Annual SPS meeting 28-31 August 2018, EPFL

LANDAU DAMPING LIMITATIONS IN HIGH ENERGY HADRON COLLIDERS

Dr. Claudia Tambasco
(EPFL Thesis n. 7867)
Supervisors: Prof. Rivkin, T. Pieloni
Particle Accelerator Physics Laboratory (LPAP)
Institute of Physics
EPF Lausanne, Switzerland

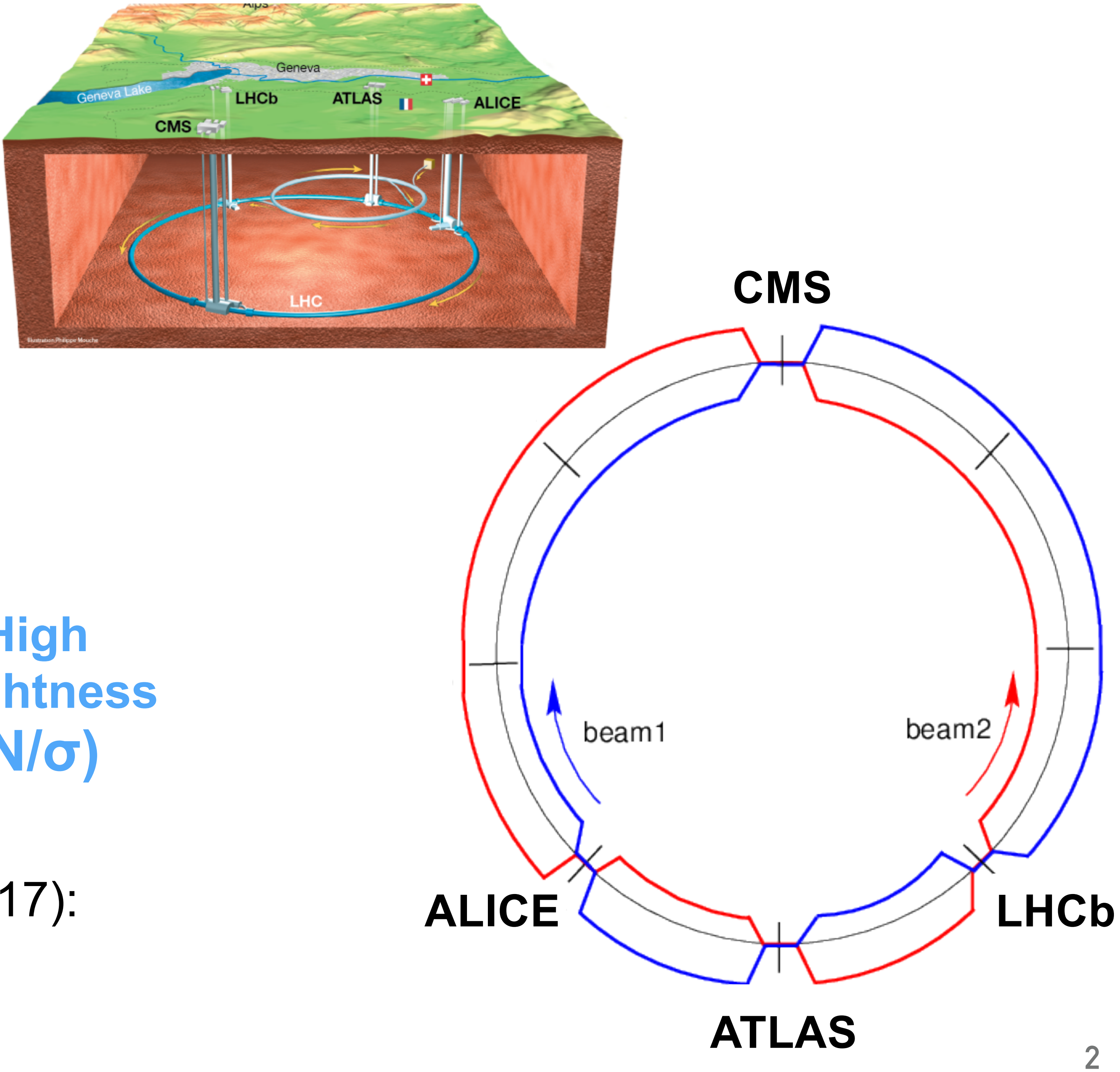
THE LARGE HADRON COLLIDER

LHC is the world's largest and most powerful particle accelerator. Its main application is high-energy physics research thanks to 4 experiments where the beams collide.

Event Rate = $L \cdot \sigma_{ev}$

Luminosity:

$$L = \frac{N^2 f_{\mathrm{rev}} n_b}{2\pi\sigma^2}$$



- **Large number of bunches**
- **High Intensity**
- **Small r.m.s. beam size**

} **High brightness (N/σ)**

Reached Luminosity in the LHC (2017):

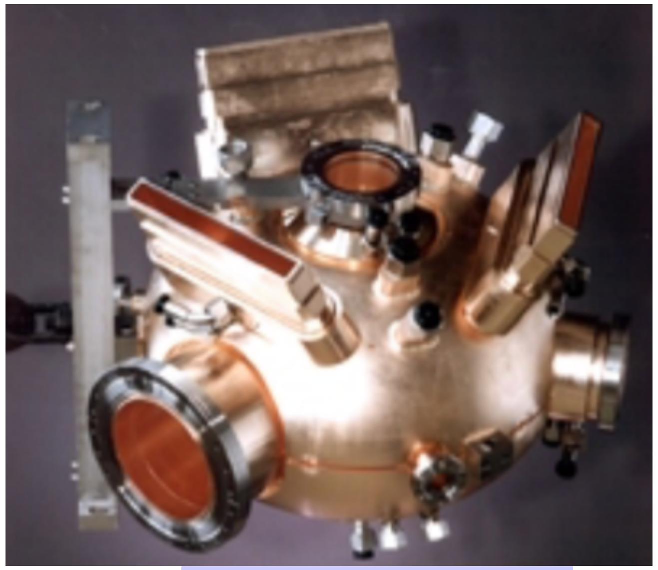
$$L = 2.2 \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

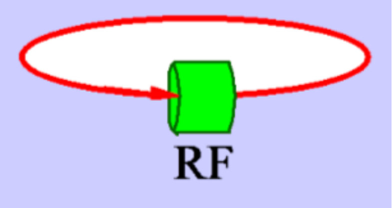
BASIC PRINCIPLES OF BEAM DYNAMICS IN A SYNCHROTRON

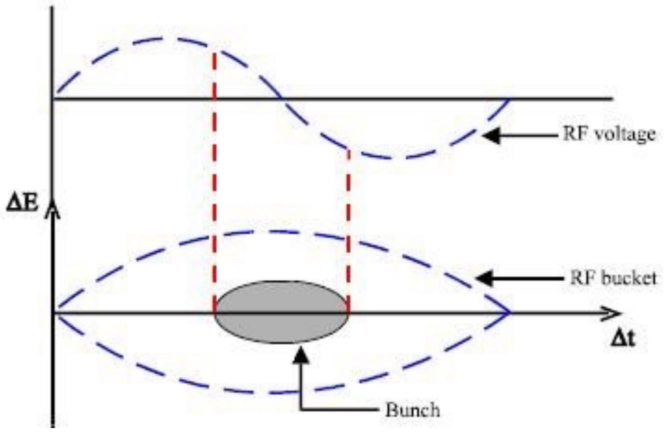
Basic principle: LORENTZ FORCE $$\vec{F} = \underbrace{q\vec{E}}_{\text{Electric force}} + \underbrace{q\vec{v}\;x\;\vec{B}}_{\text{Magnetic force}}$$

Charged particles

RF Cavities accelerate and bunch the particles

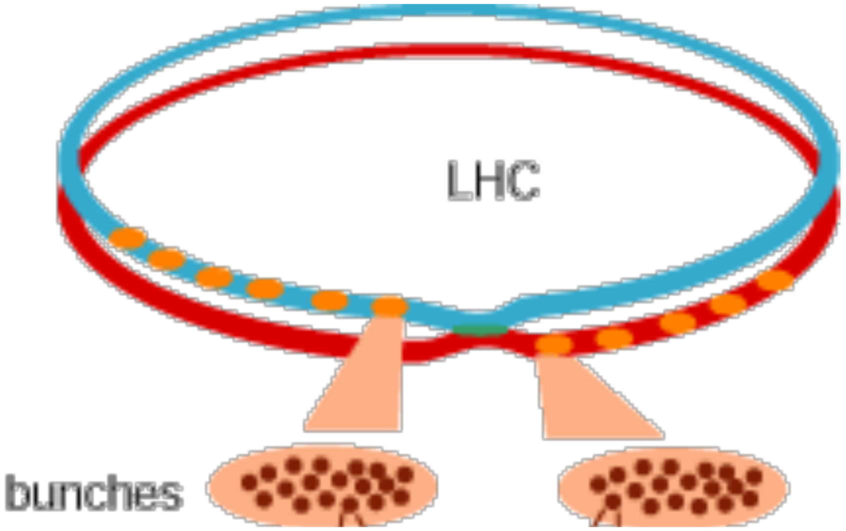






Longitudinal Plane

The **RF cavities** accelerate the particles and bunch the beams along the longitudinal direction



~2800 bunches per beam

The particles oscillate in each bunch with a frequency proportional to

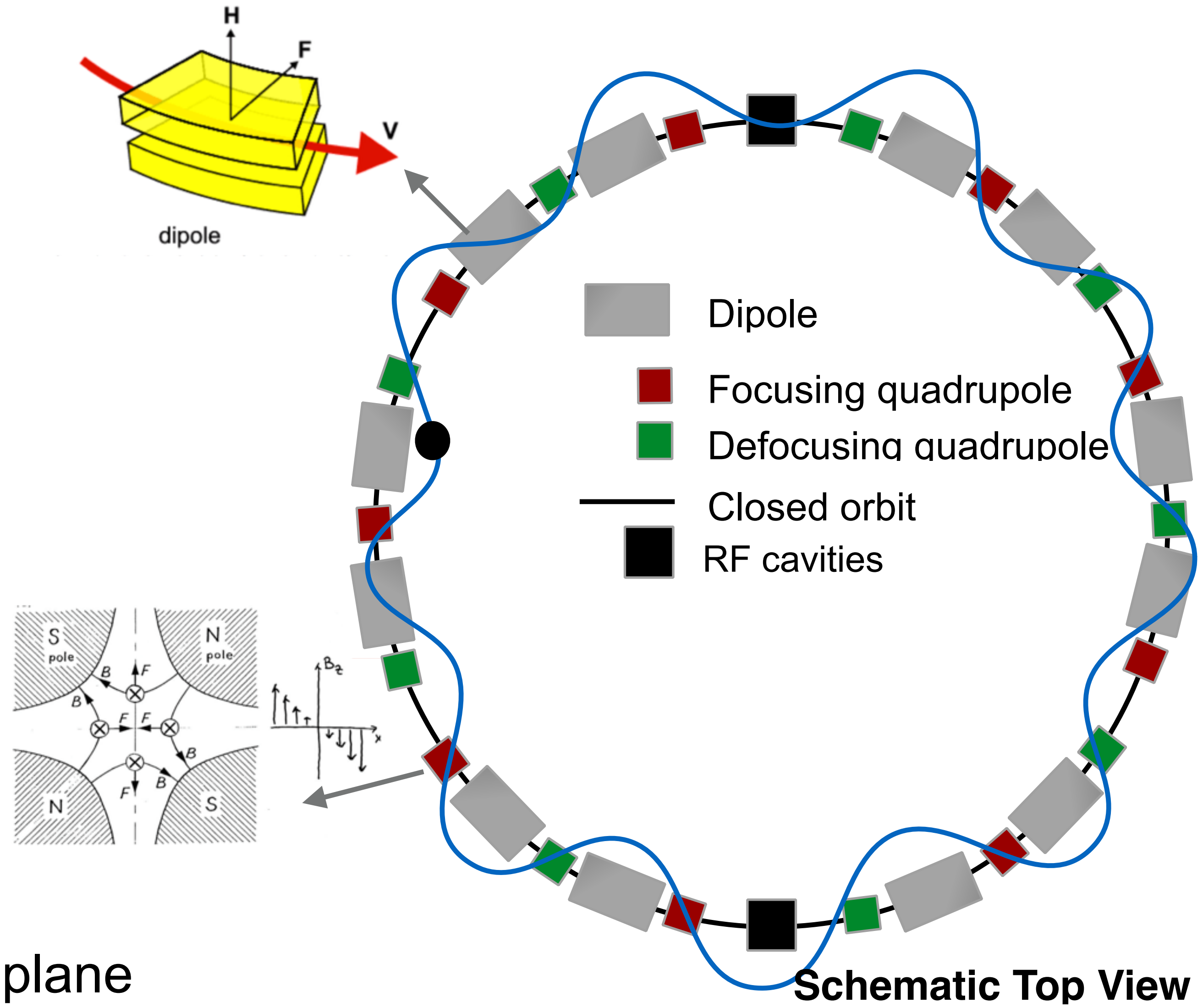
Synchrotron tune: Q_s

LHC synchrotron tunes:
Q_s=0.005 (injection energy)
Q_s=0.002 (top energy)

BASIC PRINCIPLES OF BEAM DYNAMICS IN A SYNCHROTRON

Magnetic fields

- Dipoles: bend and guide the particles along the accelerator
- Quadrupoles: focus the particles (avoid beam divergency)
- Sextupoles: correct for chromatic effects
- Octupoles: provide beam stability (see next)
- and higher order magnetic fields



Schematic Top View

Transverse Plane

Particle motion ≈ oscillations in the transverse plane under the action of periodic external fields produced by the machine **lattice (arrangement of magnets):**

- **Betatron frequency ω_β**: oscillation frequency in the transverse plane

→

Betatron tune: Q_β

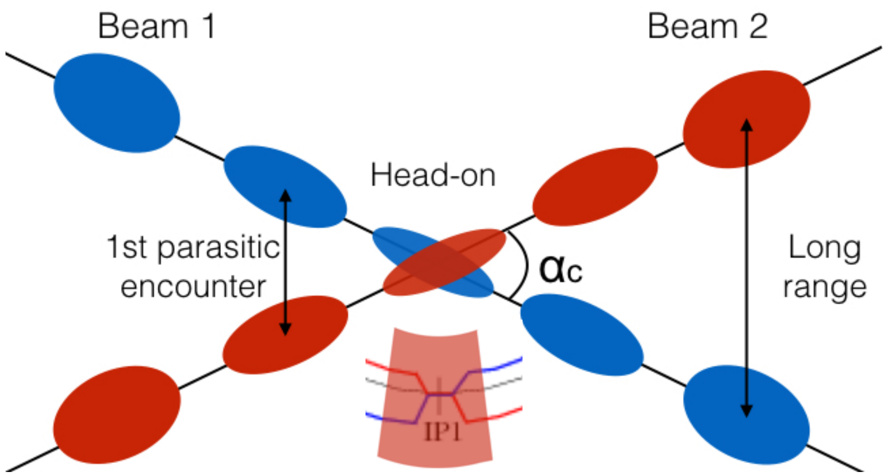
LHC tunes:
H=64.31
V=59.32
(collisions)

COLLECTIVE EFFECTS

Additional (unwanted) electromagnetic fields perturb the beam dynamics and induce coherent motion of particles inside the beam ➞ coherent beam instabilities (loss of stable motion)

Stronger for higher brightness beams

$$L = \frac{N^2 f_{\mathrm{rev}} n_b}{2\pi\sigma^2}$$



Interaction Point

EM fields from other charge distribution

- Beam – beam effects in colliders, EM interaction of two beams

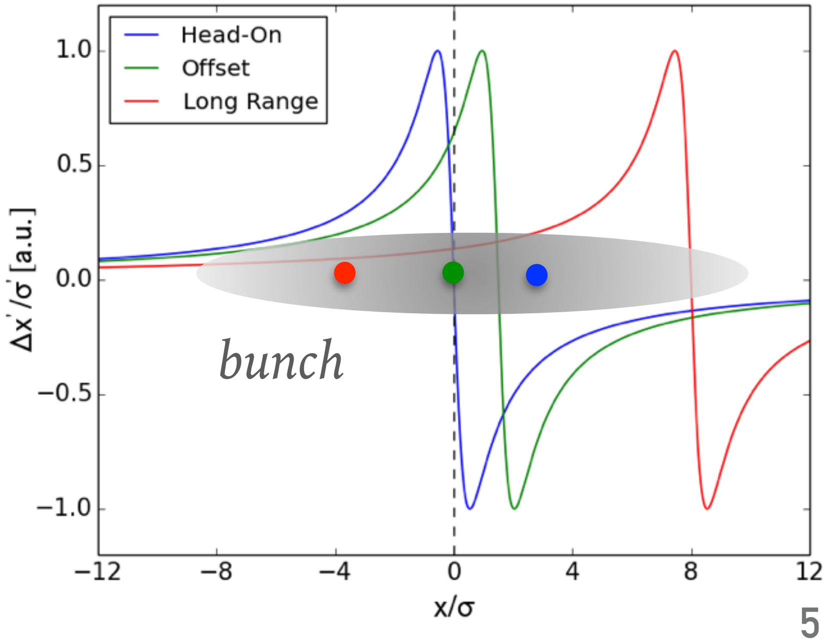
  when sharing common pipe

Self-induced EM fields

- EM interaction of the beam with the surrounding environment

  Wake fields can remain trapped and decay

Beam-Beam force, highly non-linear



COLLECTIVE EFFECTS

Additional (unwanted) electromagnetic fields perturb the beam dynamics and induce coherent motion of particles inside the beam ➞ coherent beam instabilities (loss of stable motion)

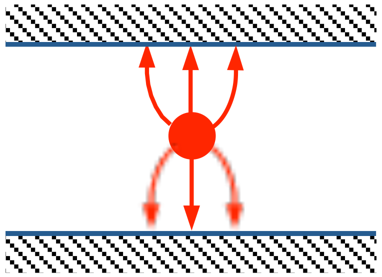
Stronger for higher brightness beams

$$L = \frac{N^2 f_{\mathrm{rev}} n_b}{2\pi\sigma^2}$$

EM fields from other charge distribution

- Beam – beam effects in colliders, EM interaction of two beams

  when sharing common pipe



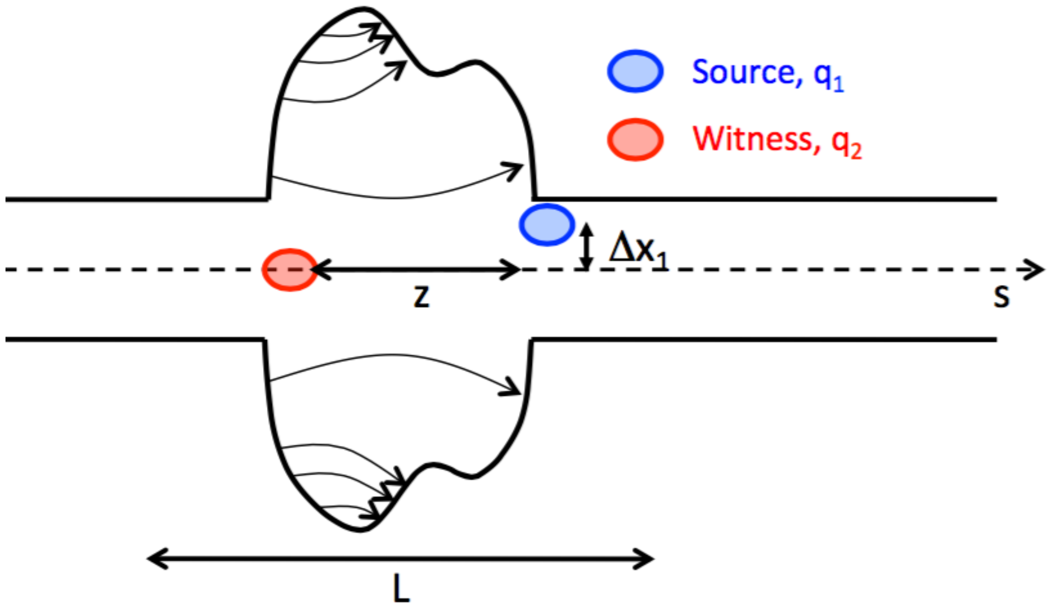
Self-induced EM fields

- EM interaction of the beam with the surrounding environment

  Wake fields can remain trapped and decay

BEAM COUPLING IMPEDANCE

The source particle induces electromagnetic wake fields (**impedance**) that act back on the trailing (witness) particles



Strong for:

- High brightness beams (N/σ)

- Small aperture elements (collimator 5.5σ)

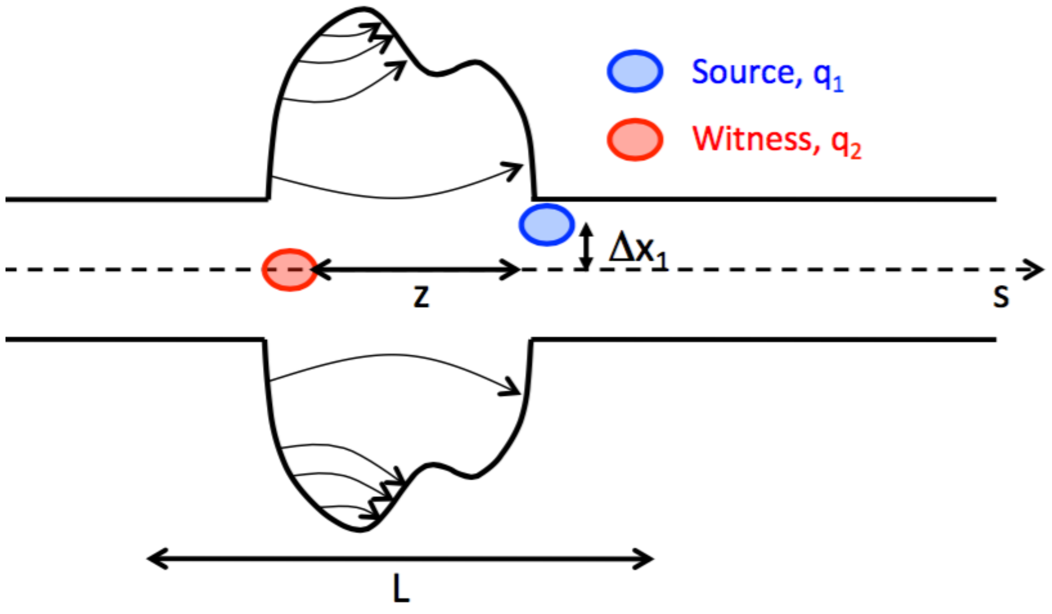
The impedance drives so-called **head-tail instabilities** → different modes of beam oscillations

Complex Tune shifts:

- **Im(ΔQ):** instability rise time
- **Re(ΔQ):** real coherent tune shift

BEAM COUPLING IMPEDANCE

The source particle induces electromagnetic wake fields (**impedance**) that act back on the trailing (witness) particles

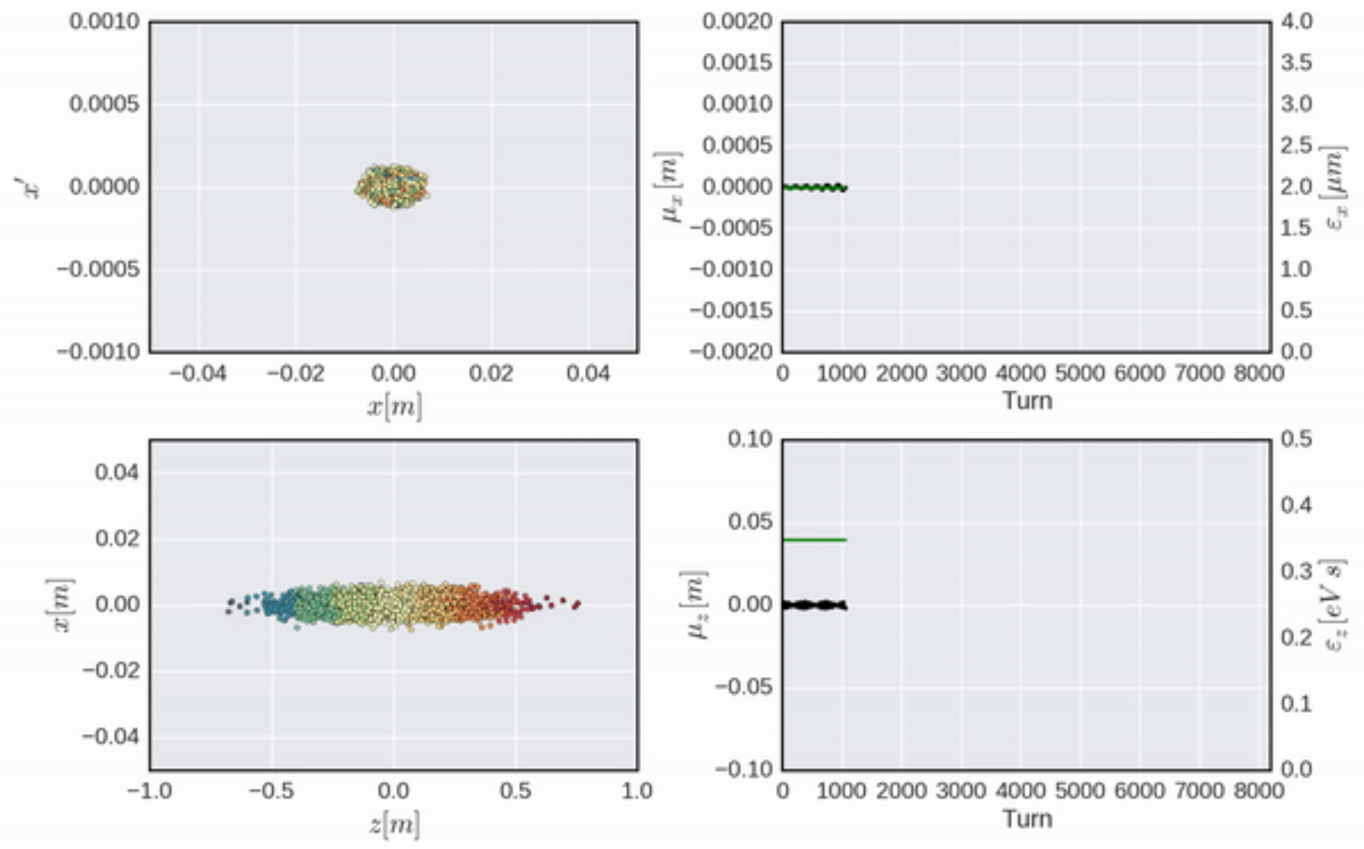


Strong for:

- High brightness beams (N/σ)

- Small aperture elements (collimator 5.5σ)

Courtesy of M. Schenk



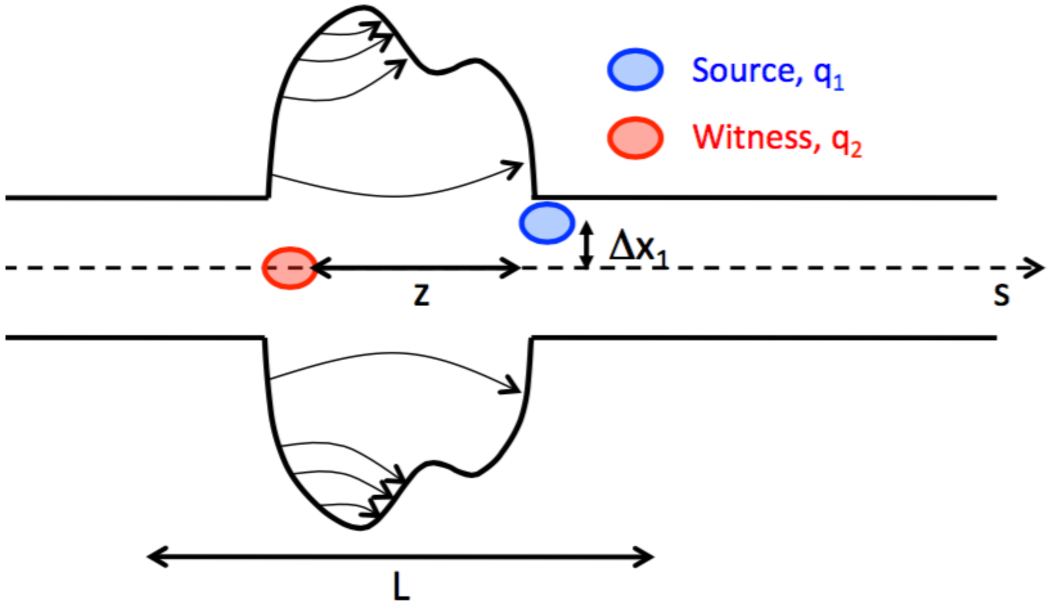
The impedance drives so-called **head-tail instabilities** → different modes of beam oscillations

Complex Tune shifts:

- **Im(ΔQ):** instability rise time
- **Re(ΔQ):** real coherent tune shift

BEAM COUPLING IMPEDANCE

The source particle induces electromagnetic wake fields (**impedance**) that act back on the trailing (witness) particles



Strong for:

- High brightness beams (N/σ)

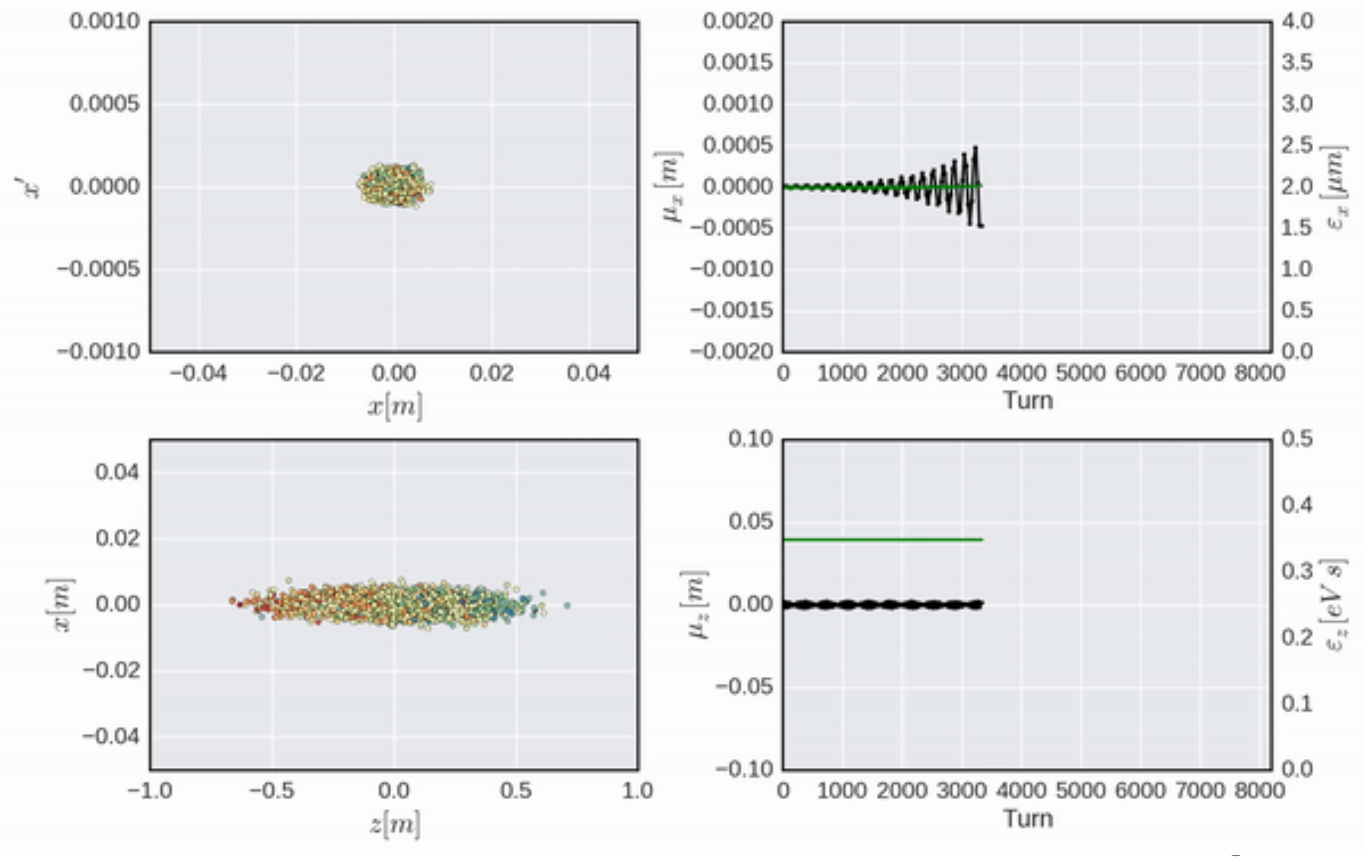
- Small aperture elements (collimator 5.5σ)

The impedance drives so-called **head-tail instabilities** → different modes of beam oscillations

Complex Tune shifts:

- **Im(ΔQ):** instability rise time
- **Re(ΔQ):** real coherent tune shift

Courtesy of M. Schenk



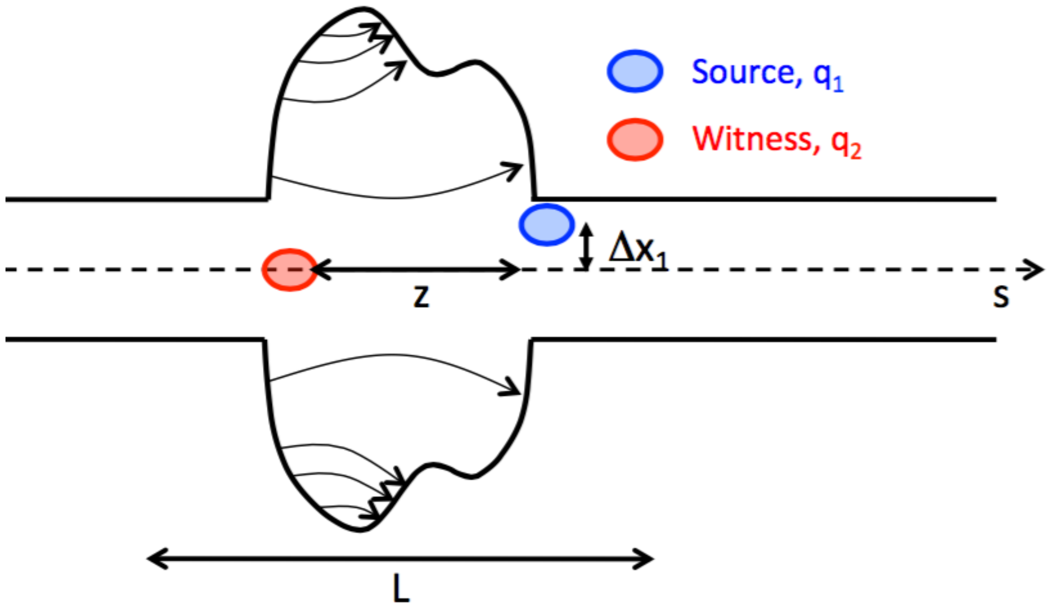
BEAM COUPLING IMPEDANCE

The source particle induces electromagnetic wake fields (**impedance**) that act back on the trailing (witness) particles

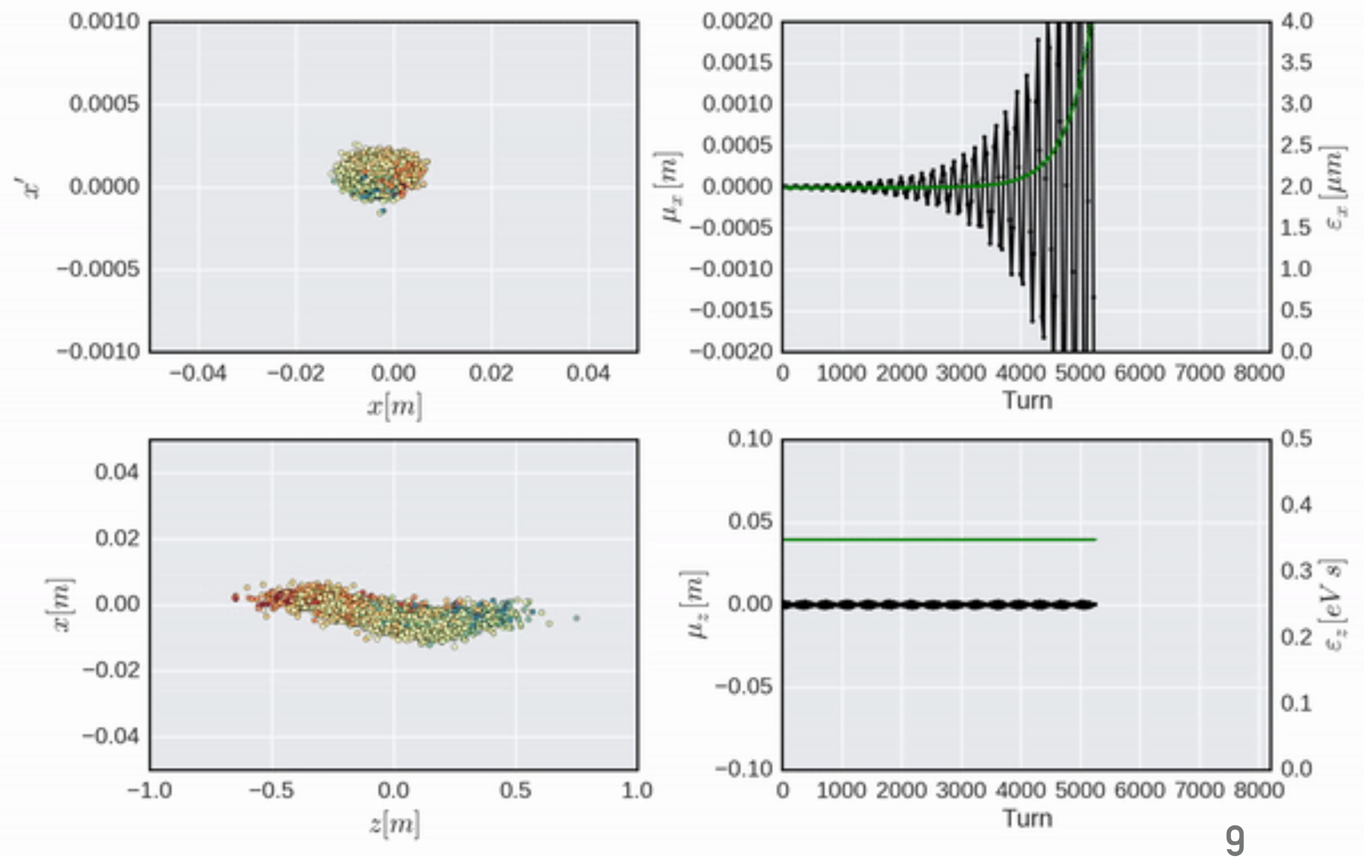
Strong for:

- High brightness beams (N/σ)

- Small aperture elements (collimator 5.5σ)



Courtesy of M. Schenk



The impedance drives so-called **head-tail instabilities** → different modes of beam oscillations

Complex Tune shifts:

- **Im(ΔQ):** instability rise time
- **Re(ΔQ):** real coherent tune shift

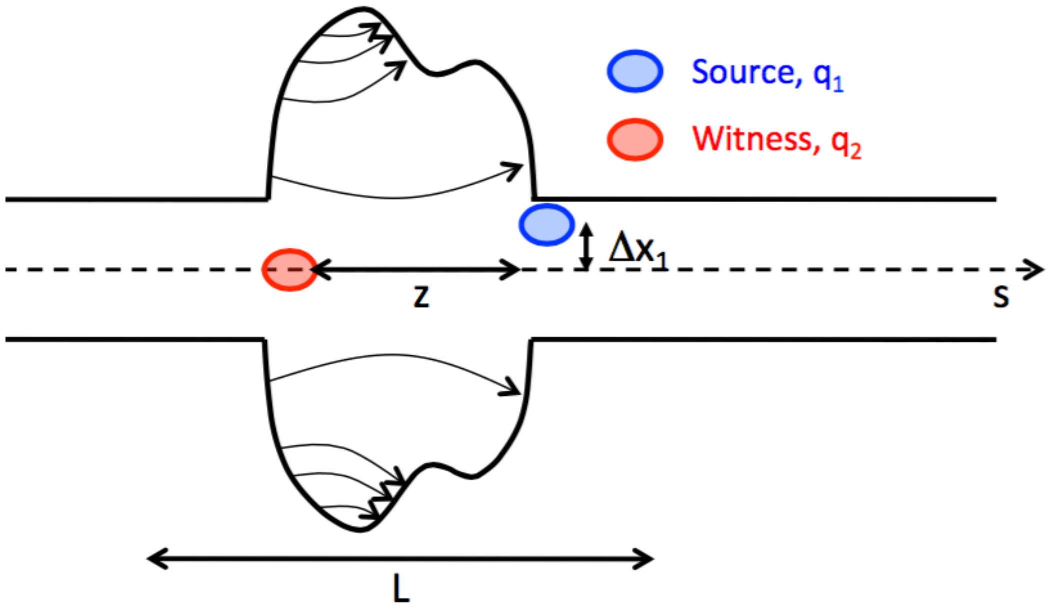
BEAM COUPLING IMPEDANCE

The source particle induces electromagnetic wake fields (**impedance**) that act back on the trailing (witness) particles

Strong for:

- High brightness beams (N/σ)

- Small aperture elements (collimator 5.5σ)

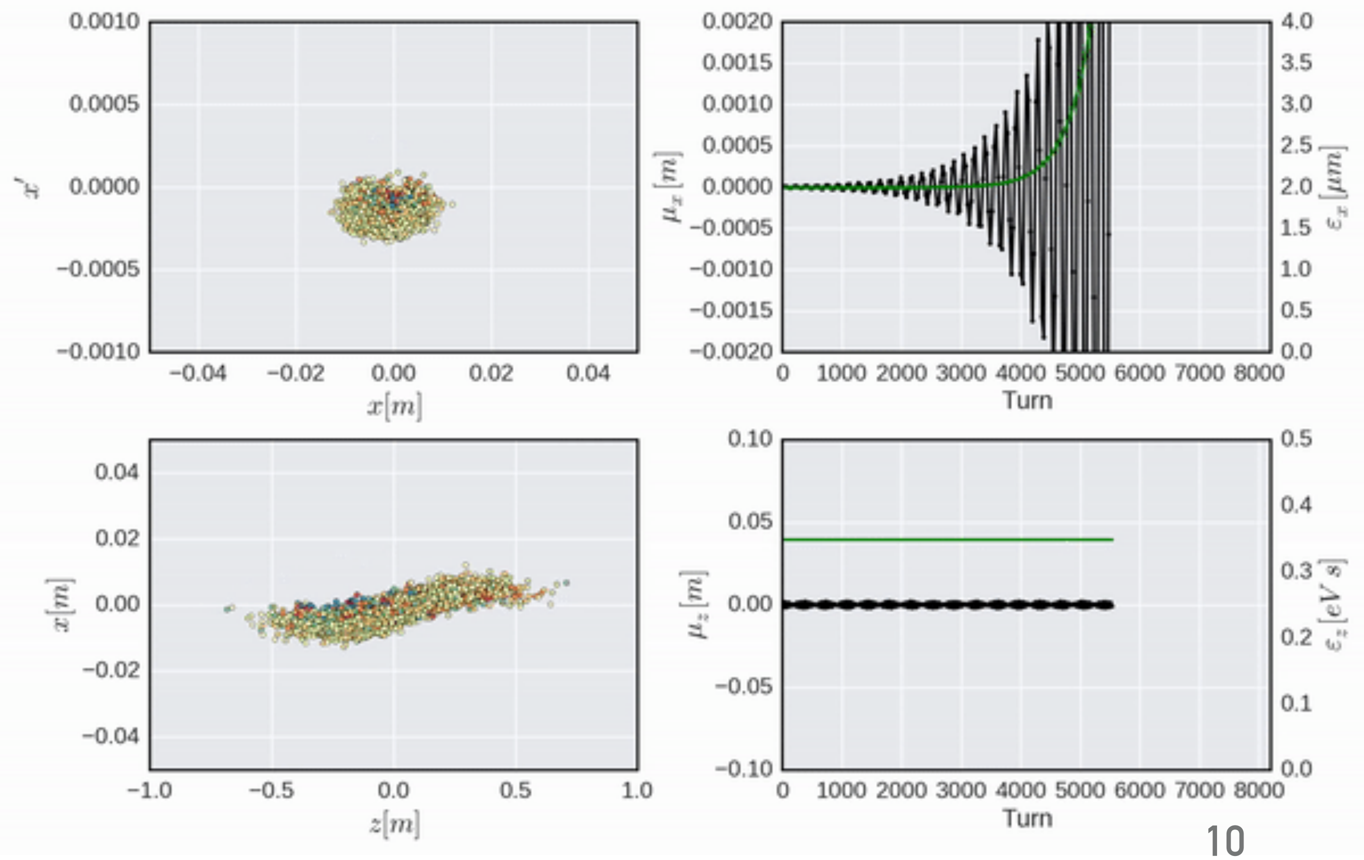


The impedance drives so-called **head-tail instabilities** → different modes of beam oscillations

Complex Tune shifts:

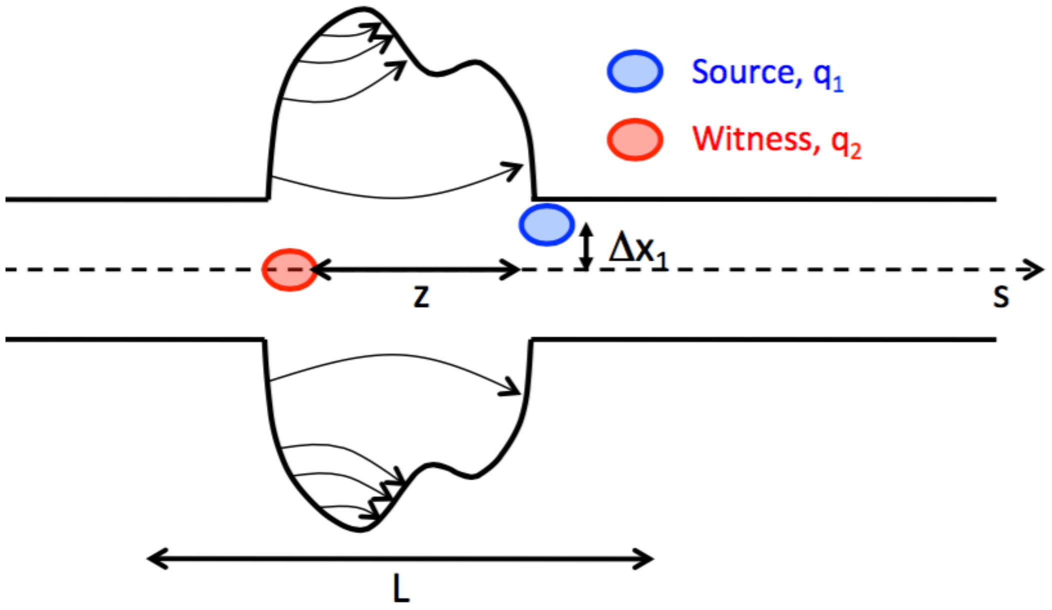
- **Im(ΔQ):** instability rise time
- **Re(ΔQ):** real coherent tune shift

Courtesy of M. Schenk



BEAM COUPLING IMPEDANCE

The source particle induces electromagnetic wake fields (**impedance**) that act back on the trailing (witness) particles

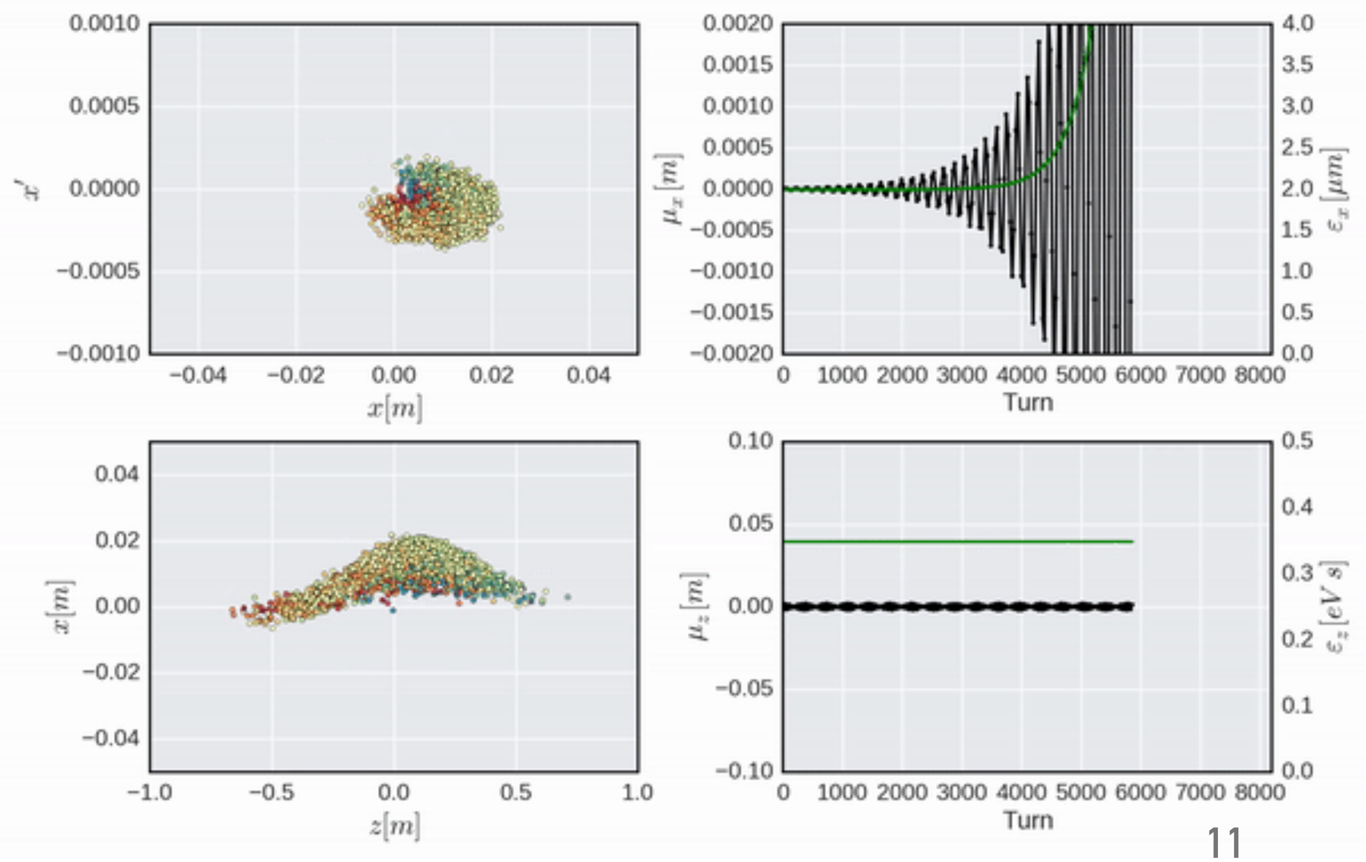


Strong for:

- High brightness beams (N/σ)

- Small aperture elements (collimator 5.5σ)

Courtesy of M. Schenk



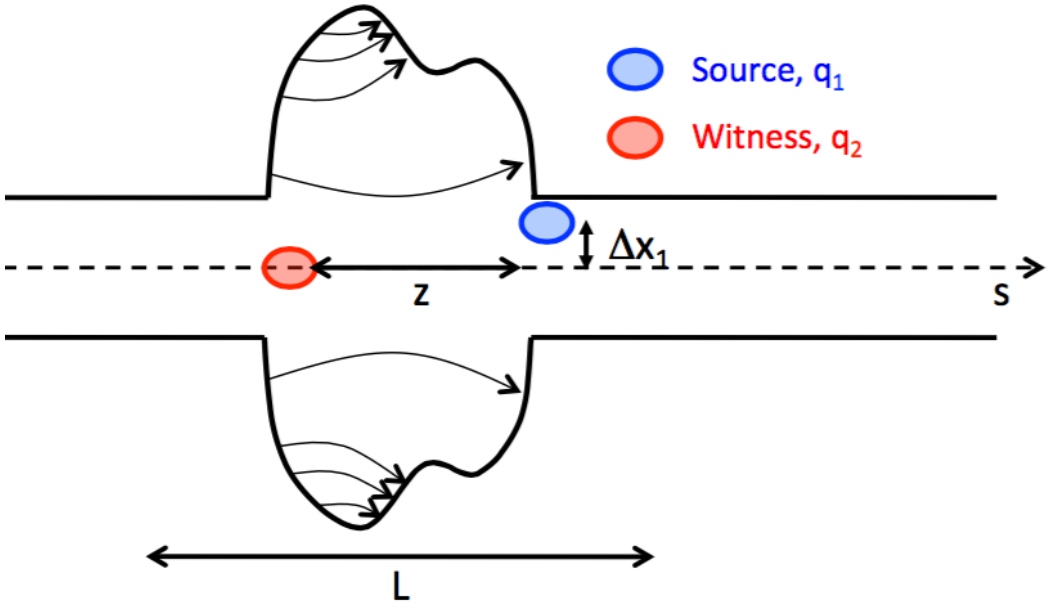
The impedance drives so-called **head-tail instabilities** → different modes of beam oscillations

Complex Tune shifts:

- **Im(ΔQ):** instability rise time
- **Re(ΔQ):** real coherent tune shift

BEAM COUPLING IMPEDANCE

The source particle induces electromagnetic wake fields (**impedance**) that act back on the trailing (witness) particles



Strong for:

- High brightness beams (N/σ)

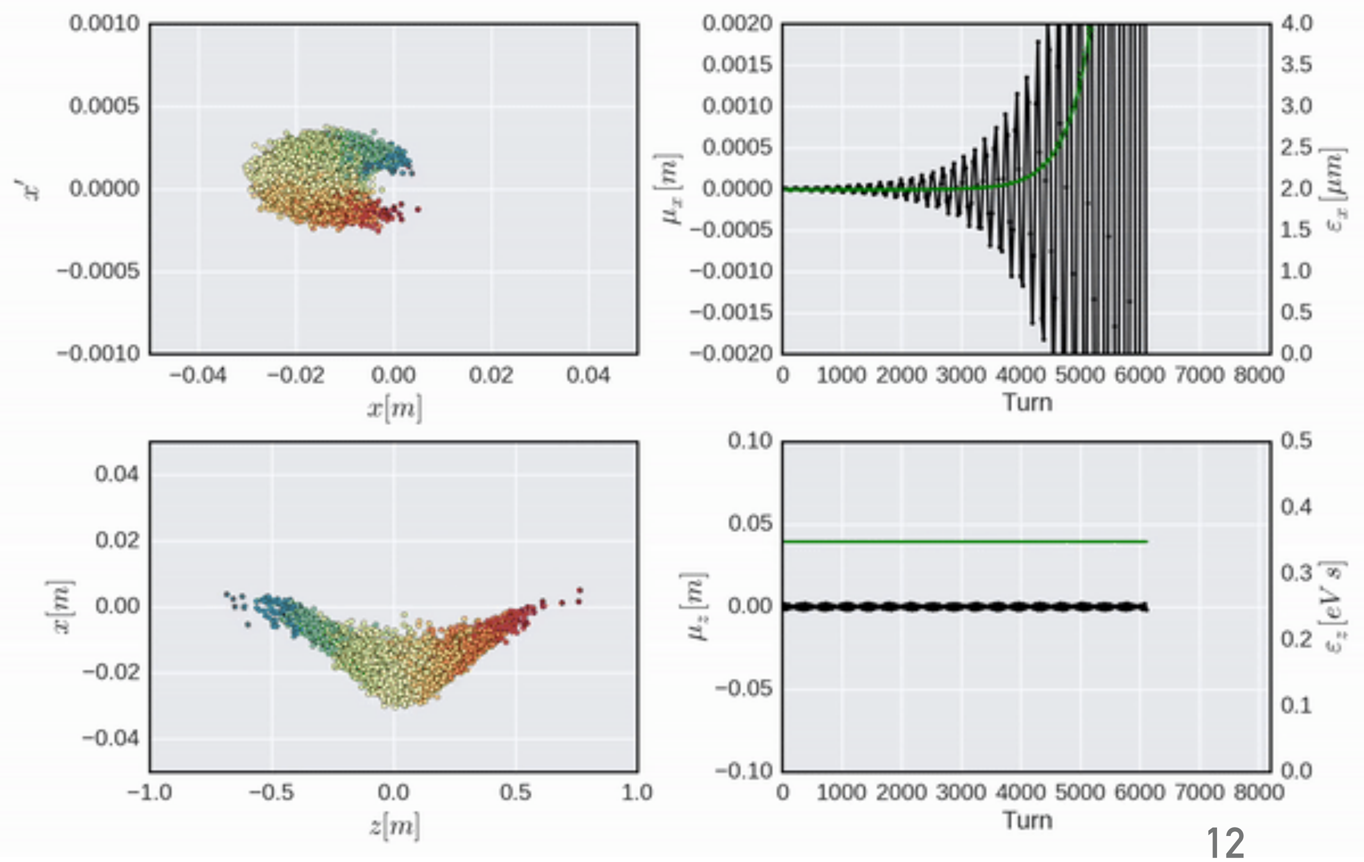
- Small aperture elements (collimator 5.5σ)

The impedance drives so-called **head-tail instabilities** → different modes of beam oscillations

Complex Tune shifts:

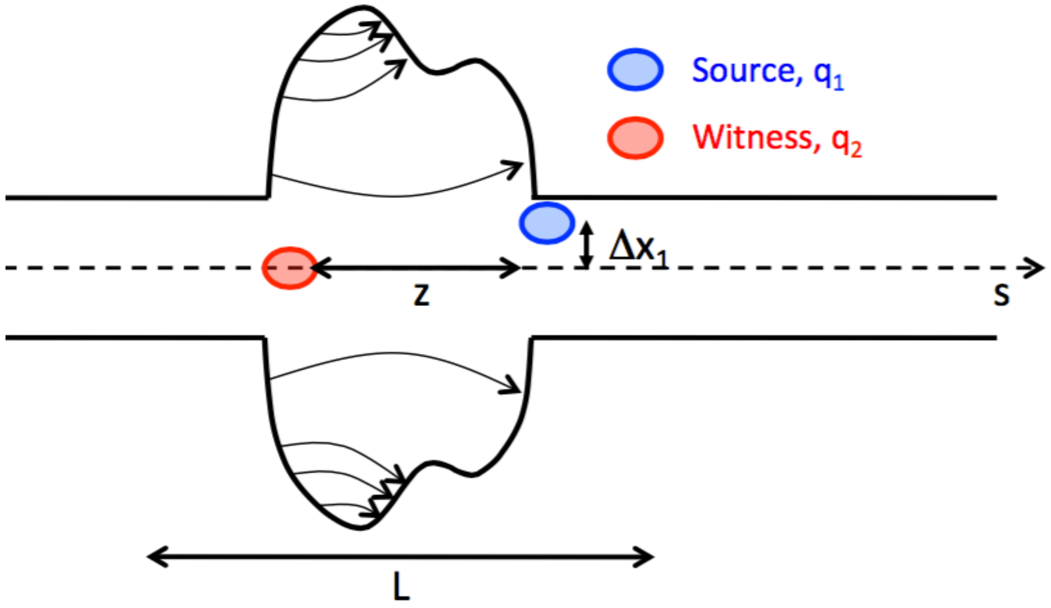
- **Im(ΔQ):** instability rise time
- **Re(ΔQ):** real coherent tune shift

Courtesy of M. Schenk



BEAM COUPLING IMPEDANCE

The source particle induces electromagnetic wake fields (**impedance**) that act back on the trailing (witness) particles

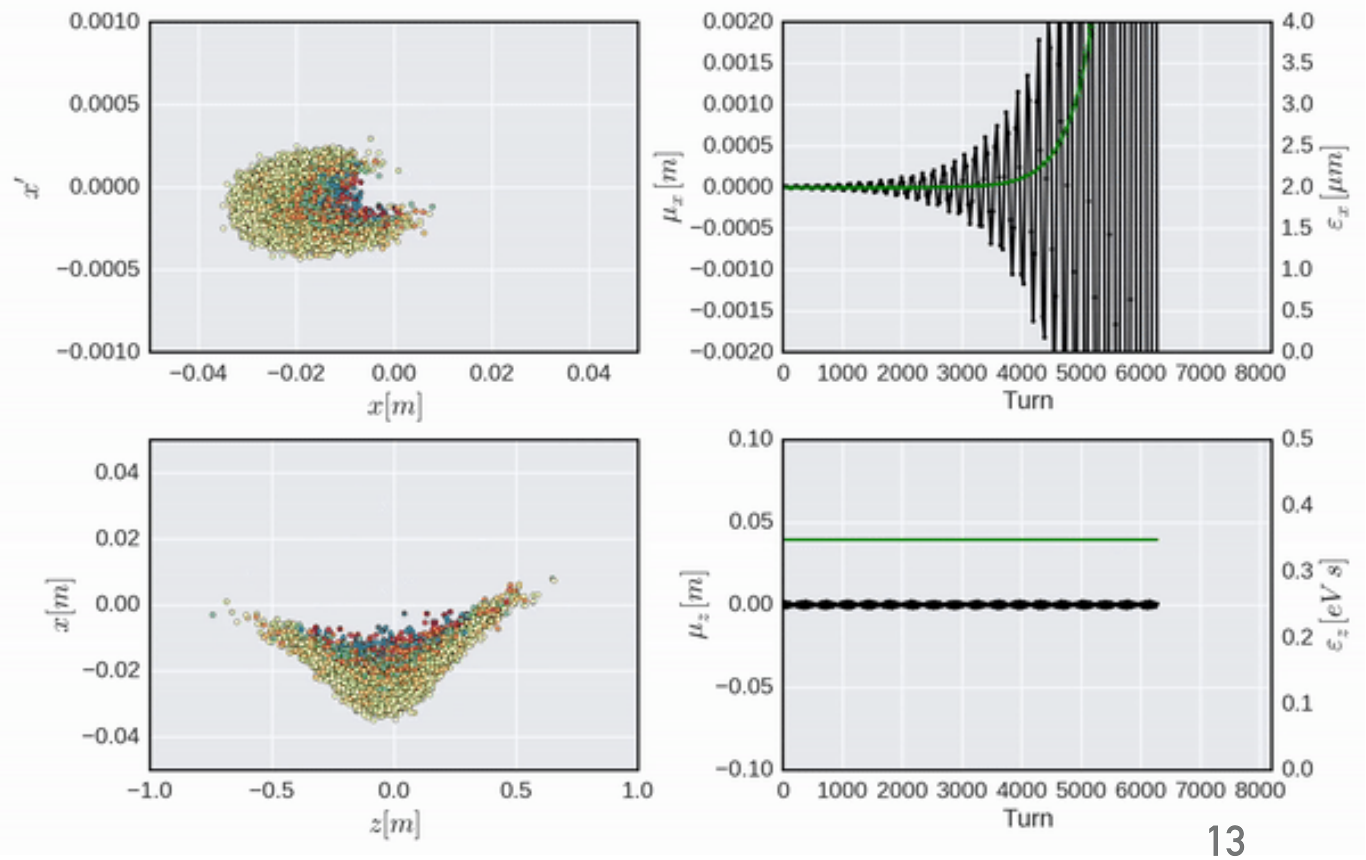


Strong for:

- High brightness beams (N/σ)

- Small aperture elements (collimator 5.5σ)

Courtesy of M. Schenk



The impedance drives so-called **head-tail instabilities** → different modes of beam oscillations

Complex Tune shifts:

- **Im(ΔQ):** instability rise time
- **Re(ΔQ):** real coherent tune shift

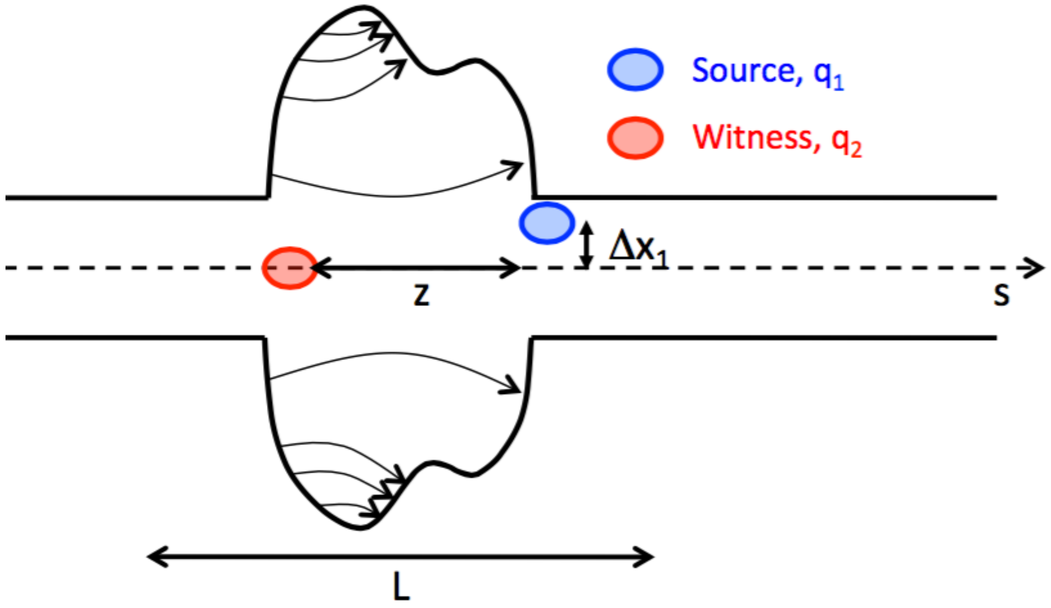
BEAM COUPLING IMPEDANCE

The source particle induces electromagnetic wake fields (**impedance**) that act back on the trailing (witness) particles

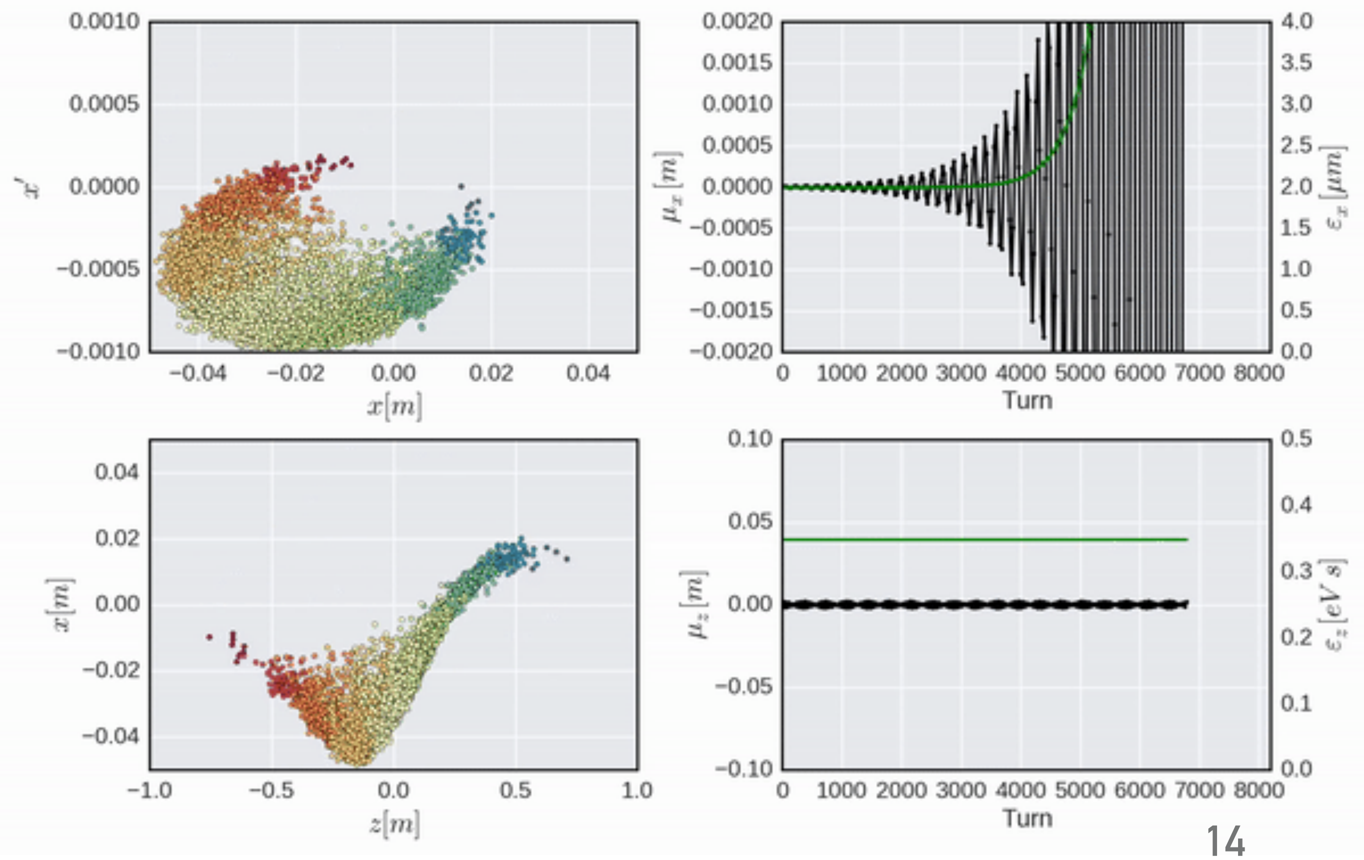
Strong for:

- High brightness beams (N/σ)

- Small aperture elements (collimator 5.5σ)



Courtesy of M. Schenk



The impedance drives so-called **head-tail instabilities** → different modes of beam oscillations

Complex Tune shifts:

- **Im(ΔQ):** instability rise time
- **Re(ΔQ):** real coherent tune shift

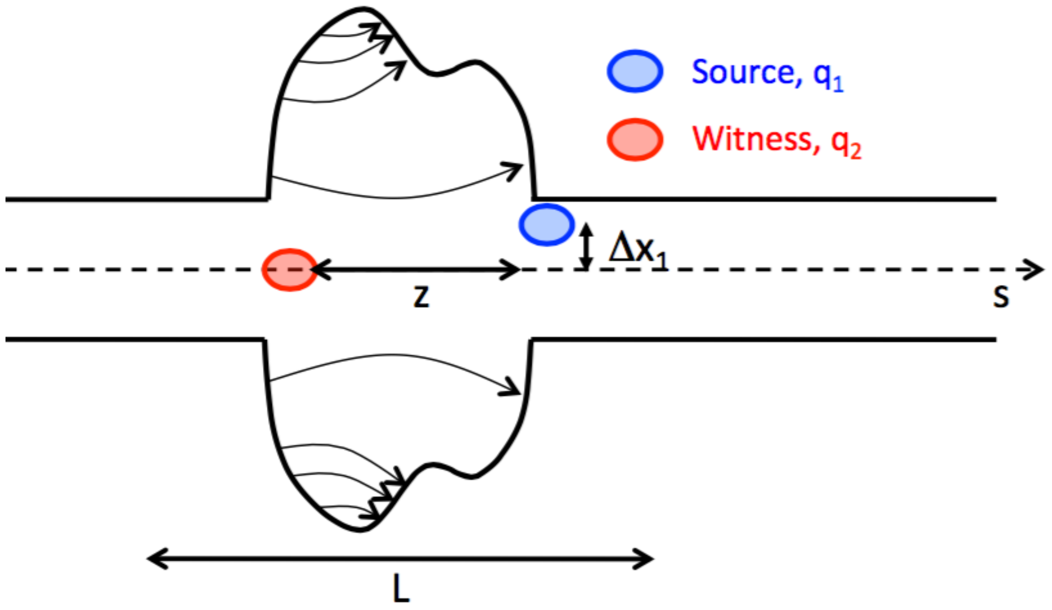
BEAM COUPLING IMPEDANCE

The source particle induces electromagnetic wake fields (**impedance**) that act back on the trailing (witness) particles

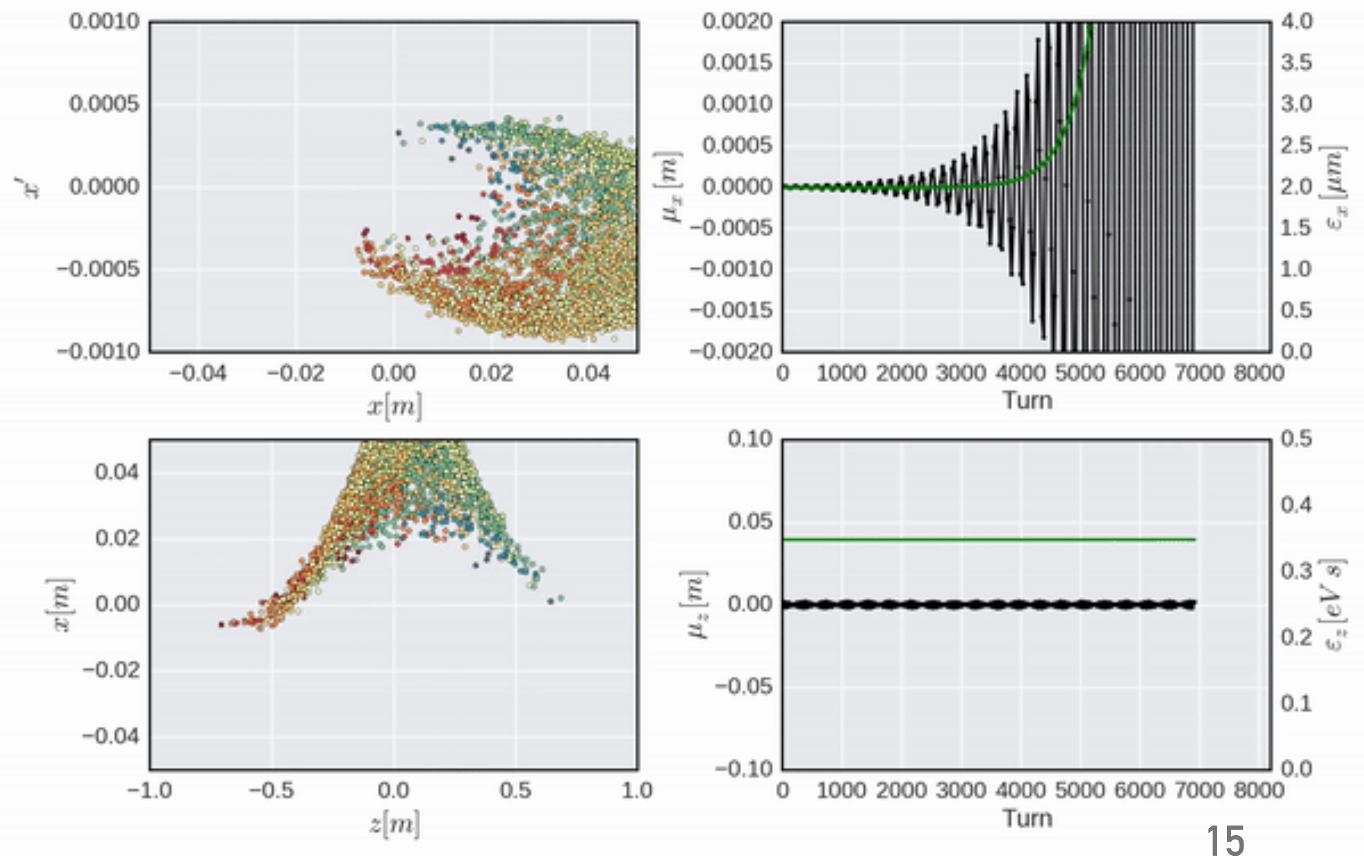
Strong for:

- High brightness beams (N/σ)

- Small aperture elements (collimator 5.5σ)



Courtesy of M. Schenk



The impedance drives so-called **head-tail instabilities** → different modes of beam oscillations

Complex Tune shifts:

- **Im(ΔQ):** instability rise time
- **Re(ΔQ):** real coherent tune shift

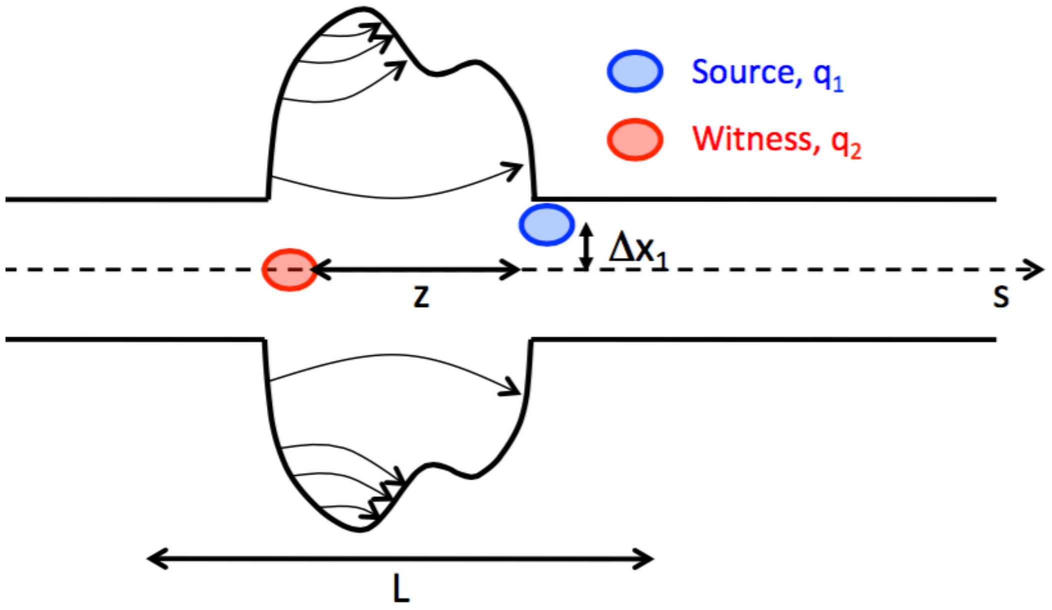
BEAM COUPLING IMPEDANCE

The source particle induces electromagnetic wake fields (**impedance**) that act back on the trailing (witness) particles

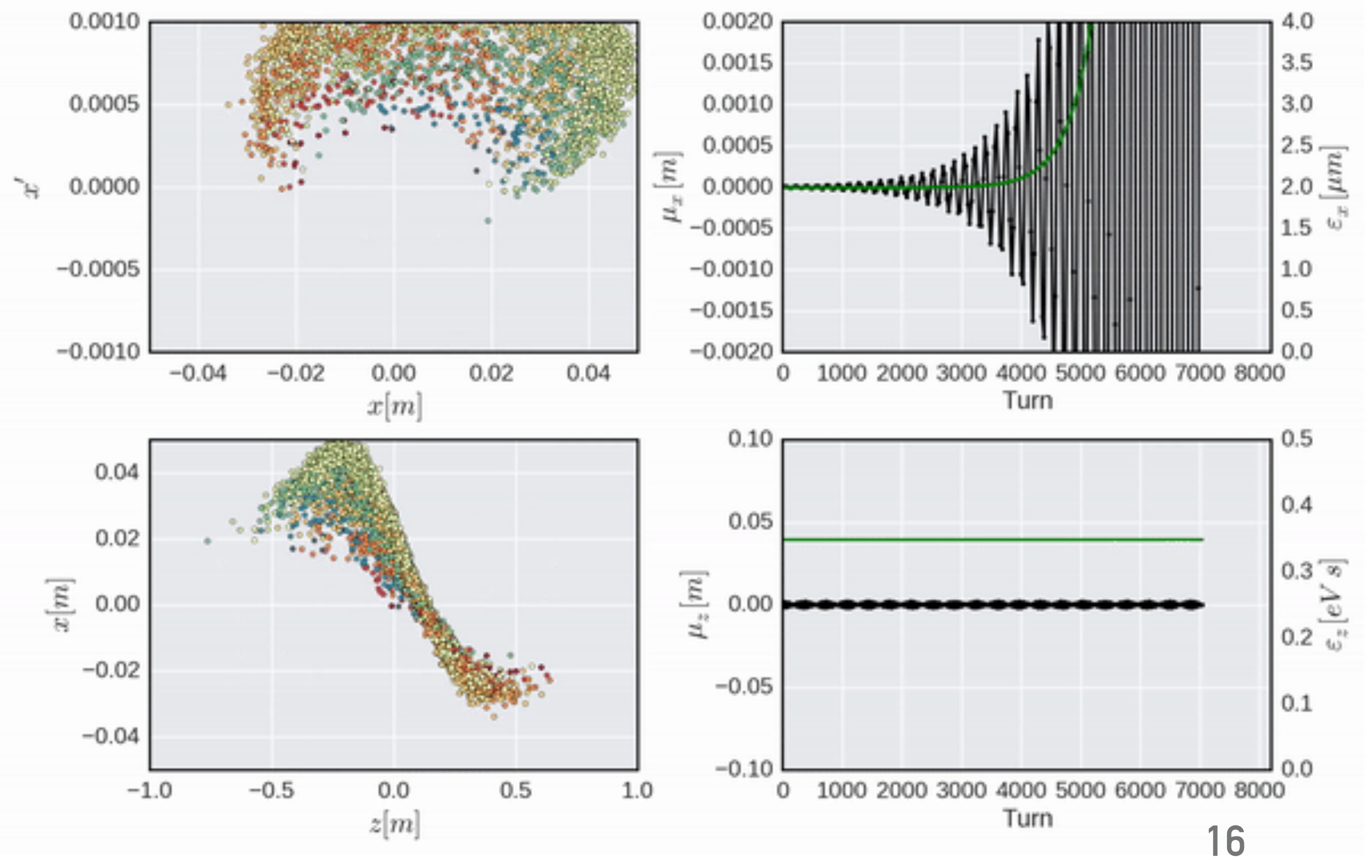
Strong for:

- High brightness beams (N/σ)

- Small aperture elements (collimator 5.5σ)



Courtesy of M. Schenk



The impedance drives so-called **head-tail instabilities** → different modes of beam oscillations

Complex Tune shifts:

- **Im(ΔQ):** instability rise time
- **Re(ΔQ):** real coherent tune shift

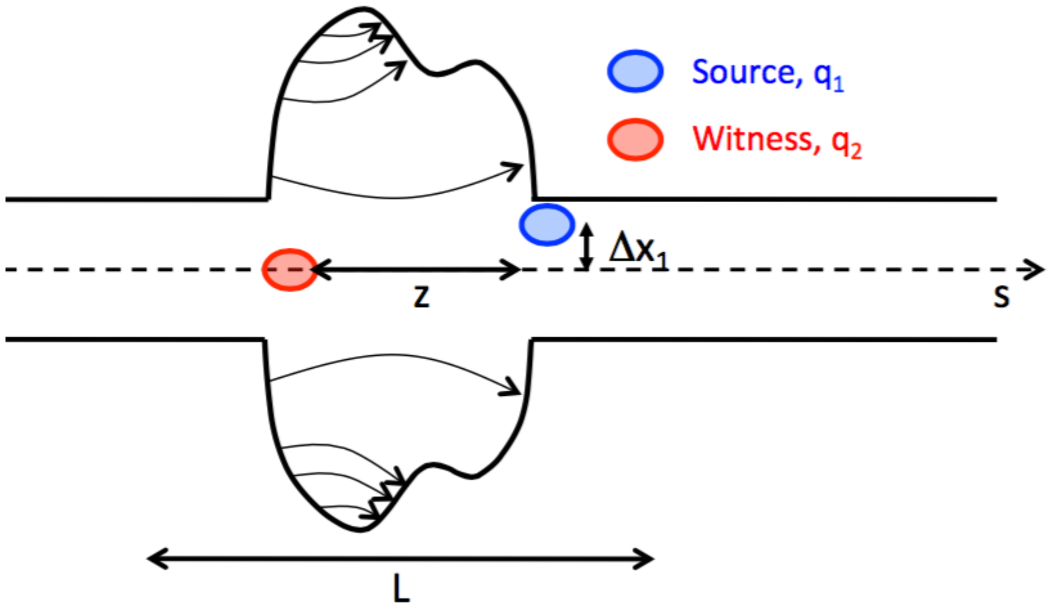
BEAM COUPLING IMPEDANCE

The source particle induces electromagnetic wake fields (**impedance**) that act back on the trailing (witness) particles

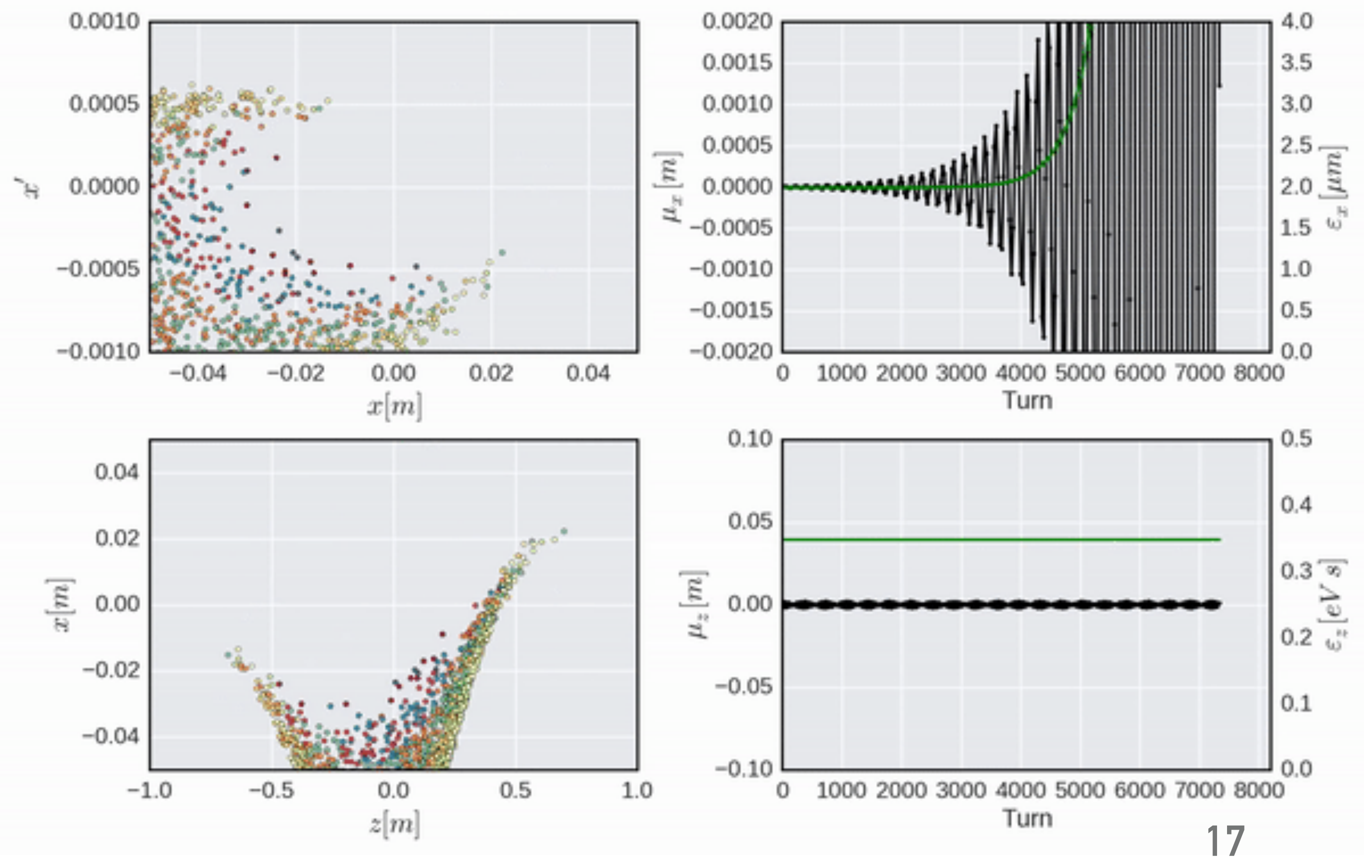
Strong for:

- High brightness beams (N/σ)

- Small aperture elements (collimator 5.5σ)



Courtesy of M. Schenk



The impedance drives so-called **head-tail instabilities** → different modes of beam oscillations

Complex Tune shifts:

- **Im(ΔQ):** instability rise time
- **Re(ΔQ):** real coherent tune shift

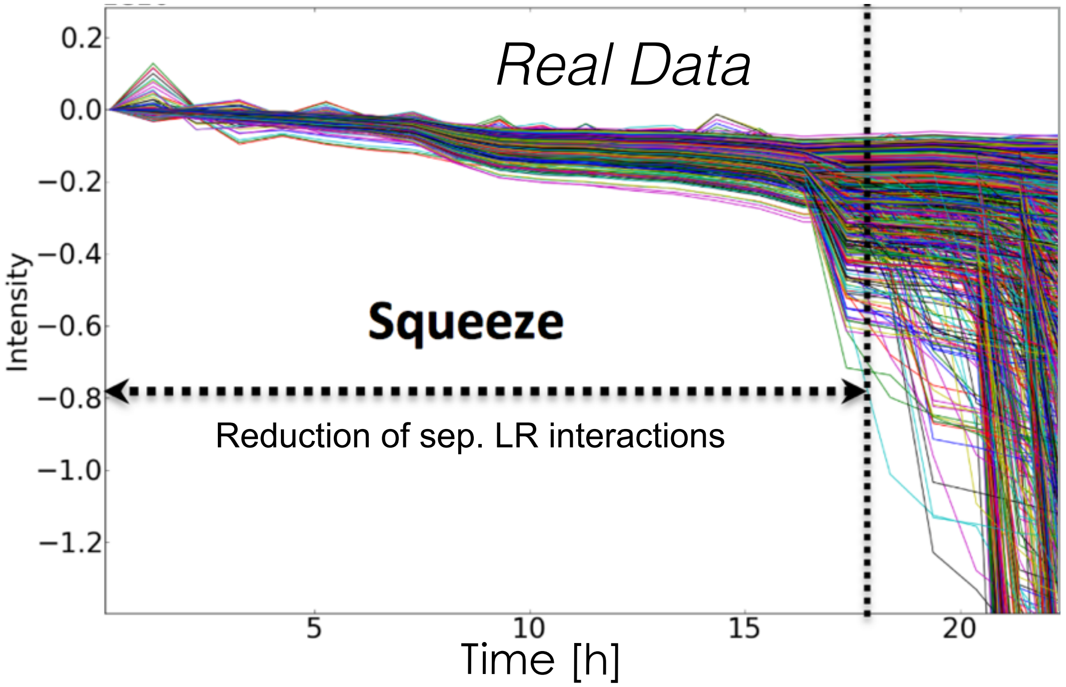
COHERENT INSTABILITIES AT LHC

Several coherent instabilities since the first run:

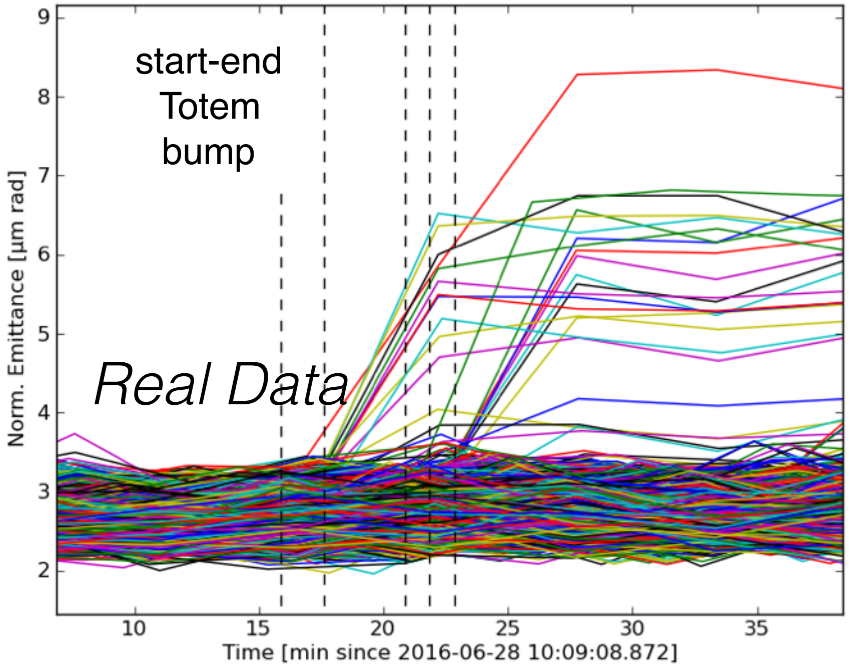
- Emittance blow-up (increase of the rms beam size)
- Loss of intensity
- Coherent oscillations of single bunches

→ **REDUCTION OF LUMINOSITY REACH** ⚠

End of squeeze instability (2012)



Adjust instability (2016)



COHERENT INSTABILITIES AT LHC

Several coherent instabilities since the first run:

- Emittance blow-up (increase of the rms beam size)
- Loss of intensity
- Coherent oscillations of single bunches

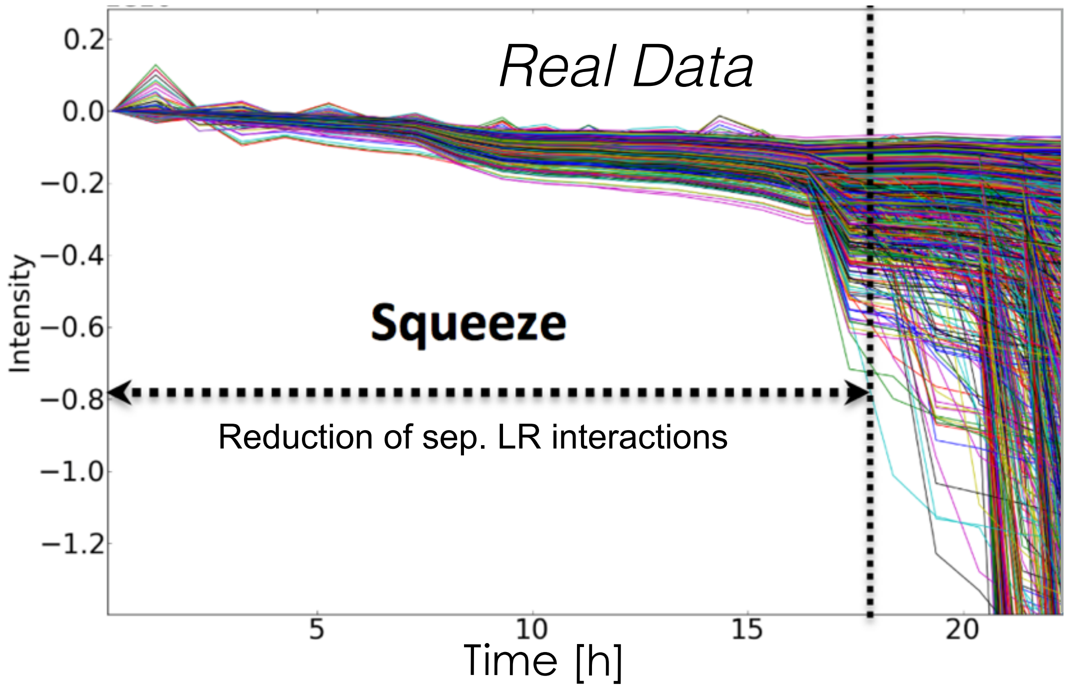
→ REDUCTION OF LUMINOSITY REACH ⚠

Mitigation techniques:

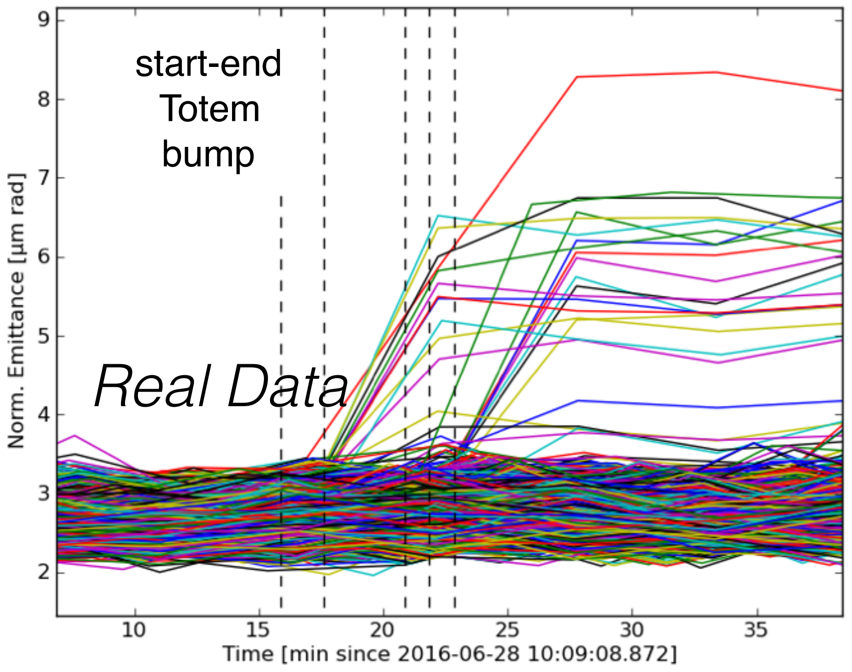
High chromaticity
Transverse feedback → Change of impedance modes

Landau damping → Passive mitigation

End of squeeze instability (2012)

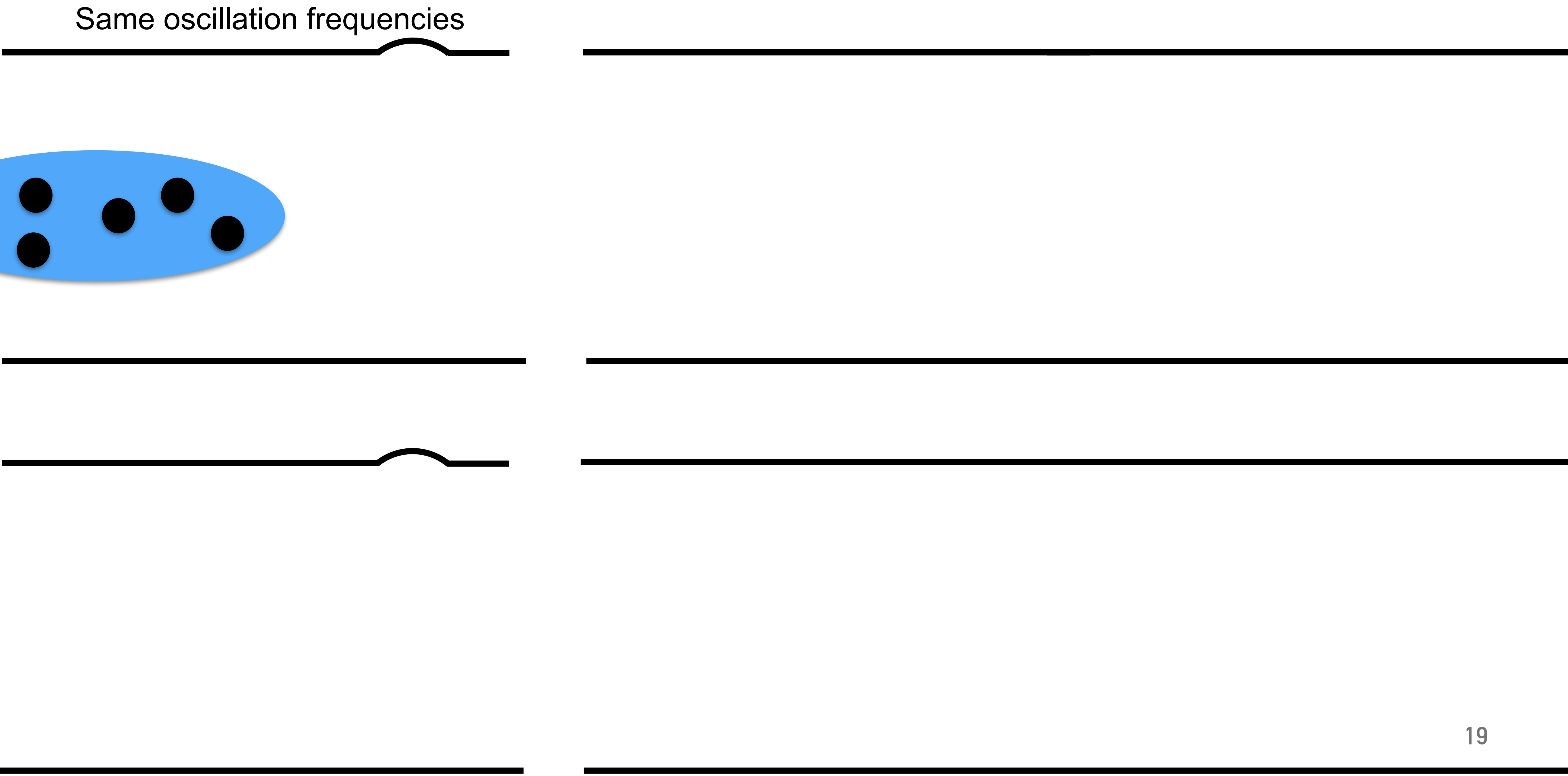


Adjust instability (2016)



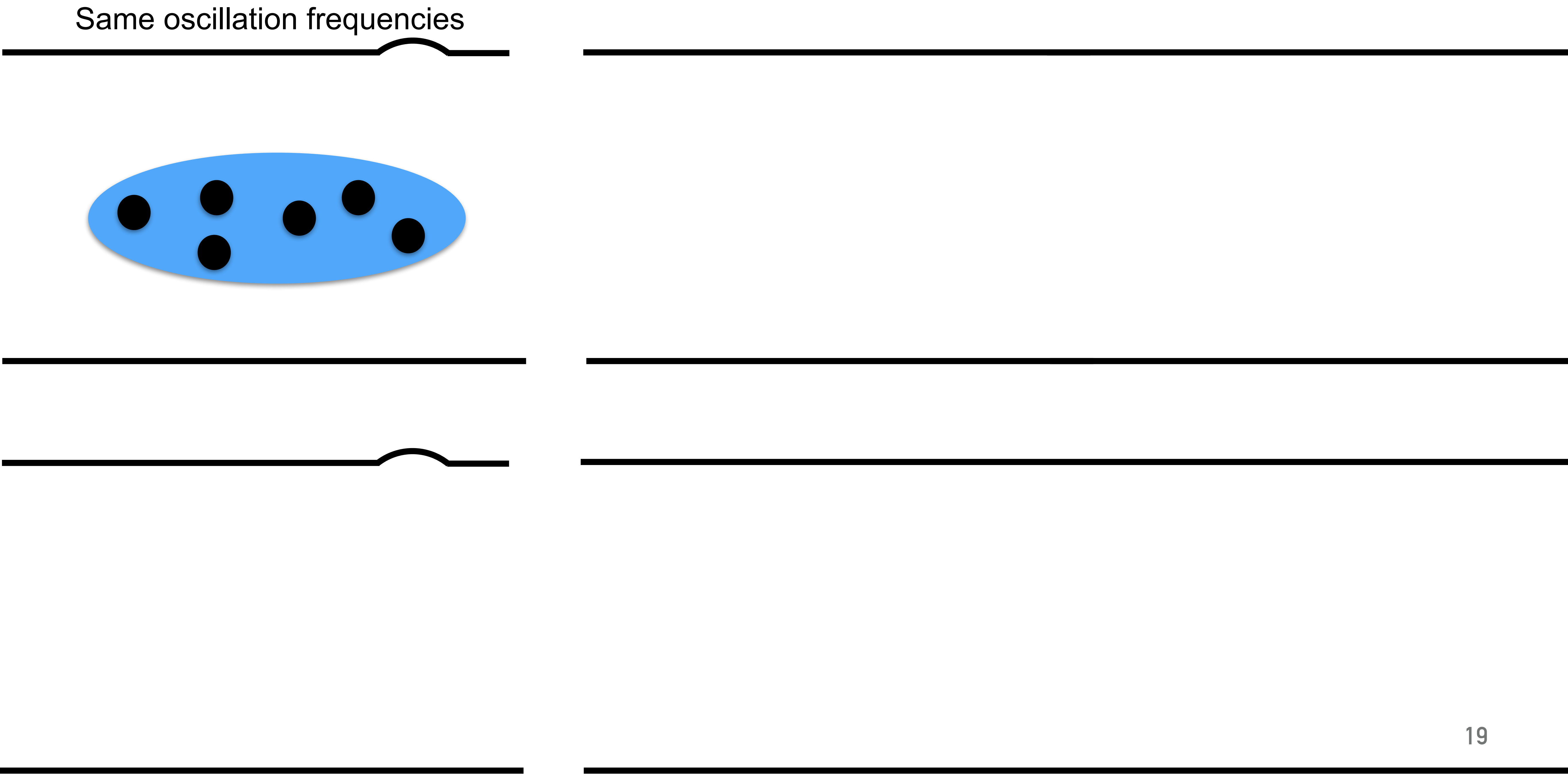
LANDAU DAMPING MECHANISMS

This mechanism **prevents an instability from developing** (region of stability)
In accelerators it is provided by the **diversification of oscillation frequencies** of the particles in the beams (**tune spread**)



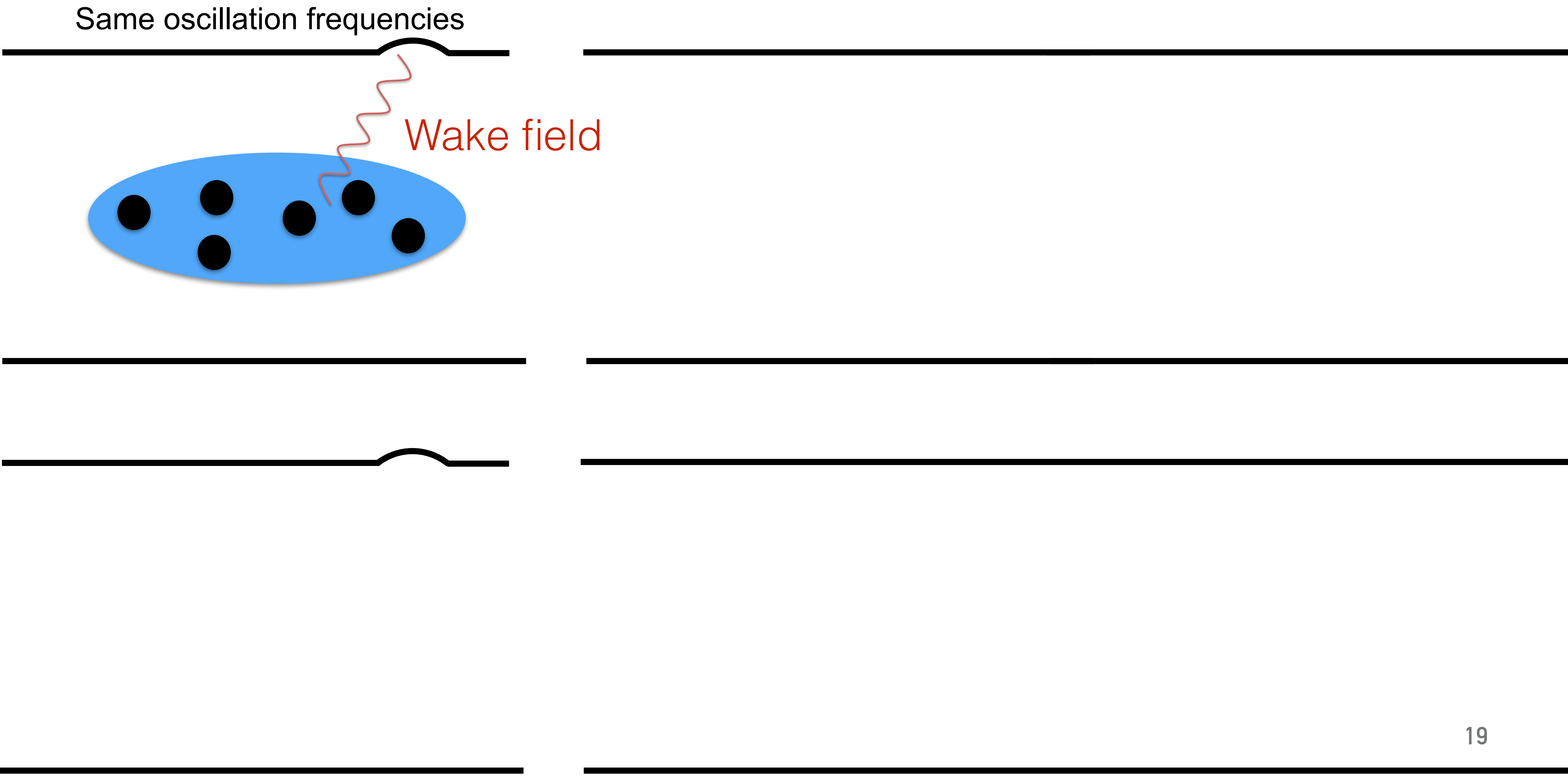
LANDAU DAMPING MECHANISMS

This mechanism **prevents an instability from developing** (region of stability)
In accelerators it is provided by the **diversification of oscillation frequencies** of the particles in the beams (**tune spread**)



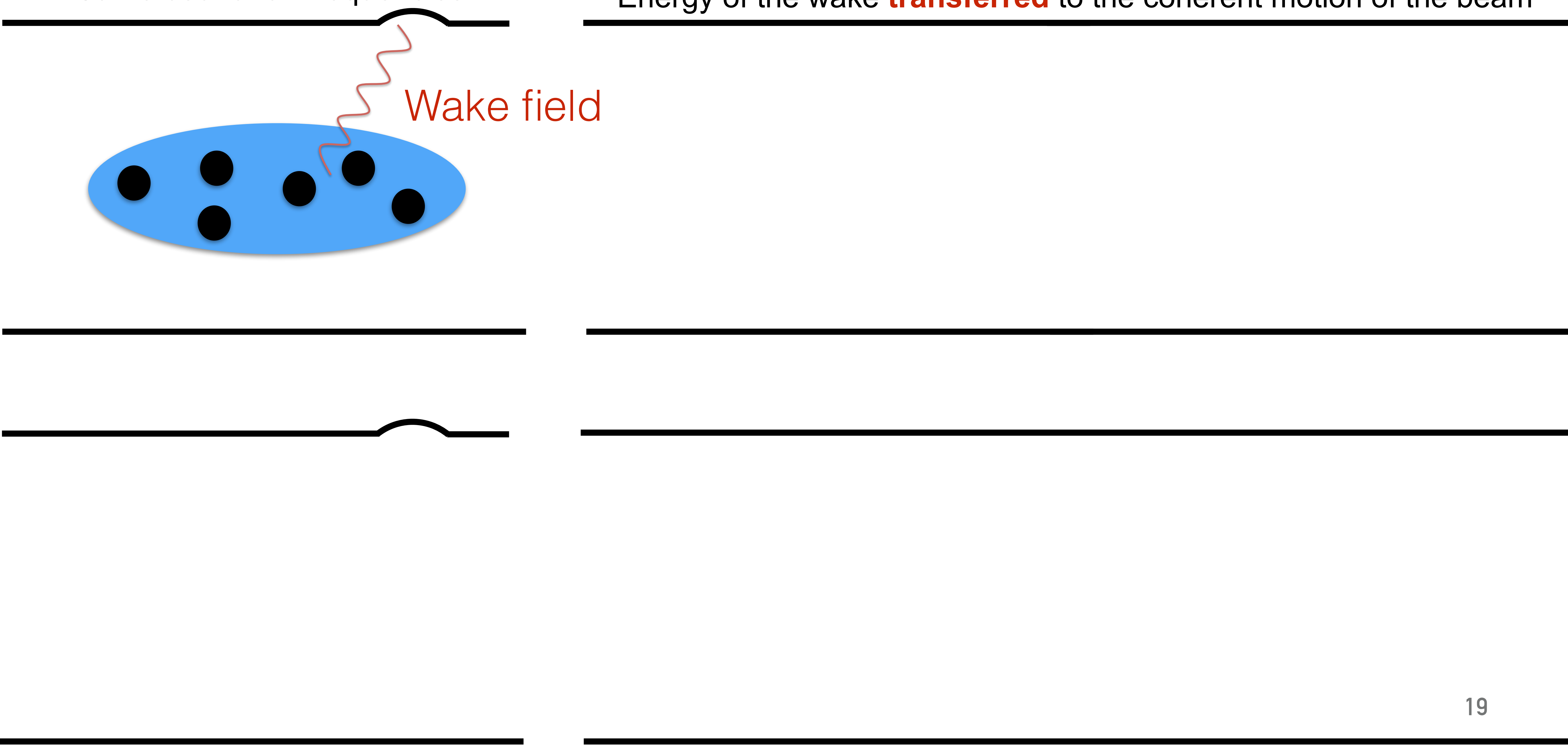
LANDAU DAMPING MECHANISMS

This mechanism **prevents an instability from developing** (region of stability)
In accelerators it is provided by the **diversification of oscillation frequencies** of the particles in the beams (**tune spread**)



LANDAU DAMPING MECHANISMS

This mechanism **prevents an instability from developing** (region of stability)
In accelerators it is provided by the **diversification of oscillation frequencies** of the particles in the beams (**tune spread**)

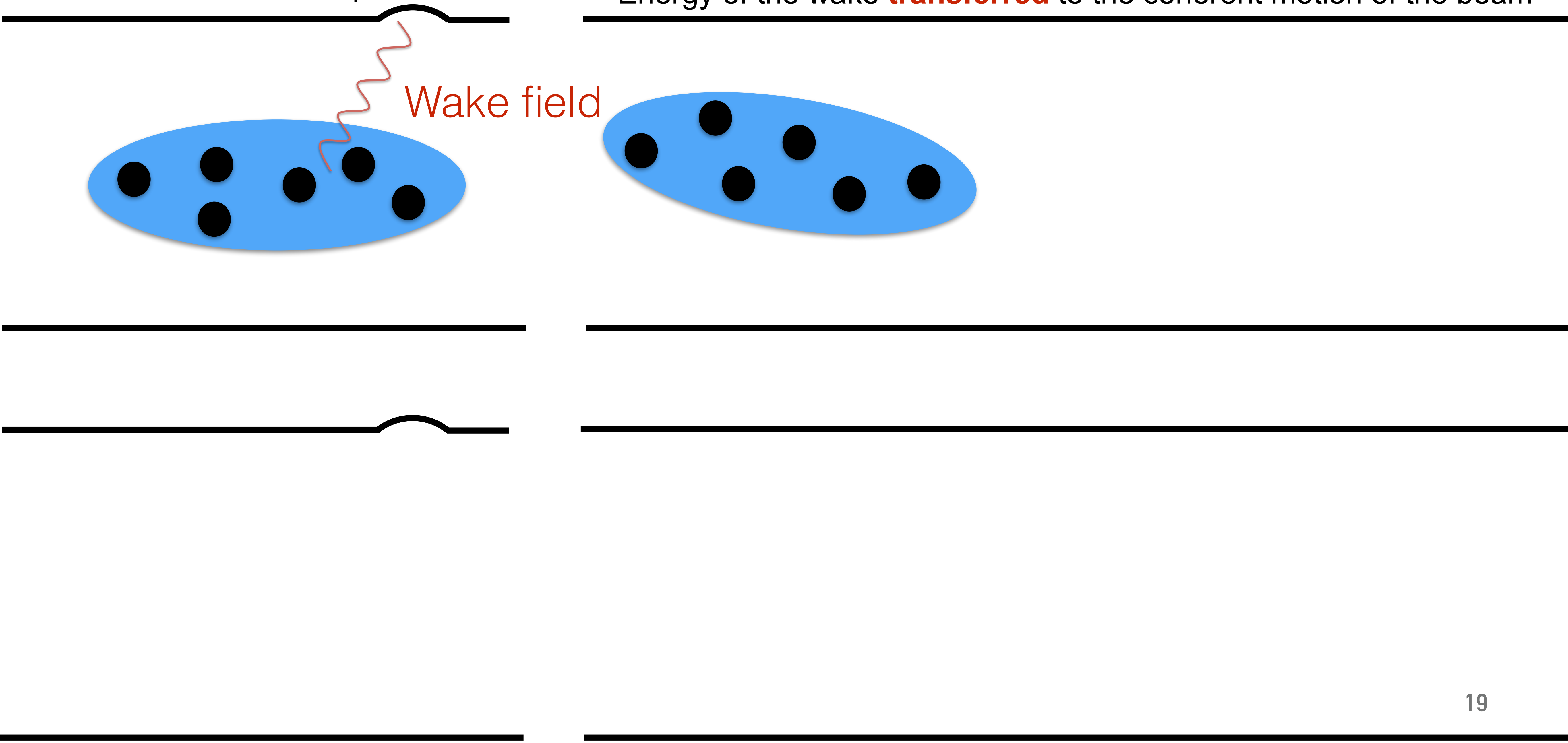


Same oscillation frequencies

Energy of the wake **transferred** to the coherent motion of the beam

LANDAU DAMPING MECHANISMS

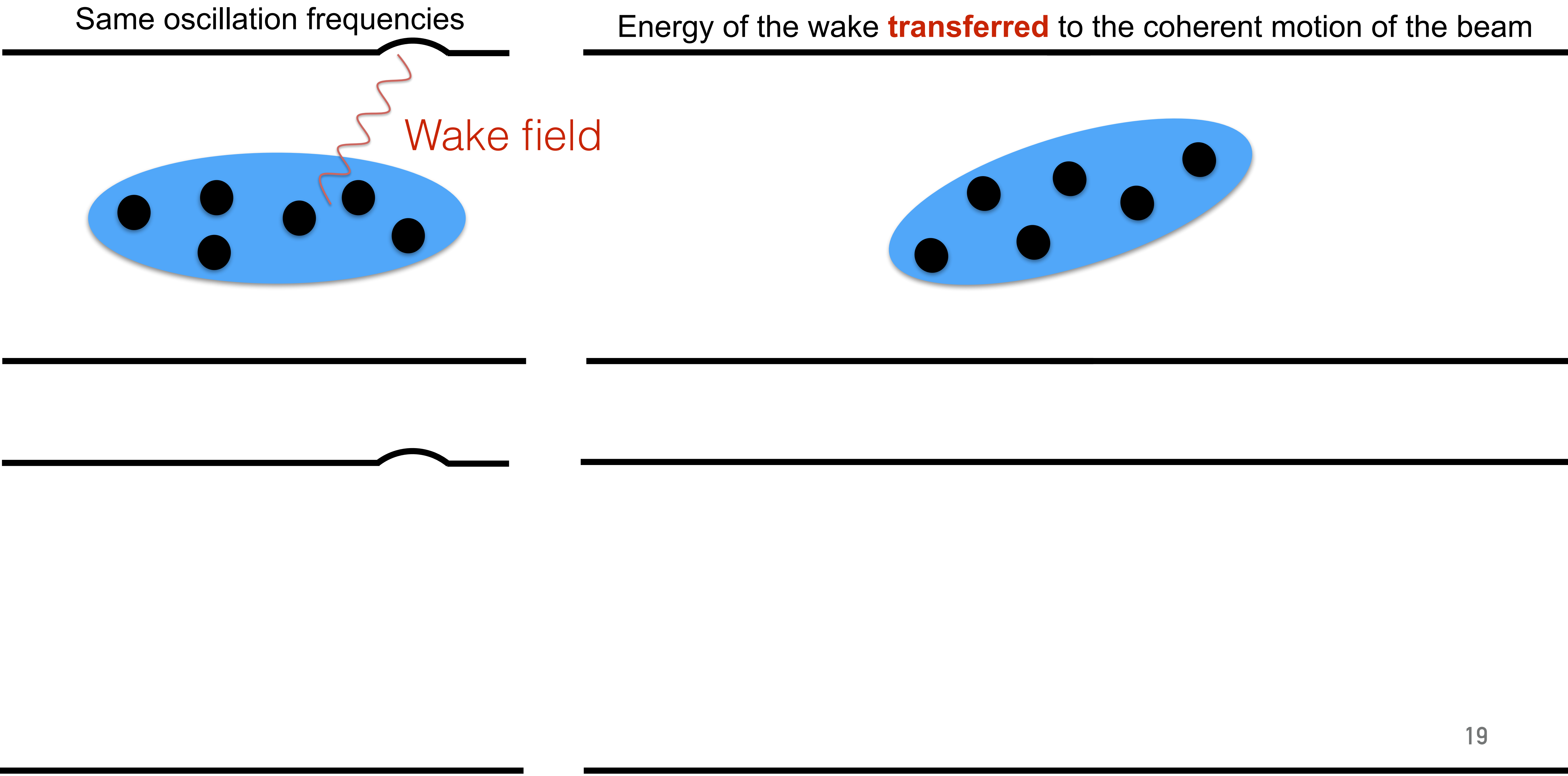
This mechanism **prevents an instability from developing** (region of stability)
In accelerators it is provided by the **diversification of oscillation frequencies** of the particles in the beams (**tune spread**)


Same oscillation frequencies

Energy of the wake **transferred** to the coherent motion of the beam

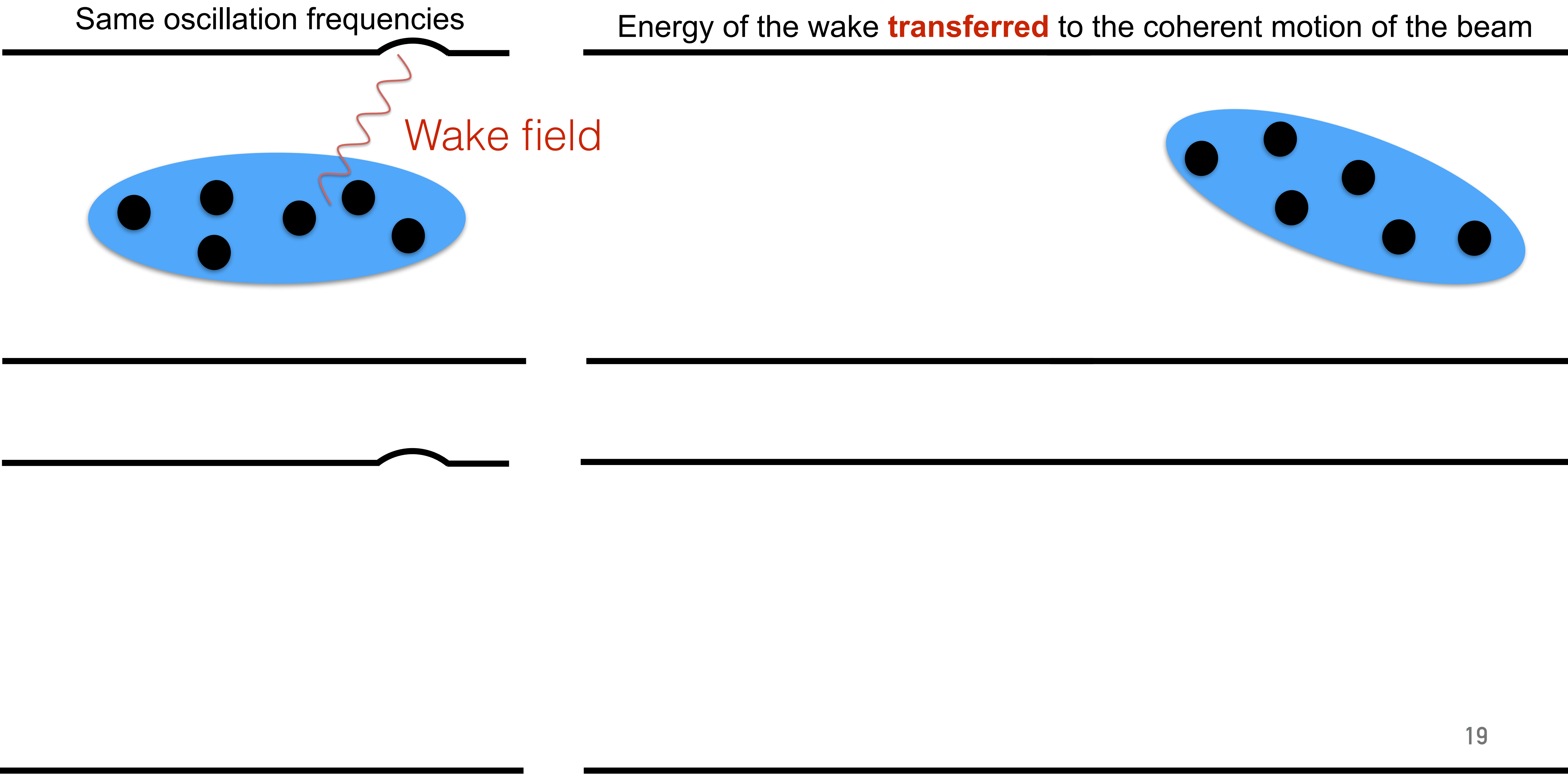
LANDAU DAMPING MECHANISMS

This mechanism **prevents an instability from developing** (region of stability)
In accelerators it is provided by the **diversification of oscillation frequencies** of the particles in the beams (**tune spread**)



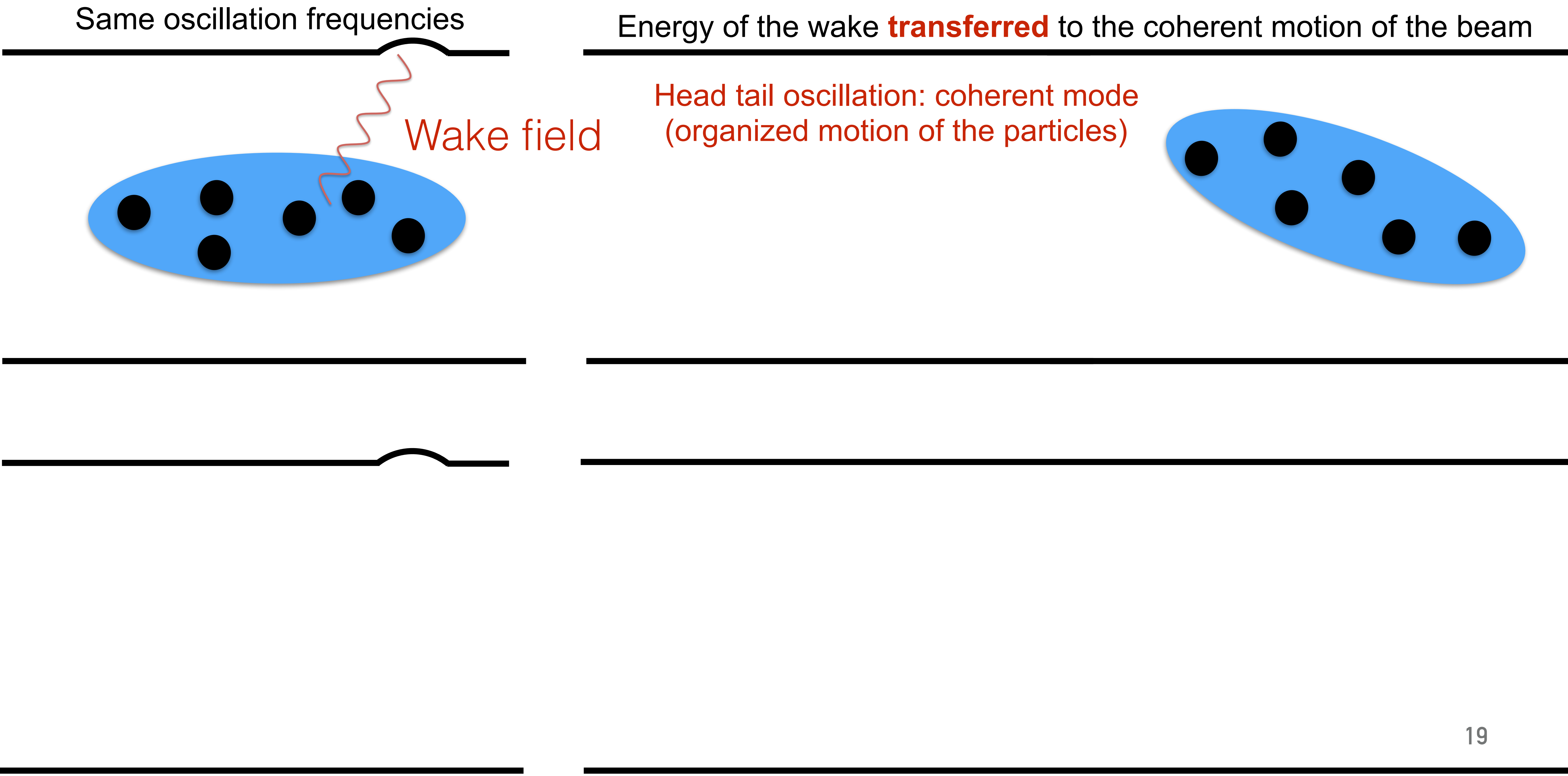
LANDAU DAMPING MECHANISMS

This mechanism **prevents an instability from developing** (region of stability)
In accelerators it is provided by the **diversification of oscillation frequencies** of the particles in the beams (**tune spread**)



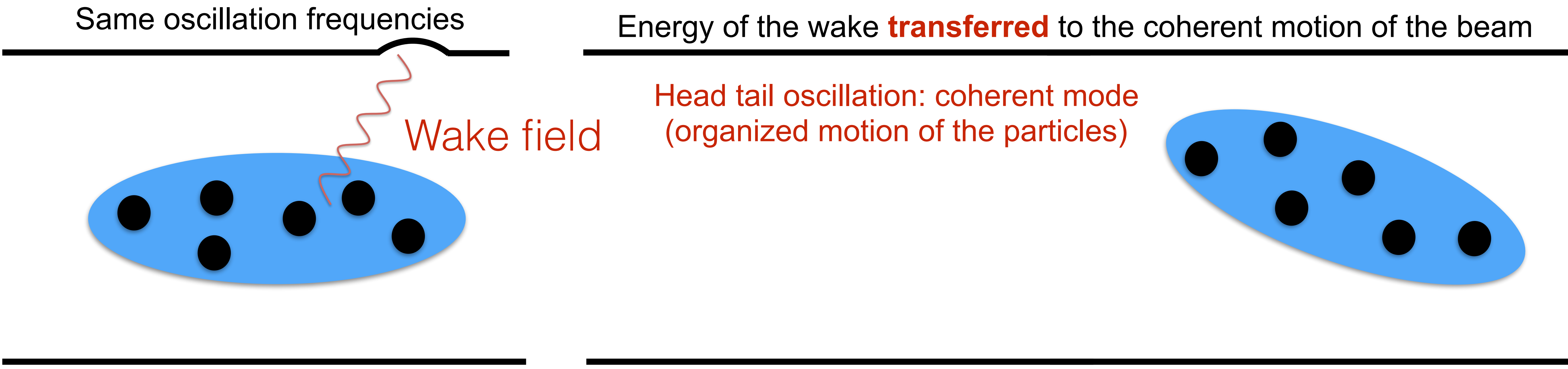
LANDAU DAMPING MECHANISMS

This mechanism **prevents an instability from developing** (region of stability)
In accelerators it is provided by the **diversification of oscillation frequencies** of the particles in the beams (**tune spread**)



LANDAU DAMPING MECHANISMS

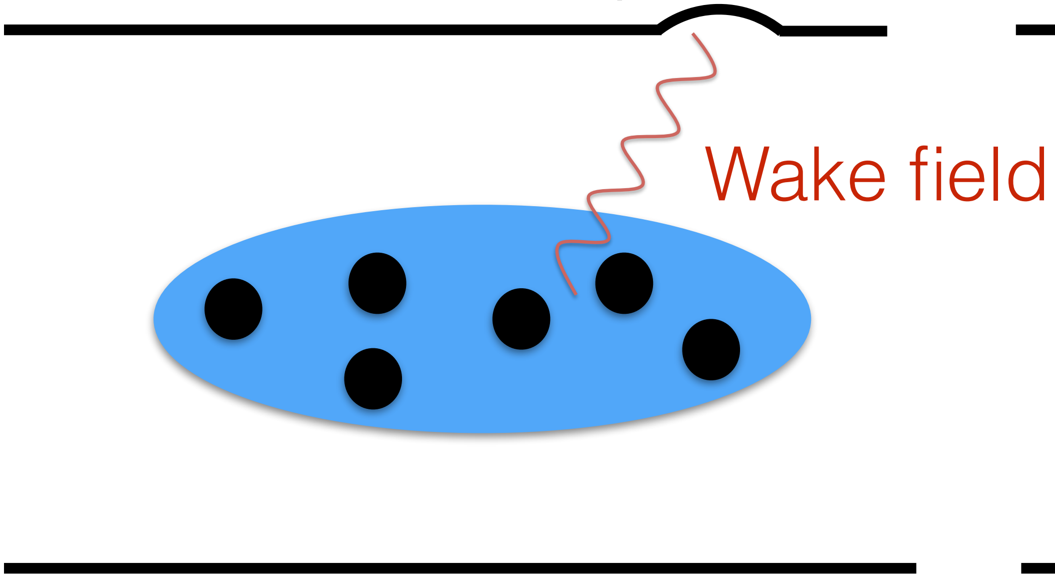
This mechanism **prevents an instability from developing** (region of stability)
In accelerators it is provided by the **diversification of oscillation frequencies** of the particles in the beams (**tune spread**)



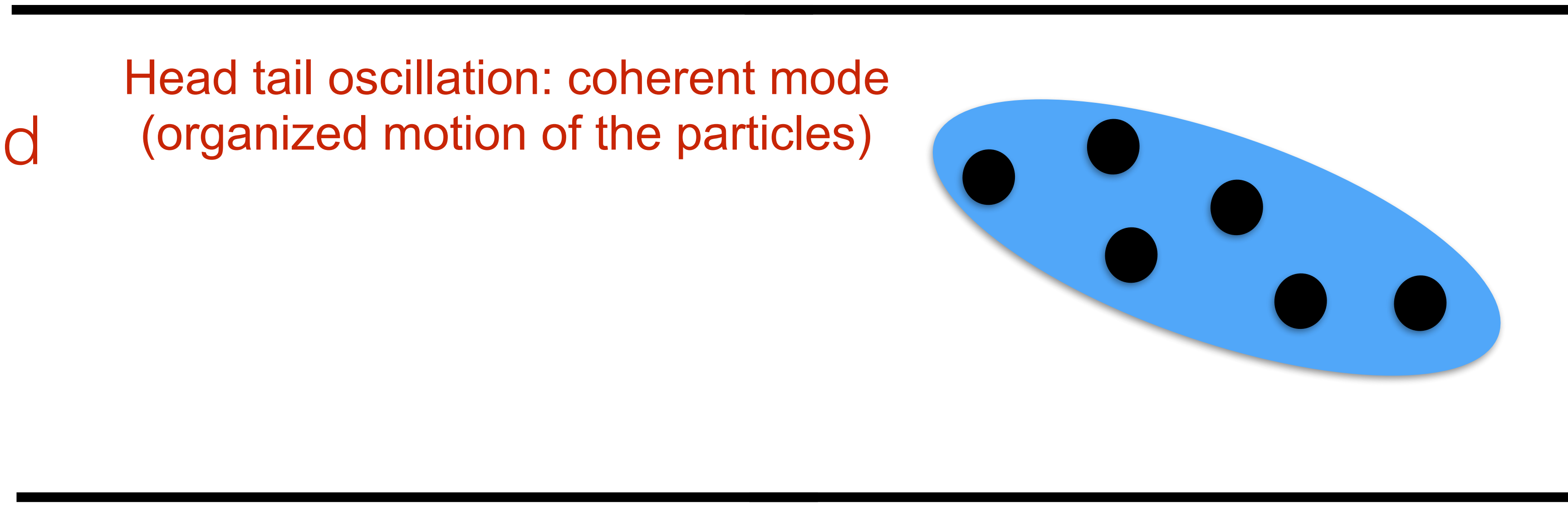
LANDAU DAMPING MECHANISMS

This mechanism **prevents an instability from developing** (region of stability)
In accelerators it is provided by the **diversification of oscillation frequencies** of the particles in the beams (**tune spread**)

Same oscillation frequencies

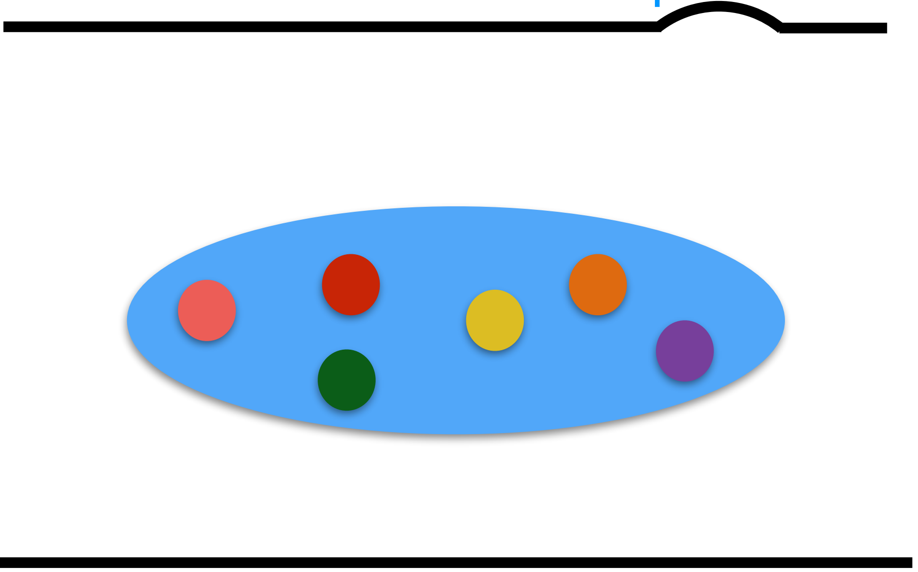


Energy of the wake **transferred** to the coherent motion of the beam



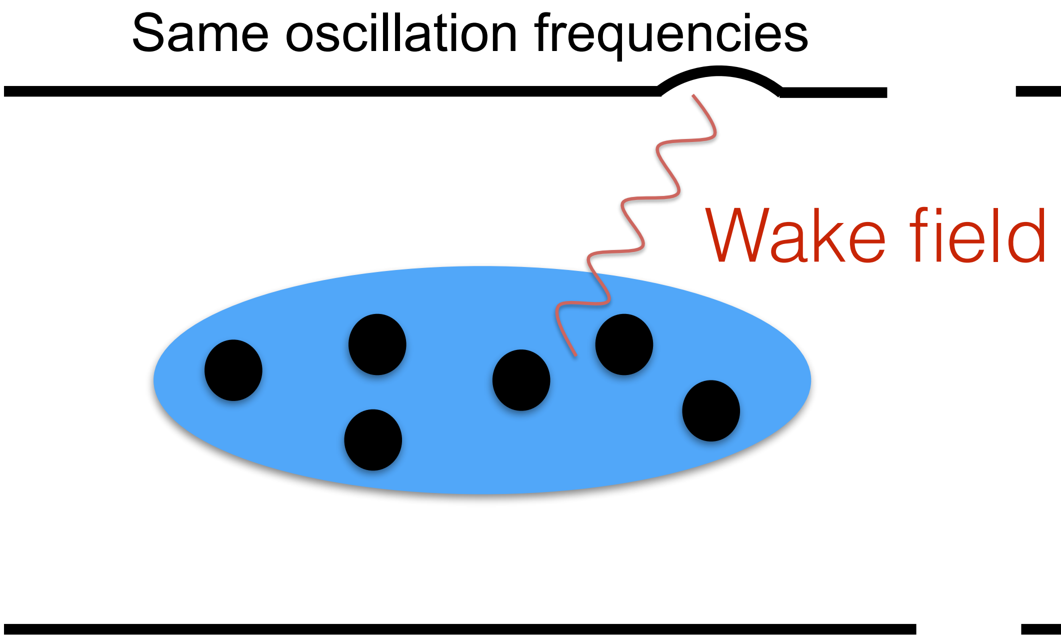
Head tail oscillation: coherent mode
(organized motion of the particles)

Different oscillation frequencies

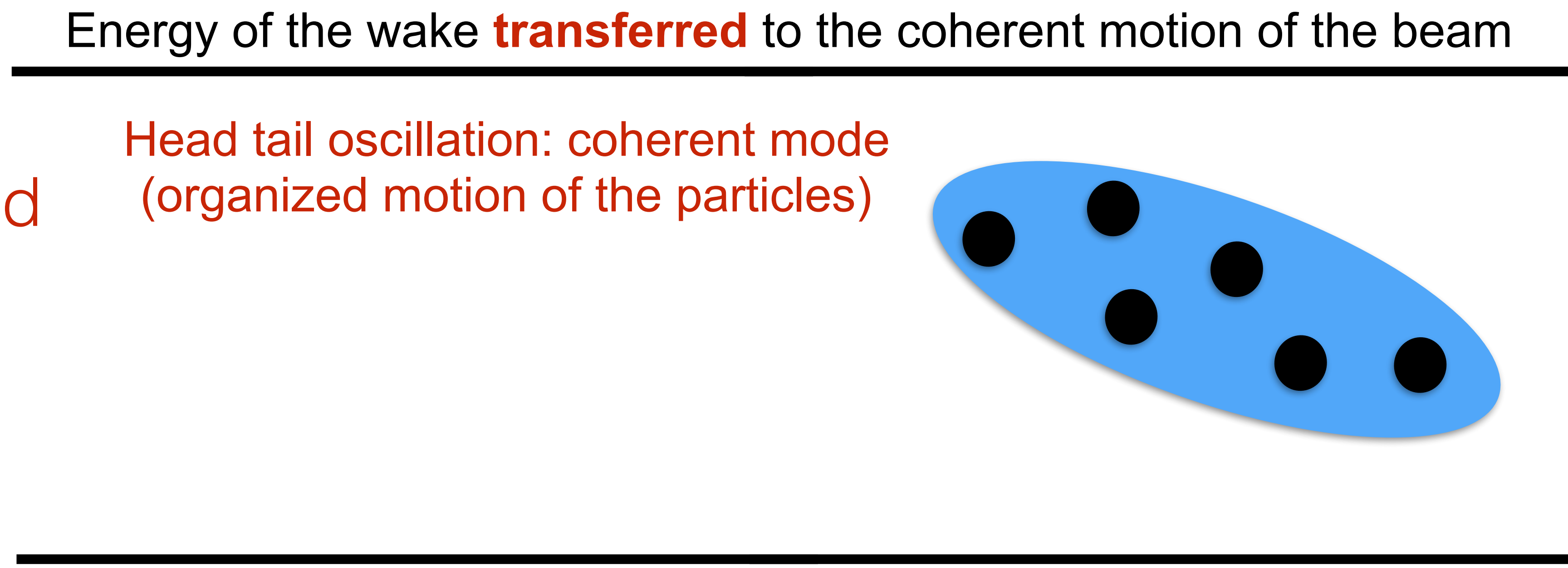


LANDAU DAMPING MECHANISMS

This mechanism **prevents an instability from developing** (region of stability)
In accelerators it is provided by the **diversification of oscillation frequencies** of the particles in the beams (**tune spread**)

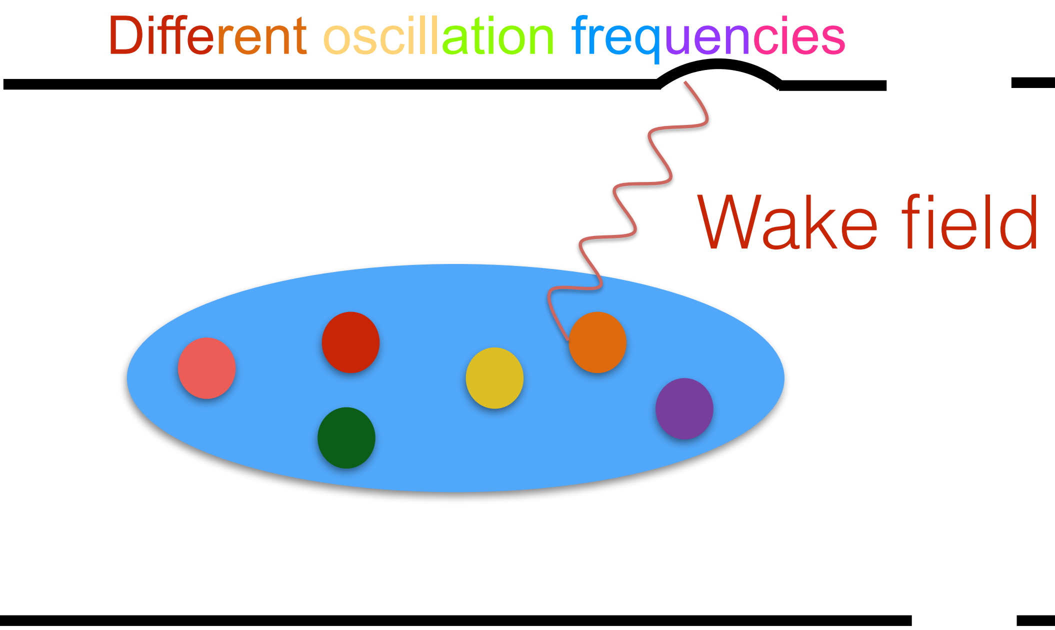


Same oscillation frequencies



Energy of the wake **transferred** to the coherent motion of the beam

Head tail oscillation: coherent mode (organized motion of the particles)

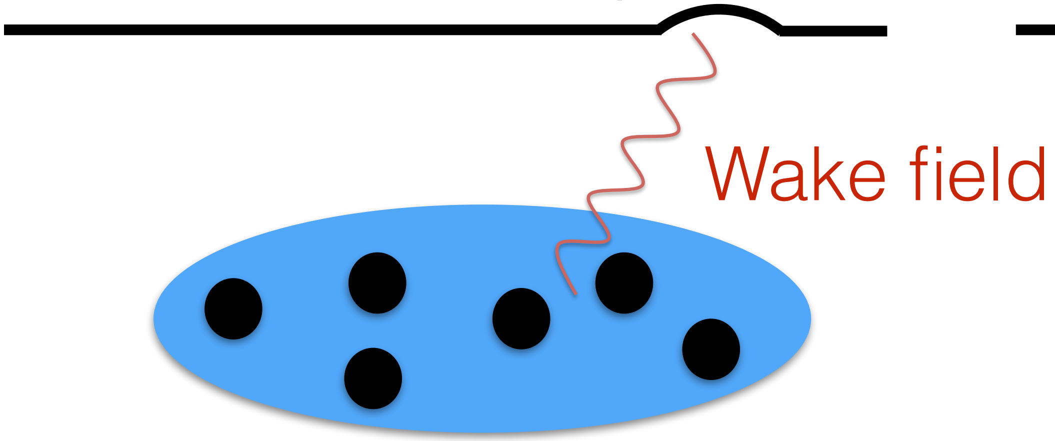


Different oscillation frequencies

LANDAU DAMPING MECHANISMS

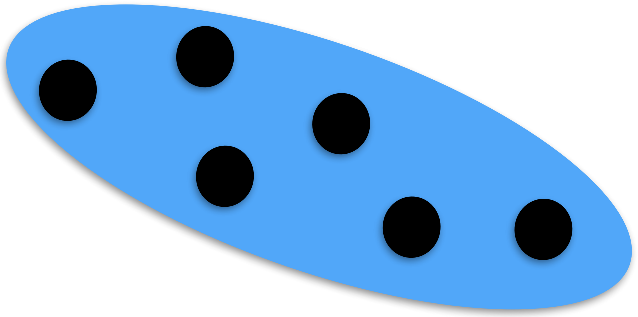
This mechanism **prevents an instability from developing** (region of stability)
In accelerators it is provided by the **diversification of oscillation frequencies** of the particles in the beams (**tune spread**)

Same oscillation frequencies

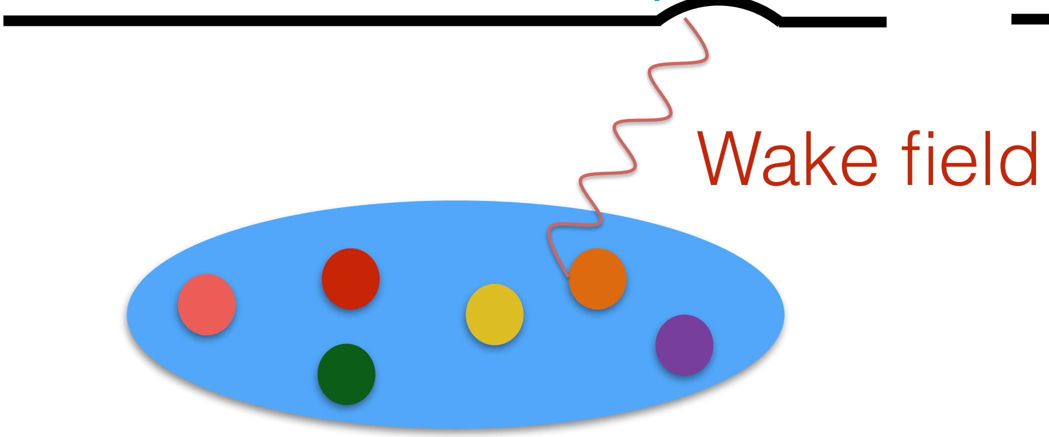


Energy of the wake **transferred** to the coherent motion of the beam

Head tail oscillation: coherent mode
(organized motion of the particles)



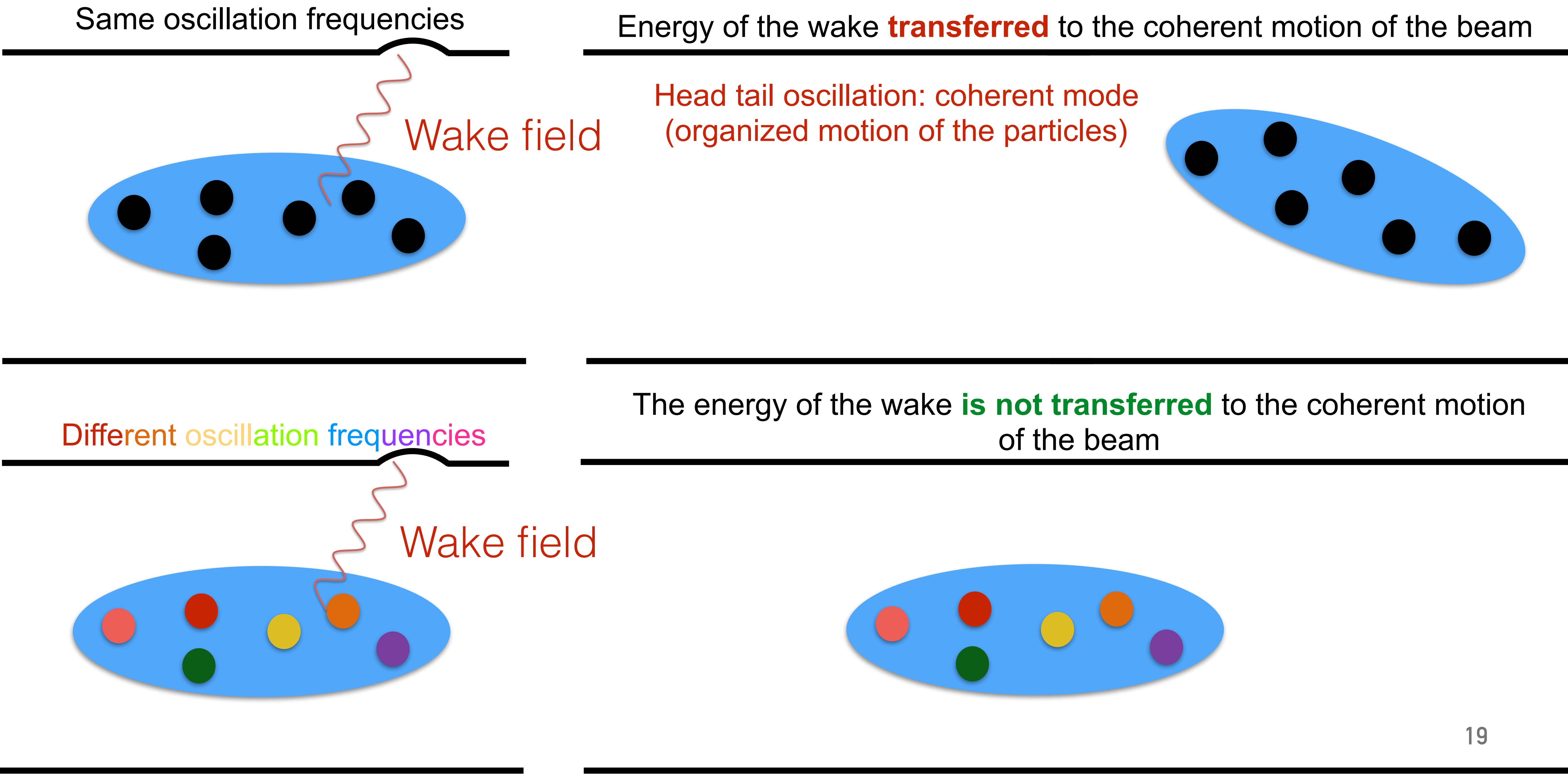
Different oscillation frequencies



The energy of the wake **is not transferred** to the coherent motion of the beam

LANDAU DAMPING MECHANISMS

This mechanism **prevents an instability from developing** (region of stability)
In accelerators it is provided by the **diversification of oscillation frequencies** of the particles in the beams (**tune spread**)



Same oscillation frequencies

Wake field

Energy of the wake **transferred** to the coherent motion of the beam

Head tail oscillation: coherent mode (organized motion of the particles)

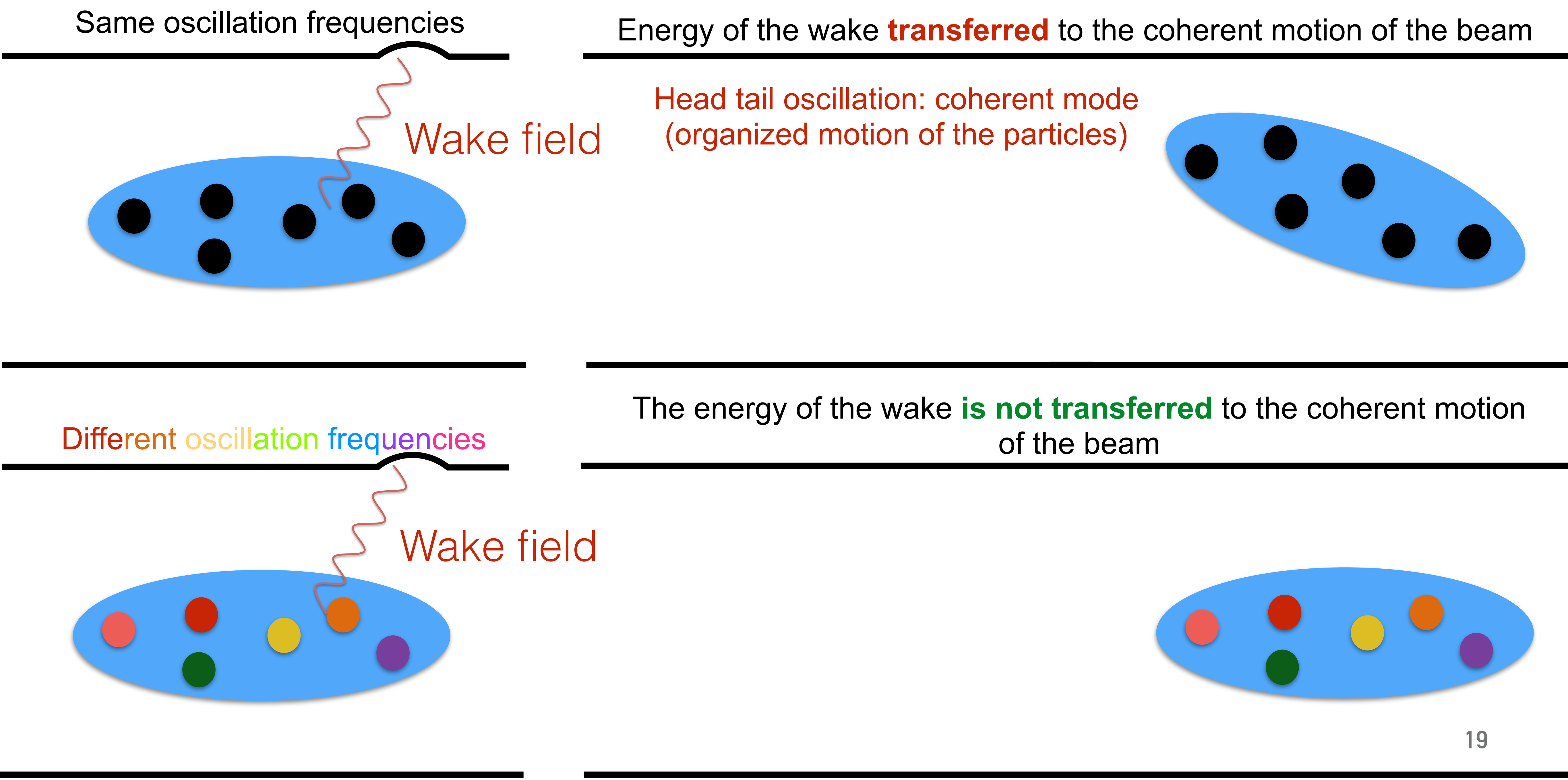
Different oscillation frequencies

Wake field

The energy of the wake **is not transferred** to the coherent motion of the beam

LANDAU DAMPING MECHANISMS

This mechanism **prevents an instability from developing** (region of stability)
In accelerators it is provided by the **diversification of oscillation frequencies** of the particles in the beams (**tune spread**)



Same oscillation frequencies

Energy of the wake **transferred** to the coherent motion of the beam

Head tail oscillation: coherent mode (organized motion of the particles)

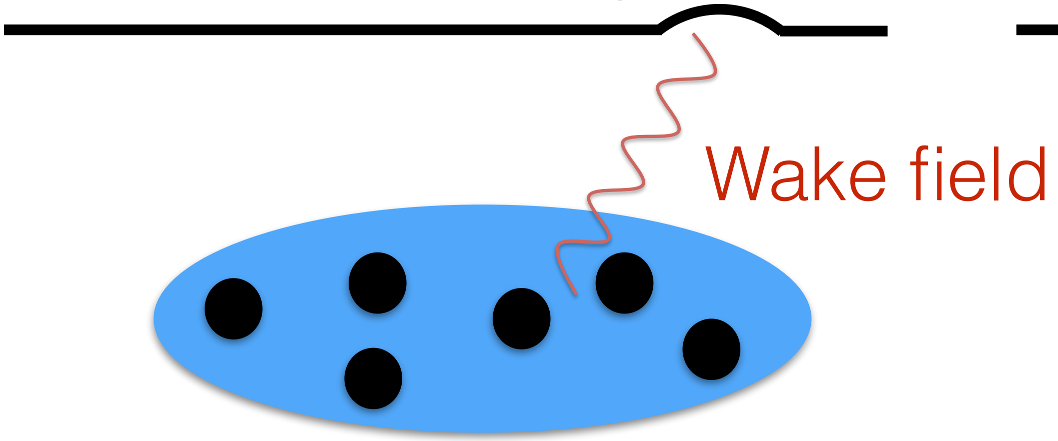
Different oscillation frequencies

The energy of the wake **is not transferred** to the coherent motion of the beam

LANDAU DAMPING MECHANISMS

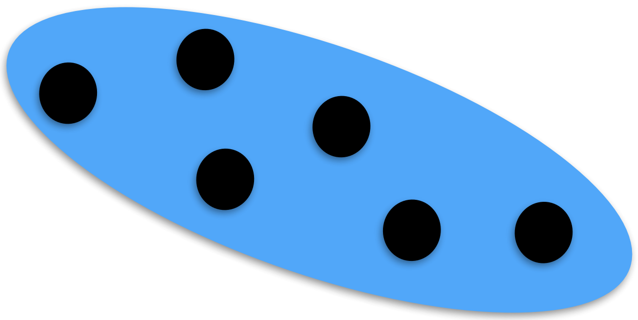
This mechanism **prevents an instability from developing** (region of stability)
In accelerators it is provided by the **diversification of oscillation frequencies** of the particles in the beams (**tune spread**)

Same oscillation frequencies

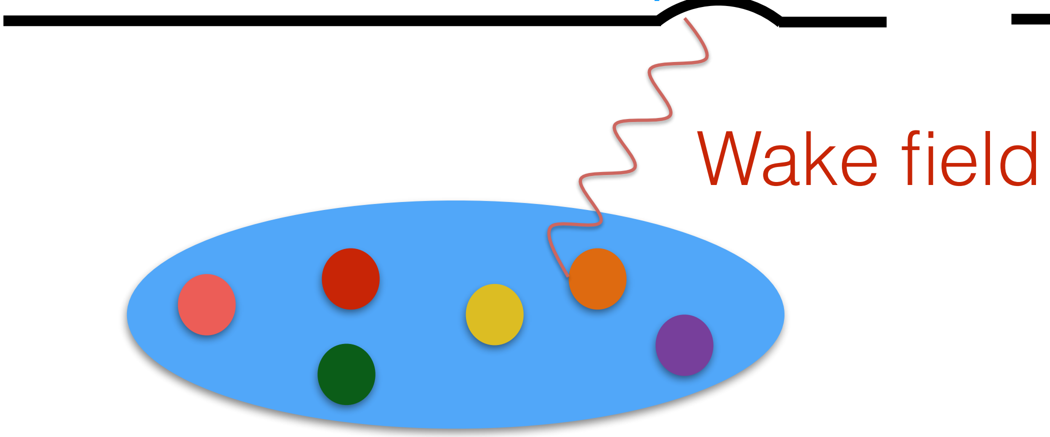


Energy of the wake **transferred** to the coherent motion of the beam

Head tail oscillation: coherent mode
(organized motion of the particles)



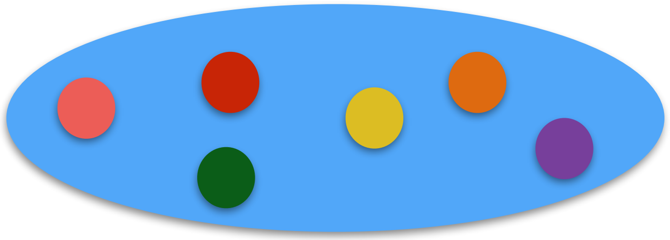
Different oscillation frequencies



The energy of the wake **is not transferred** to the coherent motion of the beam

Landau damping: the coherent
oscillation does not develop

The coherent motion is Landau damped!



LANDAU DAMPING AND STABILITY DIAGRAMS

The Landau damping of head-tail instabilities is quantified by solving the dispersion integral:

Particle distribution

$$\mathrm{SD}^{-1} = \int_0^\infty \int_0^\infty \frac{J_{x,y} \frac{d\Psi_{x,y}(J_x,J_y)}{dJ_{x,y}}}{Q_0 - q_{x,y}(J_x, J_y) - i\epsilon} dJ_x dJ_y$$

Stable region

Detuning with amplitude (tune spread)
Octupoles + beam-beam (any non-linearities)

J_x, J_y → particle amplitudes (in units of beam size)

q_x,q_y → particle transverse tunes

TUNE SPREAD FOR LANDAU DAMPING

What helps to stabilize the beams?

TUNE SPREAD FOR LANDAU DAMPING

What helps to stabilize the beams?

→ **Any non-linearities** that cause detuning with amplitude (tune spread)

- Main source of tune spread: **Landau octupole magnets** (linear detuning with amplitude)

Non-linear effects:

- **beam-beam interactions**
- non-linear errors from magnets
- electron cloud, space charge…

TUNE SPREAD FOR LANDAU DAMPING

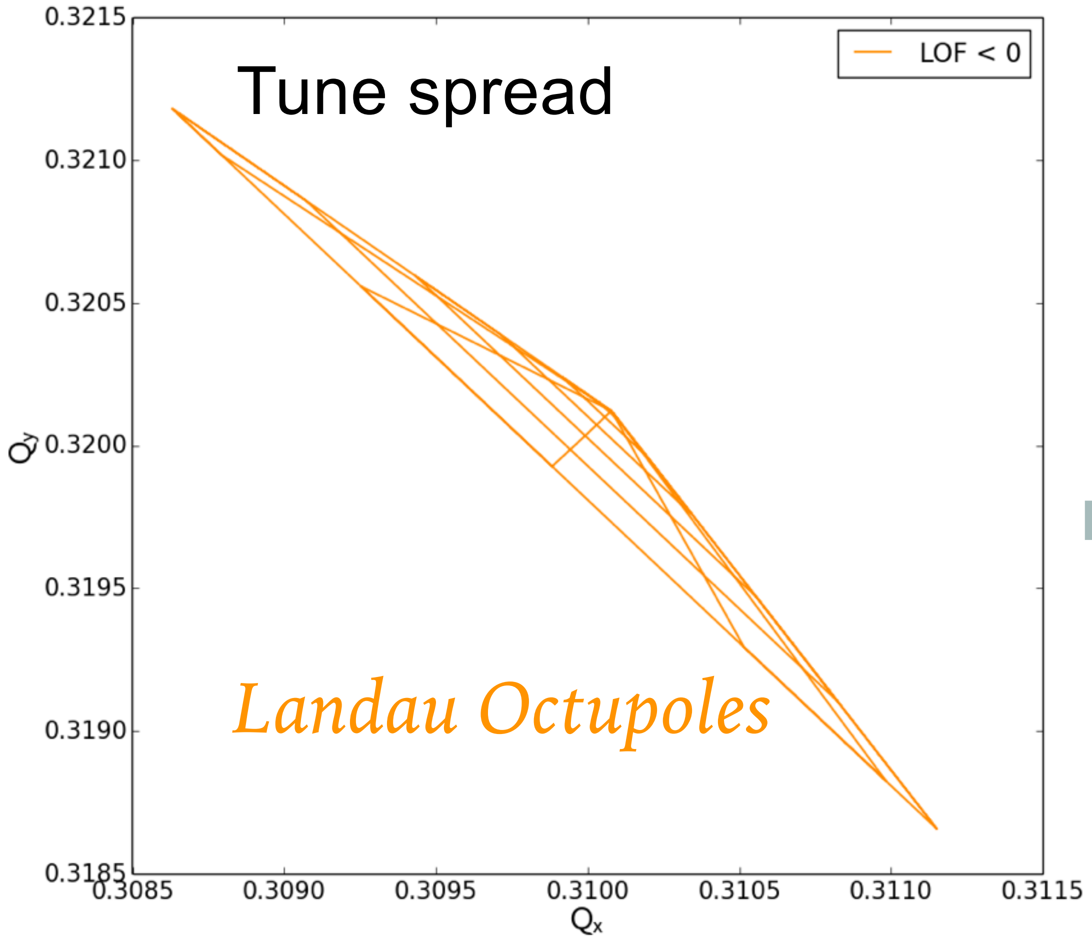
What helps to stabilize the beams?

→ **Any non-linearities** that cause detuning with amplitude (tune spread)

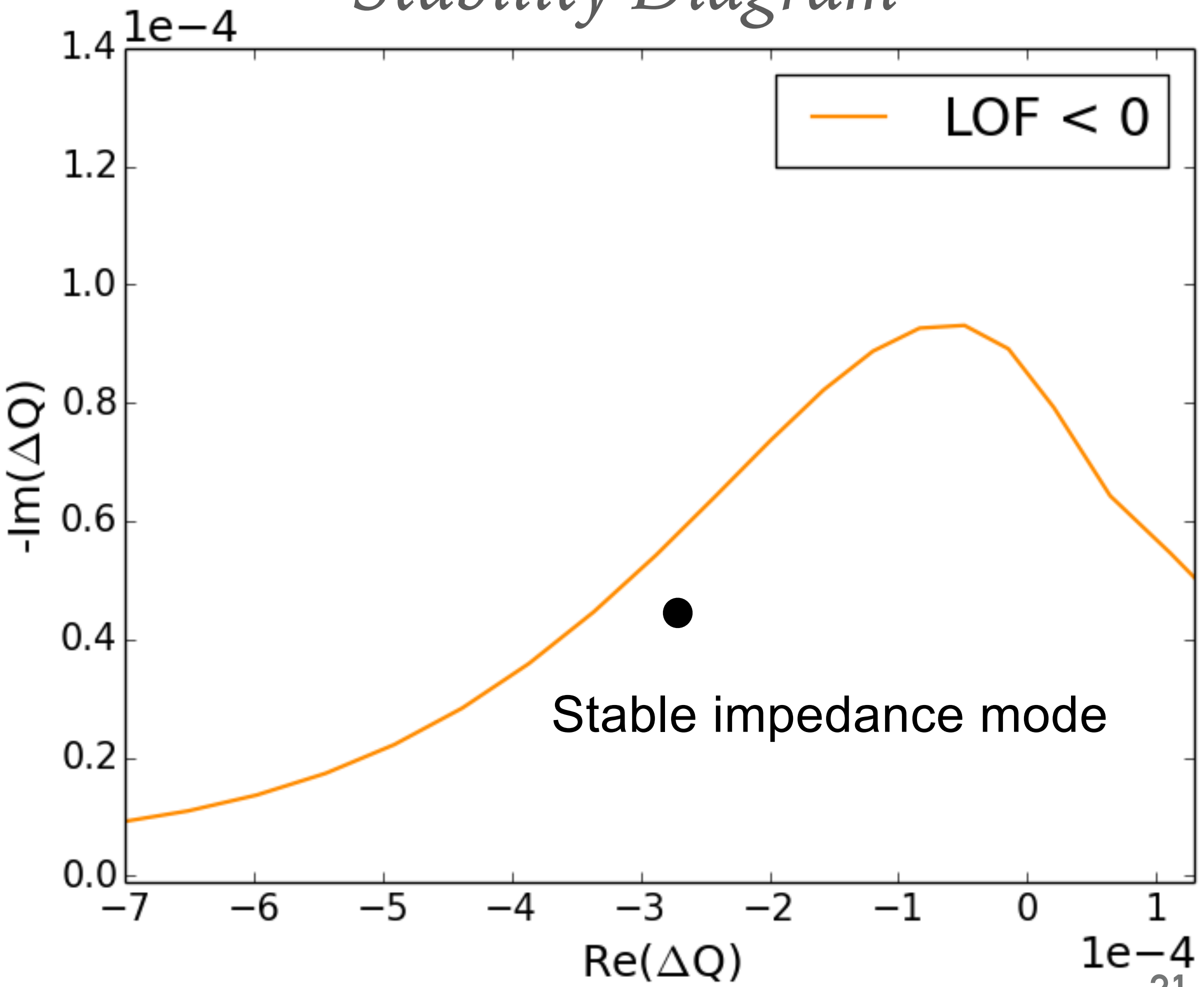
- Main source of tune spread: **Landau octupole magnets** (linear detuning with amplitude)

Non-linear effects:

- **beam-beam interactions**
- non-linear errors from magnets
- electron cloud, space charge…



Stability Diagram



TUNE SPREAD FOR LANDAU DAMPING

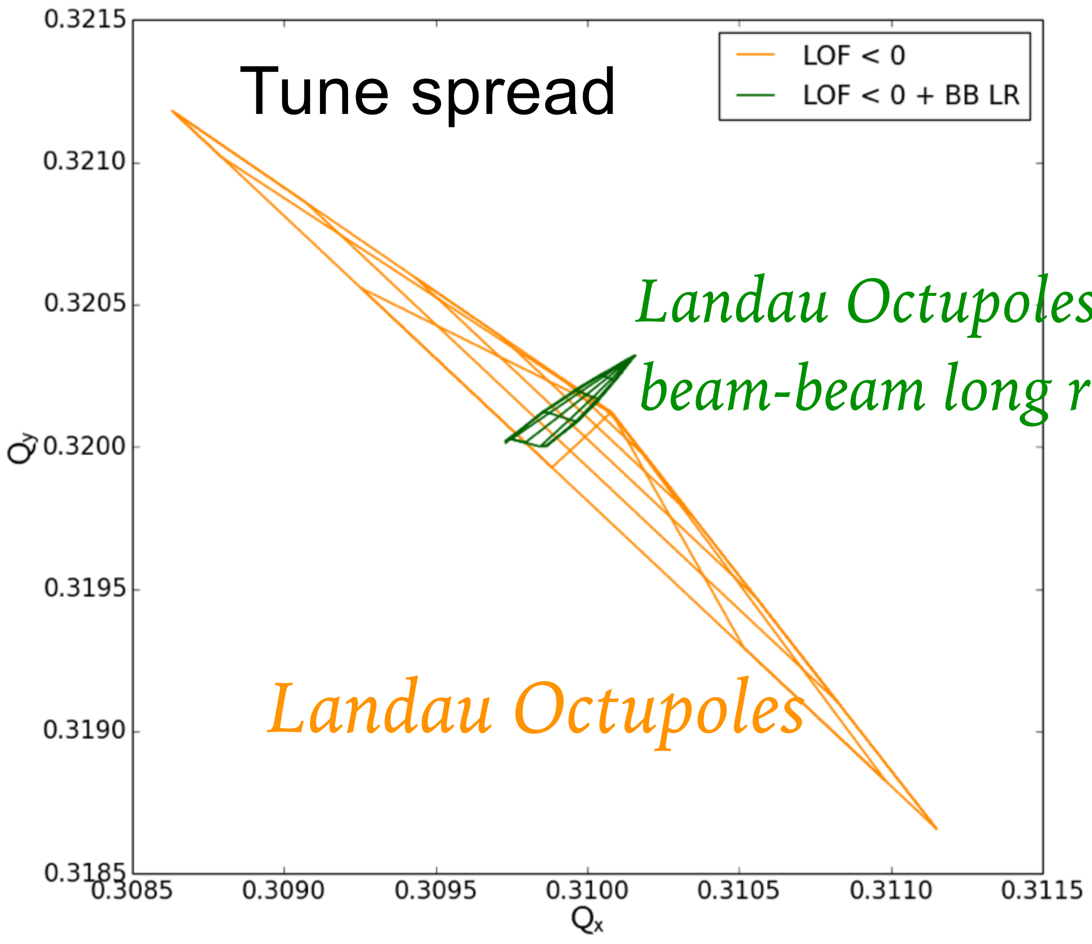
What helps to stabilize the beams?

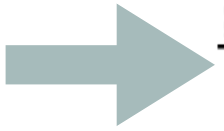
→ **Any non-linearities** that cause detuning with amplitude (tune spread)

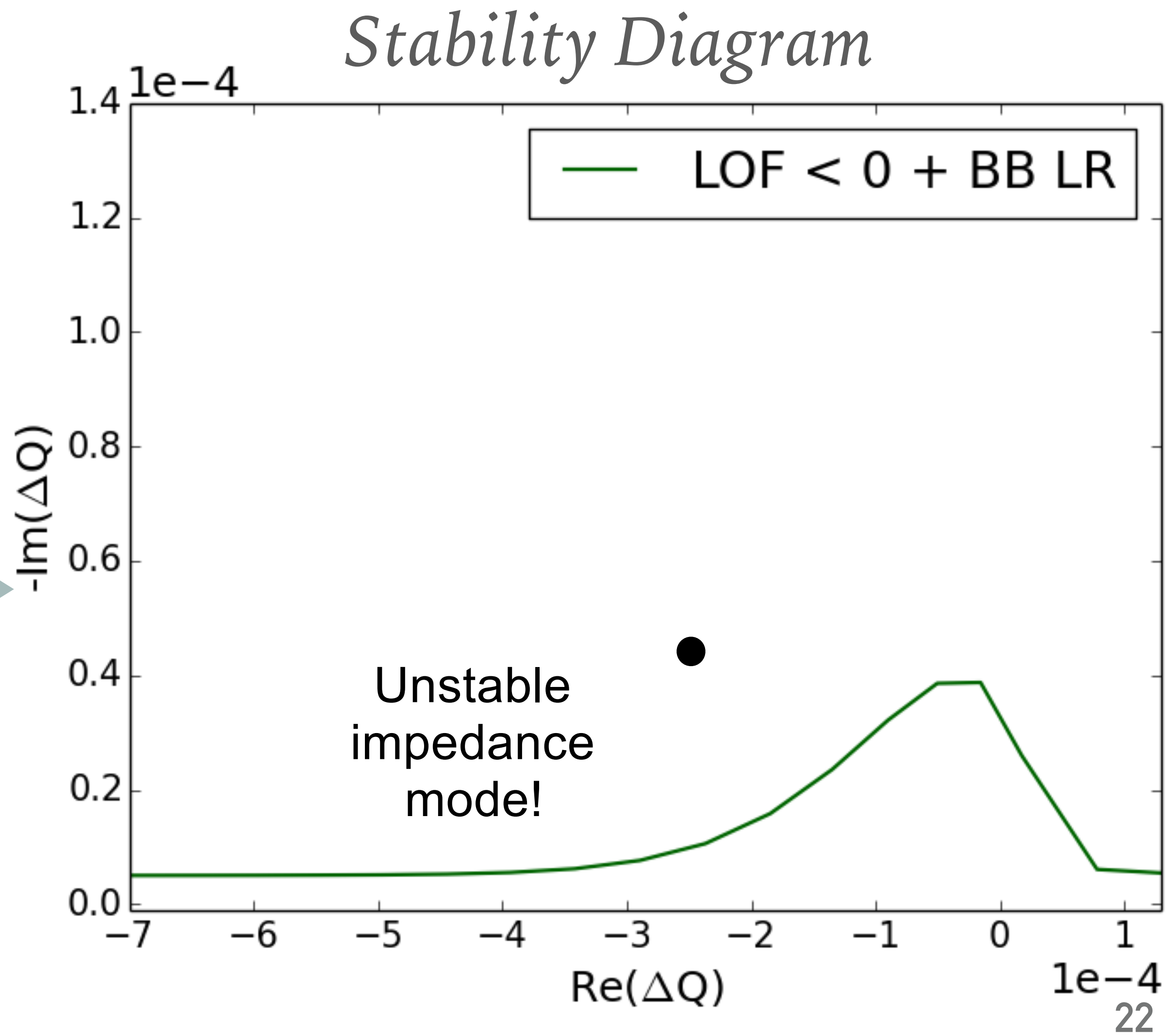
- Main source of tune spread: **Landau octupole magnets** (linear detuning with amplitude)

Non-linear effects:

- **beam-beam interactions**
- non-linear errors from magnets
- electron cloud, space charge…

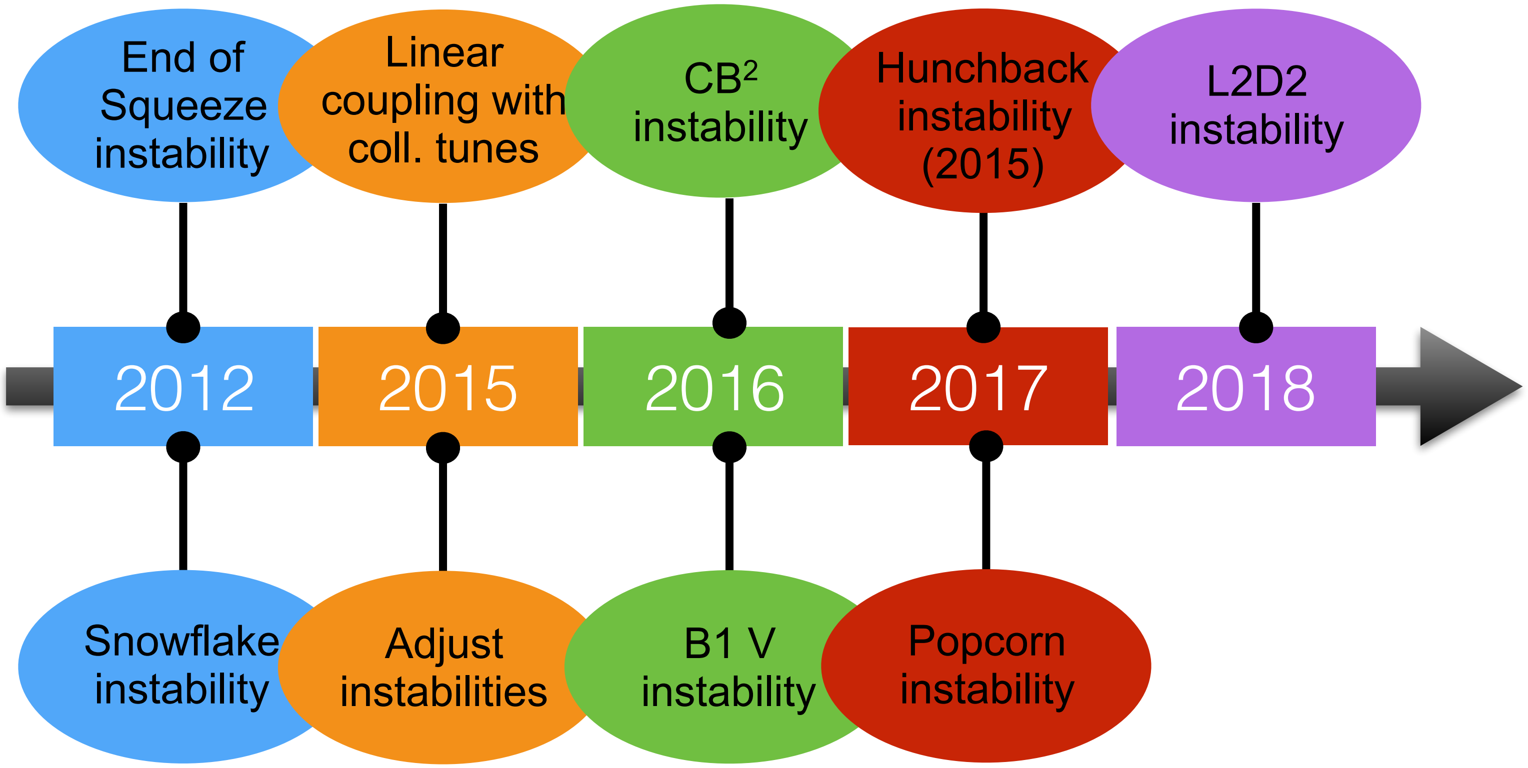






LANDAU DAMPING AND INSTABILITIES IN THE LHC

Models predict stability margins but coherent instabilities present in the LHC during Physics runs



2012
- End of Squeeze instability
- Snowflake instability

2015
- Linear coupling with coll. tunes
- Adjust instabilities

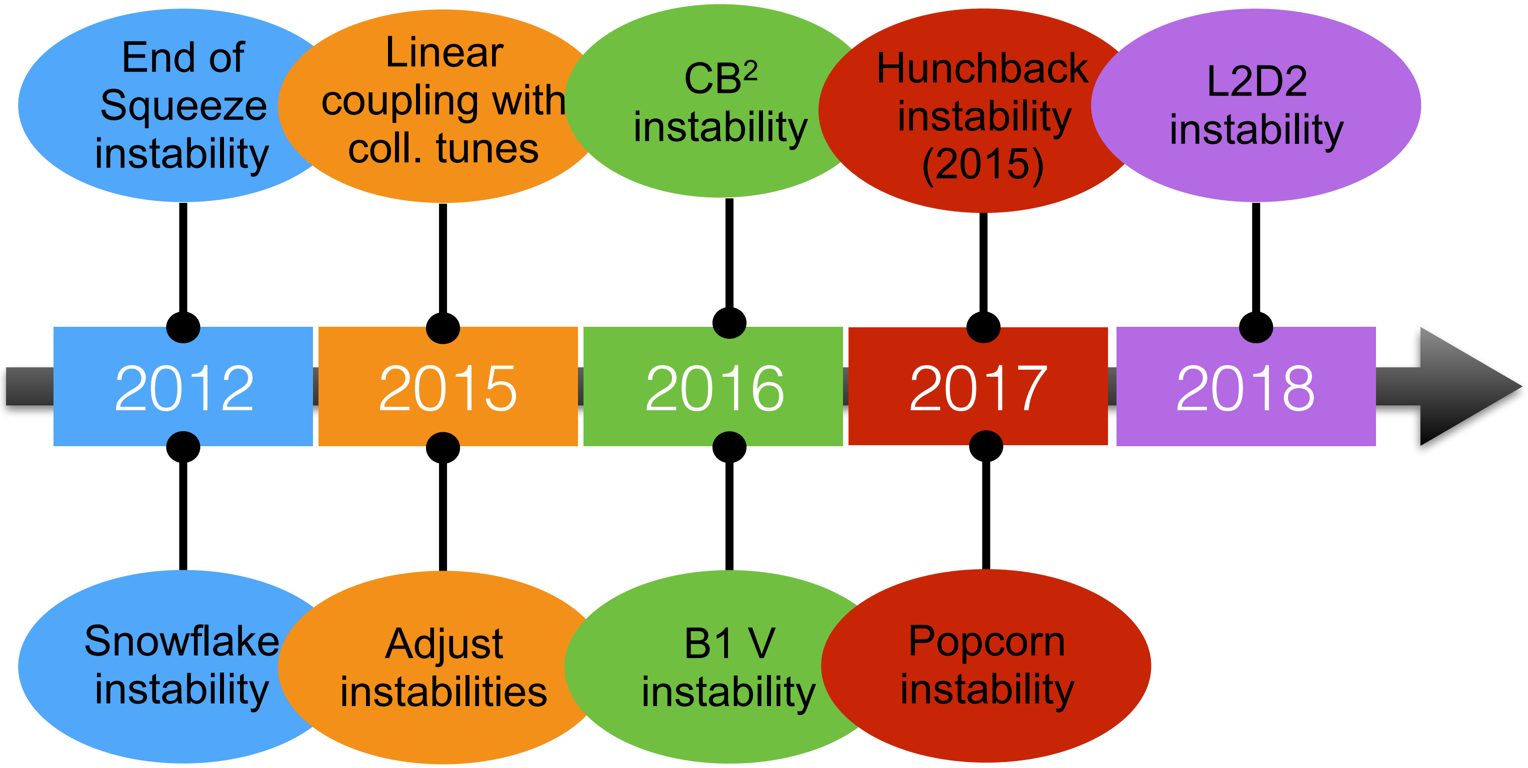
2016
- CB^2 instability
- B1 V instability

2017
- Hunchback instability (2015)
- Popcorn instability

2018
- L2D2 instability

LANDAU DAMPING AND INSTABILITIES IN THE LHC

Models predict stability margins but coherent instabilities present in the LHC during Physics runs



2012

End of Squeeze instability

Snowflake instability

2015

Linear coupling with coll. tunes

Adjust instabilities

2016

CB^2 instability

B1 V instability

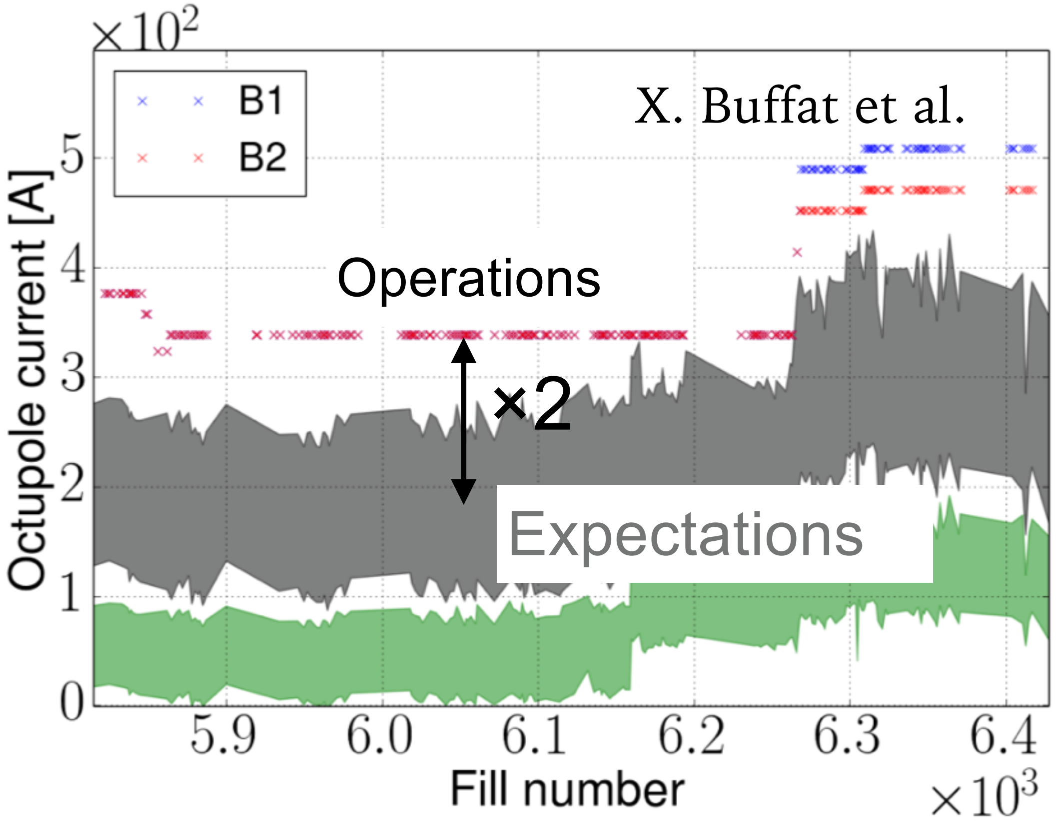
2017

Hunchback instability (2015)

Popcorn instability

2018

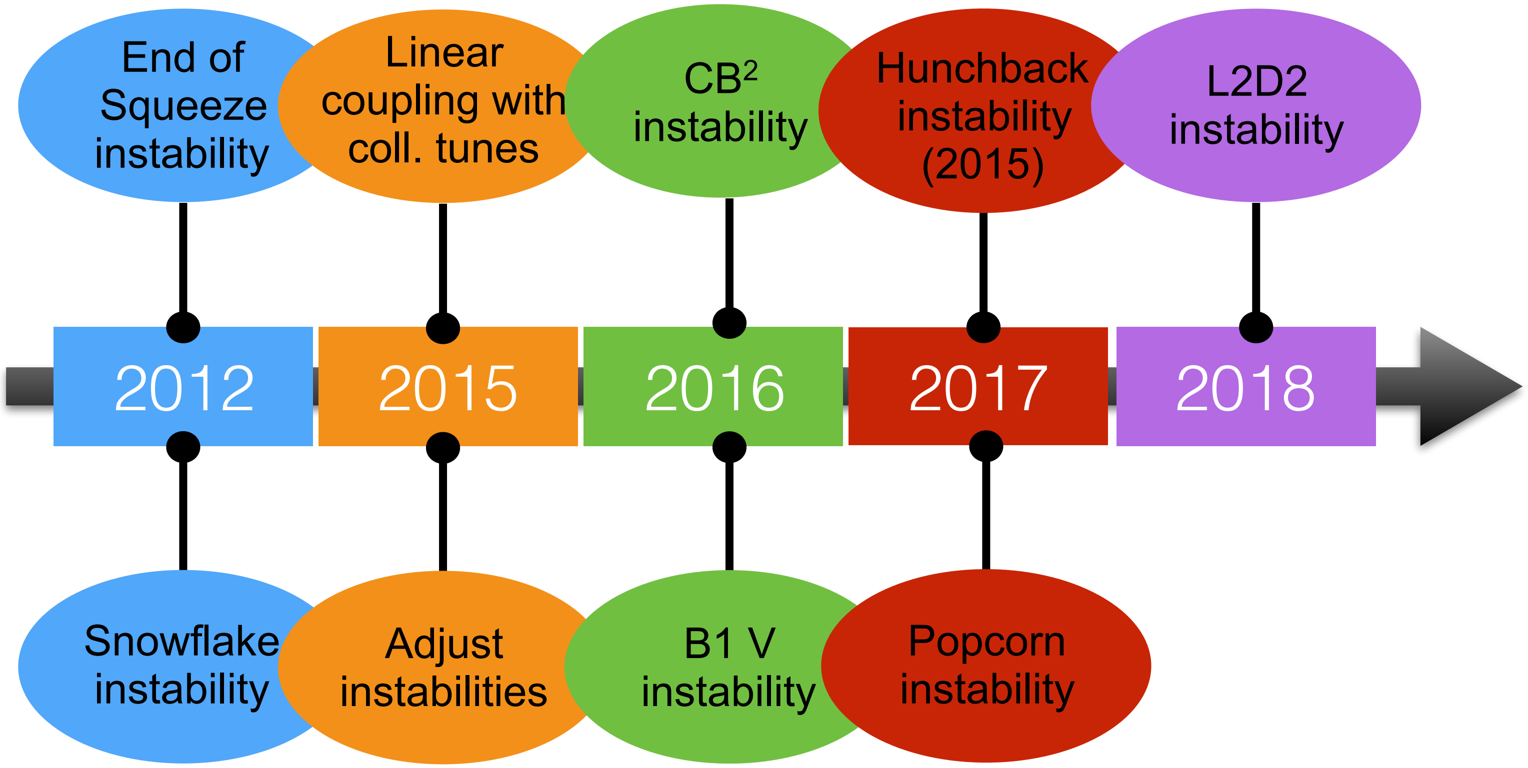
L2D2 instability



- A factor 2 in the tune spread provided by Landau octupoles is required to stabilize the beams during operations ➞ **good understanding of the mechanisms is still needed**
- The tune spread provided by the octupole is limited by the beam brightness

LANDAU DAMPING AND INSTABILITIES IN THE LHC

Models predict stability margins but coherent instabilities present in the LHC during Physics runs

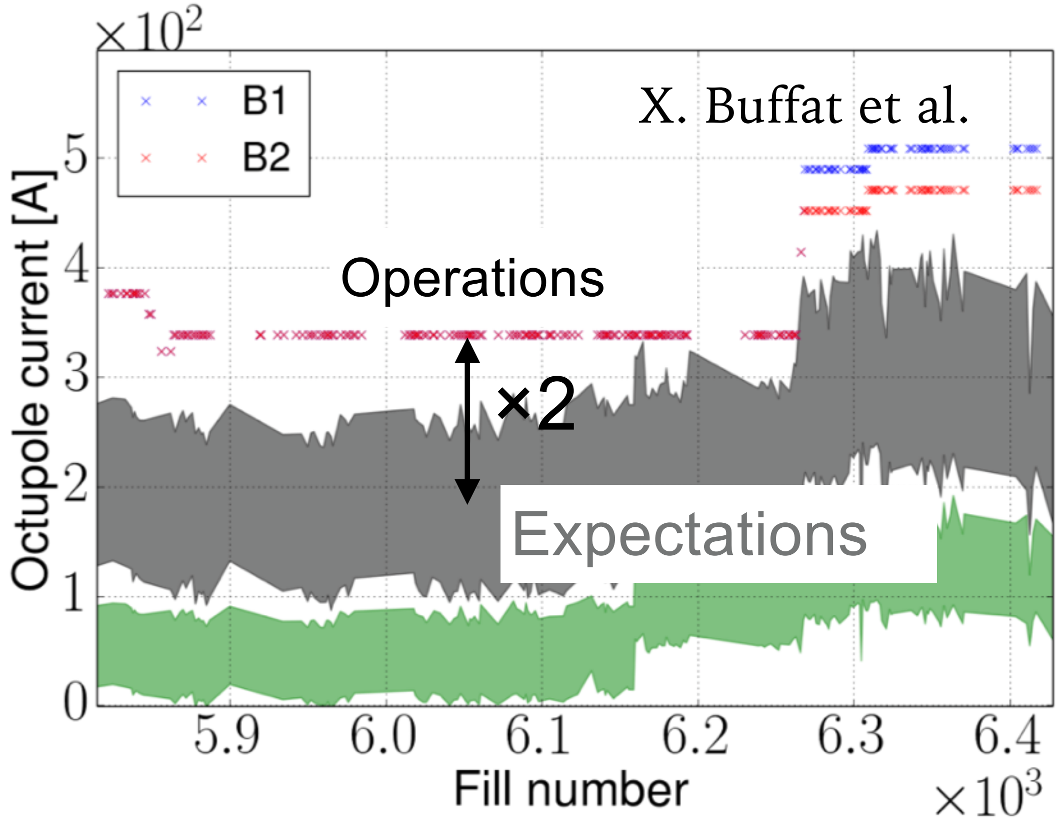

2012: End of Squeeze instability; Snowflake instability

2015: Linear coupling with coll. tunes; Adjust instabilities

2016: CB^2 instability; B1 V instability

2017: Hunchback instability (2015); Popcorn instability

2018: L2D2 instability



- A factor 2 in the tune spread provided by Landau octupoles is required to stabilize the beams during operations ➞ **good understanding of the mechanisms is still needed**
- The tune spread provided by the octupole is limited by the beam brightness

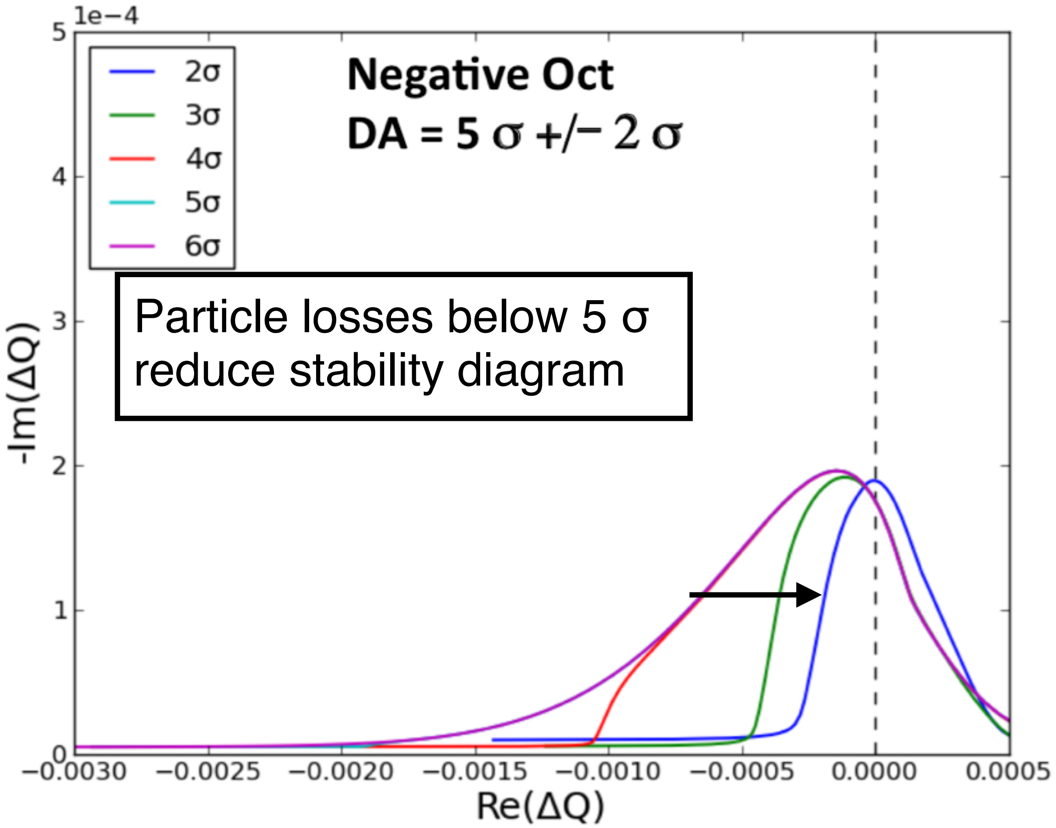
The understanding of the limitations of the models is fundamental in the perspective of future projects that aims to double LHC beam intensities (HL-LHC)

➞ EXTENSION OF MODELS AND BENCHMARK WITH EXPERIMENTAL DATA

IMPACT OF PARTICLE DISTRIBUTION ON BEAM STABILITY

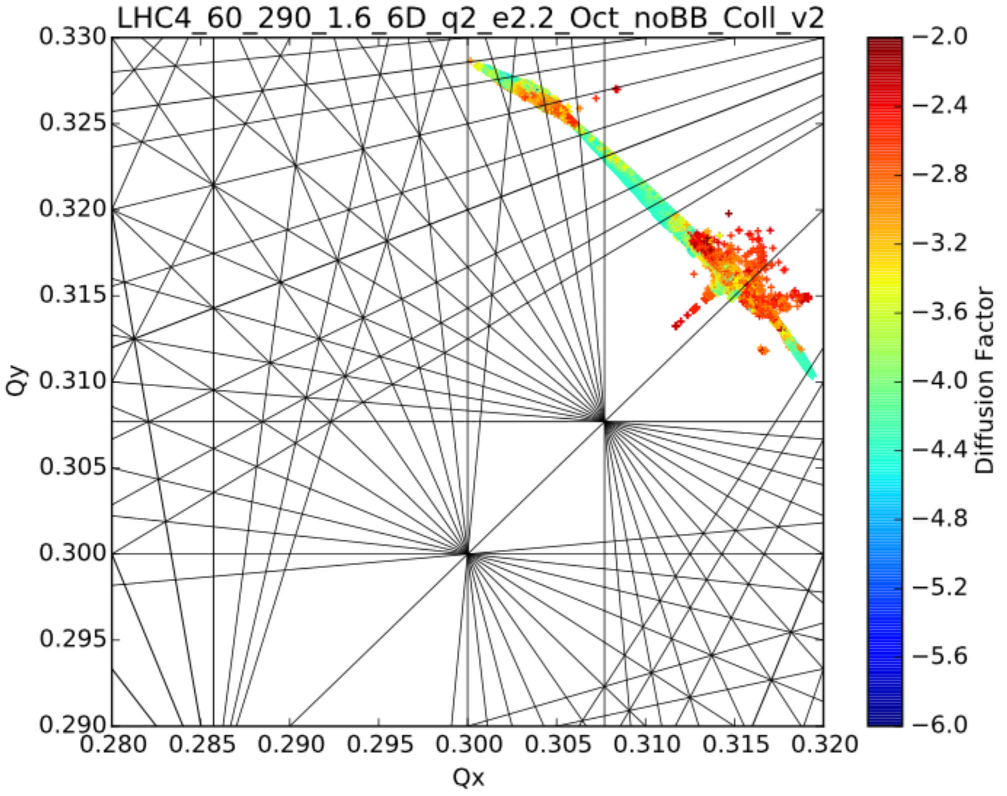
In presence of diffusive mechanisms the particle distribution changes

$$\frac{d\Psi_{x,y}(J_x,J_y)}{dJ_{x,y}}$$



Negative Oct
DA = 5 σ +/− 2 σ

Particle losses below 5 σ reduce stability diagram



- Beam beam long range interactions excite resonances
- Particles are trapped on the resonances and the frequency particle distribution is changing

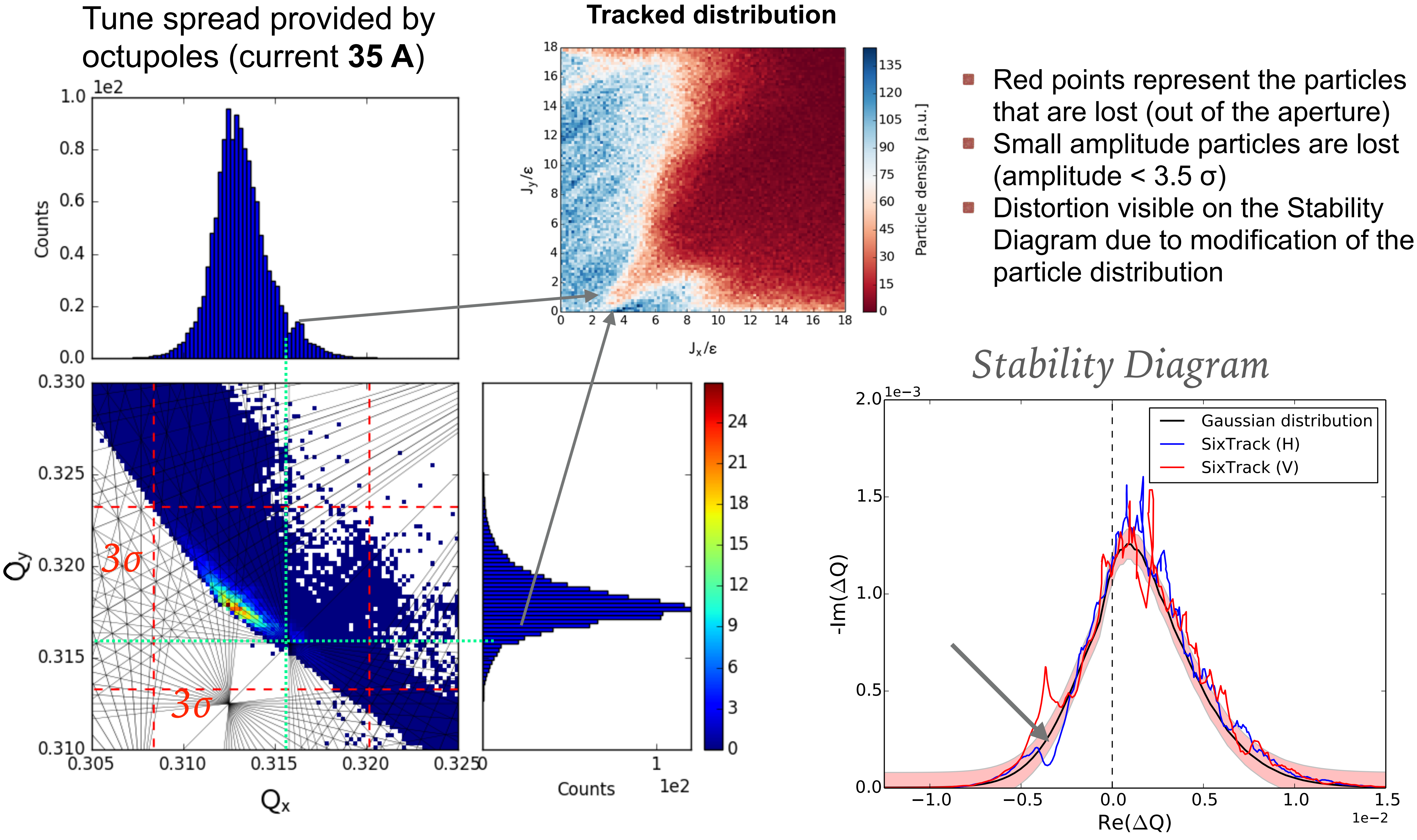
EXTENSION OF MODELS:

Characterize the impact of realistic lattice on particle distribution for the computation of Landau damping → done for the first time!

IMPACT OF PARTICLE DISTRIBUTION ON BEAM STABILITY

Tune spread provided by octupoles (current **35 A**)

Tracked distribution



- Red points represent the particles that are lost (out of the aperture)
- Small amplitude particles are lost (amplitude < 3.5 σ)
- Distortion visible on the Stability Diagram due to modification of the particle distribution

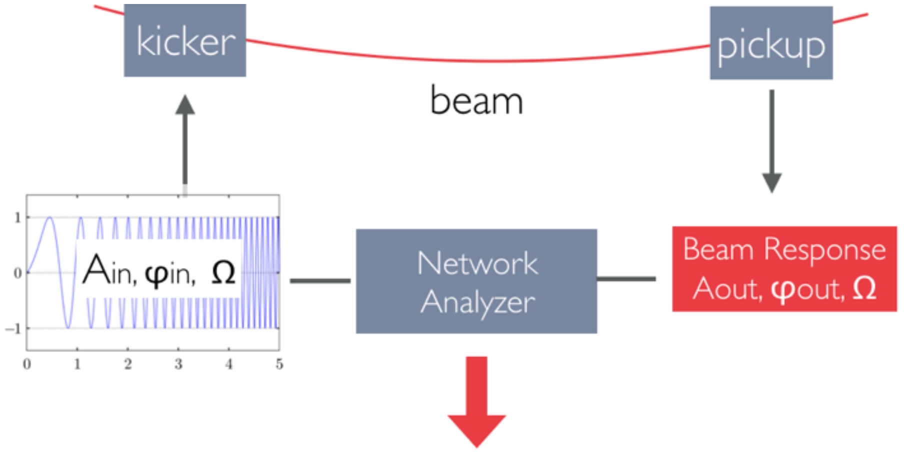
BEAM TRANSFER FUNCTION
TO MEASURE BEAM STABILITY

BENCHMARK WITH EXPERIMENTAL DATA :

Installation of Beam Transfer Function system in the LHC to quantify and measure beam stability

Beam **T**ransfer **F**unction measurements are direct measurements of the dispersion integral:

$$\mathrm{BTF} \propto \int_0^\infty \int_0^\infty \frac{J_{x,y} \frac{d\Psi_{x,y}(J_x,J_y)}{dJ_{x,y}}}{Q_0 - q_{x,y}(J_x,J_y) - i\epsilon} dJ_x dJ_y$$

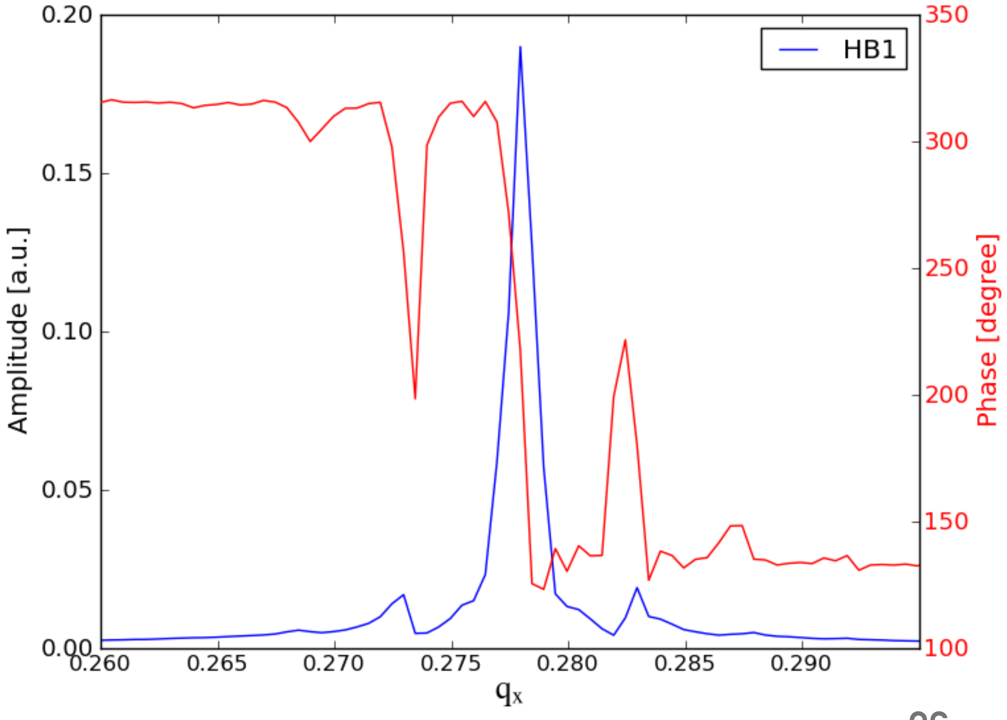


BTF: Amplitude (Ω), phase (Ω)

BTF can experimentally verify the stability

→ direct measurements of SD!

- Tune and chromaticity measurements
- Coherent mode observations
- **Sensitive to particle distribution changes**
- **Tune spread of the beams**



FITTING METHOD TO RECONSTRUCT STABILITY DIAGRAM FROM MEASUREMENTS

Uncalibrated system and difficulty to reconstruct stability diagrams from BTF measurements

→ Solution: develop a fitting method that allows quantitative comparisons of measurements with expectations

BTF (complex response) → **Amplitude (Q)**

BTF (complex response) → **Phase (Q)**

$SD \propto 1/BTF = A^{-1} e^{-i\varphi}$

Fitting method allows to compare measurements w.r.t. models (reference case, i.e. octupoles)

$$Q_{fit} = p_0 + p_1 \cdot (Q_{analyt} - Q_0)$$

$$A_{fit} = p_2 / p_1 \cdot A_{analyt}$$

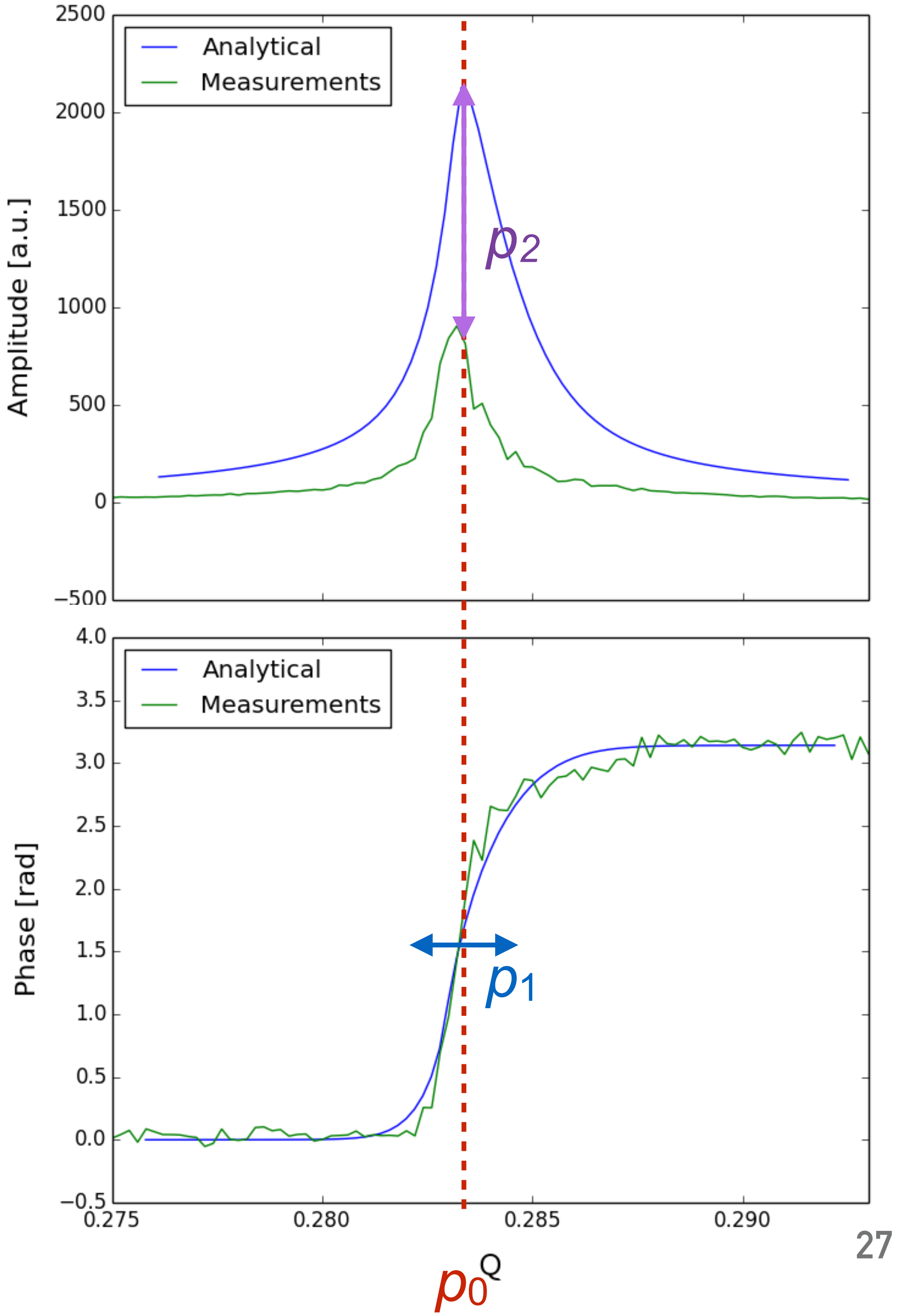
p_0 = Tune

p_1 = Tune spread factor w.r.t. a reference case

independent from calibration factor, (phase slope)

p_2 = Amplitude factor:

calibration, proportionality constant

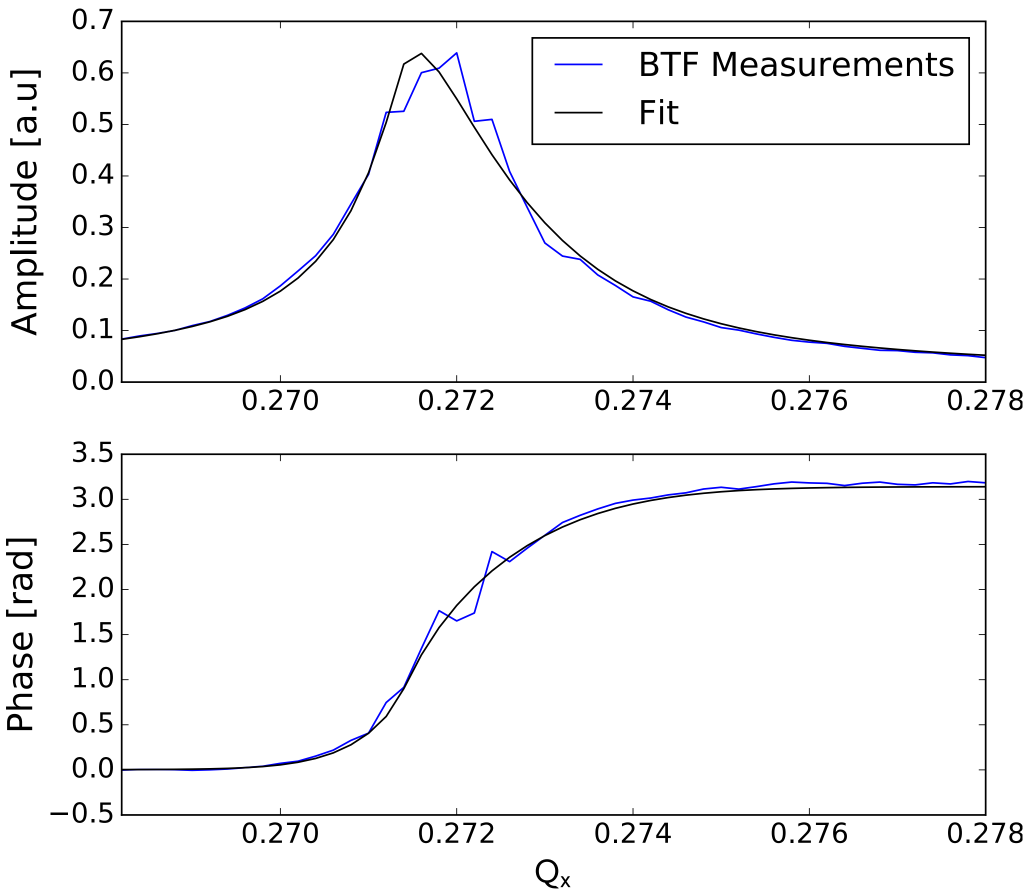


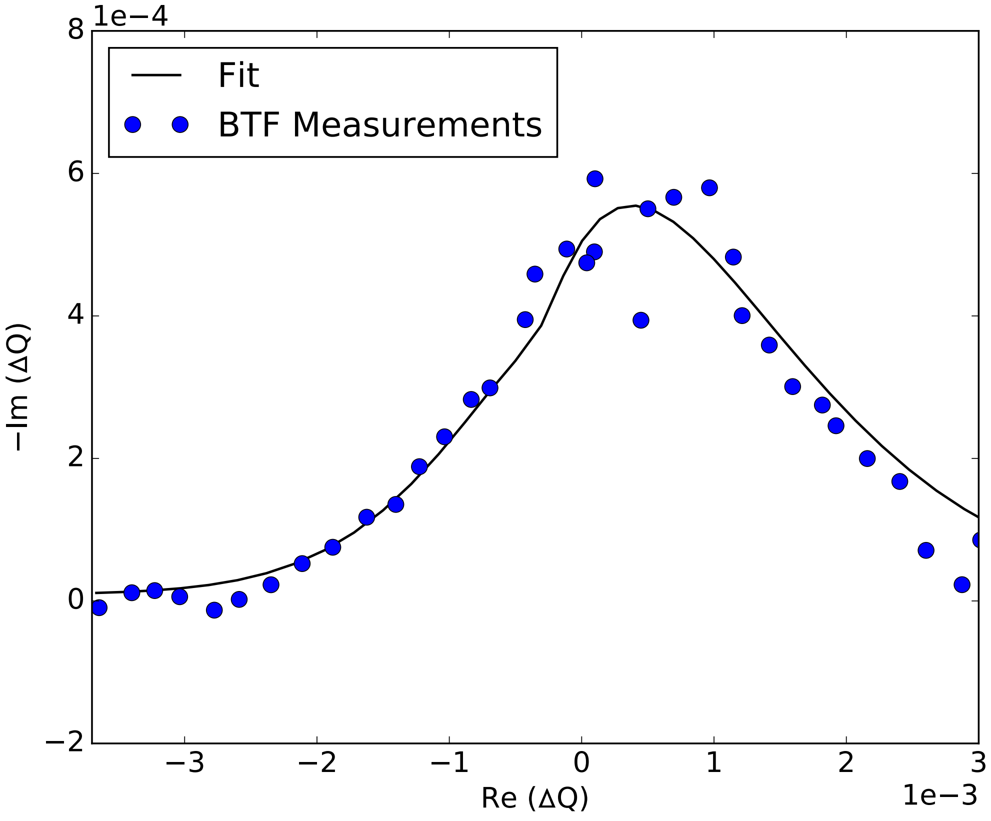
MEASUREMENTS OF STABILITY DIAGRAMS

RECONSTRUCTION OF STABILITY DIAGRAM FROM BTF MEASUREMENTS

$$Q_{fit} = p_0 + p_1 \cdot (Q_{analyt} - Q_0)$$

$$A_{fit} = p_2 / p_1 \cdot A_{analyt}$$



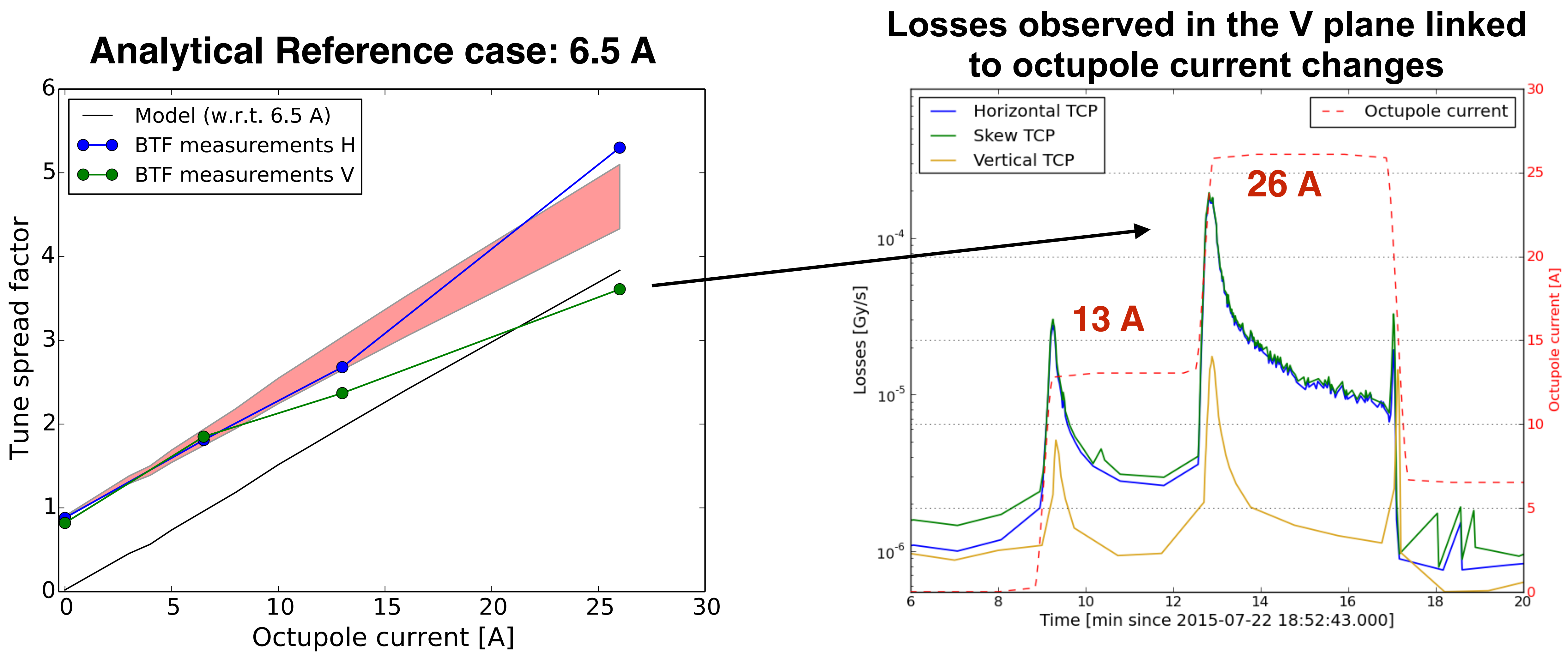


Stability diagrams have been measured for the first time in the LHC by using BTFs

Tune spread p_1=1.71

(10 A octupole current@injection energy)

MEASURED TUNE SPREAD AND EFFECT OF PARTICLE LOSSES

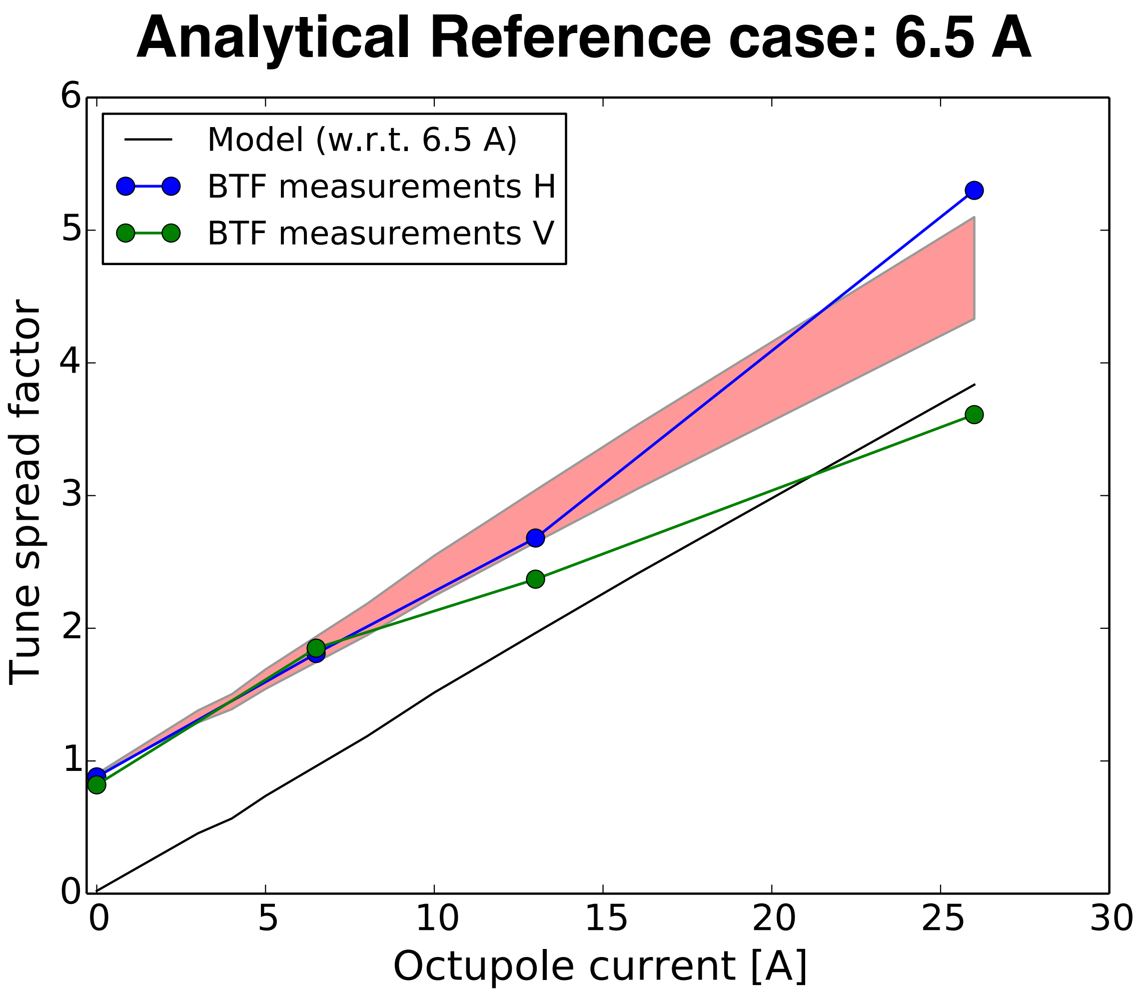


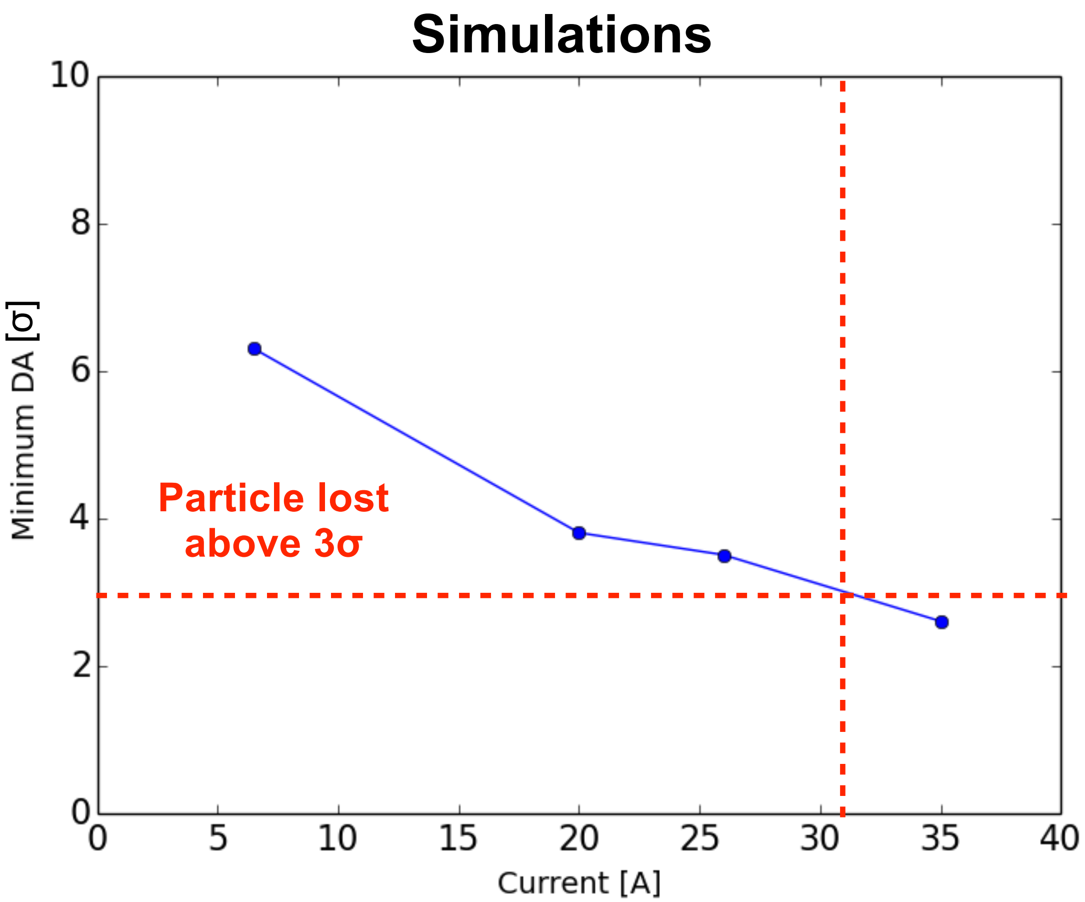
Analytical Reference case: 6.5 A

Losses observed in the V plane linked to octupole current changes

- **Fitting method to compare measurements and expectations (tune spread factor)**
- Case with no octupoles: consistent with optics measurements in 2015 of spread from magnet non-linearities (equivalent to 5 A octupole spread)
- Linear trend reproduced

MEASURED TUNE SPREAD AND EFFECT OF PARTICLE LOSSES



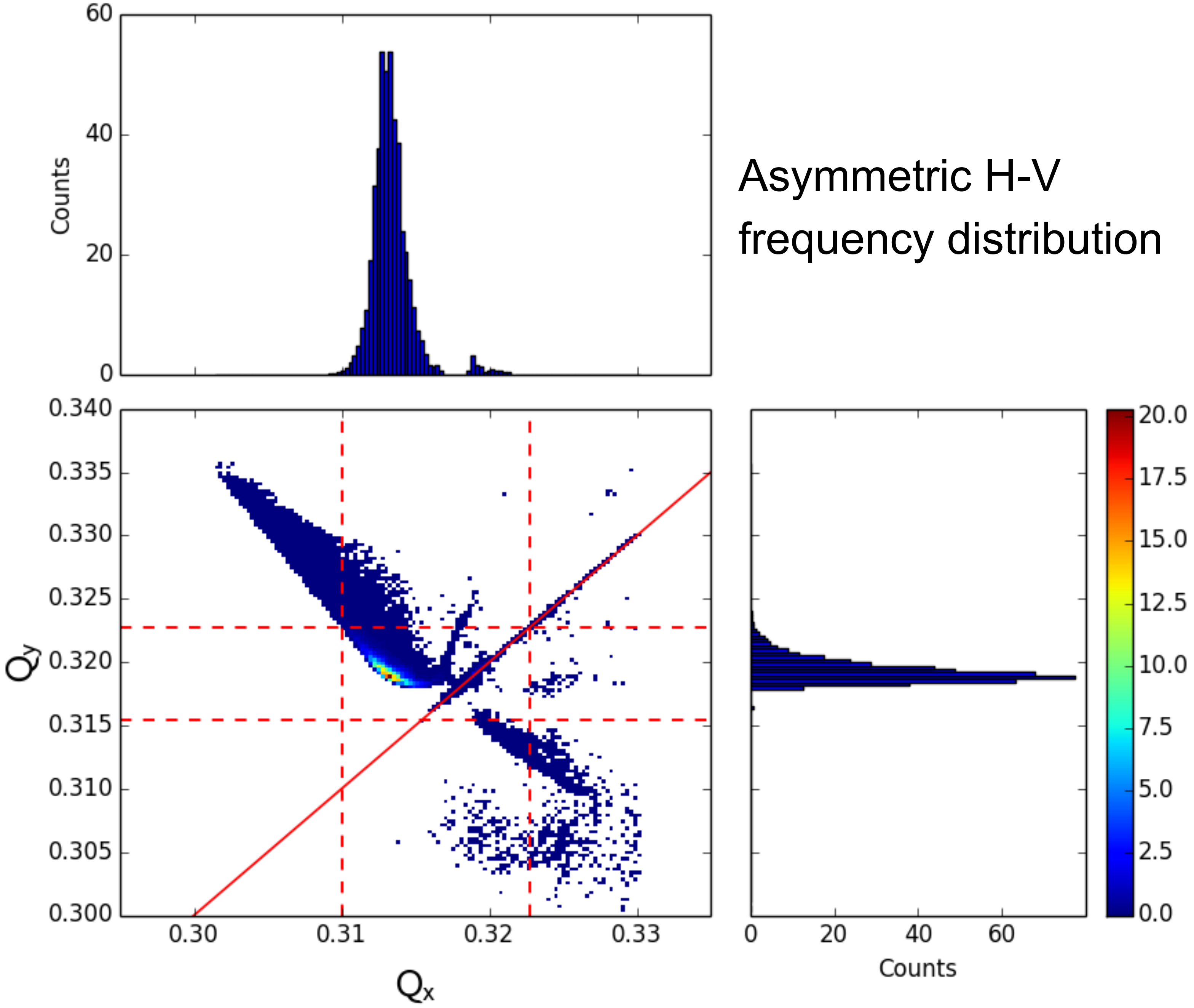


- According to simulations, **particles above 3 σ are lost considering the measured tune spread factor that corresponds to ~31 A** (= p_1 × ref. case)
- **Particle losses at 3 σ reduce Landau damping in the beams**

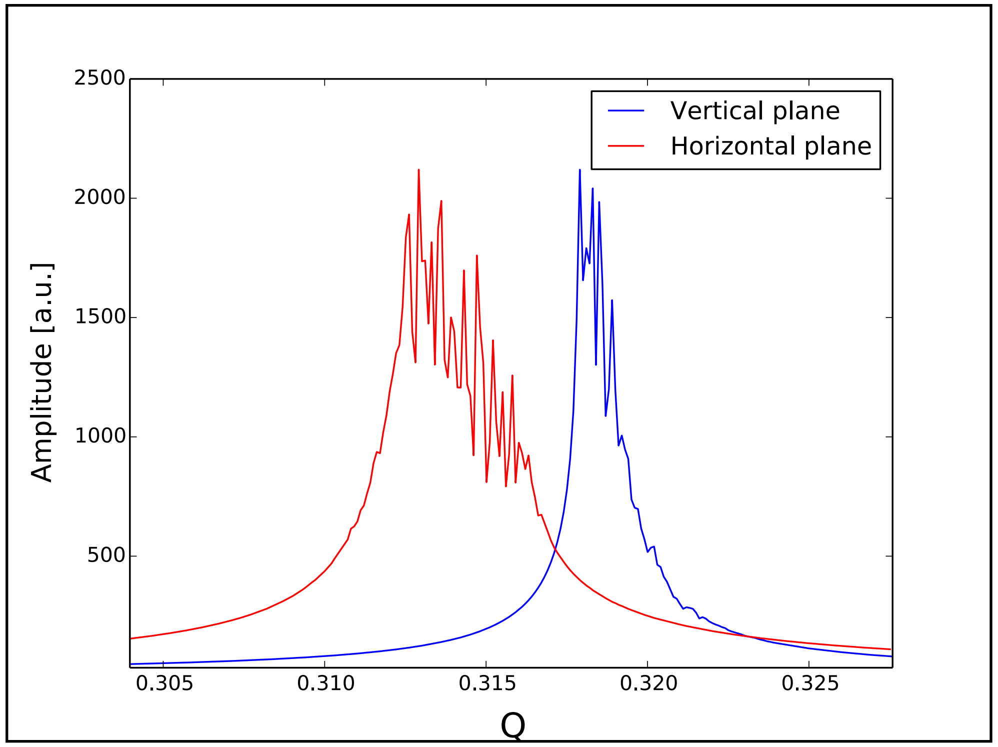
INCREASING THE TUNE SPREAD IS BENEFICIAL FOR LANDAU DAMPING AS LONG AS NO PARTICLE LOSSES ARE PRESENT (FIRST EXPERIMENTAL OBSERVATION)

EFFECT OF LINEAR COUPLING

Effect of **linear coupling**: coupled motion between H-V plane



Asymmetric H-V frequency distribution

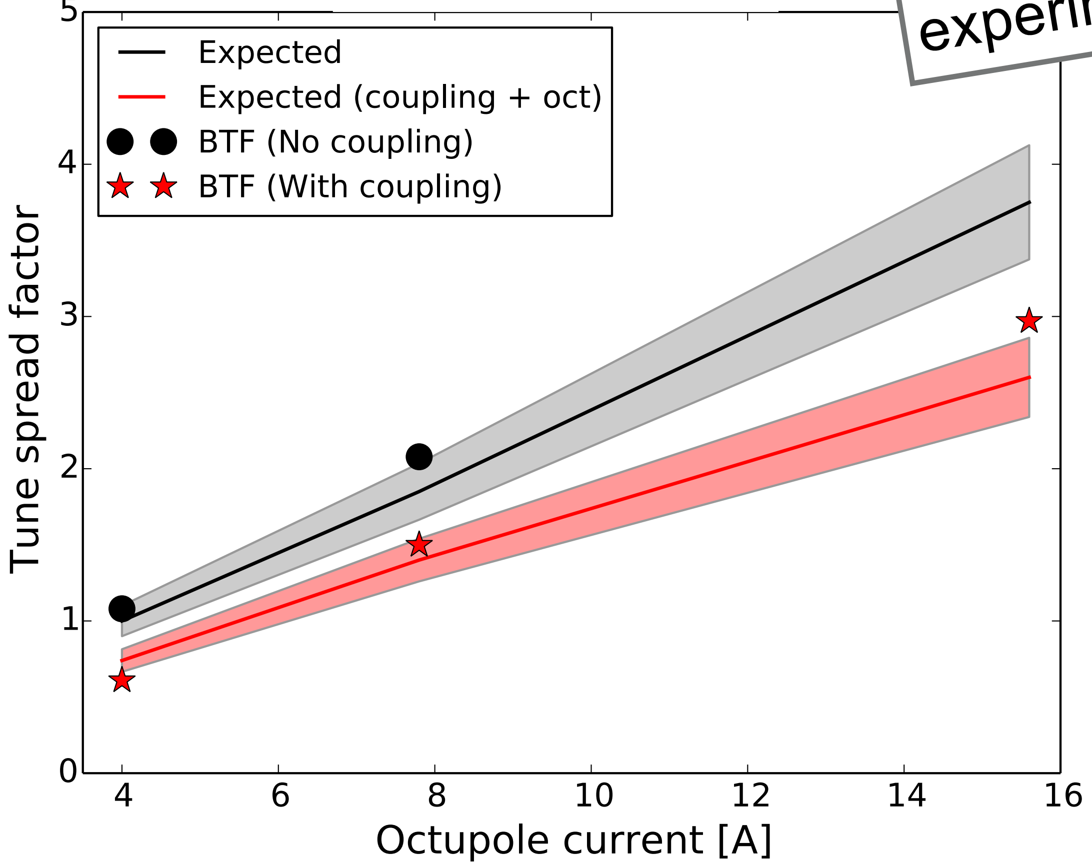


MEASURED EFFECTS OF LINEAR COUPLING ON STABILITY

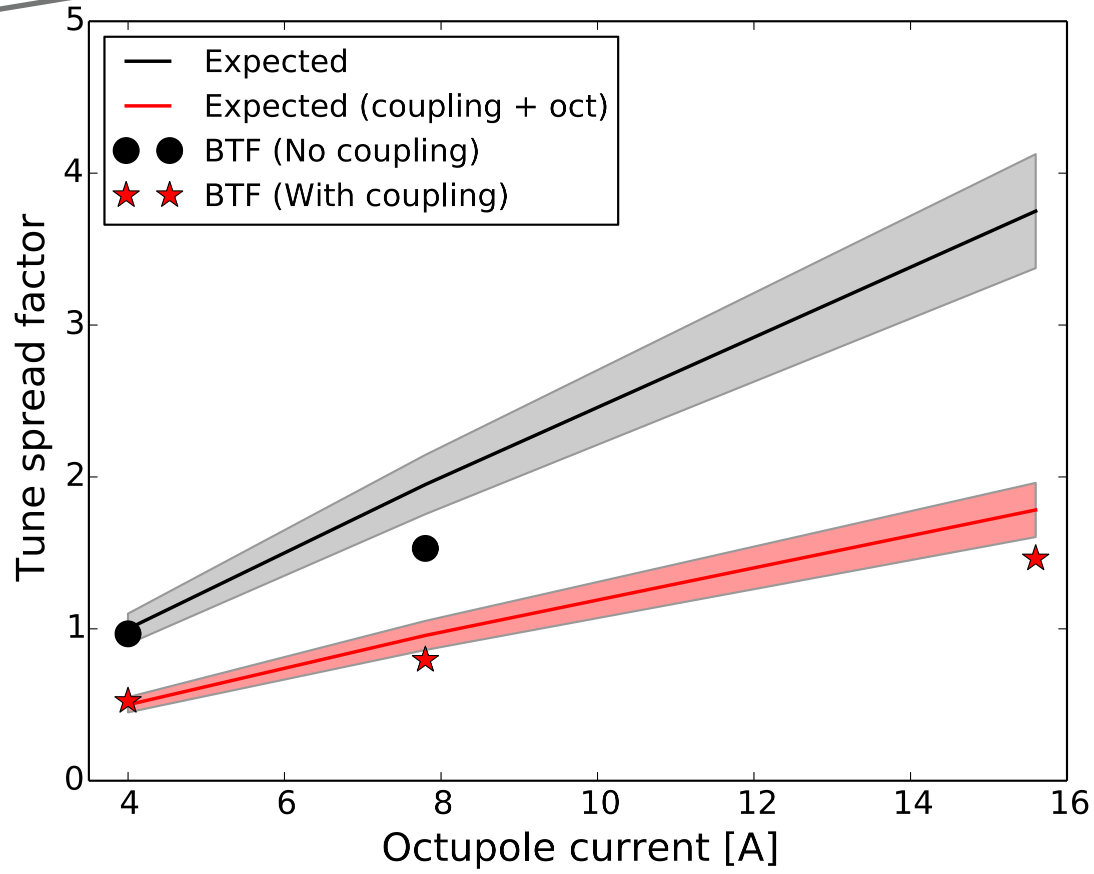
Fitting function method is applied to measure tune spread from BTFs (w.r.t to an analytical reference case of SD with 4 A octupole current)

More recent experimental results

Horizontal Plane



Vertical Plane

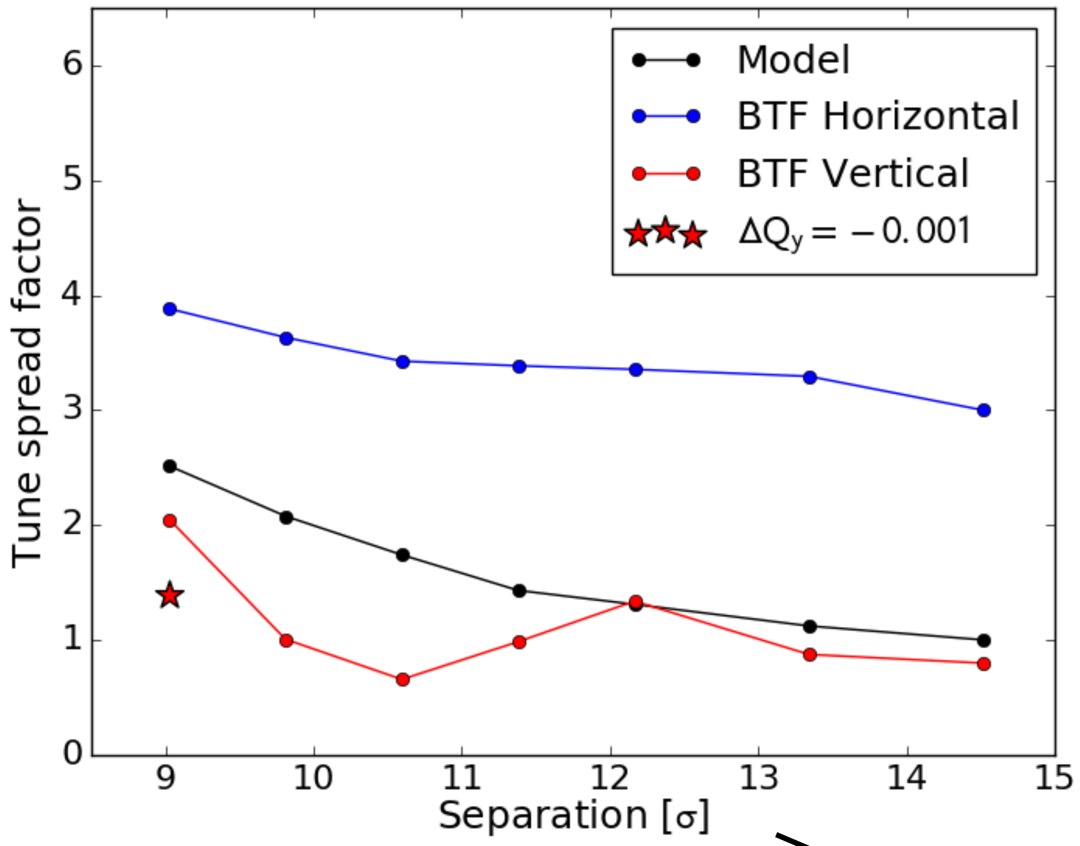


Quantitative comparison w.r.t expectations (with and without linear coupling)

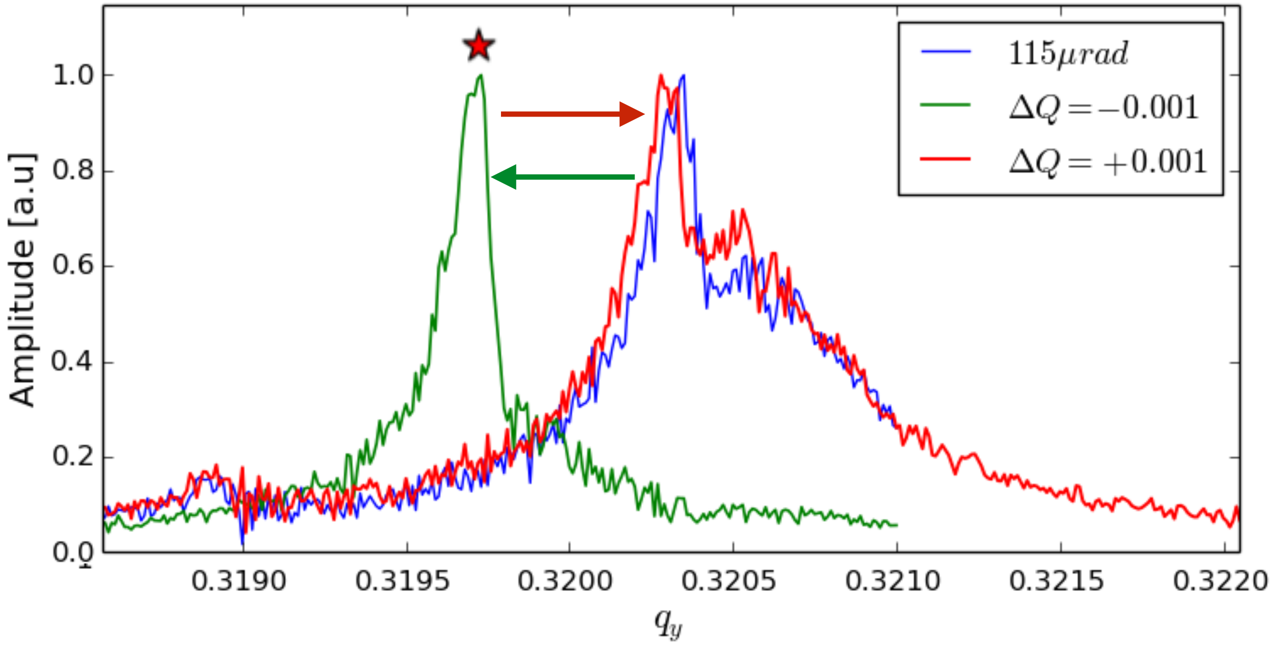
➔ BTF measurements agree well with expectations!

BEAM–BEAM INTERACTIONS AND LINEAR COUPLING

Measured beam-beam Long Range contribution on beam stability as a function of BB LR separation



BTF measurements during tune scan

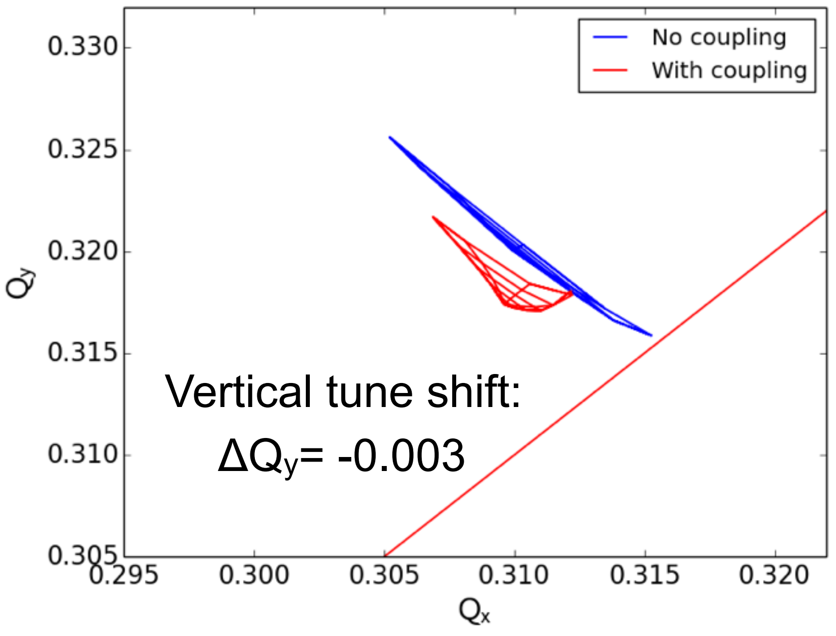


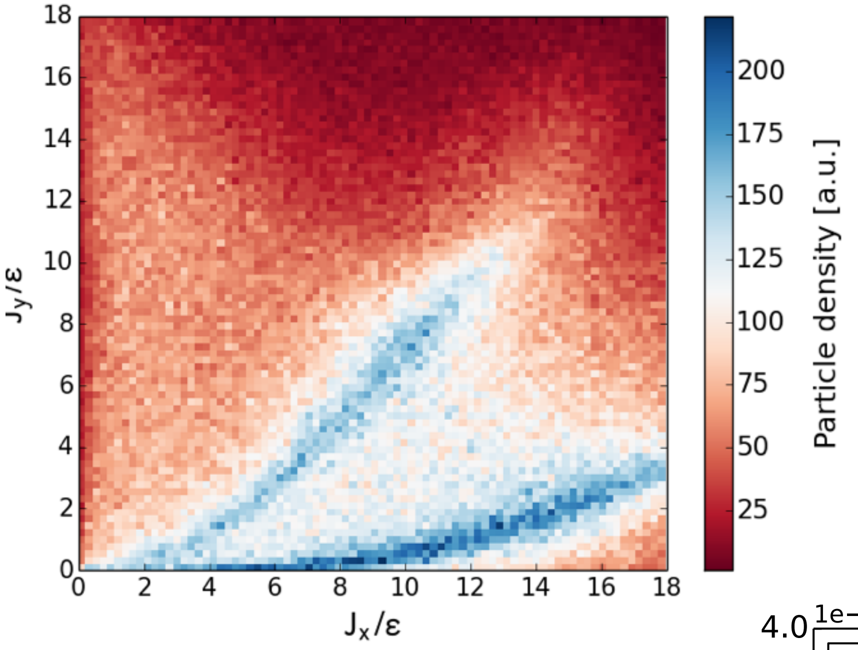
$$d_{sep} = \alpha \cdot \sqrt{\frac{\gamma \cdot \beta^*}{\epsilon}}$$

Crossing angle reduction at the IP
→ increase of BB long range effects

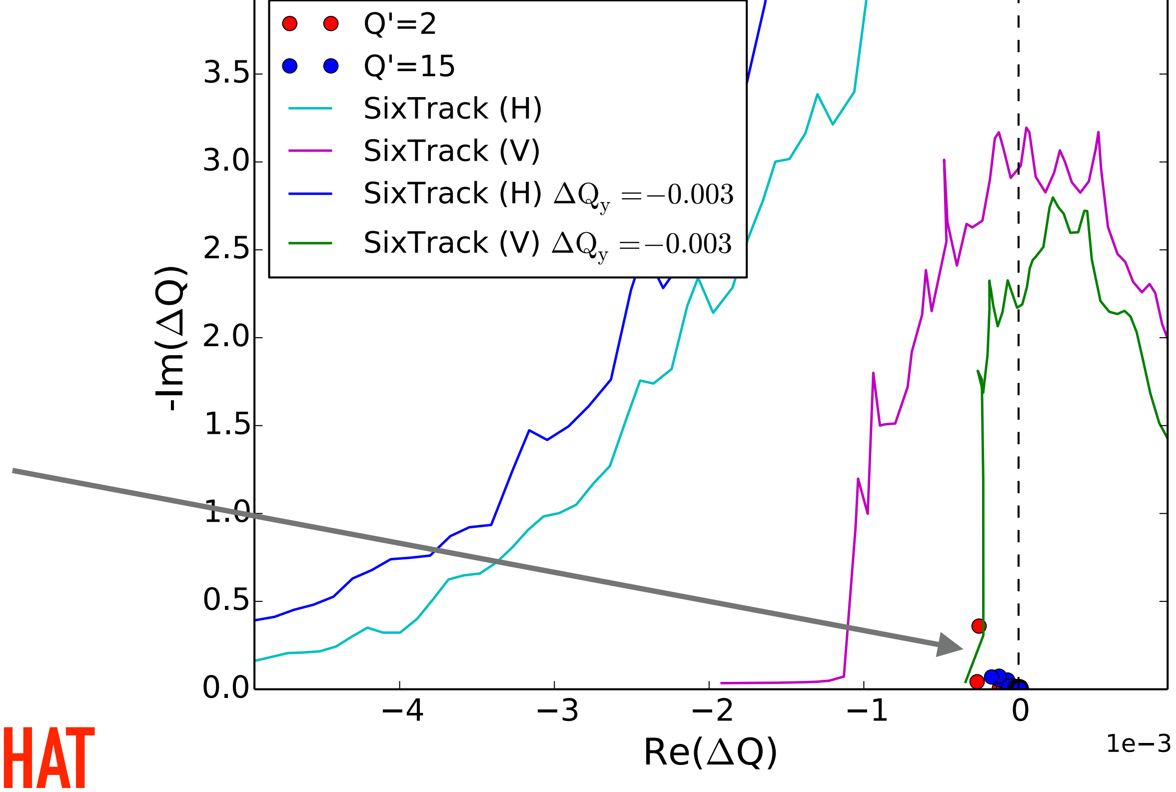
Change of tune has a strong impact on Landau damping indicating that other mechanisms may play a role → **linear coupling**

BTF IN THE PRESENCE OF BEAM-BEAM INTERACTIONS AND LINEAR COUPLING





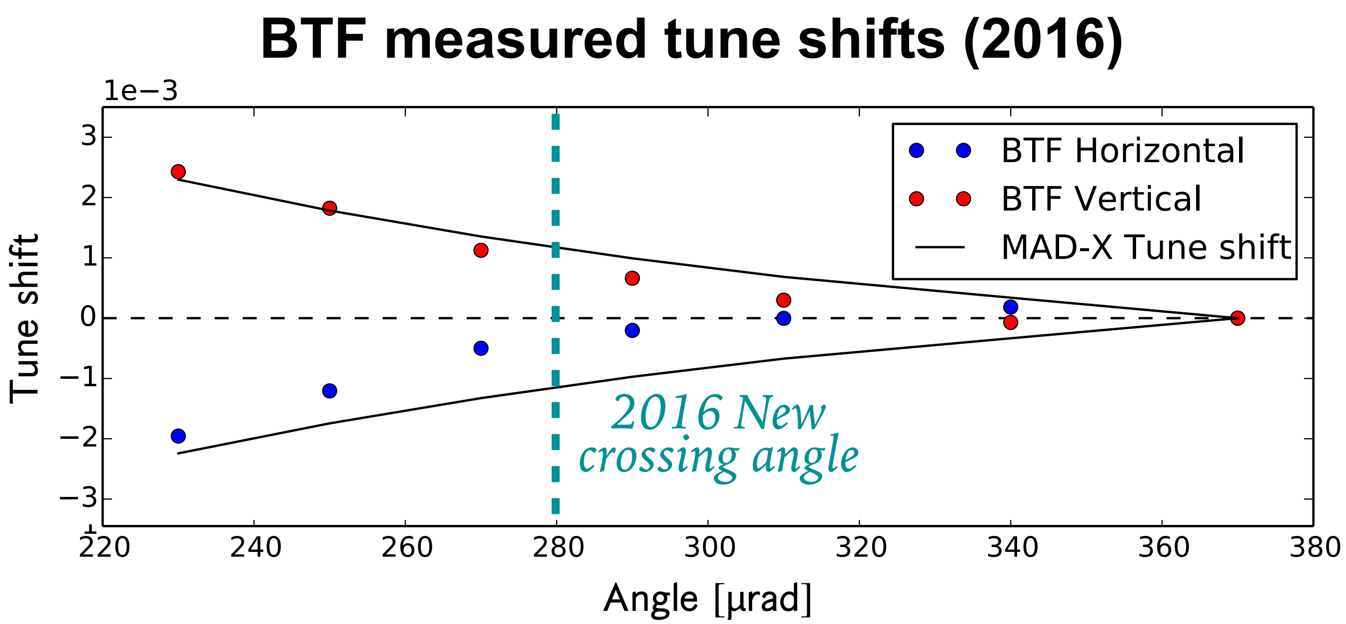
Stability Diagram (tracked distribution)



- Strong dependency on tune value
- Sharp cut visible in the vertical SD (0 - 3 σ particles approach the diagonal)
- Modes can become unstable in the vertical plane

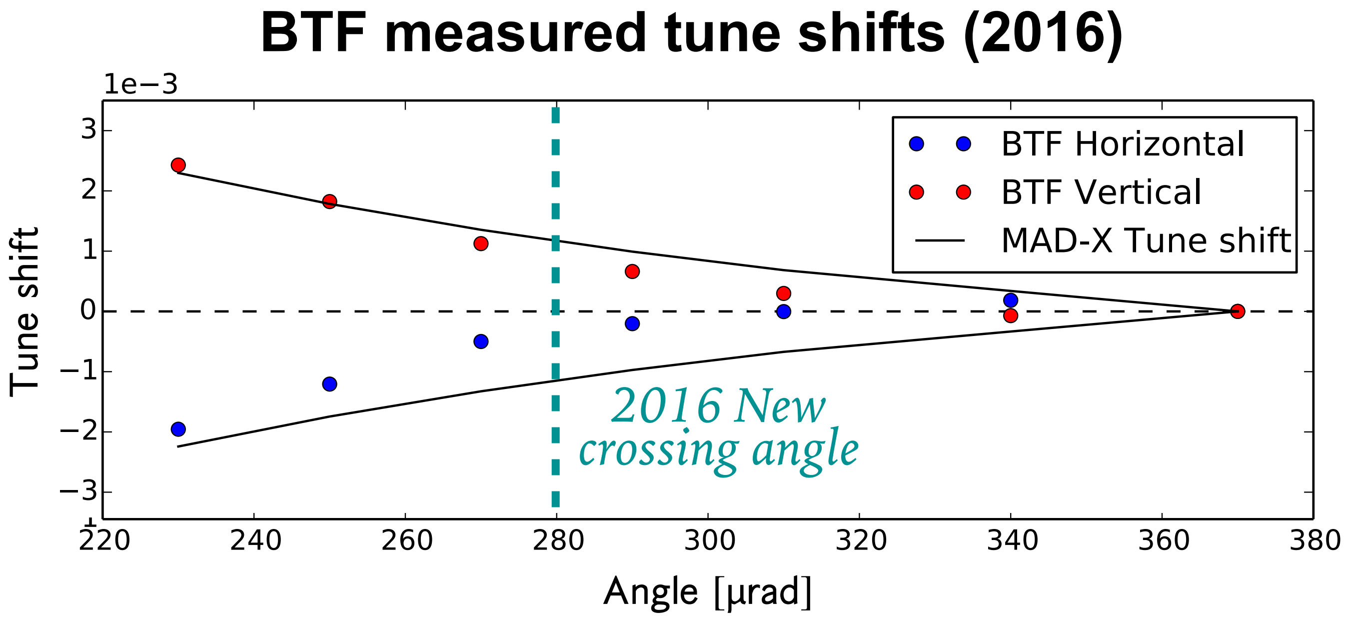
ASYMMETRIC H-V STABILITY DUE TO PARTICLE DISTRIBUTION MODIFICATIONS IN THE PRESENCE OF LINEAR COUPLING AND BEAM-BEAM INTERACTIONS THAT CAN EXPLAIN THE 2012 INSTABILITIES

BTF MEASUREMENTS WITH BEAM-BEAM INTERACTIONS

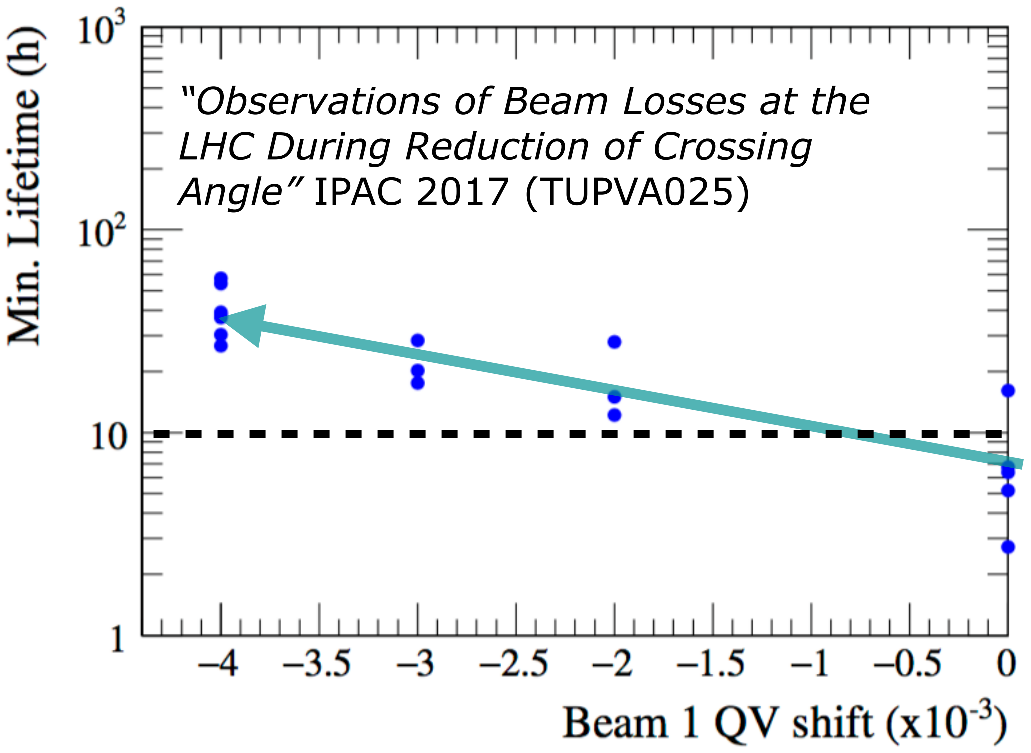


- Unexpected tune shifts were observed in the BTF response due to LR beam-beam effect
- The tunes at the LHC are only measured on the non-colliding beams: **not observed during regular operations**

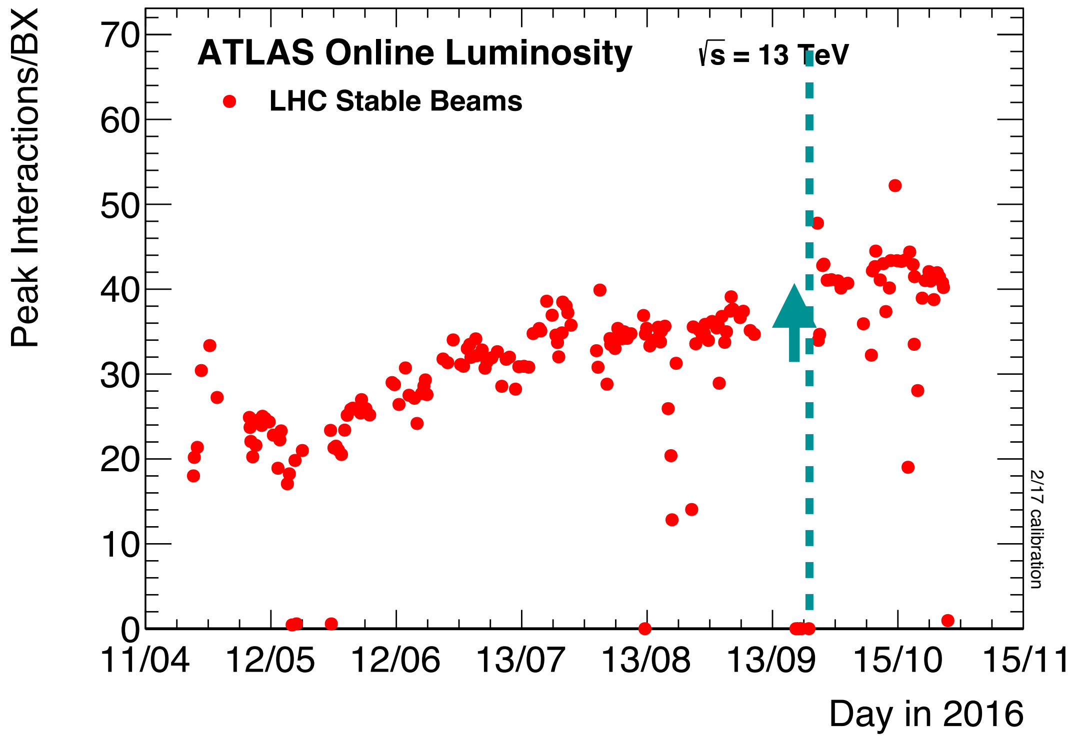
BTF MEASUREMENTS WITH BEAM-BEAM INTERACTIONS


BTF measured tune shifts (2016)

2016 New crossing angle

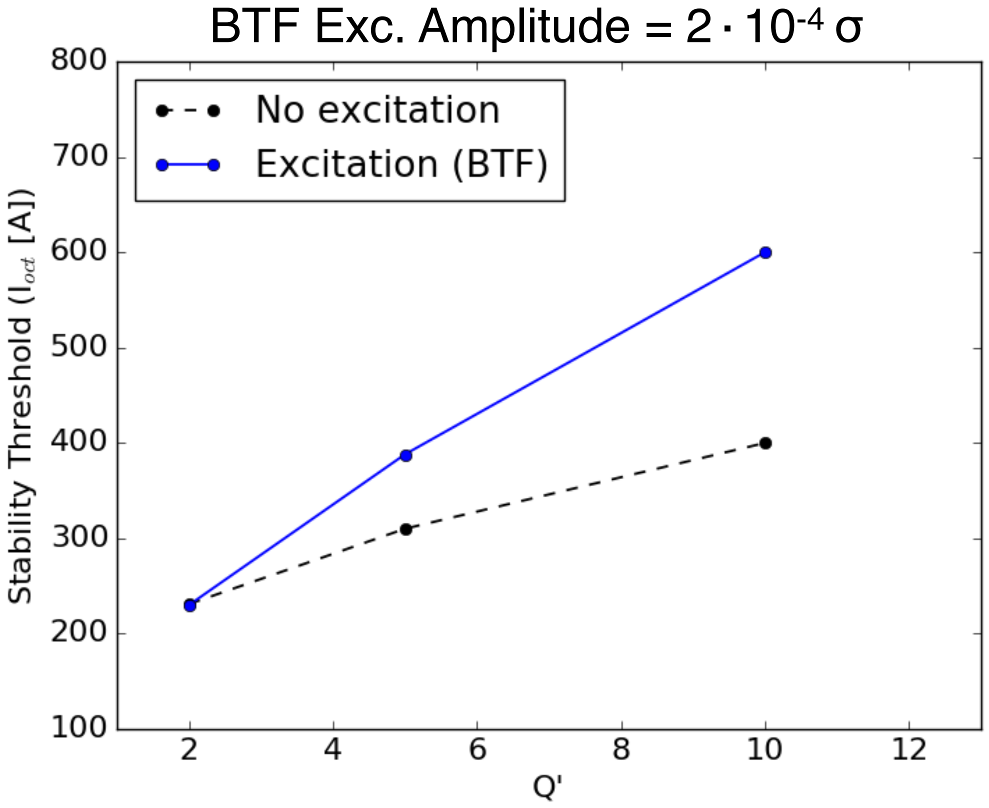

"Observations of Beam Losses at the LHC During Reduction of Crossing Angle" IPAC 2017 (TUPVA025)

- Unexpected tune shifts were observed in the BTF response due to LR beam-beam effect
- The tunes at the LHC are only measured on the non-colliding beams: **not observed during regular operations**



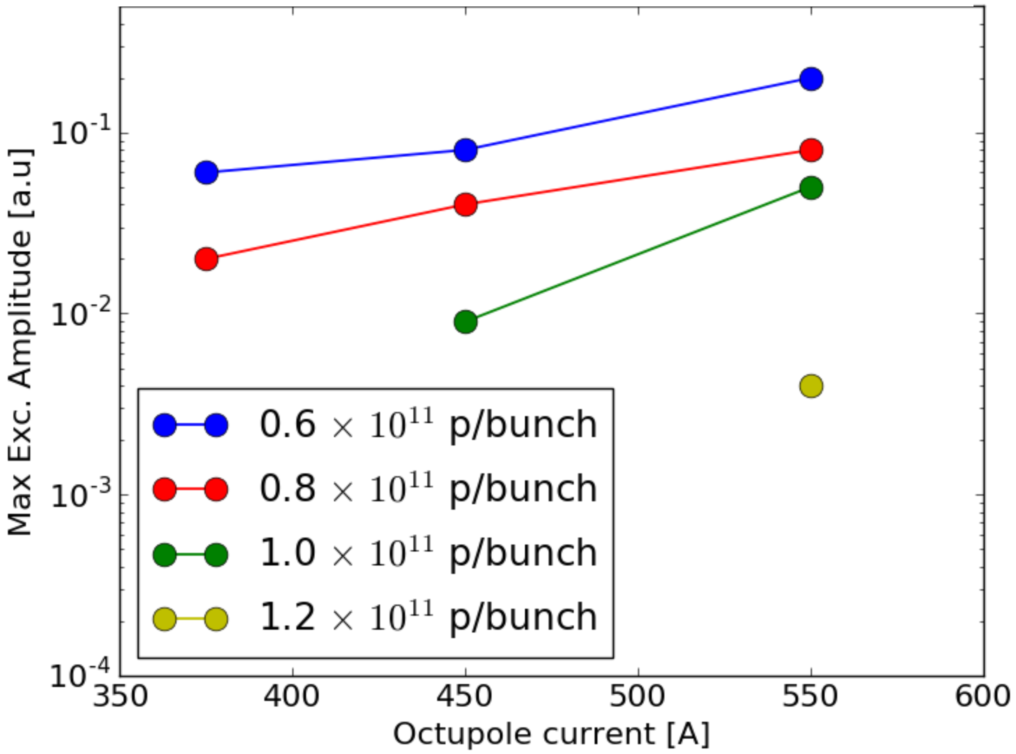
CORRECTION OF LONG-RANGE INDUCED TUNE SHIFT DURING OPERATIONS WITH DIRECT INCREASE OF BEAM LIFETIMES ➔ INCREASE OF 10% INTEGRATED LUMINOSITY

WHAT'S NEXT?



- A coherent instability linked to BTF excitation has been observed
- The instability was fully reproduced and it is linked to the increase of the impedance in 2017

Excitations at the stability limit



Higher octupole current required in the presence of external excitations (noise, small amplitude external excitation) ➔ could explain the need for higher octupole strength during LHC operation

Higher intensity bunches are more sensitive to external excitations (confirmed by recent measurements 2018)

RECENT MEASUREMENTS CONFIRMED THAT THE BEAMS ARE MUCH MORE SENSITIVE TO ANY EXTERNAL SOURCE OF NOISE OR EXCITATION IF IMPEDANCE EFFECTS ARE STRONGER

CONCLUSIONS

- **Extended models**: the particle distribution affects **Landau stability →** visible effects due to particle distributions after tracking in a realistic lattice configuration

- **First reconstruction of measured Stability Diagram in the LHC** by using BTF system

- **First tune spread measurements in the LHC** and comparison to expectations by using the fitting method → **measured effects of linear coupling in good agreement with expectations**

- It was **measured the impact of particle losses on beam stability**

- **Increase of beam lifetime and luminosity** (**10% increase in integrated luminosity**) by means of correction of Long-Range induced tune shifts measured by BTFs

- **Asymmetric Horizontal - Vertical beam stability** (observed by BTF measurements) reproduced in simulations in the presence of linear coupling and beam-beam interactions

- **Experimental studies are planned in the LHC** to measure the Landau damping of the beams including beam-beam interactions, Landau octupoles, transverse linear coupling and in the presence of noise.

Thank you for your attention!

Thank you for your attention!

Particle Accelerator Physics Laboratory (LPAP)

BE/Beam Instrumentation (BI) Group (CERN)

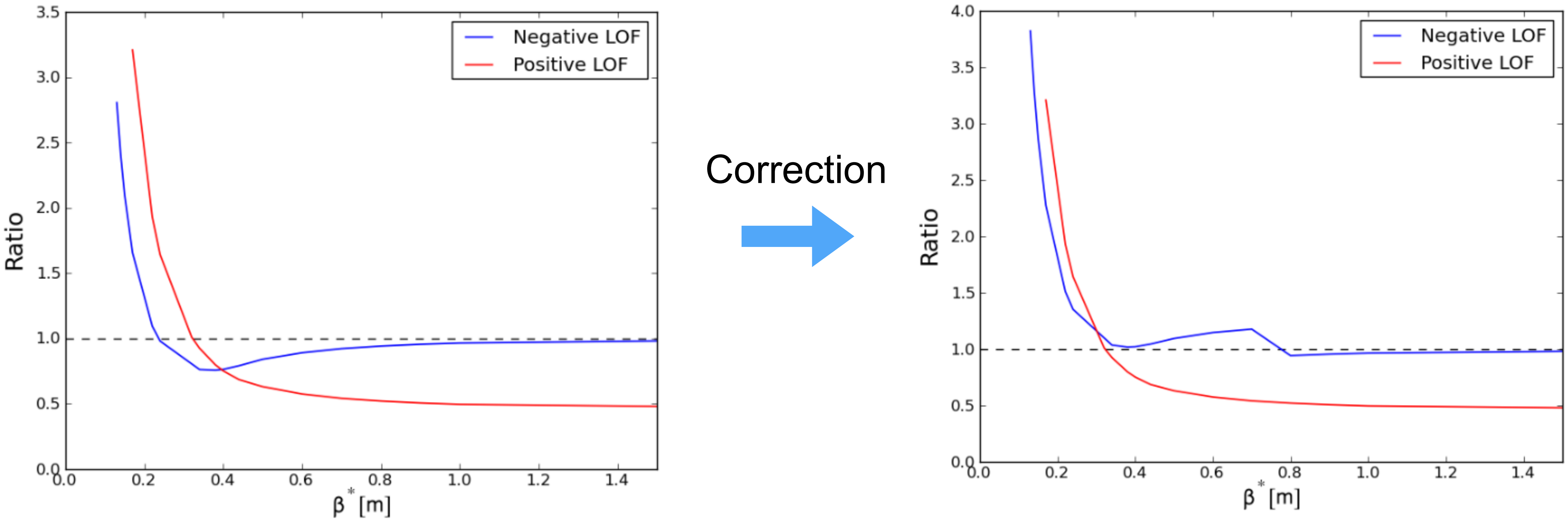
BE/ABP/Hadron Synchrotron Coherent (HSC) effects (CERN)

BE/Operation (OP) Group (CERN)

BACK UP

STABILITY STUDIES FOR HL-LHC

The beam stability during the full operational cycle **has been studied and maximized**



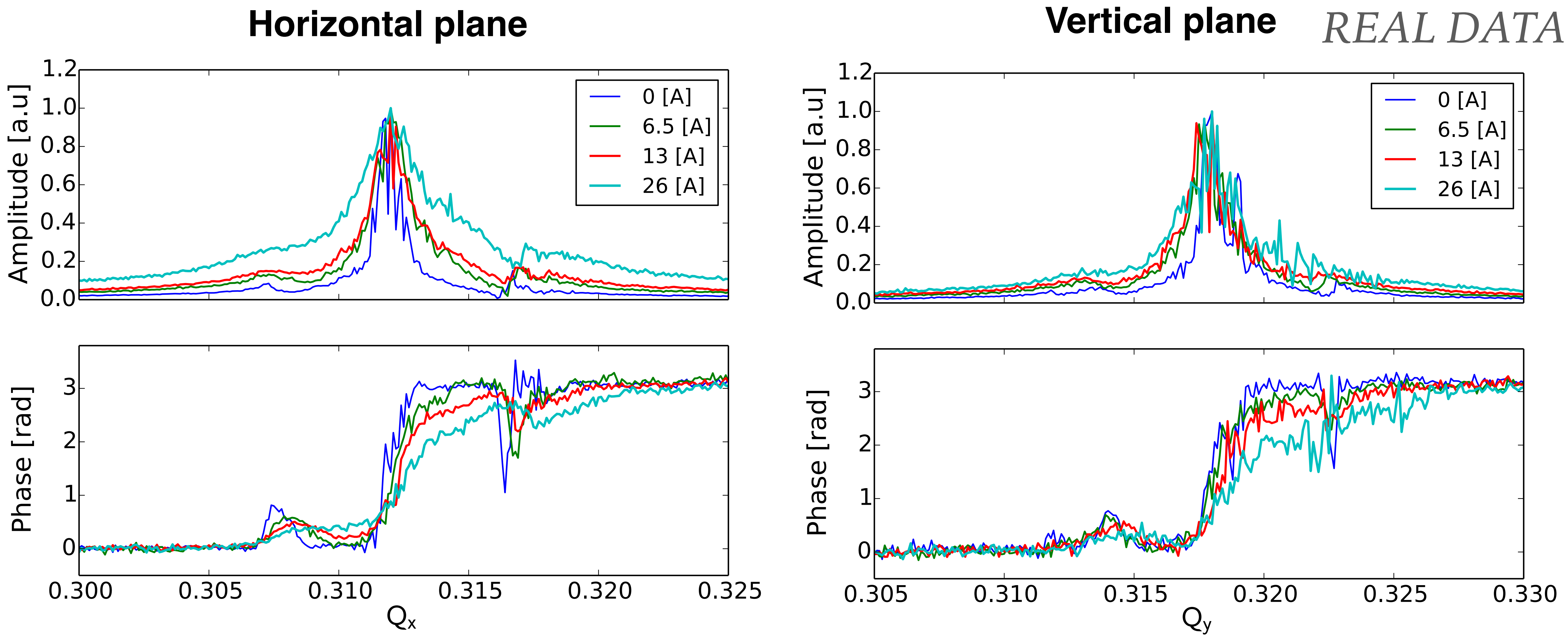
By applying a correction of the β - function (8%) in the arcs (octupole magnets) from β^*=70 cm the stability reduction is compensated and stability is maximized

RESULT: PROPOSED OPERATIONAL SCENARIO WITH MAXIMUM LANDAU STABILITY DURING OPERATIONS

→ ACCEPTED AS A BASELINE SCENARIO OF HL-LHC

BTF MEASUREMENTS WITH OCTUPOLE MAGNETS

Tune spread given by Landau octupoles and lattice non-linearities



Horizontal plane

Vertical plane

REAL DATA

For the largest octupole strength (26 A) larger spread measured in the horizontal plane than in the vertical plane

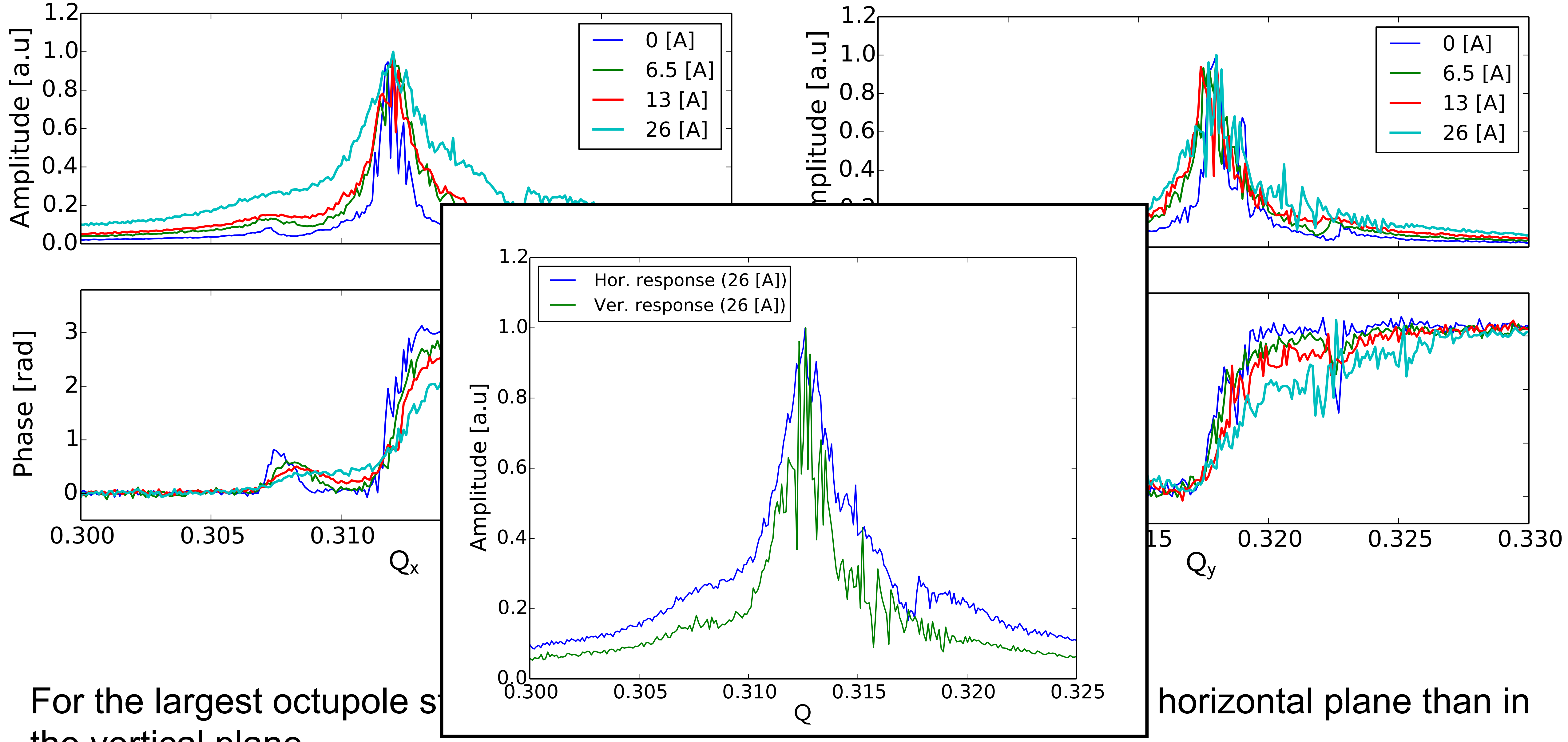
BTF MEASUREMENTS WITH OCTUPOLE MAGNETS

Tune spread given by Landau octupoles and lattice non-linearities

Horizontal plane

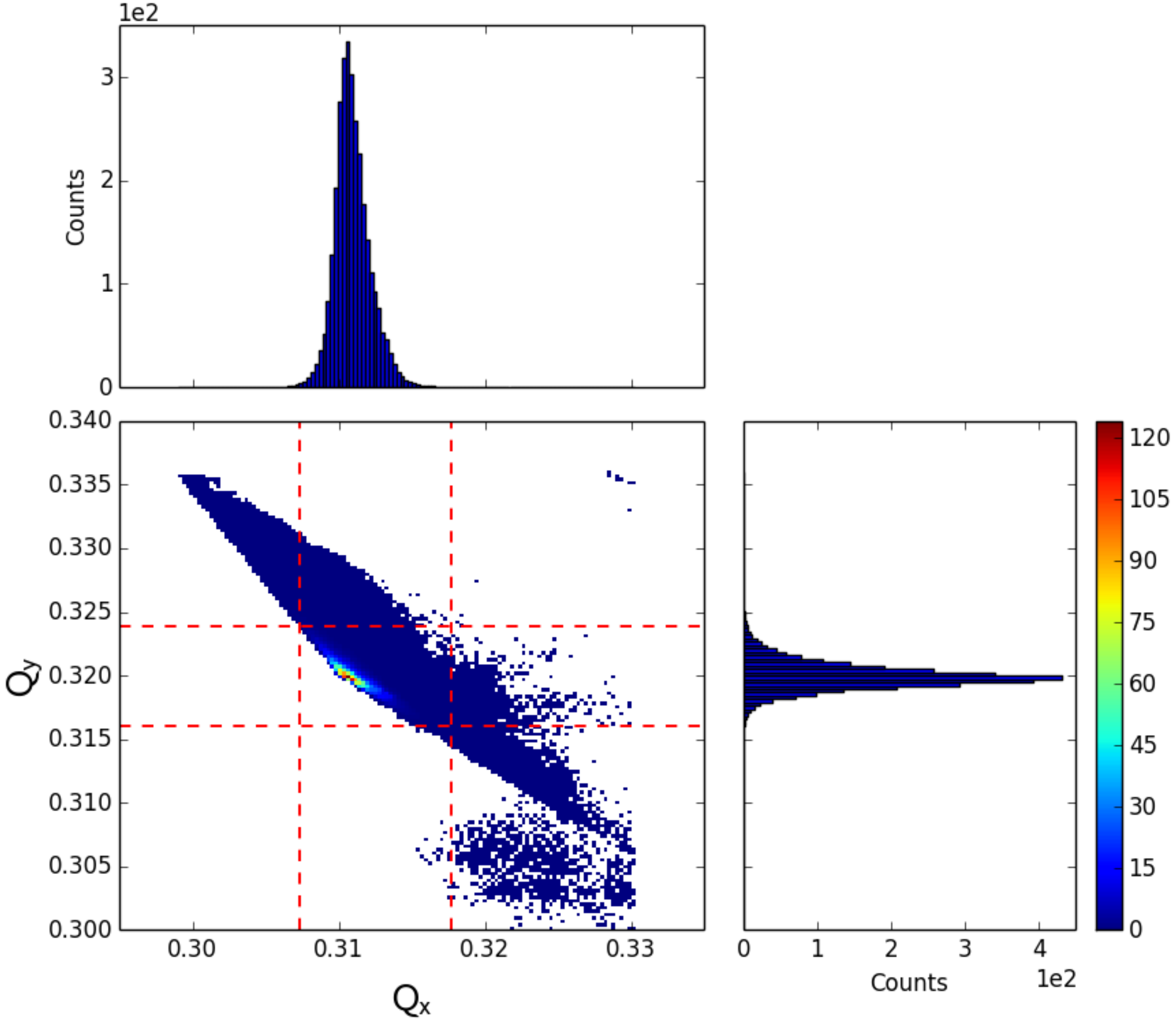
Vertical plane

REAL DATA



For the largest octupole s horizontal plane than in the vertical plane

BTF MEASUREMENTS WITH OCTUPOLE MAGNETS



No drastic change in the frequency distribution and it can not explain H-V asymmetry in the BTF amplitude