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Two beam stability and Landau damping

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Contents

- Introduction to Landau damping: computation of stability diagrams
- FCC-hh octupole magnets
- Landau damping at flat top and at the end of the betatron squeeze
- Possible solutions to increase beam stability (e-lens, larger β -function)
- Landau damping during the collapse of the separation bumps
- Future studies: noise impact on beam stability
- Summary

Computation of the stability diagram

Predictions of instability thresholds based on evaluation of the beam Landau damping by computing the [Stability Diagrams \(SD\)](#) [1]

$$SD^{-1} = \frac{-1}{\Delta Q_{x,y}} = \int_0^\infty \int_0^\infty \frac{J_{x,y} \frac{d\Psi_{x,y}(J_x, J_y)}{dJ_{x,y}}}{Q_0 - \underbrace{q_{x,y}(J_x, J_y)}_{\text{Detuning with amplitude}} - i\epsilon} dJ_x dJ_y$$

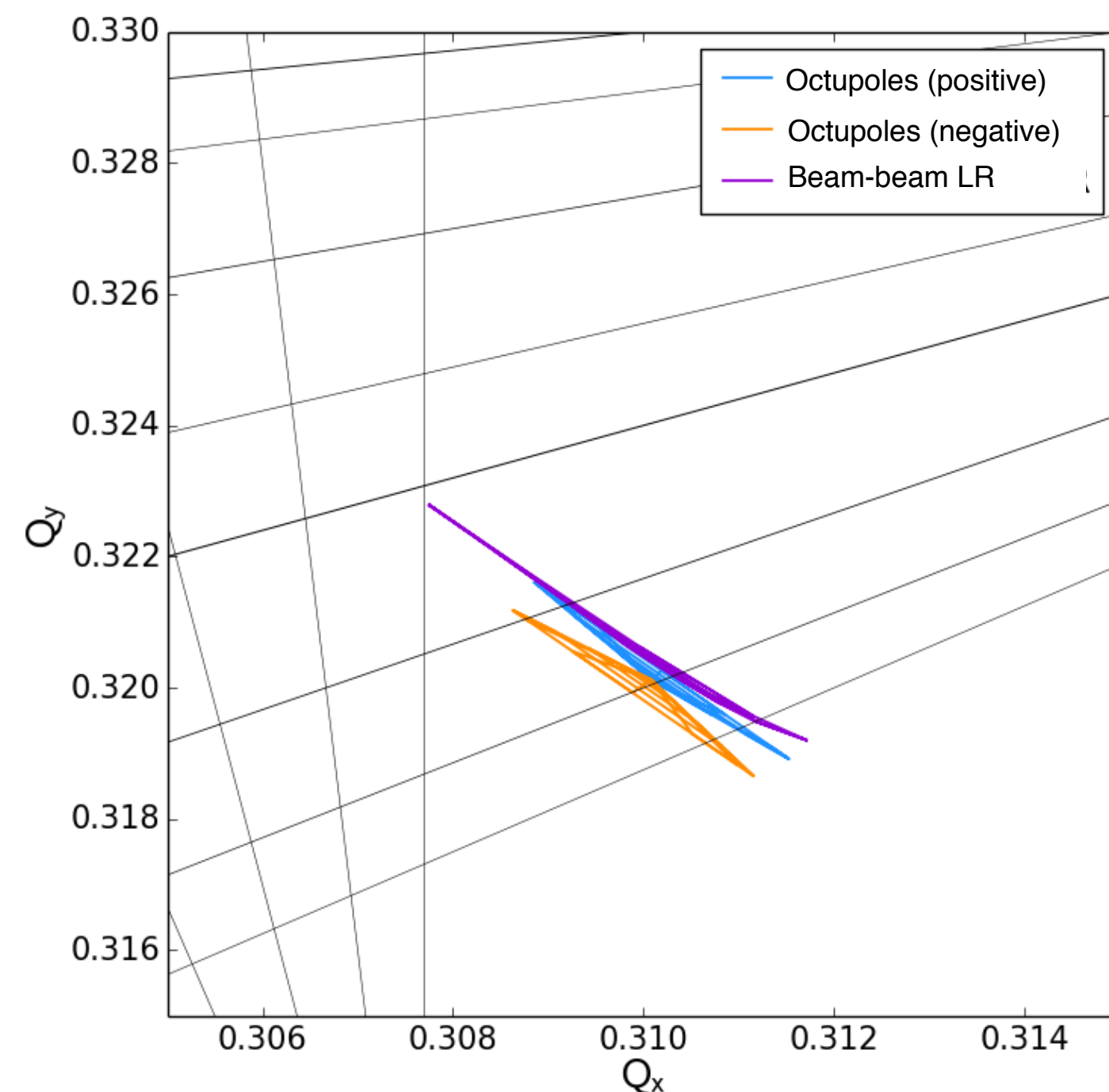
Detuning with amplitude
 (Octupoles magnets, e-lens, beam-beam
 interactions, machine non linearities)

[1] J. Berg and F. Ruggero, *Landau damping with two dimensional betatron tune spread*, CERN SL-AP-96-71 (1996)

Computation of the stability diagram

Predictions of instability thresholds based on evaluation of the beam Landau damping by computing the **Stability Diagrams (SD)** [1]

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



Detuning with amplitude
(Octupoles magnets, e-lens, beam-beam interactions, machine non linearities)

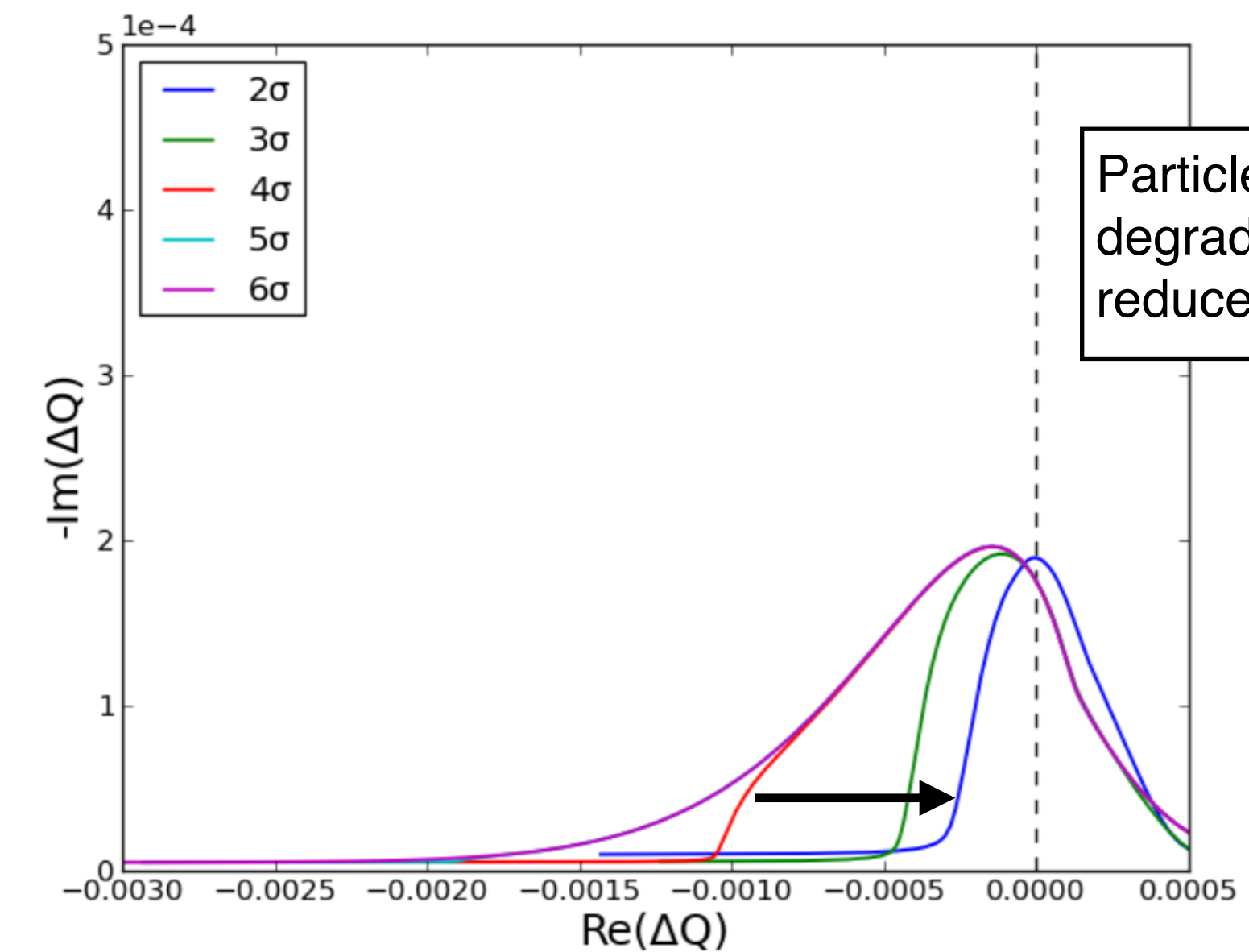
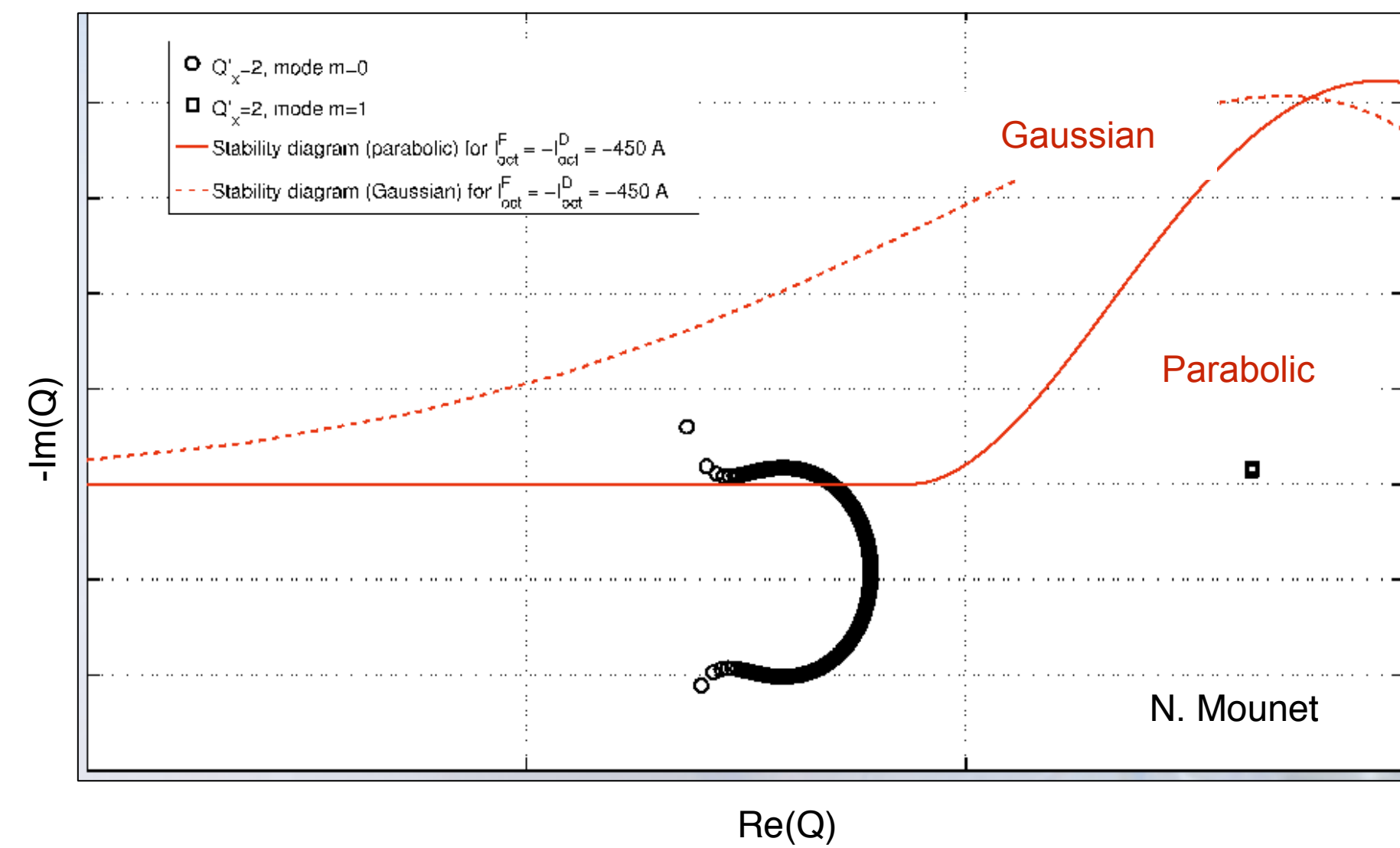
Beam-beam effects modify the stability provided by the Landau octupoles [2] (MAD-X tracking) → beam stability during different stages of the operational cycle

[2] X. Buffat et al., Stability diagrams of colliding beams in the Large Hadron Collider, PRSTAB 111002 (2014)

Computation of the stability diagram

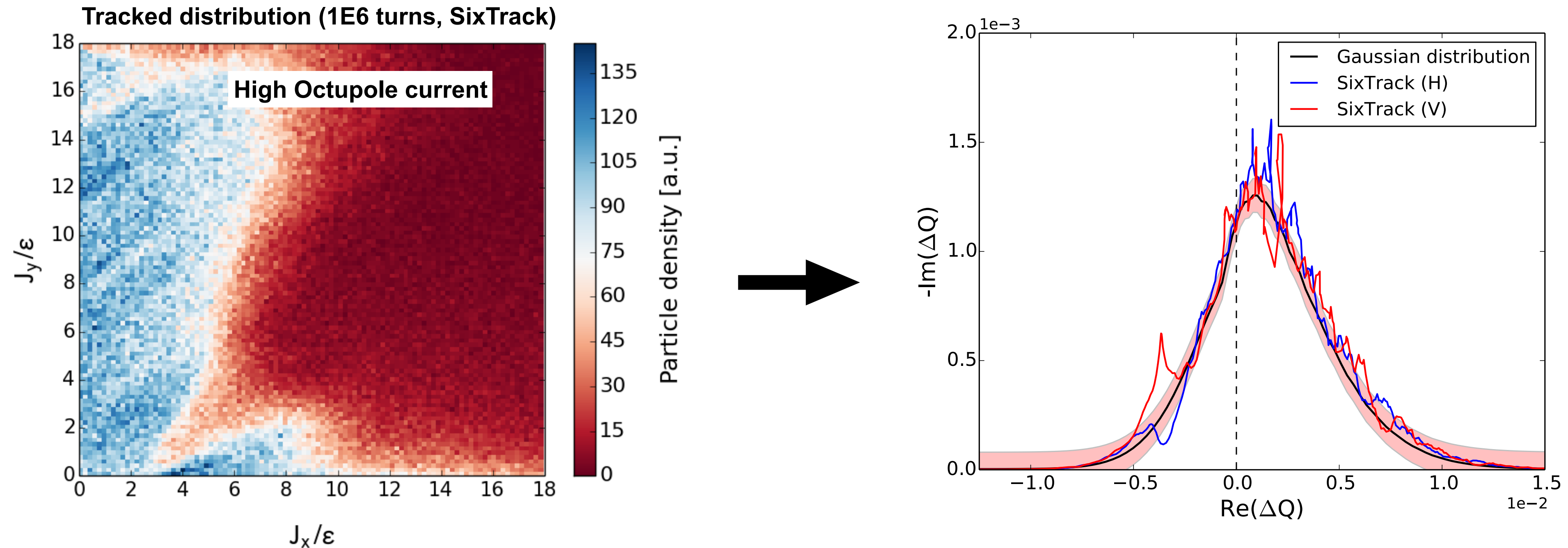
Particle distribution

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



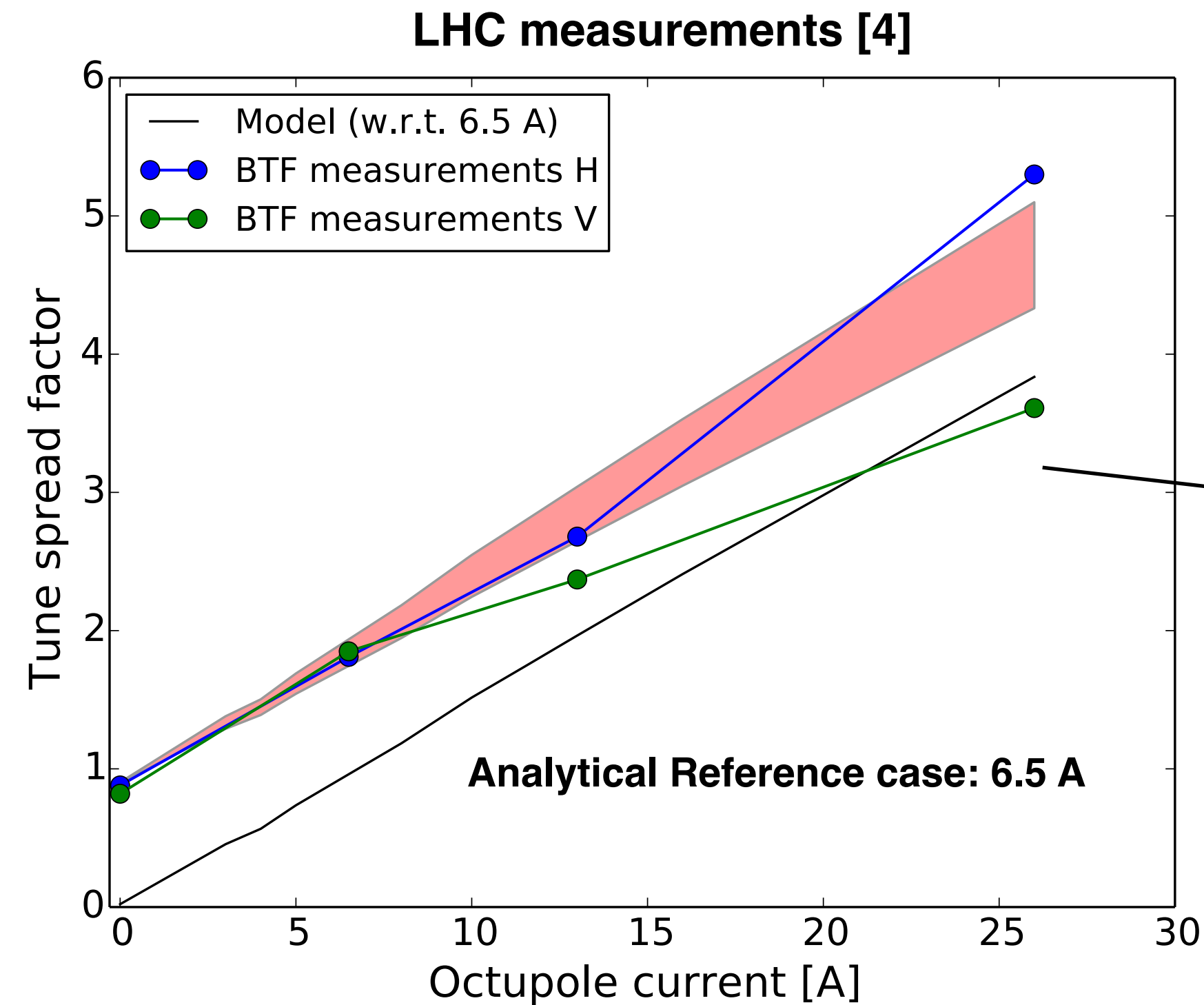
Gaussian distribution is a good assumption for $DA > 5\sigma$

Impact of incoherent effects on the Stability Diagram

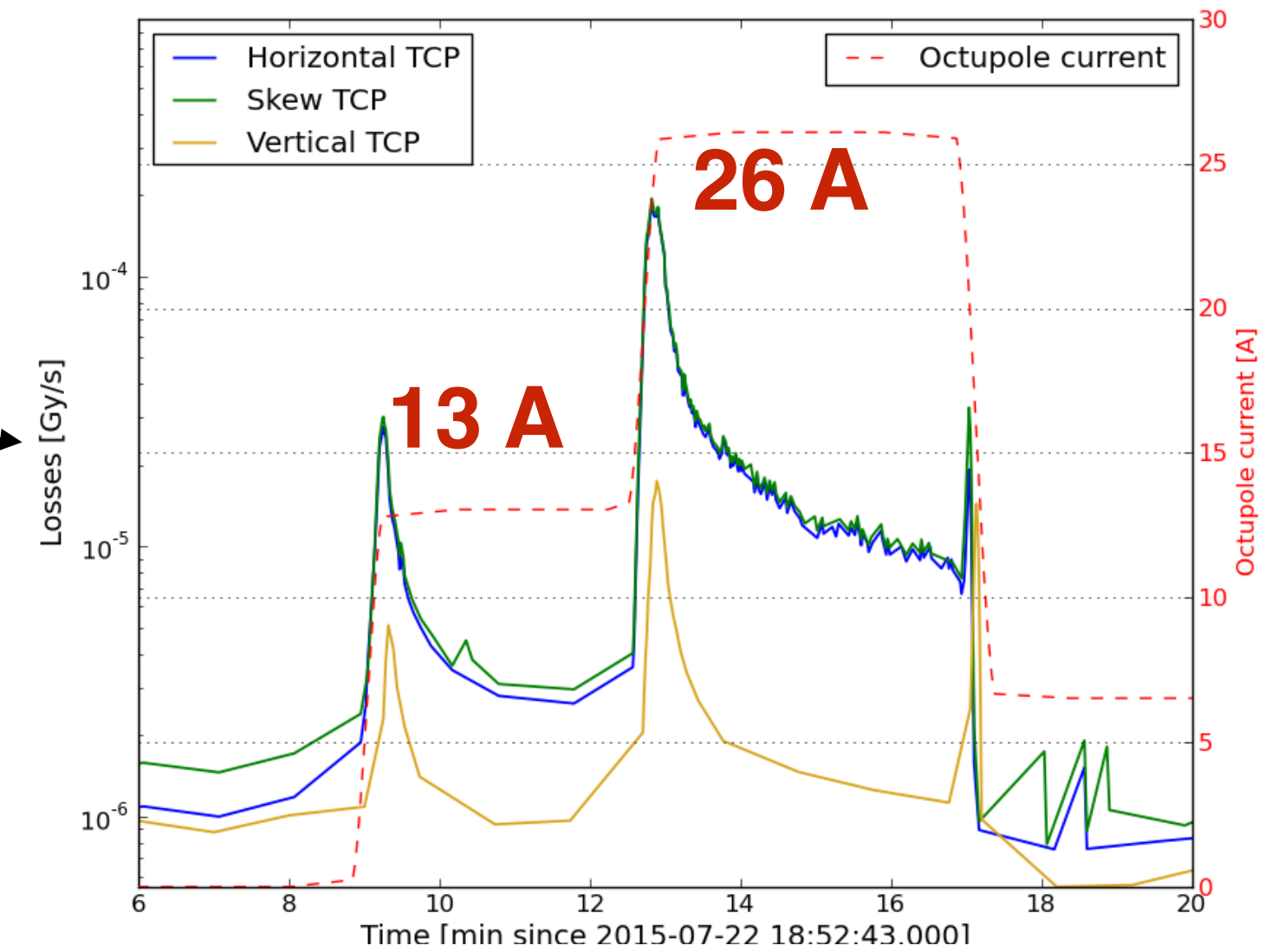


- Excitations of resonances due to high octupole current: small amplitude particles are lost (amplitude $< 3.5 \sigma$)
- Distortion visible on the Stability Diagram due to modification of particle distribution [4]

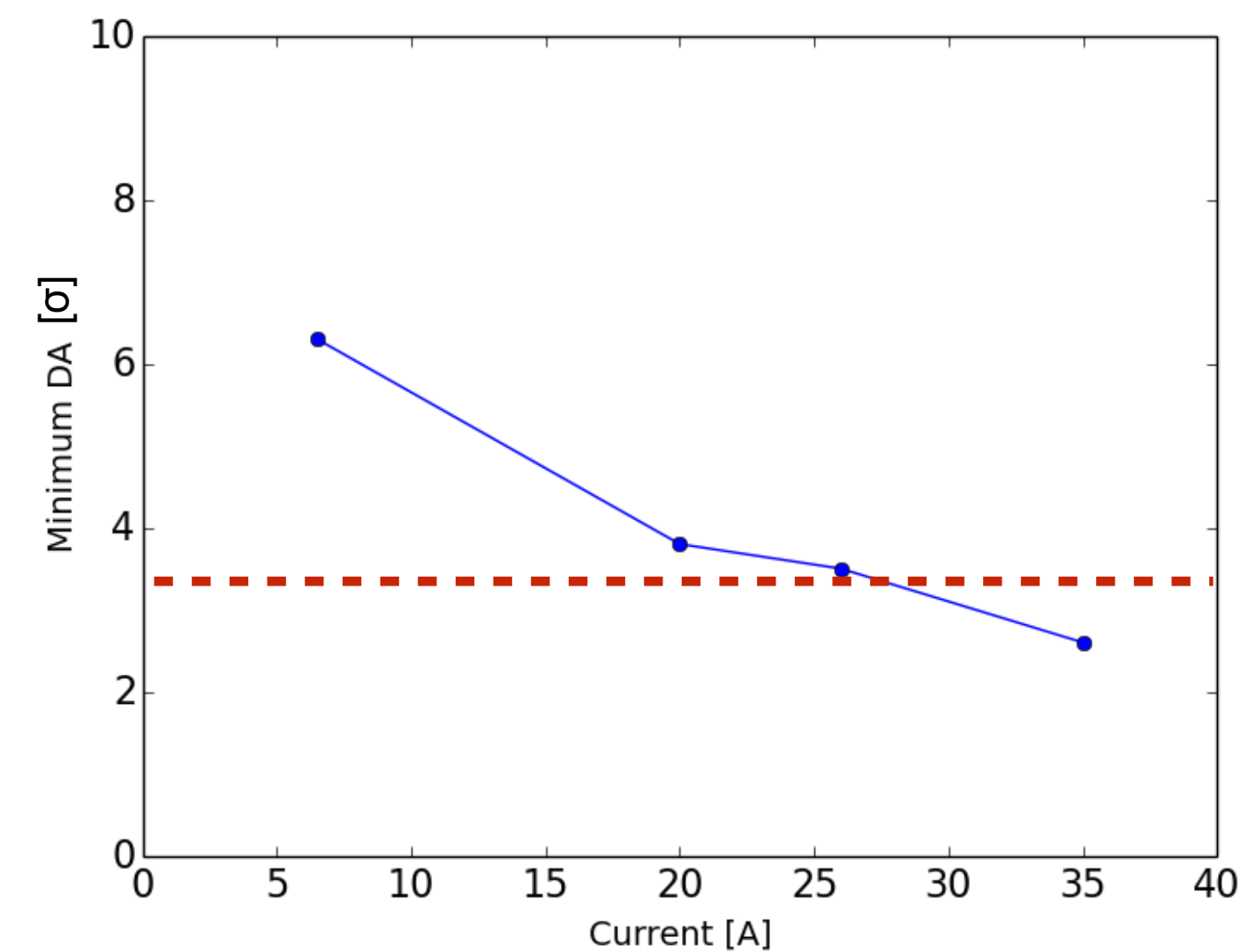
Impact of beam losses on beam stability



Losses observed in the vertical plane correlated with octupole current changes



Losses observed as a function of octupole strength due to reduction of DA ($\sim 3\sigma$)
 → Increasing the tune spread is beneficial for Landau damping as long as any diffusion mechanism is not present



Octupoles and e-lens for Landau damping

Octupoles magnets [J. Berg and F. Ruggero]	Electron lenses [V. Shiltsev et al.]	RFQ [M. Schenk, A. Grudiev et al.]
<ul style="list-style-type: none">☑ Evaluate tune spread from octupoles☑ Single beam☑ Beam-beam☑ DA	<ul style="list-style-type: none">☑ Evaluate tune spread from e-lens (injection, flat top)	<ul style="list-style-type: none">☑ Preliminary studies for FCC by M. Schenk et al. show stabilizing effects
Impact on Dynamic Aperture to be addressed		

FCC-hh Octupoles for Landau damping

	LHC (7 TeV)	FCC (50 TeV)	FCC (3.3 TeV)
Gradient [T/m ³]	53000	200000	200000
β-function [m]	100	200	100
Length [m]	0.32	0.5	0.5
Maximum Current [A]	550	720	720
Bρ [T · m]	23350	166783	11008
Oct int strength* [m ⁻³] (single magnet)	0.726	0.600	9.085

$$*=G_{\max}/(B\rho) \cdot (l_{\text{oct}}/I_{\max}) \cdot L_{\text{oct}}$$

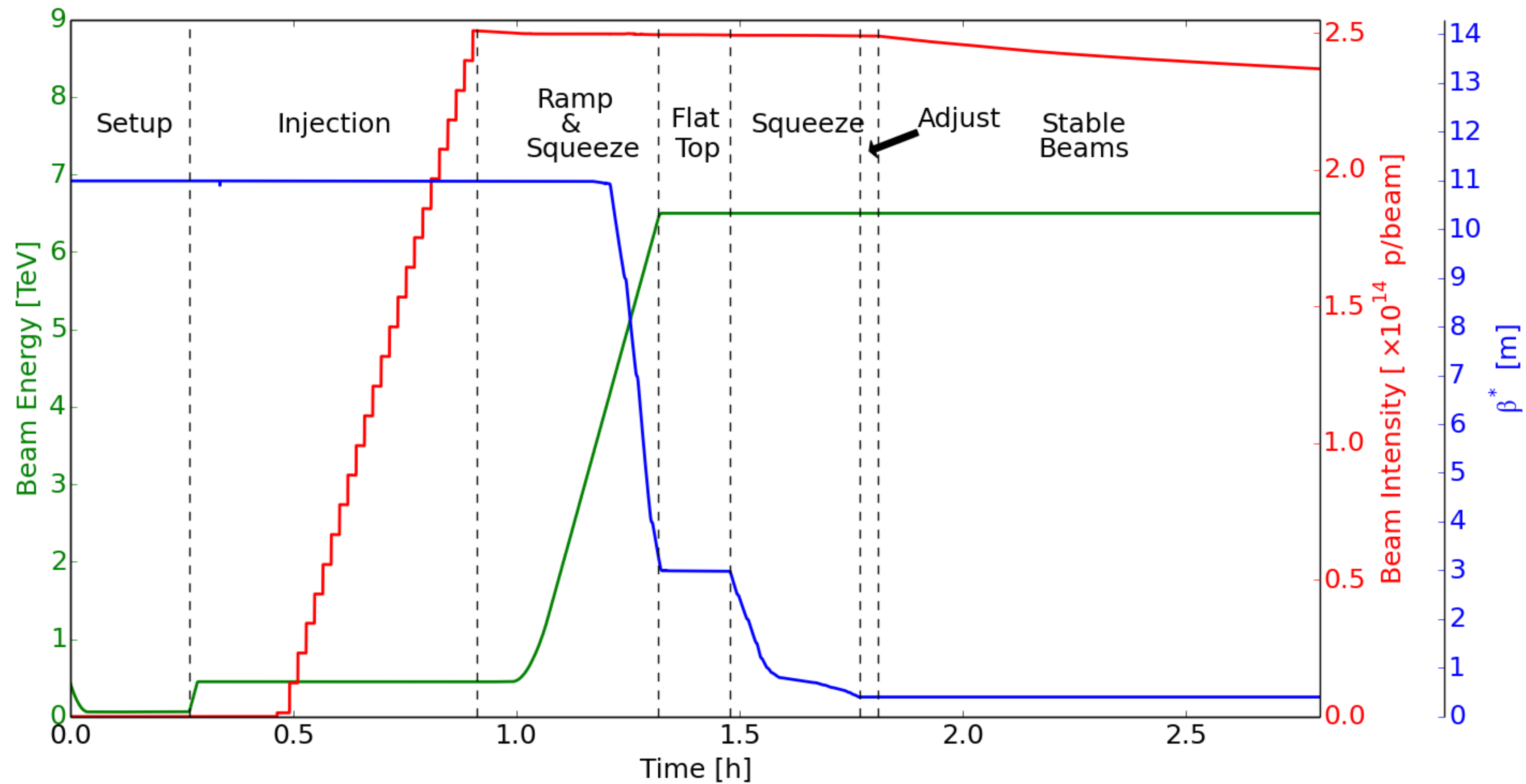
MAD-X

Beam size at the octupoles: i.e. β-function and geometric emittance
 Number of installed octupoles (480)
 + Beam-beam interactions

Tune spread for Landau damping (PySSD [3])

Beam stability during the operational cycle

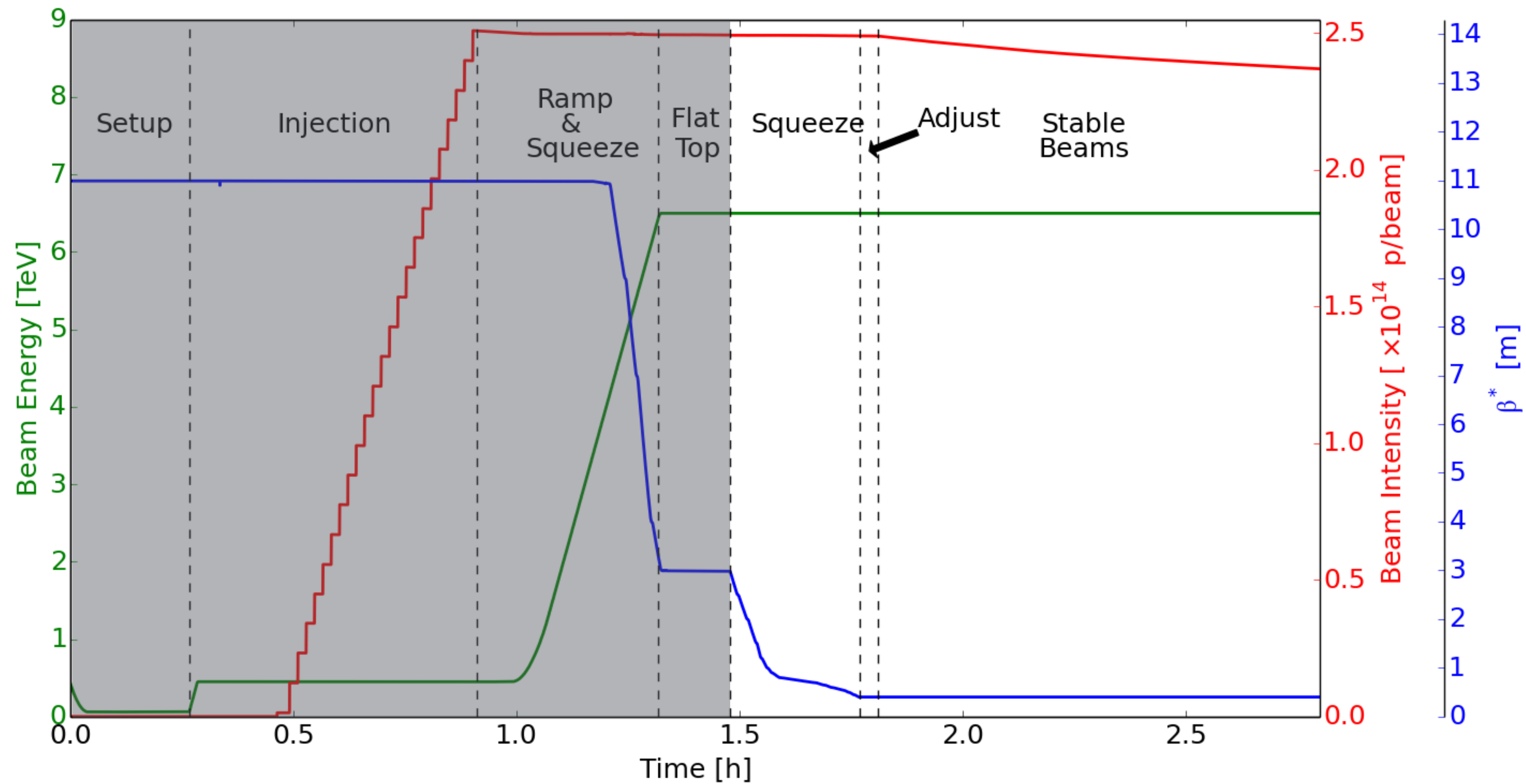
LHC Operational cycle



Beam stability has to be ensured during the full operational cycle

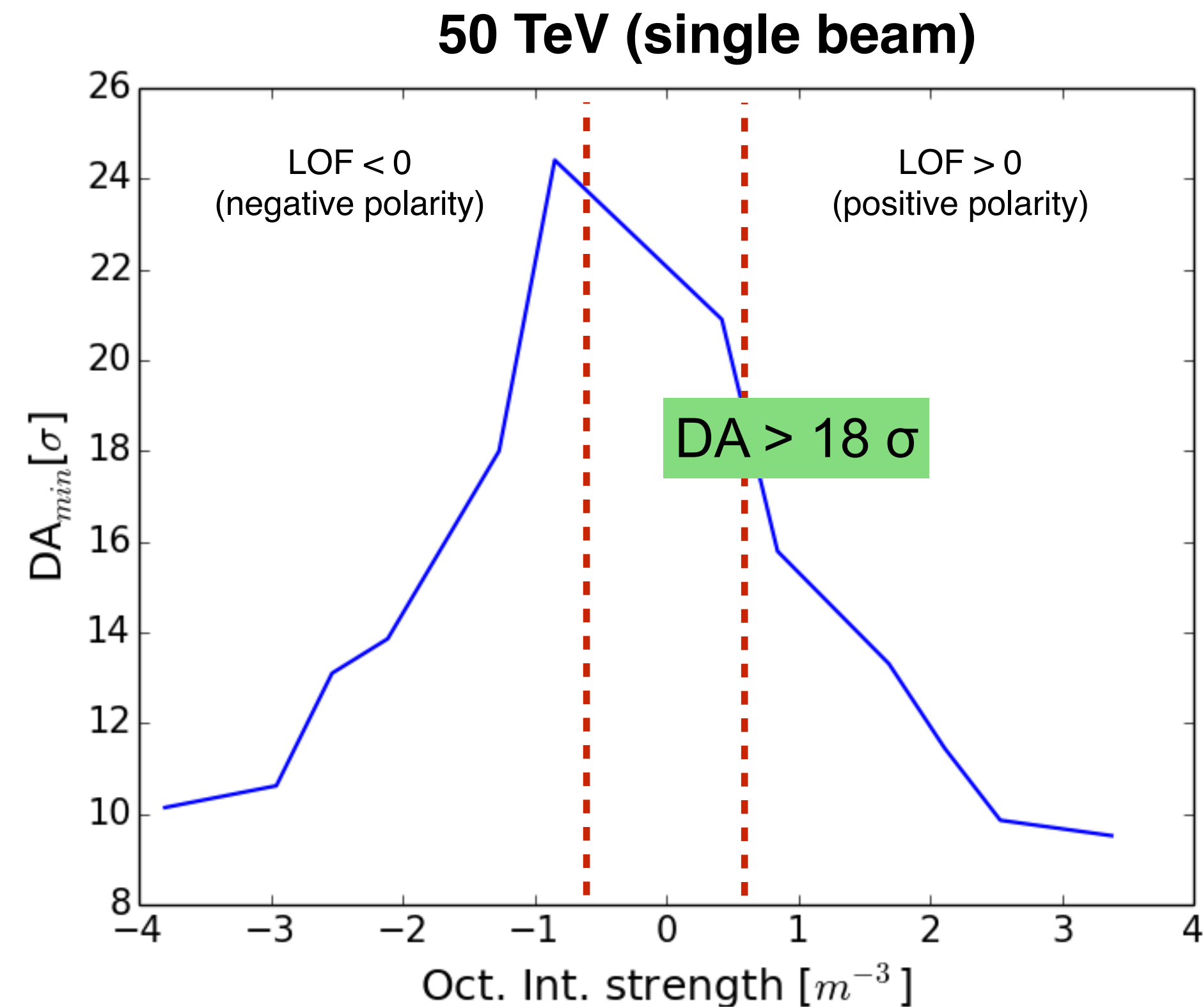
Beam stability during the operational cycle

LHC Operational cycle



Tune spread provided by Landau octupole magnets

Impact of Landau octupoles on Dynamic Aperture (flat top energy)

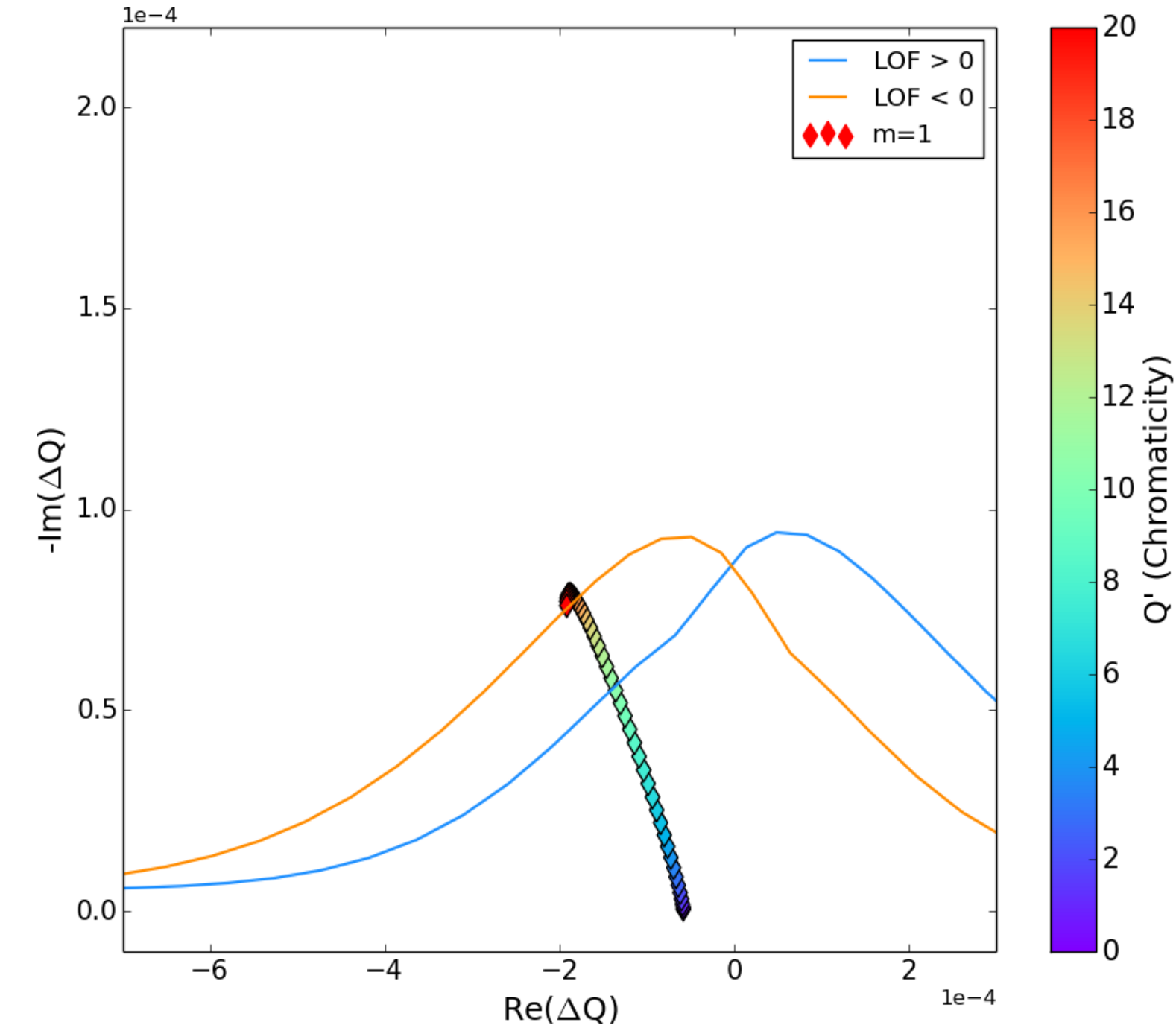
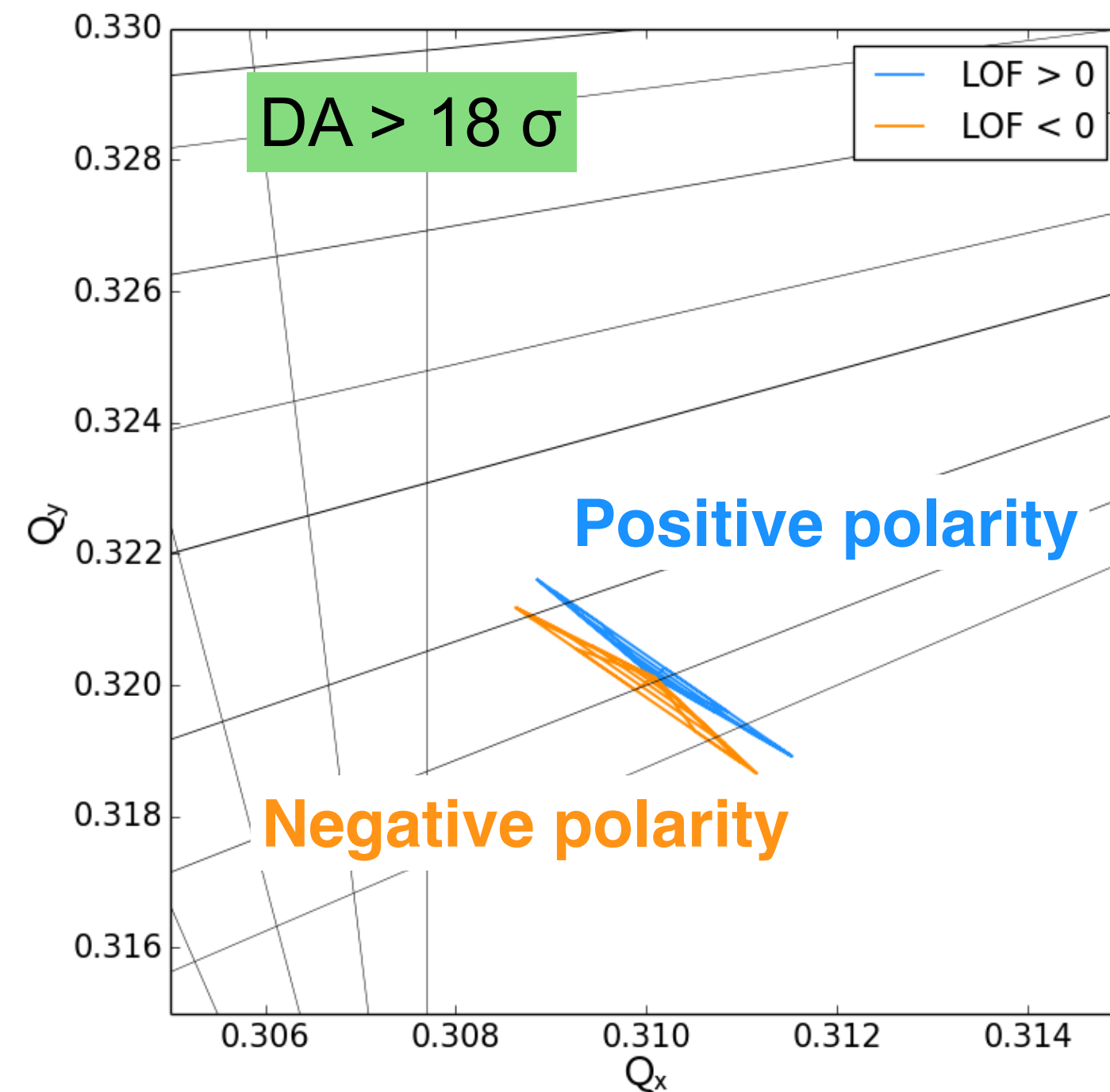


- DA decreases as a function of the octupole strength
- With the required octupole strength DA is above 18 σ for both octupole polarities

Landau damping for $m \neq 0$ and $Q' \neq 0$ at flat top energy

Flat top (no beam-beam)

$m=1$ Coupled-bunch
modes by S. Arsenyev



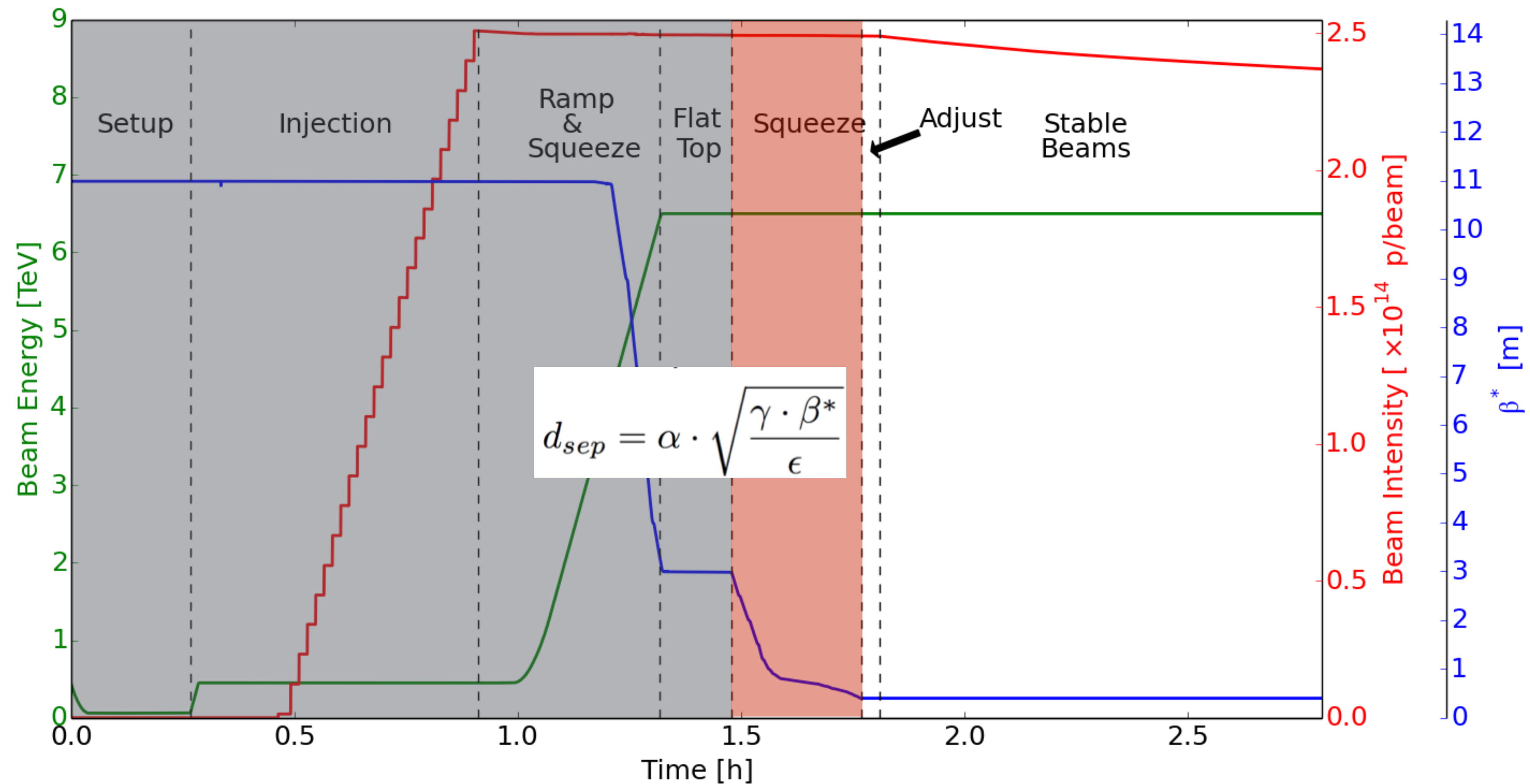
- $m=0$ damped by feedback
- stability diagrams obtained with available octupoles at their maximum strength

$m \geq 1$ modes: octupoles sufficient up to $Q'=20$ units powered in negative octupole polarity (orange line)

Beam stability during the operational cycle

Reduction of the beam size (β^*) \rightarrow Long range interactions become important

LHC Operational cycle

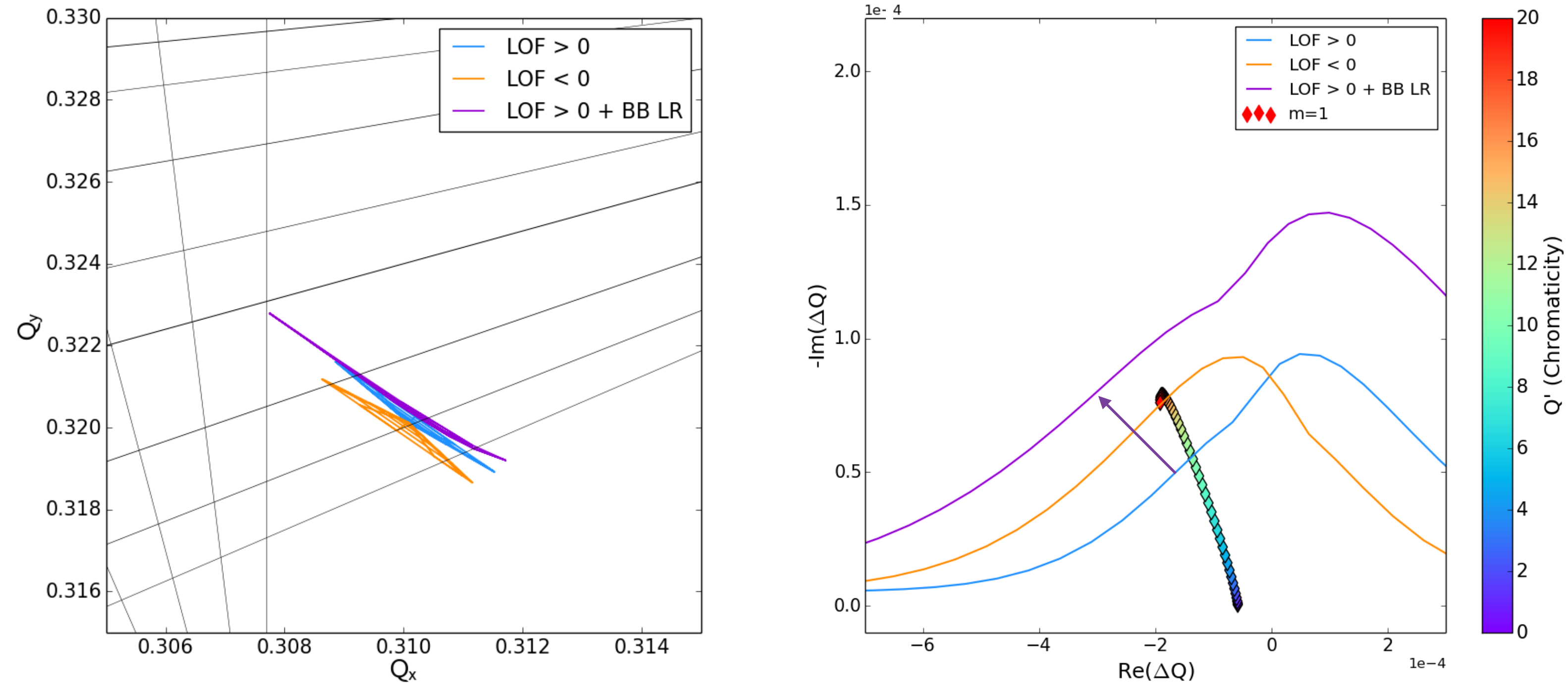


Tune spread provided by Landau octupole magnets and beam-beam long range

Landau damping for $m \neq 0$ and $Q' \neq 0$ end of betatron squeeze

End of squeeze (beam-beam)

$m=1$ Coupled-bunch
modes by S. Arsenyev

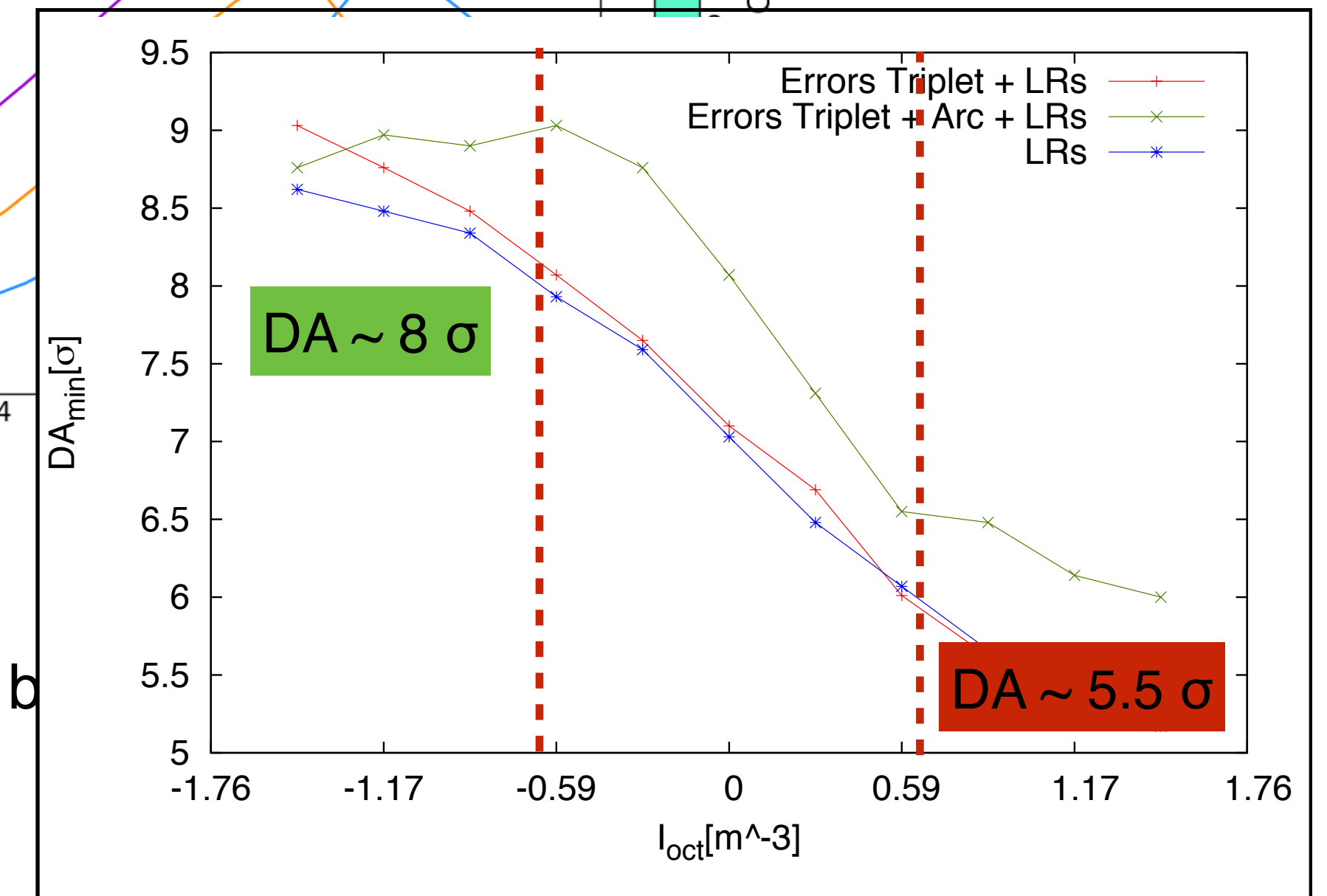
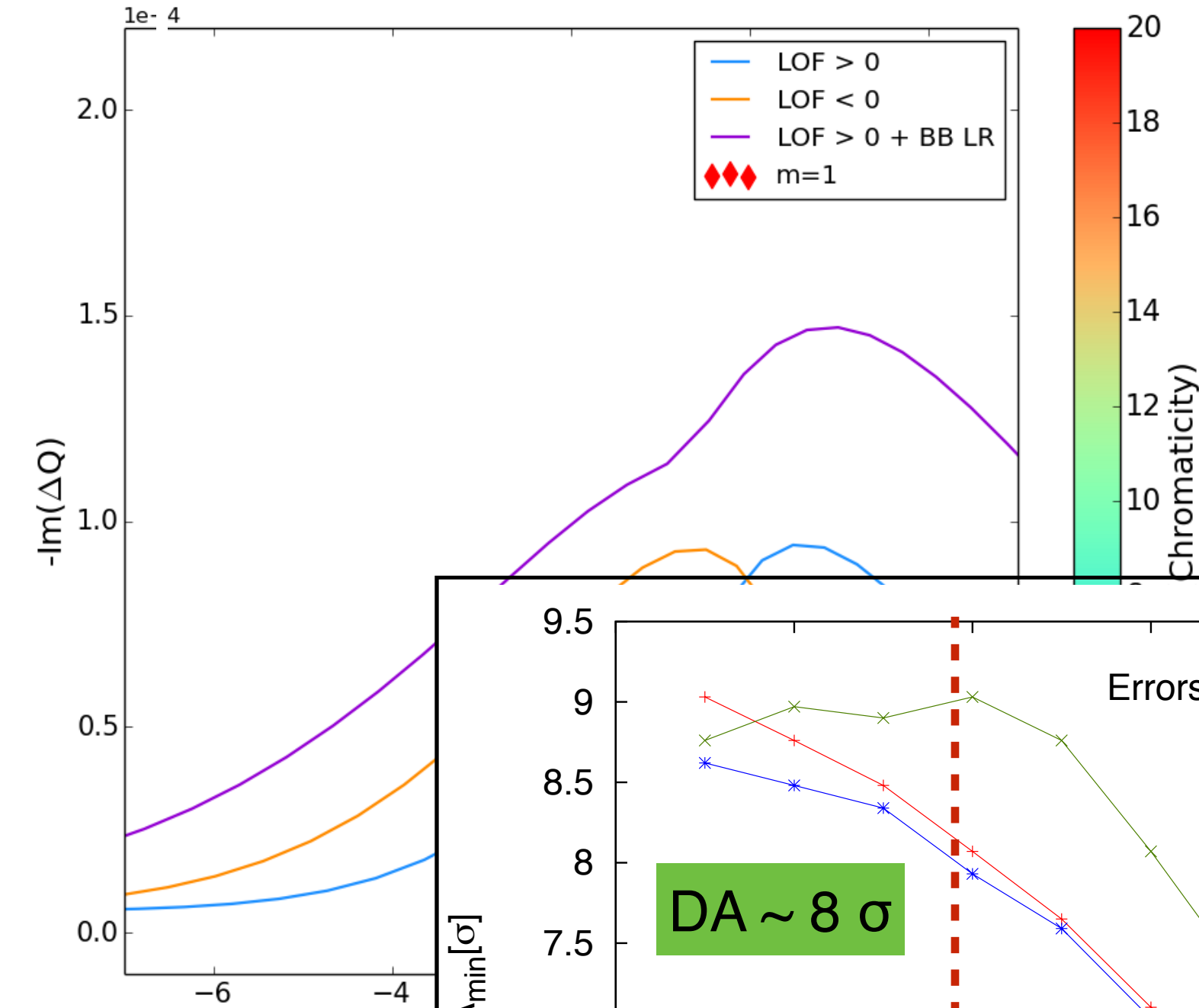
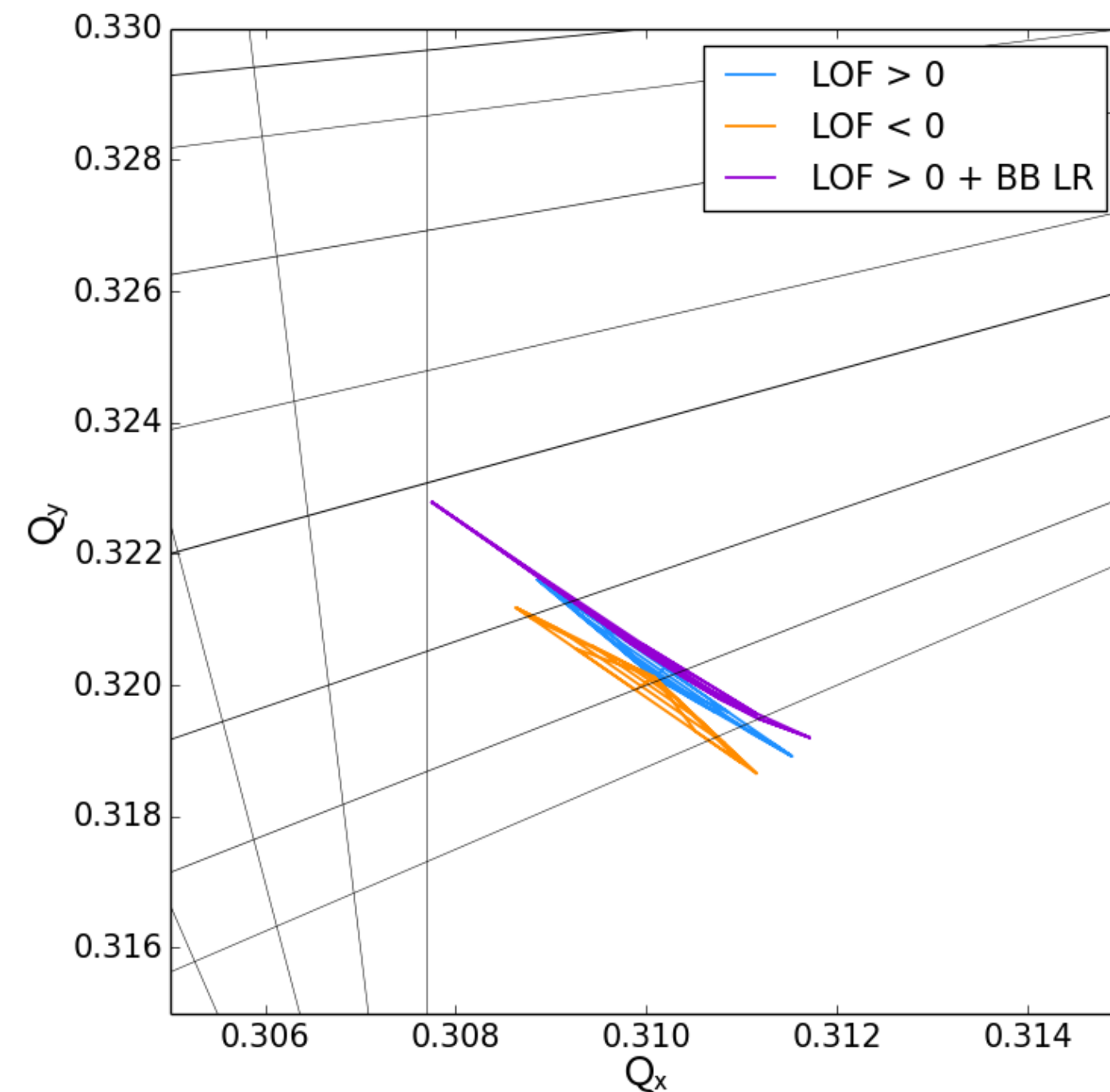


Tune spread from bb LR and positive octupoles adds up \rightarrow larger stability but smaller DA with respect to negative polarity ($DA < 6 \sigma$)

Landau damping for $m \neq 0$ and $Q' \neq 0$ end of betatron squeeze

End of squeeze (beam-beam)

$m=1$ Coupled-bunch
modes by S. Arsenyev

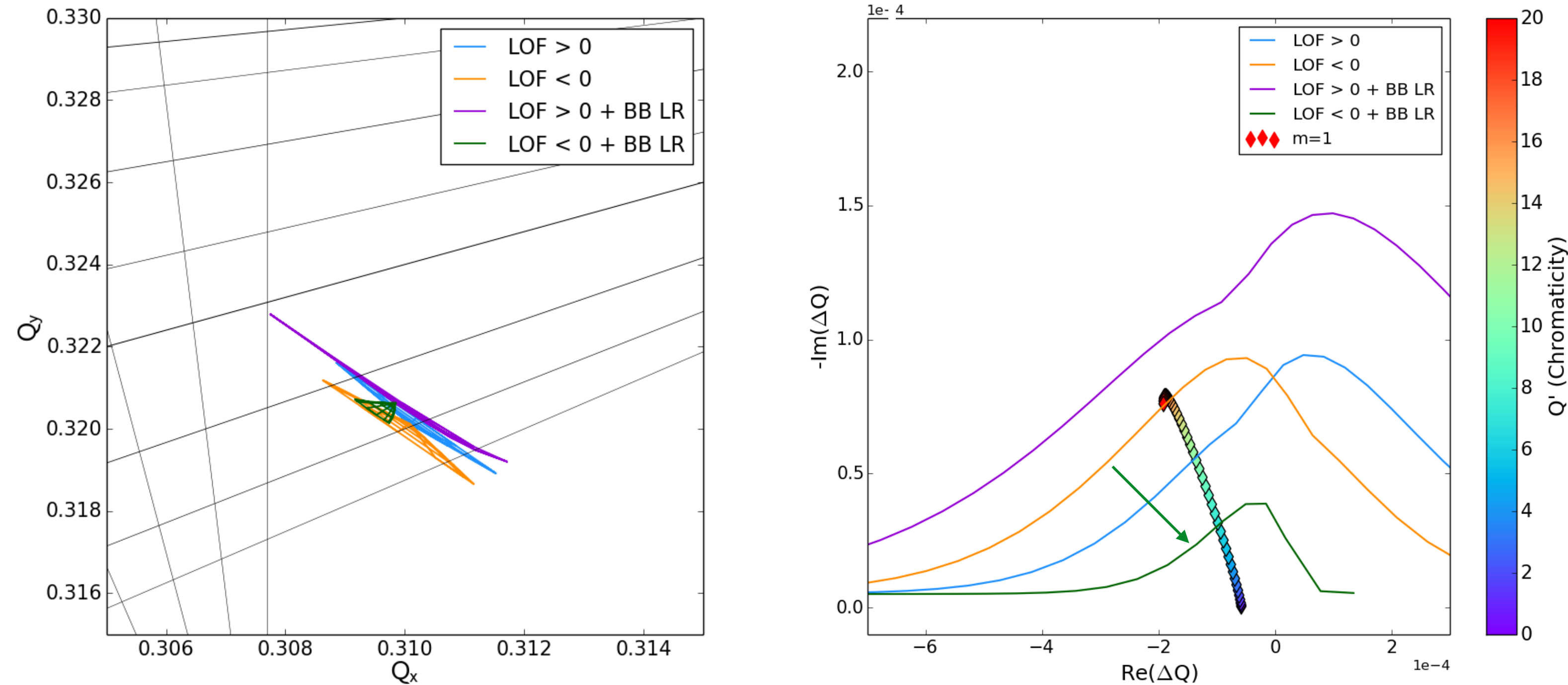


Tune spread from bb LR and positive octupoles adds up \rightarrow larger stability b
polarity ($\text{DA} < 6 \sigma$)

Landau damping for $m \neq 0$ and $Q' \neq 0$: end of betatron squeeze

End of squeeze (beam-beam)

$m=1$ Coupled-bunch
modes by S. Arsenyev



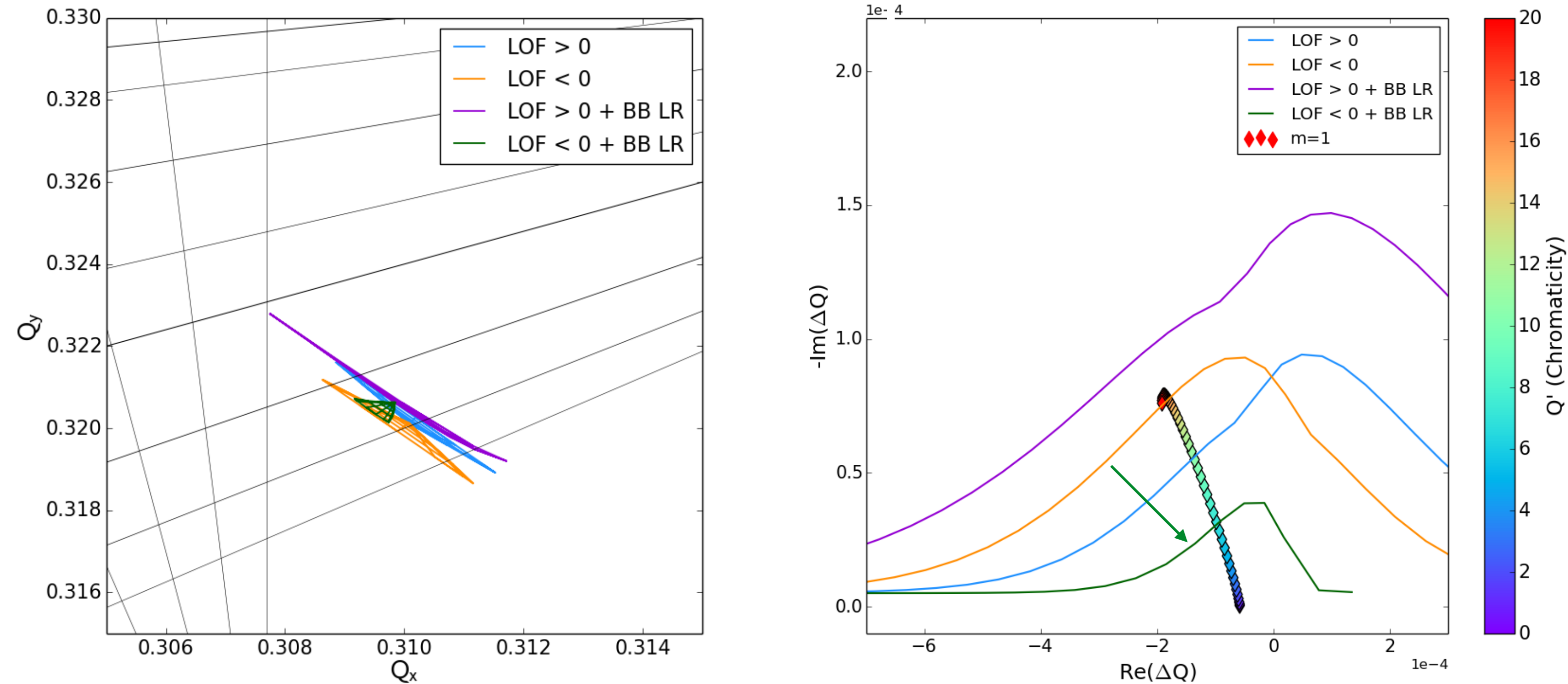
The stability diagram at flat top reduces at the end of the betatron squeeze with negative octupole polarity due to the interplay with long-range interactions (green line) **DA $\sim 8.5 \sigma$**

→ The available octupole strength allows no margins at the end of the squeeze imposing a tight control on the chromaticity value

Landau damping for $m \neq 0$ and $Q' \neq 0$: end of betatron squeeze

End of squeeze (beam-beam)

$m=1$ Coupled-bunch
modes by S. Arsenyev



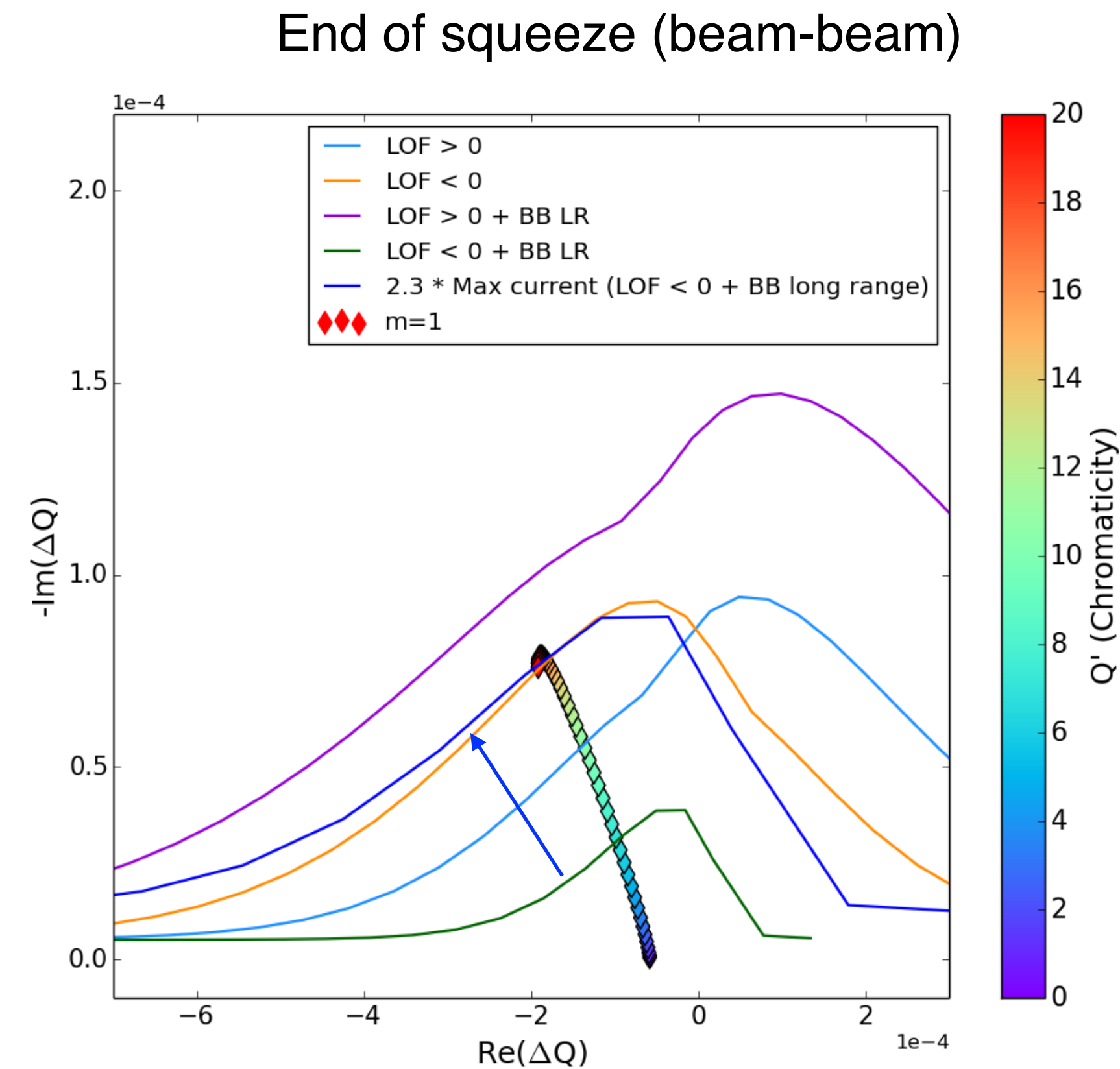
The stability diagram at flat top reduces at the end of the betatron squeeze with negative octupole polarity due to the interplay with long-range interactions (green line) **DA $\sim 8.5 \sigma$**

Possible solutions:

- The available octupole strength allows n
- Increase the β -function in the arcs
- Electron-lens for Landau damping
- a tight control on the chromaticity value

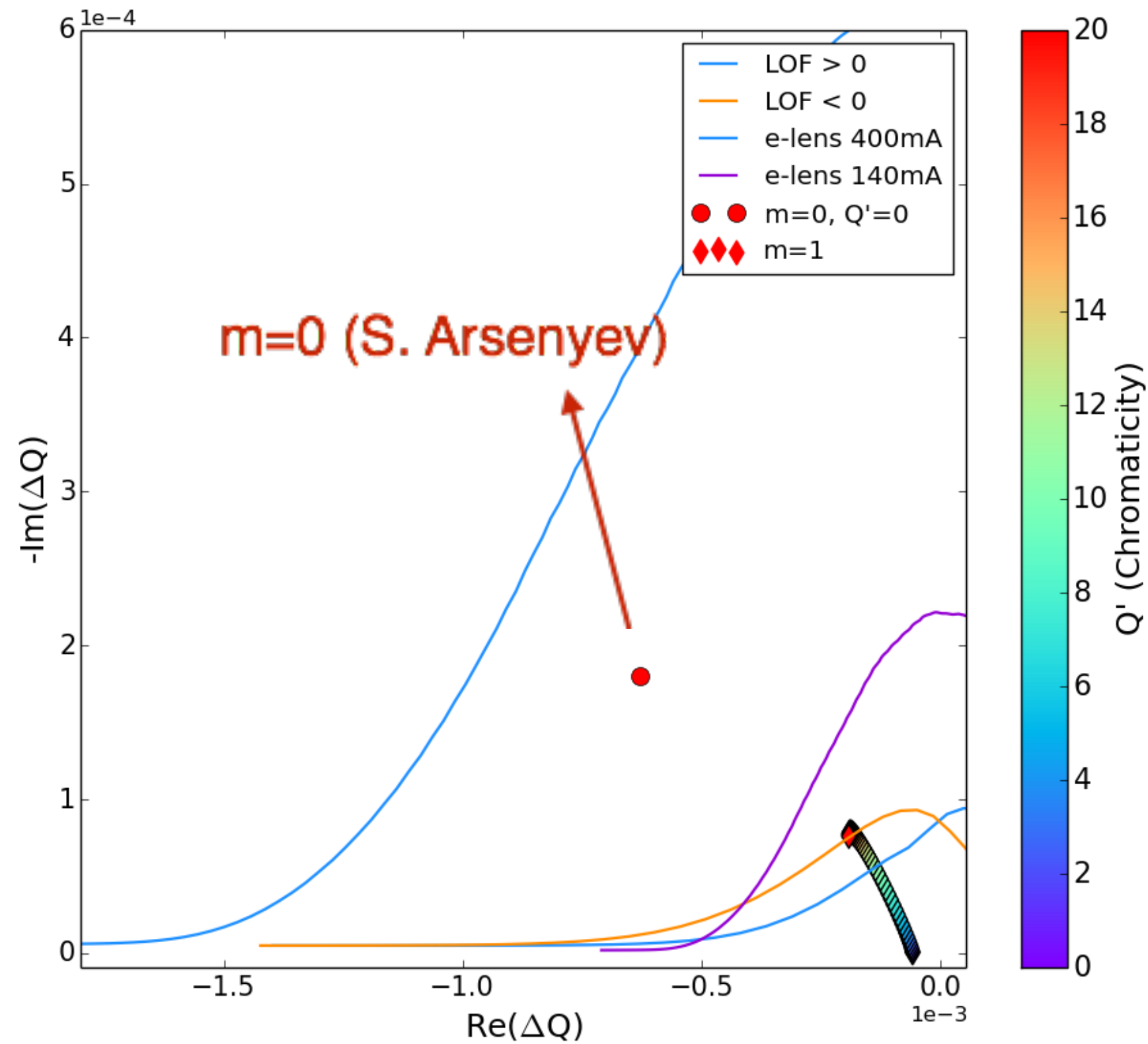
Compensation of the reduction of Landau damping due to beam-beam long range

m=1 Coupled-bunch
modes by S. Arsenyev



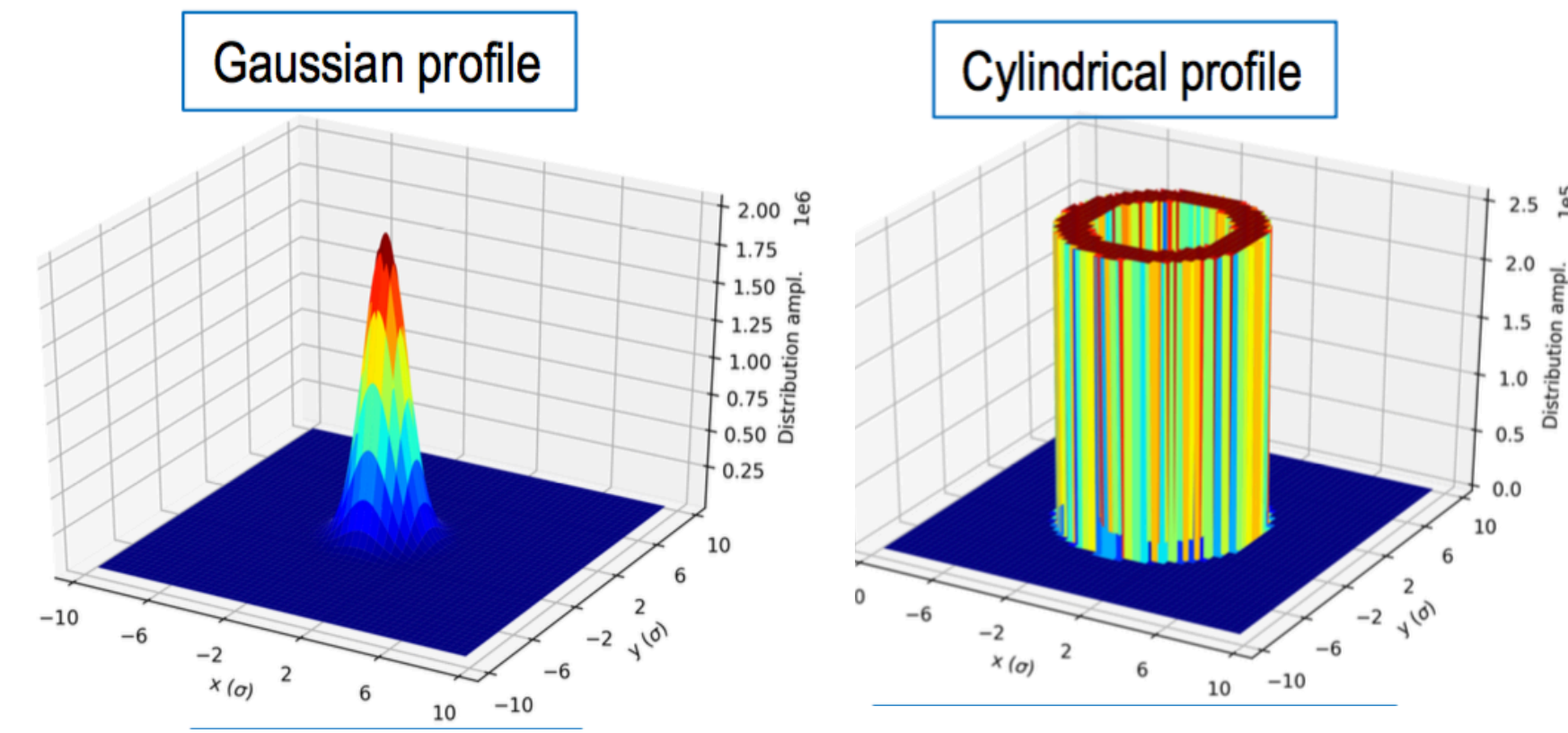
In order to relax chromaticity constraints an additional factor of 2.3 in octupole strength is required → **achievable with larger β -functions in the arcs (~50% more) and optimization of the lattice** (blue line)

Electron lens for Landau damping: flat top energy

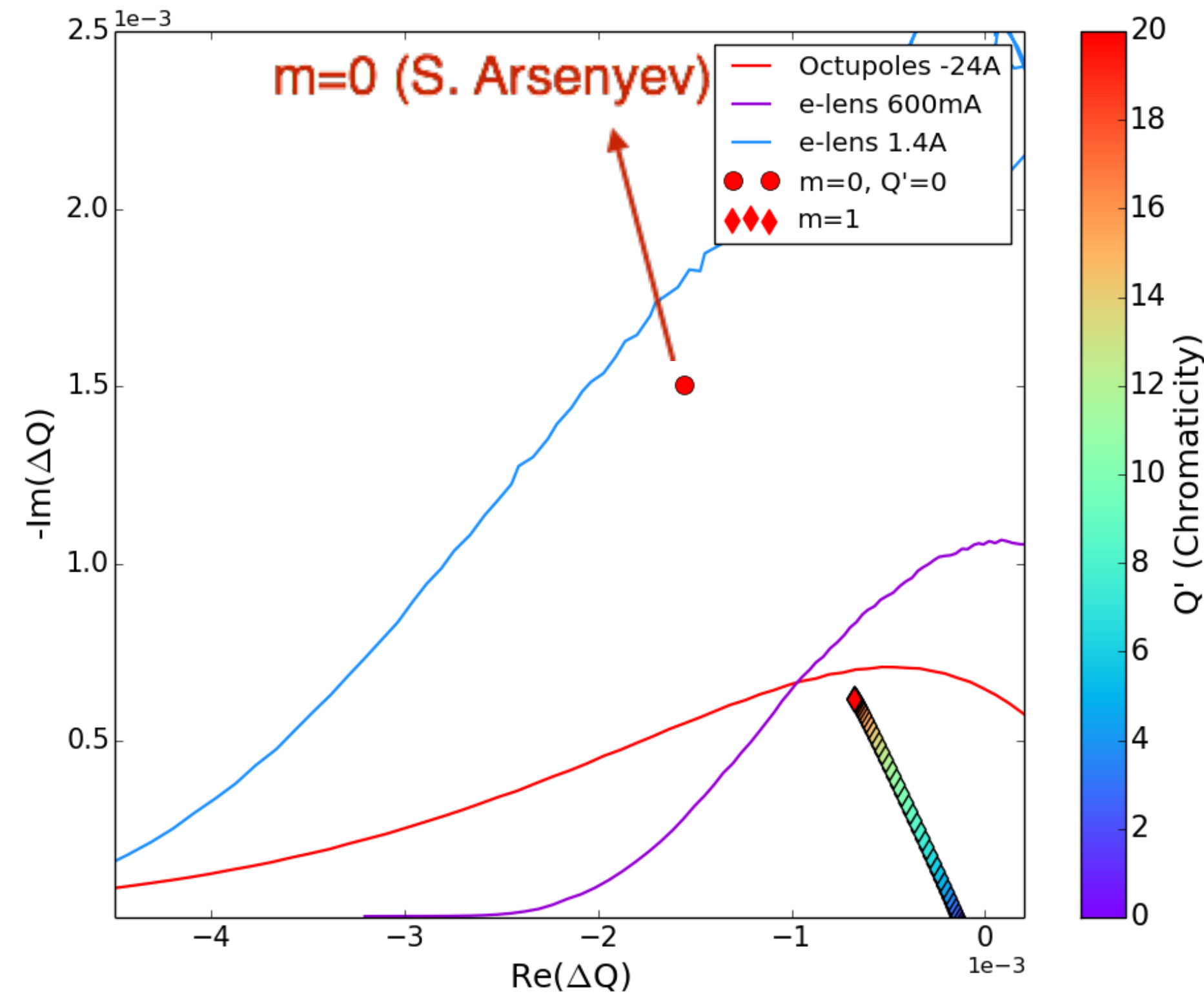


- 140 mA will be sufficient to provide enough Landau damping for $m=1$ (up to $Q'=20$ units)
- 400 mA are required to damp $m=0$ at $Q'=0$

Different e-lens profiles have been implemented in COMBI (Project by EPFL Master student F. Barantani)



Electron lens for Landau damping: injection energy

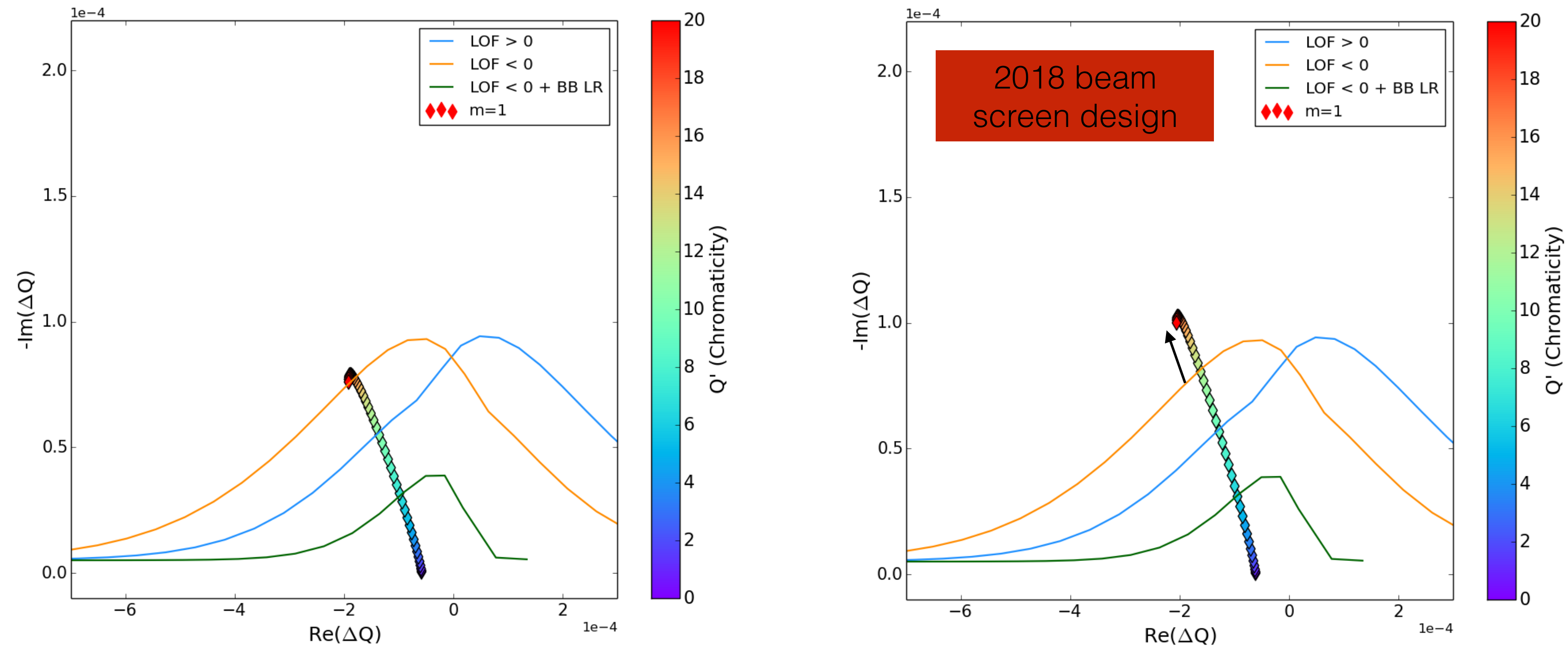


- 600 mA will be sufficient to provide enough Landau damping for $m=1$ (up to $Q'=20$ units)
- 1.4 A are required to damp $m=0$ at $Q'=0$

Landau damping for $m \neq 0$ and $Q' \neq 0$ new beam pipe

$m=1$ Coupled-bunch
modes by S. Arsenyev

Octupoles at their maximum strength

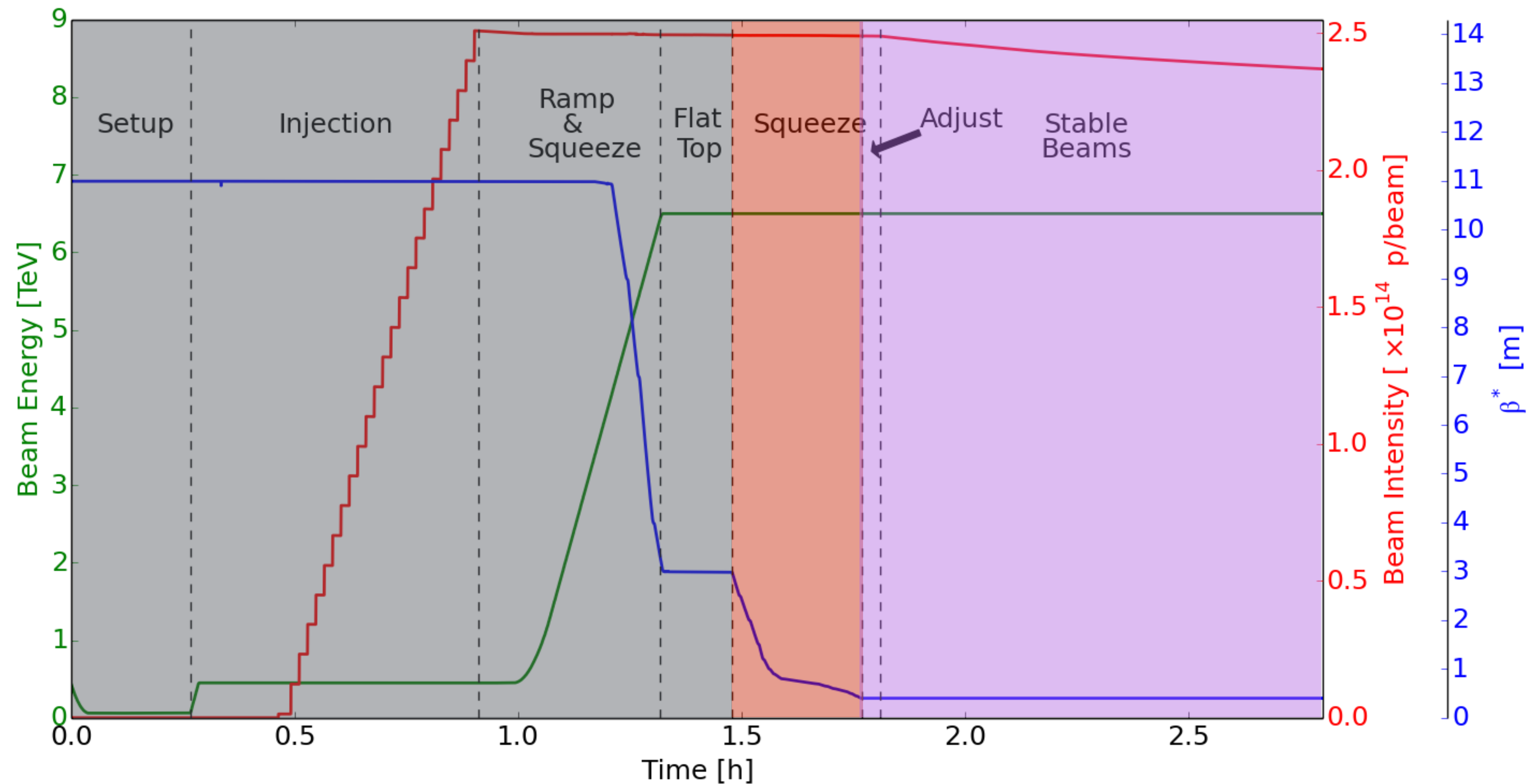


The new beam pipe increases imaginary part of $m=1$ up to 30%:

- An additional $\sim 30\%$ octupole strength is required to recover stability at flat top
- Constraints on chromaticity at the end of betatron squeeze tighter compared to previous design

Beam stability during the operational cycle

LHC Operational cycle

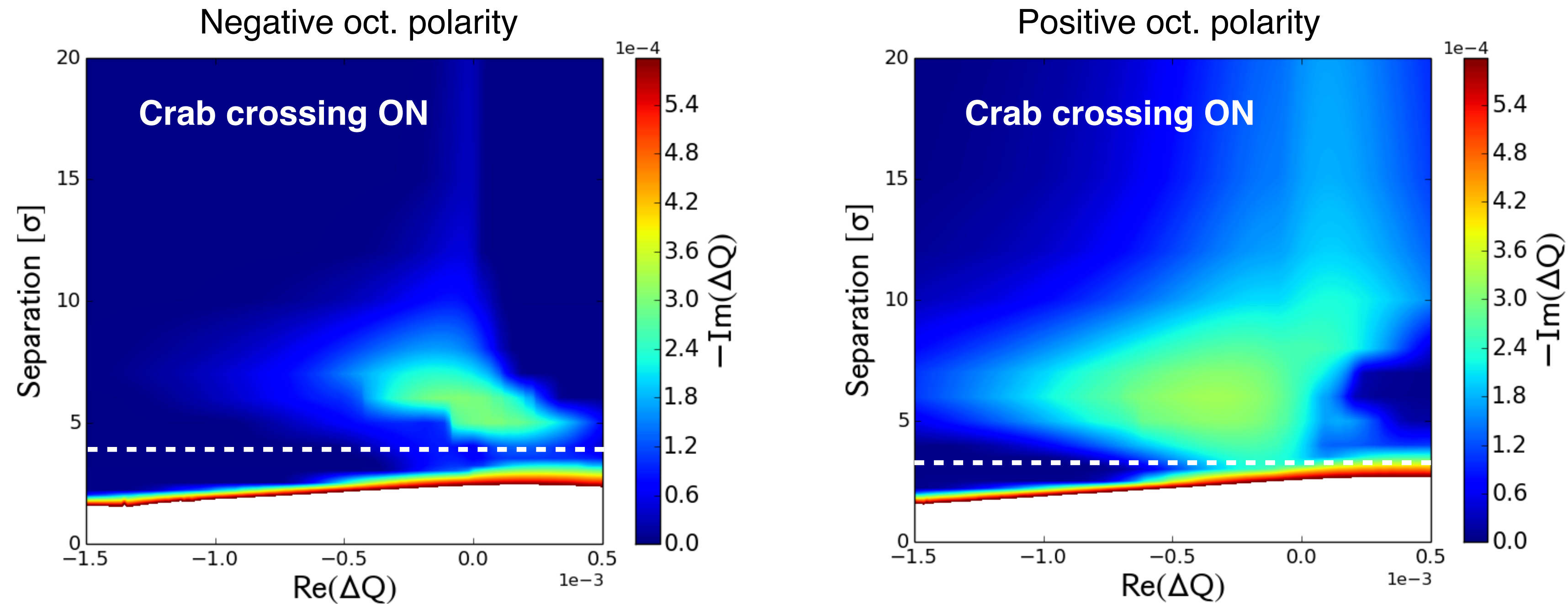


Collapse of the separation bumps: the SD at end of squeeze is modified
Head-on collision → Maximum stability

Beam stability during the collapse of the separation bumps

Evolution of stability diagram during the collapse of the separation bump

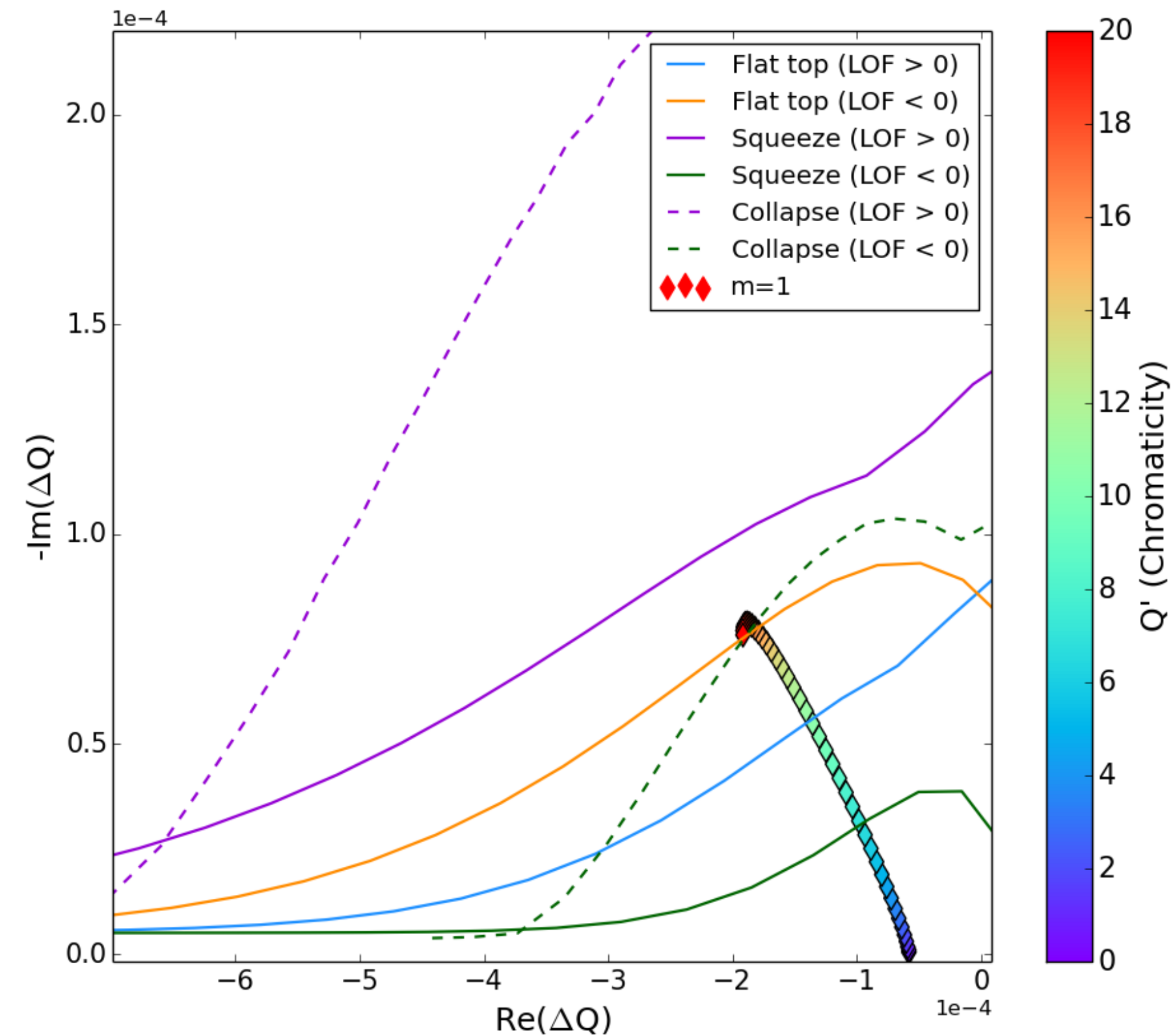
Octupoles at their maximum strength



Minimum at 3 σ during the collapse, however SD at this minimum is larger or equivalent compared to end of betatron squeeze (see next slide)

Stability summary

Octupoles at their maximum strength



Flat top (single beam): larger stability with negative octupole polarity (orange line), $m=1$ Landau damped up to high Q' values ($DA > 15 \sigma$ both polarities)

End of squeeze (beam-beam LR): strong reduction of stability with negative octupole polarity → tight control on Q' values required, $DA > 7.5 \sigma$ ($DA < 6 \sigma$ for positive oct. polarity)

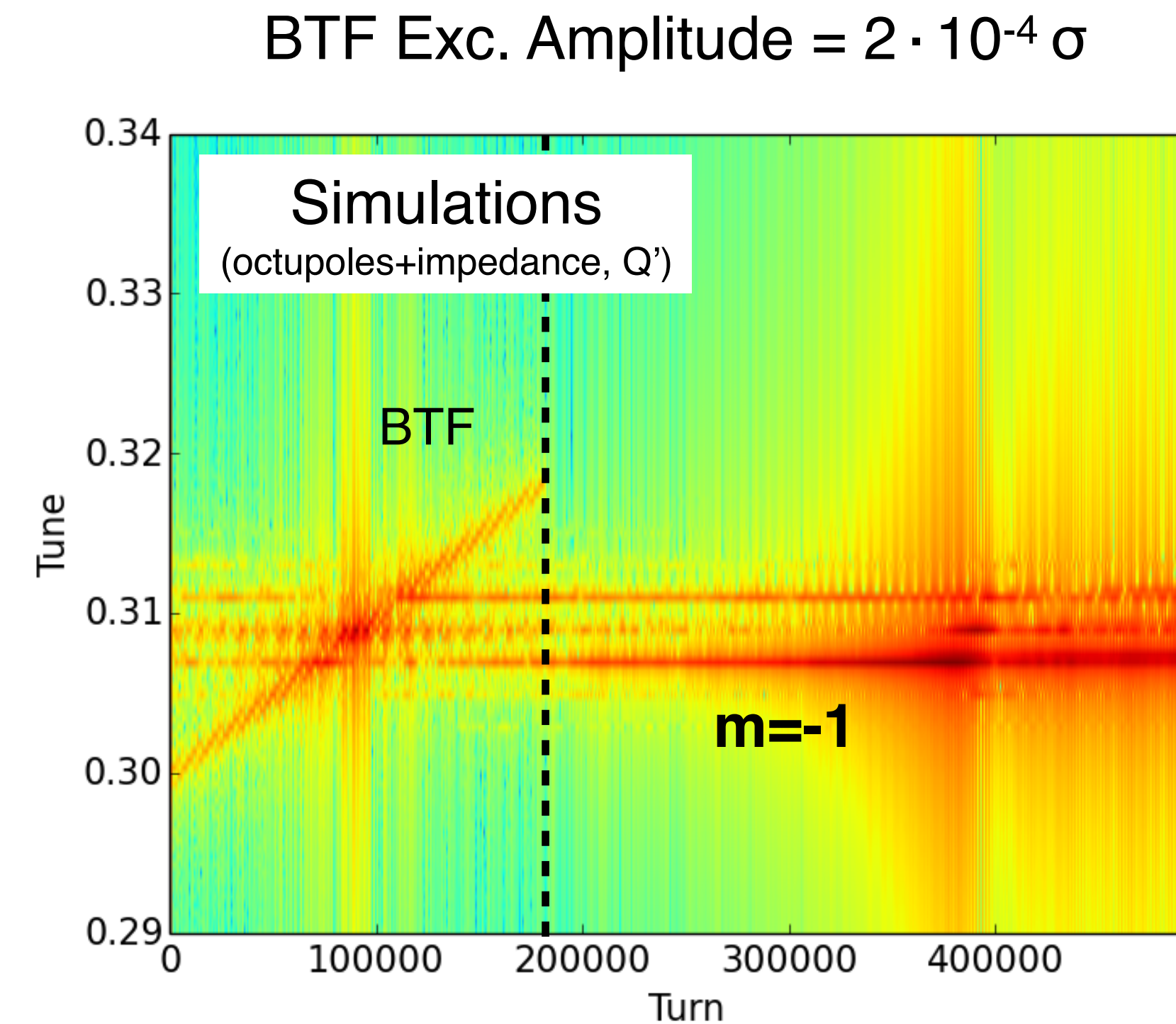
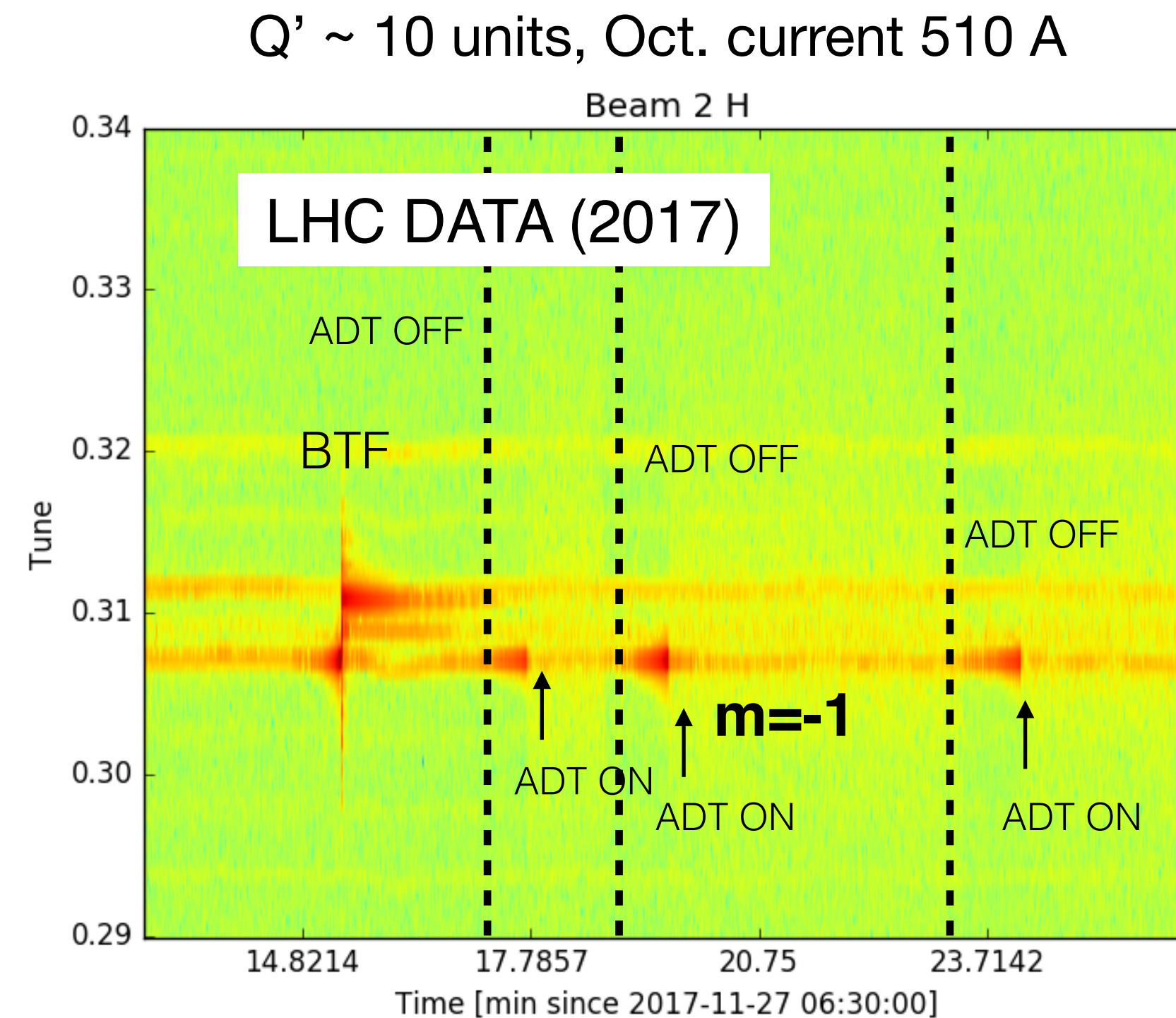
Possible solutions:

- Increase the β -function in the arcs
- Use e-lens for Landau damping
- Wide-band feedback?

Collapse of sep. bumps (LR + HO crab on): stability increases during the collapse → SD is larger or equivalent compared to end of betatron squeeze

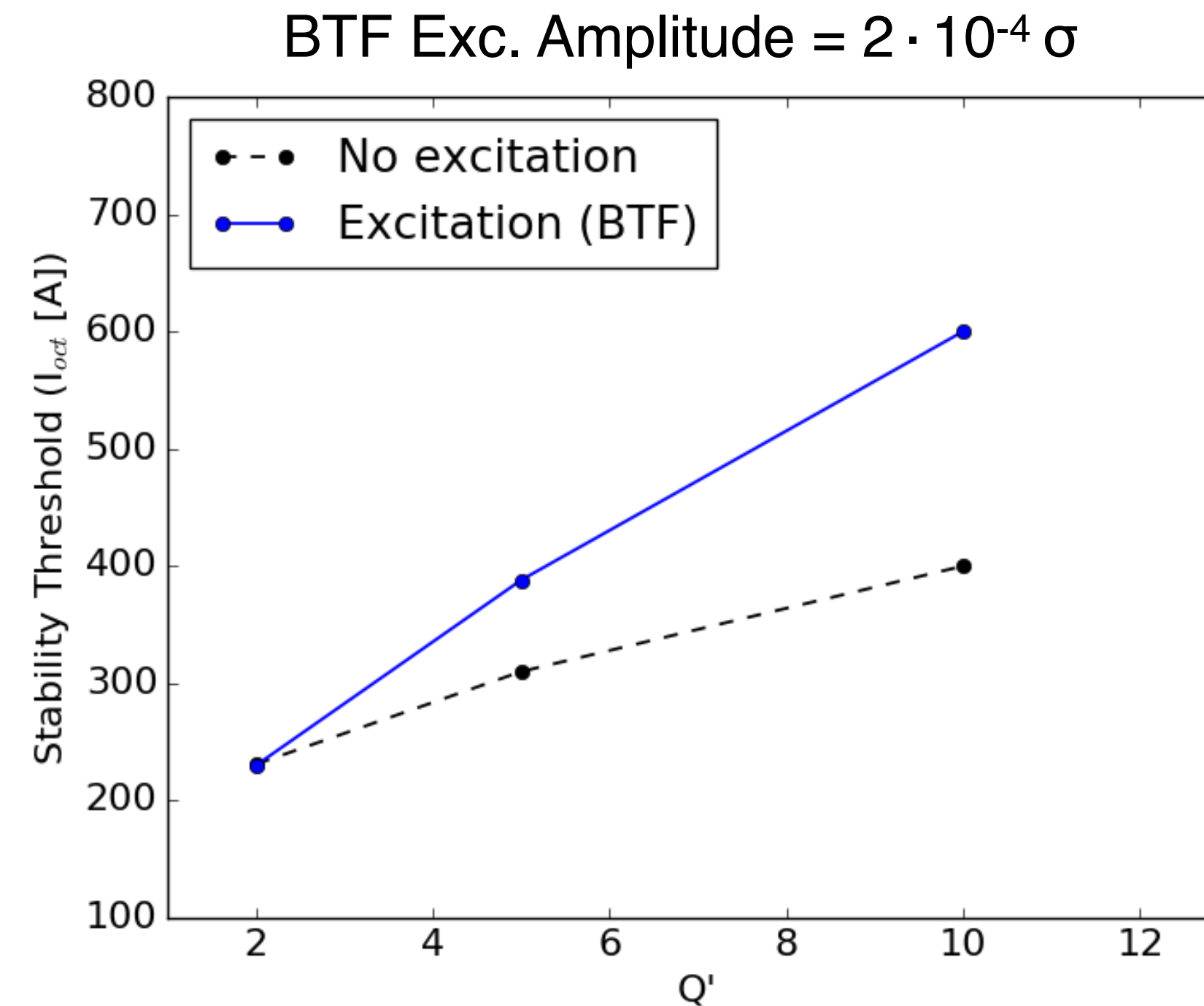
Future studies: impact of noise on beam stability

Single bunch ($I \sim 0.95 \times 10^{11}$ p/bunch)



- Measurements acquired with ADT off (single lower intensity bunch)
- Instability B2 H after (small) BTF excitation in the same plane (with a rise time of ~ 2 s)
- Increase of 30% impedance in the 2017 → (closer to stability limit?)

Stability Thresholds with external excitation (BTF)



- The higher the chromaticity, the higher the octupole current required
- For a chromaticity $Q'=10$ units the required increase is of ~50%
- Possible mechanism to explain the observed higher octupole threshold needed during LHC operation

Higher octupole current is required to stabilize the beam in the presence of external excitation (noise, small amplitude external excitation) → critical for FCC octupole magnet system

Summary

In this analysis we considered $m=0$ damped by the transverse feedback → **further studies on-going to include radial modes at $Q' \neq 0$**

For $m=1$ and positive Q' (most unstable mode):

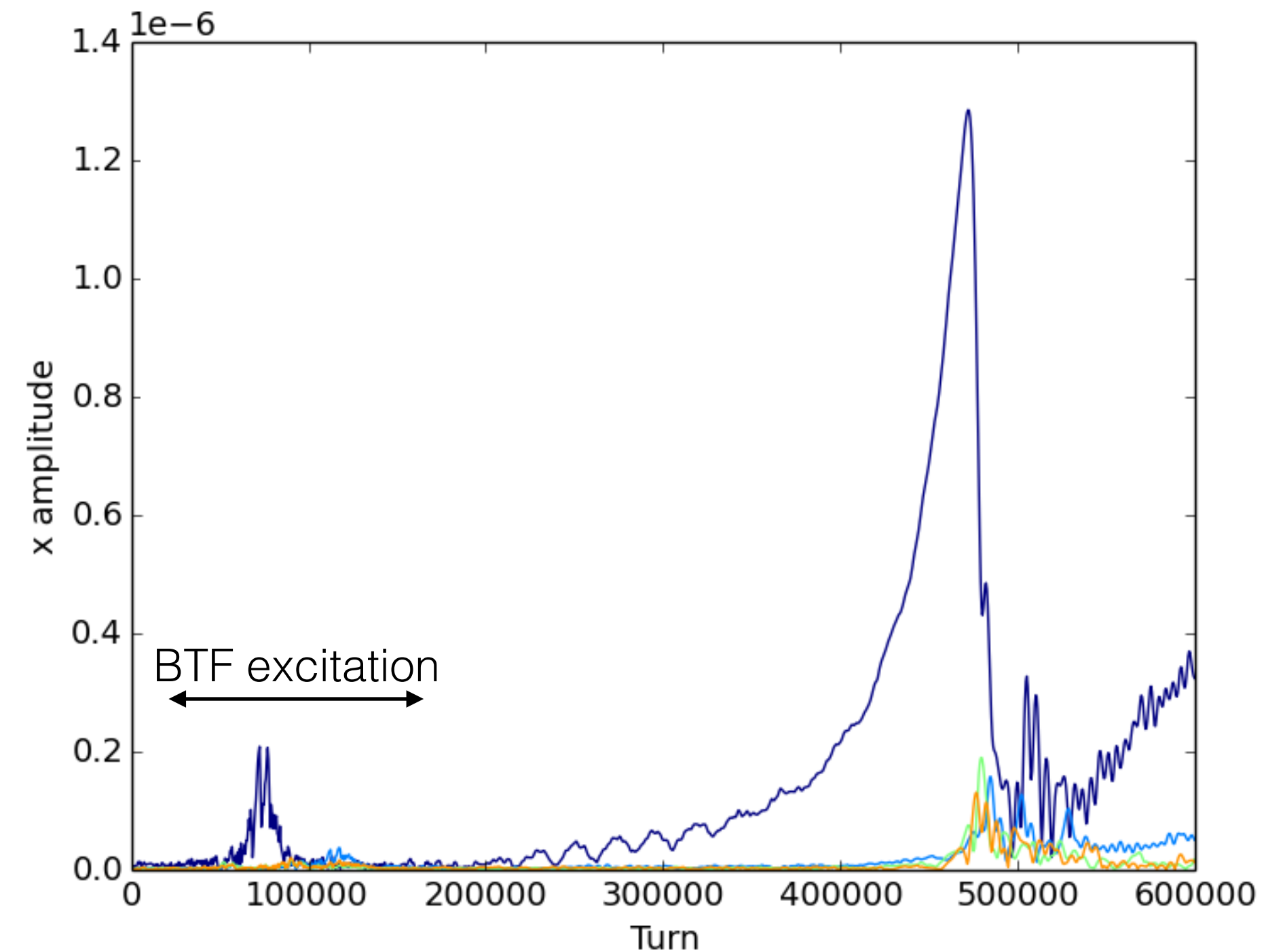
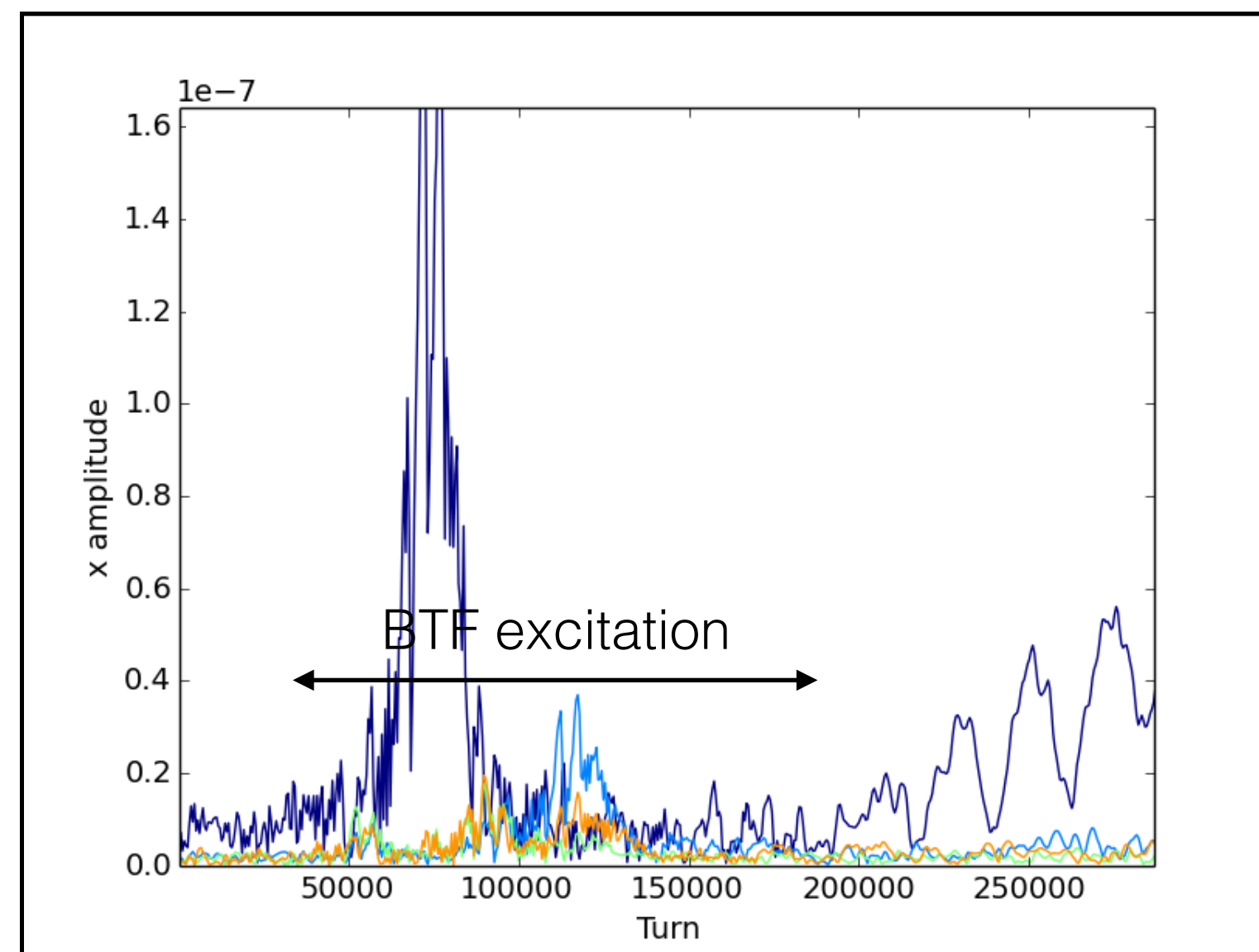
- At **flat top single beam** stability ensured by octupole magnets system ($DA > 18 \sigma$ both octupoles polarities)
- **End of squeeze (beam-beam LR):** reduction of stability with negative octupole polarity with $DA > 7.5 \sigma$ ($DA < 6 \sigma$ for positive oct. polarity) → **tight control on Q' values required (difficult in operations), alternatives proposed:**
 - **e-lens for Landau damping:**
 - **flat top energy:** 140 mA provide Landau damping ($m=1$ up to $Q'=20$ units), 400 mA required for $m=0$ at $Q=0$
 - **injection energy:** 600 mA will provide Landau damping ($m=1$ up to $Q'=20$ units), 1.4 A required for $m=0$ at $Q=0$
 - An **increase of the β -function** in the arcs of 50 % will compensate the reduction of the SD at the end of the squeeze
 - Use of **wide-band feedback**
- **Collapse sep. bumps (LR + HO crab on):** SD always larger or equivalent compared to the end of squeeze case
- **The new beam pipe would require ~30% more octupole strength to damp coherent modes**

Next studies:

- BIM-BIM simulations to include beam-beam LR coupling to impedance modes + transverse feedback and high chromaticity
- Noise impact on beam stability: with a small amplitude excitation ($2 \cdot 10^{-4} \sigma$) a higher octupole current is required for stability → this could be critical for FCC octupole magnet system

Thanks for your attention!

SVD - Mode Analysis



- From SVD analysis **mode $m=-1$** is unstable (as during measurements)
- Mode $m=-1$ is the most excited during BTF excitation
- **Mode $m=-1$ is not Landau damped anymore** due to non zero oscillations → increase of stability thresholds in terms of octupole current