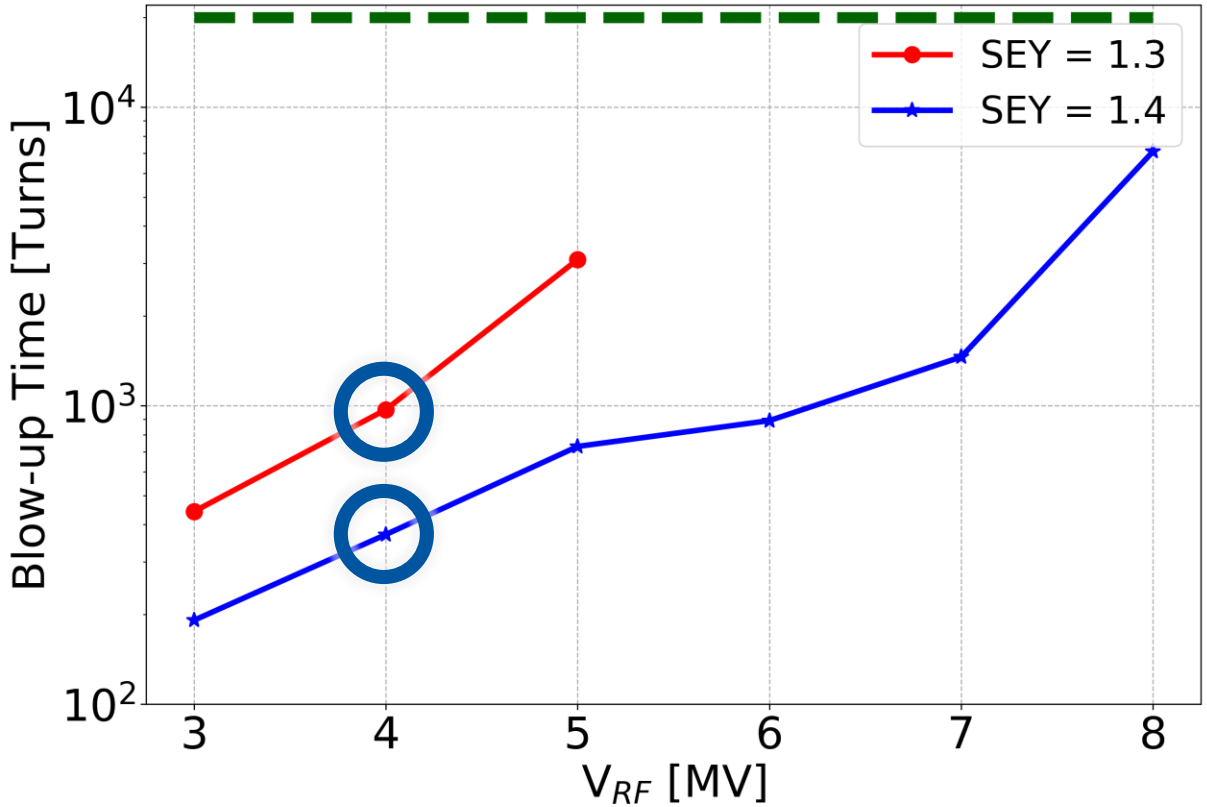
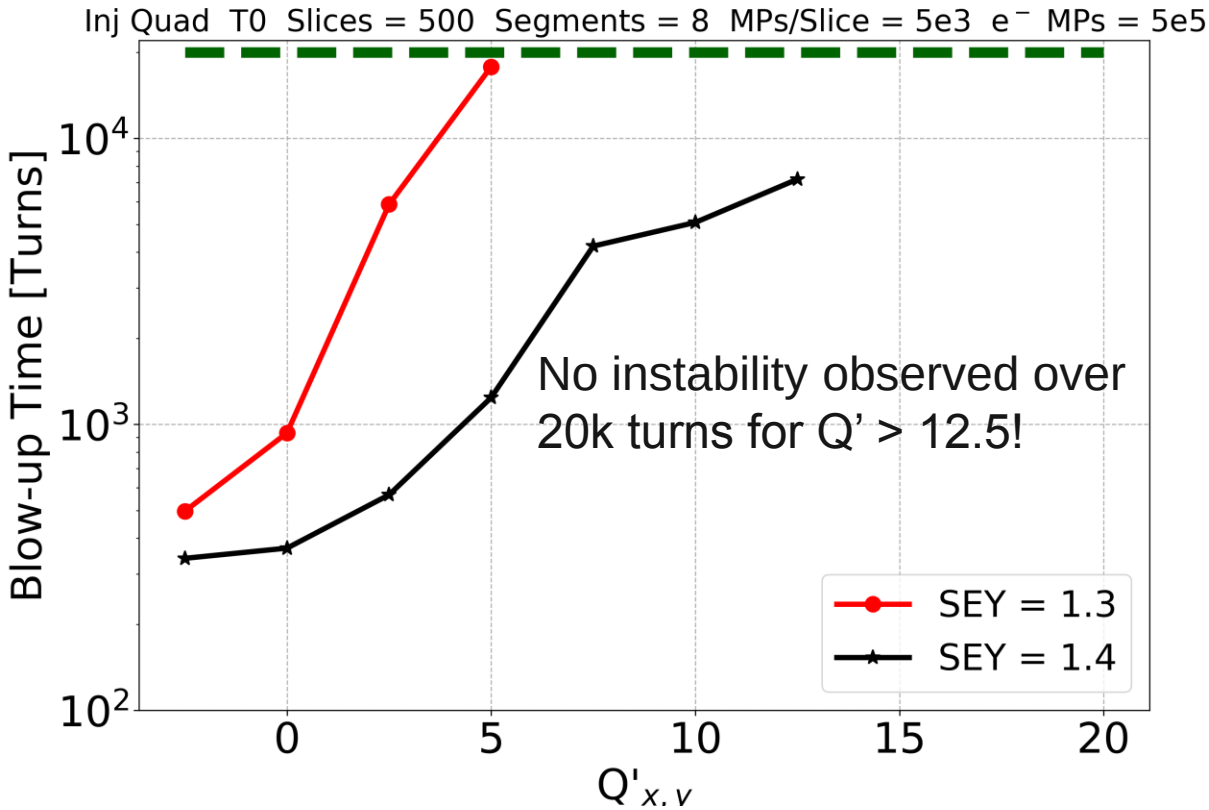
Chromaticity and Damper



- Scanned around these points

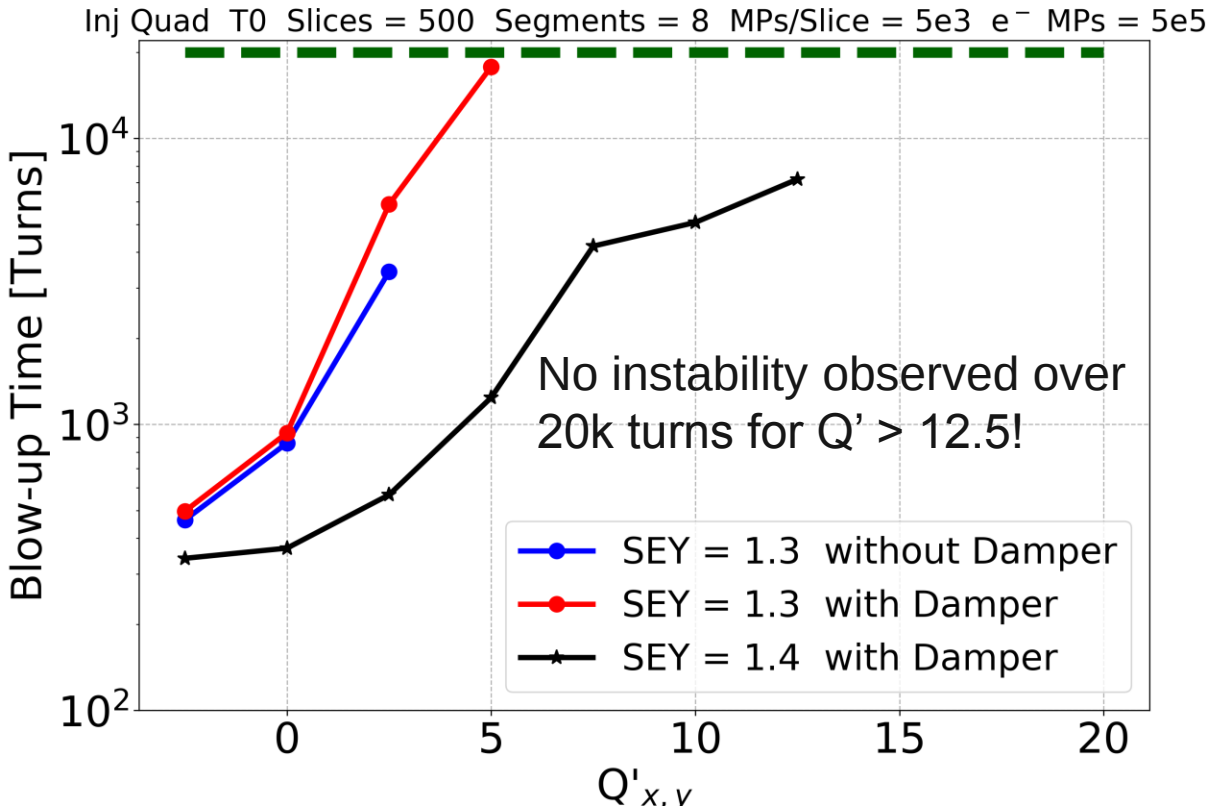
Chromaticity and Damper



- V_{RF} = 4 MV
- SEY = 1.3 – 1.4
- Feedback damping time is 10 turns

- For the case of LHC intensity (which an instability could be observed) the **effectiveness of different mitigation measures** has been investigated:
  - The instability is **strongly mitigated** by increasing the **chromaticity** settings

Chromaticity and Damper



- V_{RF} = 4 MV
- SEY = 1.3 – 1.4
- Feedback damping time is 10 turns

- For the case of LHC intensity (in which an instability could be observed) the **effectiveness of different mitigation measures** has been investigated:
  - 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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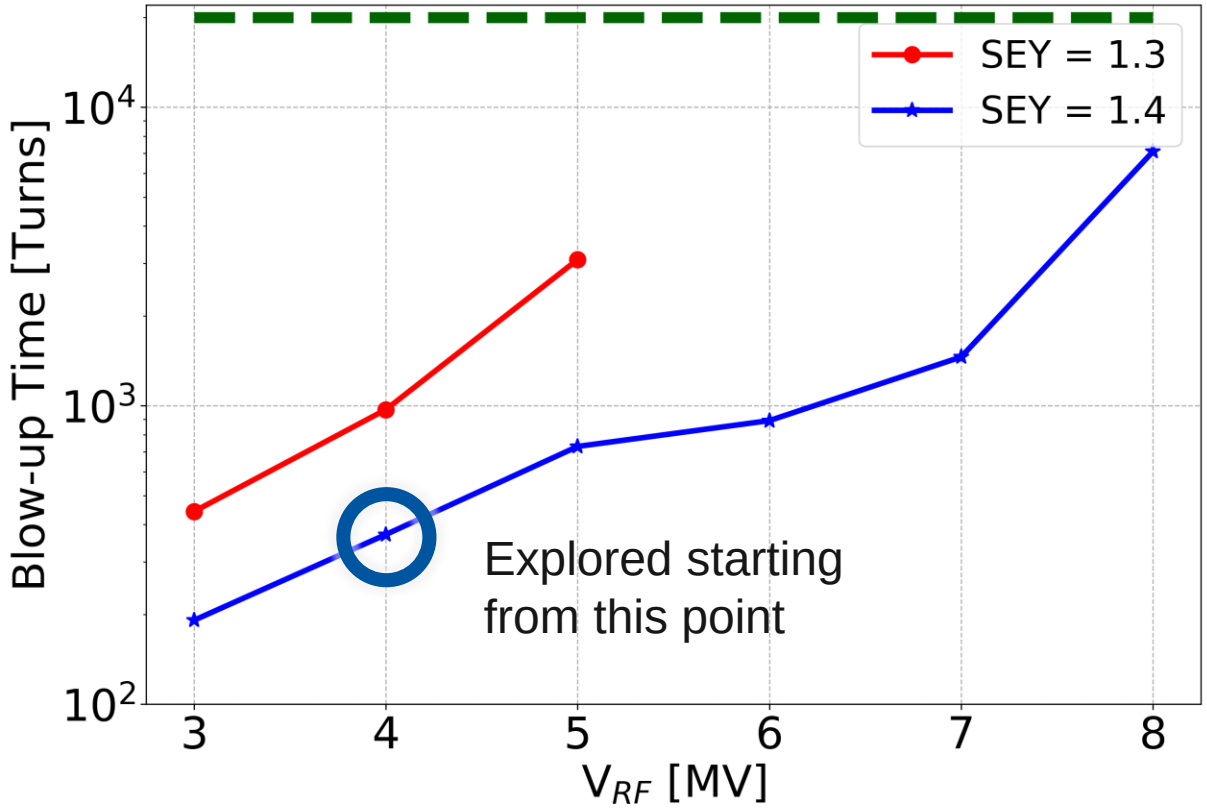
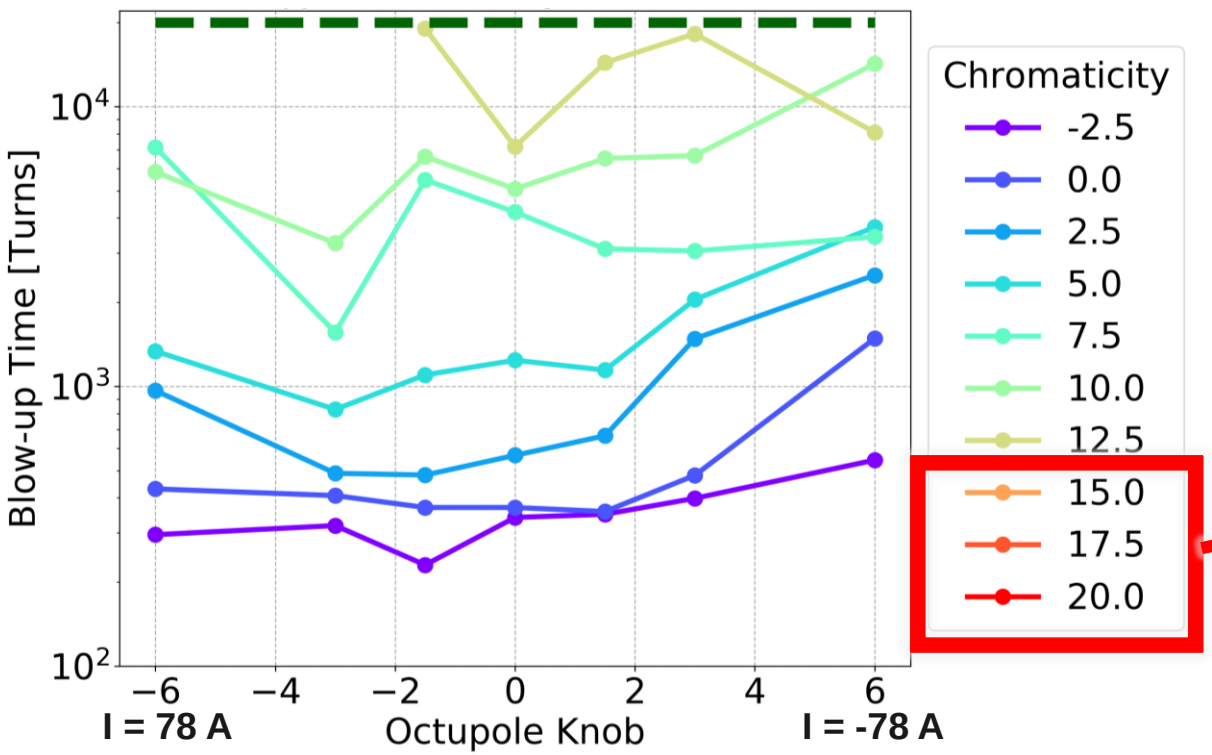
Octupoles


SEY = 1.3
SEY = 1.4
Blow-up Time [Turns]
10^4
10^3
10^2
3
4
5
6
7
8
V_{RF} [MV]
Explored starting
from this point

Octupoles

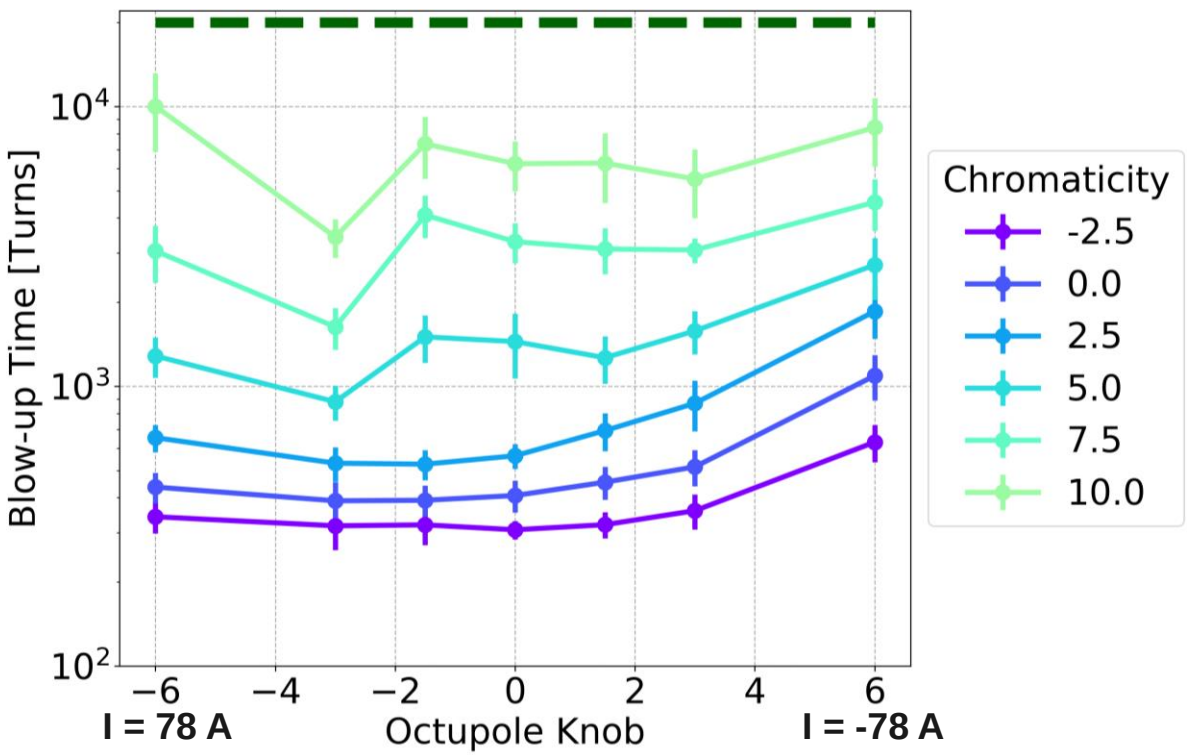


- V_{RF} = 4 MV
- SEY = 1.4
- Damper = 10 turns

No instabilities over 20,000 turns

- For the case of LHC intensity the **octupole current** has also been scanned
  → **less effective** compared to **chromaticity**
- **Large oscillations for high chromaticity driven by random component**

Octupoles



- V_{RF} = 4 MV
- SEY = 1.4
- Damper = 10 turns
- 20 repetitions

- 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

  → to be further investigated

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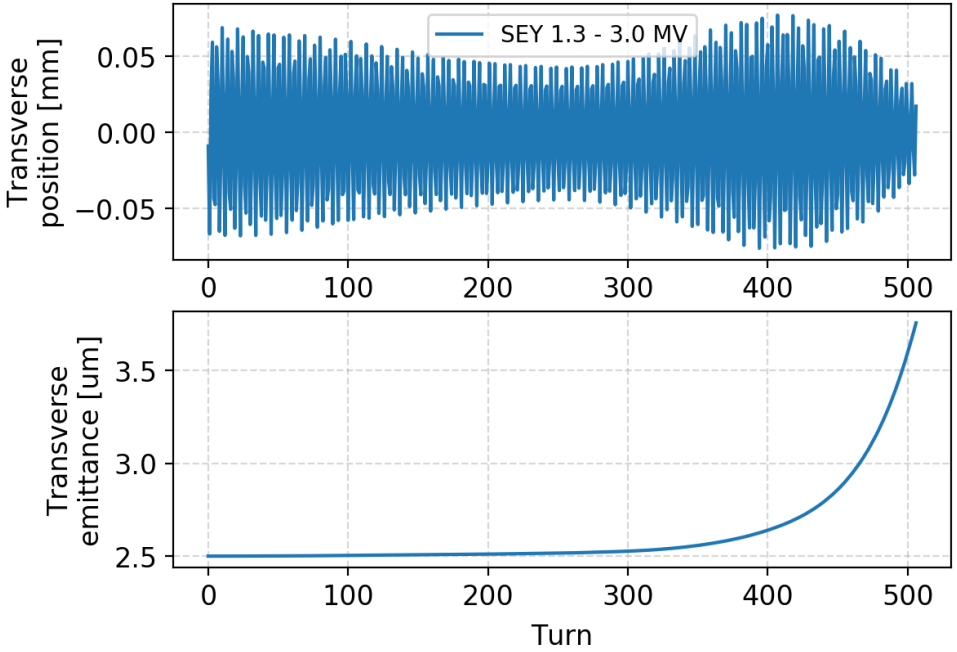
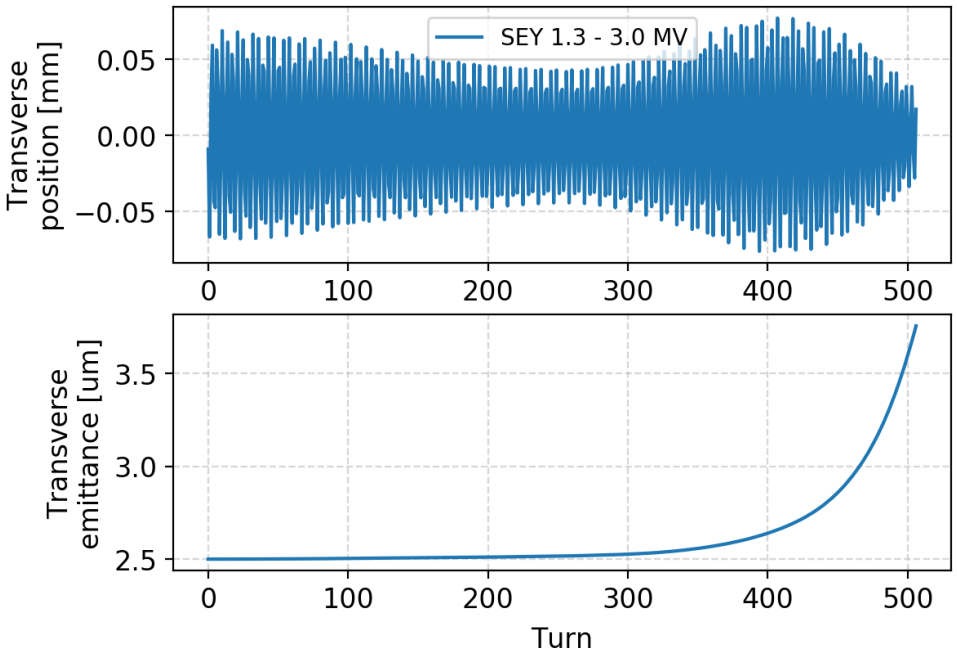
Frequency Analysis

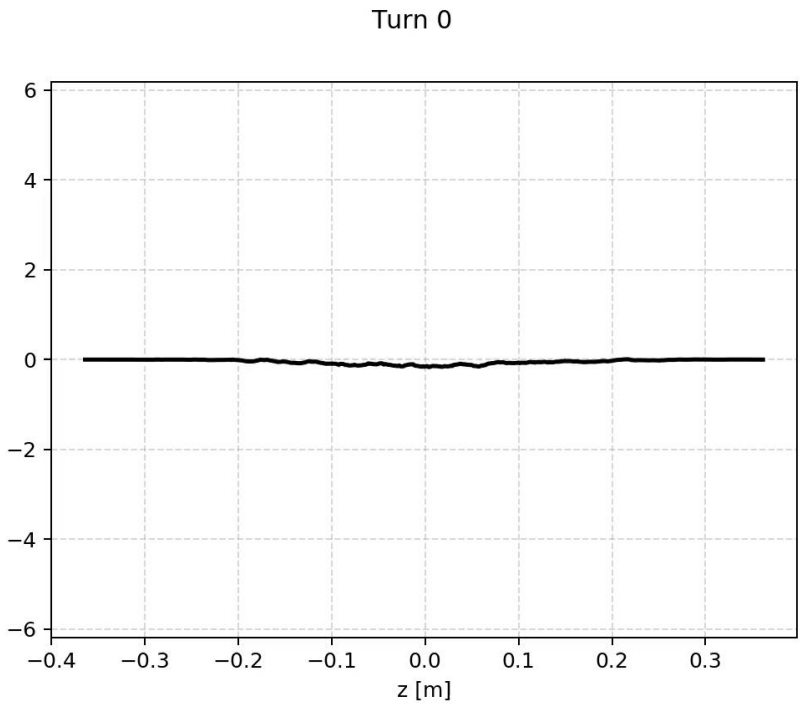
- An **~exponential rise** is visible on the **transverse emittance**
- The centroid motion does not show clear signs of instability



Frequency Analysis

- An **~exponential rise** is visible on the **transverse emittance**
- The centroid motion does not show clear signs of instability
- The development of the instability is visible on **the intra-bunch motion**

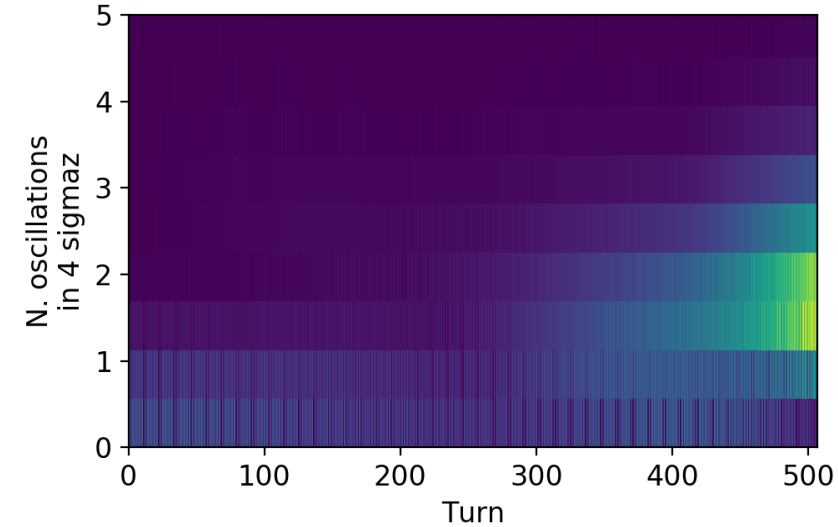


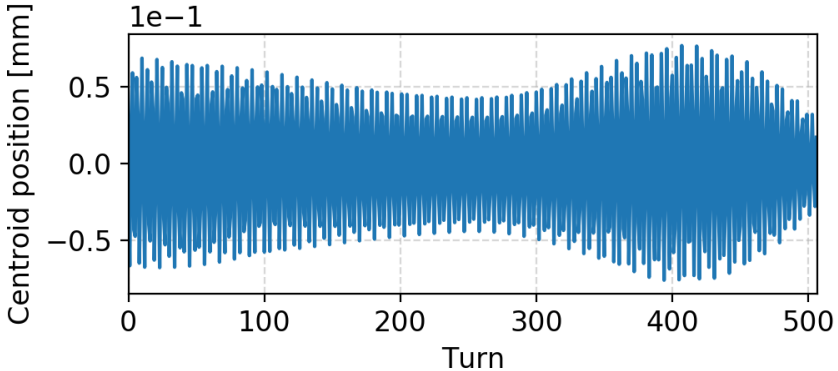


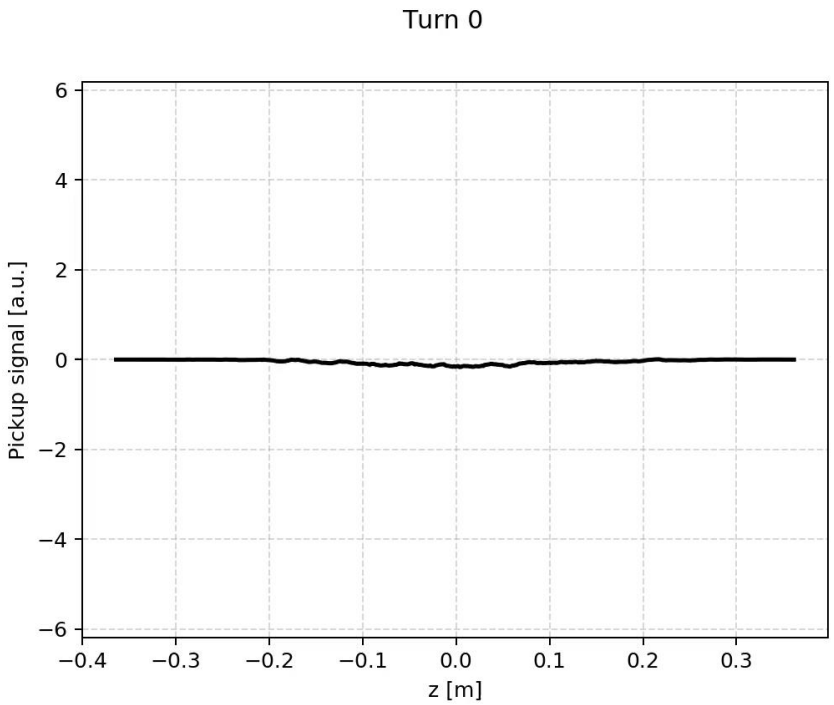
Frequency Analysis

We perform a **Fourier transform of the intra-bunch motion**

- We are measuring the number of the intra-bunch oscillations







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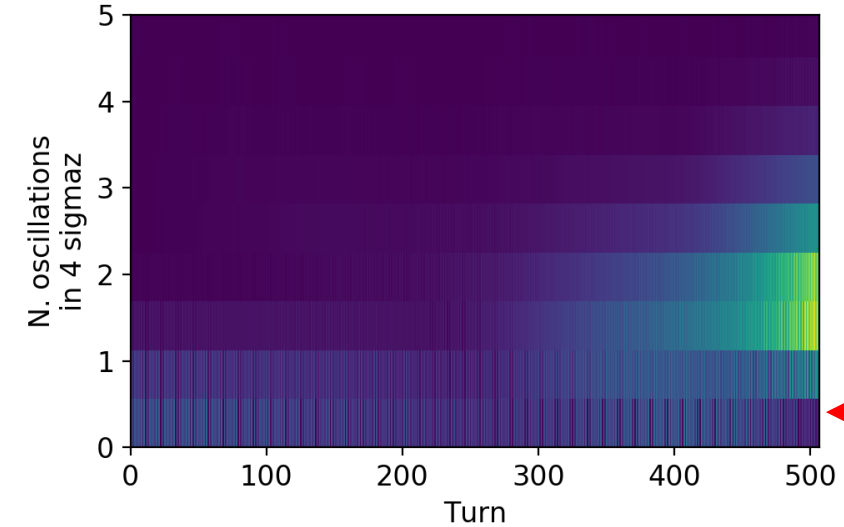
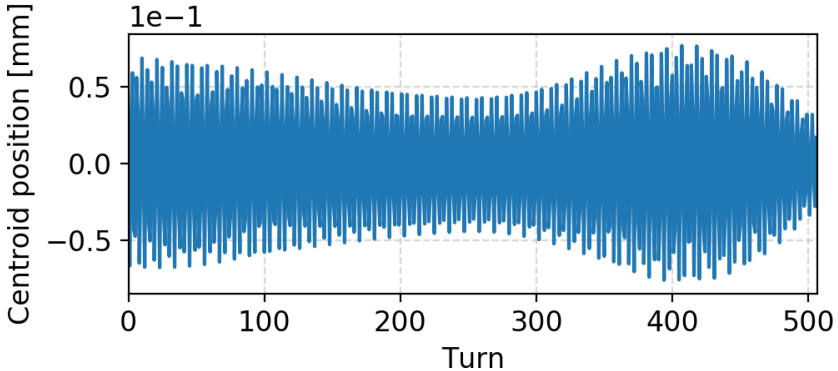


Not much activity on the **"rigid bunch" line**



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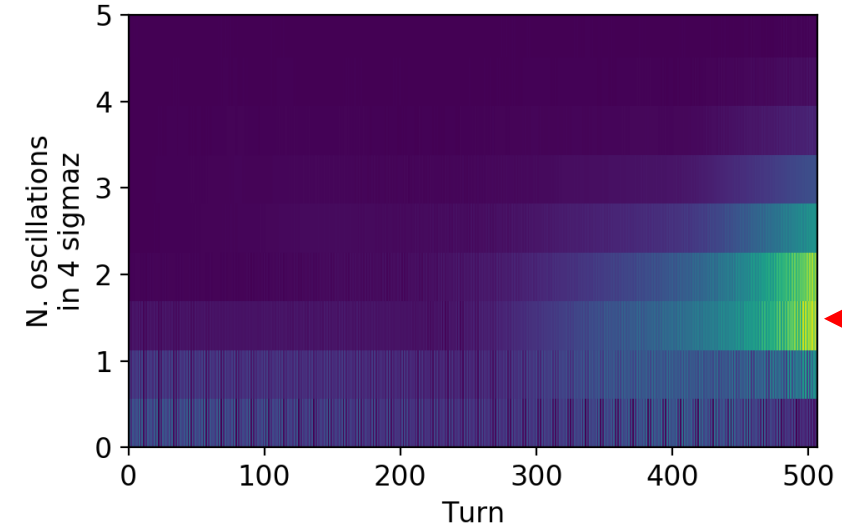

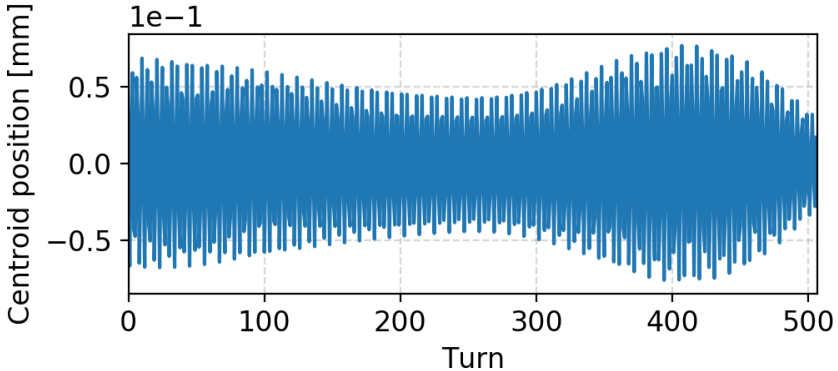

Instability clearly visible on **higher intra-bunch ""mode""**

Frequency Analysis

We perform a **Fourier transform of the intra-bunch motion**

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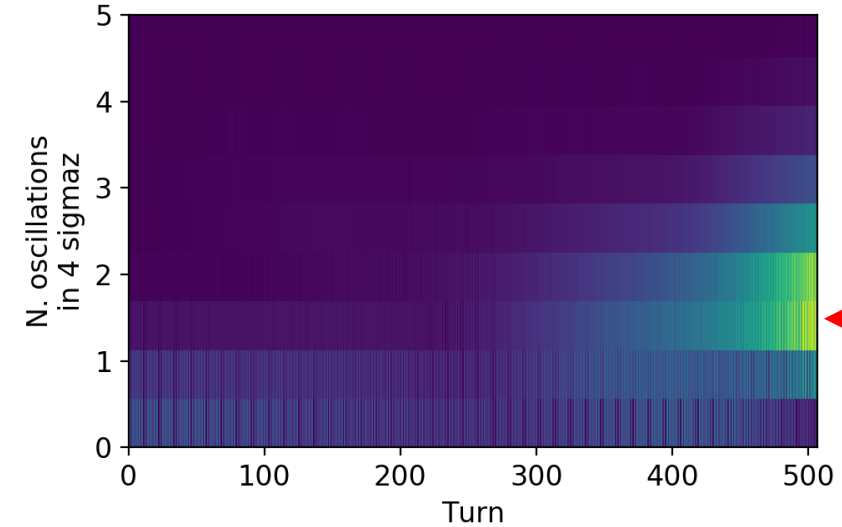
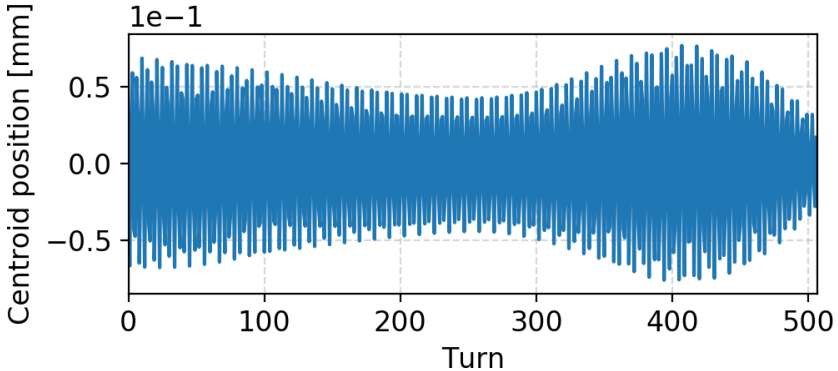
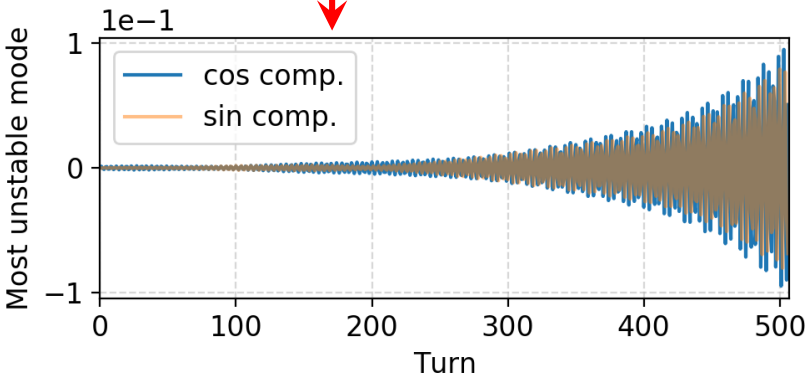


Instability clearly visible on **higher intra-bunch ""mode""**





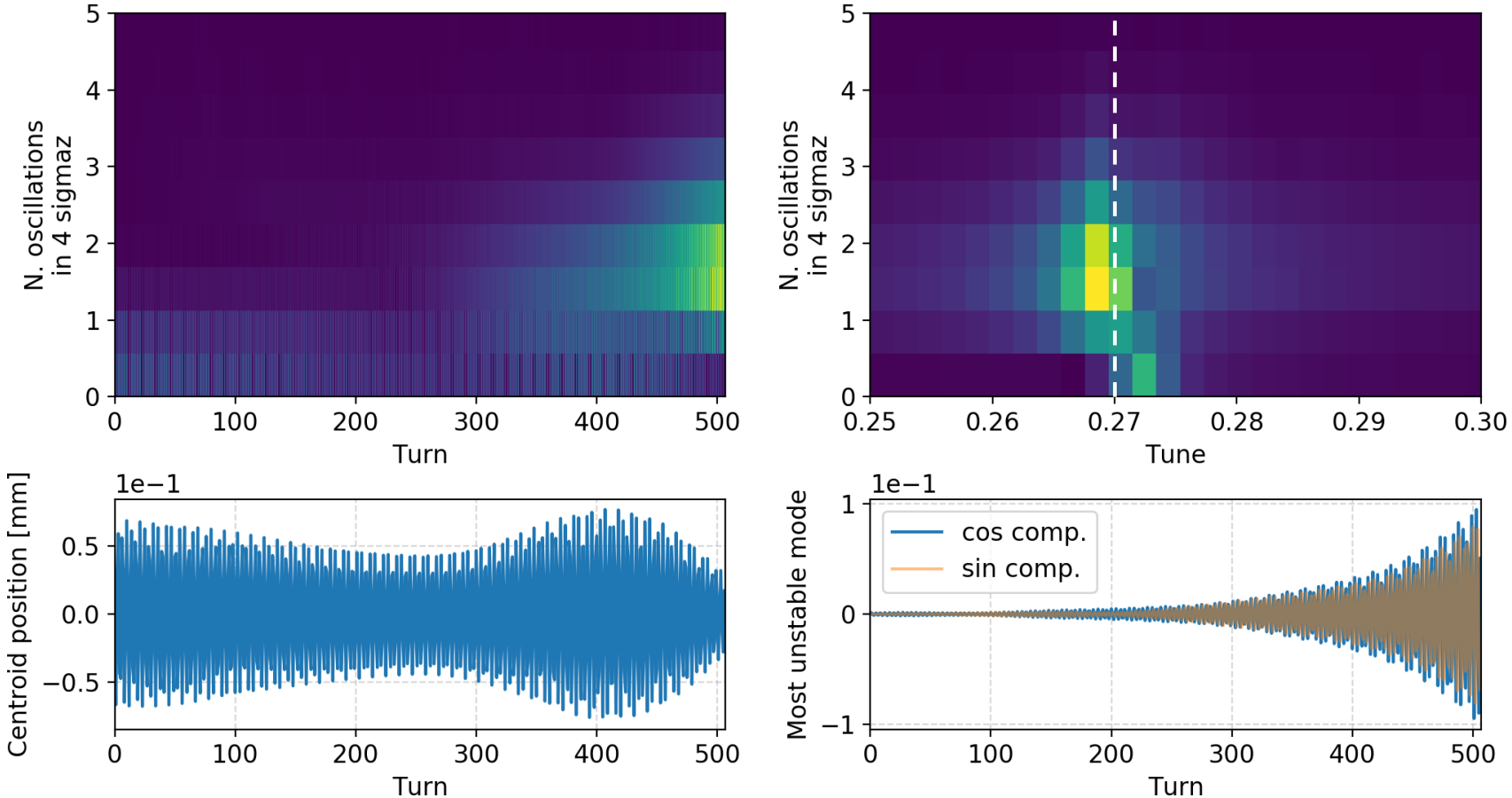
Frequency Analysis

We perform a **Fourier transform of the intra-bunch motion**

- We are measuring the number of the intra-bunch oscillations

We apply **another Fourier** transform w.r.t. turn number

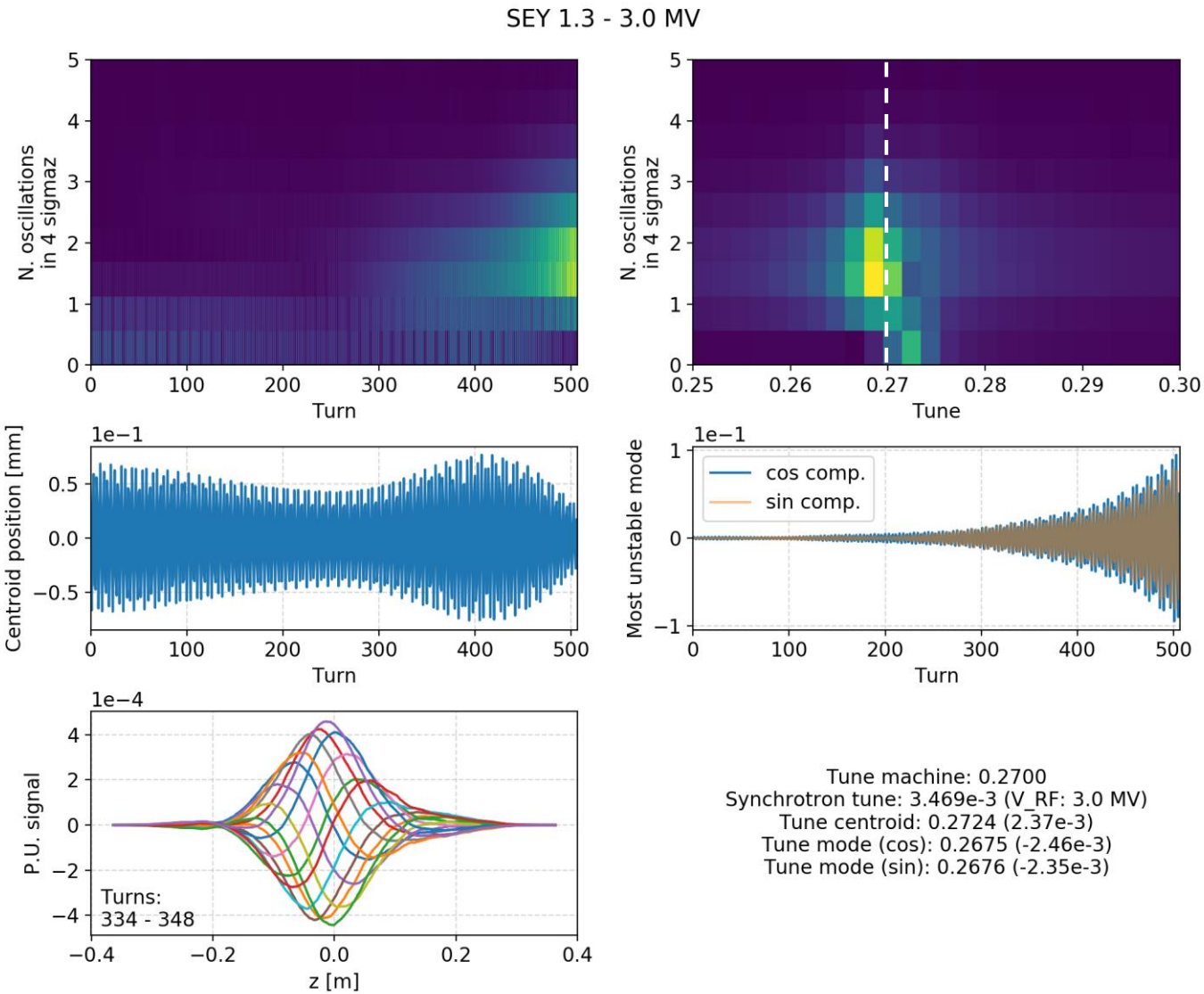
- The **rigid bunch line** that has a **positive tune shift** (typical for e-cloud)
- The **unstable “”mode””** has a **negative tune shift**



Frequency Analysis

These features are **observed systematically over the simulation set**

- The tune of the unstable line seems **correlated to Q_s**



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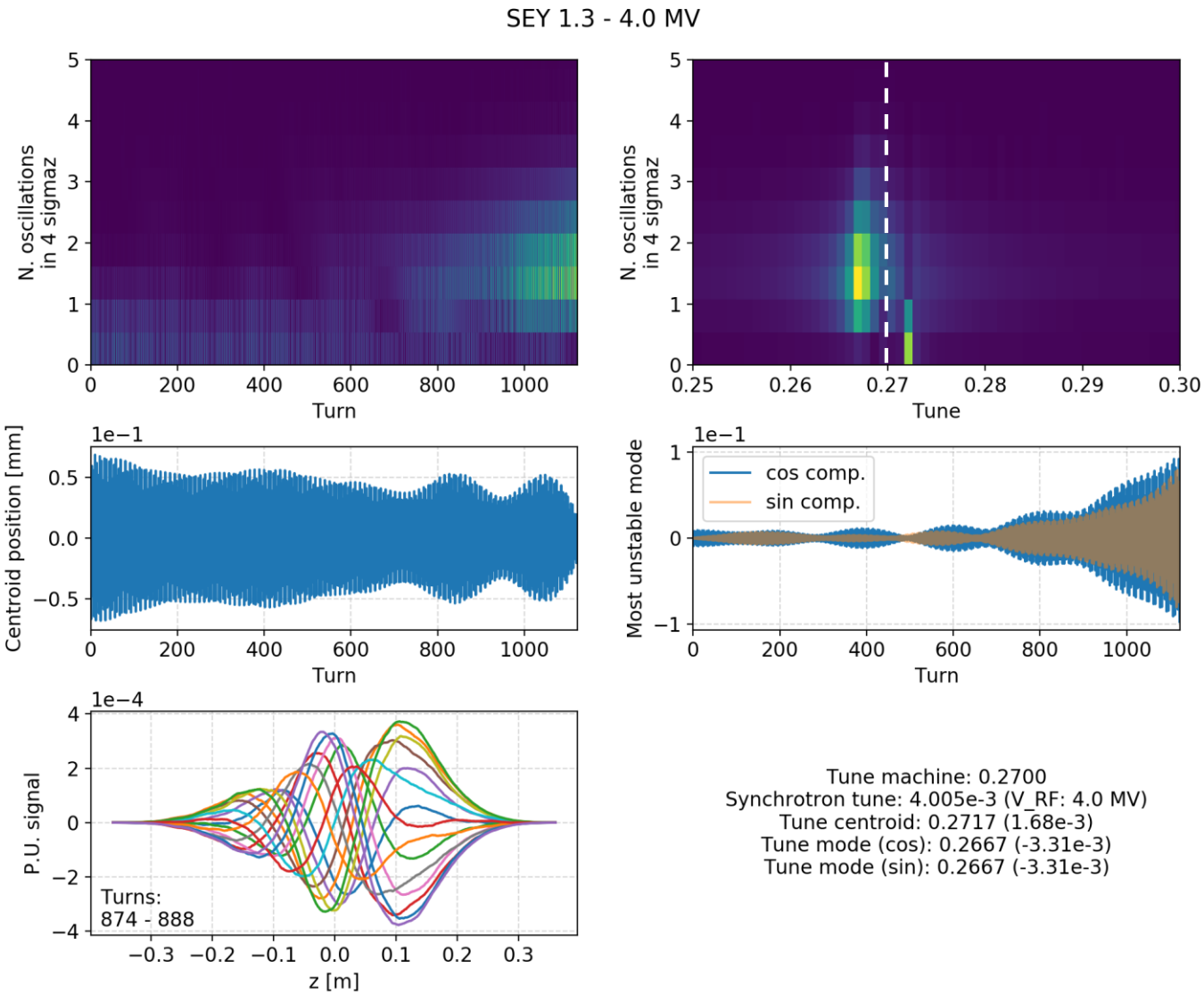

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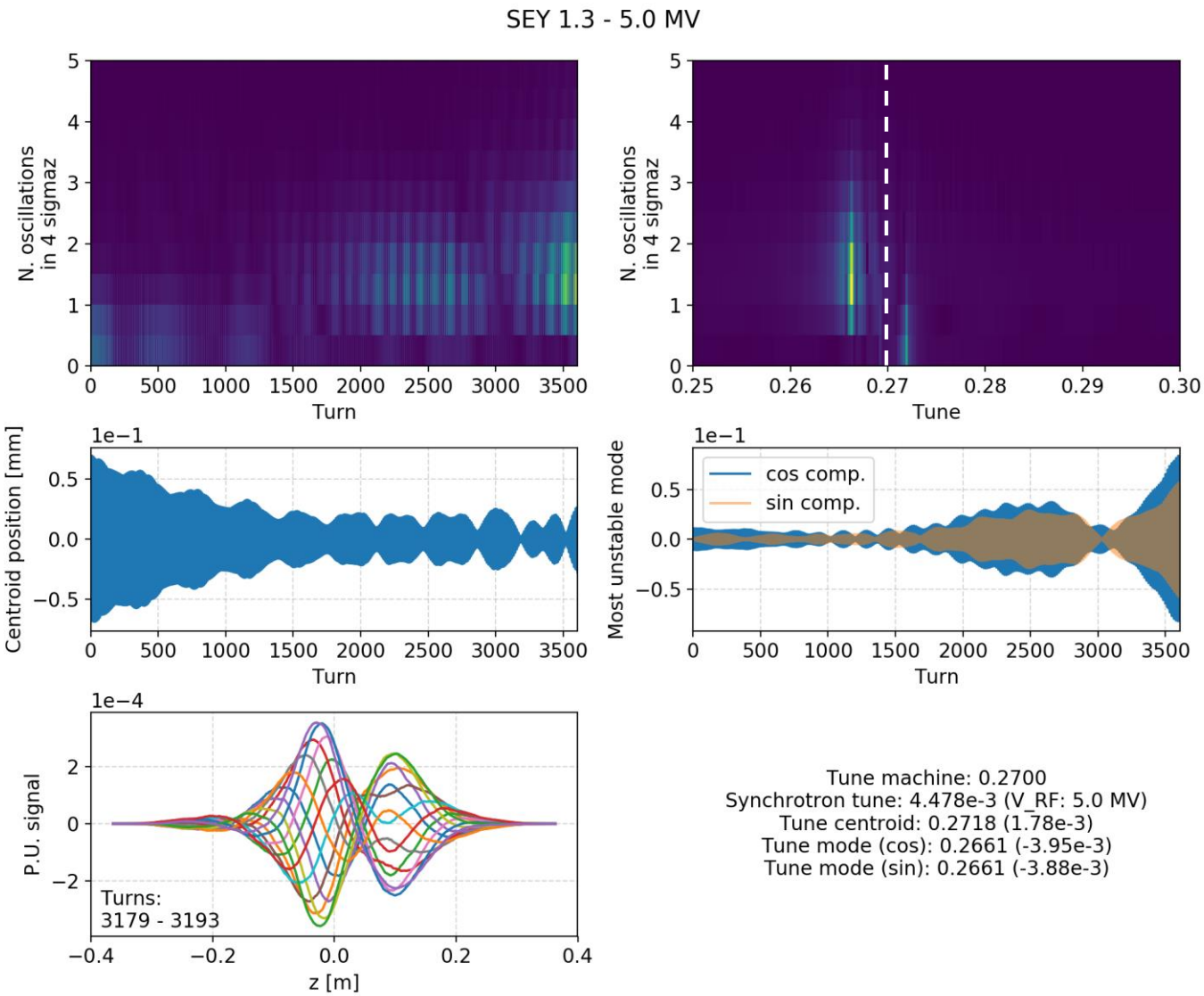

Frequency Analysis

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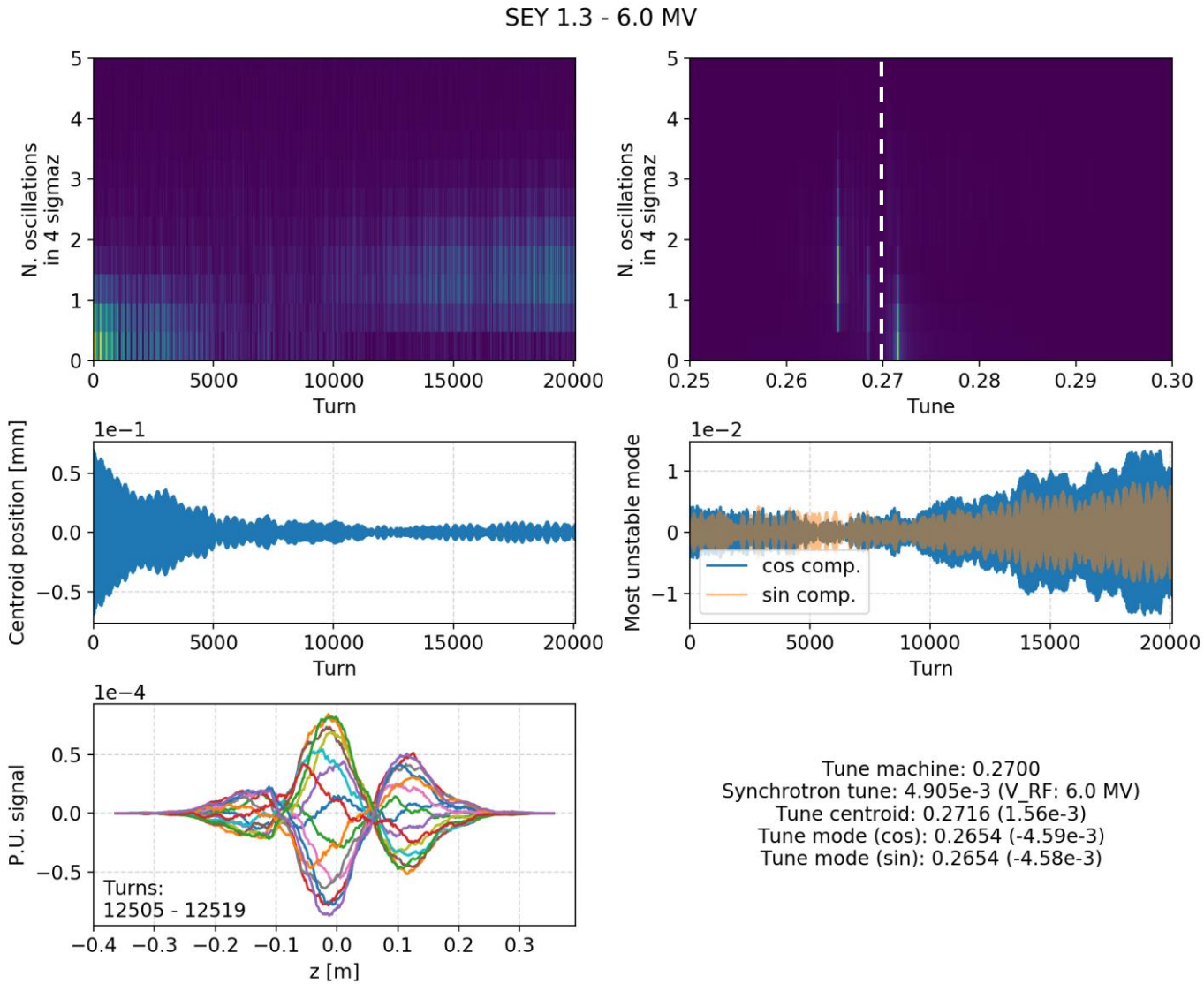

Frequency Analysis

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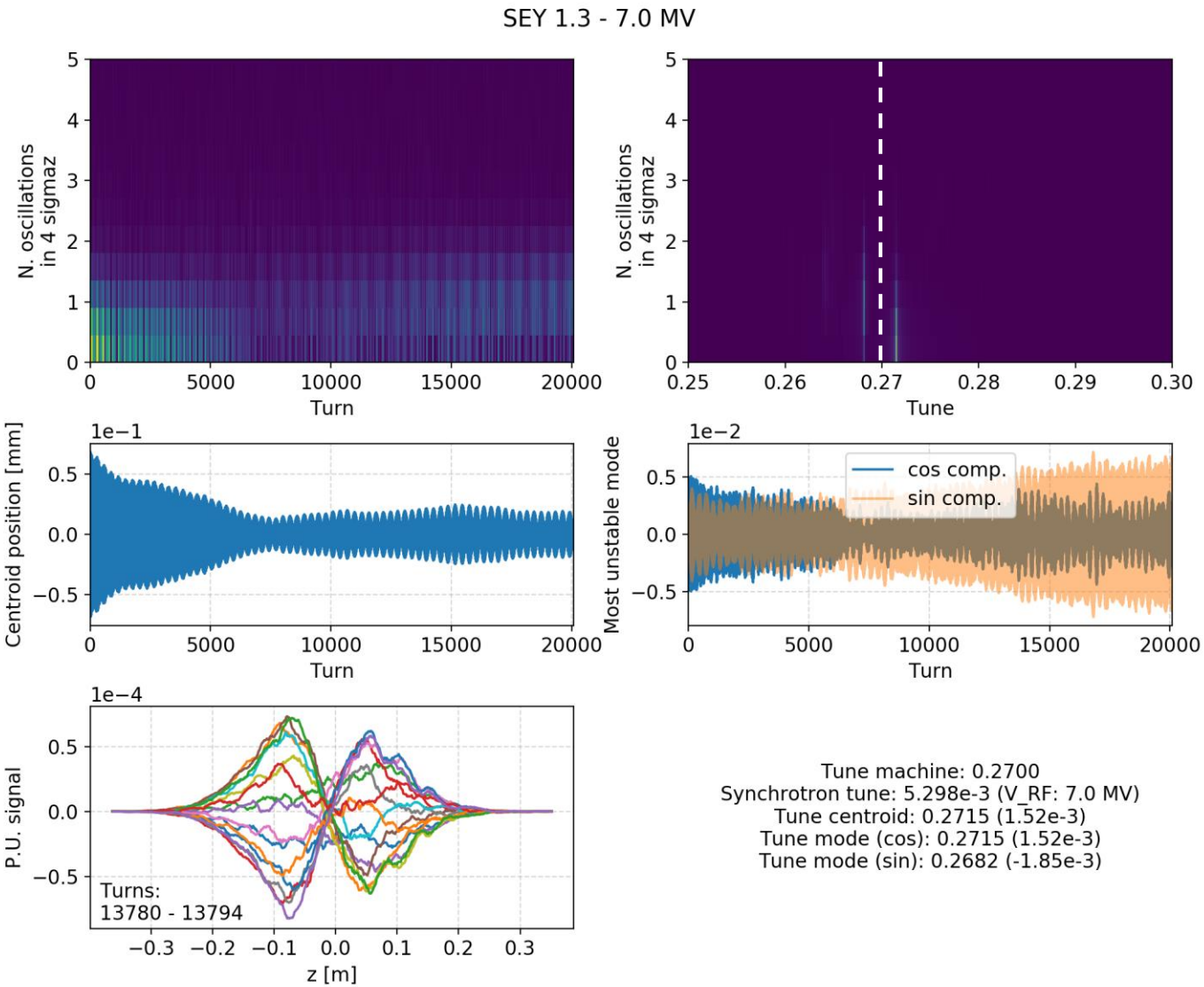
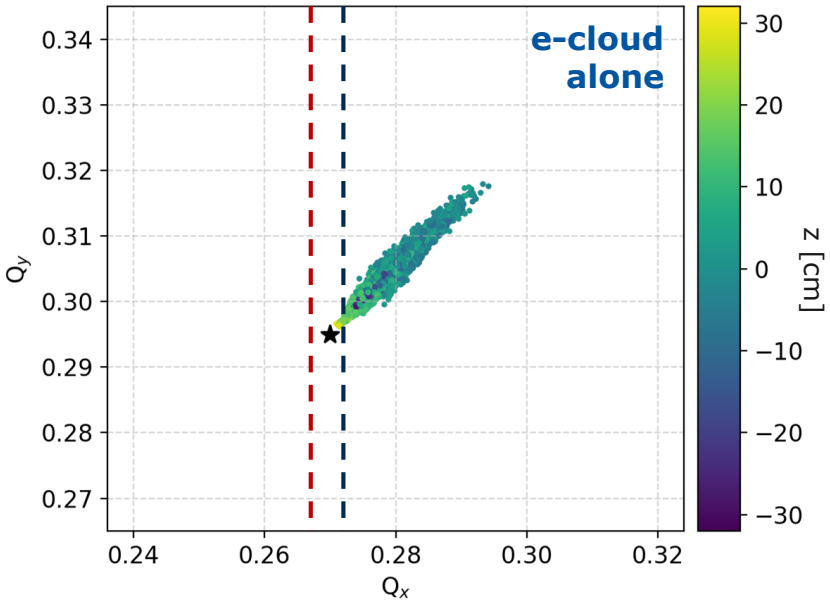
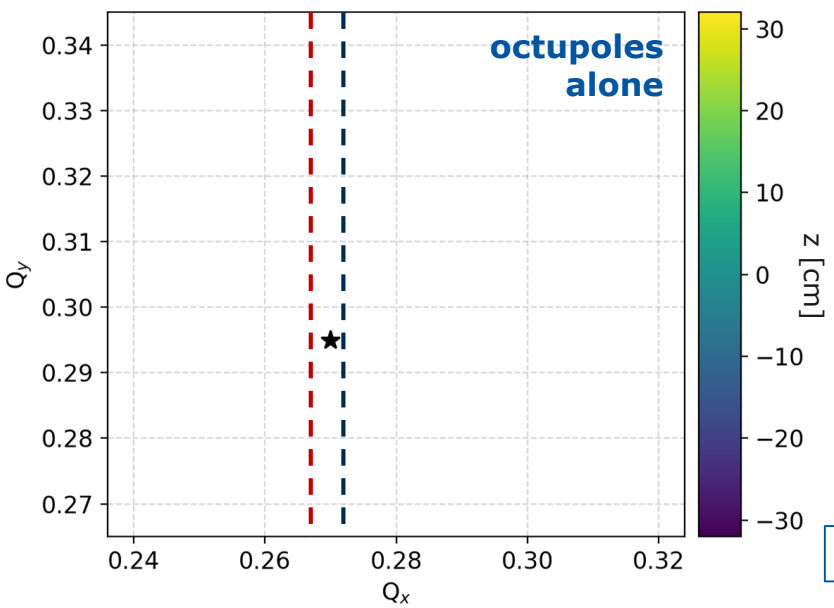
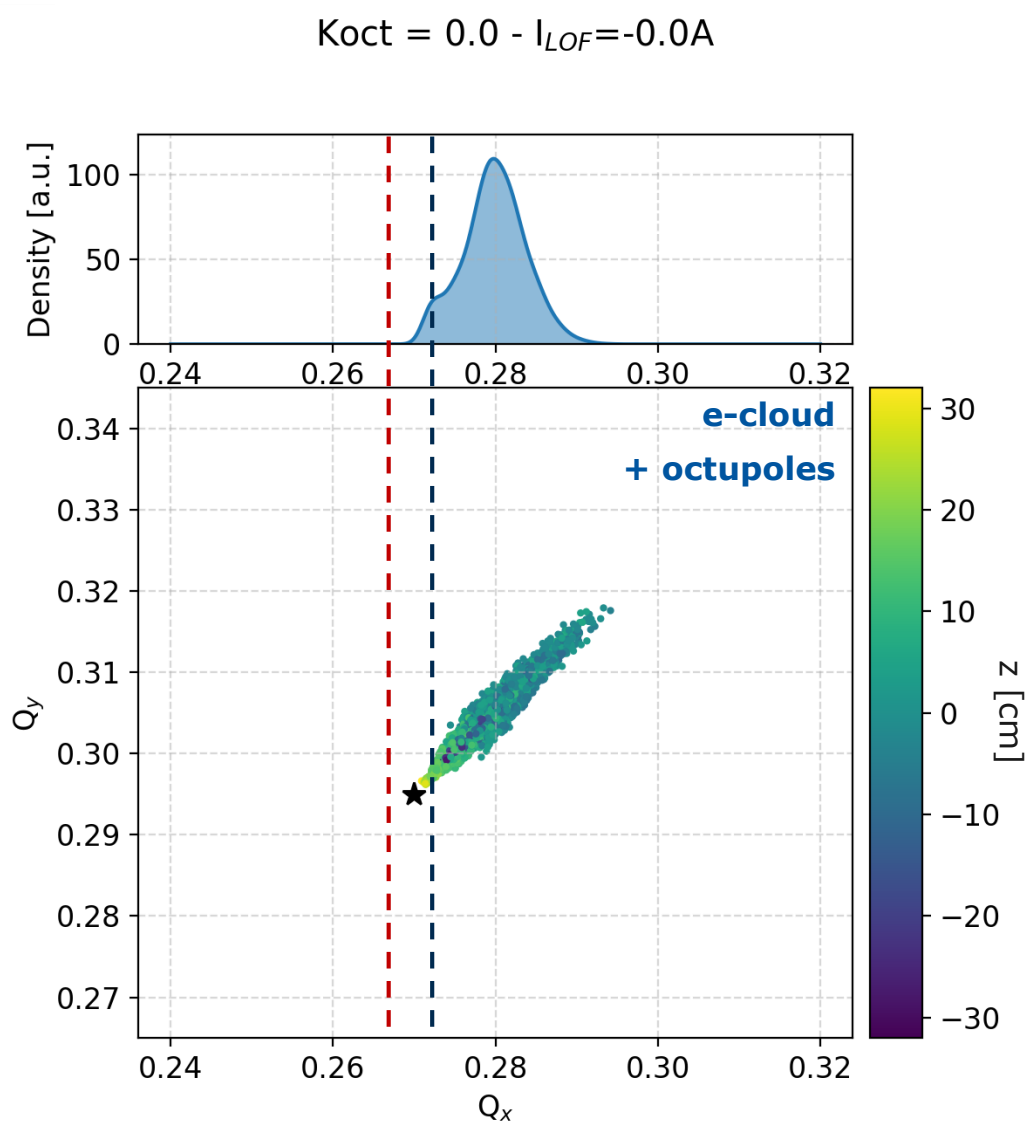


Footprints - Effect of the Octupoles

There is **little overlap** between the spread and the unstable frequency



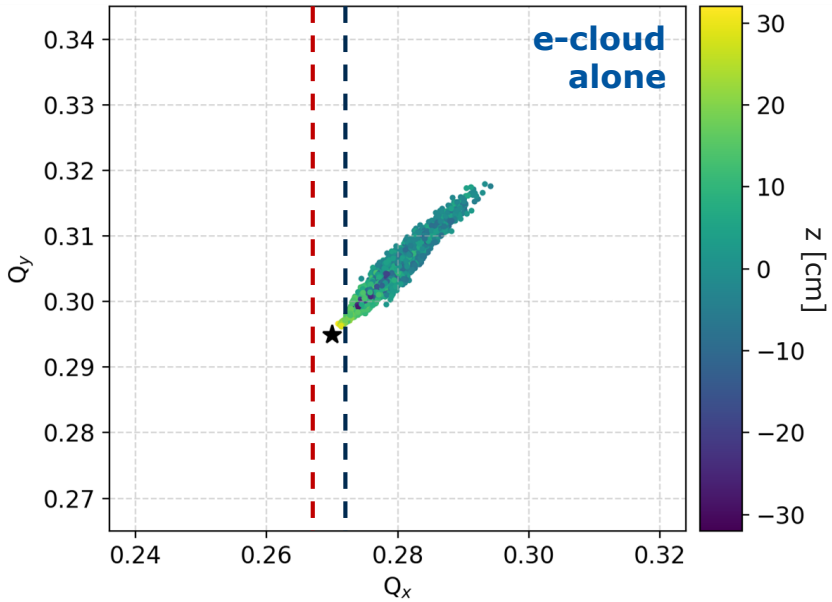


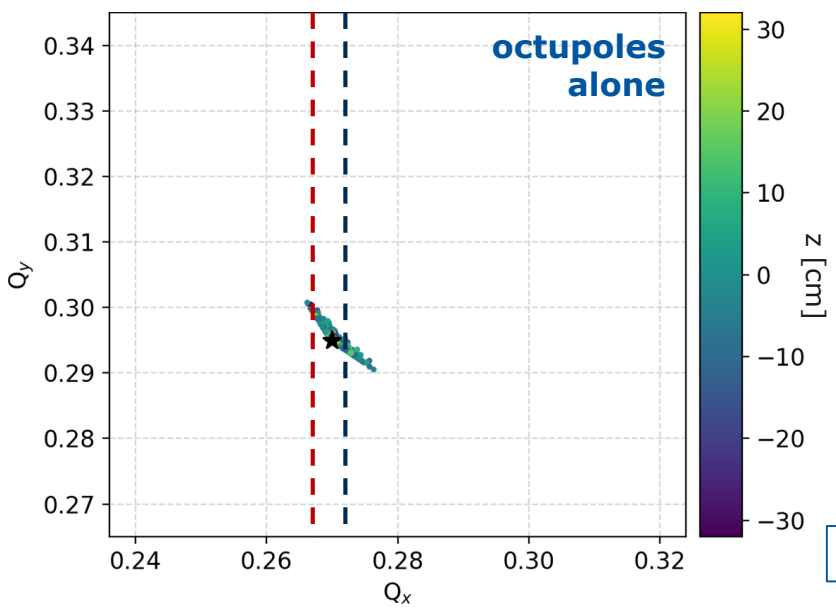


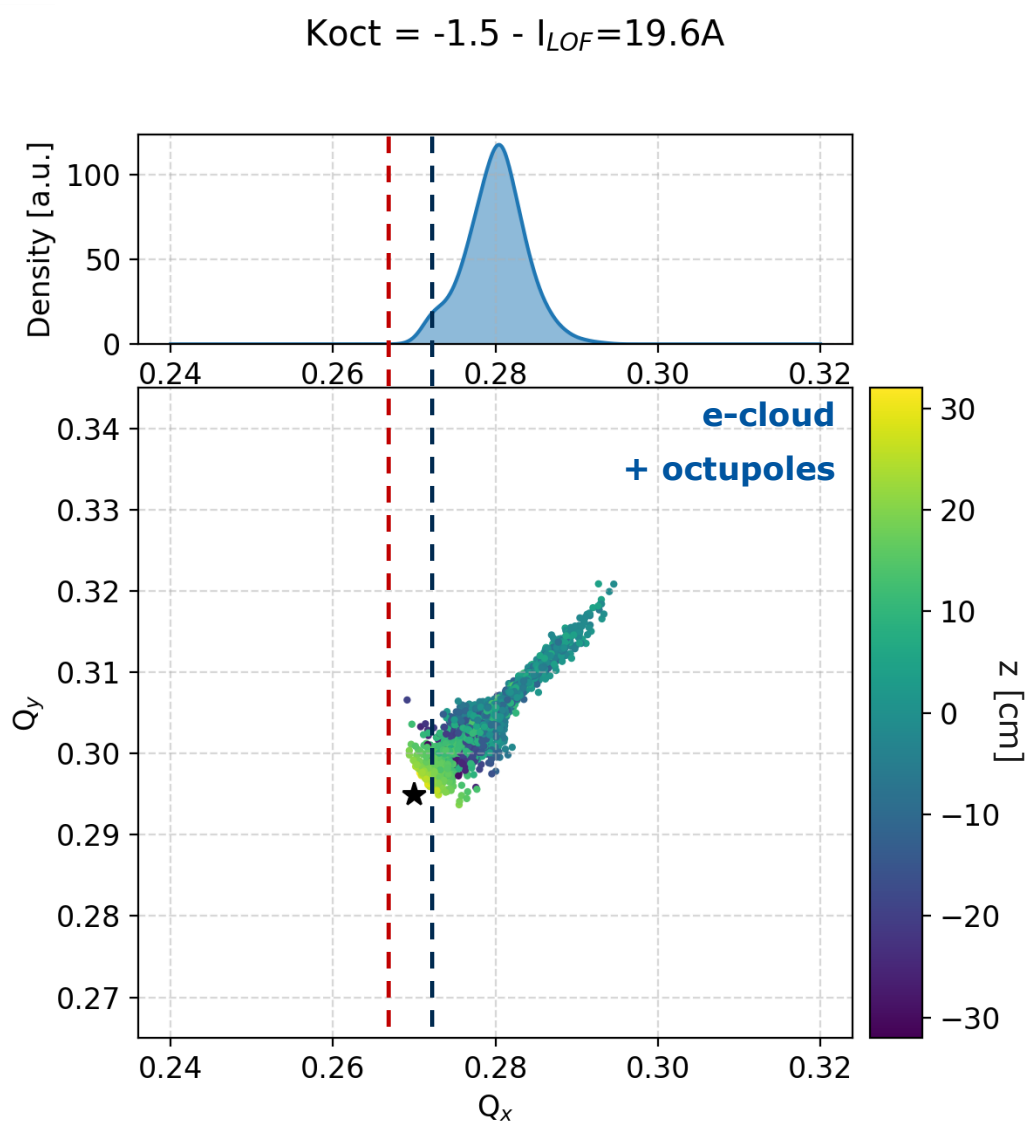
★ Machine tune - - - Instability freq. - - - Centroid freq.

Footprints - Effect of the Octupoles

There is **little overlap** between the spread and the unstable frequency







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Footprints - Effect of the Octupoles

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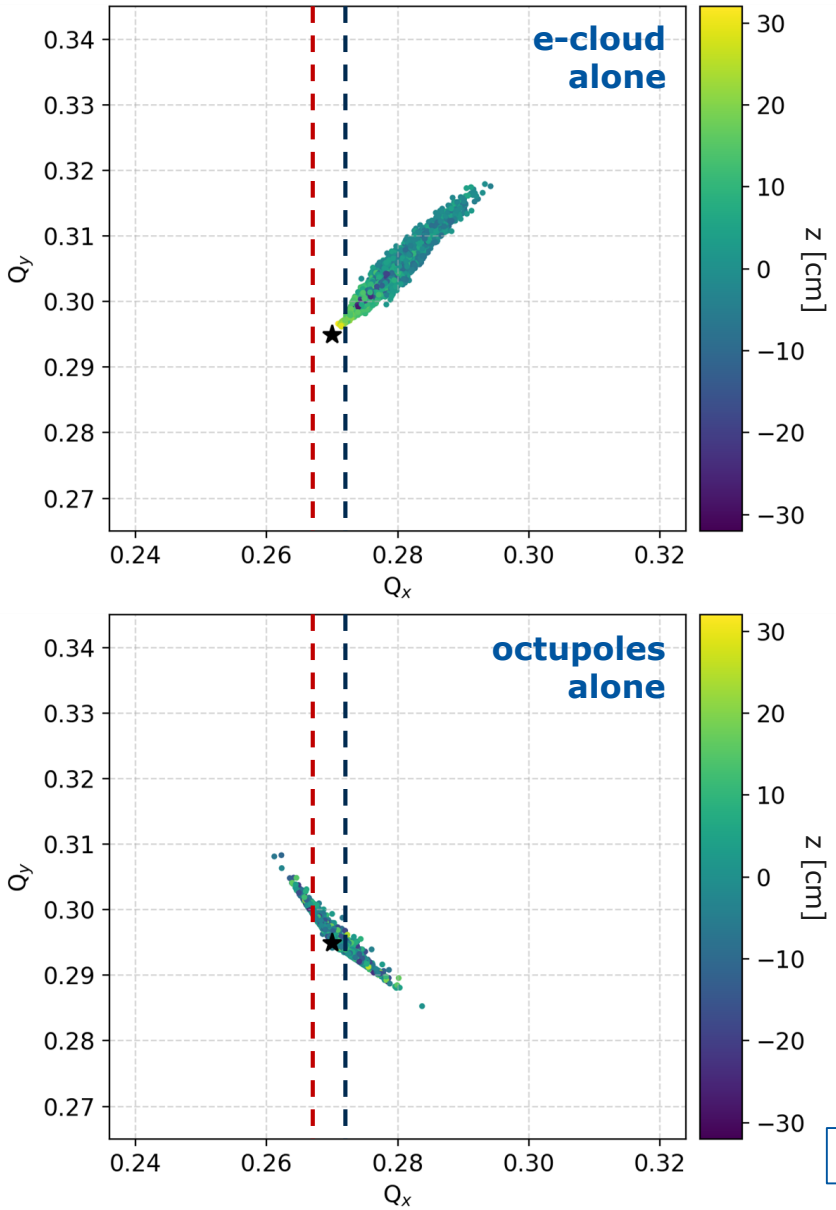

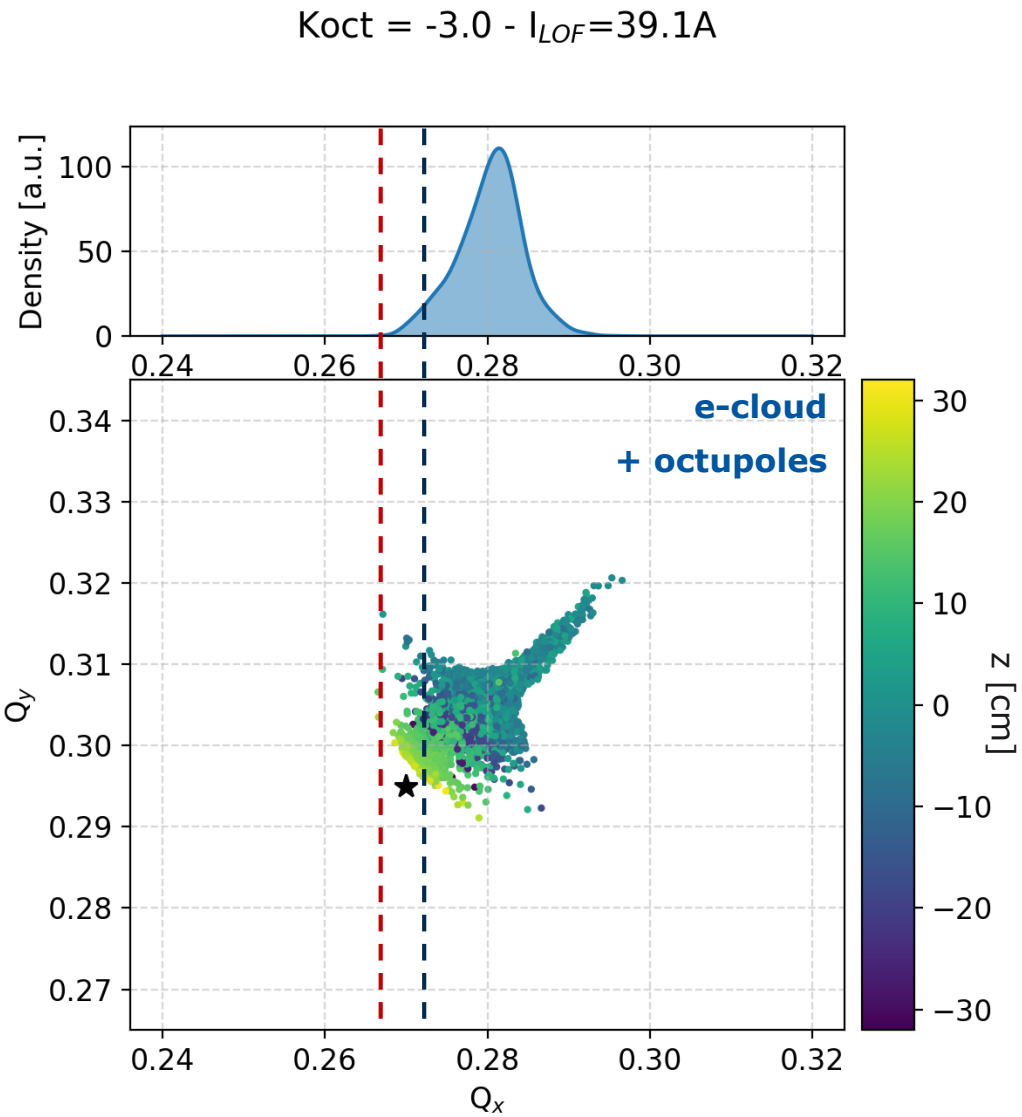

★ Machine tune - - - Instability freq. - - - Centroid freq.

Footprints - Effect of the Octupoles

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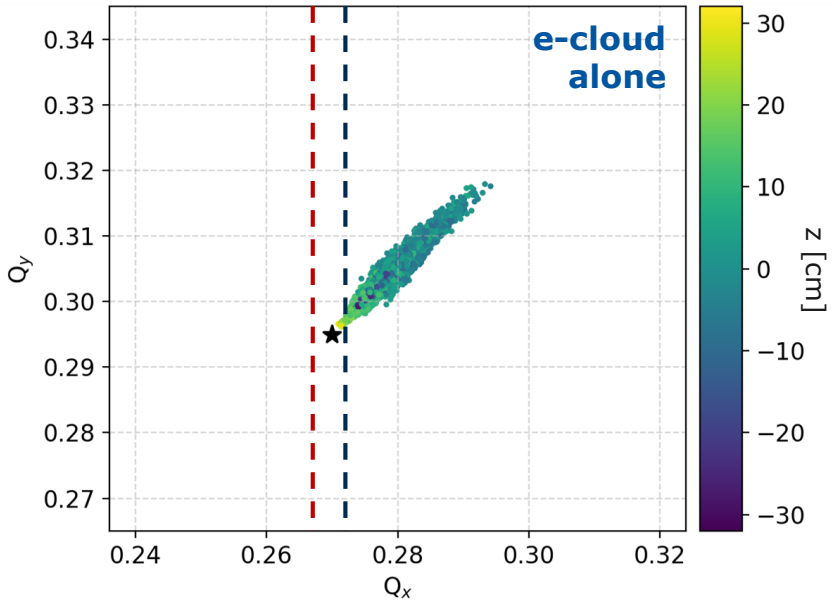

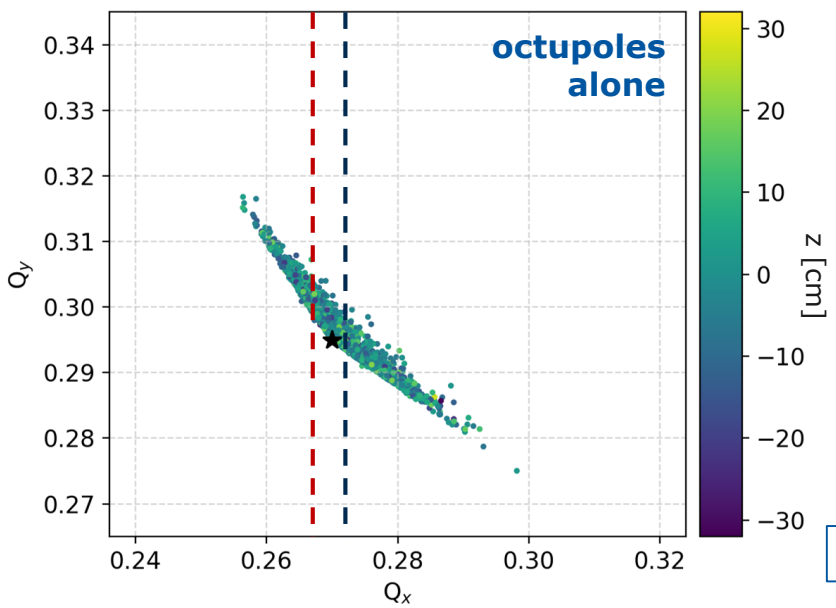

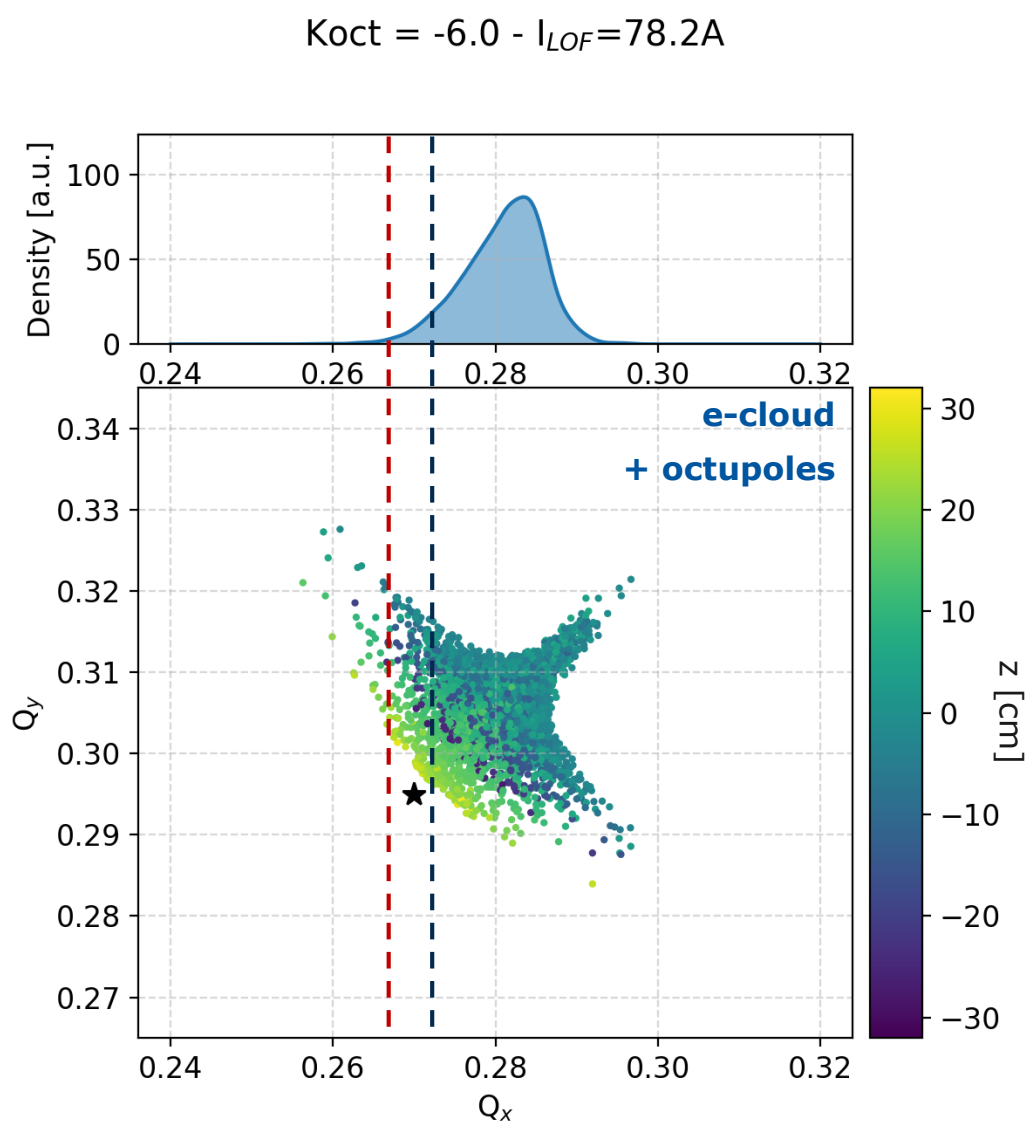

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Footprints - Effect of the Octupoles

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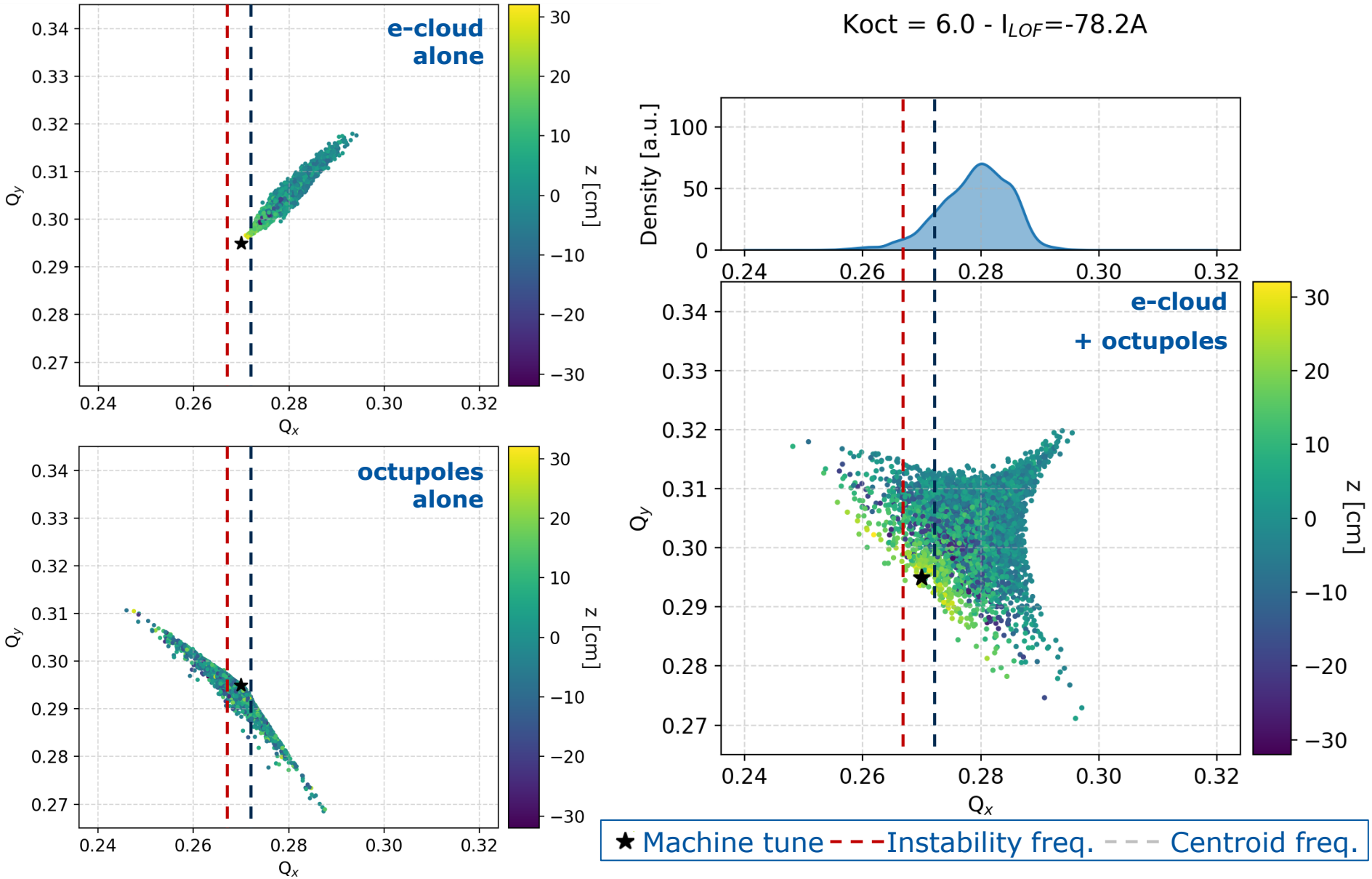
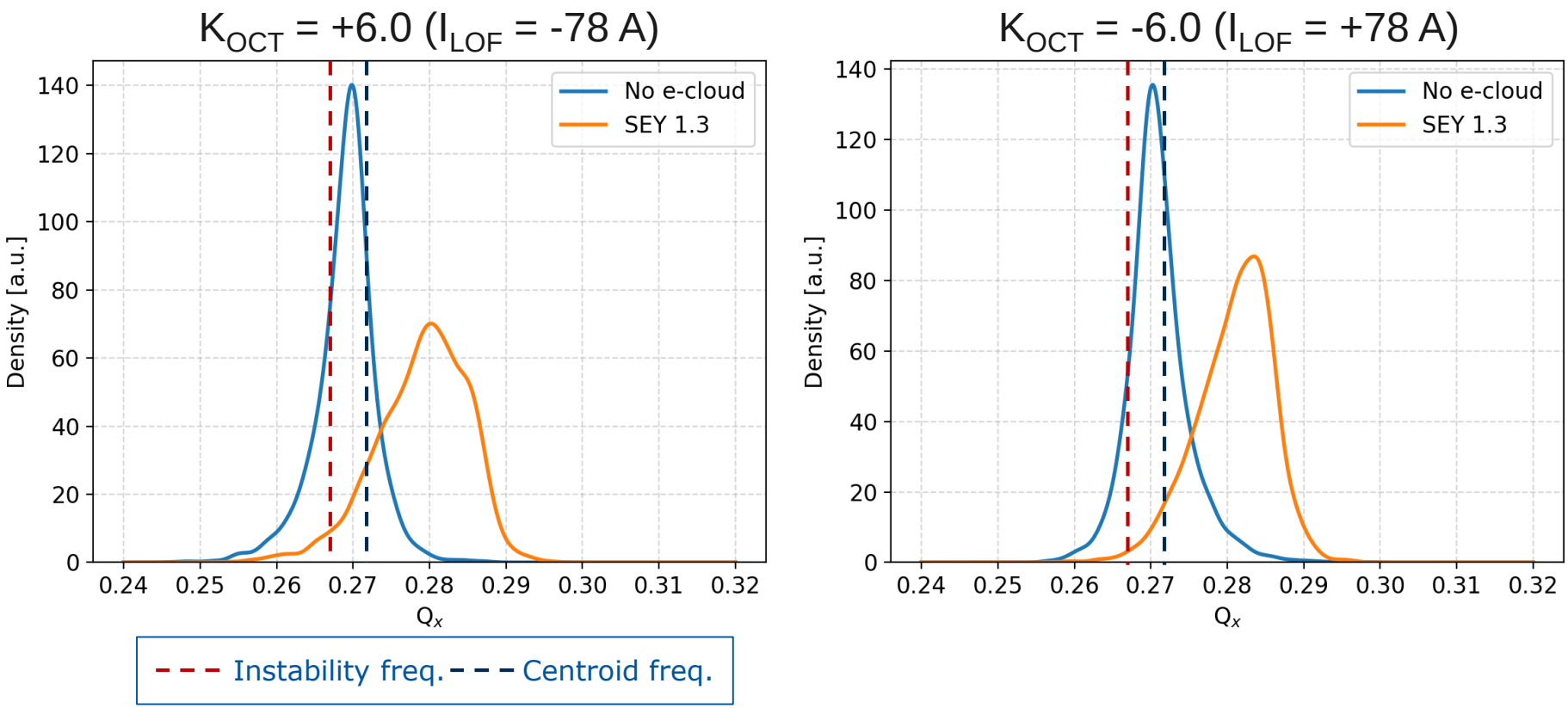


Footprints - Effect of the Octupoles



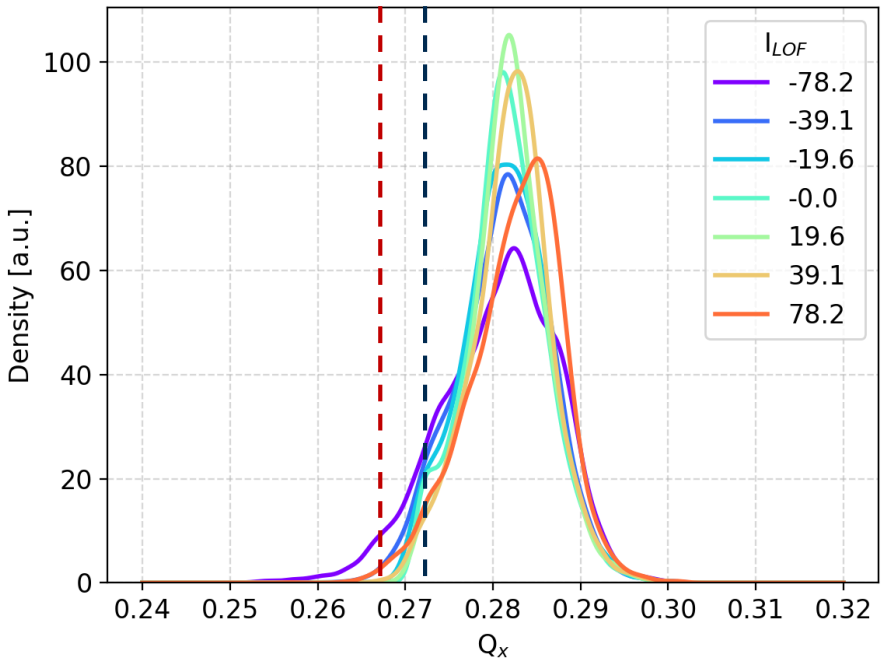
The e-cloud is **pushing the tune spread away** from the the instability frequency

- Effect of **octupole polarity** is minor but visible

Footprints - Effect of the Octupoles

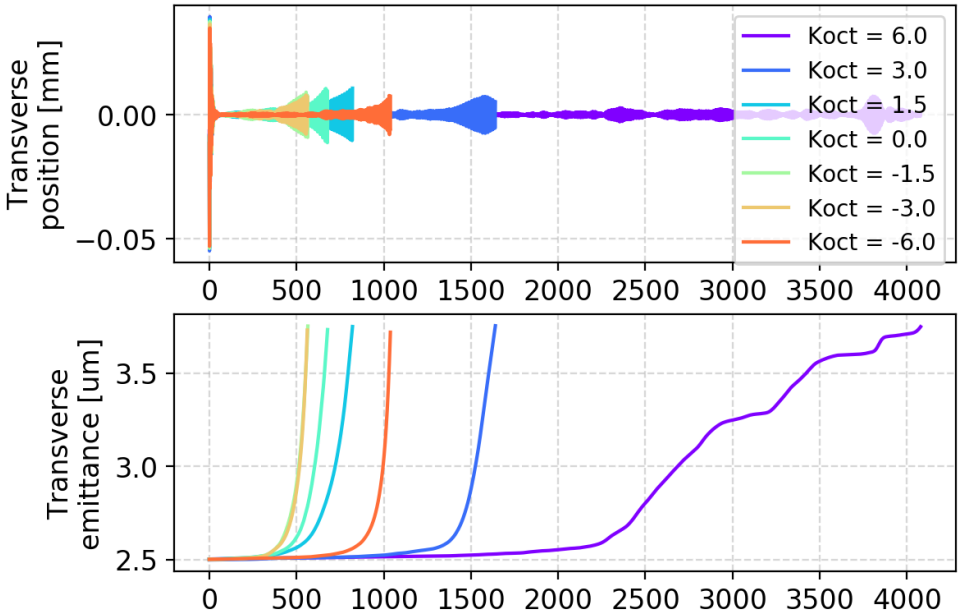
- The **instability risetime** looks **correlated with the tune-spread population around the unstable frequency**

Tune spreads



Instability freq. Centroid freq.

Coherent instability (Q' = 2.5)



Outline

- Introduction
- Convergence Studies
- Bunch Length and RF voltage
- Effect of SEY and Bunch Charge
- Chromaticity and Damper
- Octupoles
- Frequency Analysis
- **Conclusions and Future Developments**

Conclusions

- Extensive convergence studies at injection are carried out
- Decreasing V_{RF} the bunch is more unstable
  - dominant factor is the de-stabilising effect due to the change of the synchrotron tune
- No instability for 2.3e11 ppb in the entire range of parameters
  - electron density at bunch location is smaller for high intensity
- Damper does not affect significantly the instability (unable to suppress intra-bunch motion)
- Positive chromaticity strongly mitigates the instability
- Octupoles are less effective compared to chromaticity
- Frequency analysis reveals that
  - The unstable line has a negative tune shift
  - E-cloud pushes the tune spread away from the unstable line, fighting against Landau damping

Thanks for your attention

Spares

Introduction: Numerical Parameters

The motivation of these convergence studies is to find the lower acceptable values for the numerical parameters:

5. transverse grids

Introduction: Numerical Parameters

The motivation of these convergence studies is to find the lower acceptable values for the numerical parameters:

5. transverse grids
   - Single grid
     - PyPICmode = ‘FiniteDifference_ShortleyWeller’
     - Dh_sc_ext

Introduction: Numerical Parameters

The motivation of these convergence studies is to find the lower acceptable values for the numerical parameters:

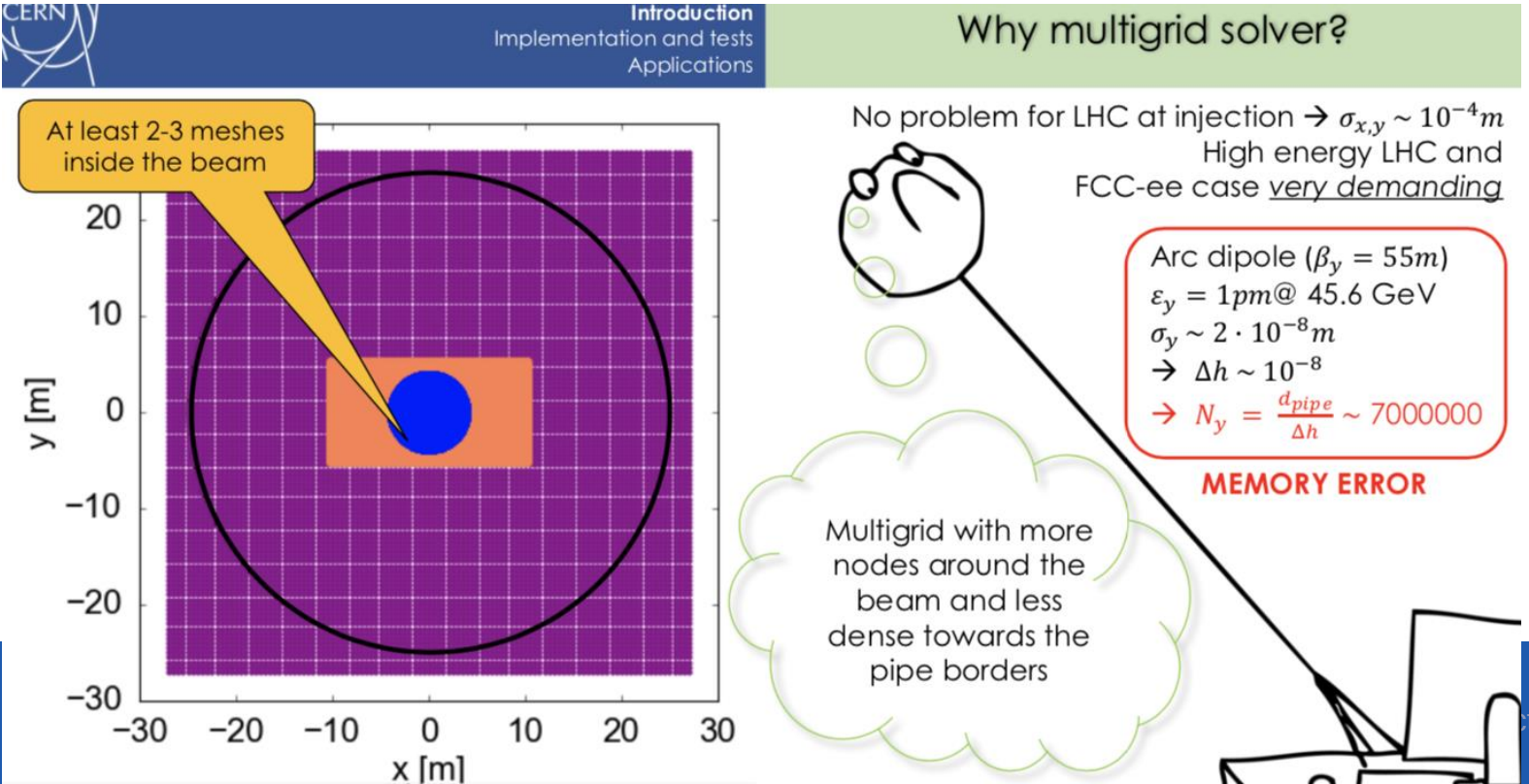
5. transverse grids
   - Multigrid **[1]**:

[1] E. Belli, "PyPIC: the multigrid solver", EC Meeting #32 – September 2, 2016

Introduction: Numerical Parameters

The motivation of these convergence studies is to find the lower acceptable values for the numerical parameters:

5. transverse grids
   - Multigrid:



Courtesy of E. Belli

Introduction: Numerical Parameters

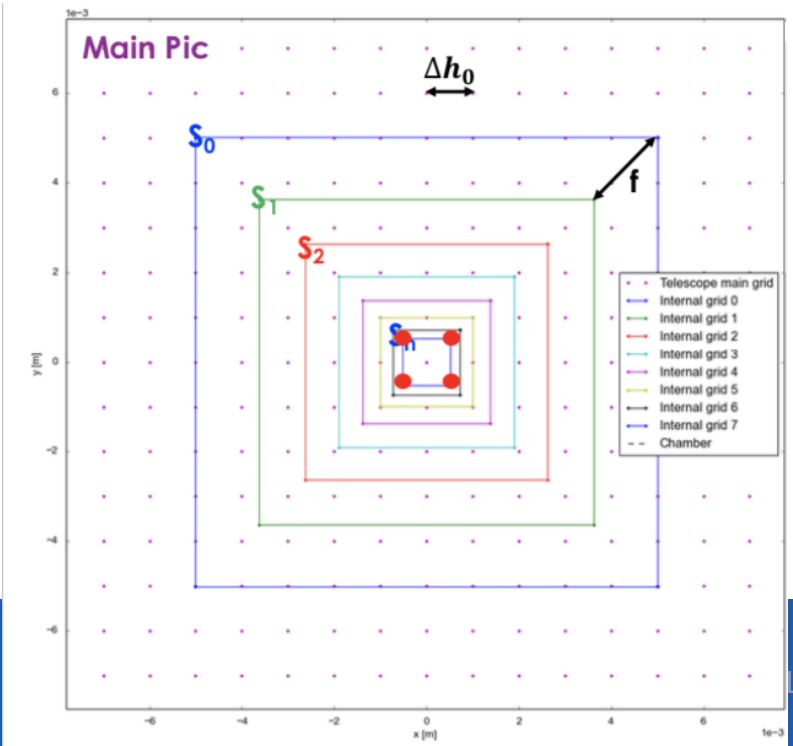
The motivation of these convergence studies is to find the lower acceptable values for the numerical parameters:

5. transverse grids
   - Multigrid:
     - PyPICmode = ‘ShortleyWeller_WithTelescopicGrids’
     - f_telescope
     - target_grid
       - target_size_internal_grid_sigma
       - target_Dh_internal_grid_sigma
     - N_nodes_discard
     - N_min_Dh_main
     - Dh_sc_ext

Introduction: Numerical Parameters

The motivation of these convergence studies is to find the lower acceptable values for the numerical parameters:

5. transverse grids
   - Multigrid:
     - **f_telescope**: Magnification factor between grids (0 < f < 1)



Size of the i-th internal grid

$$S_i = f\ S_{i-1} \quad (0 < f < 1)$$

Size of the final grid

$$S_n = f^n S_0$$

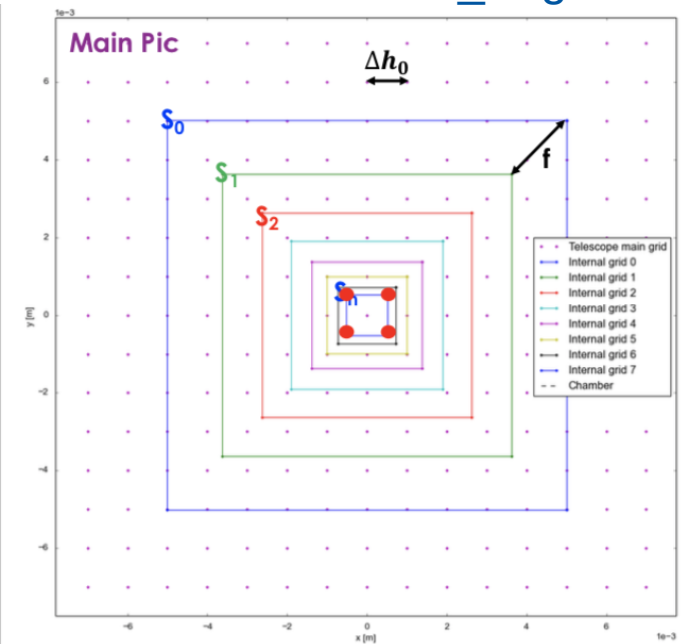
f: Magnification factor between grids $0 < f < 1$

Courtesy of E. Belli

Introduction: Numerical Parameters

The motivation of these convergence studies is to find the lower acceptable values for the numerical parameters:

5. transverse grids
   - Multigrid:
     - **target_grid**: dictionary with the internal grid parameters: ‘x_min_target’, ‘x_max_target’, ‘y_min_target’, ‘y_max_target’, ‘Dh_target’



Parameters of the target grid

$x_{min}, x_{max}, y_{min}, y_{max}, \Delta h_{target}$

Size of target grid

$S_n = f^n \cdot N \cdot \Delta h_0 = S_{target}$

Courtesy of E. Belli

Introduction: Numerical Parameters

The motivation of these convergence studies is to find the lower acceptable values for the numerical parameters:

5. transverse grids
   - Multigrid:
     - target_grid: dictionary with the internal grid parameters

Can be given also in terms of transverse sigma of the beam:

- **target_size_internal_grid_sigma**
- **target_Dh_internal_grid_sigma**

```
target_grid_arcs = {
        'x_min_target':-pp.target_size_internal_grid_sigma*sigma_x_smooth,
        'x_max_target':pp.target_size_internal_grid_sigma*sigma_x_smooth,
        'y_min_target':-pp.target_size_internal_grid_sigma*sigma_y_smooth,
        'y_max_target':pp.target_size_internal_grid_sigma*sigma_y_smooth,
        'Dh_target':pp.target_Dh_internal_grid_sigma*sigma_x_smooth}
```

Introduction: Numerical Parameters

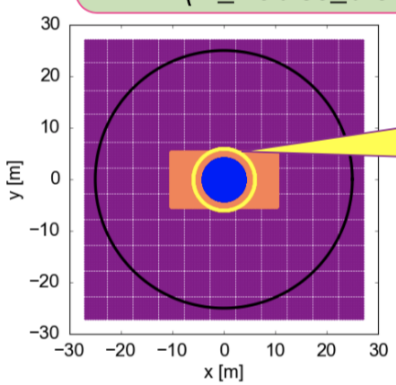
The motivation of these convergence studies is to find the lower acceptable values for the numerical parameters:

5. transverse grids
   - Multigrid:
     - **N_nodes_discard**: number of nodes at the edge of the internal grids which are discarded in the field interpolation

Step 4: GATHER

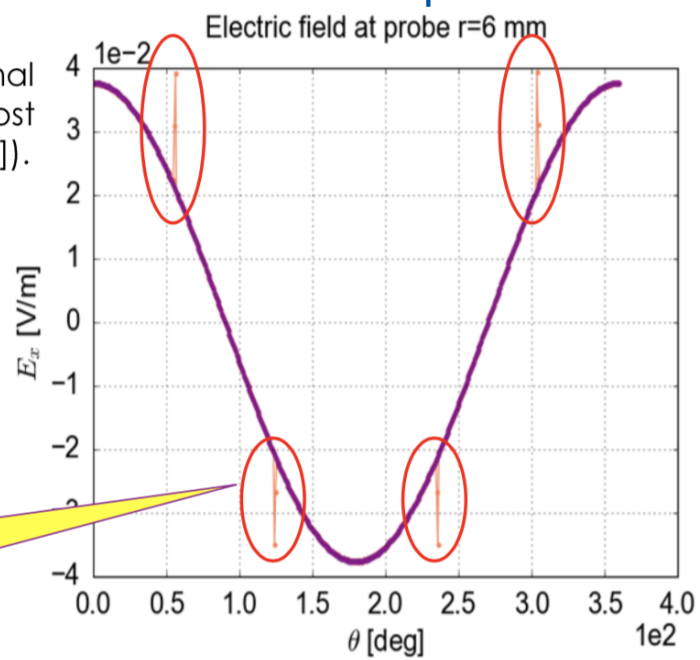
An artifact is introduced at the edge of the internal grid, which can be avoided by discarding the most external nodes when interpolating (as described in [1]).

The user can define the number of nodes to be discarded : (**N_nodes_discard** to be set ≠ 0)



The probe ($r = 6mm$) crosses the edges of the internal grid

If **N_nodes_discard=0** *an error is introduced during interpolation*



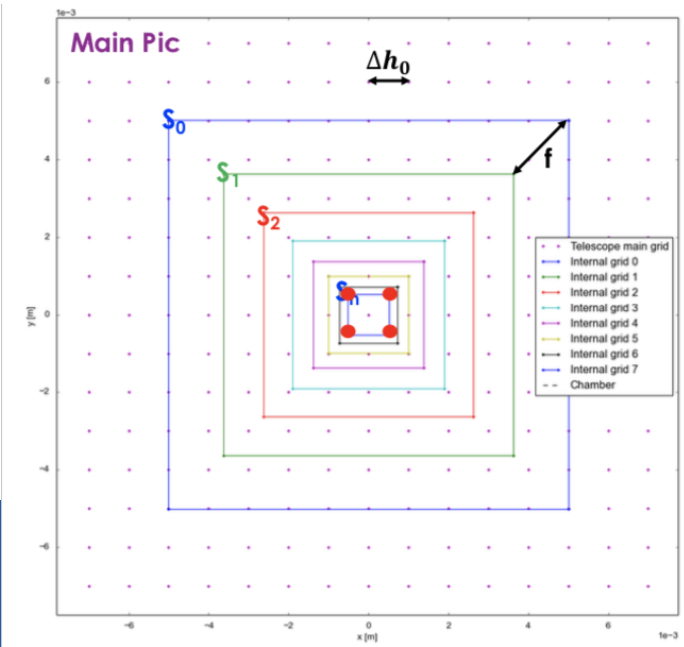
Courtesy of E. Belli

[1] Friedman A. *et al.*, Computational Methods in the Warp Code Framework for Kinetic Simulations of Particle Beams and Plasmas

Introduction: Numerical Parameters

The motivation of these convergence studies is to find the lower acceptable values for the numerical parameters:

5. transverse grids
   - Multigrid:
     - **N_min_Dh_main**: minimum size of the first internal grid, in number of points of the step of the main grid



Size of the refinement grid of the main pic

$$S_0 = N\Delta h_0$$

N: Minimum number of points of the first internal grid in the Δh_0 of the main grid

Courtesy of E. Belli

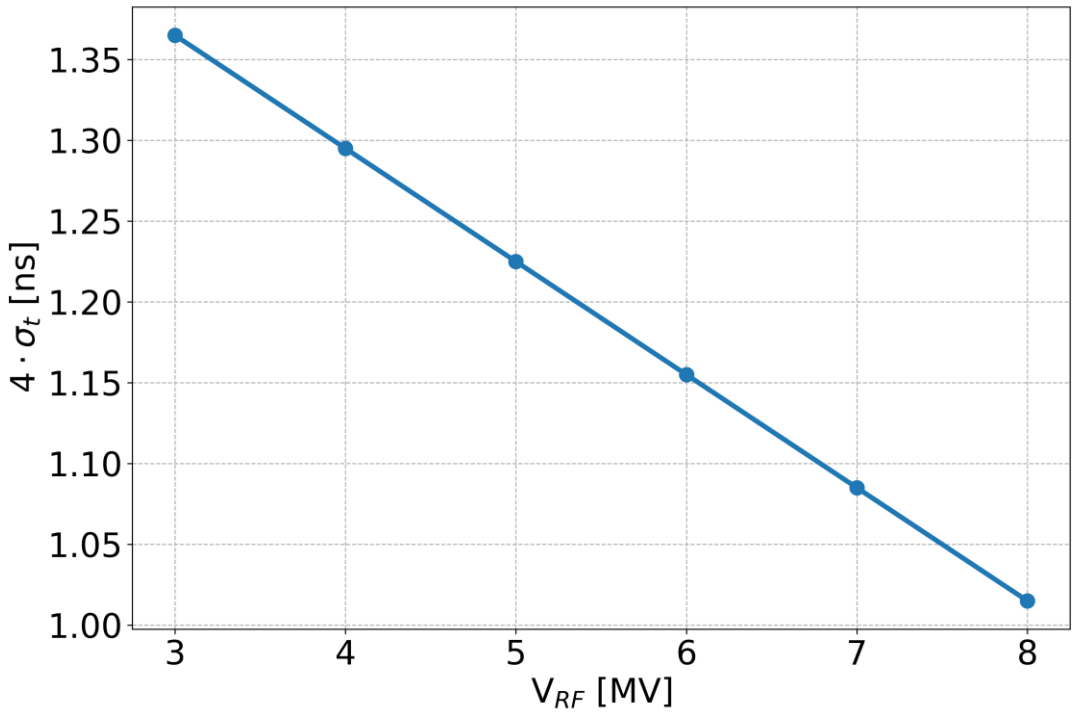
Introduction: Numerical Parameters

The motivation of these convergence studies is to find the lower acceptable values for the numerical parameters:

5. transverse grids
   - Multigrid:
     - **Dh_sc_ext**: step of the external grid

Introduction: Numerical Parameters

- Scan: $4\sigma_t$ (1.37 – 1.02 ns) / RF voltage (3 - 8 MV)

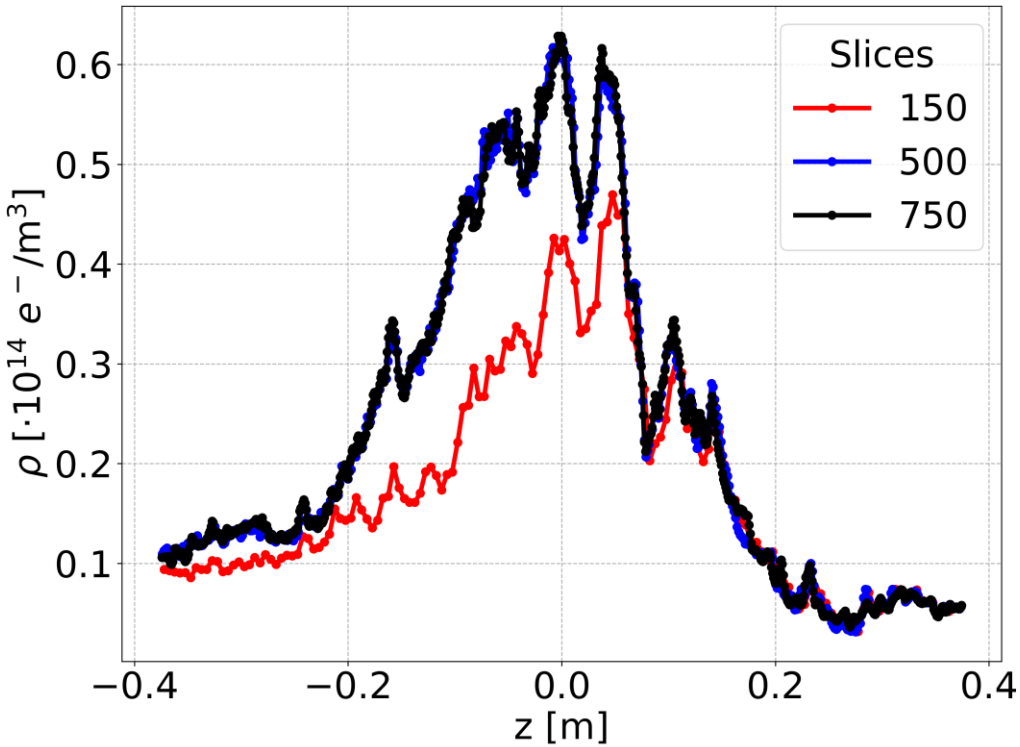


[1] H. Timko, "Injection Voltage Reduction In the LHC" – September 5, 2018

Convergence Studies: Pinch

To understand why such a large number of slices is required we look at the electron evolution during the individual pinch

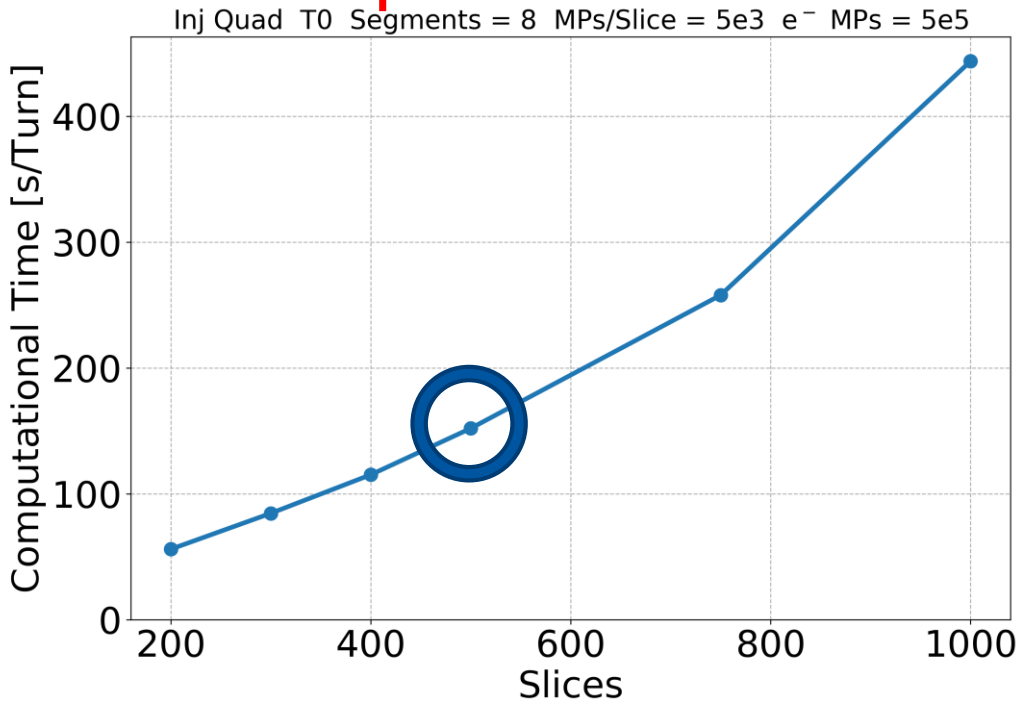
Electron density average ($|y| < 0.25\sigma_y$ and $x = 0$) along the bunch



- Single passage simulation confirms: 150 slices are not enough
- Smaller electron density peak (around 20%) during the pinch ➔ bunch more stable

Convergence Studies: Slices

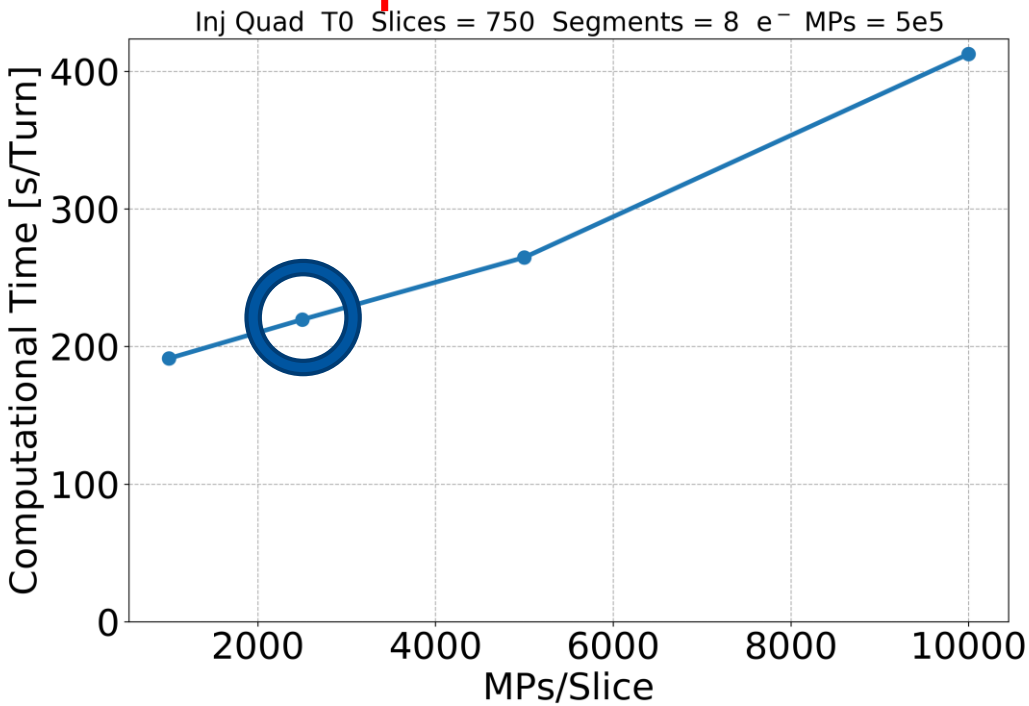
Computational Time



1. The simulations are: 108.
2. The finished simulations are: 108. The killed simulations are: 0.
3. Total computational time: 858 days (8 cores).
4. 28.5 GB stored.

Convergence Studies: MPs/Slice

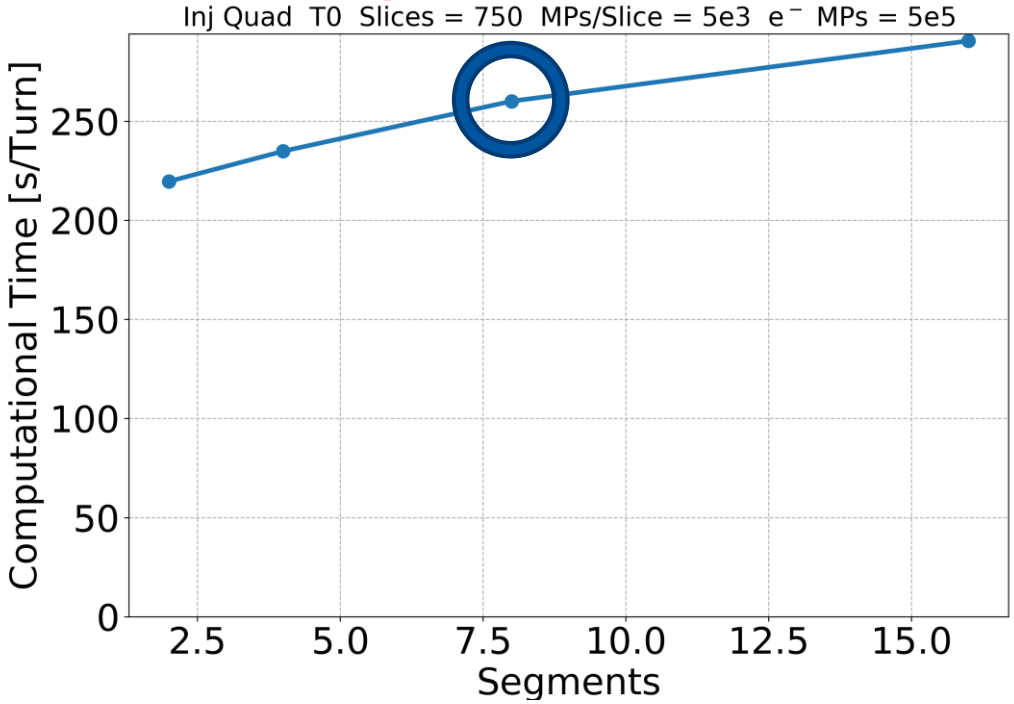
Computational Time



1. The simulations are: 72.
2. The finished simulations are: 72. The killed simulations are: 0.
3. Total computational time: 818 days (8 cores).
4. 24.6 GB stored.

Convergence Studies: Segments

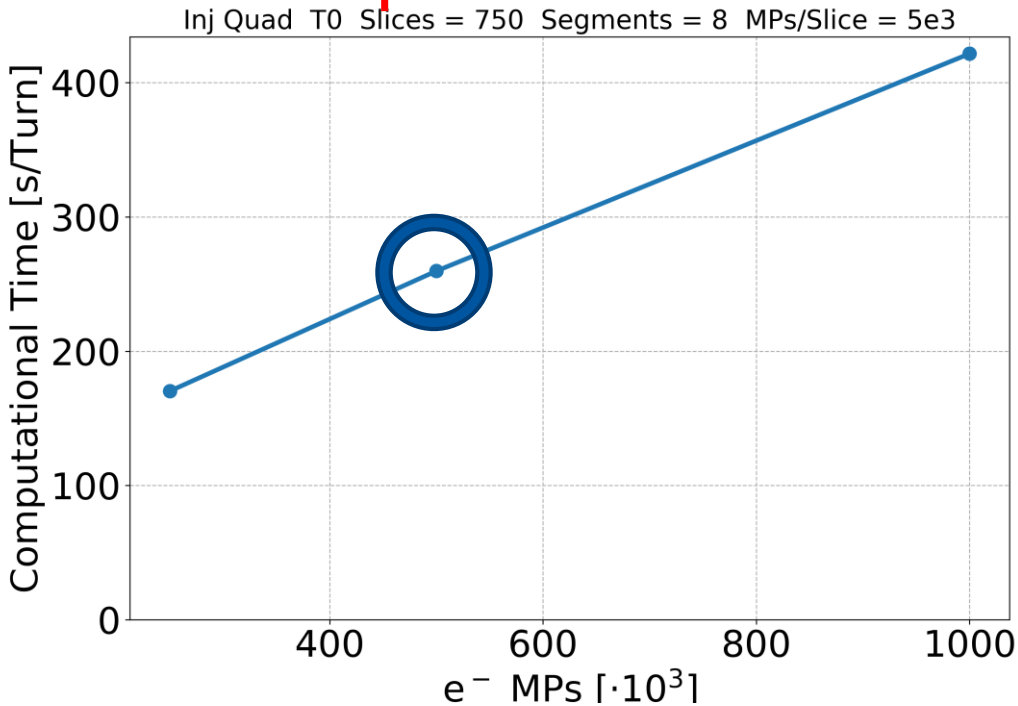
Computational Time



1. The simulations are: 72.
2. The finished simulations are: 72. The killed simulations are: 0.
3. Total computational time: 748 days (number of cores depends on segments).
4. 25.7 GB stored.

Convergence Studies: e^- MPs

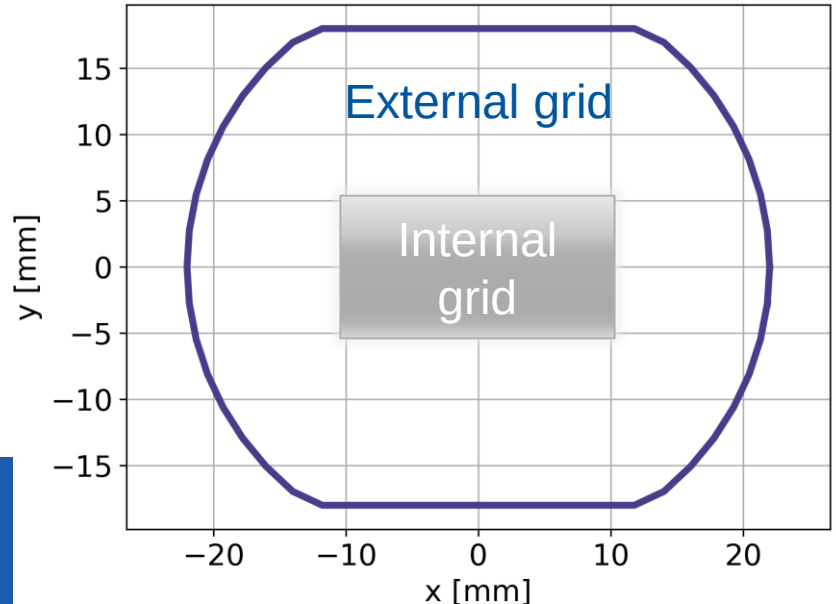
Computational Time



1. The simulations are: 54.
2. The finished simulations are: 54. The killed simulations are: 0.
3. Total computational time: 645 days (8 cores).
4. 19.7 GB stored.

Convergence Studies: Transverse Grid

	T_0	T_{inj}		
Parameter	**Value**	**Value**	**Value**	**Value**
f (magnification factor)	0.3	0.5	0.5	0.5
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
N_nodes_discard	5	10	10	10
N_min_Dh_main	10	40	40	40

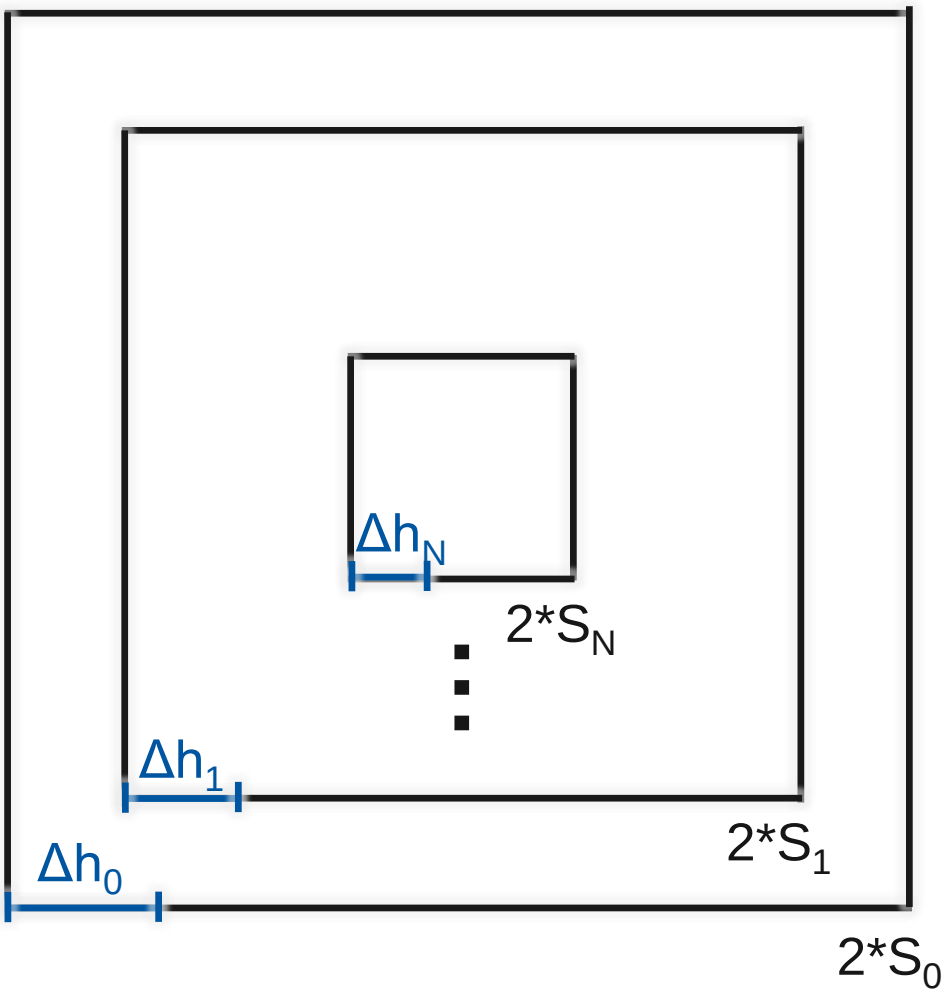


Beam chamber

Convergence Studies: Transverse Grid

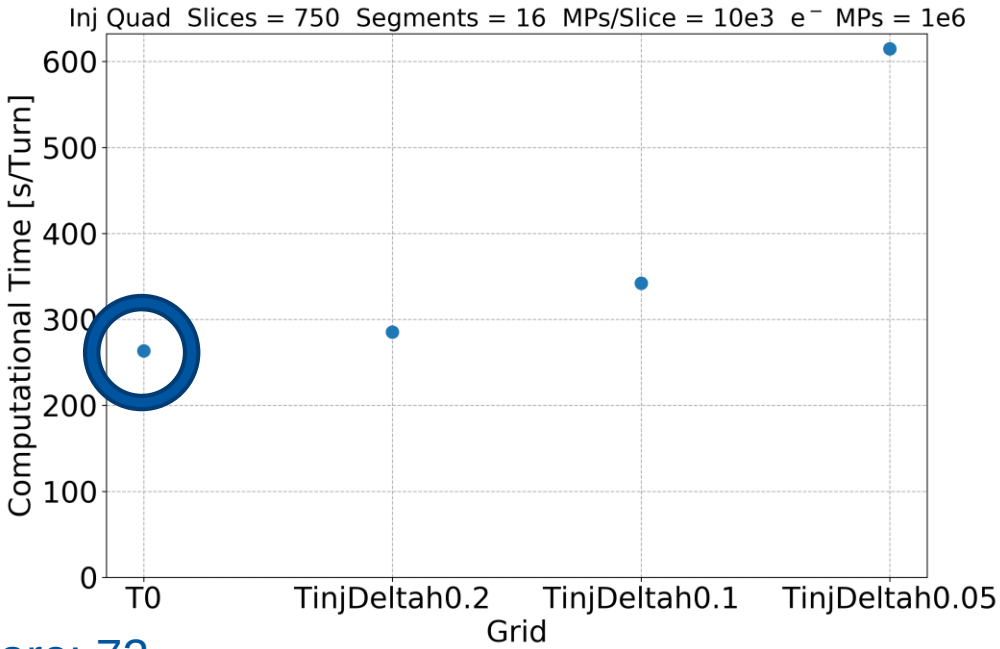
T_0

Parameter	Value
f (magnification factor)	0.3
S_N [mm]	6.95 (10σ)
Δh_N [mm]	0.139 (0.2σ)
Δh_0 [mm]	0.8
N_nodes_discard	5
N_min_Dh_main	10



Convergence Studies: Transverse Grid

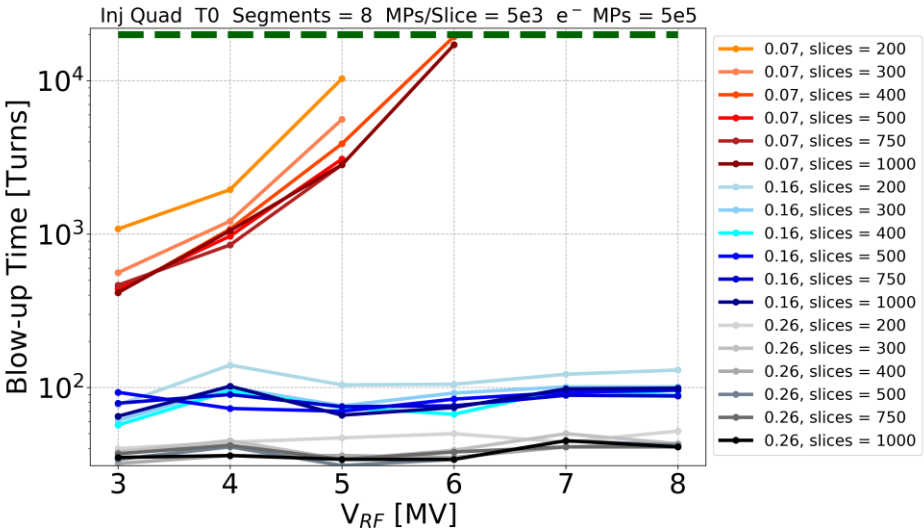
Computational Time



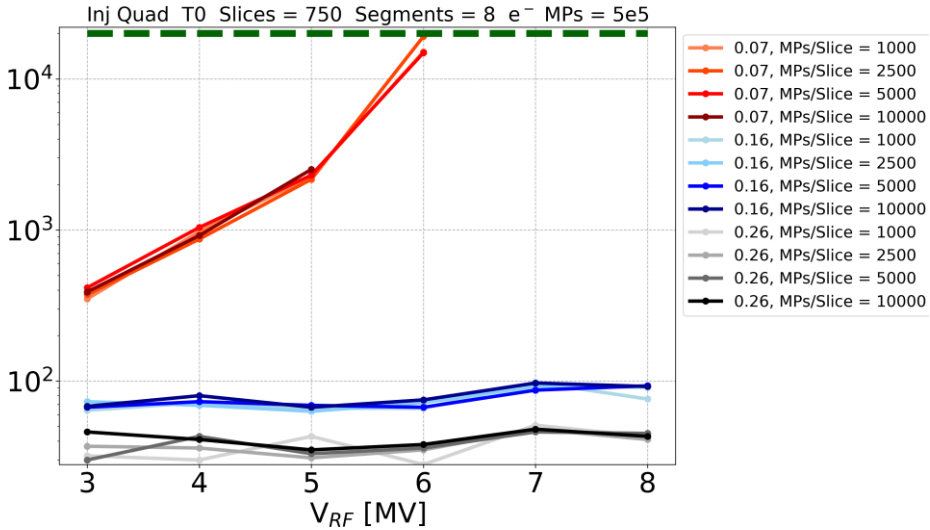
1. The simulations are: 72.
2. The finished simulations are: 69. The killed simulations are: 0.
3. Total computational time: 1035 days (8 cores).
4. 25.4 GB stored.
5. The slowest simulation needs 35 days to reach 20,000 turns.
6. The fastest simulation needs 26 days to reach 20,000 turns.
7. (last download 19/11/2019)

Convergence Studies: 16% - 26%

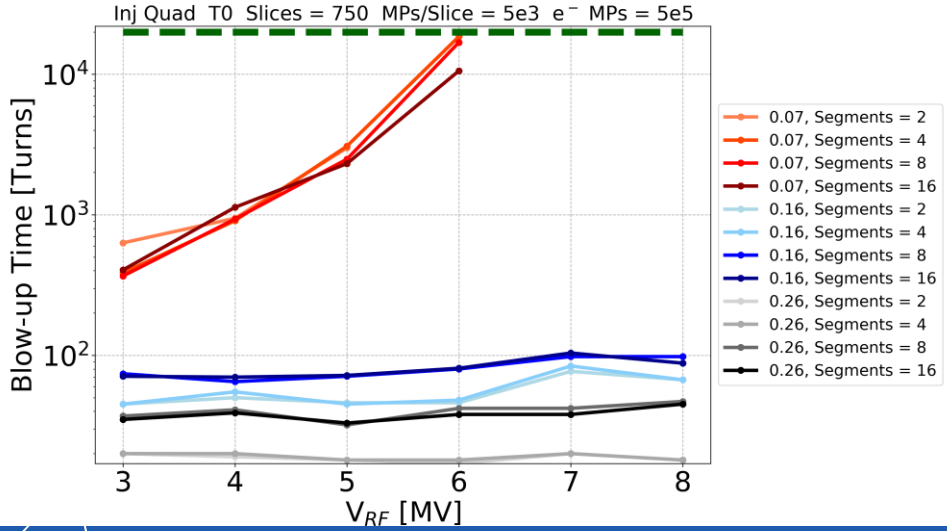
Slices



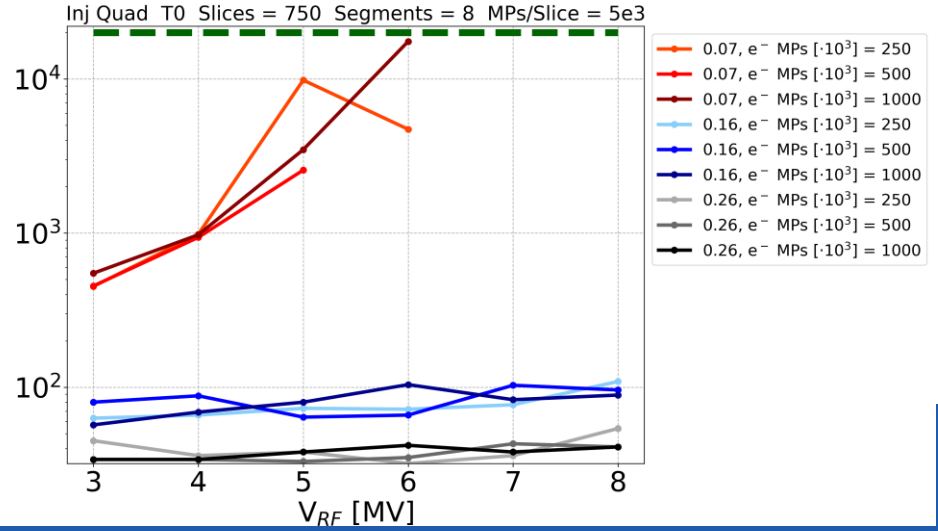
MPs/Slice



Segments

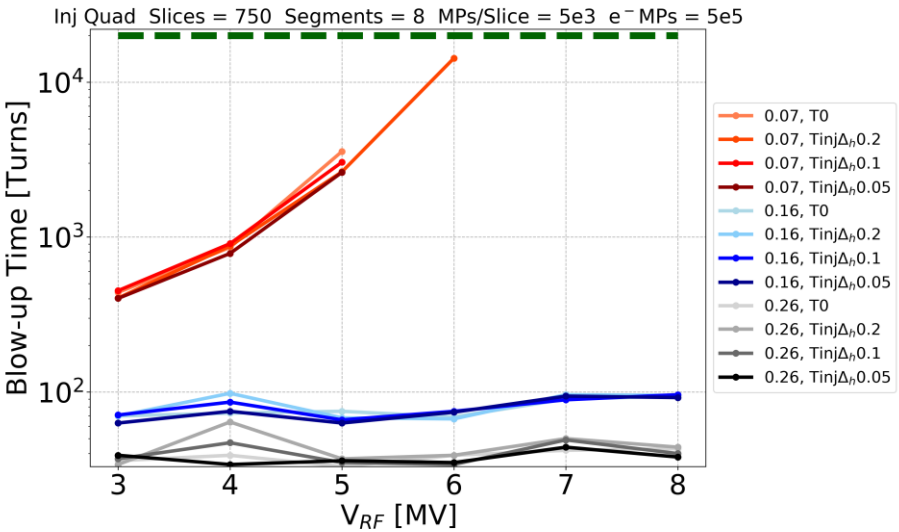


e⁻ MPs



Convergence Studies: 16% - 26%

Transverse Grids



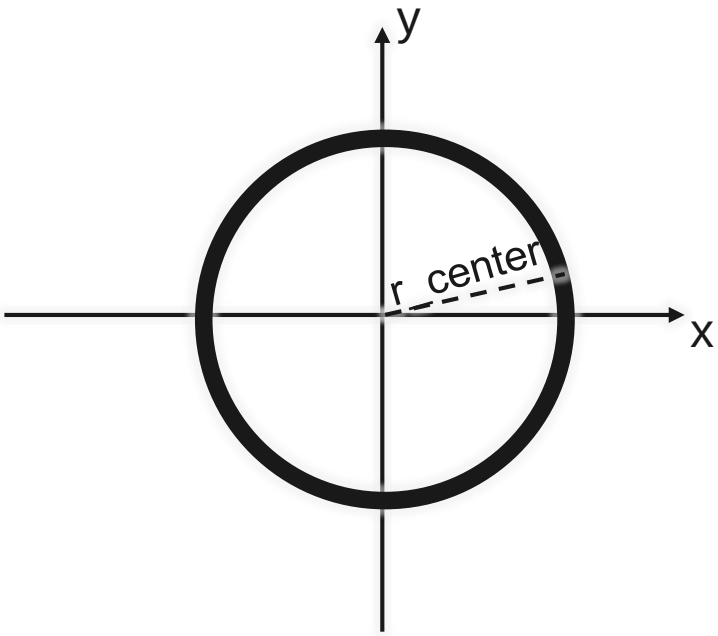
Why no Instability at High Intensity?

- It can be related to the number of electrons around the chamber centre (from build-up simulations)

Useful Parameter in PyECLOUD

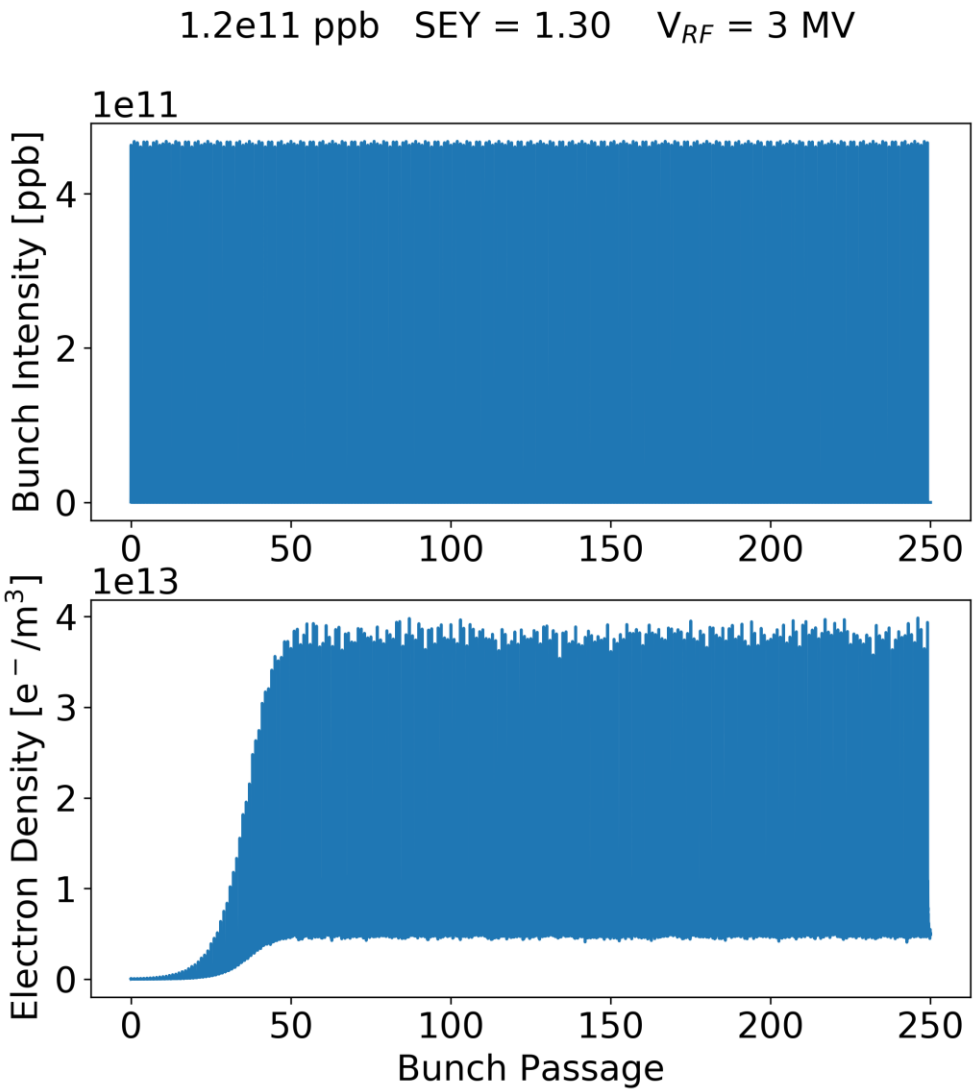
- cen_density [e^-/m^3]: electron volumetric density in a sphere around the chamber centre with radius r_center (input simulation parameter)

- r_center = 1 mm

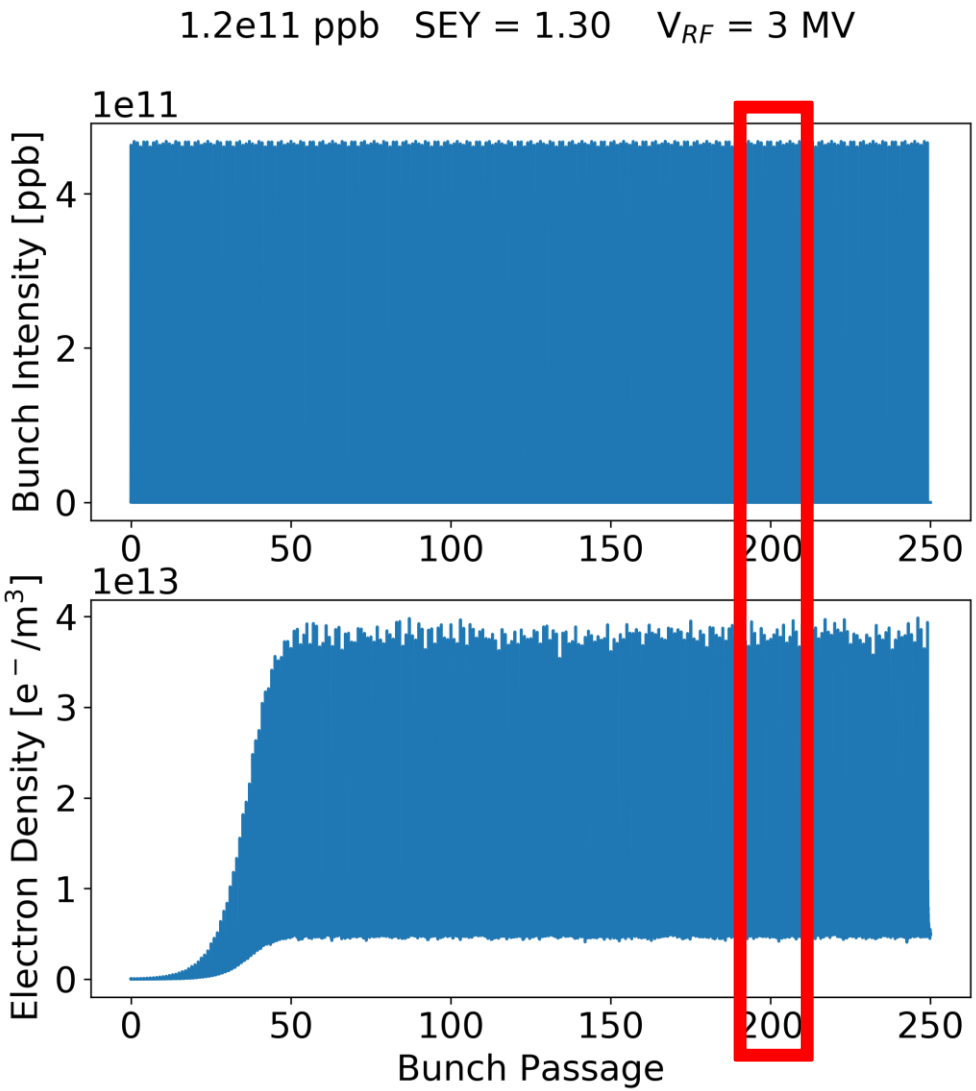


Why no Instability at High Intensity?

Build-up: Full Plot



Why no Instability at High Intensity?

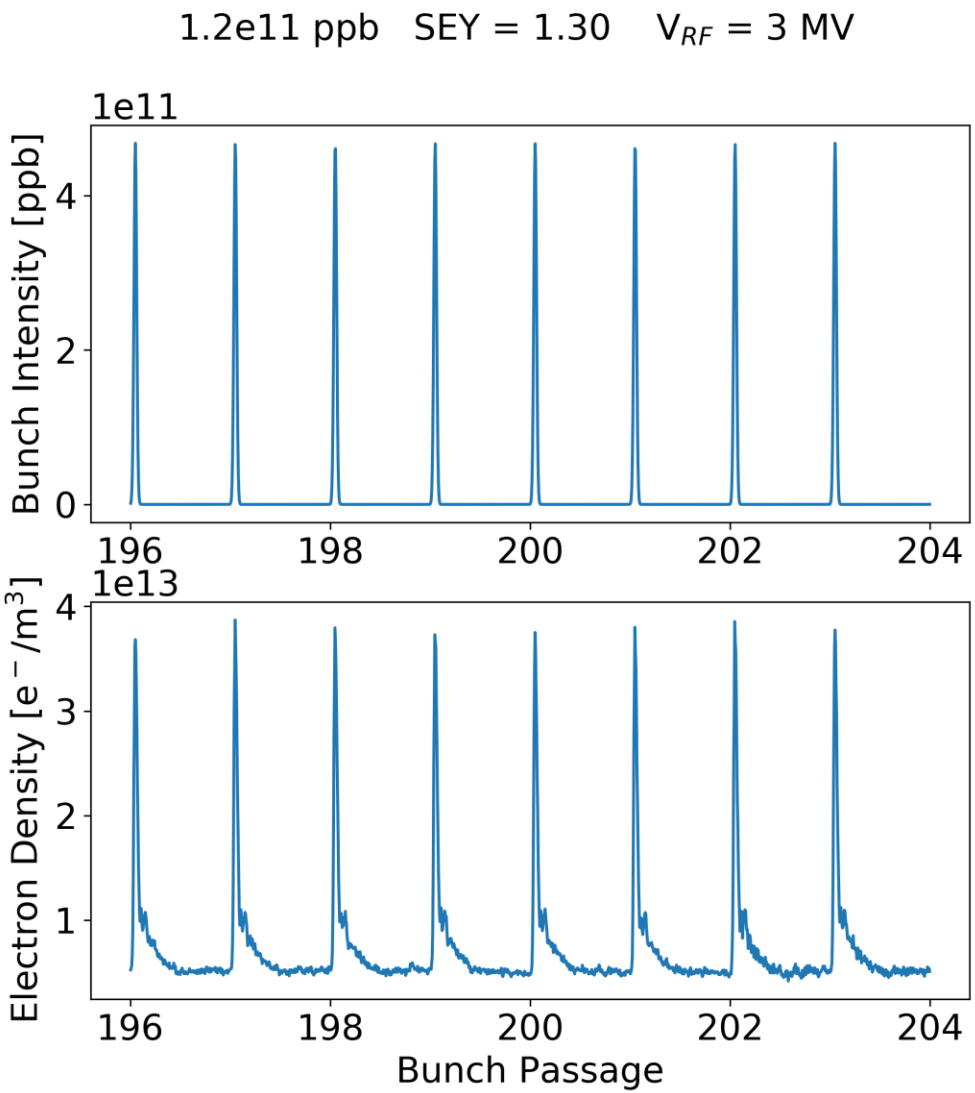


Build-up: Full Plot

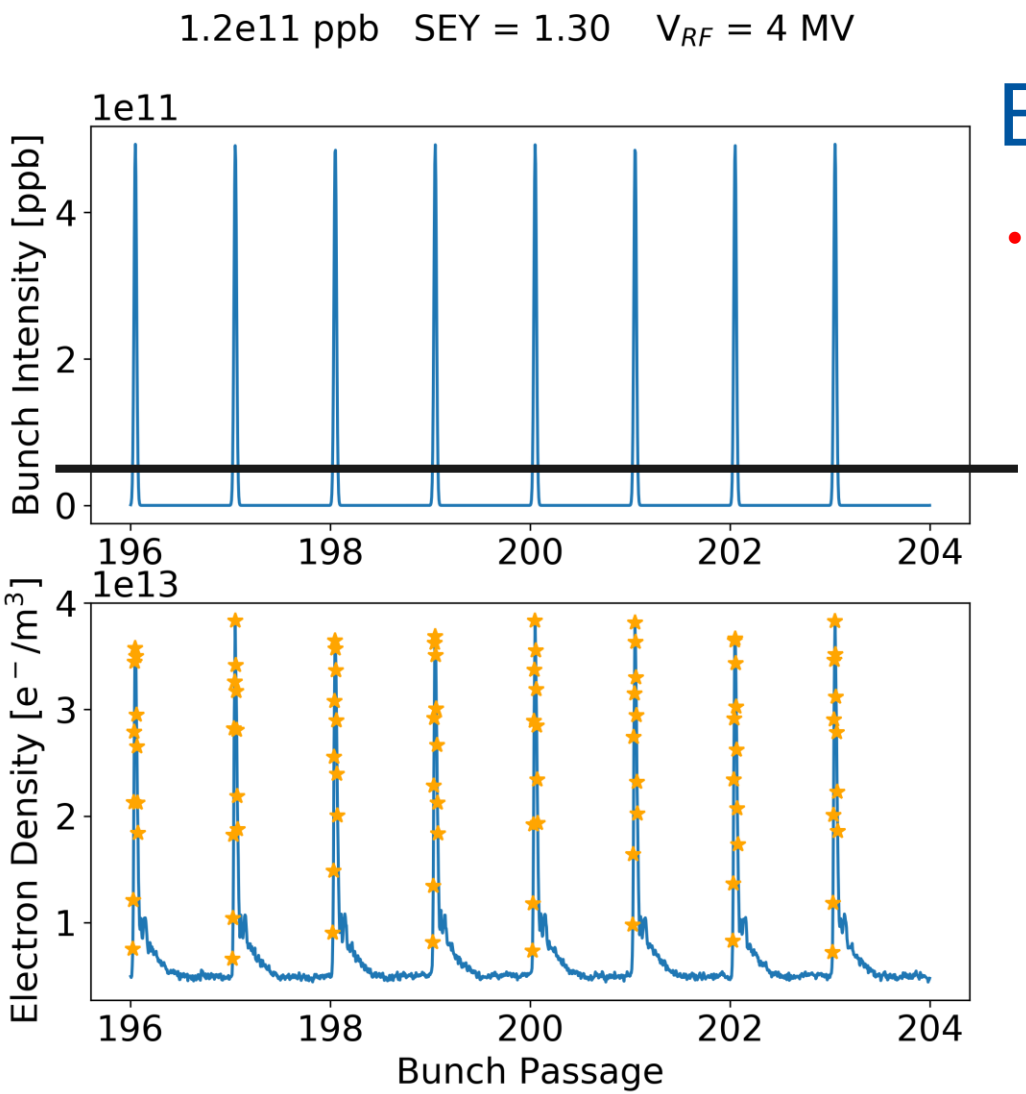
- The combined build-up status are: 196 – 204 bunches
- Build-up in saturation

Why no Instability at High Intensity?

Build-up: Zoom Plot



Why no Instability at High Intensity?

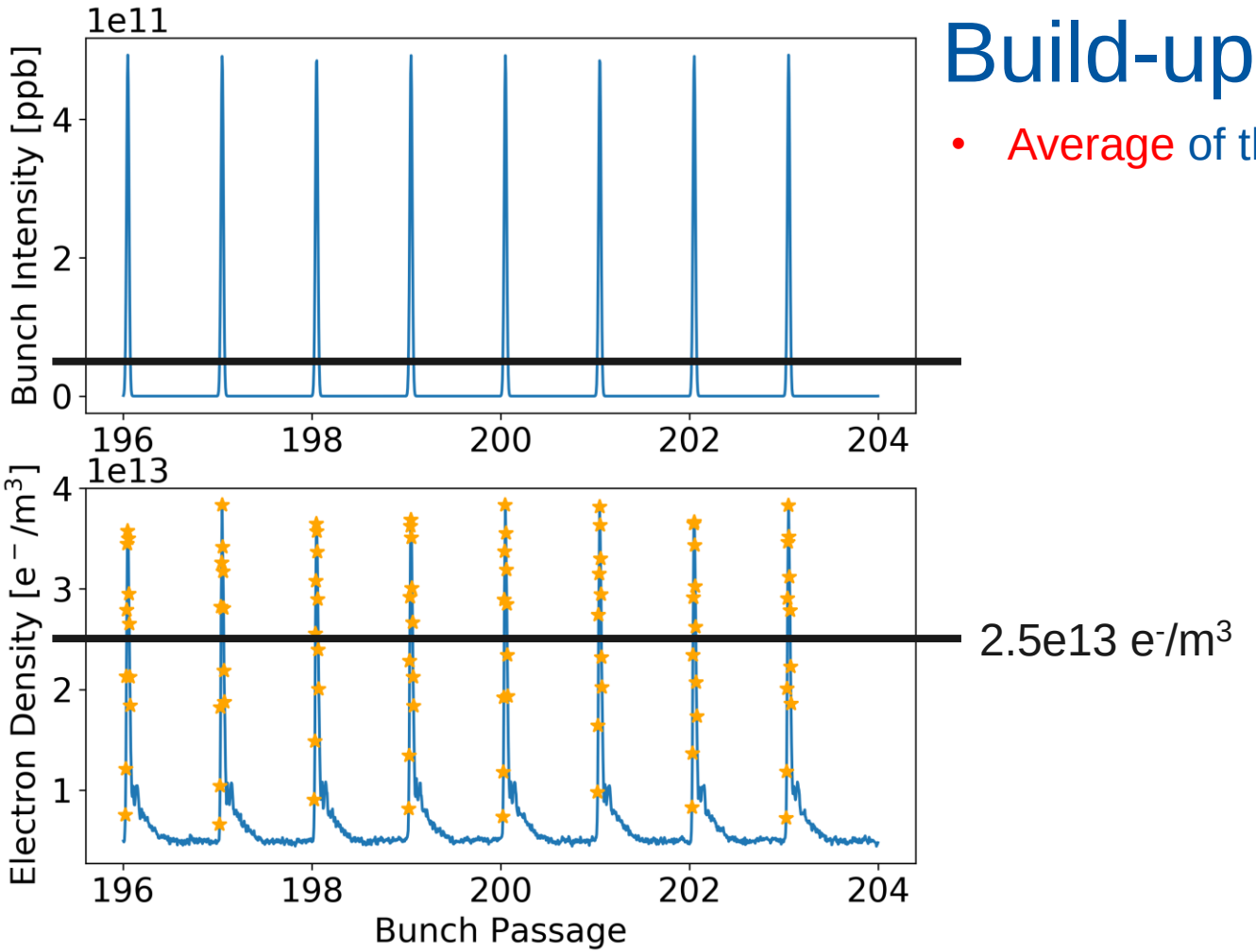


Build-up: Zoom Plot

- Mask: points only when the number of the proton bunch is larger than 10% of the maximum

Why no Instability at High Intensity?

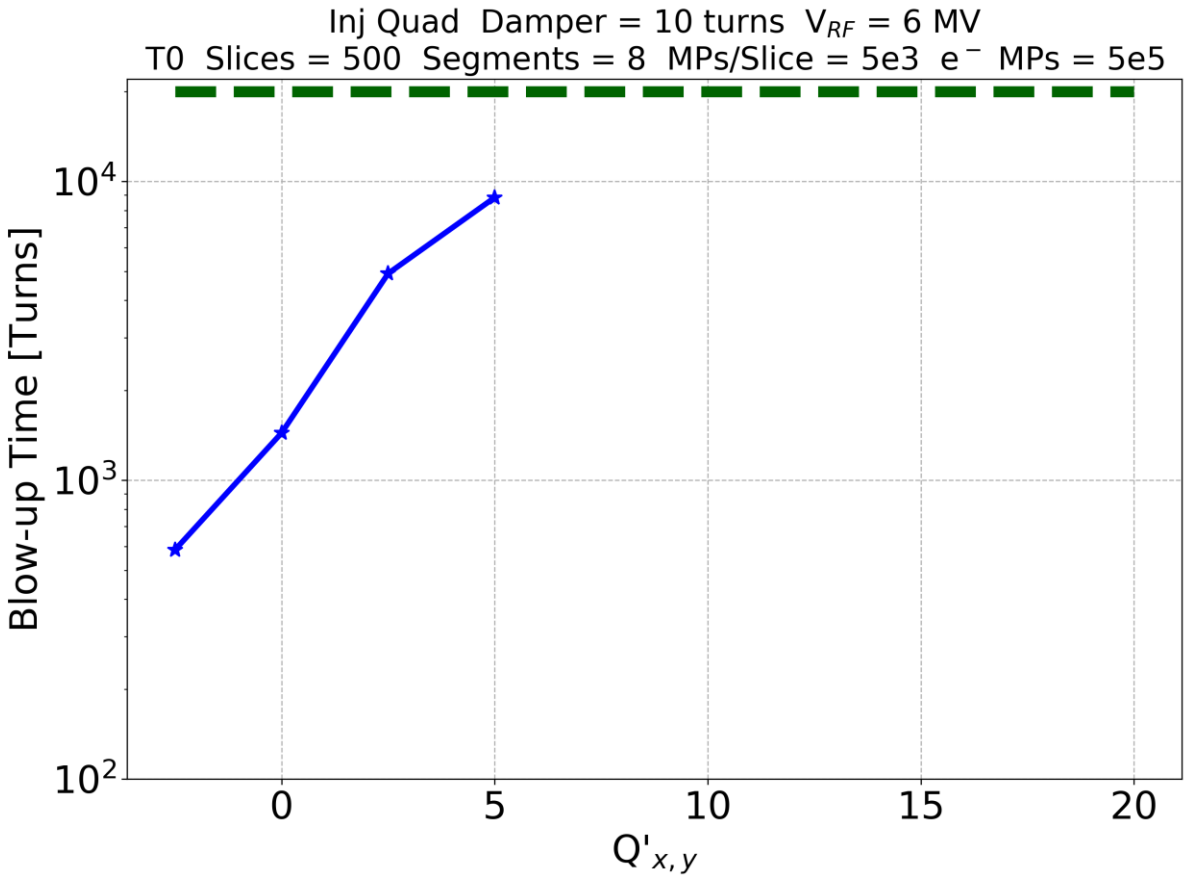
1.2e11 ppb SEY = 1.30 V_{RF} = 4 MV



Build-up: Zoom Plot

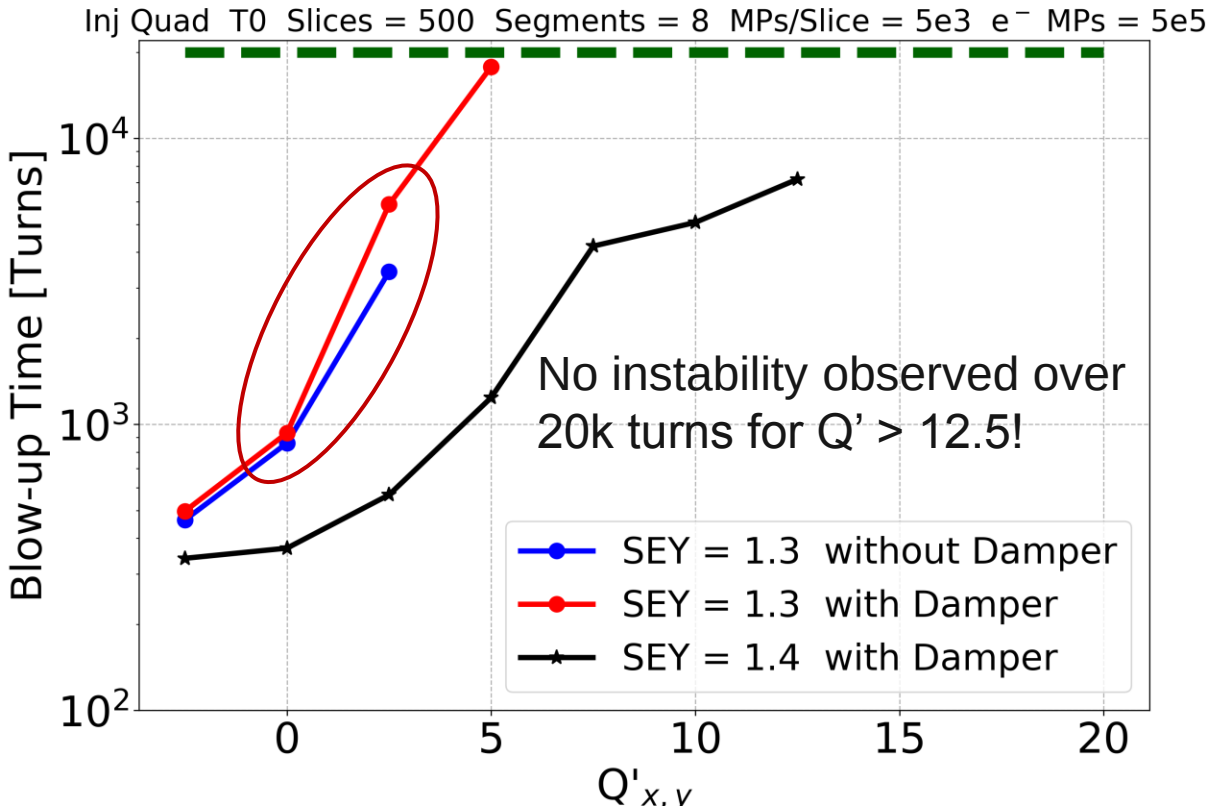
- Average of these values

Chromaticity



- V_{RF} = 6 MV
- SEY = 1.4
- Damper = 10 turns

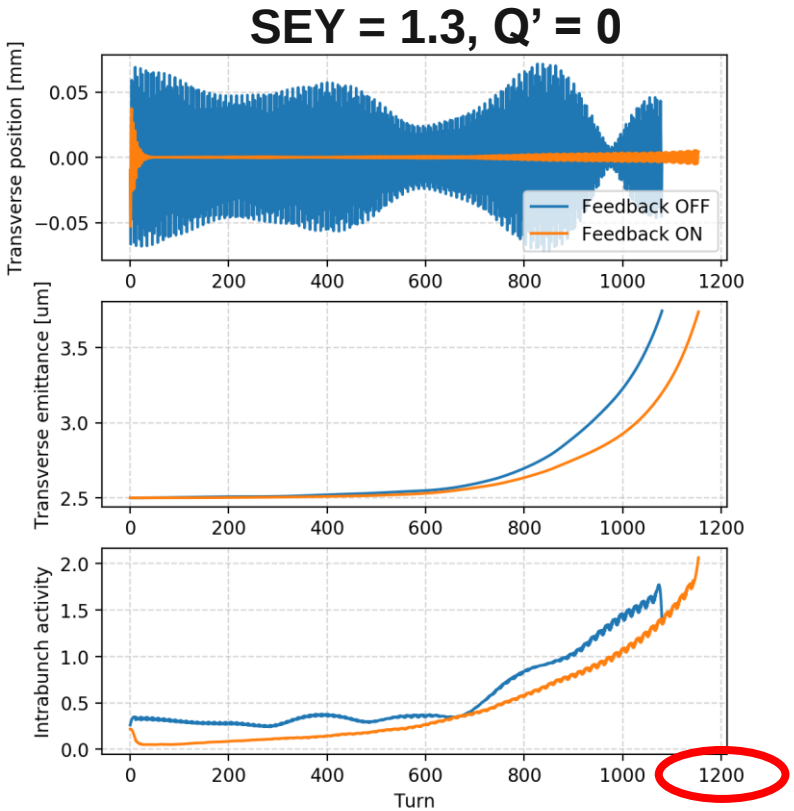
Chromaticity and Damper

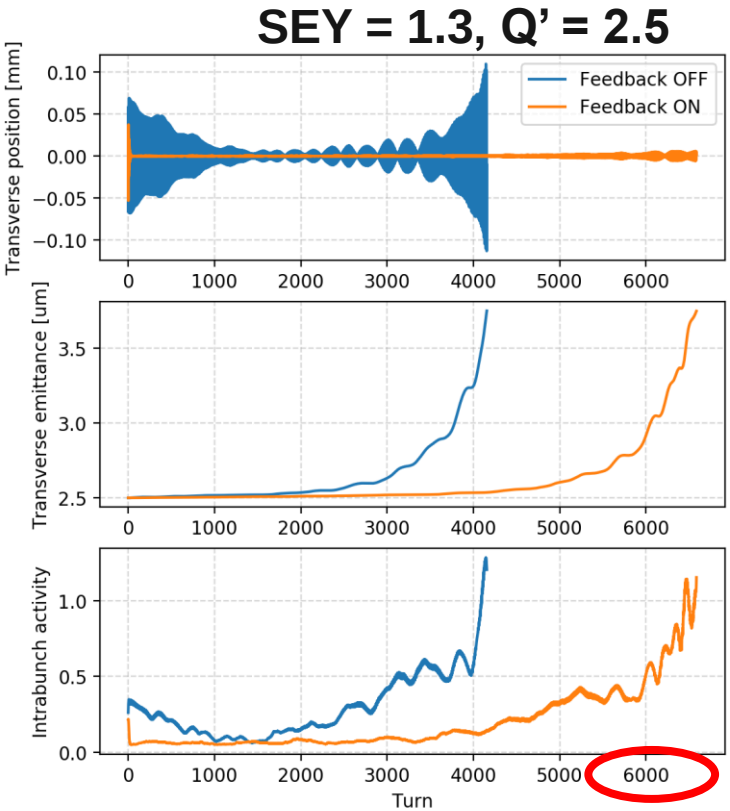


- V_{RF} = 4 MV
- SEY = 1.3 – 1.4
- Feedback damping time is 10 turns

- For the case of LHC intensity (which an instability could be observed) the **effectiveness of different mitigation measures** has been investigated:
  - The instability is **strongly mitigated** by increasing the **chromaticity** settings
  - The **transverse feedback** is **mostly ineffective** →cannot damp **intra-bunch motion**

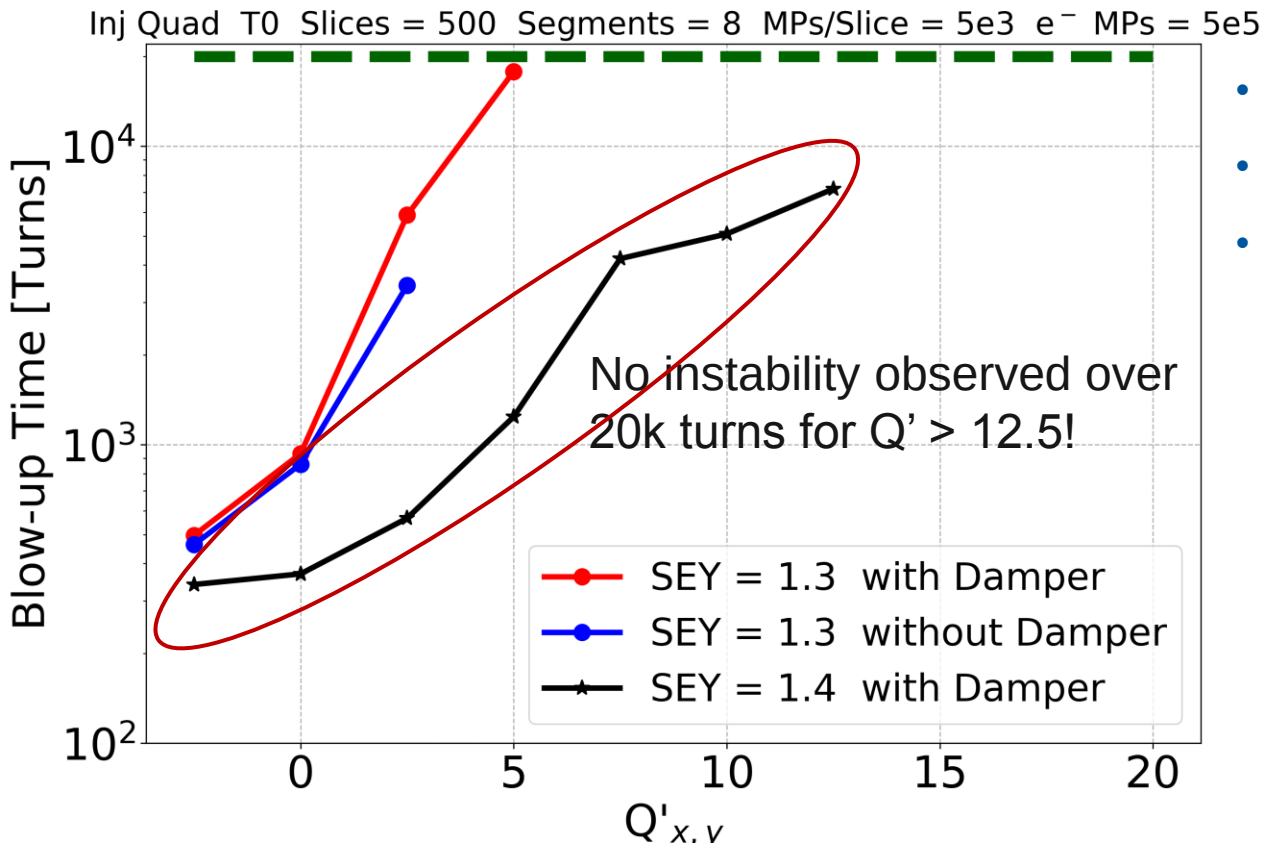
Chromaticity and Damper





- For the case of LHC intensity (which an instability could be observed) the **effectiveness of different mitigation measures** has been investigated:
  - The instability is **strongly mitigated** by increasing the **chromaticity** settings
  - The **transverse feedback** (bunch-by-bunch, damping time of 10 turns) is **mostly ineffective** → cannot damp **intra-bunch motion**

Chromaticity and Damper



- V_{RF} = 4 MV
- SEY = 1.3 – 1.4
- Feedback damping time is 10 turns

- Positive **chromaticity strongly mitigates the instability**
- The damper does not affect significantly the blow-up time (unable to suppress intra-bunch motion)

Chromaticity and Damper

SEY = 1.4, Damper ON