Application of the linearized method to instabilities driven by e-cloud in the LHC dipoles

G. Iadarola and L. Sabato

Outline

- **Introduction**
- **Characterization of e-cloud dipolar and detuning forces**
- **Transverse instabilities**
  - Results from the linearized method (Vlasov vs macroparticles)
  - Comparison against PIC simulations
  - Slow instability at small e-cloud strength
- **Coherent tune shifts**

Introduction

- The recently developed **linearized method for e-cloud instabilities** was mostly tested for the case of instabilities driven by e-cloud in the LHC quadrupoles at injection energy (1)
- We now apply it to the case of **transverse instabilities driven by e-cloud in the LHC dipoles**

Parameters considered for the study

Beam energy [GeV]	450
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
Momentum compaction factor, α	3.225e-04
Arc dipole field gradient [T]	0.54
Arc quadrupole gradient [T/m]	12.1
Fraction of the ring occupied by dipoles	66 %
Fraction of the ring occupied by quadrupoles	7 %

The e-cloud was characterized for a density (before bunch arrival) of **1.2×10^{12} e^-/m^3**

The **e-cloud strength was scanned in the range 0.1-1.2** to study the effect on stability

The transverse stability will be studied exclusively in the **vertical plane**

(1) *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* ***23****, 081002 – Published 26 August 2020*

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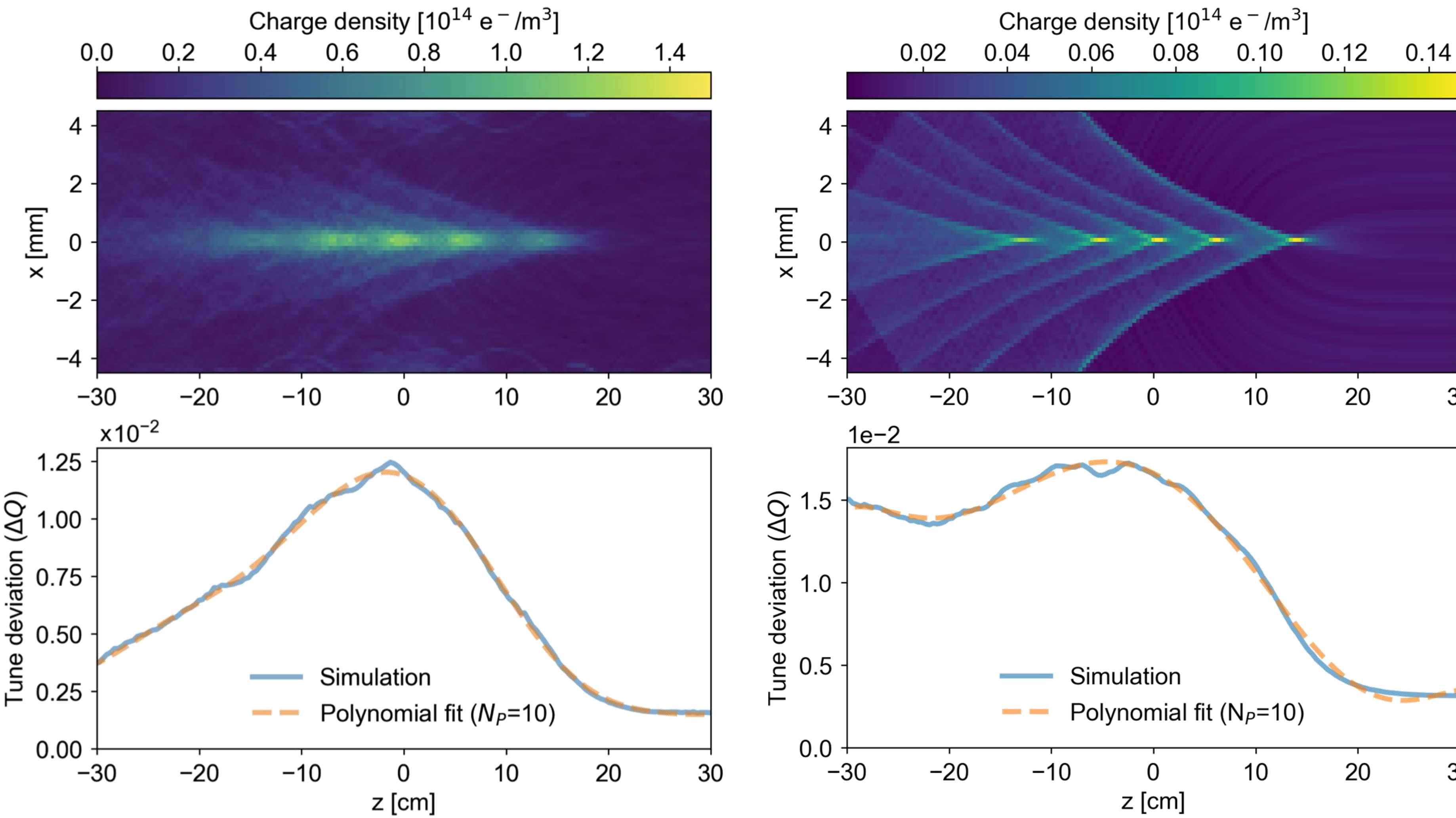
Detuning forces from the e-cloud

- As for the case of the quadrupole e-cloud, the dependence of the **detuning forces** on the z coordinate is **described by a polynomial**

e-cloud in quadrupoles **e-cloud in dipoles**

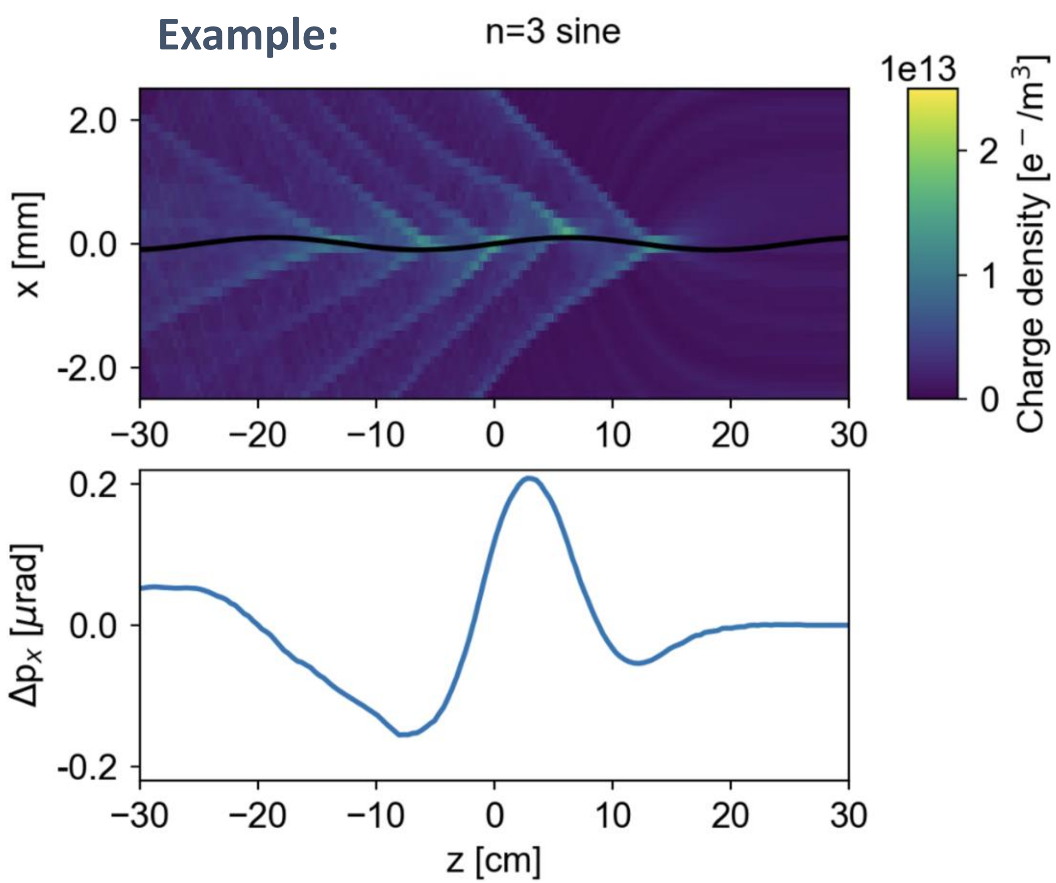


- As for the case of the quadrupole, the **dipolar forces** are characterized my means of **single-pass PyECLOUD-PyHEADTAIL simulations** with a set of **pre-distorted bunches**

Test functions:

$$h_n(z) = \begin{cases} \mathcal{A}_n \cos\left(2\pi f_n^z z\right), & \text{if } n \text{ is even} \\ \mathcal{A}_n \sin\left(2\pi f_n^z z\right), & \text{if } n \text{ is odd} \end{cases} \qquad f_n^z = \begin{cases} \frac{n}{2}\frac{1}{L_{\mathrm{bkt}}} & \text{if } n \text{ is even} \\ \frac{n+1}{2}\frac{1}{L_{\mathrm{bkt}}} & \text{if } n \text{ is odd} \end{cases}$$

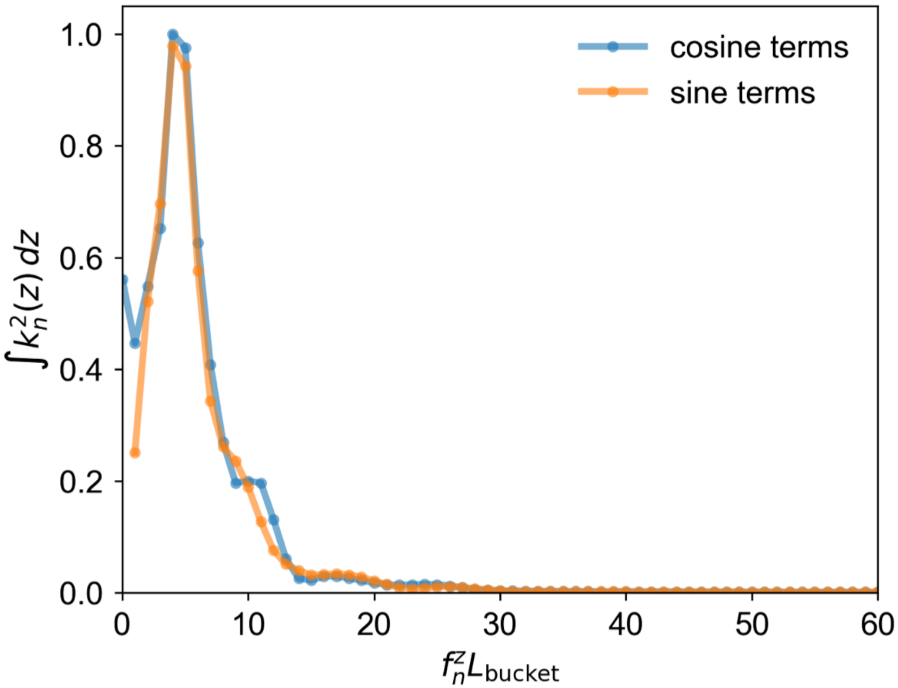
Example:



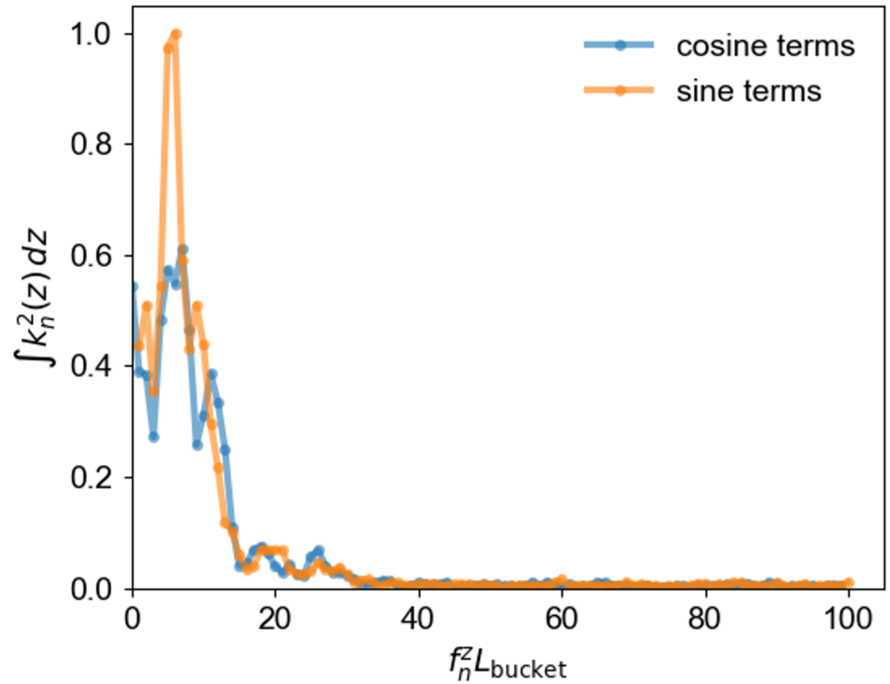
Characterization of the dipolar forces

- A **dipolar response of the e-cloud** is visible for **frequencies up to 30 x f_{RF}**

e-cloud in quadrupoles

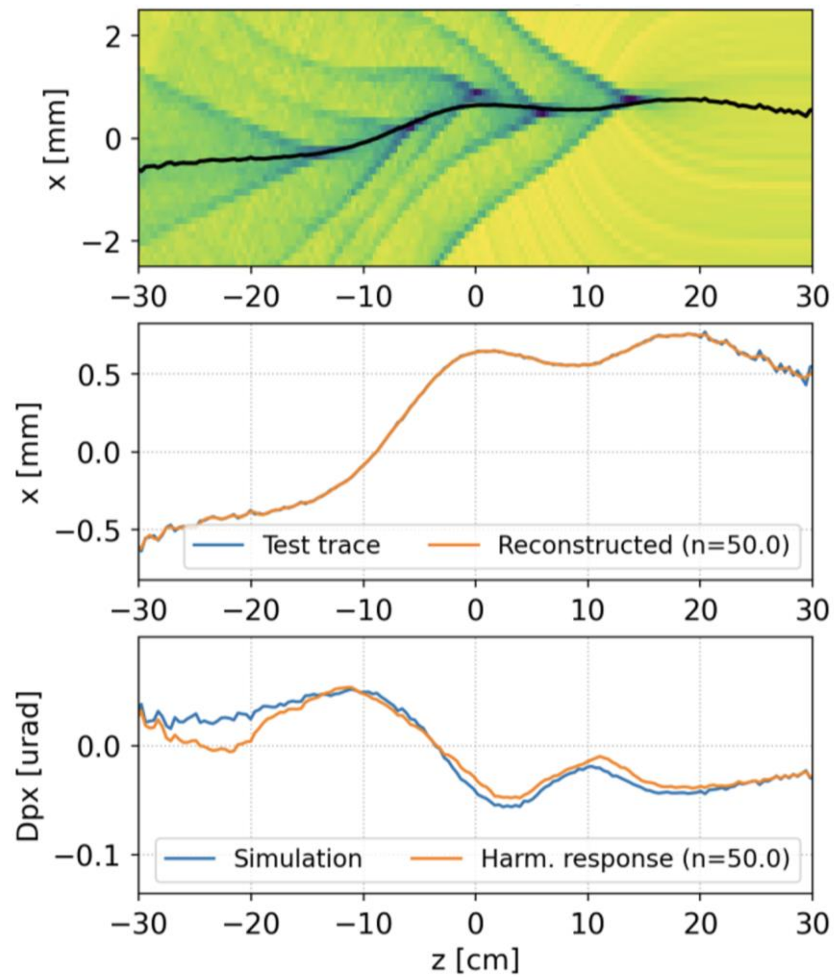


e-cloud in dipoles



Characterization of the dipolar forces

- The validity of the **superposition principle** was verified on **the intra-bunch kick from a PIC simulation**
  - → Reconstruction is satisfactory
  - → Non-linearity in the response is visible at the tail of the bunch



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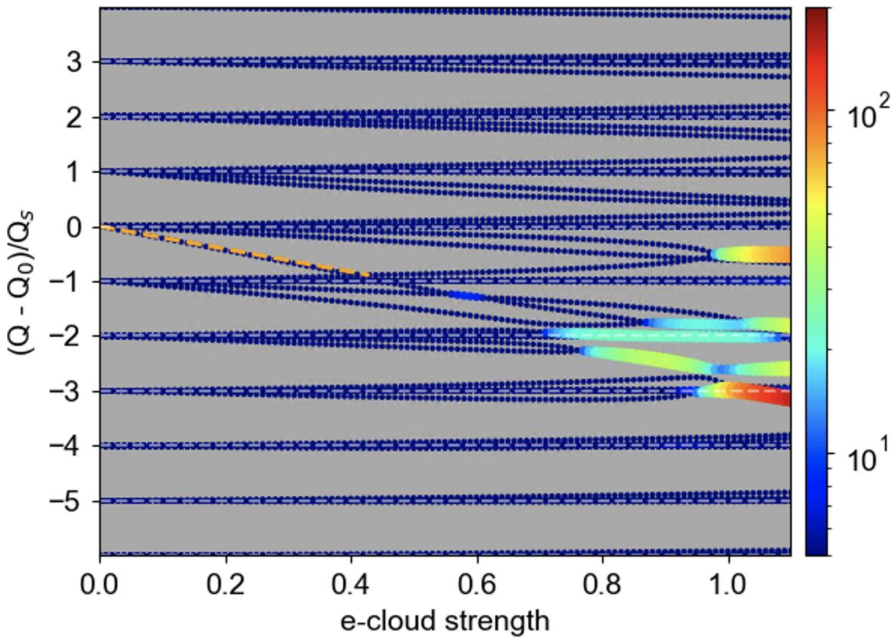
- **Coherent tune shifts**

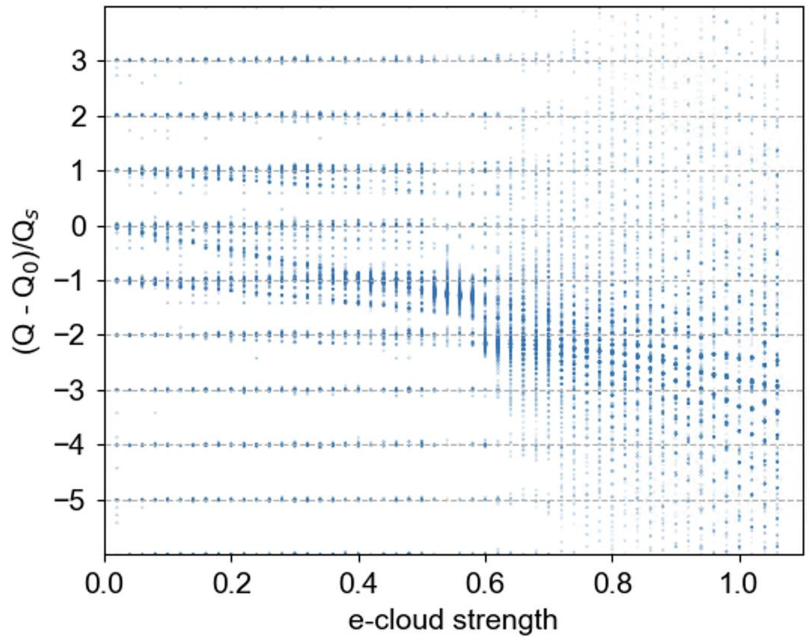
- Transverse stability has been studied using the linearized model, both with the **Vlasov method** and with **macroparticle simulations**
  - **Good agreement** is found **between the two methods**
  - Instabilities triggered by **transverse mode coupling**

Dipolar forces alone

eDELPHI



PyHEADTAIL - linearized model



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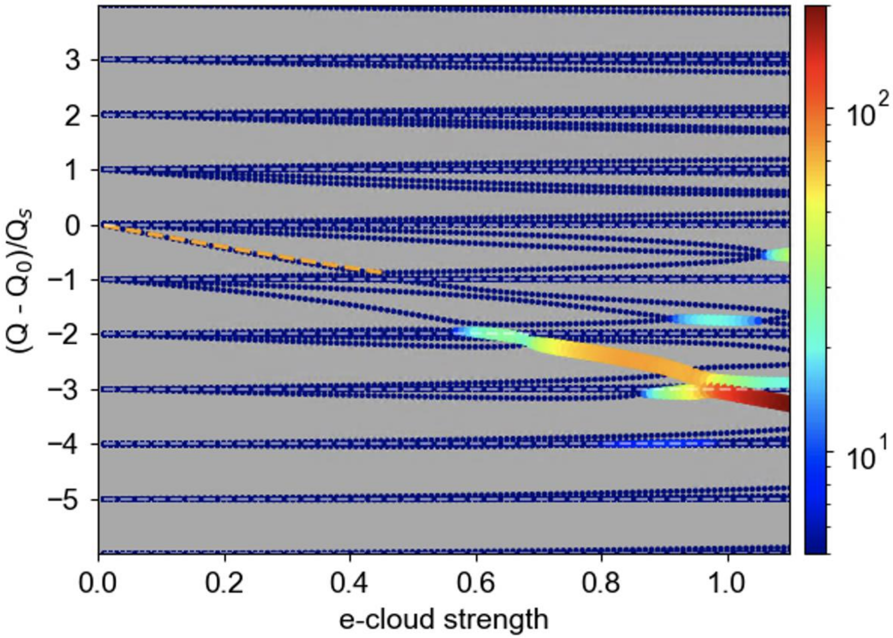
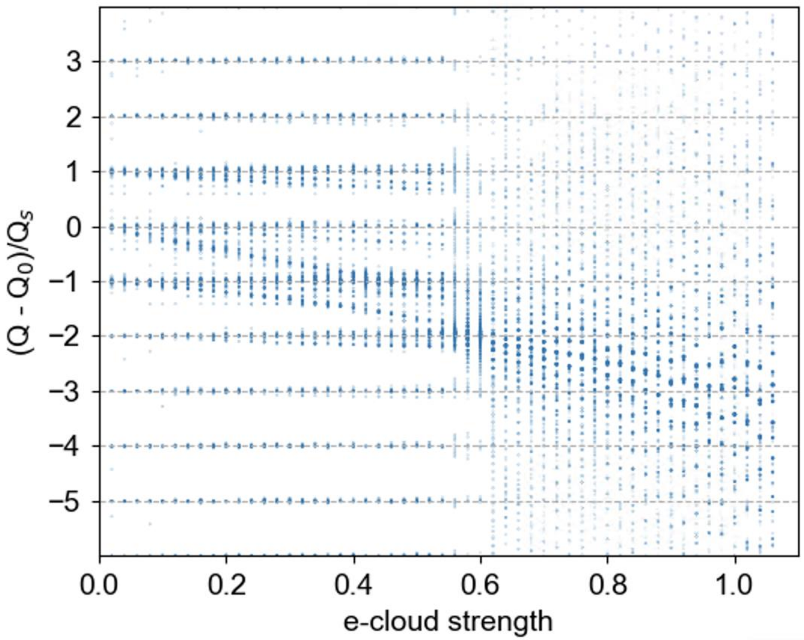
Dipolar forces + phase shift from quadrupolar forces

eDELPHI



PyHEADTAIL - linearized model



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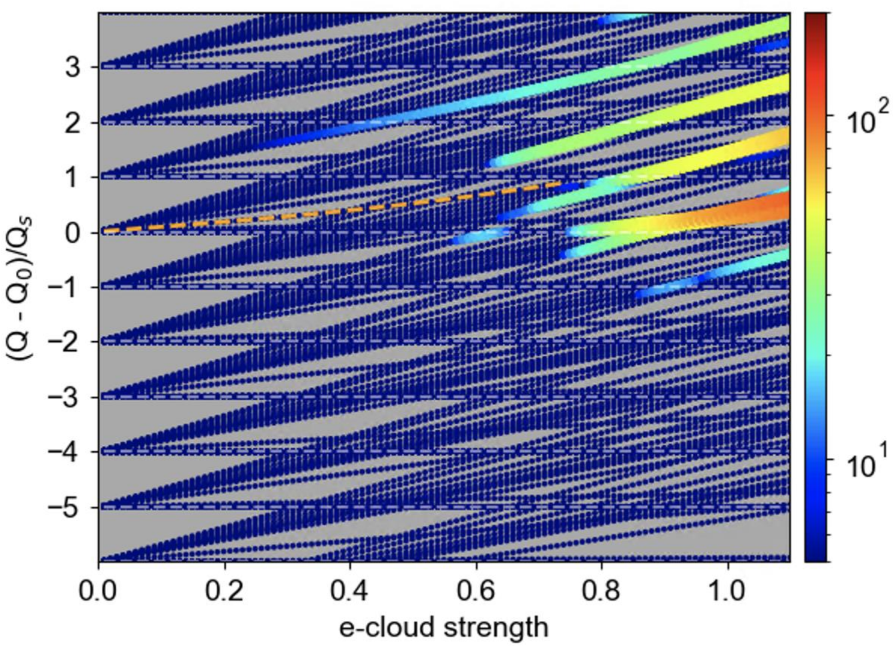
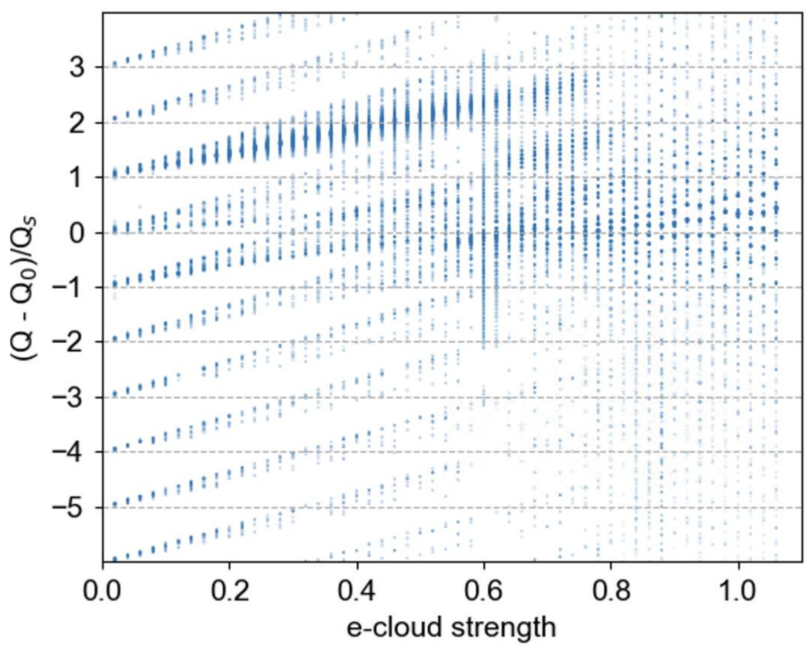
Dipolar forces + full effect of quadrupolar forces

eDELPHI



PyHEADTAIL - linearized model



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Comparison against conventional PIC simulations

- As for the case of the e-cloud in the quyadrupoles, the **frequency of the most unstable mode is consistent with the results of PIC simulations**

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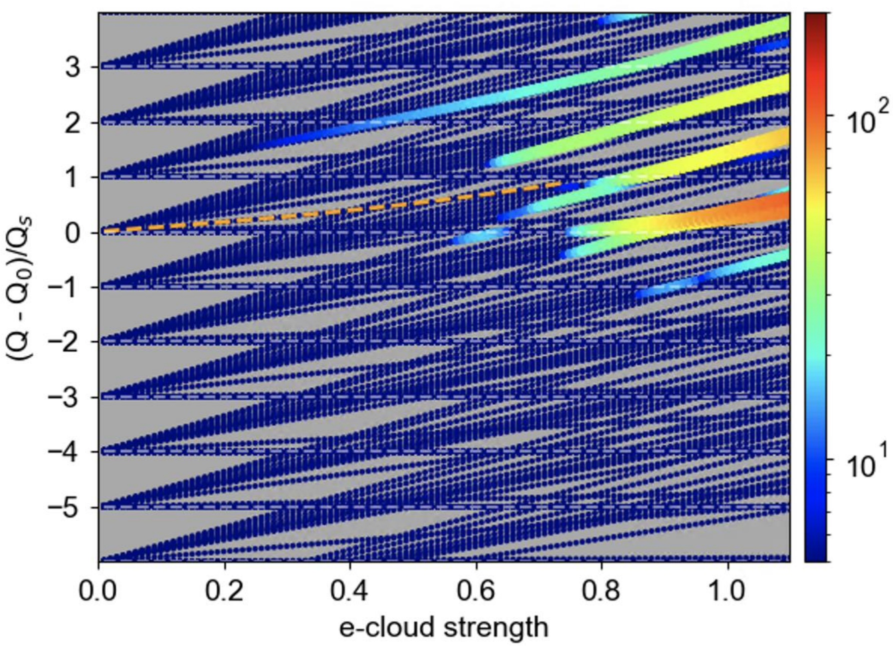
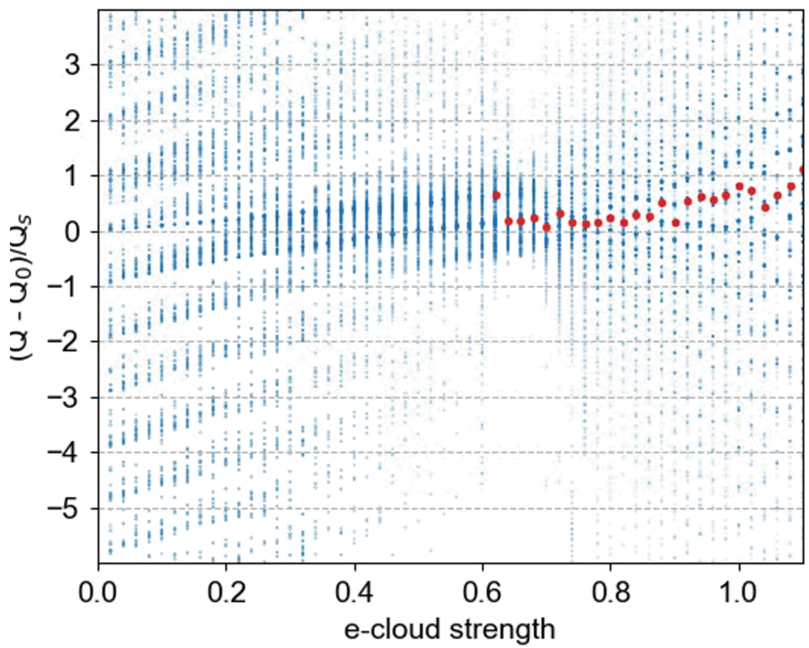
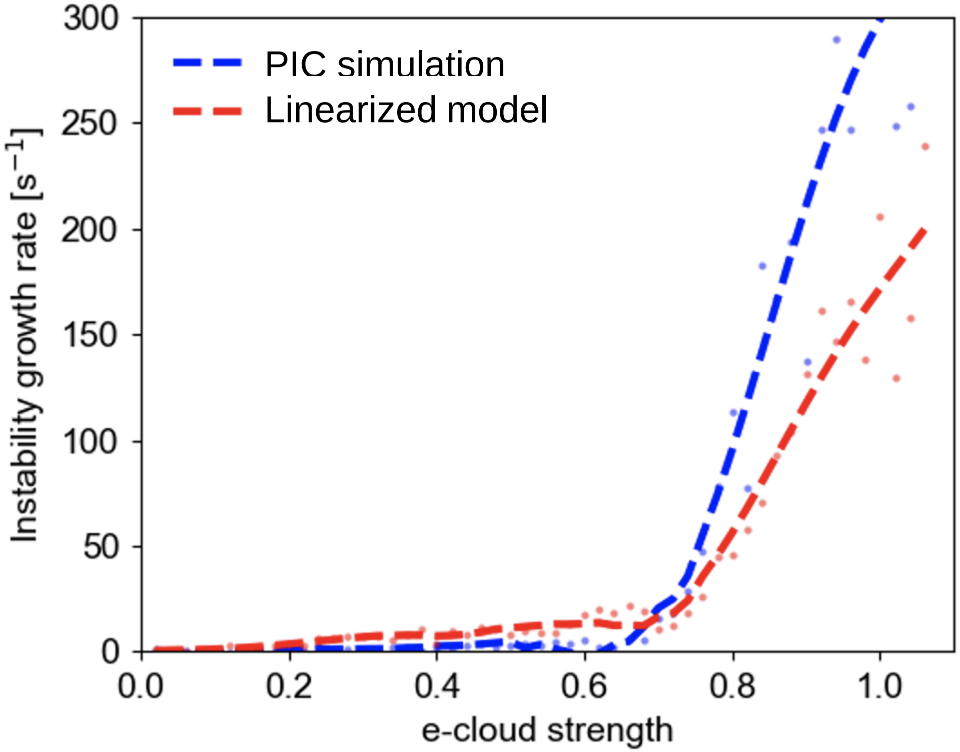


PyHEADTAIL – Particle in Cell



Comparison against conventional PIC simulations

- The instability **threshold** and the risetime of the instability are also **identified quite well by the linearized model**



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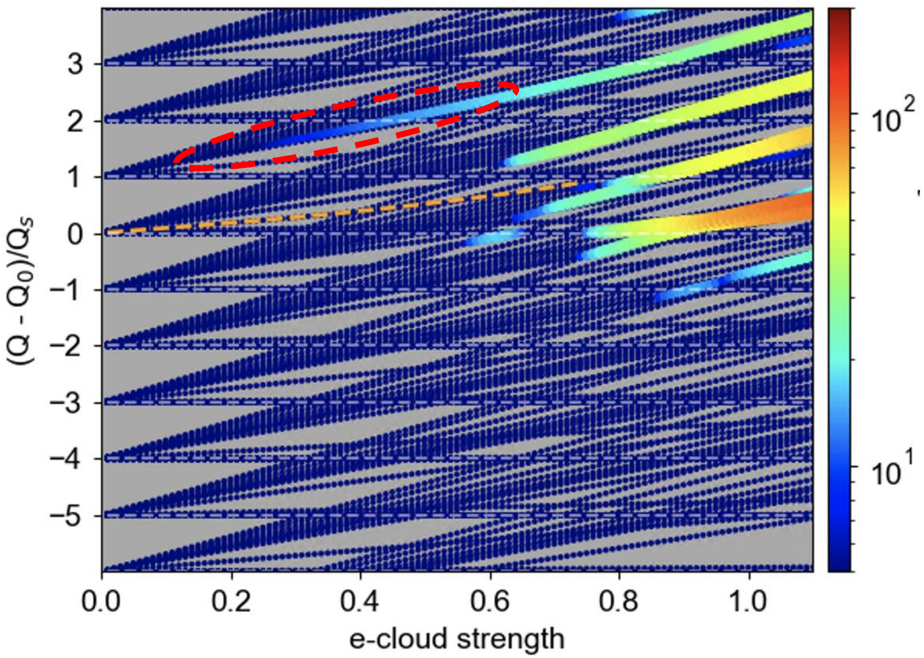
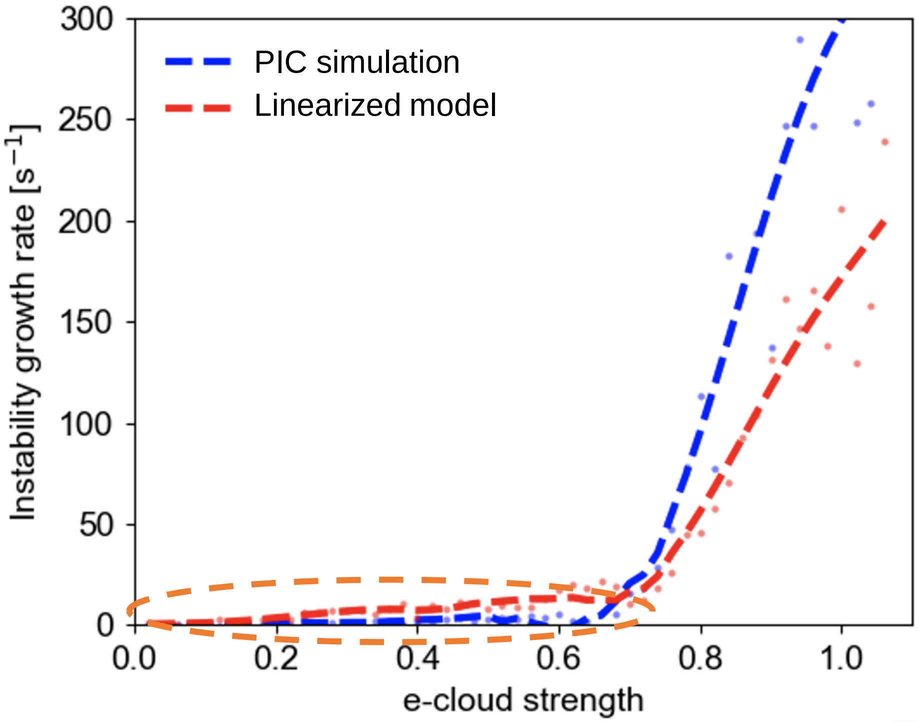
Slow instability for low e-cloud strength

- The linearized model predicts a **slow instability for low e-cloud strength**
- It is **driven by transverse mode coupling** (as it is visible from the imaginary part of the eigenvalues)





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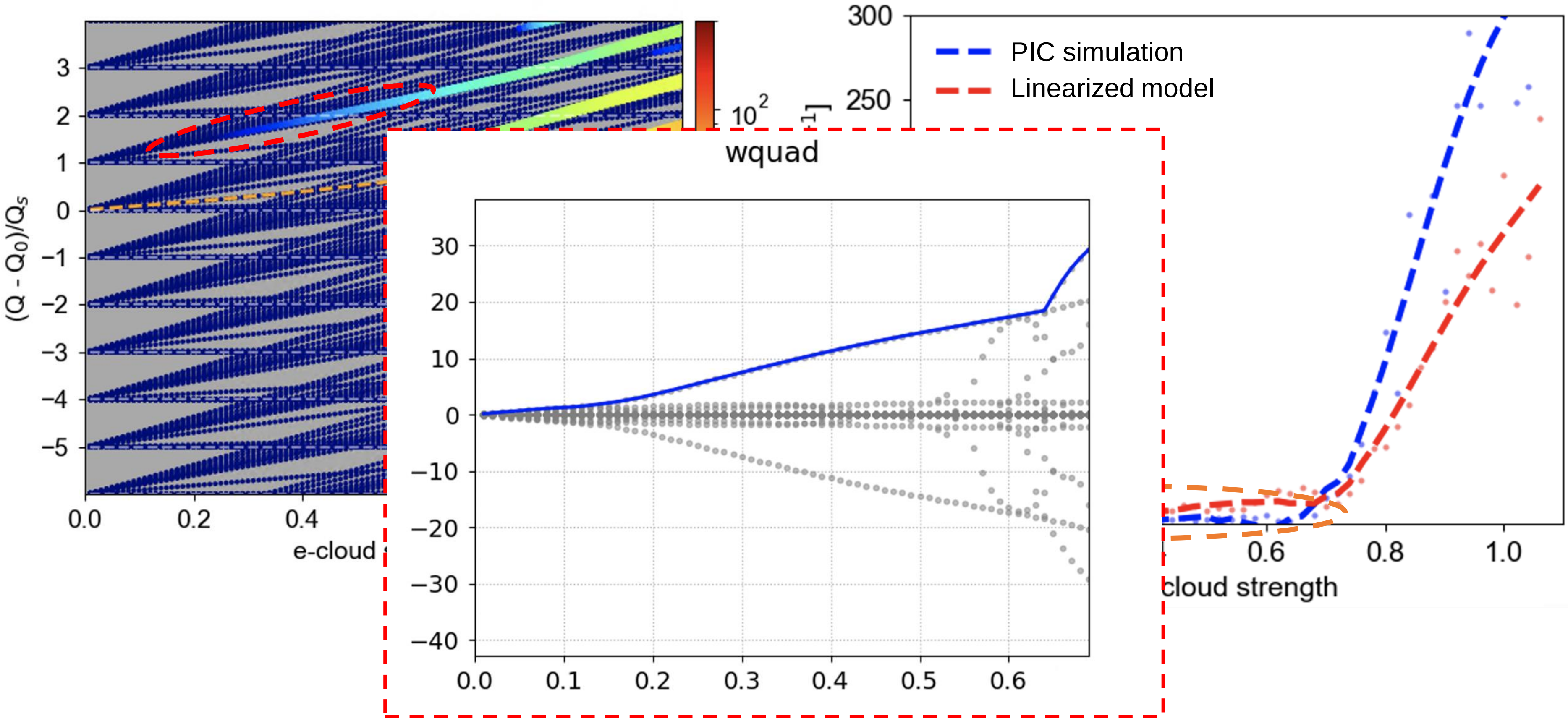
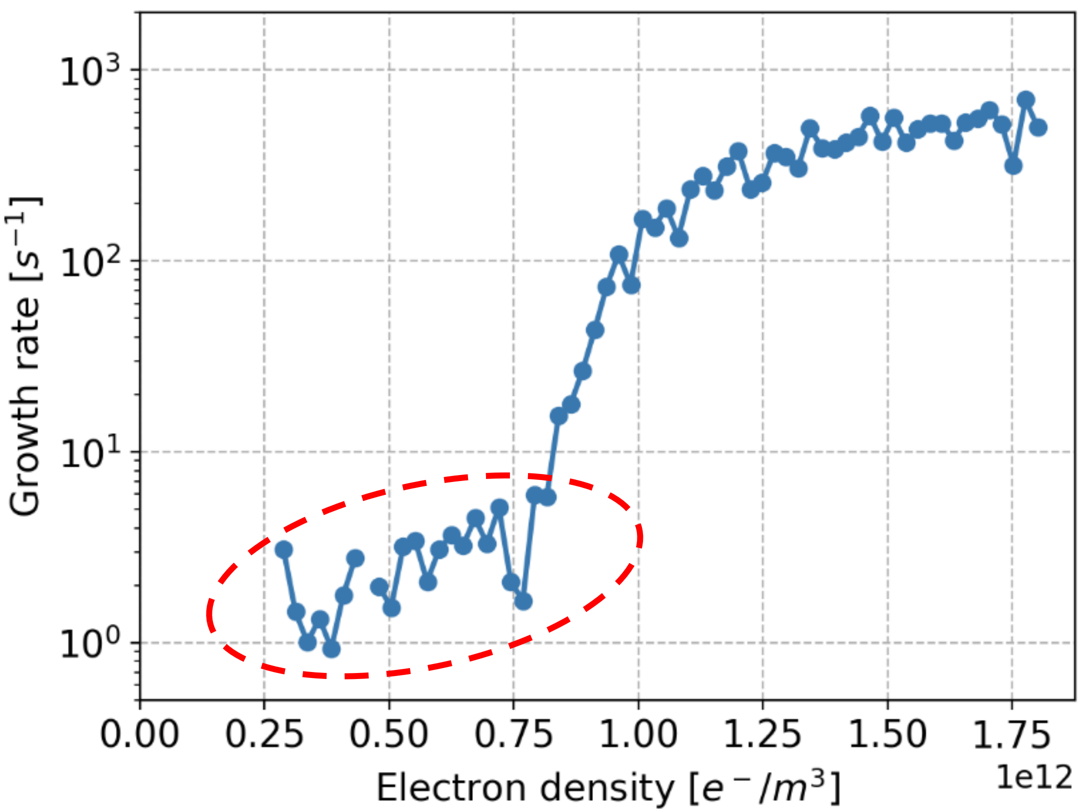


Slow instability for low e-cloud strength

- The linearized model predicts a **slow instability for low e-cloud strength**
- It is **driven by transverse mode coupling** (as it is visible from the imaginary part of the eigenvalues)
- Such an instability is **clearly visible also in the PIC simulations**, although very weakly



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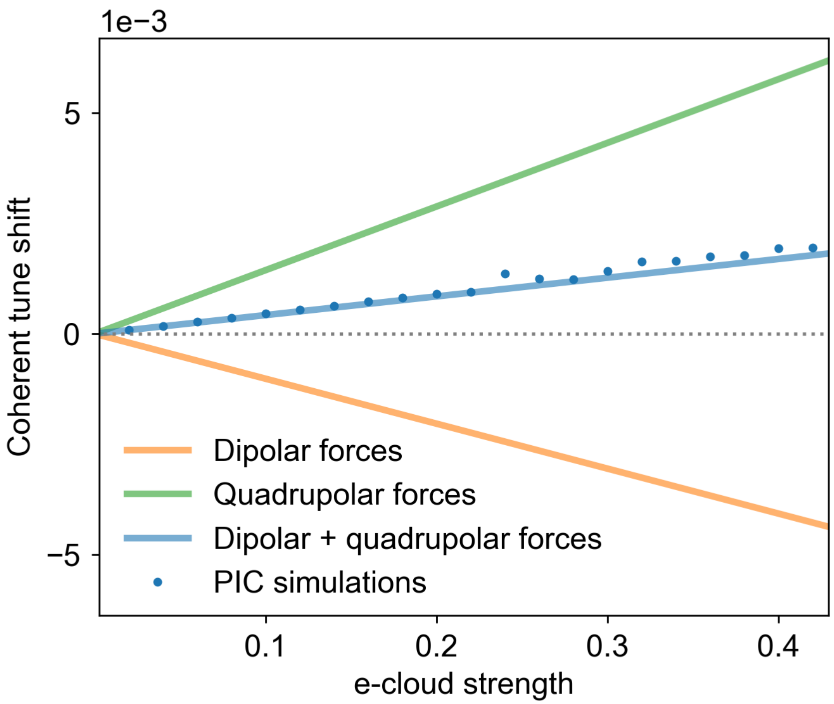
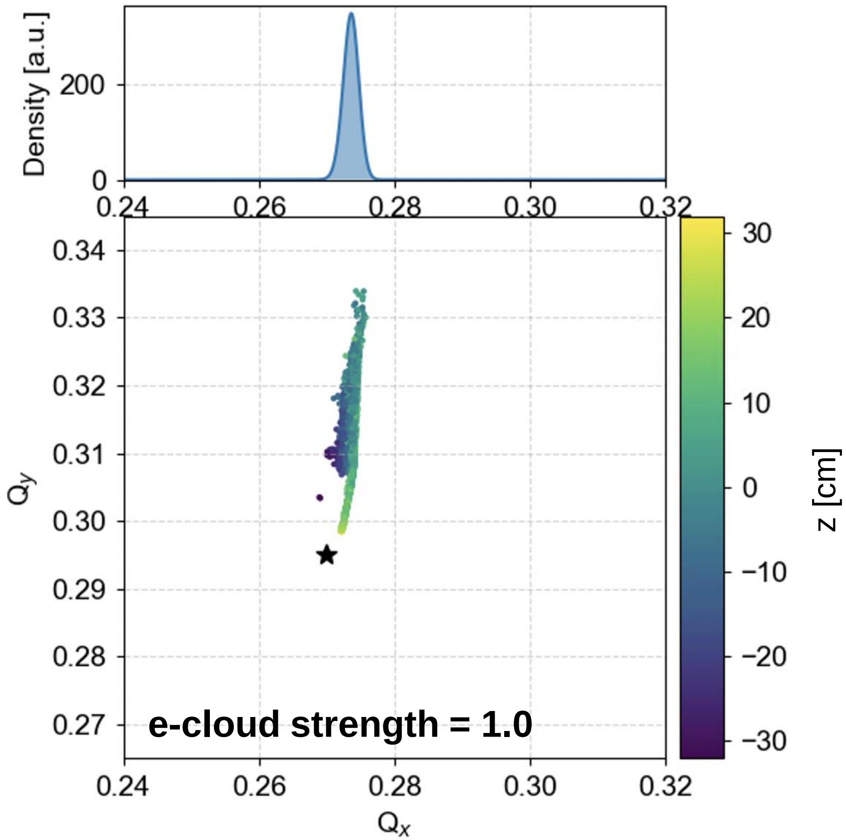
- **Coherent tune shifts**

- As observed for the case of the e-cloud in the quadrupoles, the linearized model provides a **very good estimates of the coherent tune shift** (below the instability threshold)
  - A **cancellation between the detuning from dipolar and quadrupolar forces** is observed
  - The coherent tune shift is **much smaller that the incoherent tune spread**

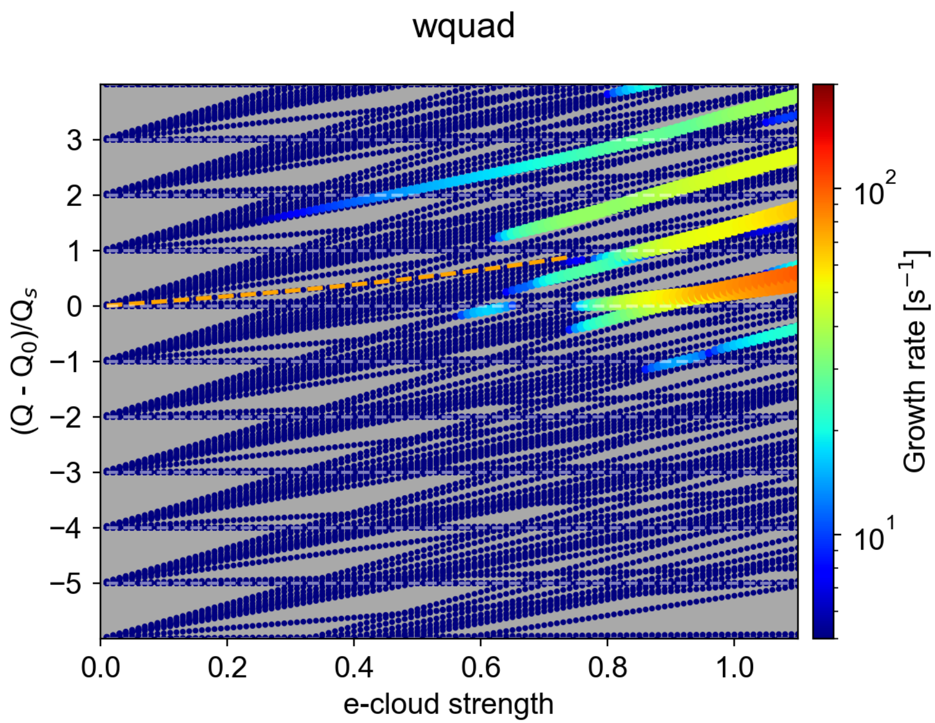


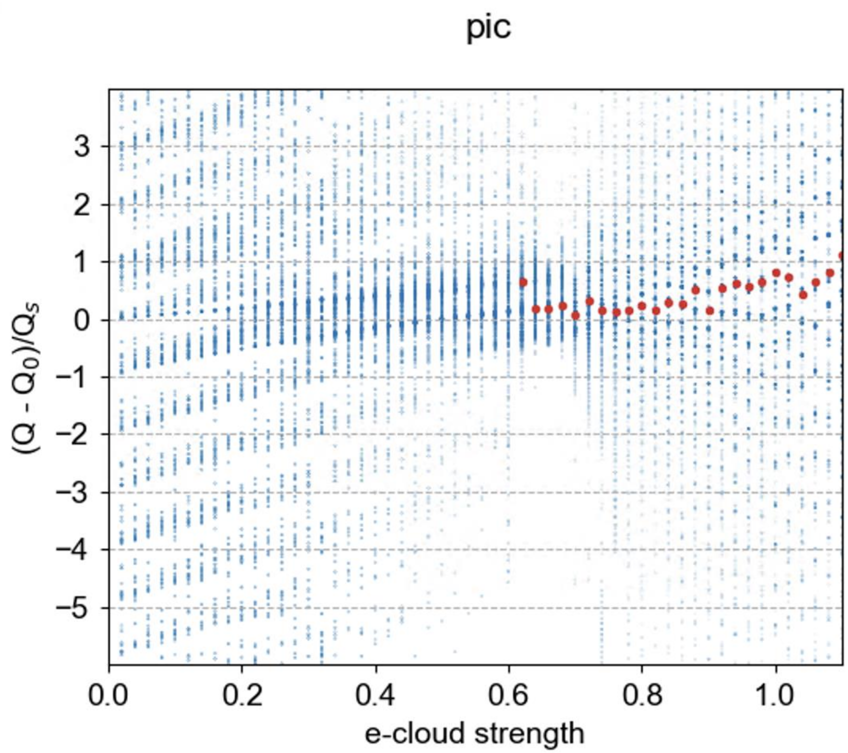


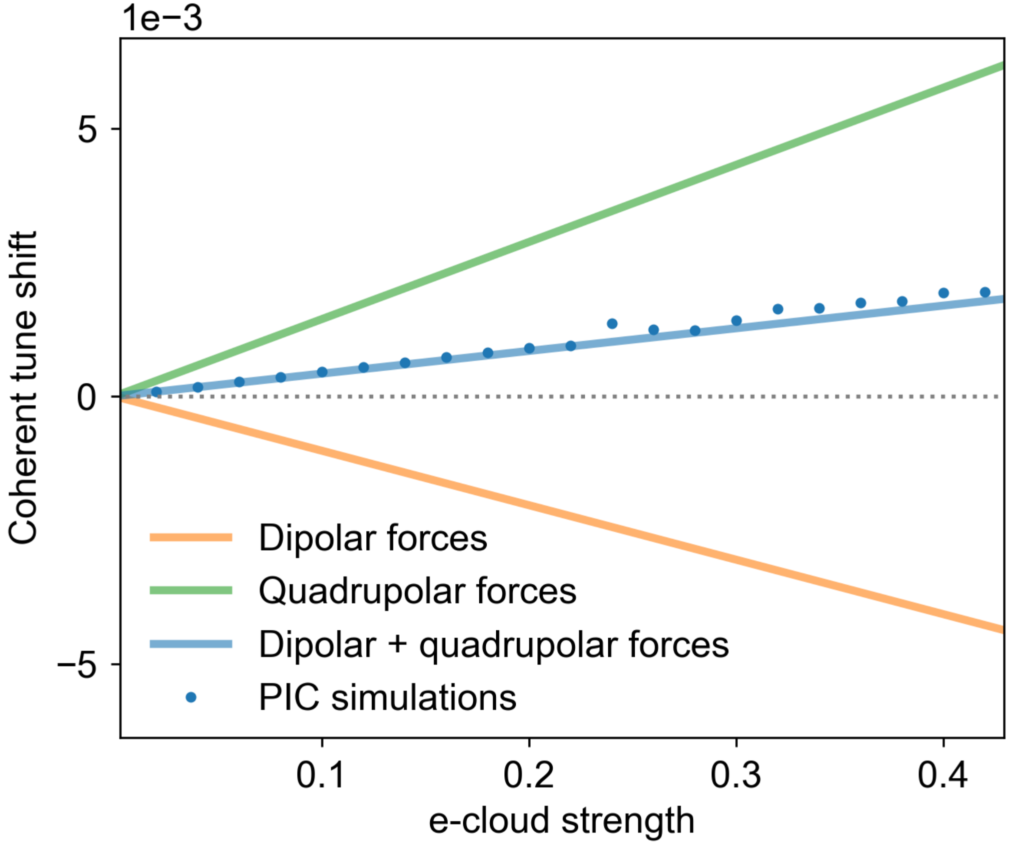
Summary and conclusions

- The **linearized model** was applied to instabilities driven by the **e-cloud in the LHC dipoles:**
  - Instabilities are found to be **triggered by transverse mode coupling**
  - The **main features of the instabilities** (tune of the unstable line, threshold, risetime) are found to be **consistent with the results of PIC simulations**
  - A **slow instability** found in the **PIC simulations** for low e-cloud strength is also identified by the **linearized method**
  - The **coherent tune shift** below the (fast-)instability threshold is **predicted very well** by the linearized method

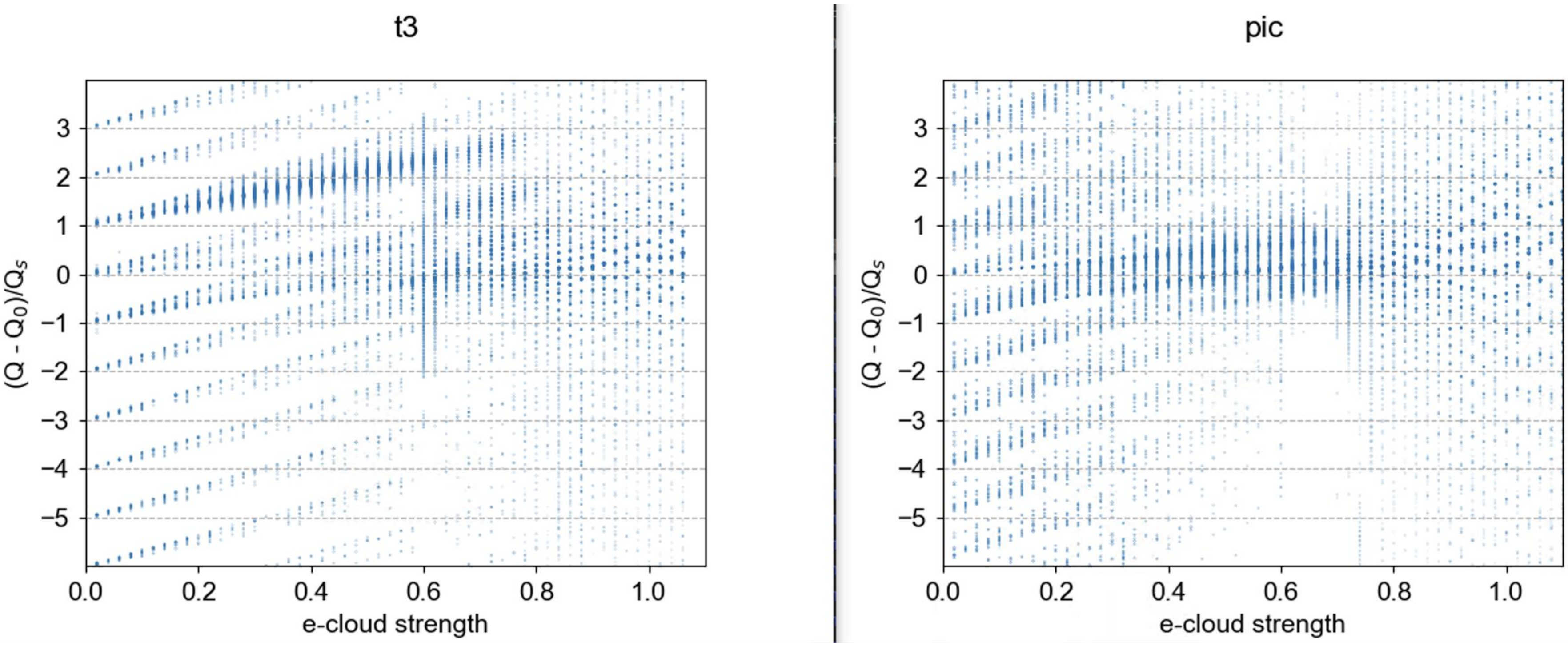
Thanks for your attention!


wquad
(Q - Q0)/Qs
e-cloud strength
Growth rate [s−1]
0.0
0.2
0.4
0.6
0.8
1.0
3
2
1
0
−1
−2
−3
−4
−5
10^2
10^1

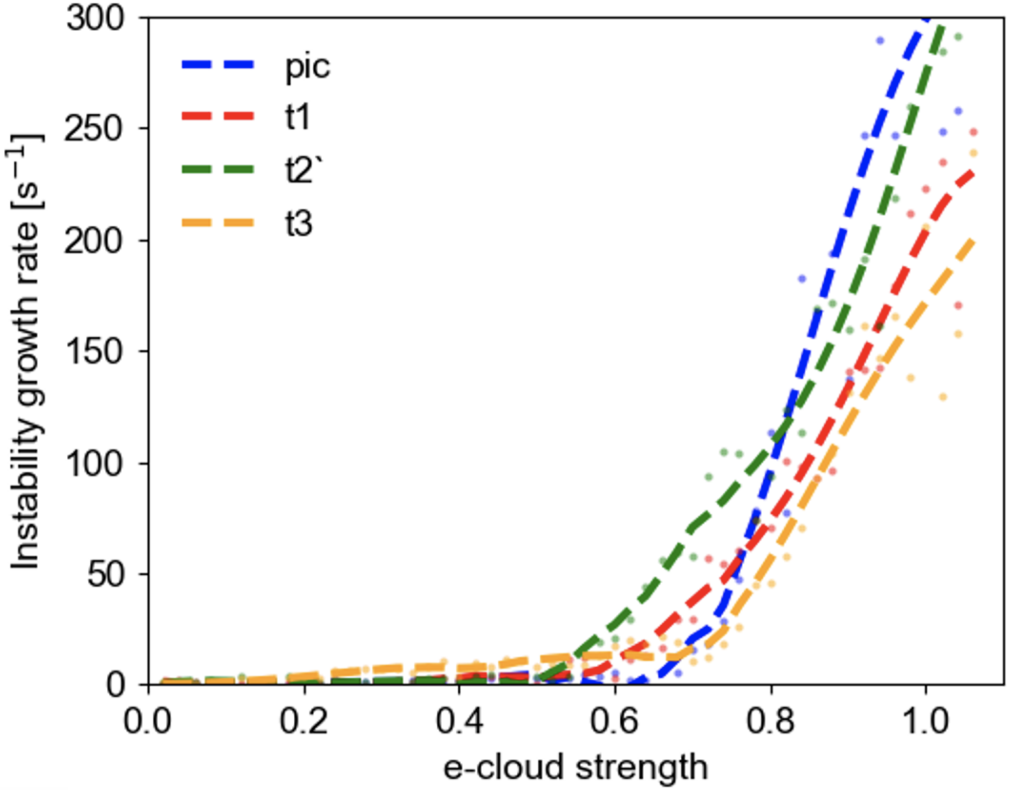

pic
(Q - Q0)/Qs
e-cloud strength
0.0
0.2
0.4
0.6
0.8
1.0
3
2
1
0
−1
−2
−3
−4
−5



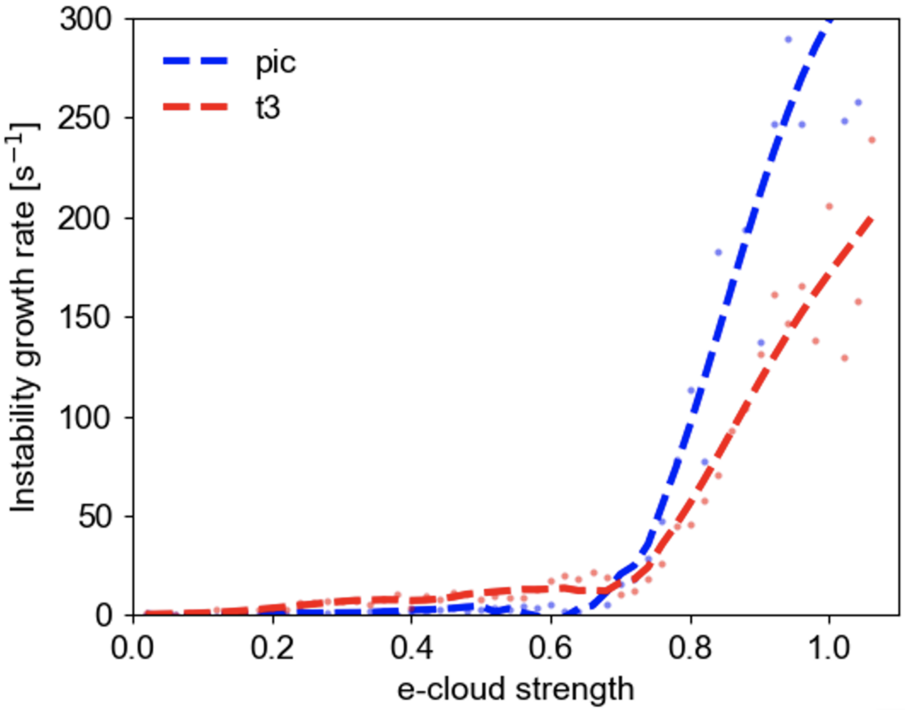
1e−3
5
0
−5
Coherent tune shift
0.1
0.2
0.3
0.4
e-cloud strength
Dipolar forces
Quadrupolar forces
Dipolar + quadrupolar forces
PIC simulations



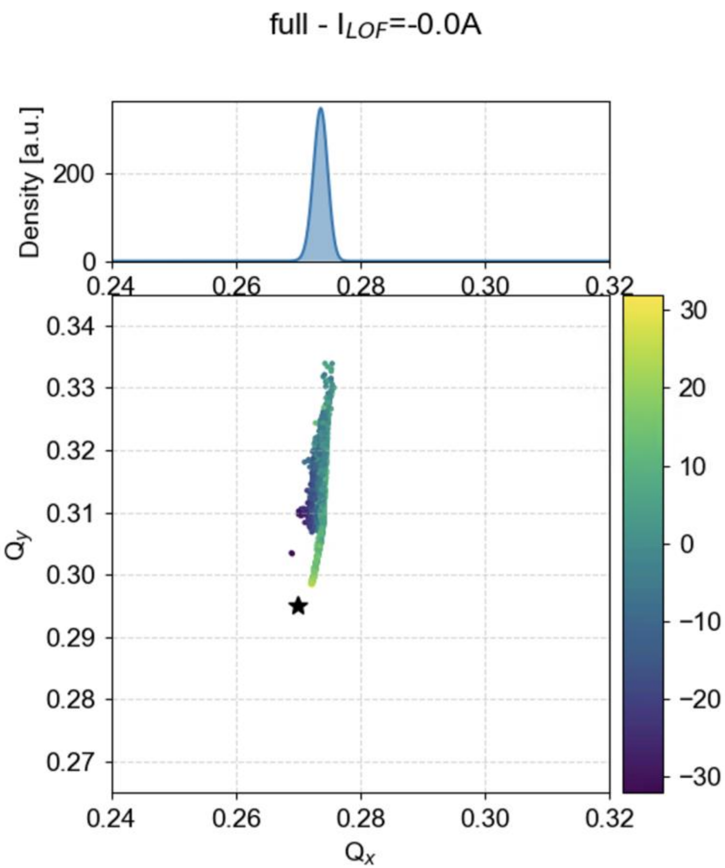
t3
pic
(Q - Q0)/Qs
e-cloud strength



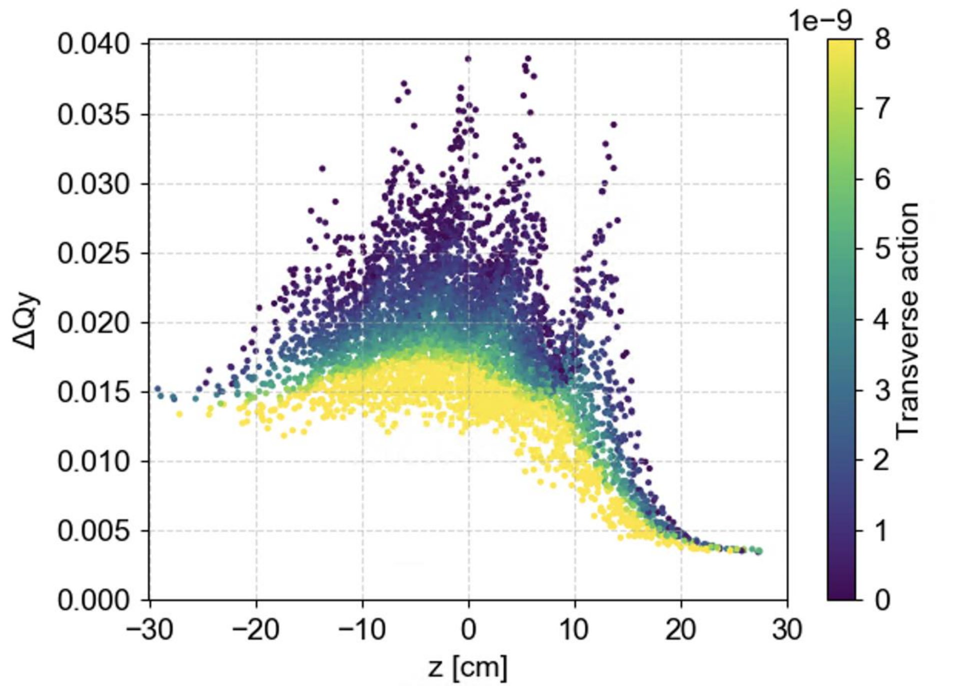
pic
t1
t2`
t3
Instability growth rate [s^{-1}]
e-cloud strength
0
50
100
150
200
250
300
0.0
0.2
0.4
0.6
0.8
1.0



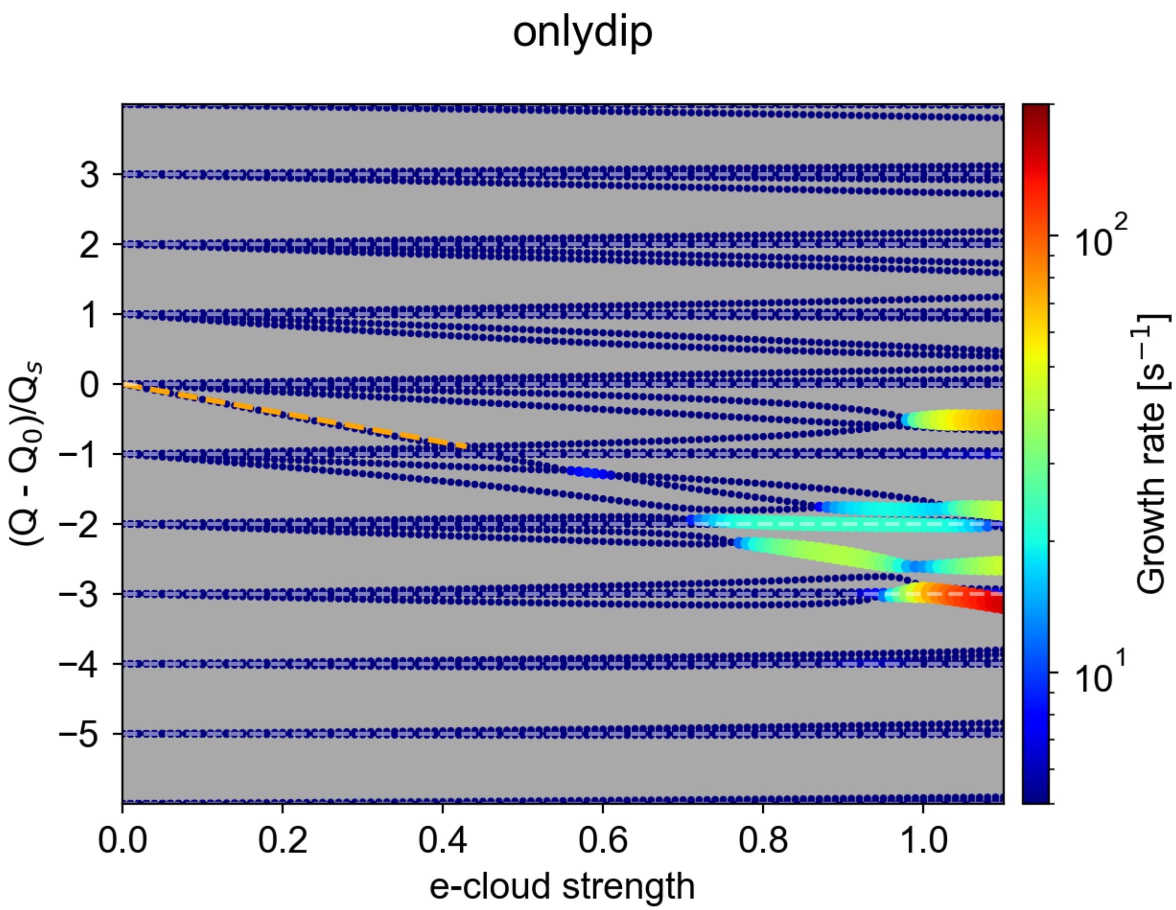
300
250
200
150
100
50
0
Instability growth rate [s^{-1}]
0.0
0.2
0.4
0.6
0.8
1.0
e-cloud strength
pic
t3



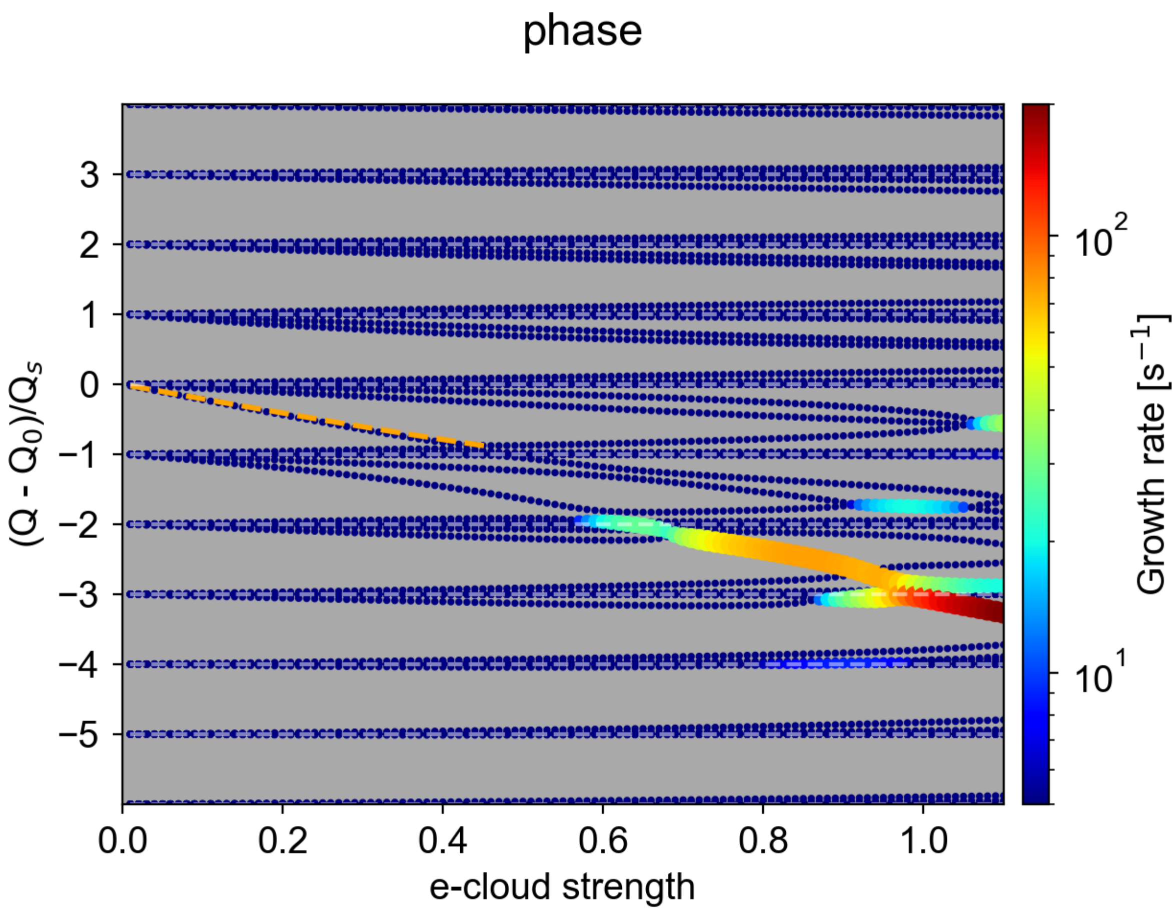
full - I_{LOF}=-0.0A
Density [a.u.]
Q_y
Q_x



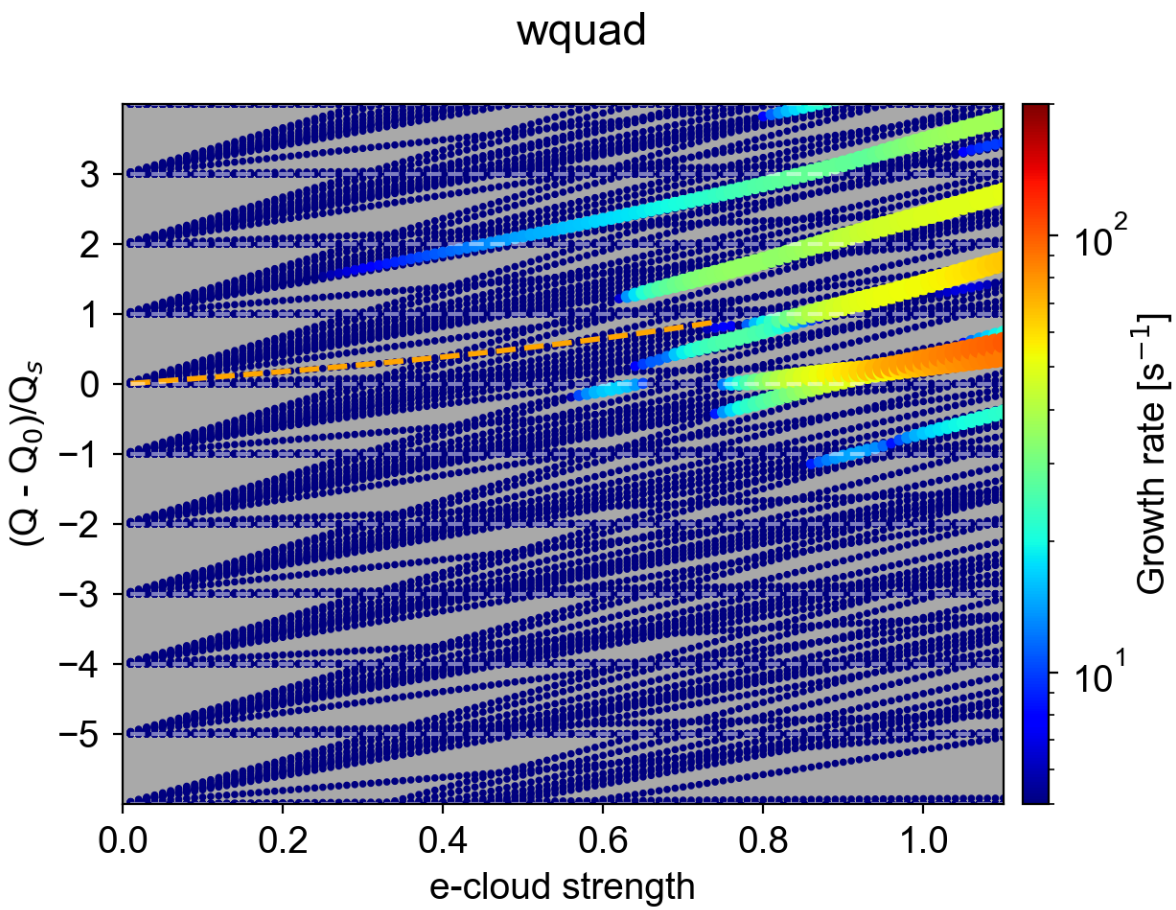
ΔQy
z [cm]
Transverse action
1e−9



onlydip
(Q - Q$_0$)/Q$_s$
3
2
1
0
−1
−2
−3
−4
−5
0.0
0.2
0.4
0.6
0.8
1.0
e-cloud strength
Growth rate [s^{-1}]
10^2
10^1



phase
(Q - Q_0)/Q_s
3
2
1
0
−1
−2
−3
−4
−5
0.0
0.2
0.4
0.6
0.8
1.0
e-cloud strength
Growth rate [s^−1]
10^2
10^1


wquad
(Q - Q$_0$)/Q$_s$
3
2
1
0
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−2
−3
−4
−5
0.0
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0.4
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Growth rate [s^{-1}]
10^2
10^1