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Beam-beam effects, octupoles and Landau damping

J. Barranco, X. Buffat, T. Pieloni, C. Tambasco

Acknowledgements: S. Antipov, D. Schulte, O. Boine-Frankenheim, R. Tomas, A. Seryi, M. Schenk, D. Amorin, V. Schiltzev, B. Dalena, S. Arsenyev, V. Kornilov, E. Metral, B. Salvant

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- Introduction: Landau damping and dynamic aperture
- Set-up of the octupoles in MAD-X and lattice
- Stability studies at collision energy:
    - Landau damping from octupole magnets (single beam and beam-beam)
    - Impact on DA
    - Landau damping from e-lens
- Stability studies at injection energy:
    - Landau damping from octupoles
    - Impact on DA
    - Landau damping from e-lens
- Summary and Outlook

Landau Damping

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

Particle distribution
(Dynamic Aperture)

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

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

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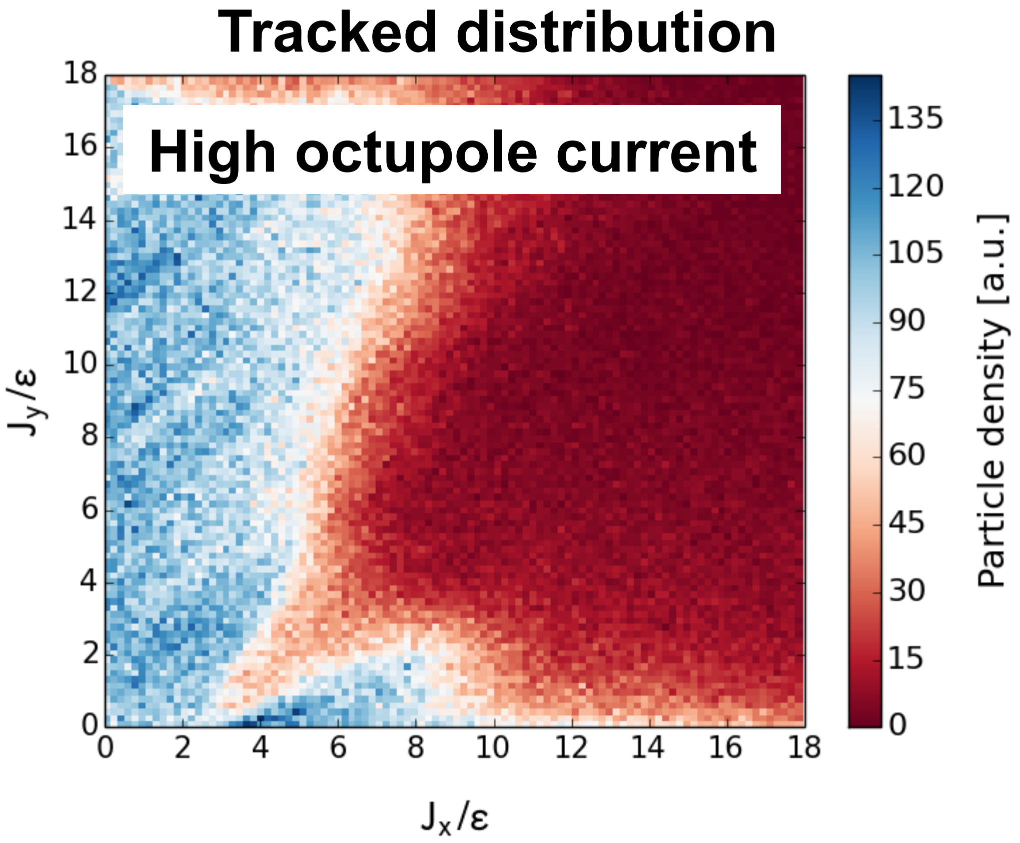
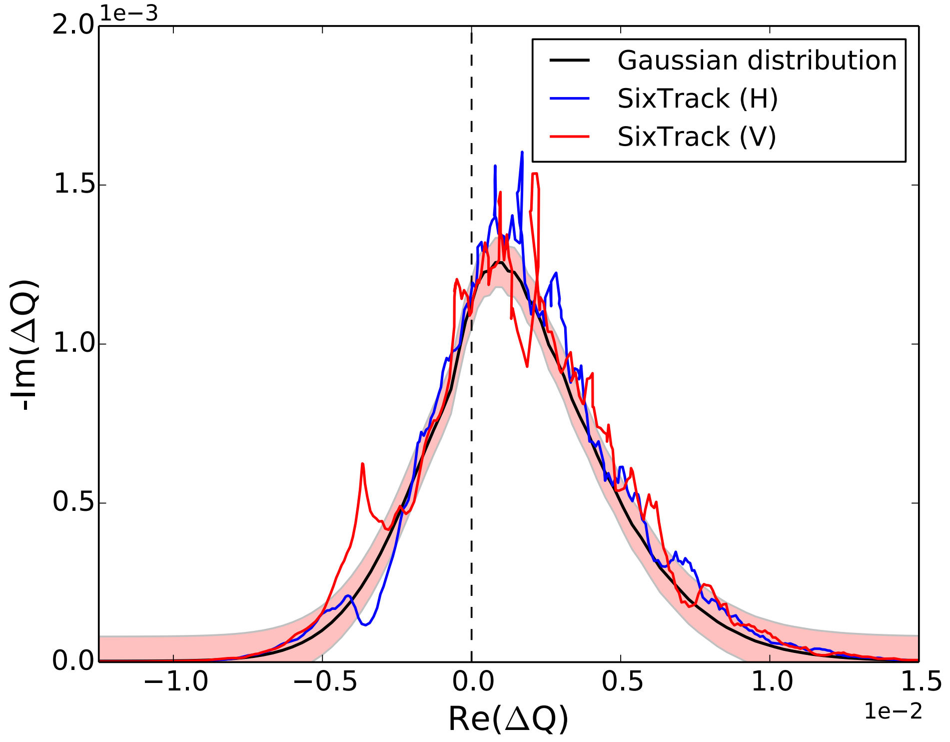

Tracked distribution

High octupole current



In presence of diffusive mechanisms and/or reduced dynamic aperture expected Landau damping may be reduced → evaluate impact of Dynamic Aperture [2]

[2] C. Tambasco, EPFL Thesis 7867 (2017)]

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Detuning with amplitude
(Octupoles magnets, machine non-linearities)

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Detuning with amplitude
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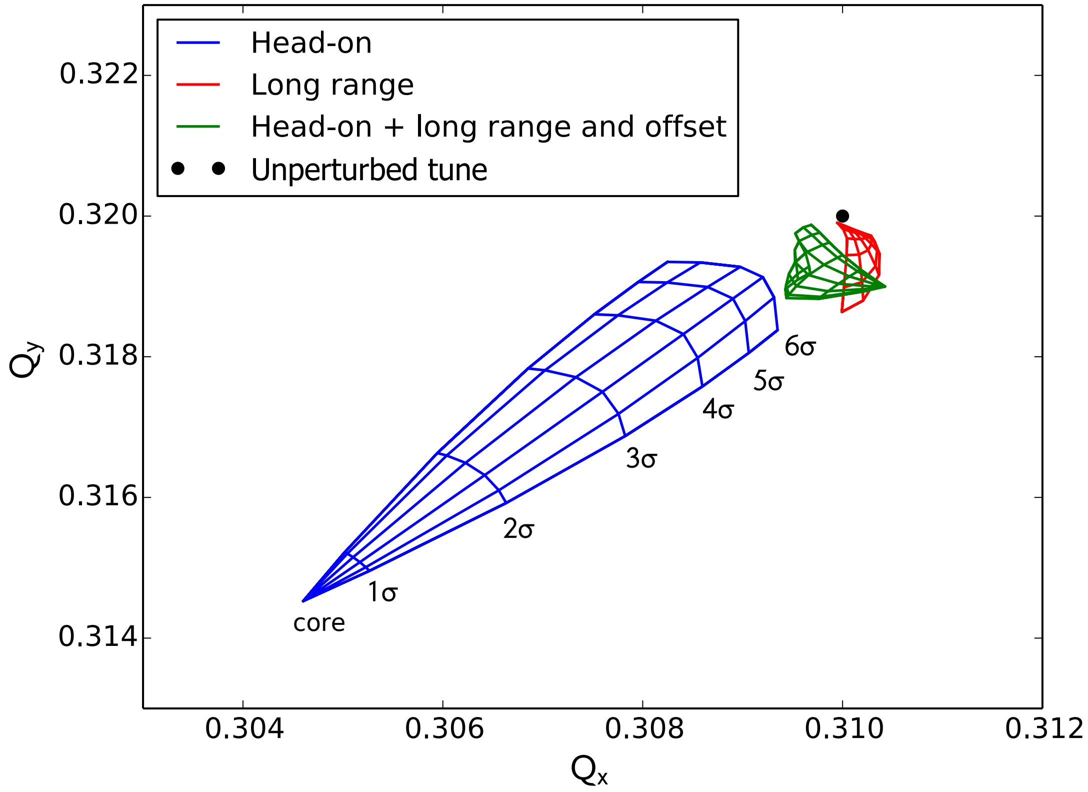
Tune Footprint with beam-beam



Beam-beam effects modify the stability provided by the Landau octupoles [3]

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

Landau Damping

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Detuning with amplitude
(Octupoles magnets, machine non-linearities)

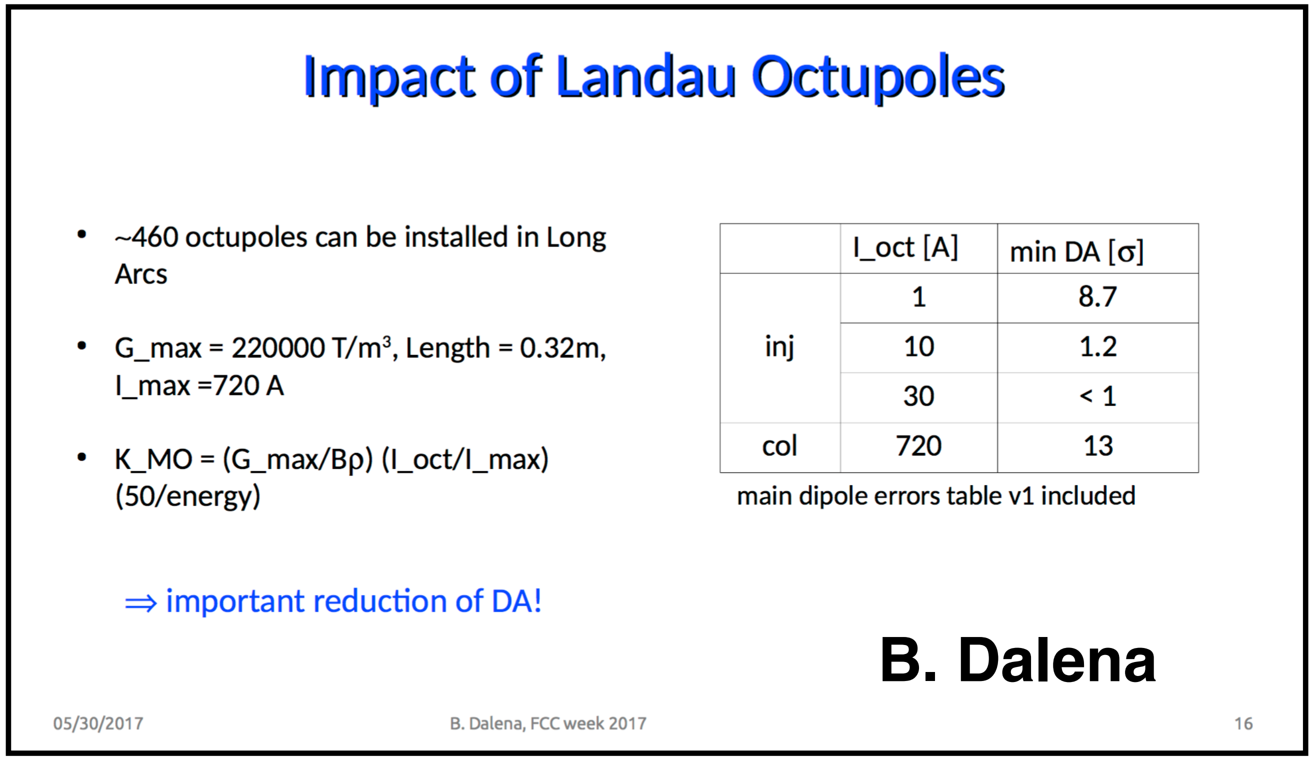
Simulation Tools:

- **MAD-X** → Frequency Distribution from tracking (**Landau octupoles, beam-beam interactions**, machine non-linearities)
- **SixTrack** → Particle distribution after long particle tracking and Dynamic Aperture
- **PySSD** → Semi analytical calculation of the SD by using detuning and particle distribution from from tracking

Octupoles and e-lens for Landau damping

Octupole magnets [J. Berg and F. Ruggero]	Electron lenses [V. Shiltsev et al.]
☑ Evaluate tune spread from octupoles ☑ Single beam (injection, flat top) ☑ Beam-beam ☑ Dynamic Aperture	☑ Evaluate tune spread from e-lens (injection, flat top)

Octupoles strength for FCC



Impact of Landau Octupoles

- ~460 octupoles can be installed in Long Arcs
- G_max = 220000 T/m^3, Length = 0.32m, I_max =720 A
- K_MO = (G_max/Bρ) (I_oct/I_max) (50/energy)

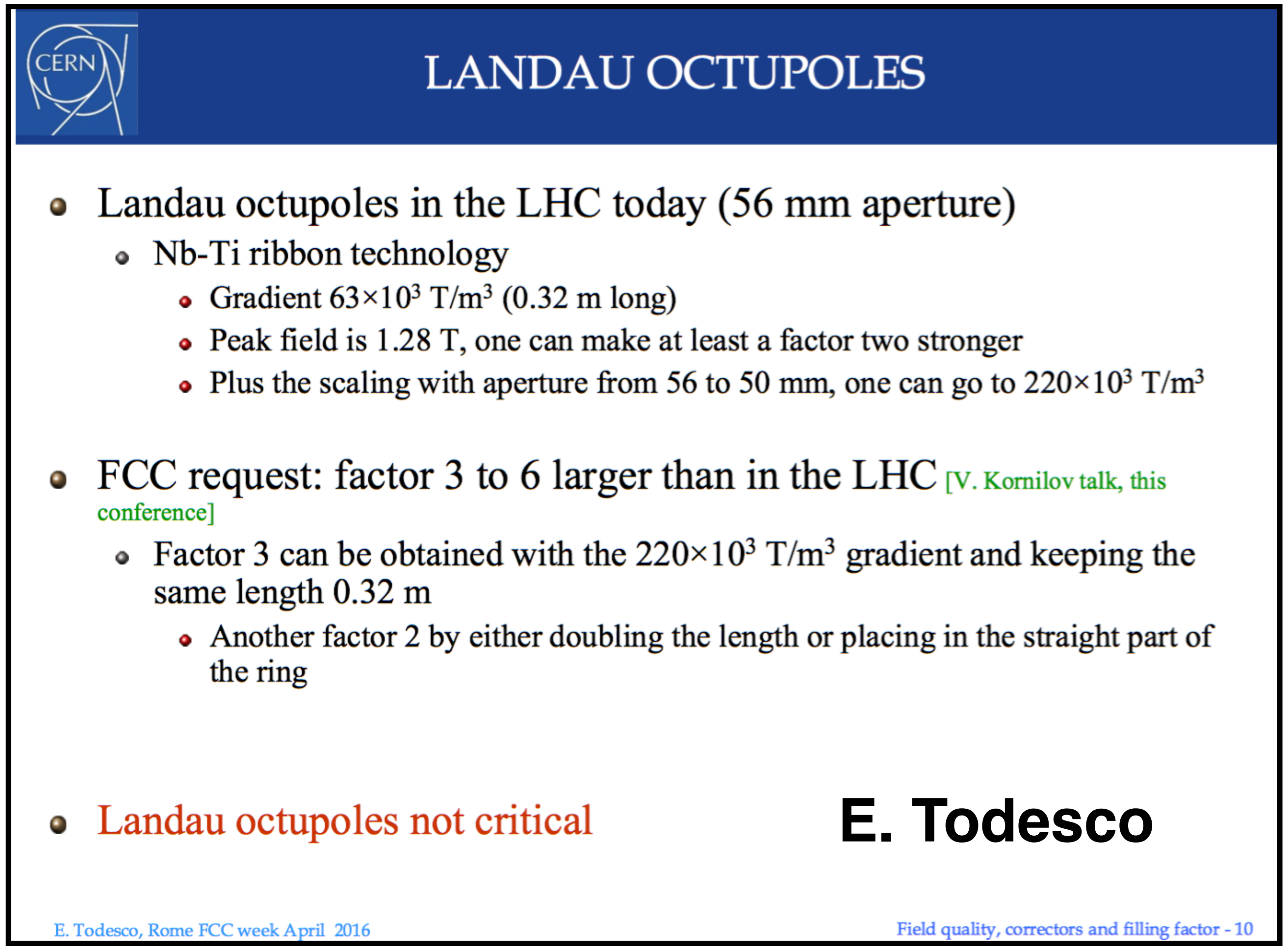
⇒ important reduction of DA!

	I_oct [A]	min DA [σ]
inj	1	8.7
	10	1.2
	30	< 1
col	720	13

main dipole errors table v1 included

B. Dalena

05/30/2017 B. Dalena, FCC week 2017 16



LANDAU OCTUPOLES

- Landau octupoles in the LHC today (56 mm aperture)
  - Nb-Ti ribbon technology
    - Gradient 63×10^3 T/m^3 (0.32 m long)
    - Peak field is 1.28 T, one can make at least a factor two stronger
    - Plus the scaling with aperture from 56 to 50 mm, one can go to 220×10^3 T/m^3
- FCC request: factor 3 to 6 larger than in the LHC [V. Kornilov talk, this conference]
  - Factor 3 can be obtained with the 220×10^3 T/m^3 gradient and keeping the same length 0.32 m
    - Another factor 2 by either doubling the length or placing in the straight part of the ring
- Landau octupoles not critical

E. Todesco

E. Todesco, Rome FCC week April 2016 Field quality, correctors and filling factor - 10

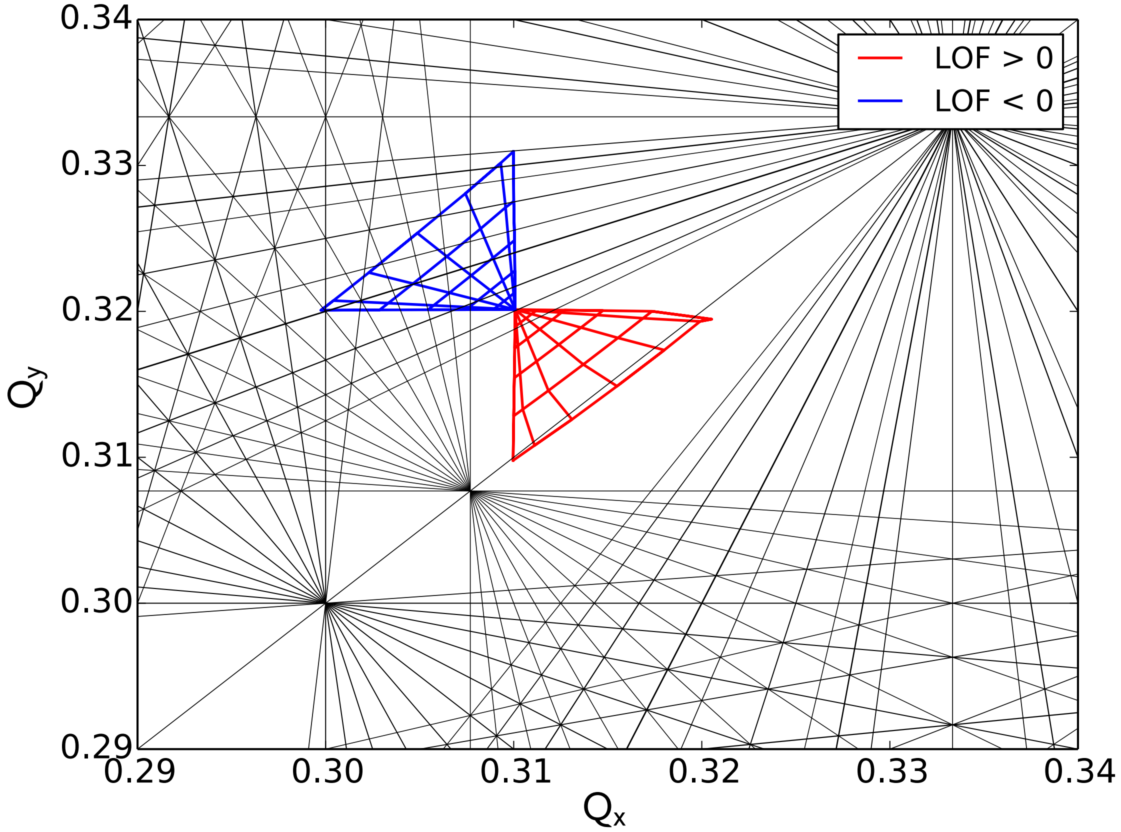
- Up to 460/520 octupoles can be installed
- Length=0.32 m
- G_{max}=220000 T/m^3
- Maximum current= 720 A

$FCC_{strength}/LHC_{strength}$ =0.48

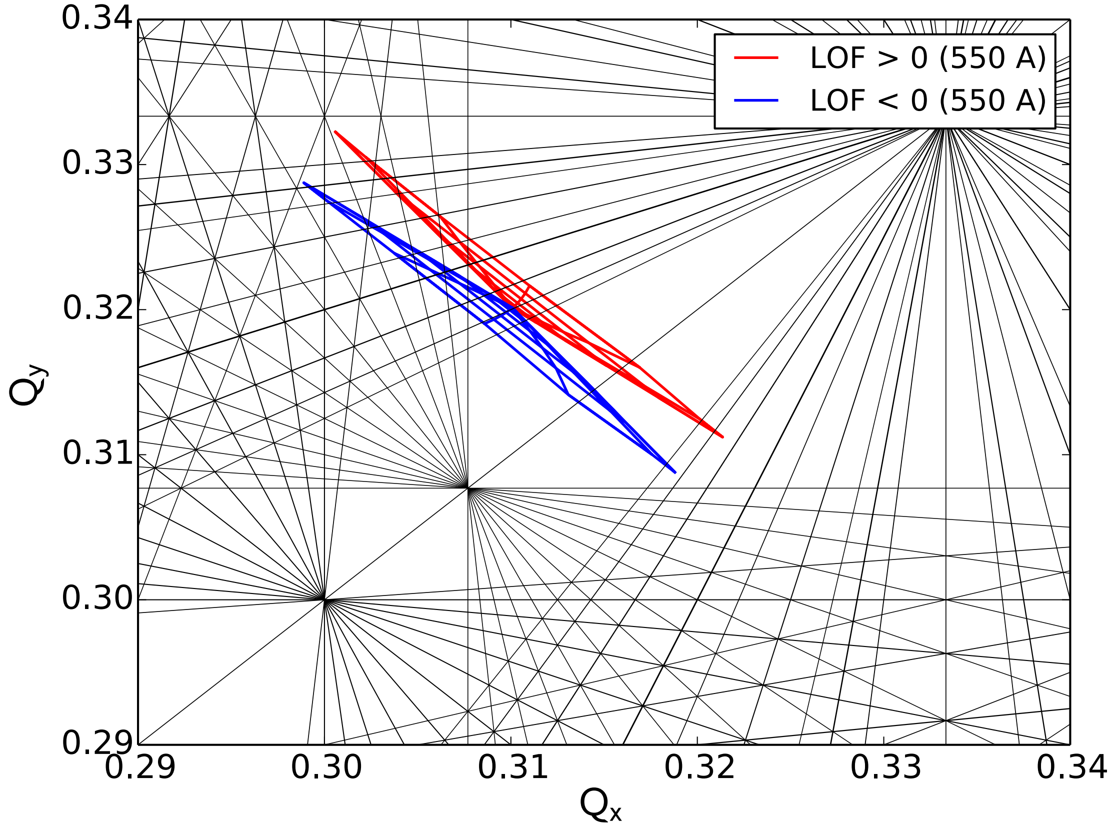
Tune spread from Landau octupoles

Computed tune footprint from MADX by using FCC collision lattice and tune spread from Landau octupoles

Two opposite sign for **“KMO“** strength (original installation)



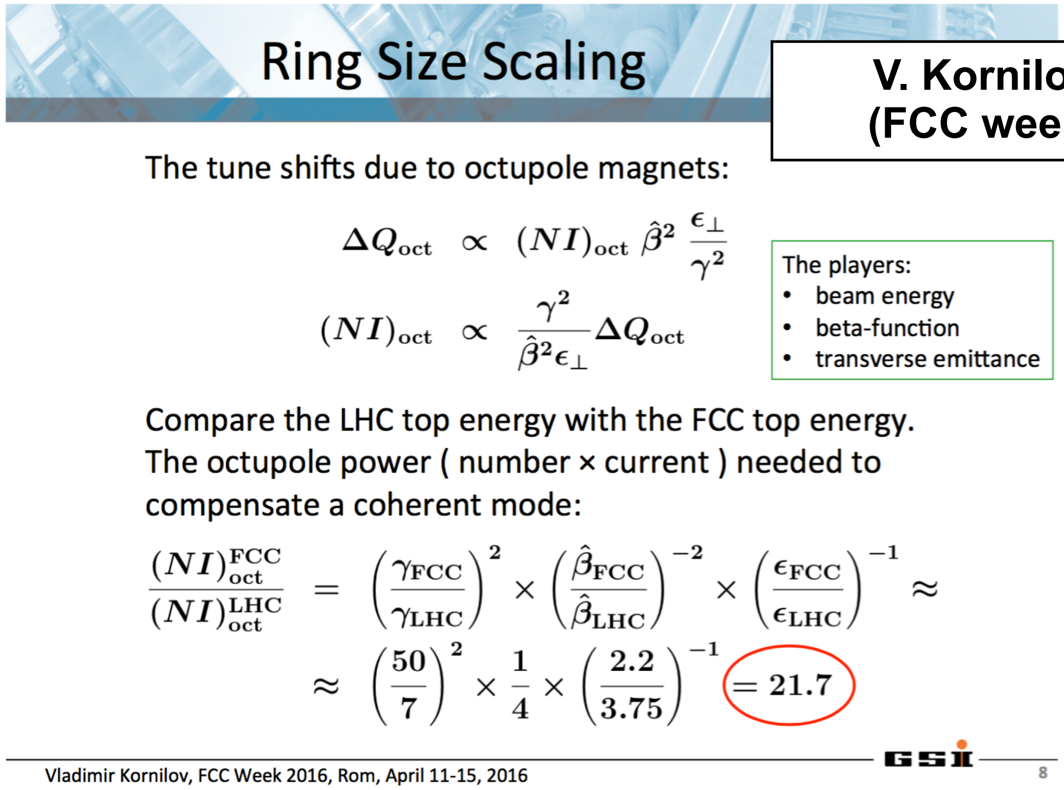
One octupole family as in the LHC (same sign for **“KOM“** strength)



The original installation of the Landau octupoles was including opposite sign for “KMO“ strength (opposite octupole polarity)

In LHC they are powered with the same polarity ➔ **improvement on DA** (see later)

Effectiveness of the Landau octupoles: LHC vs FCC



Ring Size Scaling

V. Kornilov et al. (FCC week 2016)

The tune shifts due to octupole magnets:

$$\Delta Q_{\rm oct} \propto (NI)_{\rm oct}\,\hat{\beta}^2\,\frac{\epsilon_\perp}{\gamma^2}$$

$$(NI)_{\rm oct} \propto \frac{\gamma^2}{\hat{\beta}^2\epsilon_\perp}\,\Delta Q_{\rm oct}$$

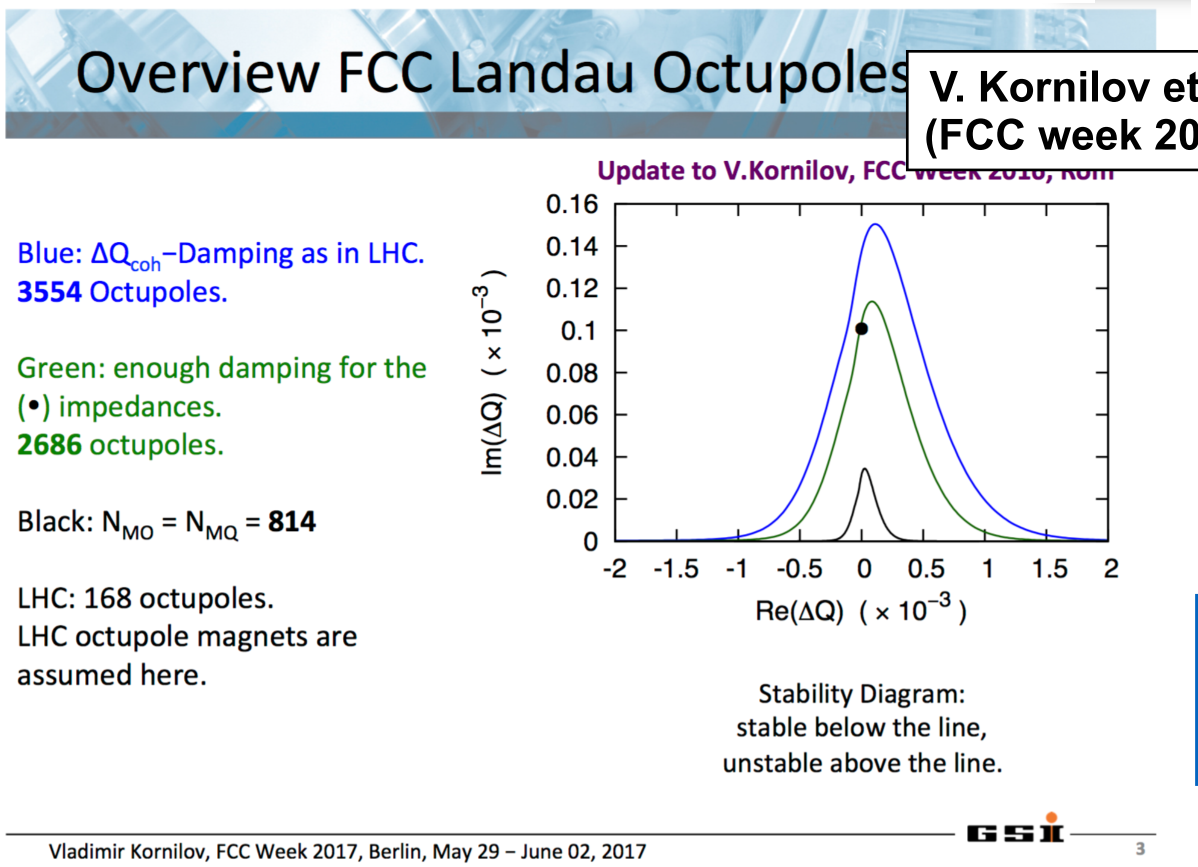
The players:
- beam energy
- beta-function
- transverse emittance

Compare the LHC top energy with the FCC top energy. The octupole power (number × current) needed to compensate a coherent mode:

$$\frac{(NI)^{\rm FCC}_{\rm oct}}{(NI)^{\rm LHC}_{\rm oct}} = \left(\frac{\gamma_{\rm FCC}}{\gamma_{\rm LHC}}\right)^2 \times \left(\frac{\hat{\beta}_{\rm FCC}}{\hat{\beta}_{\rm LHC}}\right)^{-2} \times \left(\frac{\epsilon_{\rm FCC}}{\epsilon_{\rm LHC}}\right)^{-1} \approx$$

$$\approx \left(\frac{50}{7}\right)^2 \times \frac{1}{4} \times \left(\frac{2.2}{3.75}\right)^{-1} \boxed{= 21.7}$$

Vladimir Kornilov, FCC Week 2016, Rom, April 11-15, 2016 GSI 8



Overview FCC Landau Octupoles

V. Kornilov et al. (FCC week 2017)

Update to V.Kornilov, FCC Week 2016, Rom

Blue: ΔQ_{coh}–Damping as in LHC. **3554** Octupoles.

Green: enough damping for the (•) impedances. **2686** octupoles.

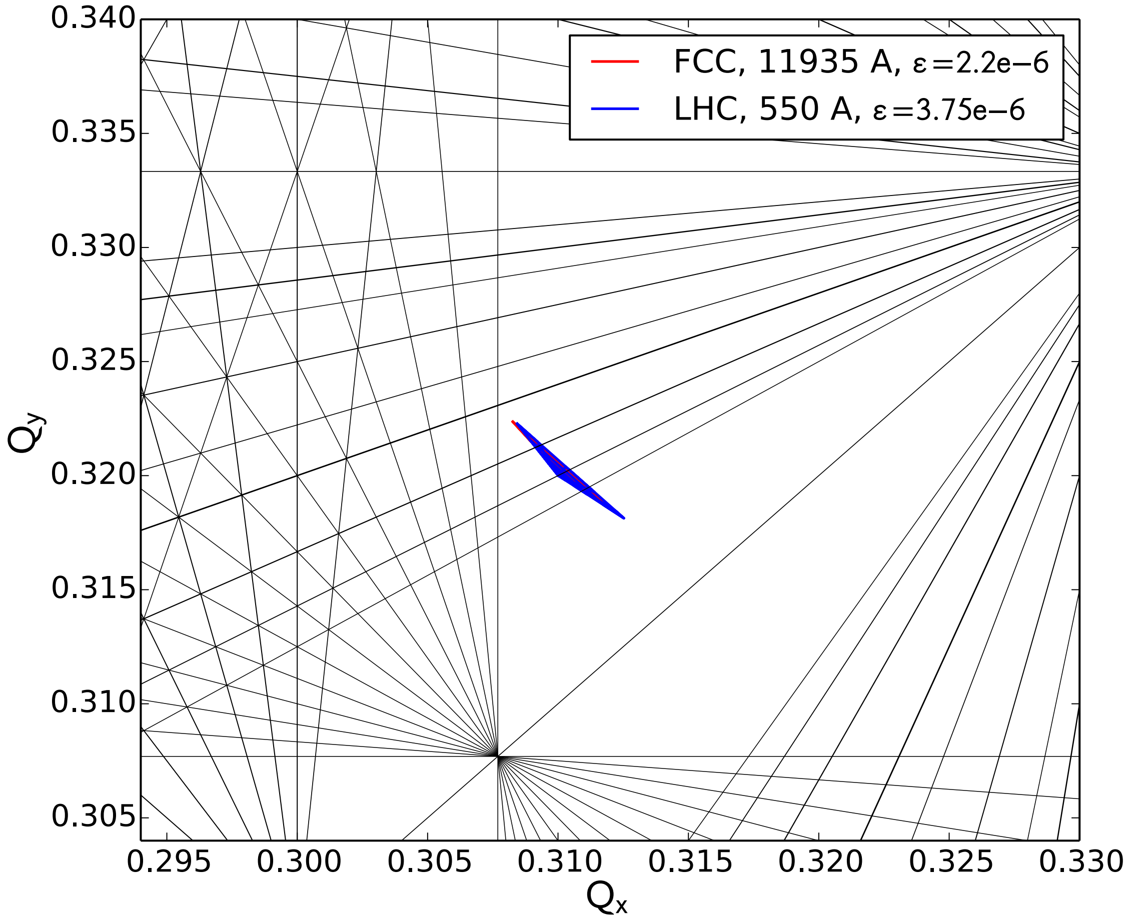
Black: $N_{MO} = N_{MQ} =$ **814**

LHC: 168 octupoles. LHC octupole magnets are assumed here.

Stability Diagram: stable below the line, unstable above the line.

Vladimir Kornilov, FCC Week 2017, Berlin, May 29 – June 02, 2017 GSI 3

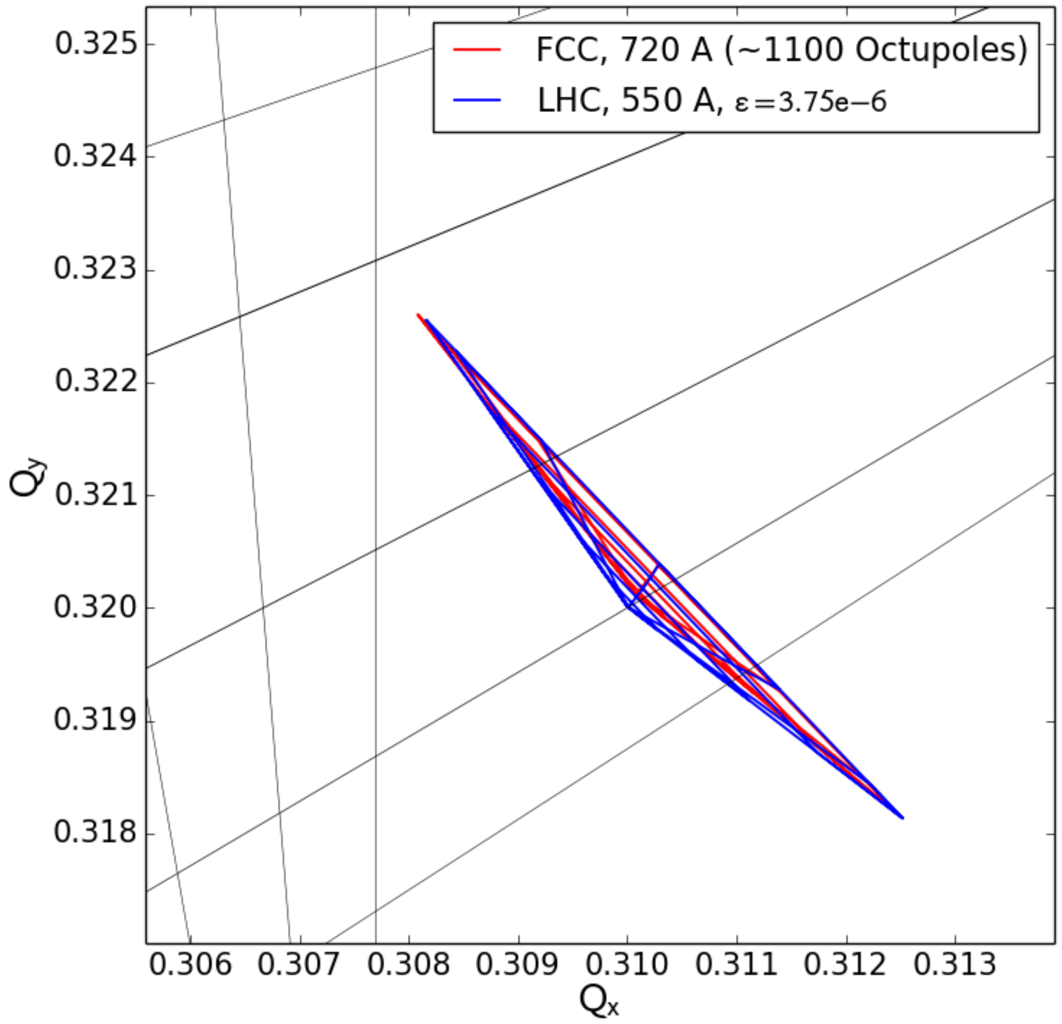
- Considering **168** Landau octupoles as in the LHC
- **LHC Octupole strength**



11935 A/550 A ➔ (3646/168)$_{\rm octupoles}$=21.7
➔ LHC tune spread recovered

Tune footprint with FCC octupole strength

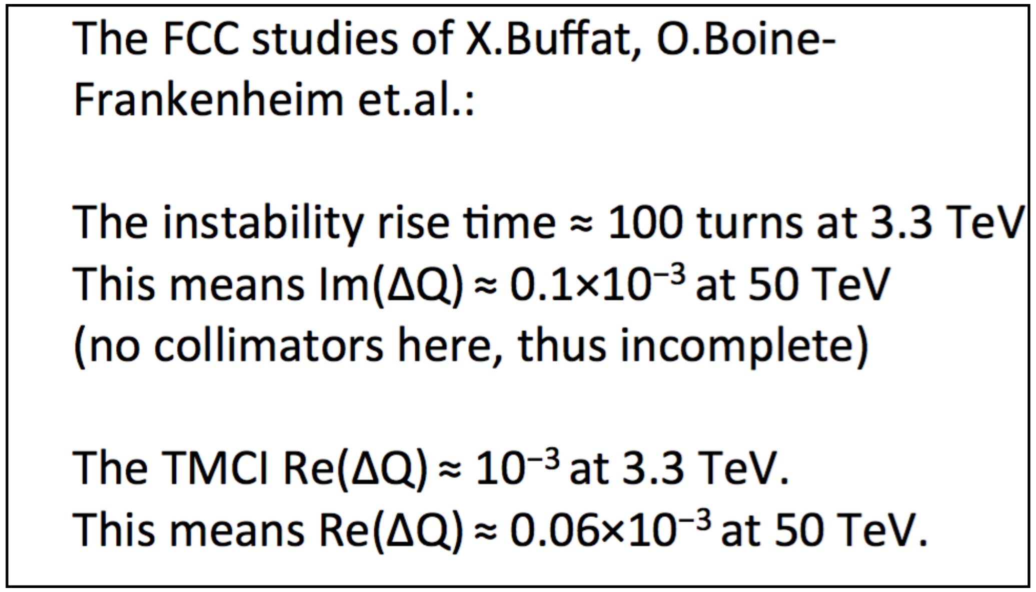
FCC case: 460 octupoles installed in MAD-X (1800 A ➔ 1150 octupoles), twice β-function and ~3.5 higher gradient than LHC



For FCC **~1100 octupoles are needed to reproduce LHC tune spread** (ε=2.2 μm) powered with the maximum current of 720 A➔ integrated strength ~ 1 [m^{-3}] (~2.5 * $FCC_{strength}$)

Computed stability diagram: LHC vs FCC

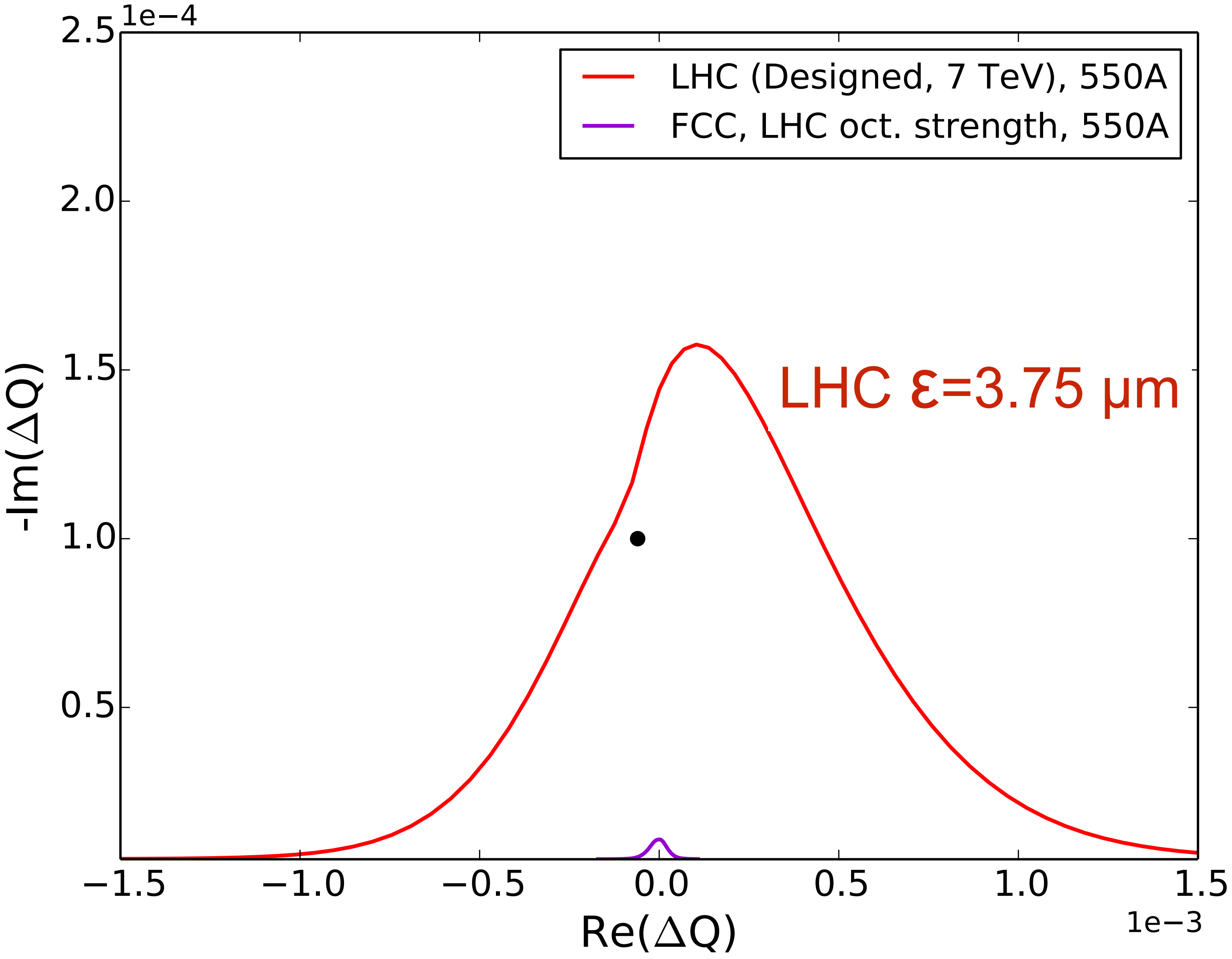
V. Kornilov (FCC week)



The FCC studies of X.Buffat, O.Boine-Frankenheim et.al.:

The instability rise time ≈ 100 turns at 3.3 TeV
This means Im(ΔQ) ≈ 0.1×10^{-3} at 50 TeV
(no collimators here, thus incomplete)

The TMCI Re(ΔQ) ≈ 10^{-3} at 3.3 TeV.
This means Re(ΔQ) ≈ 0.06×10^{-3} at 50 TeV.



Computed stability diagram: LHC vs FCC (single beam)

V. Kornilov (FCC week)

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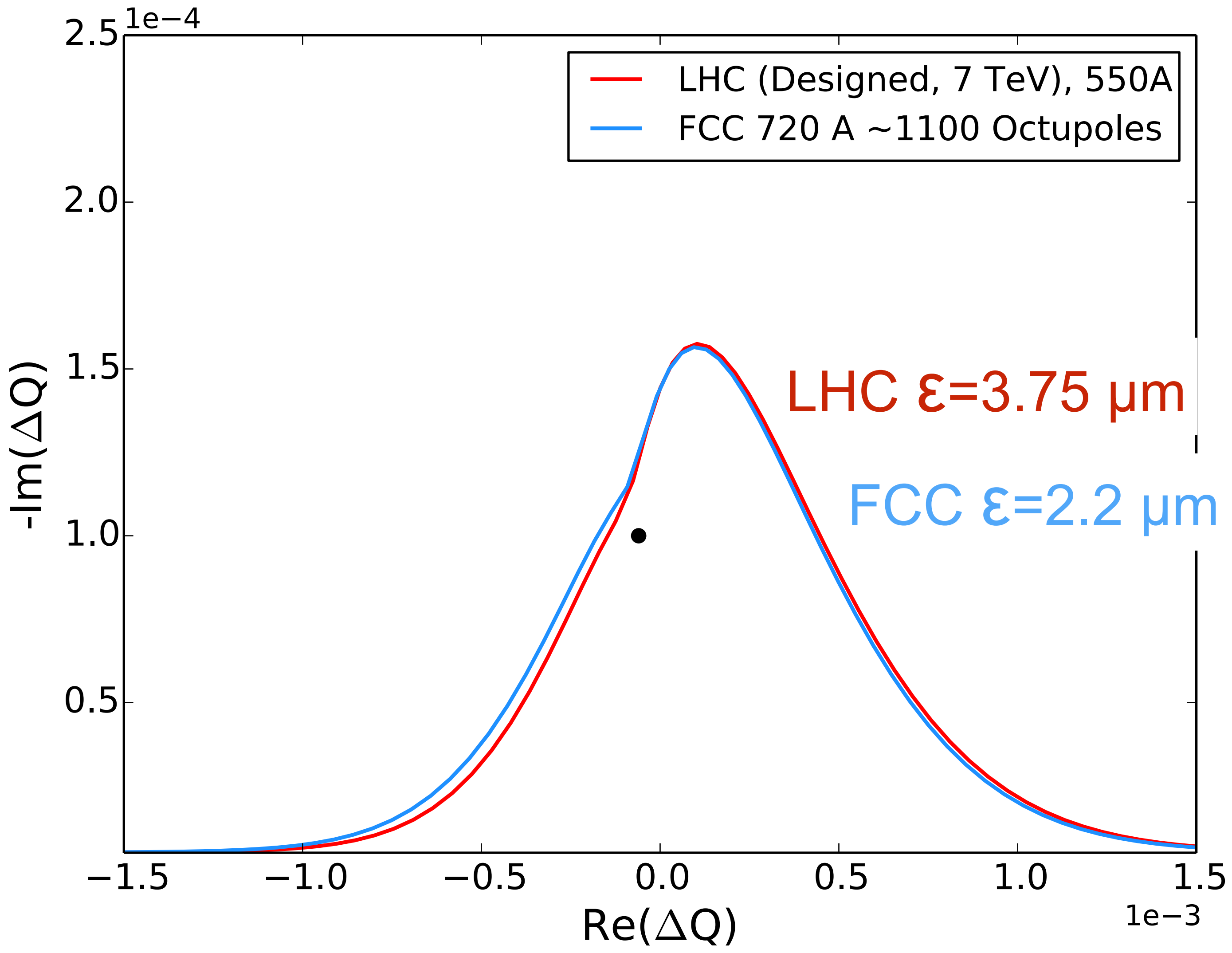
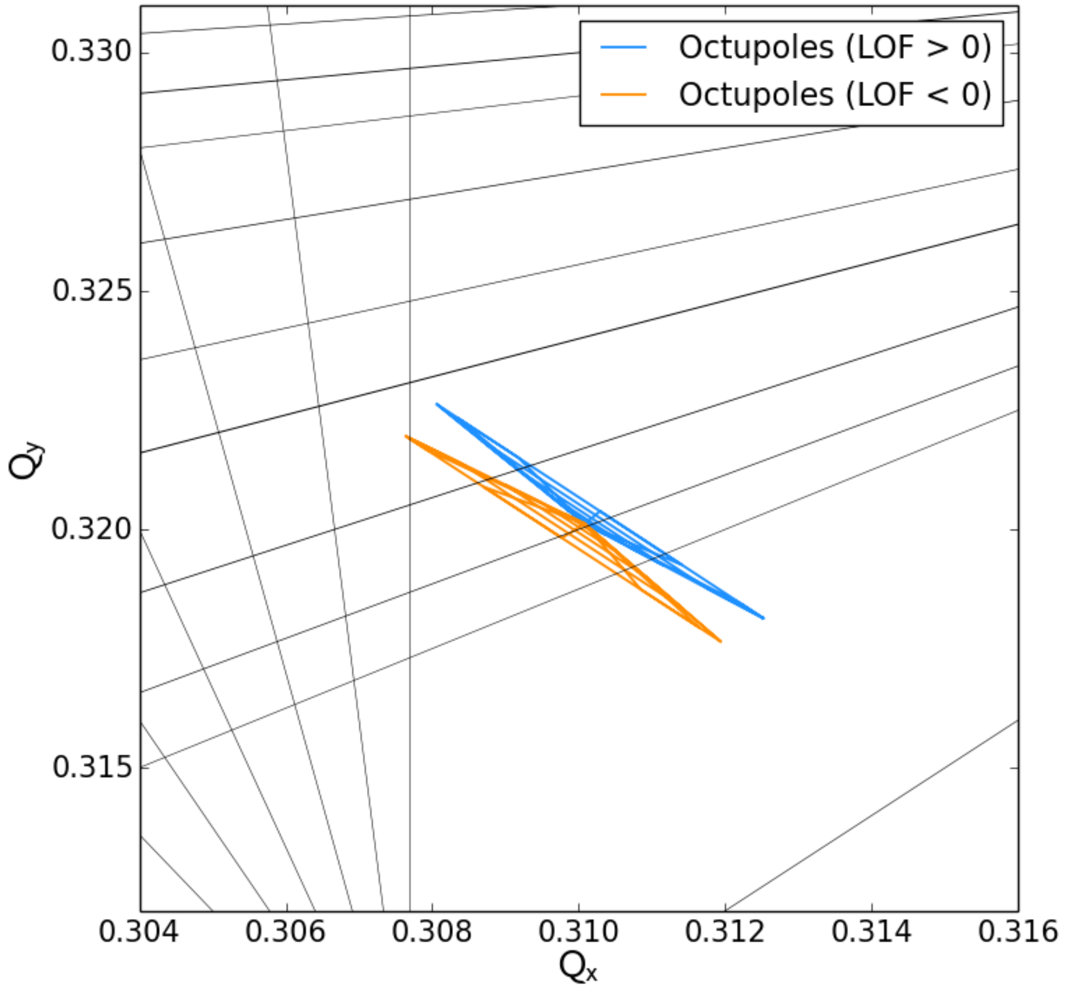


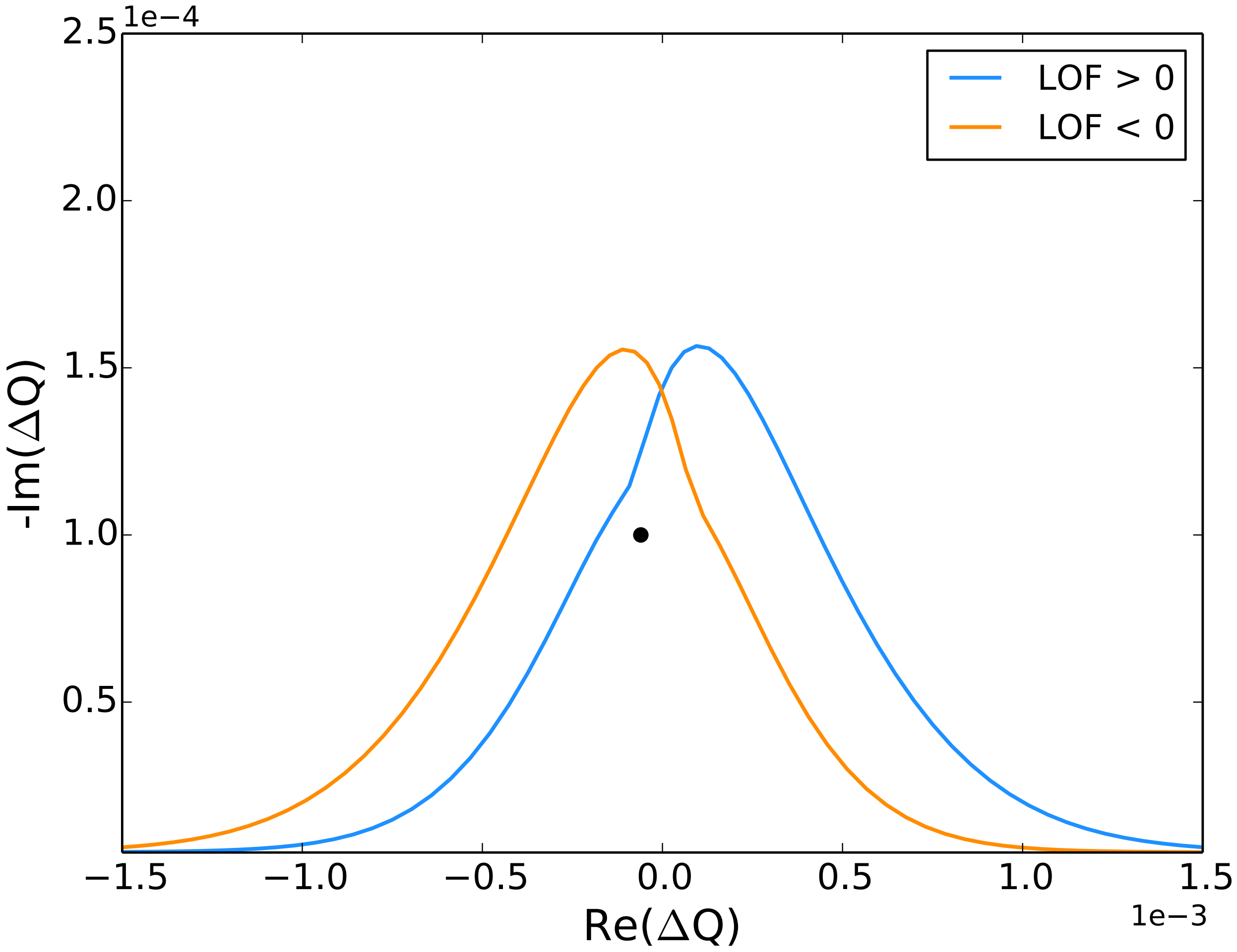
Considering the maximum FCC octupole strength and maximum current ~720 A ~1150 octupoles are needed to reproduce LHC stability (ε=3.75 μm)

Required integrated octupole strength: ~ 1.05 [m^{-3}]

Starting point: single beam

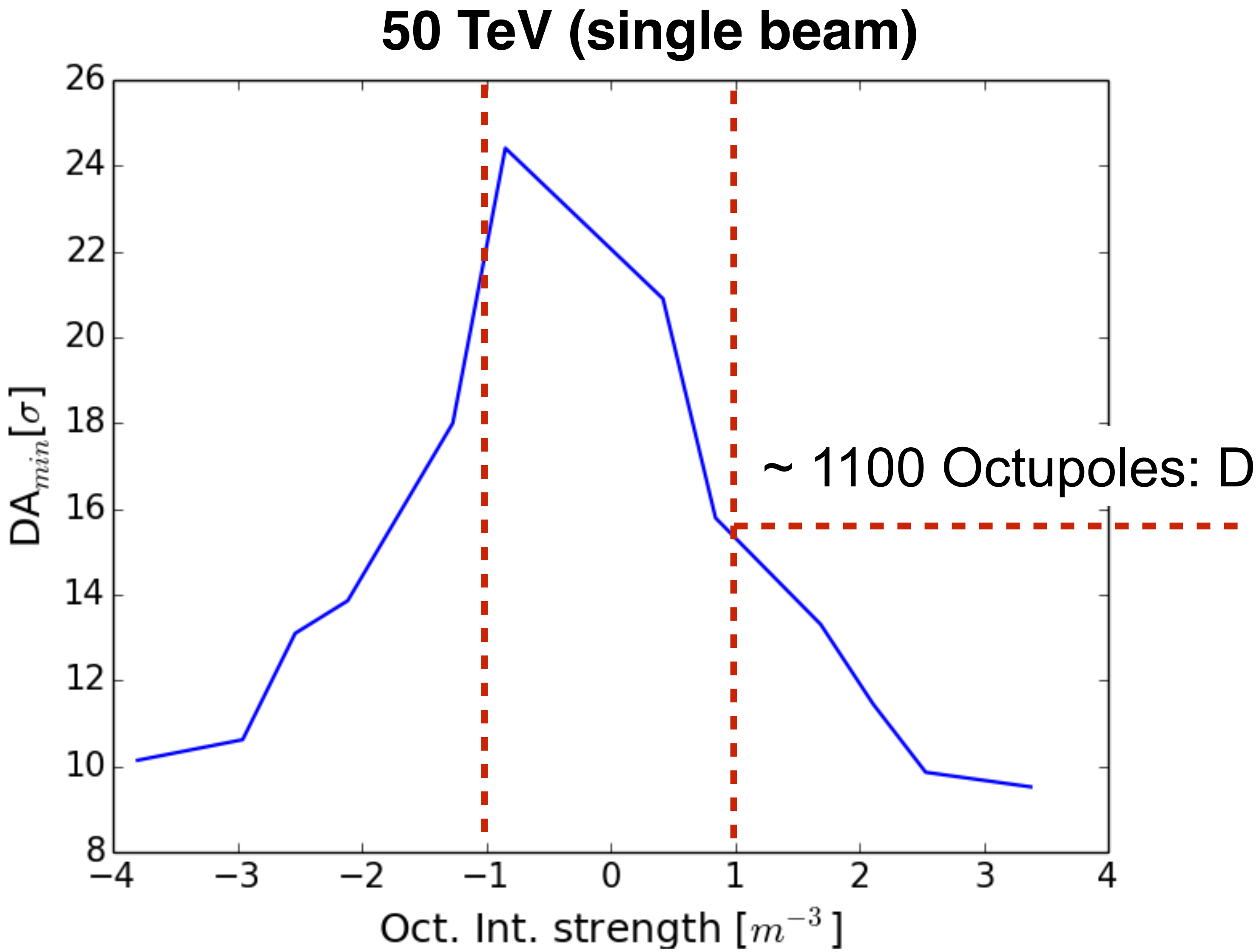
Octupole current: 720 A, ~1100 octupoles, int. oct. strength= 1.05 [m^{-3}]





- According to octupoles polarity the tune footprint is reversed
- The octupoles strength is chosen to provide sufficient tune spread to damp coherent impedance mode (m=0, q'=0)
- Larger stability expected for negative octupole polarity (int. oct. strength= 1.05 [m^{-3}])

Impact of Landau octupoles on DA

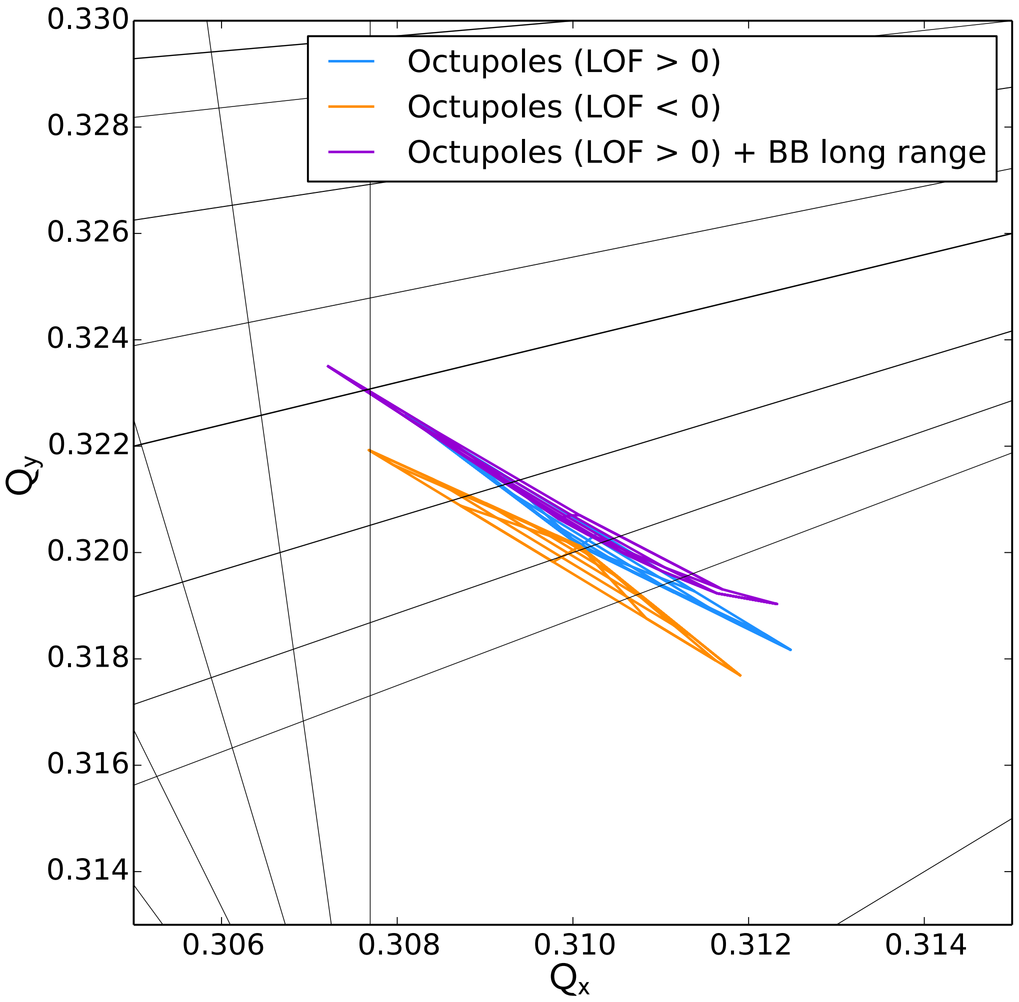


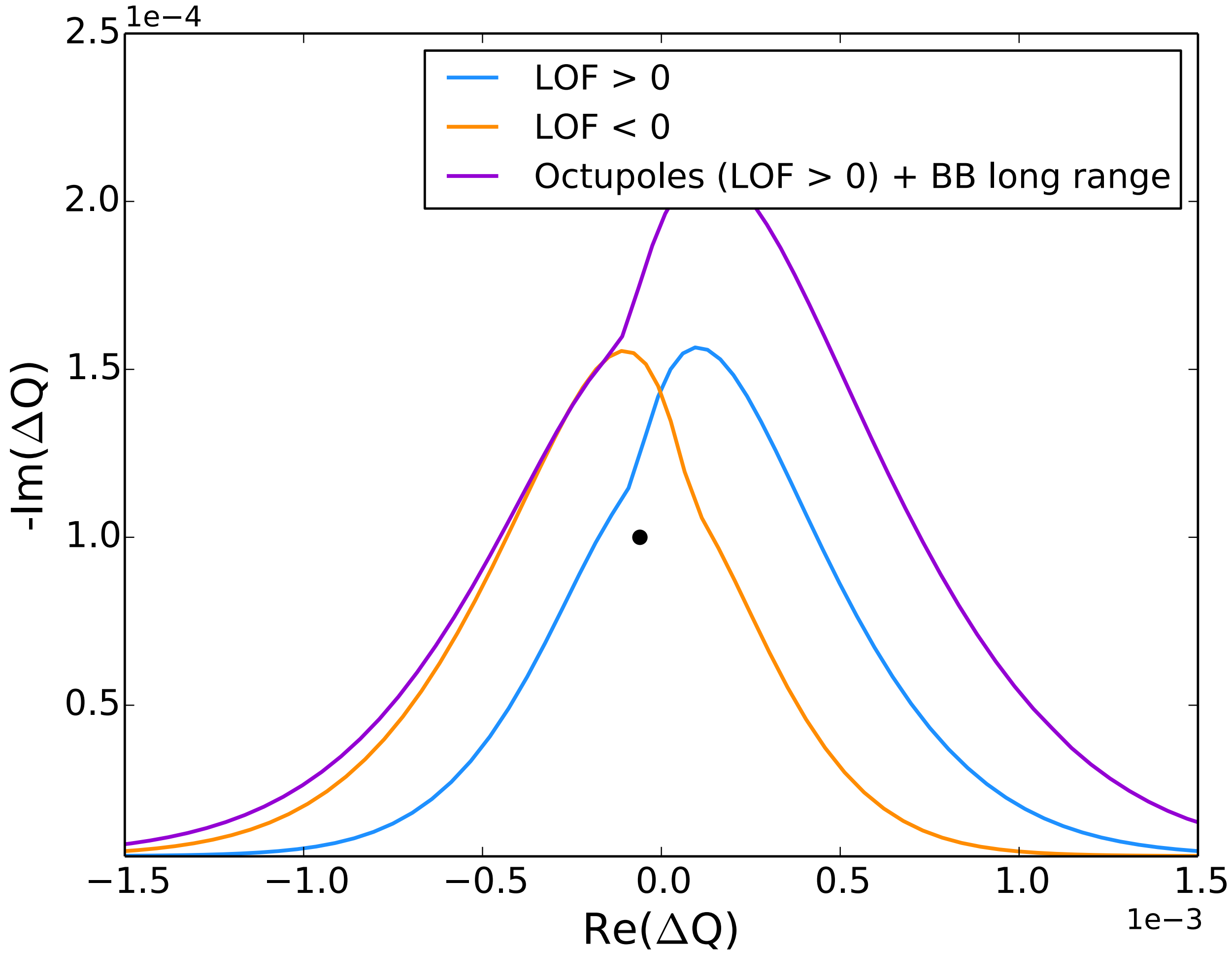
~ 1100 Octupoles: DA > 15σ (LOF> 0)

- DA above 15 σ in case of single beam and octupoles magnets
- Better DA with negative octupole polarity

Stability in presence of LR beam-beam interactions

Octupole current: 720 A, ~1100 octupoles (int. oct. strength= 1.05 [m^{-3}])

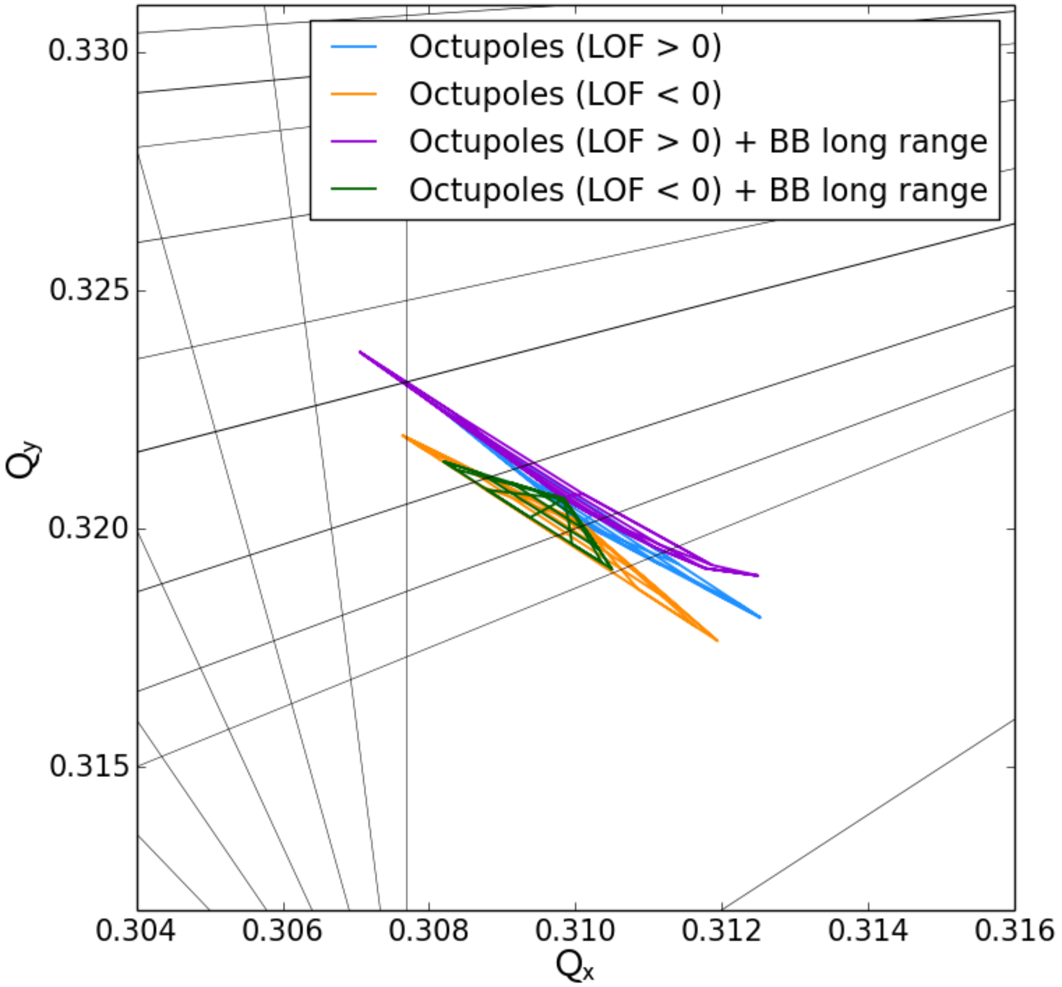


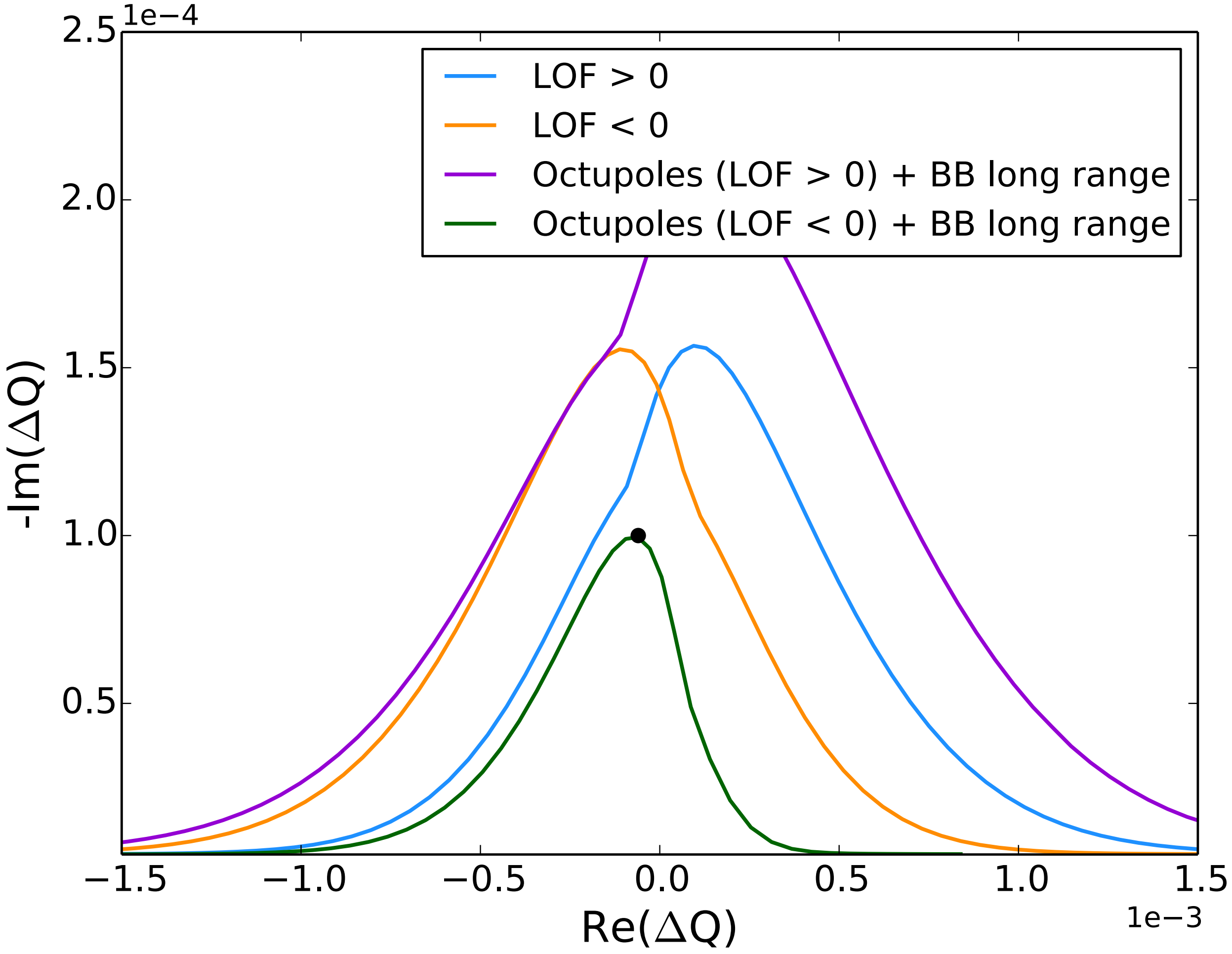


- Beam beam long range interaction (end of squeeze configuration) modifies the stability provided by the Landau octupoles
- With positive octupole polarity and BB long range interactions, the stability with negative polarity is recovered ➔ **impact on DA must to be taken into account**

Stability in presence of LR beam-beam interactions

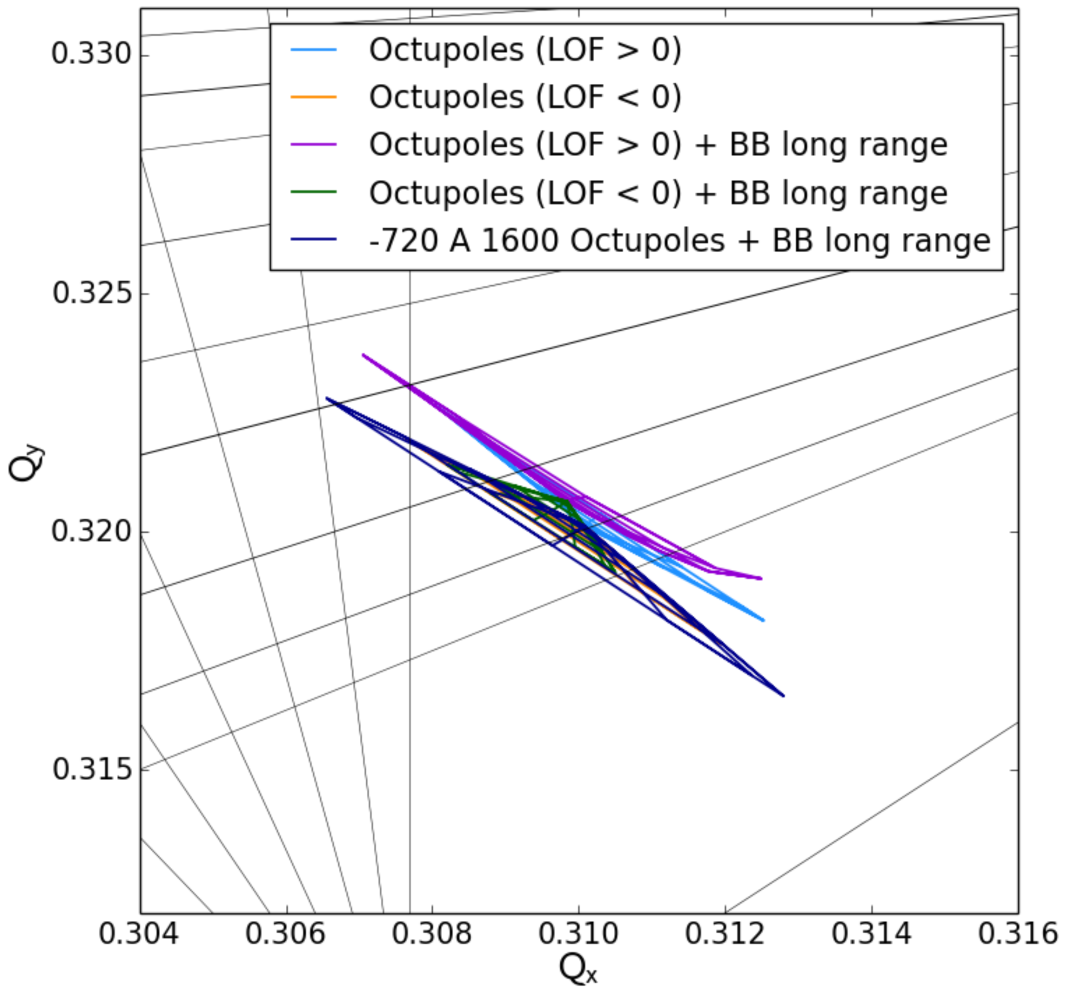
Octupole current: 720 A, ~1100 octupoles (int. oct. strength= 1.05 [m^{-3}])

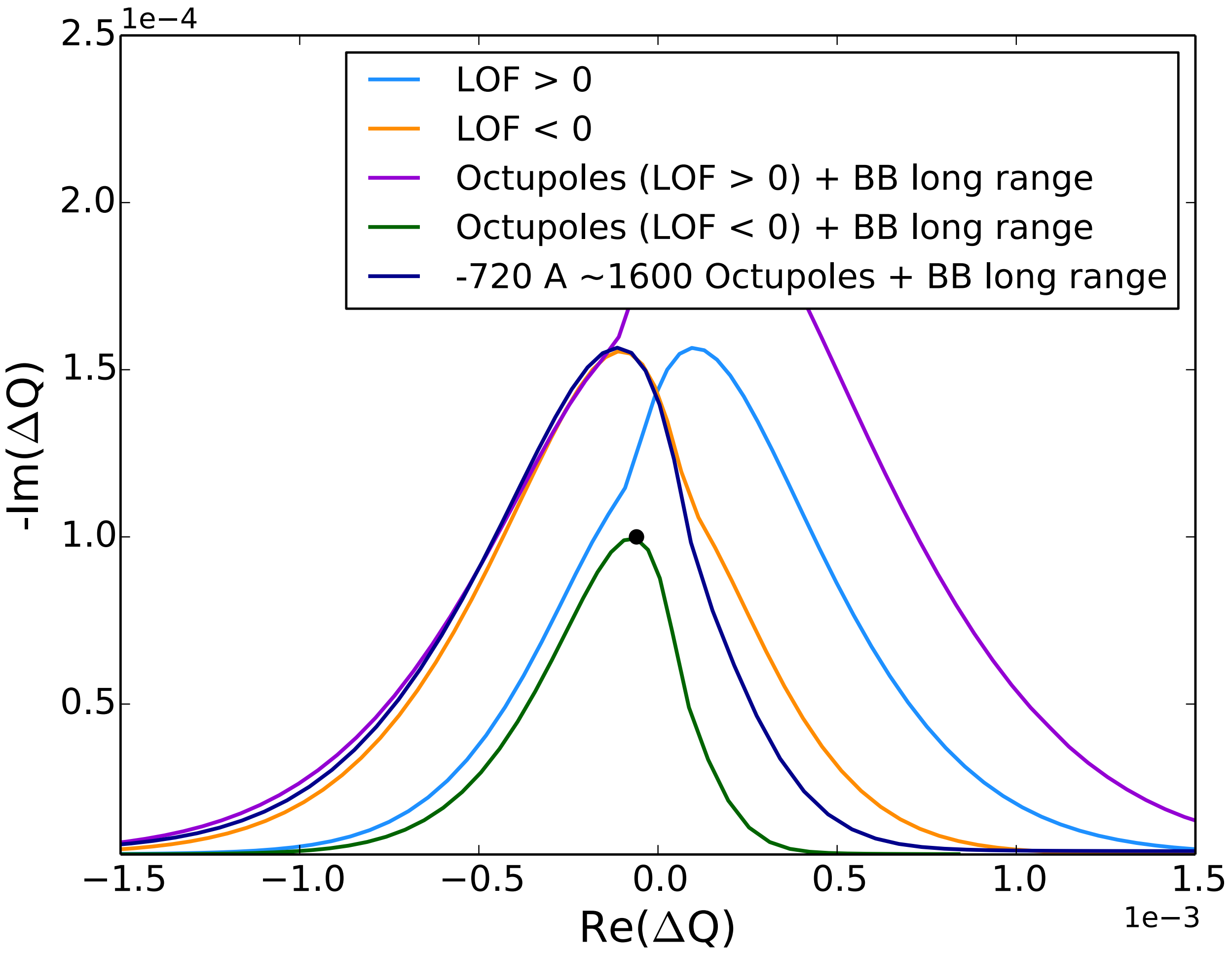




- With negative octupole polarity and BB long range interactions, the stability is strongly reduced ➔ **the coherent impedance mode is not Landau damped**

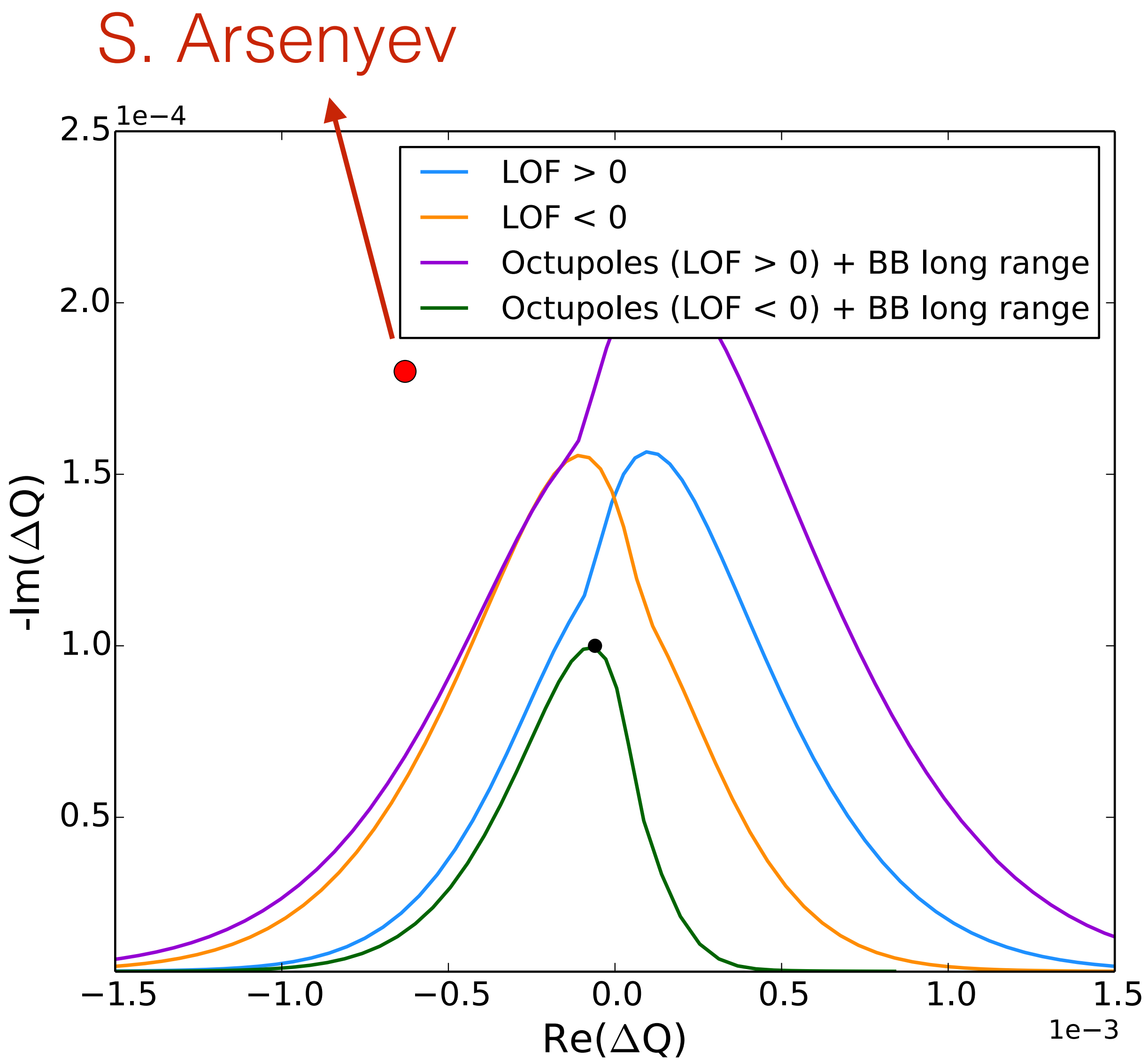
Compensation of stability reduction with beam-beam LR at the end of the betatron squeeze



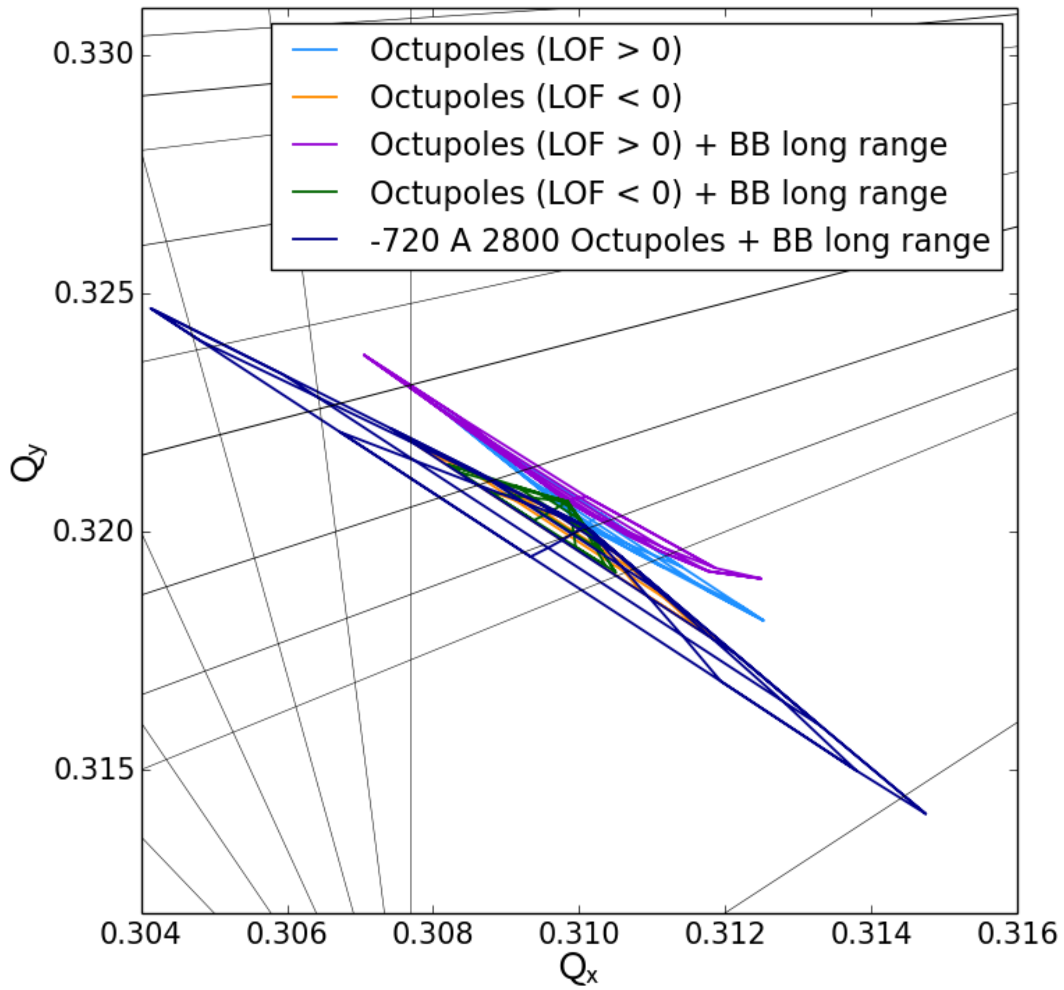


- In order to recover the needed tune spread, an **int. oct strength of ~1.5 m^{-3}** in case of negative octupole polarity and beam-beam long range interactions

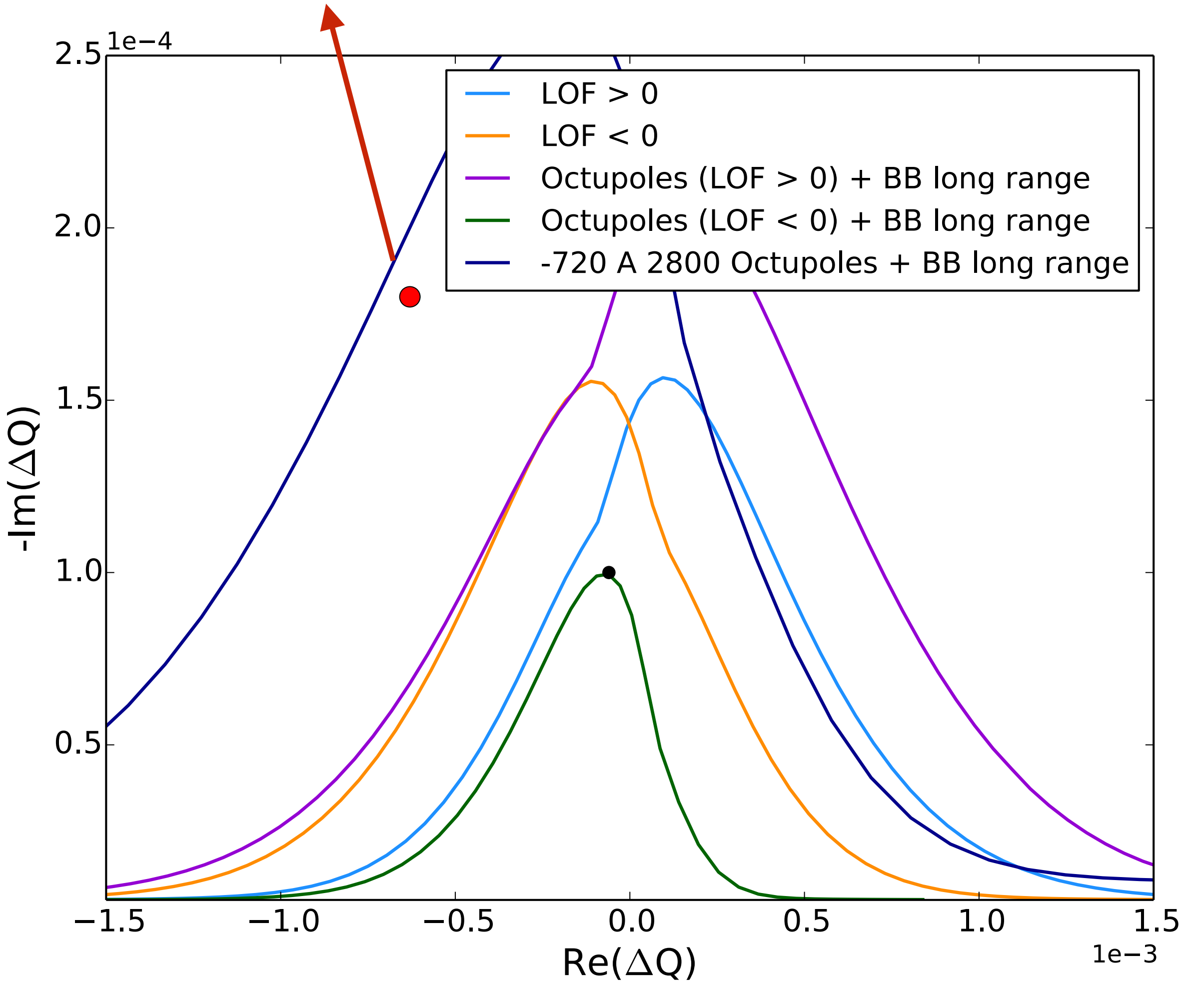
Compensation of stability reduction with beam-beam LR at the end of the betatron squeeze



Compensation of stability reduction with beam-beam LR at the end of the betatron squeeze

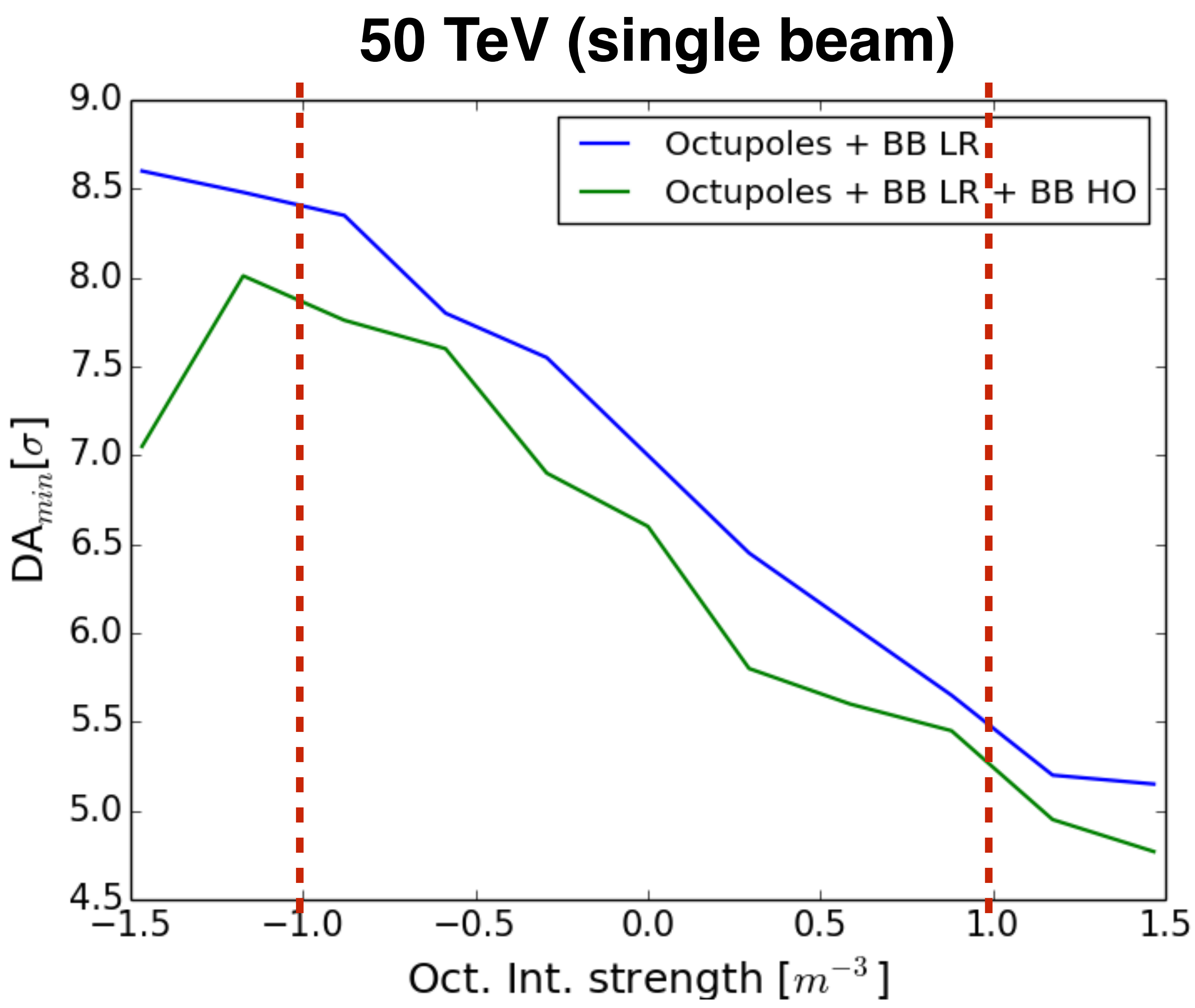


S. Arsenyev



- 2800 Octupoles are needed to damp impedance mode from S. Arsenyev ➔ **int. oct. strength of ~2.5 m^{-3} (6 times FCC strength)**
- Better DA is expected with negative octupole polarity w.r.t. positive polarity case with single beam and in presence of beam-beam interactions

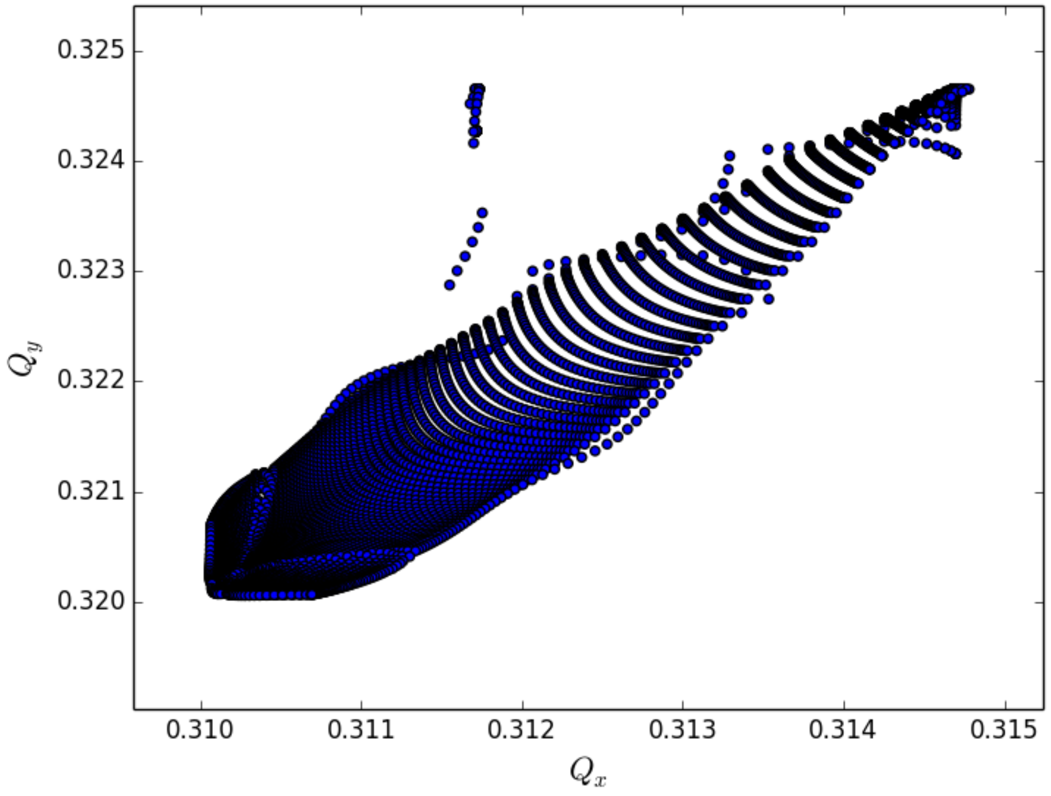
Impact of Landau octupoles and beam-beam interactions on DA

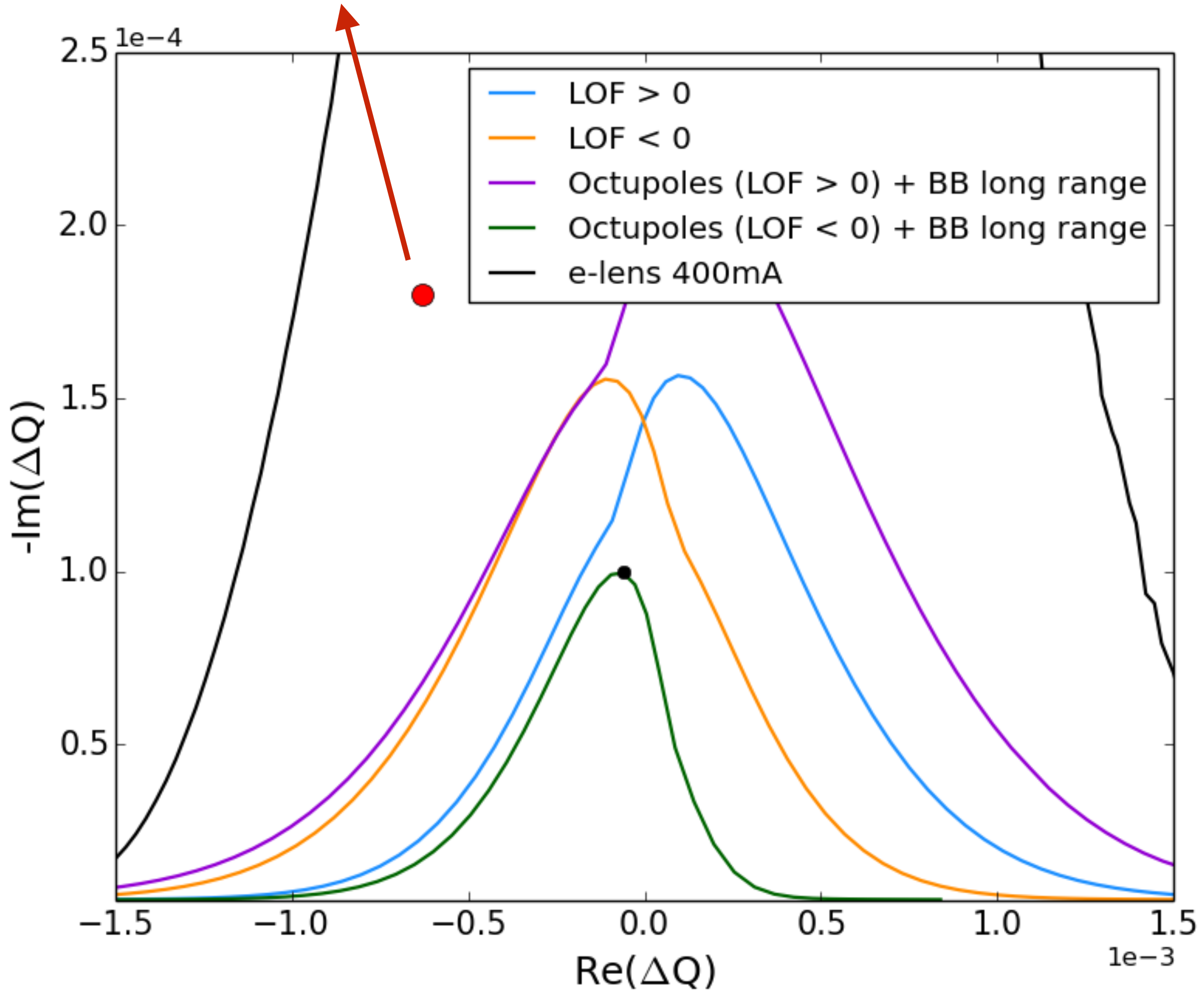


- **Compensation of LR BB observed for negative octupoles** (see J. Barranco talk)
- **DA above 6.5 σ in case beam-beam long range interactions and negative octupole polarity**
- DA is reduced up to 5 σ in case of positive octupole polarity and beam-beam long range interactions

Stability diagram with e-lens

Landau damping from e-lens at flat top in collaboration with FNAL as V. Shiltsev proposed at FCC week [4]



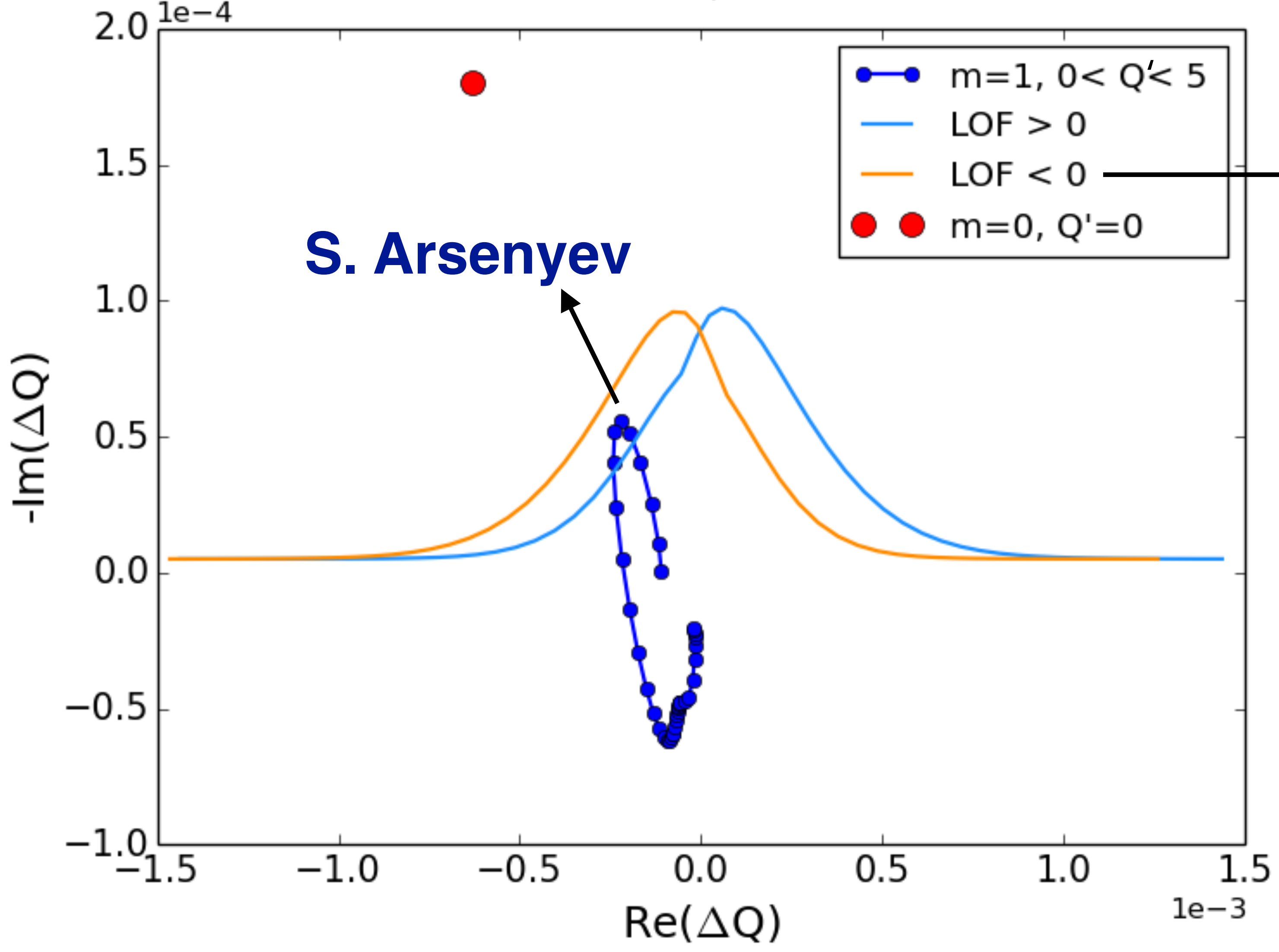

S. Arsenyev

- Tools in place: COMBI (RHIC benchmark) and SixTrack (see J. Barranco)
- An electron lens powered with 400 mA will damp the impedance mode m=0 q’=0 ➔ impact on DA must be addressed

[4] “Landau Damping of Beam Instabilities by Electron Lenses” V. Shiltsev et al. Phys. Rev. Lett. 119, 134802

Landau damping for m≠ 0 and Q≠ 0 (collision energy)

50 TeV (single beam)

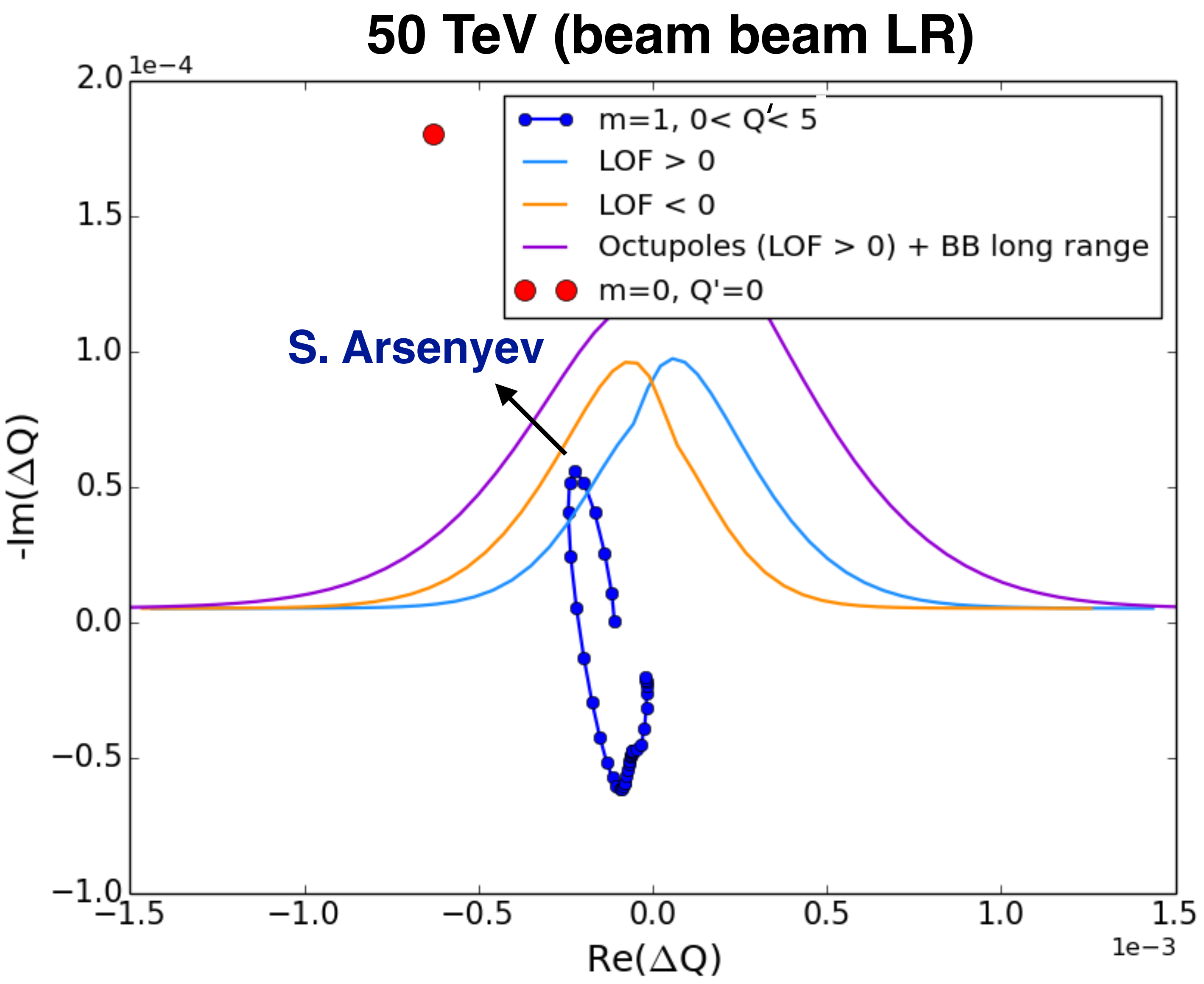


S. Arsenyev

~700 Octupoles (720 A)
(int. oct. strength= 0.6 m^{-3})

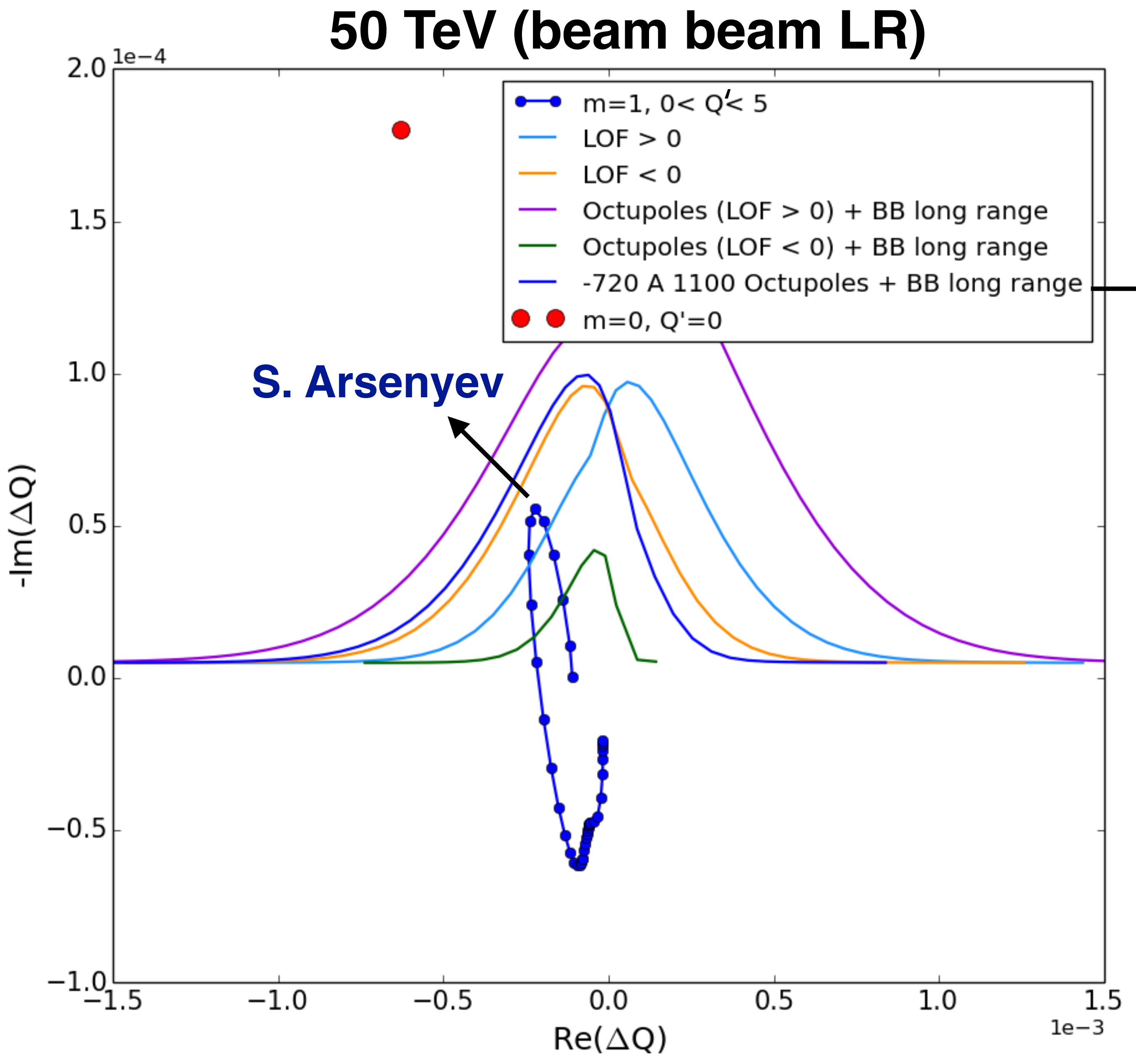
- LHC run with high chromaticity (Q’=15), m=0 damped by transverse feedback
  ➔ Different scenario: Q’ > 0 and m=0 damped by feedback
- **Less octupole current is needed to stabilize high order modes ➔ 0.6** m^{-3}

Landau damping for m≠ 0 and Q≠ 0 (collision energy)



- Tune spread from bb LR and positive octupoles adds up ➔ larger stability but smaller DA: **5.8 σ instead of ~7 σ as in case of negative octupole polarity**

Landau damping for m≠ 0 and Q≠ 0 (collision energy)


50 TeV (beam beam LR)

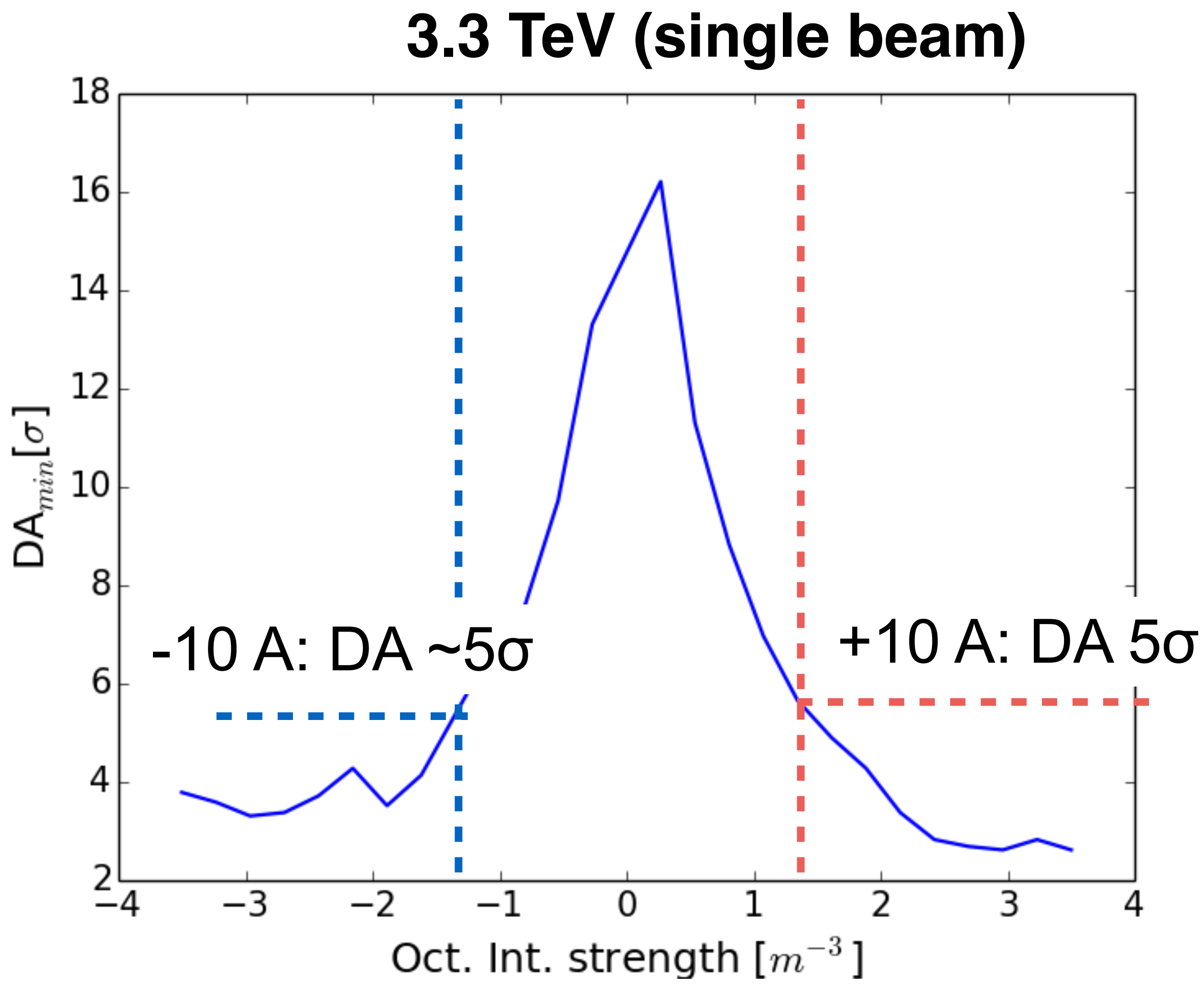
S. Arsenyev

~1100 Octupoles

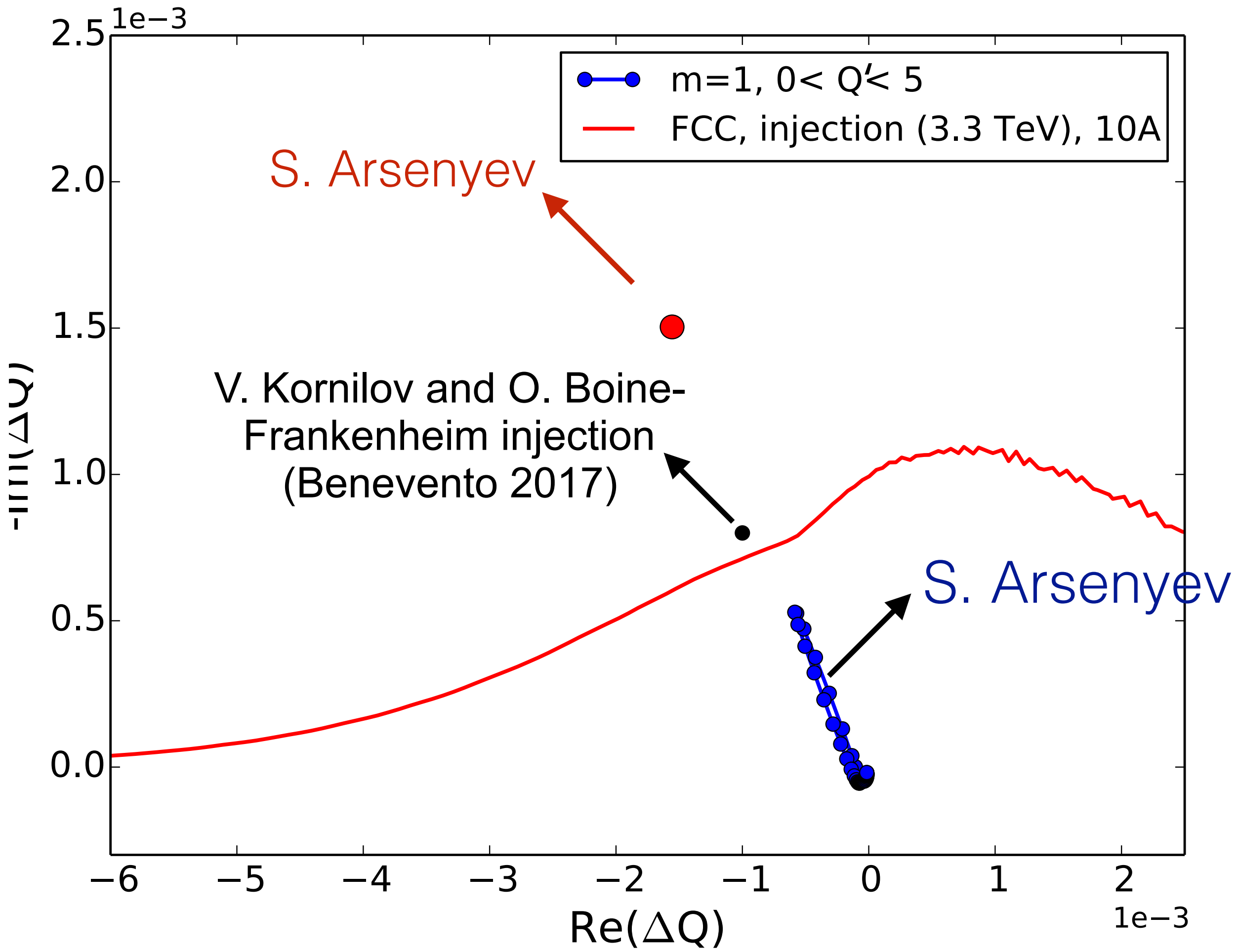
(int. oct. strength= 1.05 m^{-3})

- With negative octupoles polarity an int. oct. strength= 1.05 m^{-3} is needed to compensate reduction due to bb long range ➔ **DA ~8.5 σ**

Stability at injection energy



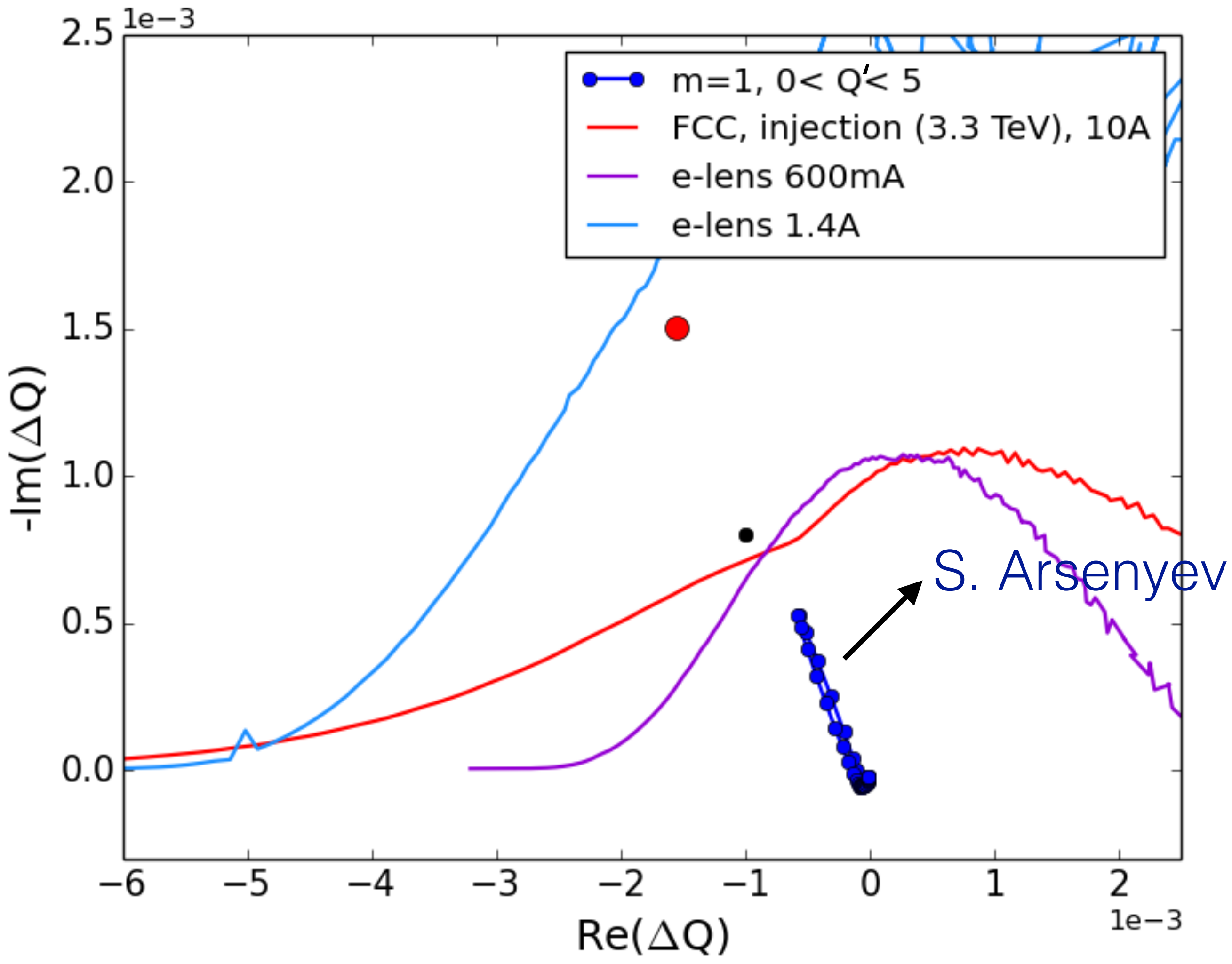
3.3 TeV (single beam)



- Bad impact of Landau octupoles at injection on DA (168 Octupoles only): **with multipolar errors situation gets worse!**
- 10 A octupole current is required at injection ➔ DA ~ 5σ Not acceptable! Need to explore different scenaria (feedback, octupoles, high chromaticity ➔ BIM-BIM code with impedance wakes)

Landau damping from e-lens at injection energy

Landau damping with e-lens at injection in collaboration with FNAL [4]



S. Arsenyev

- Investigation at injection energy, rescaling beam size for injection energy (β- function at e-lens ~100 m)
- An electron lens powered with 1.4 A provides enough Landau damping for m=0 Q'=0
- Ongoing studies: evaluation of DA at injection and alternatives

RFQ for Landau damping

Octupoles magnets [J. Berg and F.	Electron lenses [V. Shiltsev et al.]	RFQ [M. Schenk, A. Grudiev
☑ Evaluate tune spread from octupoles ☑ Single beam (injection, flat top) ☑ Beam-beam ☑ DA	☑ Evaluate tune spread from e-lens (injection, flat top)	☑ Preliminary studies for FCC by M. Schenk et al. that show stabilizing effects ➔ evaluation of stability in presence of bb

Impact on Dynamic Aperture

RFQ studies for Landau damping

- “Landau damping of intra-bunch oscillations” V. Kornilov et al. (FCC week 2017)¨
- “Analysis of transverse beam stabilization with radio frequency quadrupole”, PRSTAB (2017), M. Schenk et al.

➔ **Impact on DA and particle distribution has to be evaluated**

Summary

- Recovered FCC week predictions on SD by using MADX and PySSD ➔ **numerical tools are needed to add the beam-beam interactions and evaluate particle distributions**
- As **initial strategy we considered m=0 and Q'=0** as presented during FCC week 2017 (2016) by V. Kornilov and Landau damping provided with FCC octupoles (G=220000 T/m^3, 720 A, 0.32 m long):

  Flat top:

  - 1100 octupoles (int. oct. strength= 1.05 [m^{-3}]) without beam-beam, 1600 (int. oct. strength= 1.5 [m^{-3}]) with beam-beam long range (LOF<0) needed to damp V. Kornilov m=0 Q'=0
  - 2800 octupoles (int. oct. strength= 2.5 [m^{-3}]) needed to damp m=0 Q'=0 mode from S. Arsenyev

  Preliminary:
  e-lens
  400 mA

  - **DA > 7.6 σ is not a concern** since compensation of bb LR with negative octupole polarity

  Injection:

  - **DA < 4.5 σ** for octupoles to damp m=0 Q'=0 is a concern and will be further lowered with multipolar errors

  Preliminary:
  e-lens
  1.4 A

- **Different scenario: Q' > 0 and m=0 damped by feedback open other possibilities:**

  Flat top:

  - 1100 octupoles (int. oct. strength= 1.05 [m^{-3}]) with beam-beam long range (LOF<0) **DA > 8.0 σ**

  Injection:

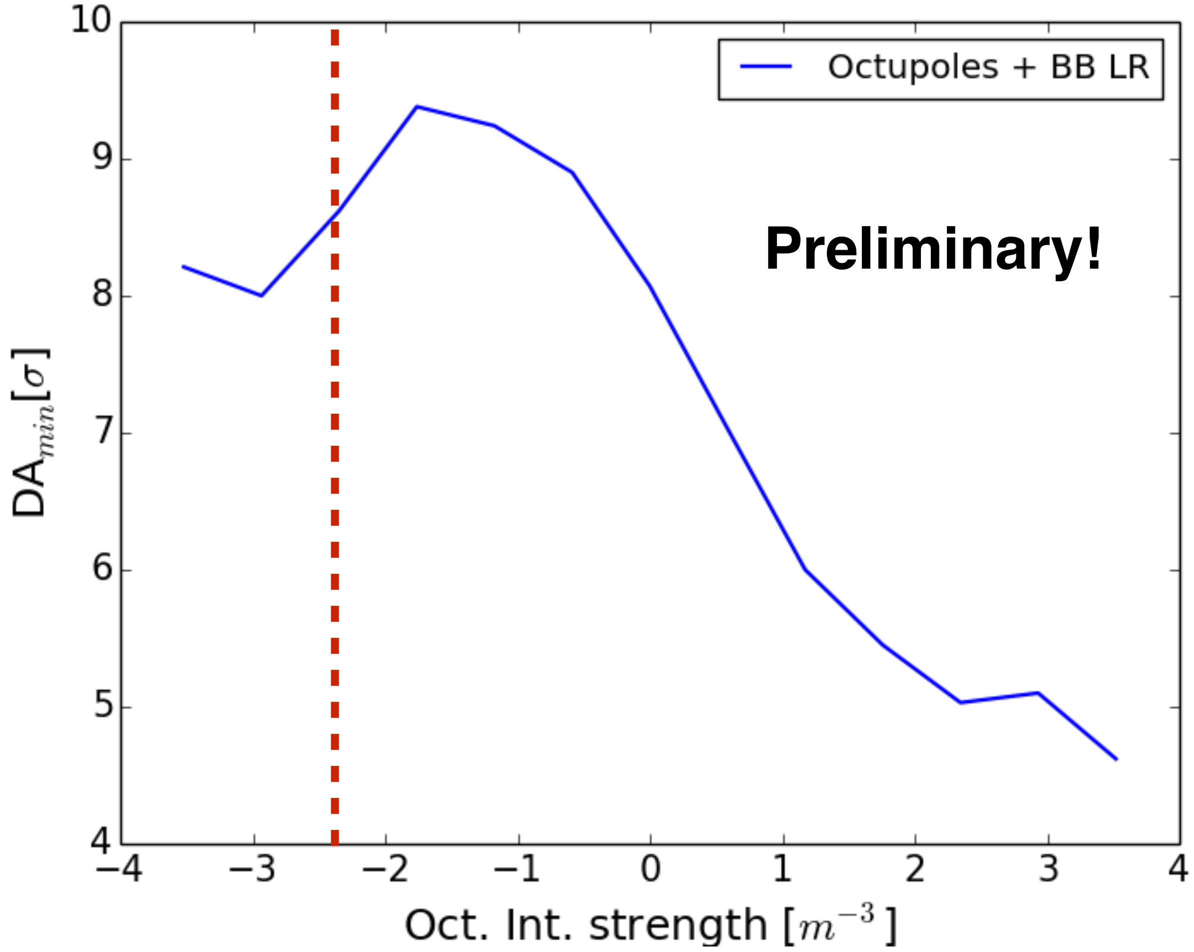
  - **e-lens of 600 mA provides enough damping ➔ DA to be evaluated**

Outlook

- DA evaluation with e-lens and impact on particle distribution (J. Barranco implementation ongoing)
- RFQ to be evaluated for FCC with DA
- Start looking at impact of bb LR to mode coupling (BIM-BIM and establish possible running scenaria with beam-beam as a function of chroma, octupoles and feedback)

Back-up slides

BB long range compensation DA



Preliminary!