RF Quadrupole Structures for Transverse Landau Damping in Circular Accelerators

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Acknowledgements
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B. Salvant, E. Shaposhnikova, LHC OP team

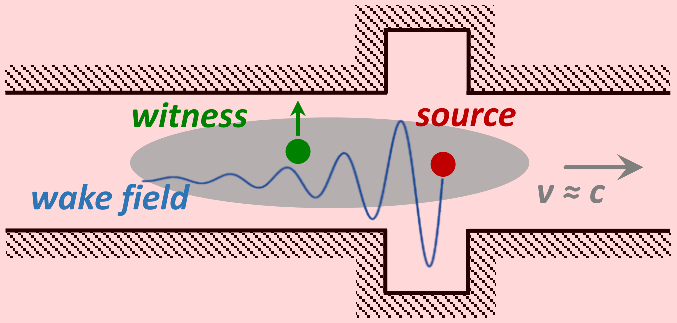
Contents

Collective instabilities … and a way around them

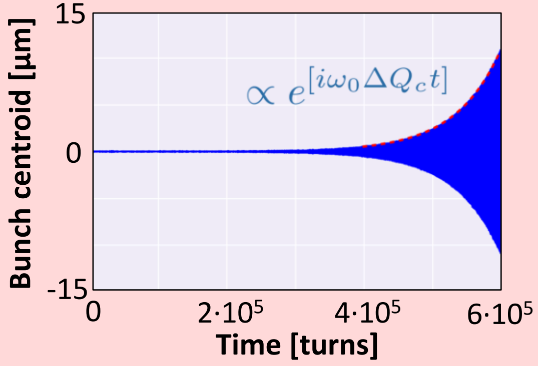
Problem:
Collective instabilities
(Impedance-driven)

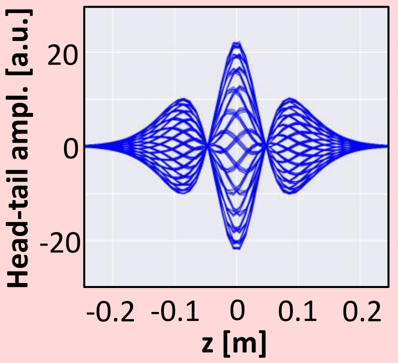
1 ***Source* particle interacts** electro-magnetically with **accelerator structure / impedance**

*Creates **wake field*** that **acts back** on trailing particles ***(witnesses)***



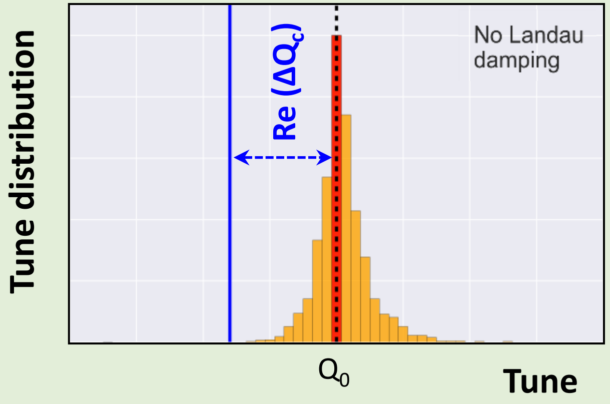
2 **Wake kicks** can **drive (head-tail) instabilities** characterised by the ***complex coherent tune shift*** ΔQ_c and the ***associated mode pattern***



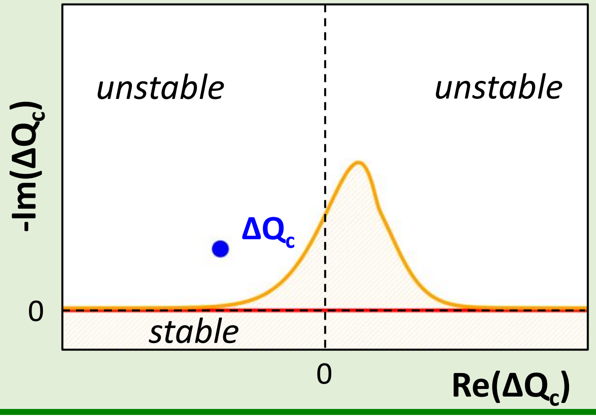


A solution:
Landau damping

1 We want to **generate** a large enough **incoherent tune spread** ***ΔQ***



Stability diagram

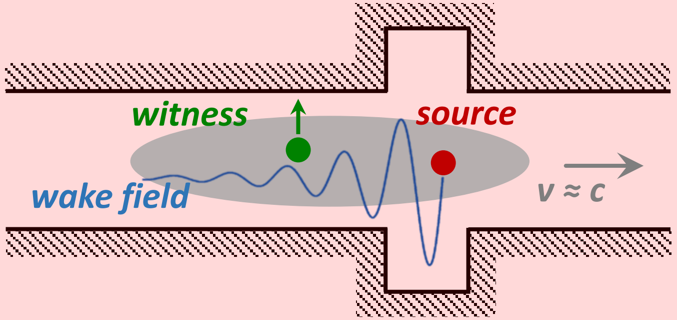


2 This **increases the area of stability** in the **complex tune space**

Collective instabilities … and a way around them

Problem: Collective instabilities (Impedance-driven)

1. ***Source* particle interacts** electro-magnetically with **accelerator structure / impedance**
   - *Creates* ***wake field*** that **acts back** on trailing particles ***(witnesses)***



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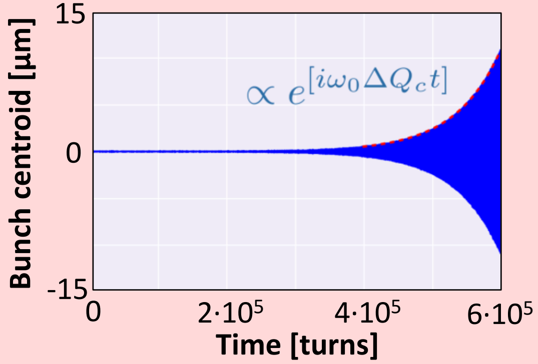
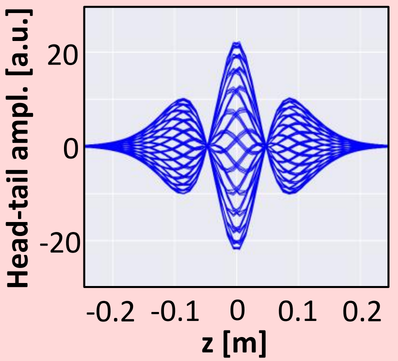
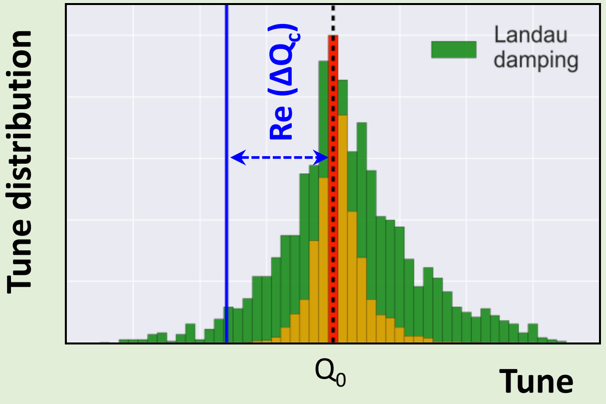




A solution: Landau damping

1. We want to **generate** a large enough **incoherent tune spread** ***ΔQ***



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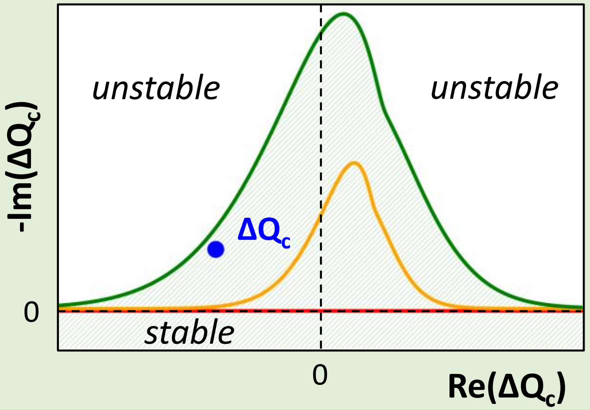
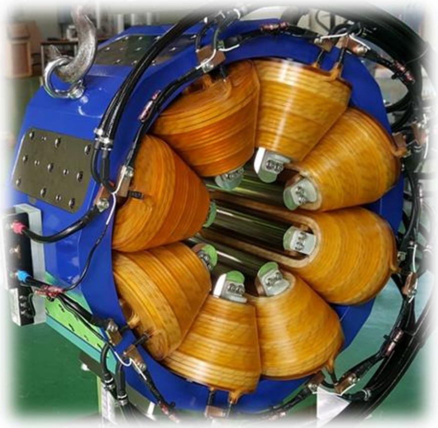
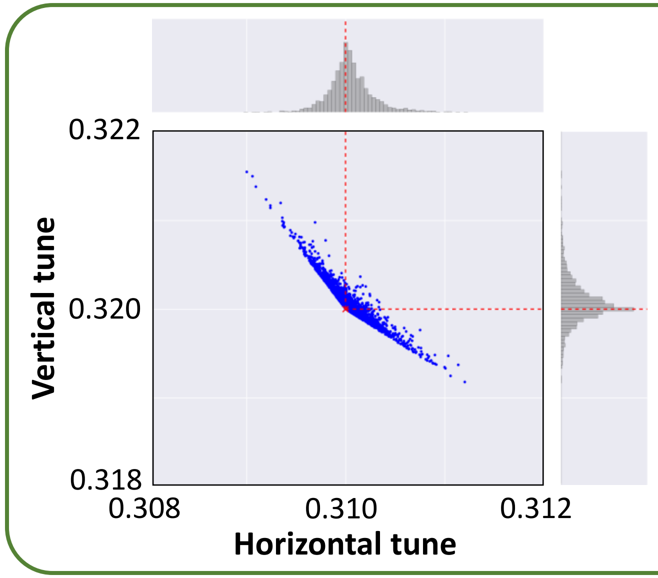


2. This **increases the area of stability** in the **complex tune space**
3. With **large enough spread**, the instability can be **suppressed**

How to generate tune spread?

1 Magnetic octupoles



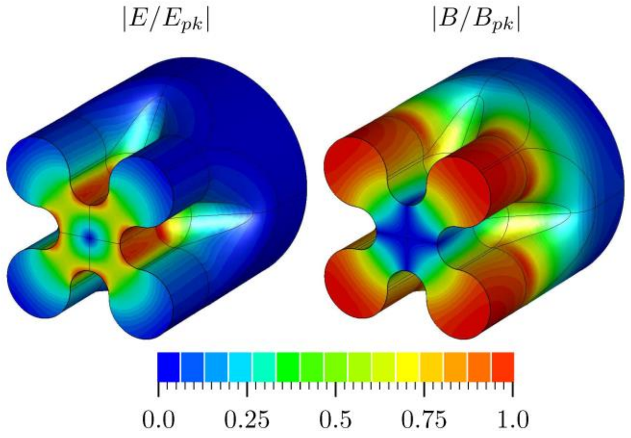


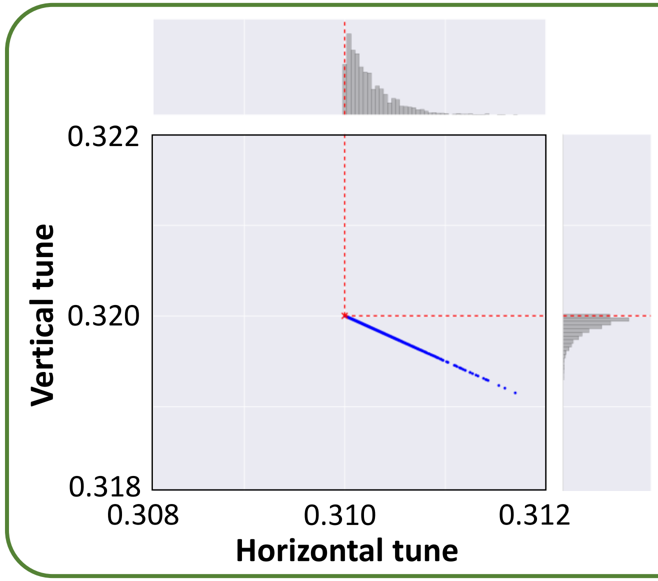
$$\Delta Q_x^i = a_{xx} J_x^i + a_{xy} J_y^i$$
$$\Delta Q_y^i = a_{yy} J_y^i + a_{xy} J_x^i$$

Betatron detuning with ***transverse action***

$$\Delta Q_{x,y}^i \left(J_x^i, J_y^i \right)$$

2 RF quadrupole[1-4]



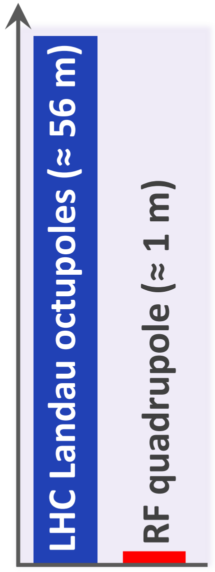


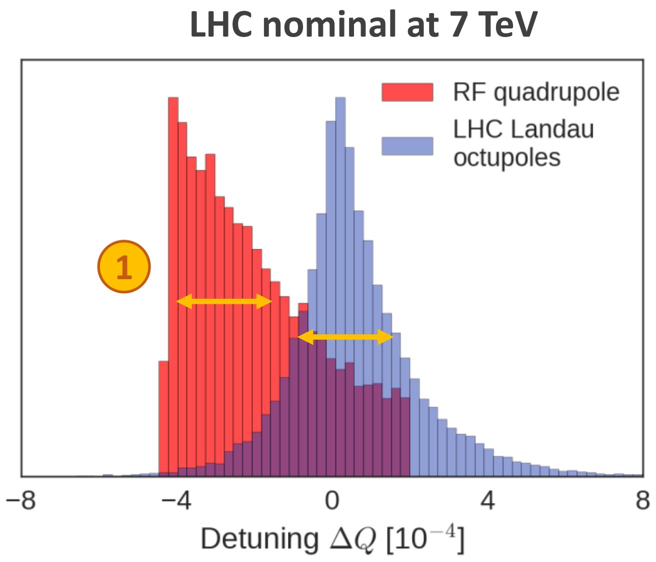
$$\Delta Q_u^i = a_{uz} J_z^i$$
$$u \in \{x, y\}$$

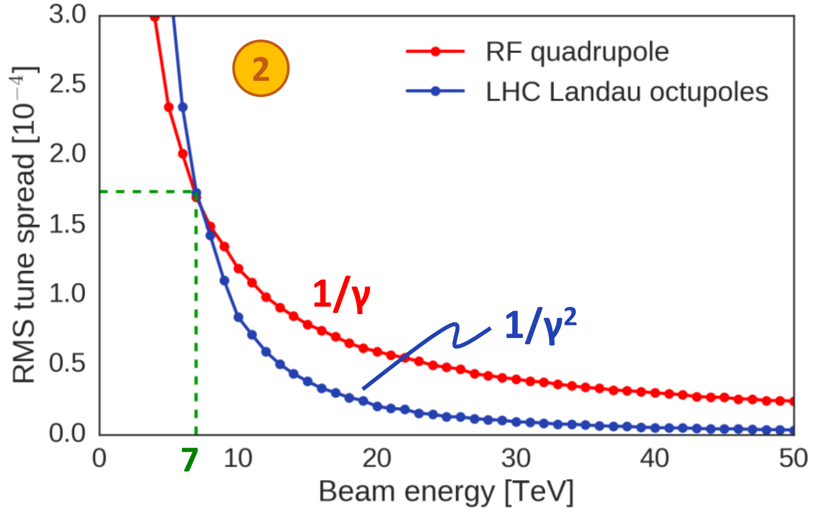
Betatron detuning with ***longitudinal action***

$$\Delta Q_{x,y}^i \left(J_z^i \right)$$

Potential advantages of an RF quadrupole



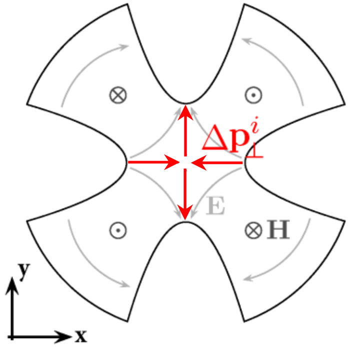




1. **1 m of RF quadrupole produces same RMS tune spread as max. LHC octupoles** (@7 TeV)
   - **$\Delta J_{x,y}$ << ΔJ_z** (LHC nom.: factor $10^4 - 10^5$ at 7 TeV)[1,5]
   - **J_z** provides **much larger handle** for detuning
2. **Higher energy machines**
   - **Octupoles:** affected by **higher beam rigidity** & **adiabatic damping** **($1/\gamma^2$)**
   - **RF quadrupole:** only affected by **higher beam rigidity** **($1/\gamma$)** (thanks to longitudinal blow-up[6])
3. **Higher intensity / higher brightness beams**
   - Potentially **more violent instabilities**
   - **Smaller transverse emittance makes octupoles less effective**
4. **Manipulations in the transverse planes**
   - E.g. **halo cleaning:** can **decrease octupole** detuning **efficiency**, while the **RF quadrupole** remains **unaffected**

Basic working principle of an RF quadrupole (I)

1 RF-modulated quadrupole kick



$$\Delta \mathbf{p}_\perp^i = q b^{(2)} \left[y_i \mathbf{u}_y - x_i \mathbf{u}_x \right] \cos\left(\frac{\omega z_i}{\beta c} + \varphi_0 \right)$$

$b^{(2)}$ [T/m m] denotes the integrated quadrupolar gradient

2 Translates into betatron detuning

Choose $\varphi_0 = 0$

$$\Delta Q_{x,y}^i(t) \propto \pm \cos\left(\omega \frac{z_i(t)}{\beta c} + \varphi_0 \right) = \dots$$

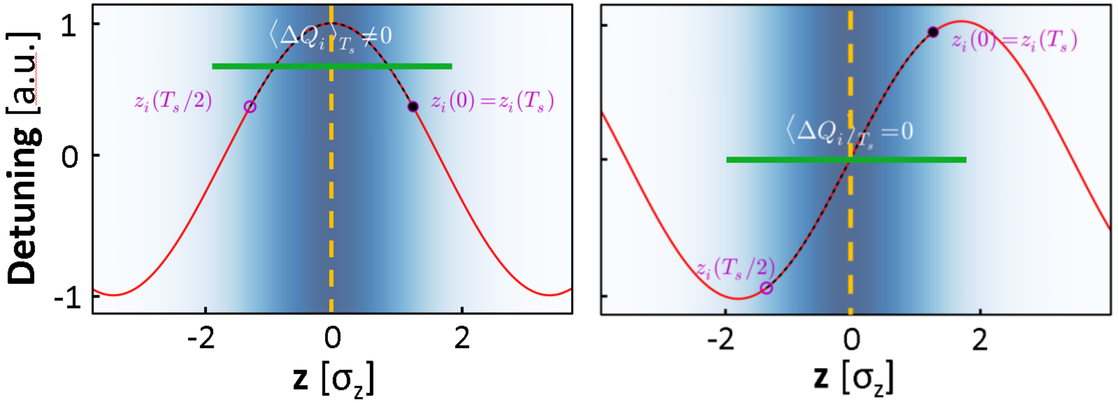
$$\dots = \pm \left[1 - \frac{1}{2} \left(\frac{\omega}{\beta c} \right)^2 z_i(t)^2 + \mathcal{O}\left(z_i(t)^4 \right) \right] \quad \sigma_z \ll \beta c / \omega$$

$$\langle \Delta Q_{x,y}^i \rangle_{T_s} \propto \pm \left[1 - \frac{1}{2} \left(\frac{\omega}{\beta c} \right)^2 \beta_z J_z^i \right]$$

2nd order: Detuning with **longitudinal** action

Why $\varphi_0 = 0$?

$\varphi_0 = 0$ | **$\varphi_0 = \pm \pi/2$**



Particles get **detuning with J_z** over time scales of slow head-tail instabilities (>> T_s)

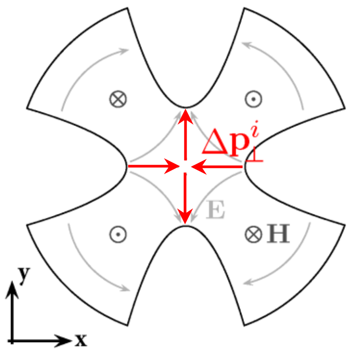
Landau damping of slow head-tail instabilities possible

Tune spread vanishes: Particles have zero detuning for time scales >> T_s

Effect on fast head-tail instability (TMCI)[7,8]

Basic working principle of an RF quadrupole (II)

1 **RF-modulated** quadrupole kick



$$\Delta\mathbf{p}_\perp^i = q b^{(2)} \left[y_i \mathbf{u}_y - x_i \mathbf{u}_x \right] \cos\left(\frac{\omega z_i}{\beta c} + \varphi_0 \right)$$

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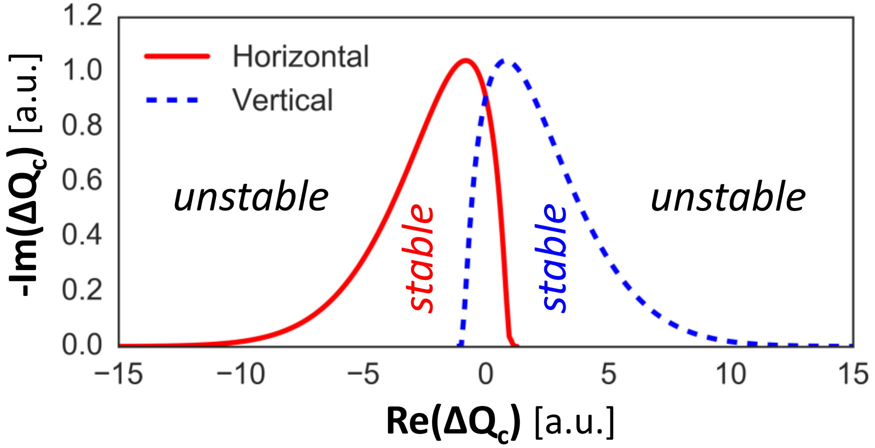
$$\langle \Delta Q^i_{x,y} \rangle_{T_s} \propto \pm \left[1 - \frac{1}{2} \left(\frac{\omega}{\beta c} \right)^2 \beta_z J_z^i \right]$$

2nd order: Detuning with **longitudinal** action

J. Scott Berg and F. Ruggiero developed basic stability diagram theory for detuning with J_z[9]



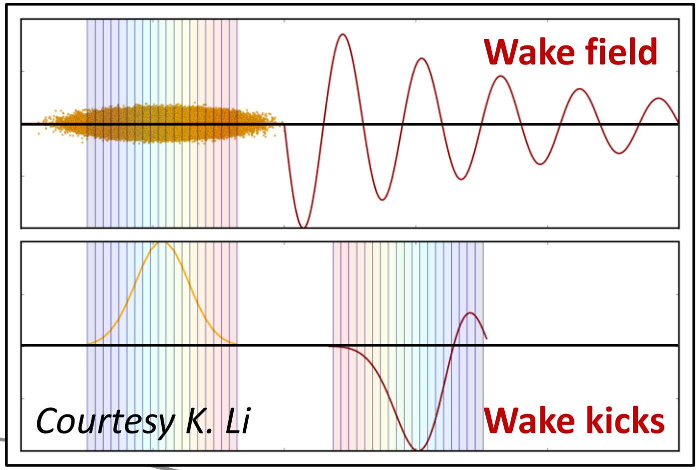
- Theory is approximate and does not include all the beam dynamics
  - At present best addressed with tracking codes
- Asymmetry in the two planes can be reduced with a two-family scheme, similarly to octupoles (see [10] for details)

Contents

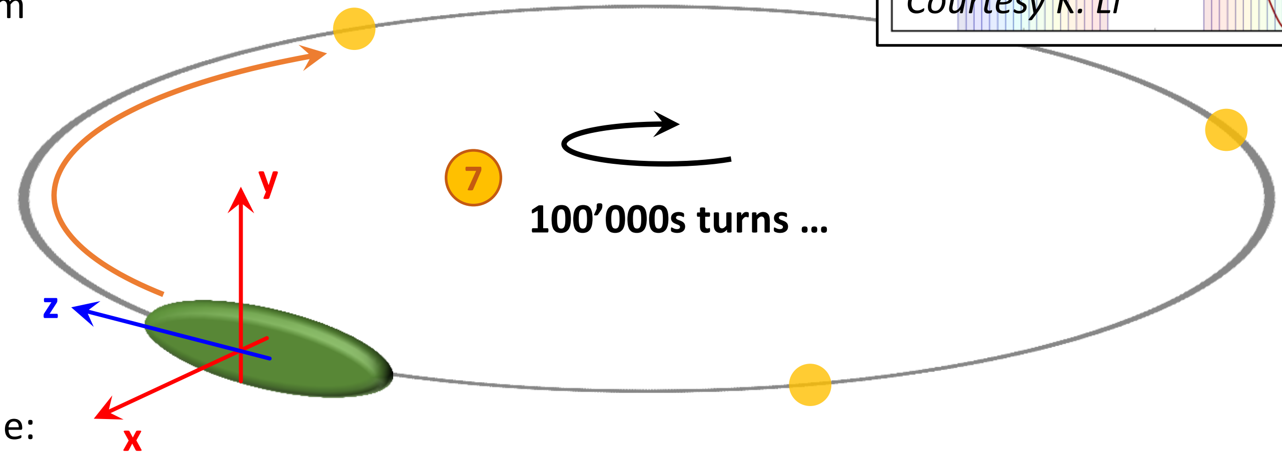
- Introduction
- Working principle
- Numerical simulations
- Experimental studies
- Summary and outlook

The PyHEADTAIL model[11]

4 Interaction point
- Wake field kicks
- Chromaticity
- Octupoles, RF quadrupole
- Electron cloud (PyECLOUD)
- …

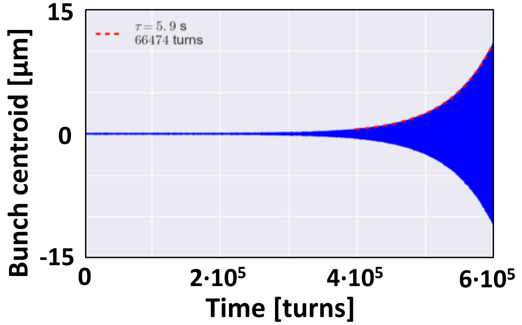


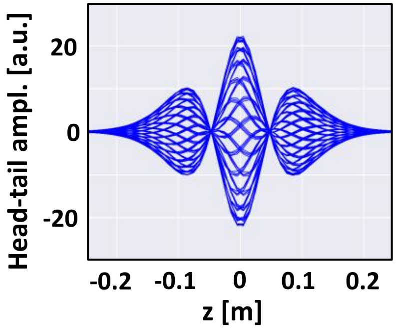
3 Linear periodic maps for transverse tracking from one IP to the next



2 Initialise bunch
- Typically 10^6 macroparticles
- Various distributions possible: Gaussian, waterbag, matched to rf bucket (longitudinal), …

5 Data acquisition



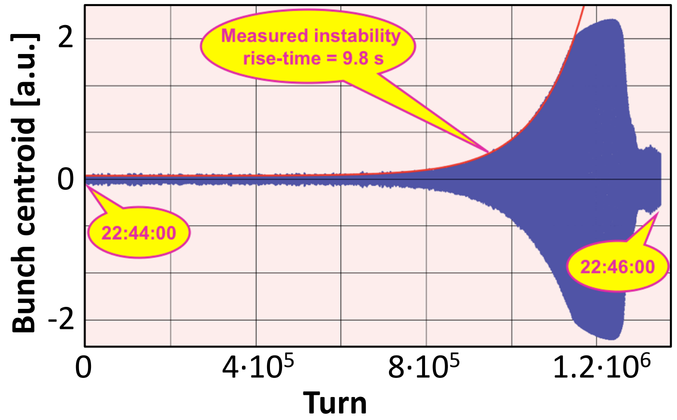


6 Once per turn:
Apply (non-)linear synchrotron motion

1 Divide ring into segments separated by interaction points (IP)

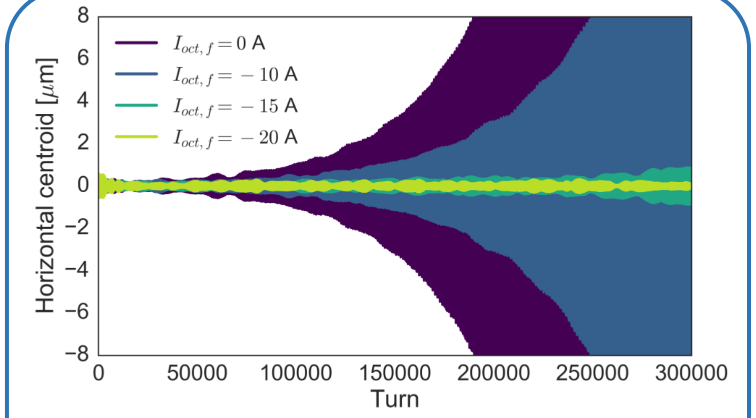
Proof of concept (I)

LHC experiment[12]



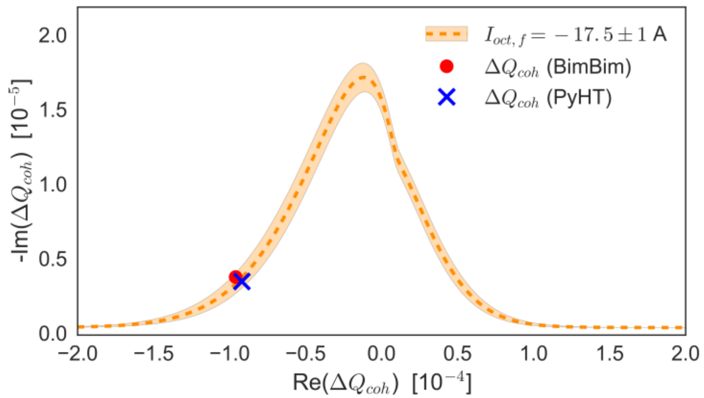
- LHC at 3.5 TeV, single bunch
- Head-tail instability m = -1
- Rise time τ ≈ 10 s at I_{oct} = -10 A
- **Cured with octupoles I_{oct} = -15 ± 5 A**

PyHEADTAIL



- Same m = -1 instability
- Rise time
  - τ ≈ 4.5 s at I_{oct} = -10 A
  - τ ≈ 12.8 s at I_{oct} = -15 A
- **I_{oct} = -17.5 ± 2.5 A**

Stability diagram theory



- Circulant matrix model (BimBim[13]) to solve eigenvalue equation
- Again m = -1 instability
- **I_{oct} = -17.5 ± 1 A**

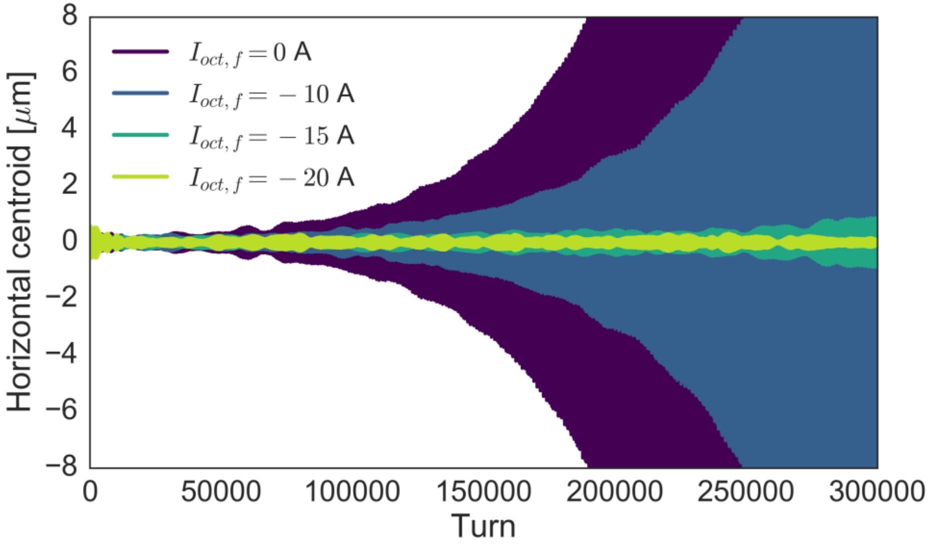
Excellent agreement between experiment, tracking, and theory

- Solid understanding of the involved mechanisms
- Landau damping from octupoles responsible for mitigation
- PyHEADTAIL models the machine accurately (e.g. reliable impedance model) and reproduces observations, in particular the Landau damping mechanism

Ideal study case to evaluate the stabilising effect of an RF quadrupole

Proof of concept (II)

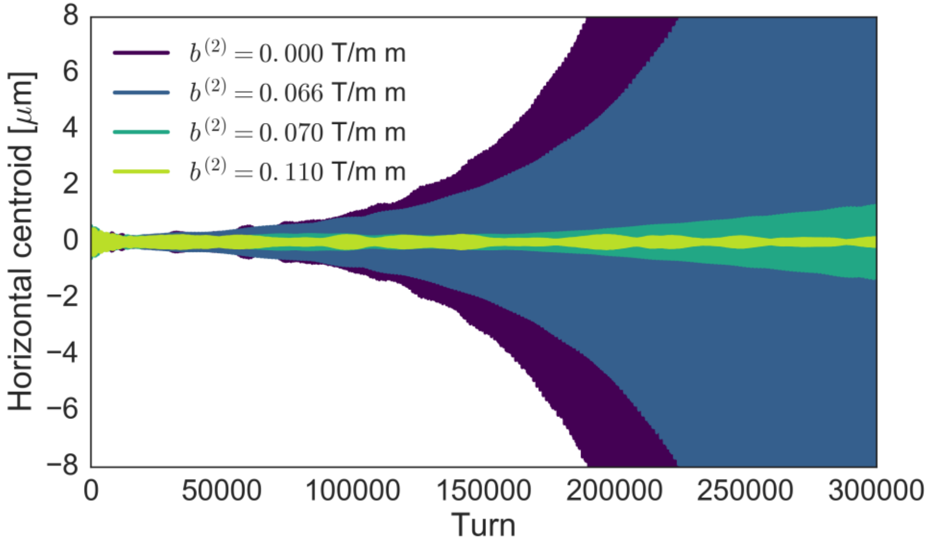
Magnetic octupoles



- Landau octupole current of -17.5 ± 2.5 A is required for stabilisation
- Corresponds to **active length ≈ 1.5 m** (LHC octupoles at max. strength)

What happens if we *replace* octupoles with RF quadrupoles?

RF quadrupoles

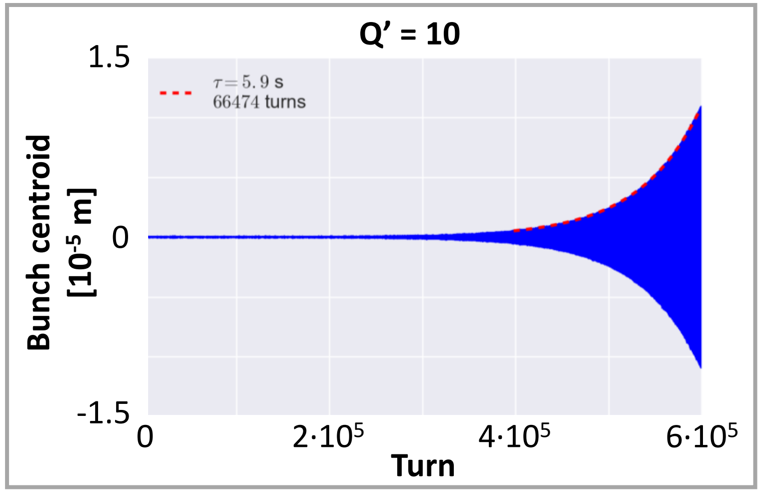


- **As expected from theory, the RF quadrupole mitigates the instability**, similarly to octupoles
- Strength can be achieved with a single cavity
- **Active length ≈ 0.15 m**

Factor 10 difference in required active lengths for this particular instability.
Expected to become even better at higher energies.

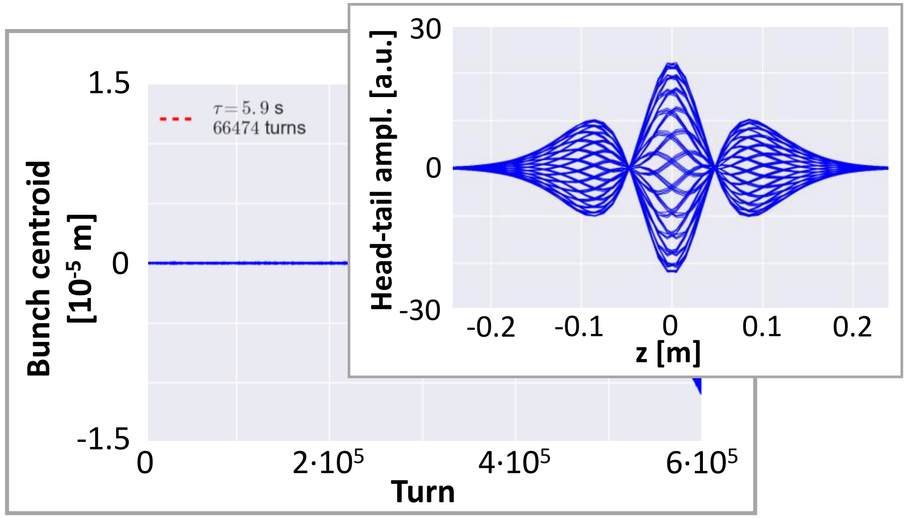
HL-LHC PyHEADTAIL study: Synergy between octupoles and RF quadrupole

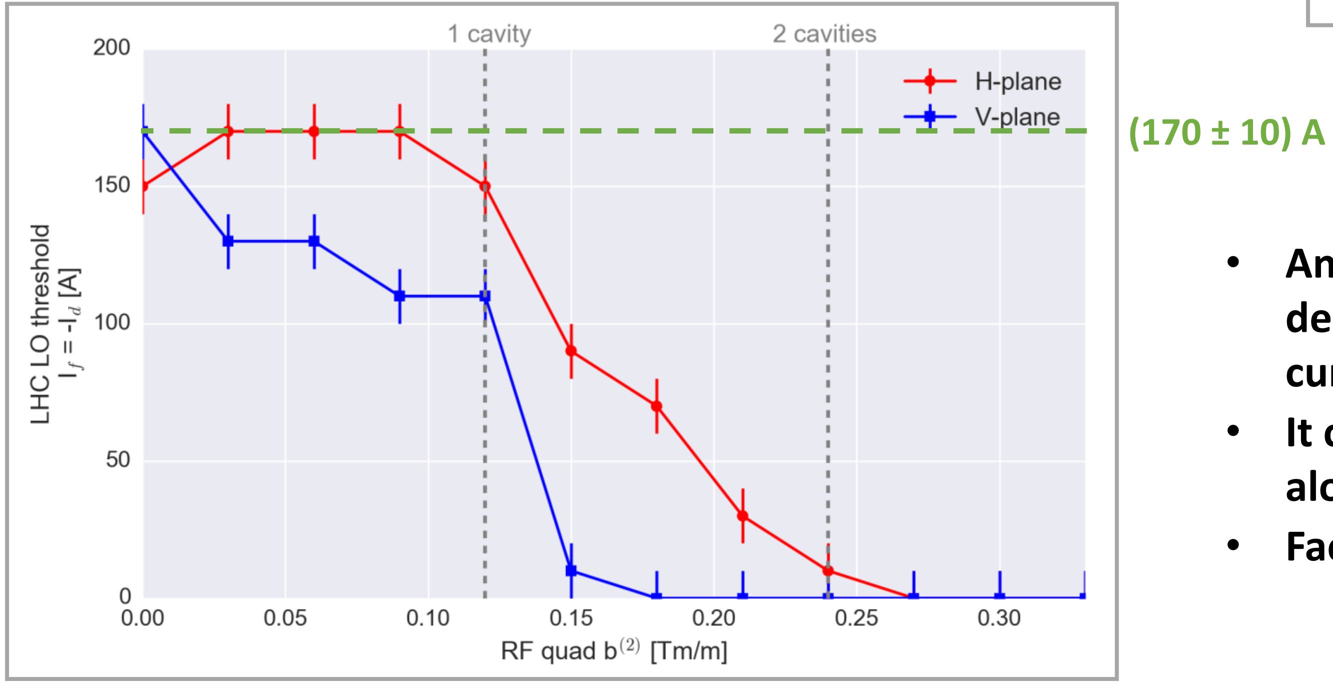
- **HL-LHC, single nominal bunch, 7 TeV**[14]
- Working point **Q' = 10**
- **Head-tail mode with two nodes –** as observed in the LHC[15]



HL-LHC PyHEADTAIL study: Synergy between octupoles and RF quadrupole

- **HL-LHC, single nominal bunch, 7 TeV[14]**
- Working point **Q' = 10**
- **Head-tail mode with two nodes –** as observed in the LHC[15]
- **Without RF quadrupole: LHC Landau octupole current I_{oct} = (170 ± 10) A** is required for stabilisation (accounting for impedance only)





- **An RF quadrupole can significantly decrease the required octupole current**
- **It can also provide beam stability alone, here with 2-3 cavities**
- **Factor 34 difference in active lengths**

Contents

Experimental studies (I)

Direct experimental validation of RF quadrupole simulations **is not possible** at present as no such cavity has been built yet

But: Stabilising mechanism *can* be verified using second order chromaticity Q''

How / why ?

RF quadrupole

RF-modulated quadrupole kick leads to betatron detuning with J_z

$$\Delta Q^i_{x,y} \propto \pm \cos\left(\frac{\omega}{\beta c} z_i\right) \approx \pm\left[1 - \frac{1}{2}\left(\frac{\omega}{\beta c}\right)^2 z_i^2\right]$$

$$\langle \Delta Q^i_{x,y} \rangle_{T_s} \propto \pm\left[1 - \frac{1}{2}\left(\frac{\omega}{\beta c}\right)^2 \beta_z J_z^i\right]$$

Chromaticity

Betatron detuning from relative momentum error $\delta_i = \Delta p_i / p$

$$\Delta Q^i_{x,y} = Q'_{x,y}\delta_i + \frac{Q''_{x,y}}{2}\delta_i^2 + \mathcal{O}\left(\delta_i^3\right)$$

Q'' term leads to

$$\langle \Delta Q^i_{x,y} \rangle_{T_s} = \frac{Q''_{x,y}}{2}\sigma_\delta^2 J_z^i$$

Q'' can be introduced in the LHC by powering the main sextupole magnets in a specific configuration[16]

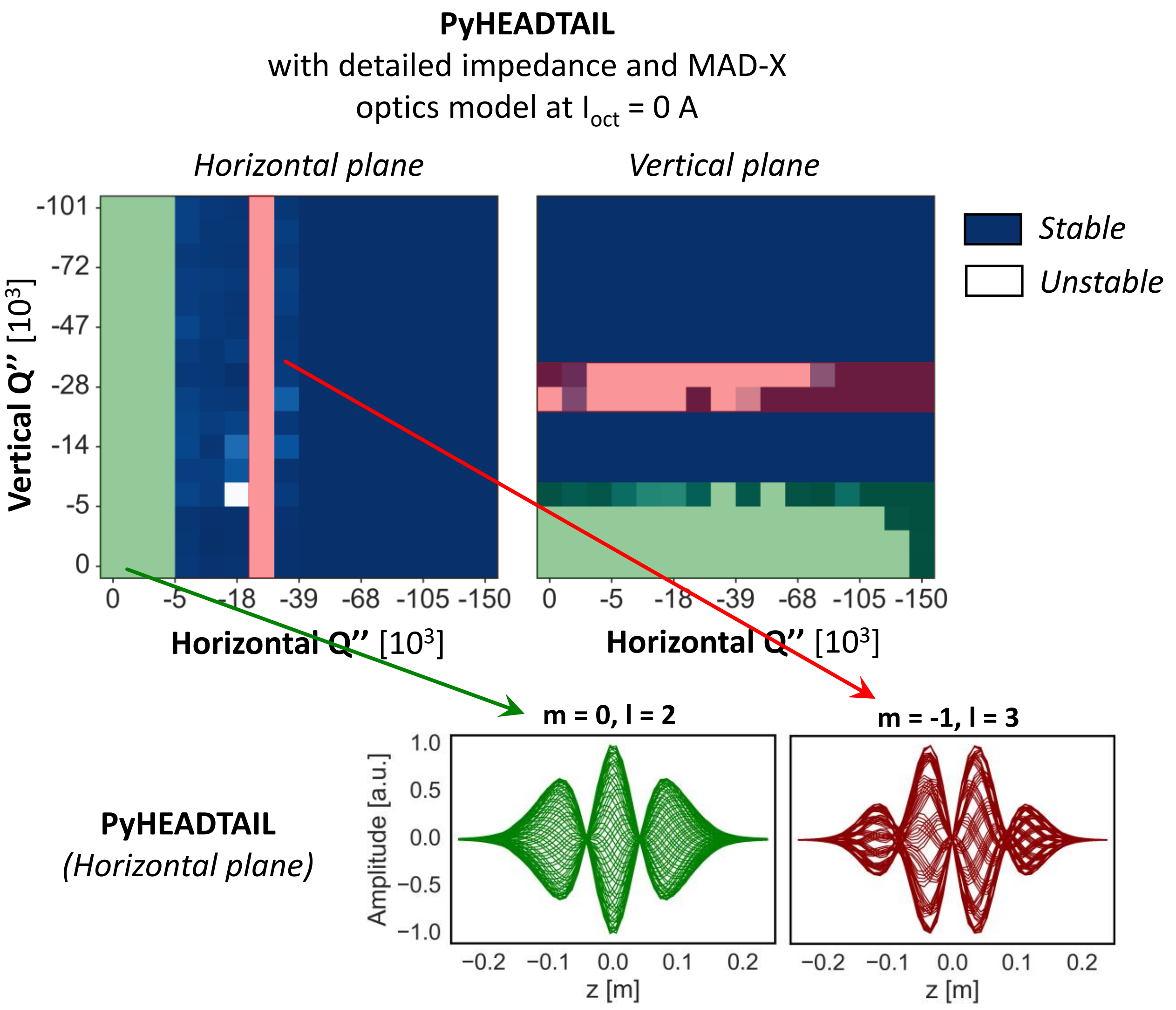
This has limitations and does not offer the same flexibility as an RF quadrupole

- Magnitude and range depend on the machine lattice
- It can in general not be a fully independent knob due to optics constraints
- It also creates detuning with *transverse* action $\Delta Q(J_x, J_y)$

Experimental studies[16,17] (II)

Goal: Stabilise single bunches at 6.5 TeV with Q''

PyHEADTAIL predictions: Q'' creates large areas of stability interleaved with two unstable bands (different head-tail modes!)



Experimental studies[16,17] (II)

Goal: Stabilise single bunches at 6.5 TeV with Q''

PyHEADTAIL predictions: Q'' creates large areas of stability interleaved with two unstable bands (different head-tail modes!)

Experiment

Procedure: Introduce Q'' and reduce the Landau octupole current to determine the single bunch stability threshold

Two different Q'' working points (both with $Q'_{x,y} = 15$)

(a) ***$Q_x'' = 0$ / $Q_y'' = 0$*** (@$I_{oct} = 0$ A)

- Bunches go unstable at $I_{oct} = 80^{+35}_{-20}$ A[14] *meas.* vs. $I_{oct} = 105 \pm 5$ A *sim.*

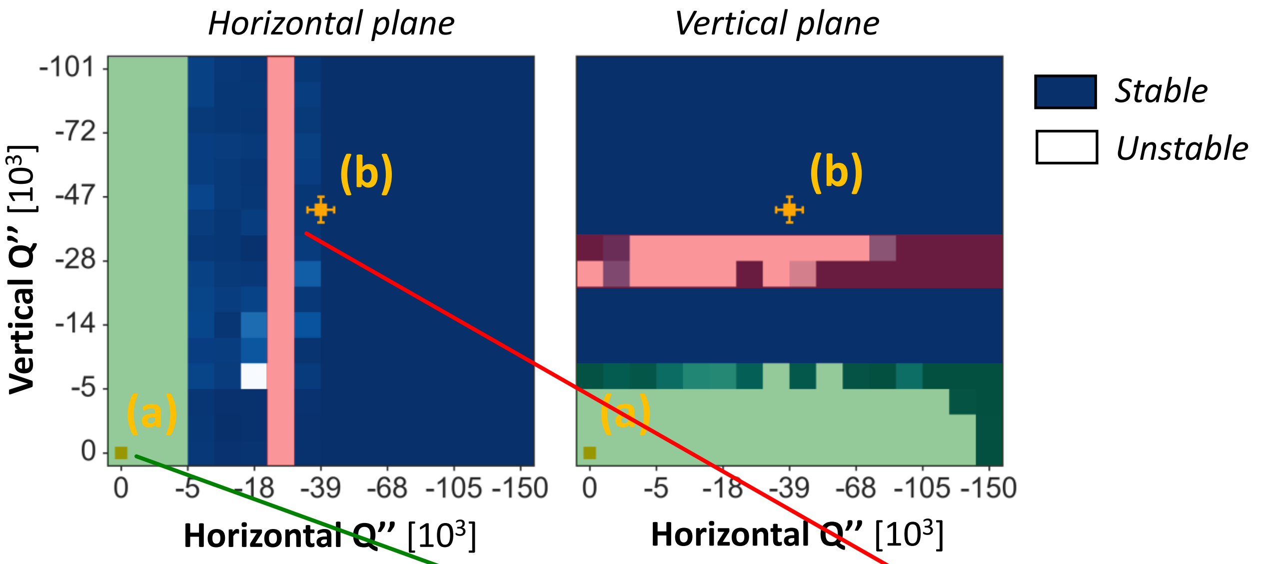
(b) ***$Q_x'' \approx -40'000$ / $Q_y'' \approx -40'000$*** (@$I_{oct} = 0$ A)

- Octupoles can be reduced to $I_{oct} = 0$ A
- 3 out of 4 bunches in the machine are stable
- One bunch goes unstable (H) when reducing from $I_{oct} = 36$ A to 0 A
- This is explained by the unstable band located next to the working point (b).

Measurements and simulations show excellent agreement on the unstable modes for both cases.

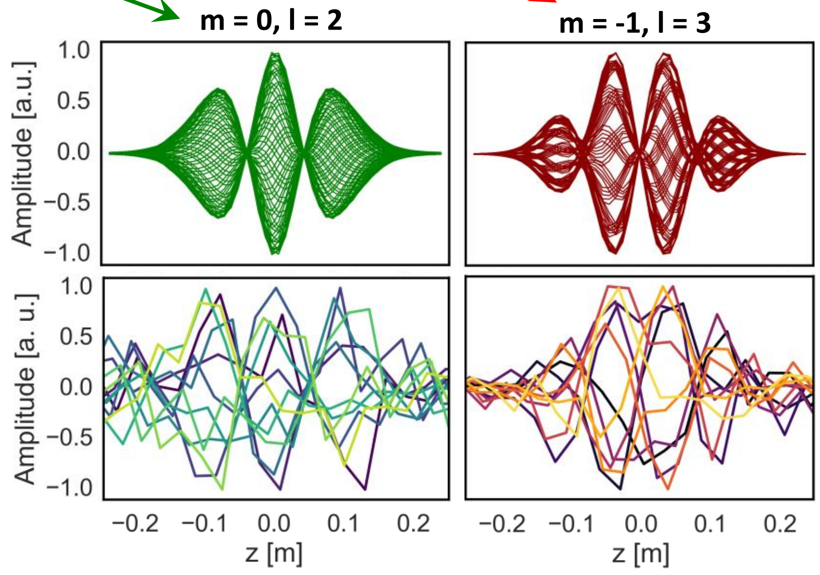
PyHEADTAIL

with detailed impedance and MAD-X optics model at $I_{oct} = 0$ A



PyHEADTAIL
(Horizontal plane)

LHC measurements
(Horizontal plane)



Experimental studies[16,17] (II)

Goal: Stabilise single bunches at 6.5 TeV with Q''

PyHEADTAIL predictions: Q'' creates large areas of stability interleaved with two ...

Experiment

Procedure: Introdu...
current to determi...

Two different Q'' ...

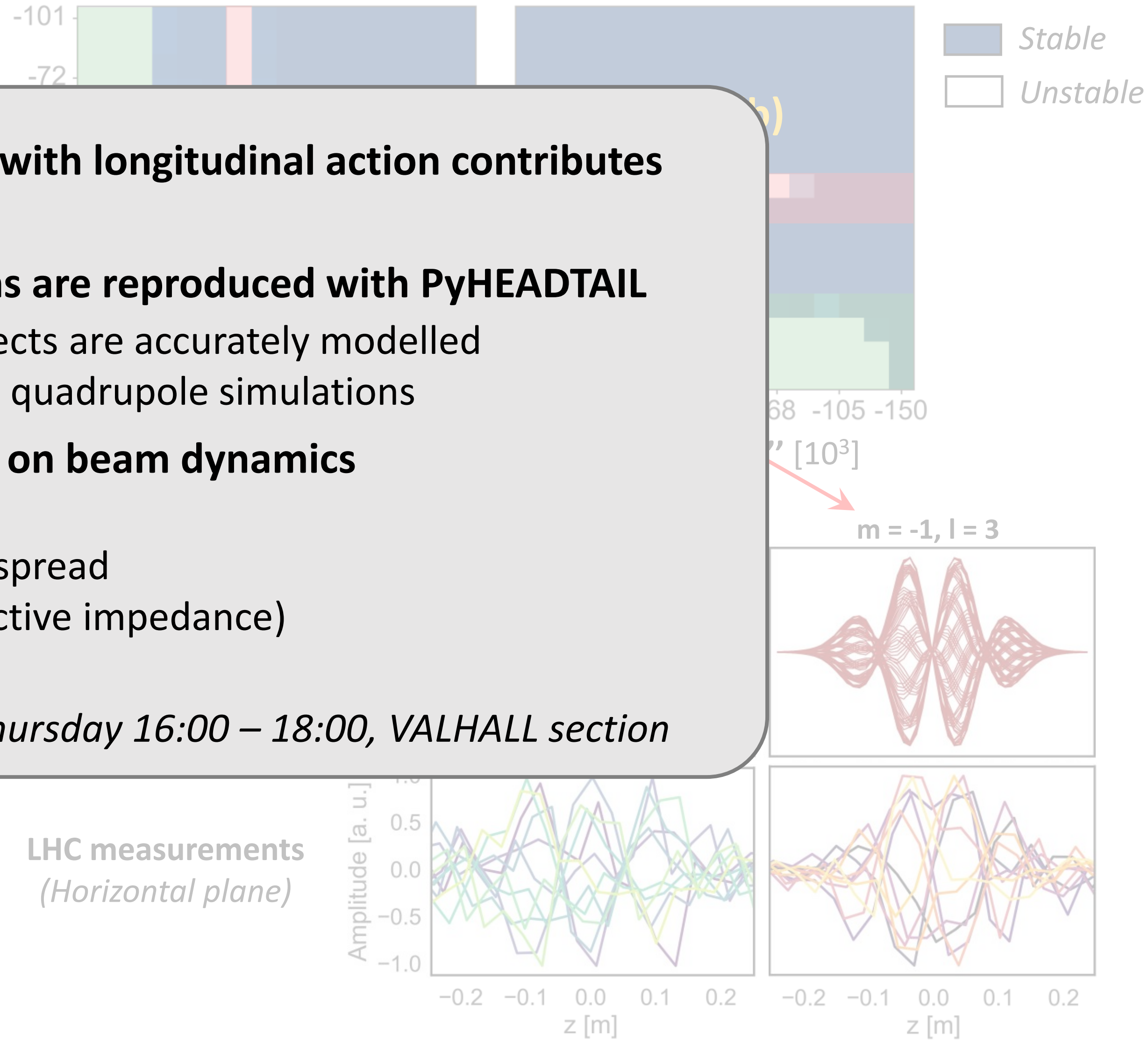
(a) $Q_x'' = 0 / Q_y$ ...

- Bunches ...
  vs. I_{oct} = ...

(b) $Q_x'' \approx$ -40'00...

- Octupol...
- 3 out of ...
- One bun...
  I_{oct} = 36 A to 0 A
- This is explained by the unstable band located next to the working point (b).

Measurements and simulations show excellent agreement on the unstable modes for both cases.



1. **Experiments confirm that detuning with longitudinal action contributes to beam stability**
2. **Details of experimental observations are reproduced with PyHEADTAIL**
   - Validation of the code: relevant effects are accurately modelled
   - Increases trustworthiness of the RF quadrupole simulations
3. **Q'' / RF quadrupole has two effects on beam dynamics**
   (see [12,17] for more details)
   - Stabilisation from incoherent tune spread
   - Change of the unstable mode (effective impedance)

More information: Poster THPVA026, Thursday 16:00 – 18:00, VALHALL section

Summary

- **Landau damping is an effective mechanism against (impedance-driven) collective instabilities**[9,12,15]

- **Required incoherent tune spread** can be produced e.g. with
  1. **Magnetic octupoles:** Detuning with **transverse action $\Delta Q(J_x, J_y)$**
  2. **RF quadrupole / Q'':** Detuning with **longitudinal action $\Delta Q\ (J_z)$**

- **$\Delta Q\ (J_z)$** offers several **advantages**
  - **Large handle** to create tune spread since **$\Delta J_{x,y} \ll \Delta J_z$** ⇨ compact RF quadrupole, saves space for other components
  - **Energy ramp:** RMS tune spread decays as $1/\gamma$ only (compared to $1/\gamma^2$ for octupoles)
  - **Low transverse emittance beams:** smaller $\Delta J_{x,y}$ makes octupoles less effective
  - **Manipulations in the transverse plane:** affect octupoles, but not RF quadrupole

- **PyHEADTAIL simulations show that the RF quadrupole works successfully and effectively either in combination with Landau octupoles or on its own**

- **Experimental tests with Q'' in the LHC demonstrate that the mechanism contributes to beam stability and that PyHEADTAIL accurately models the involved effects**

Outlook

- **In terms of collective effects:** simulations and experiments show promising results for stabilisation from an RF quadrupole or Q''
- There are still **many challenges and questions to be addressed**
  - **Theoretical / analytical work:** Further improve understanding of the involved mechanisms
  - **Incoherent effects:** Aperture and resonance studies
  - **Tolerance studies**: E.g. alignment of the cavity wrt. the bunch (effect of offset)
  - **Other collective effects:** Does the stabilising mechanism work against other types? E.g. electron cloud?
  - …
  - **Experimental proof of principle:** Fabrication of prototype cavity and tests in existing machine
  - …

Thank you

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