Beam-beam and octupoles: stability analysis for HL-LHC operational scenarios

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Acknowledges for discussion to: W. Herr, E. Metrial and M. Giovannozzi

HL-LHC WP2 Task Leader Meeting 27th March 2015

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- **Short introduction to Stability Diagrams**
- **ATS optics:** footprint
  stability diagrams
  effects of sextupoles
- **Optics effect study:** footprint with different β^* optics and beam-beam LR
  stability diagrams for different β^* optics and LR
- **Betatron squeeze:** stability diagrams with LR+optics
  Nominal and PACMAN bunch comparison
- **Can we avoid reductions of stability? How?**
- **BB head-on:** footprint
  stability diagrams
- **Summary and Outlook**

Stability diagrams

Landau octupoles provide necessary tune spread to stabilize coherent modes from Impedence

To be stable coherent modes must lie inside the stability diagrams area

Tracking with MAD-X

↓

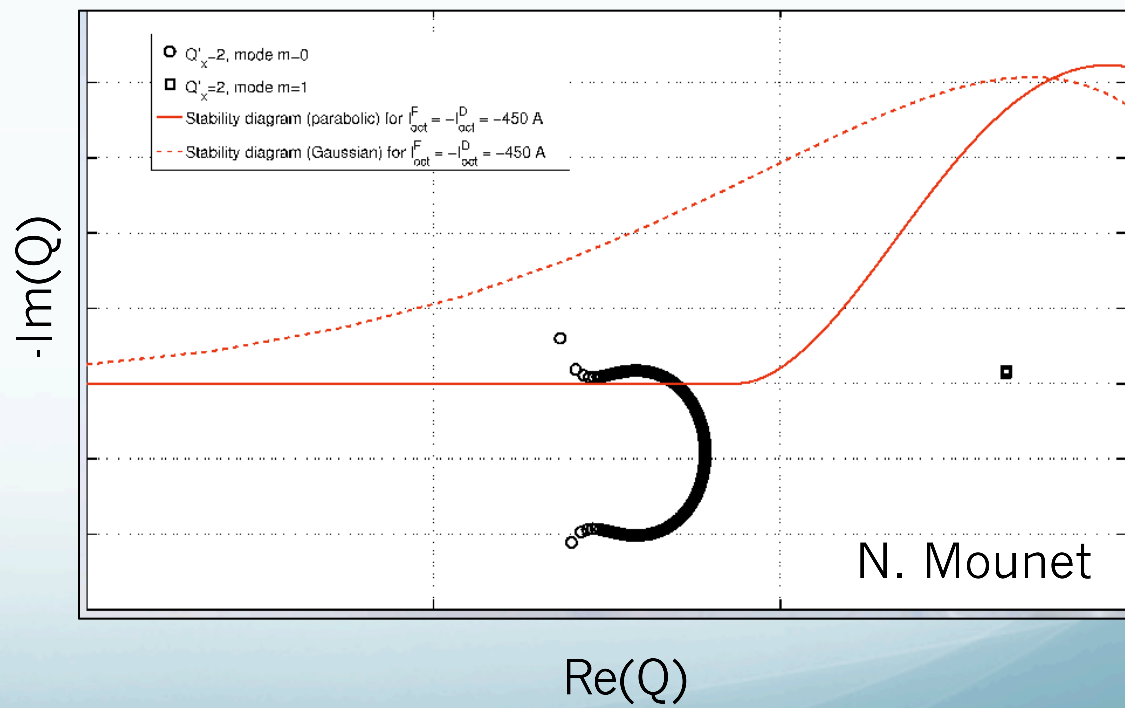
Tune spread (footprint)

↓

Pyssd Code (X.Buffat)

↓

Stability Diagrams (SD)



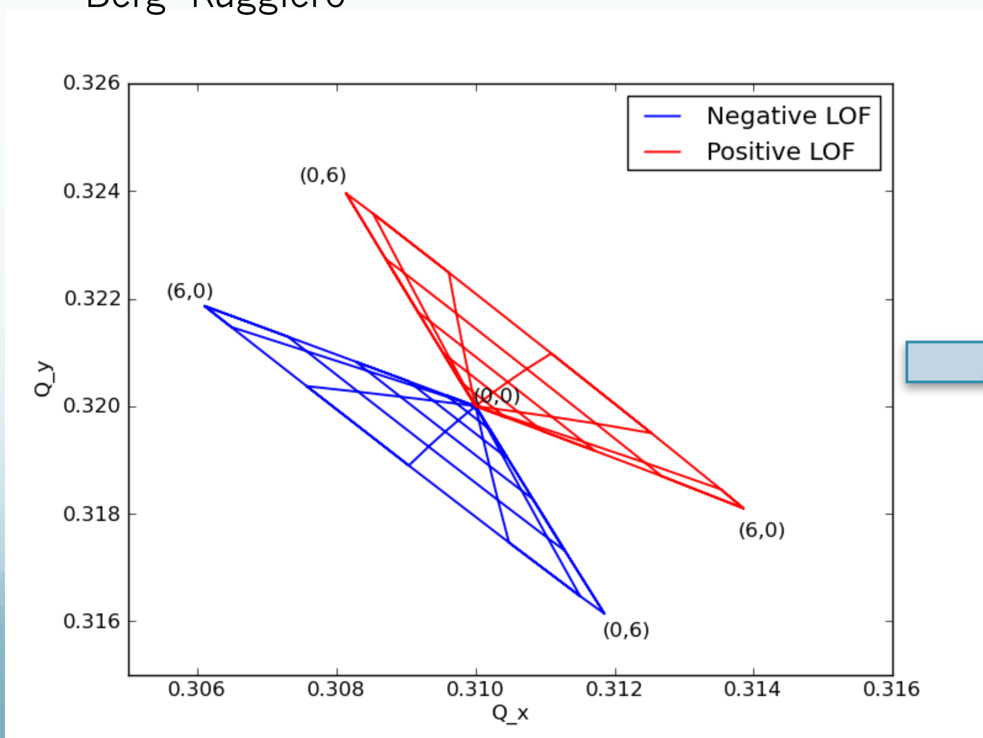
Stability diagrams

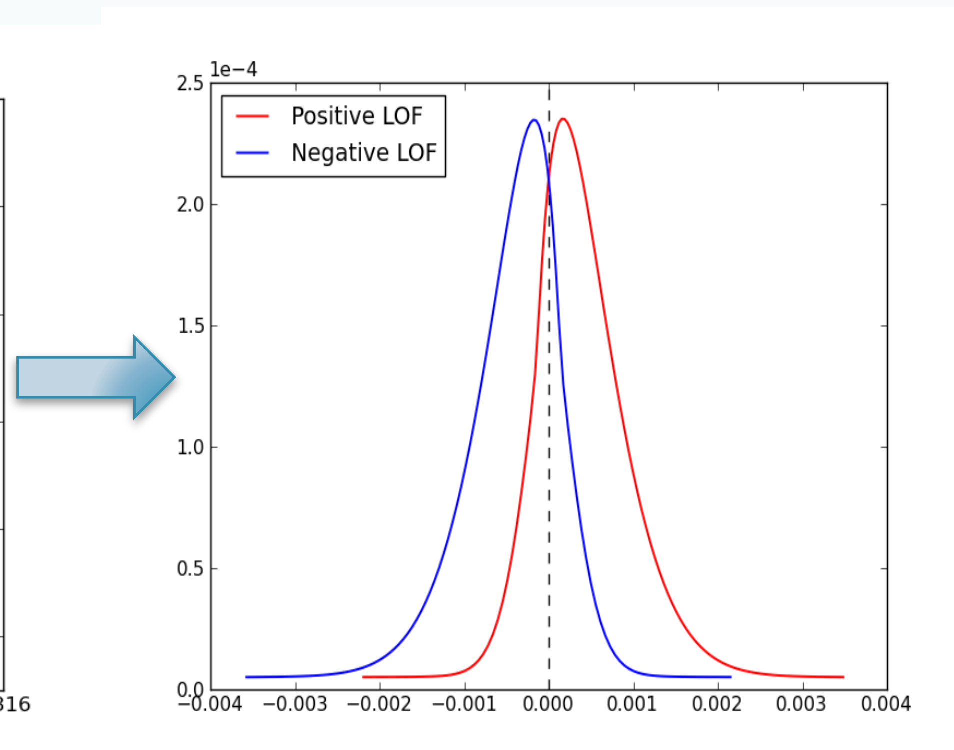
Dispersion Integral:

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

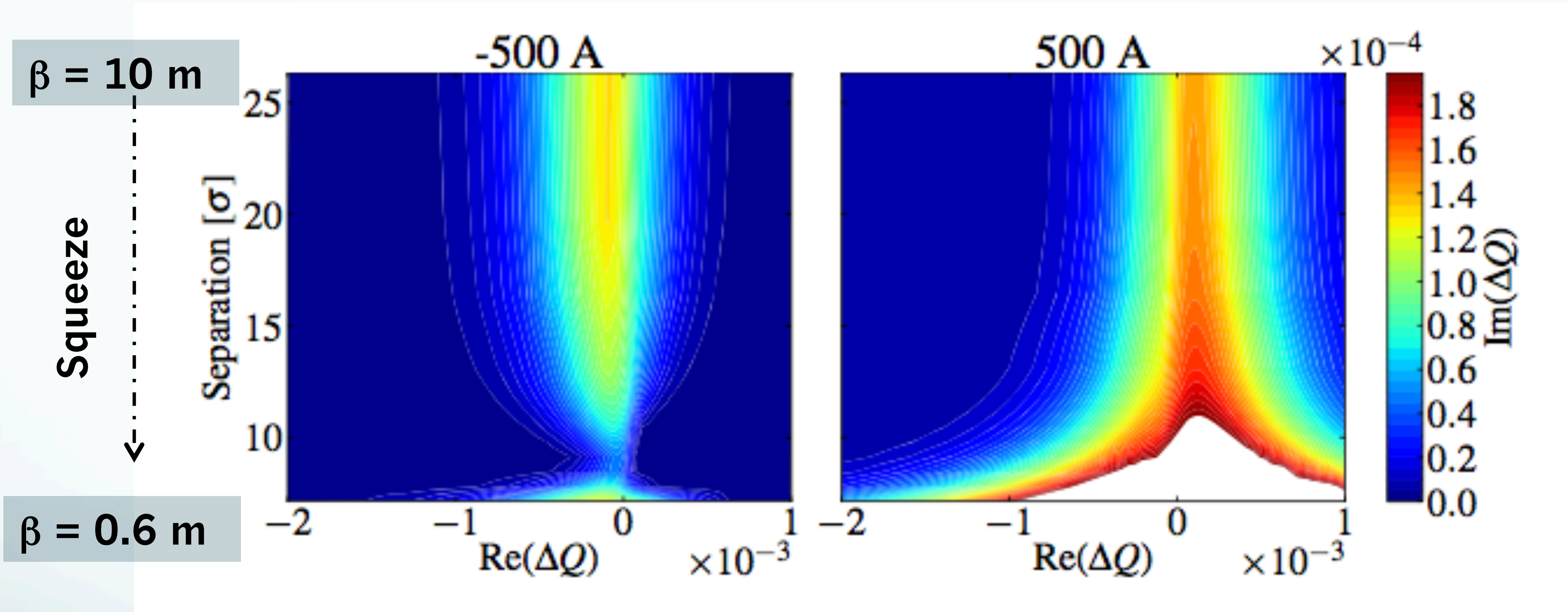
- “Landau Damping by Non-Linear Space-Charge Forces and Octupoles” D. Mohl & H. Schonauer
- Berg -Ruggiero

from Tracking





LHC 2012 Stability Diagrams



- LR effects introduce non-linear detuning with amplitude → reducing or increasing SD
- During squeeze LR becomes stronger

Hi-Lumi scenarios

I=2.2e11 ppb ε =2.5 μm

Scenario	Luminosity $cm^{-2}\ s^{-1}$	β* at collision	Long-range separation σ
Baseline	$5\ 10^{34}$	~65 cm	30
Ultimate	$7.5\ 10^{34}$	~40 cm	24
Full Squeeze	---	15 cm	15

β* levelling (Baseline, Ultimate)

If β* levelling doesn't work (Full Squeeze)

Hi-Lumi Stability Diagrams

Extend the LHC studies for Hi-Lumi → Different optics: ATS optics

A follow up of the previous studies presented at the HL-LHC WP2 Task 2.4 meeting

Now available optics files for different β^*

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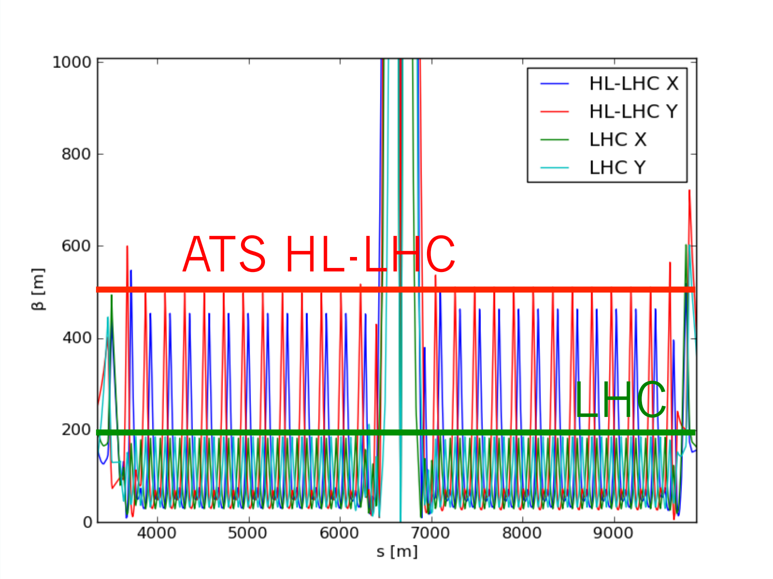
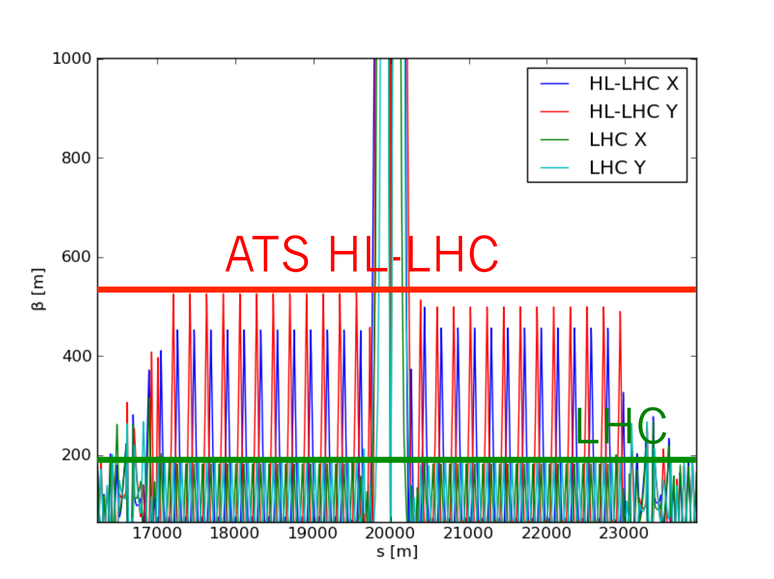
ATS optics





Reference paper on ATS optics:

Achromatic telescopic squeezing scheme and application to the LHC and its luminosity upgrade

Stéphane Fartoukh*

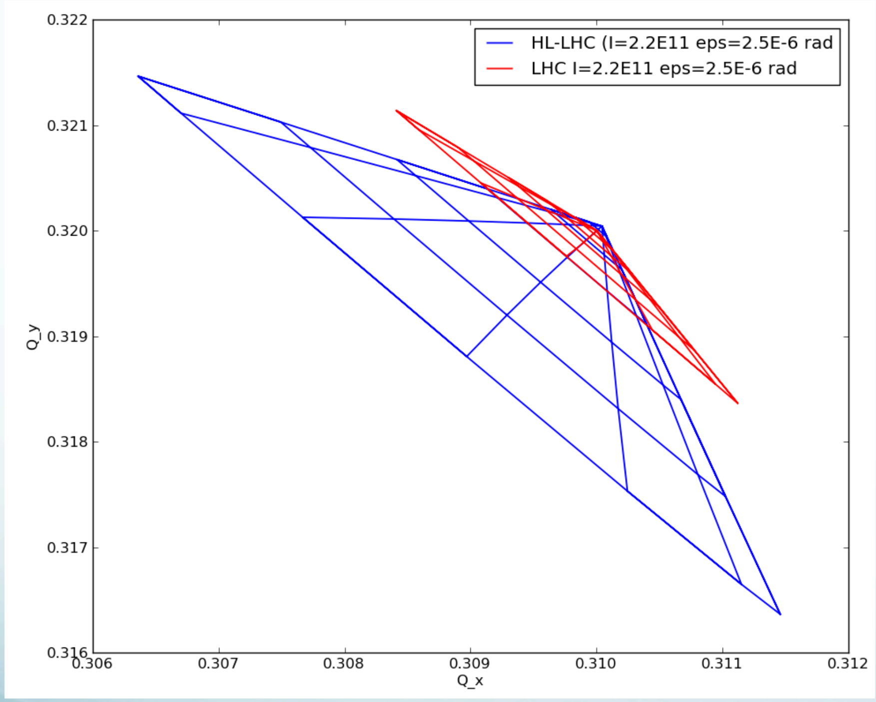
CERN, CH 1211 Geneva 23, Switzerland

(Received 26 July 2013; published 19 November 2013)

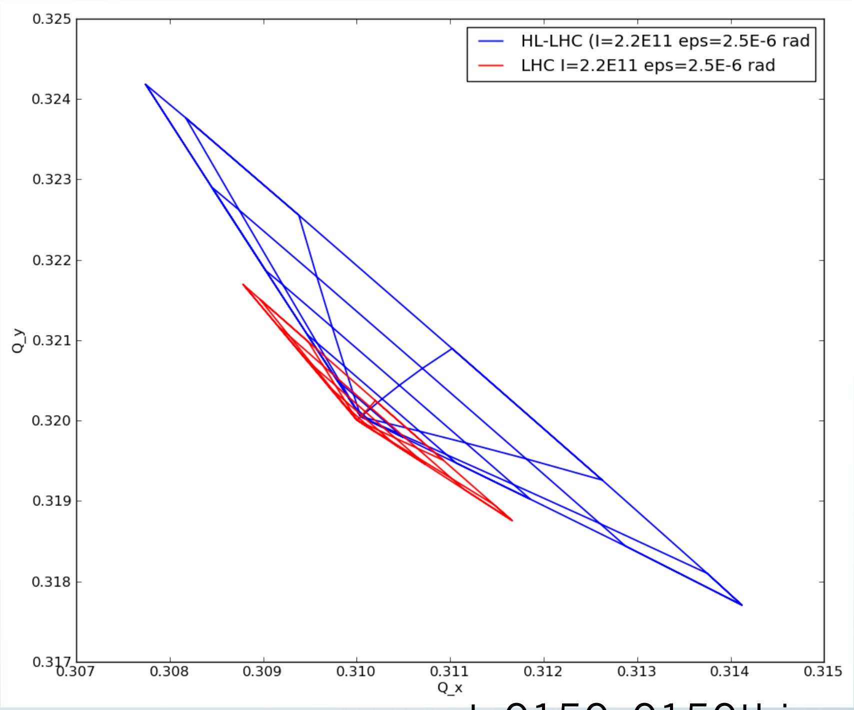
ATS: optics impact on footprint

Footprint comparisons: LHC and HL-LHC case

Negative LOF



Positive LOF



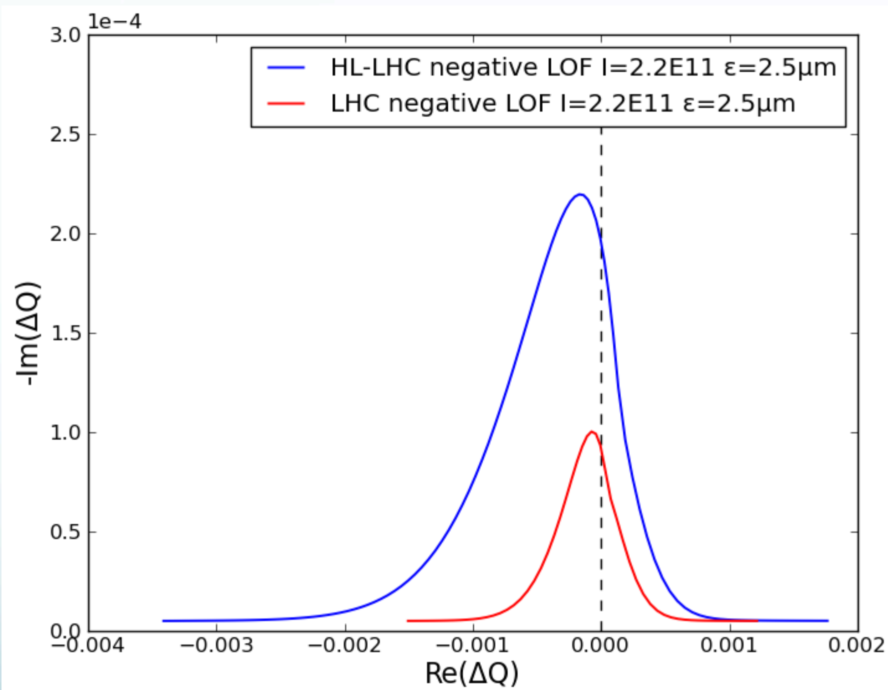
opt_0150_0150thin.madx

Strong impact for ATS optics with respect to LHC

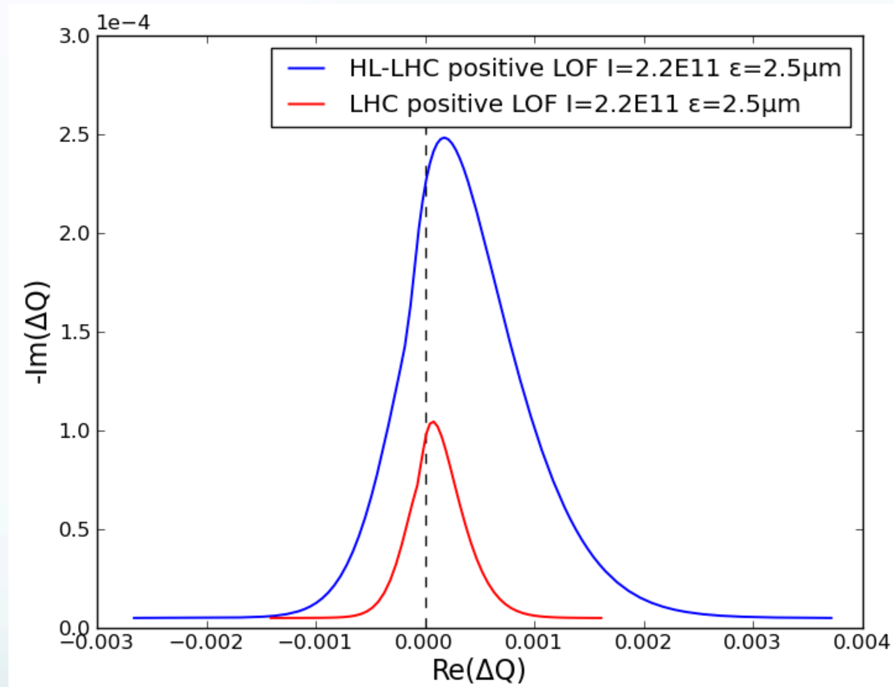
ATS: optics impact on stability diagrams

HL-LHC vs LHC (I=2.2E11, ε =2.5μm)

Negative LOF



Positive LOF



Landau Damping, Dynamic Aperture and Octupoles in LHC

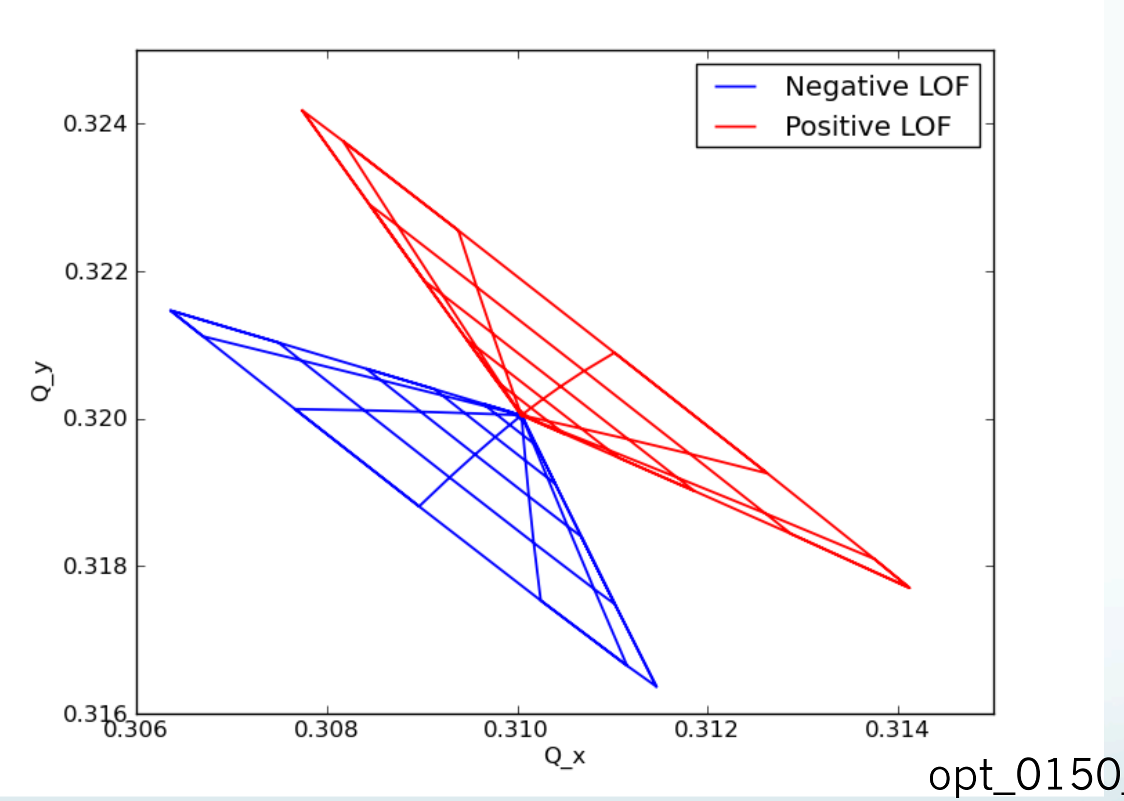
J. Gareyte, J.P. Koutchouk and F. Ruggiero

$$\Delta Q_x = \left[\frac{3}{8\pi}\int \beta_x^2 \frac{O_3}{B\rho}\,ds\right] J_x - \left[\frac{3}{8\pi}\int 2\beta_x\beta_y \frac{O_3}{B\rho}\,ds\right] J_y,$$

$\Delta Q_{oct} \propto \beta(s)^2$ $\quad \beta(s)^2_{HL\text{-}LHC} / \beta(s)^2_{LHC} \approx 2.5$ larger than the LHC case

ATS optics: footprint

Full telescopic part for positive versus negative octupole polarities



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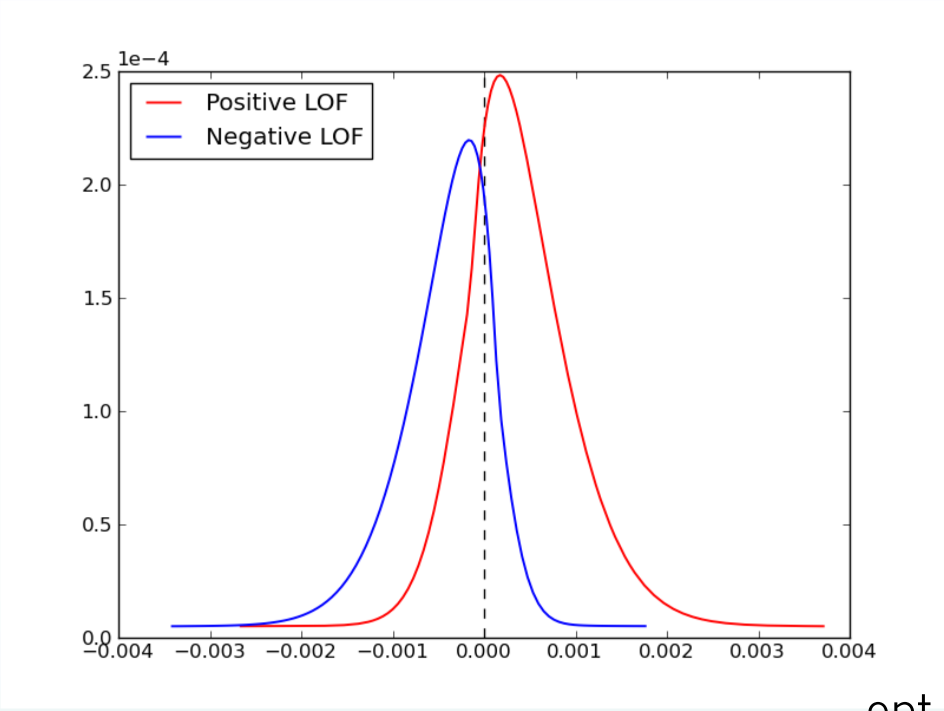
Asymmetric footprint for the two polarities

ATS optics: stability diagrams

HL-LHC case (only octupoles)



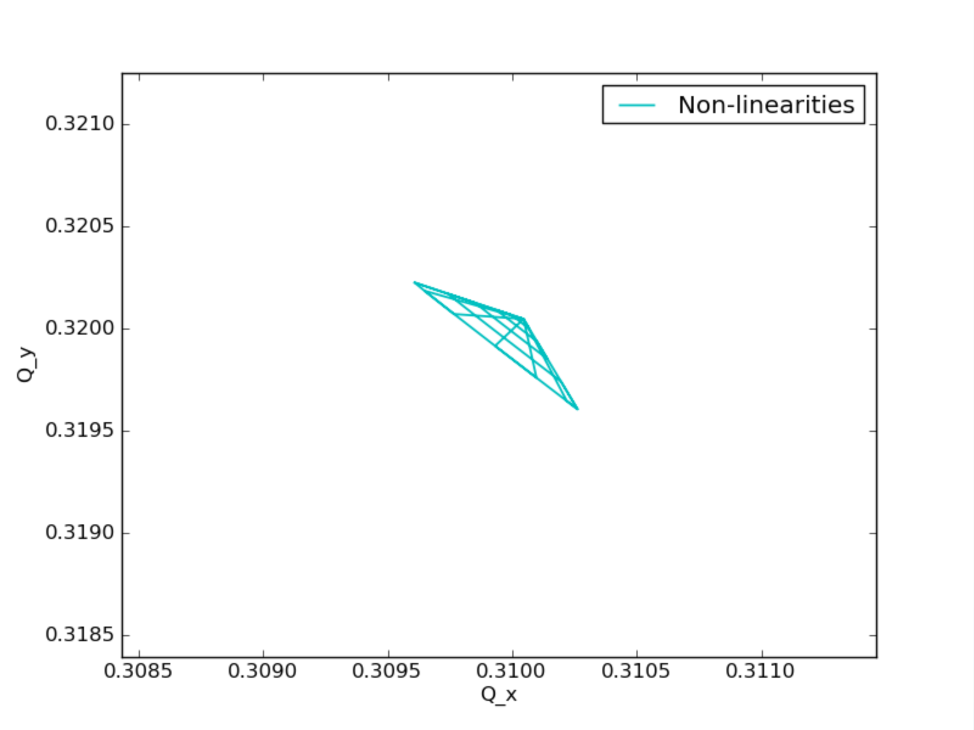
opt_0150_0150thin.madx

For single beam, larger stability diagrams for negative polarity

Asymmetric stability diagrams for opposite LOF, why?

ATS optics: effect sextupoles

ATS optics just sextupoles

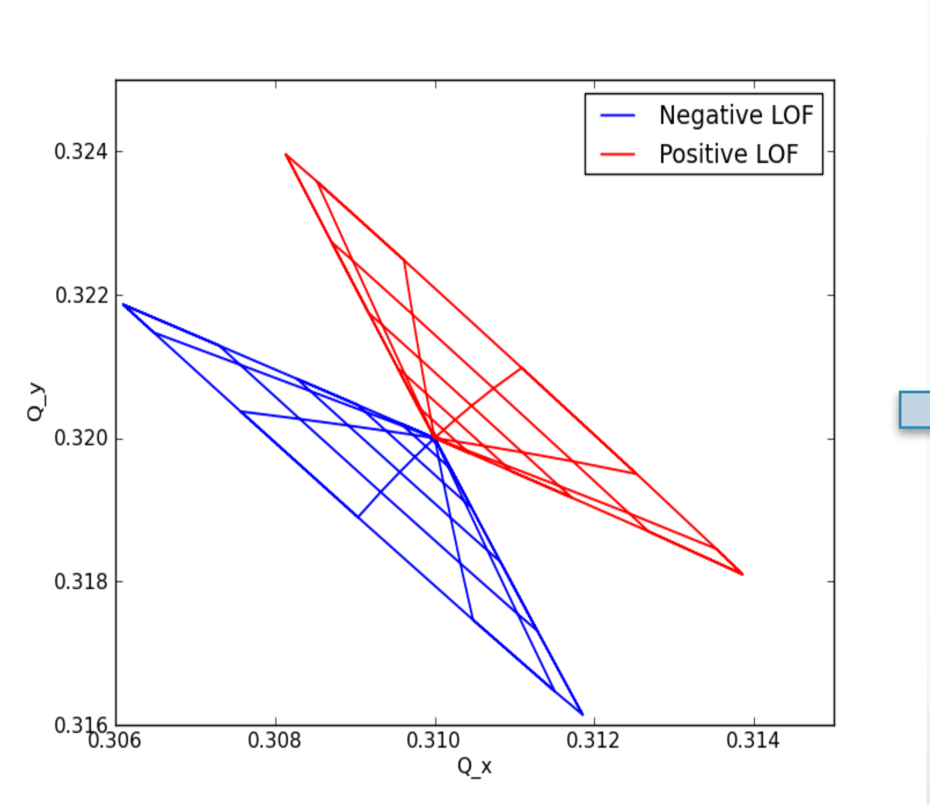


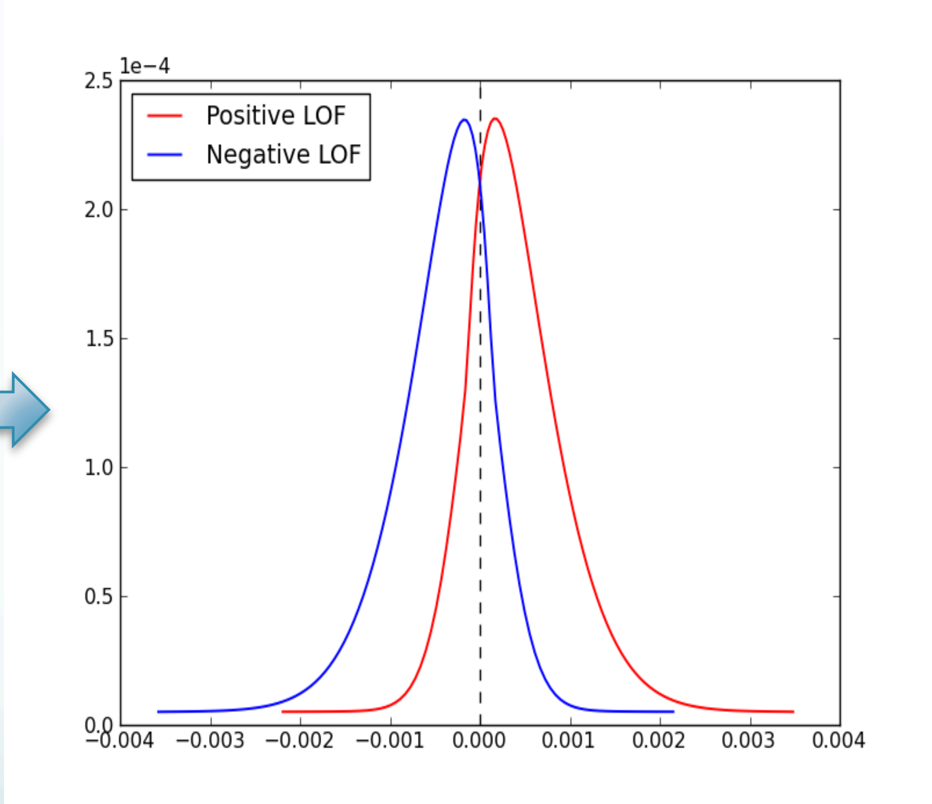
Not negligible tune spread due to the sextupoles typical of ATS

Can we reduce this spread since it reduces the spread for negative polarity?

ATS optics: effect of non-linearities

By removing the tune spread due to the sextupoles: pure octupole effect





Linear detuning of octupoles with fully telescopic part

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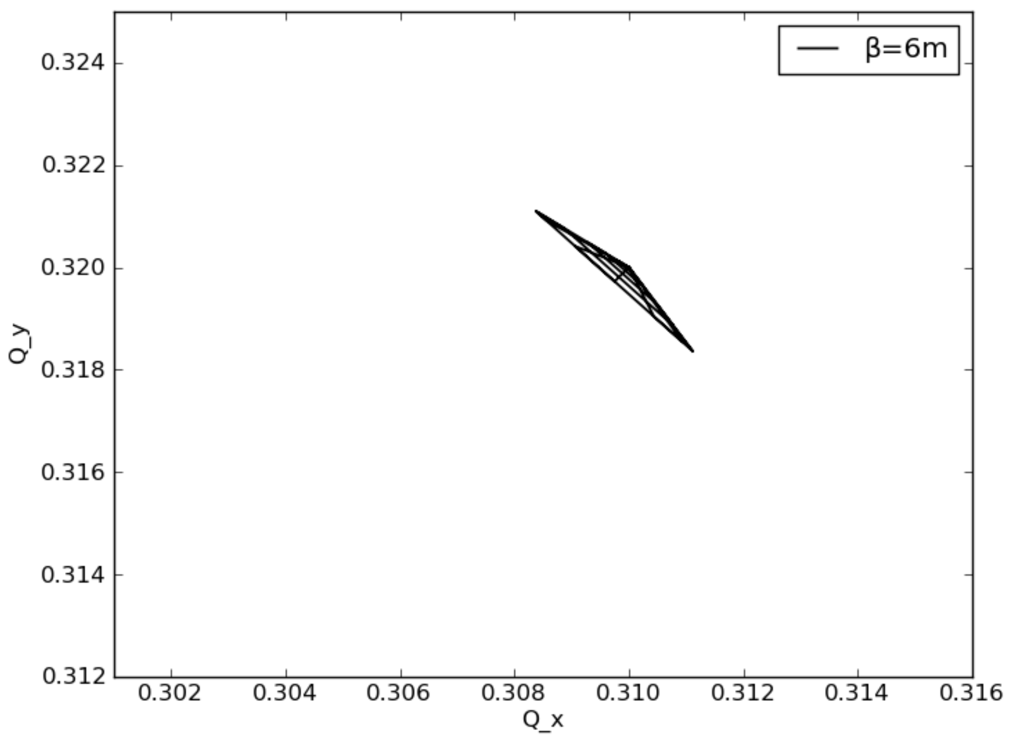
Effects of different optics: footprints

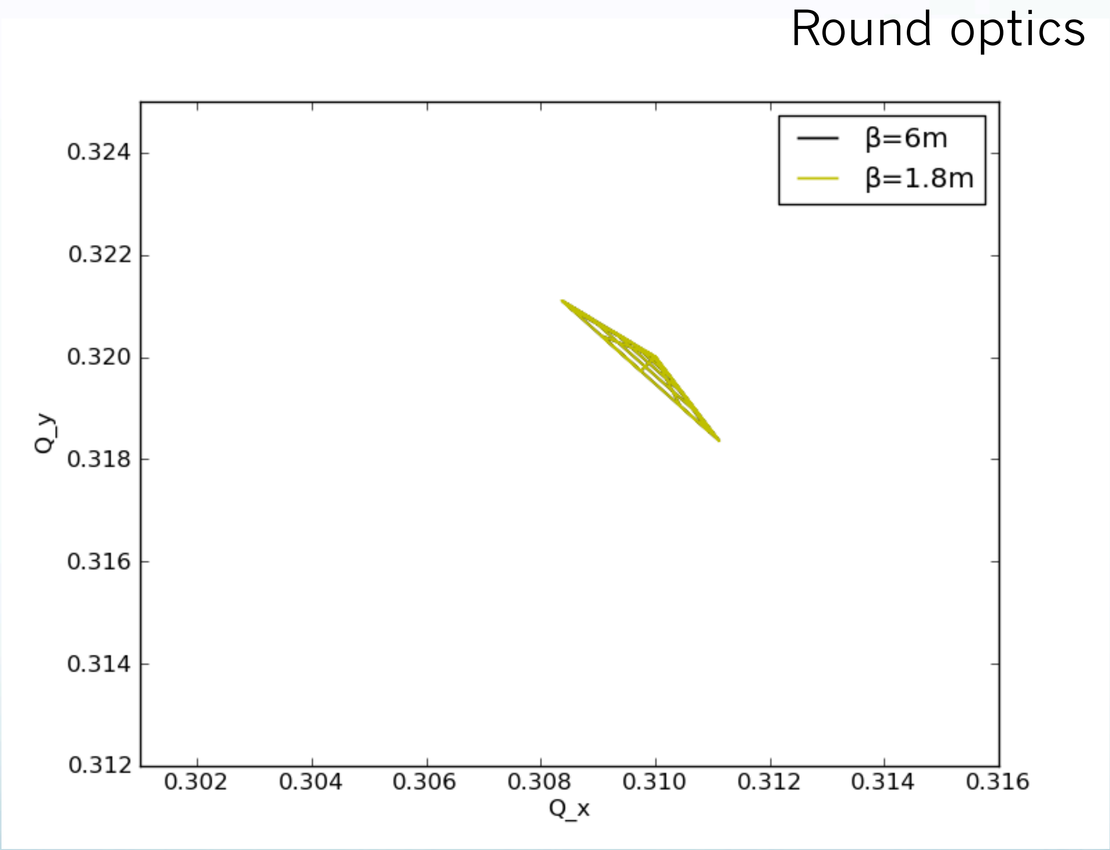
- Negative LOF

Round optics



Effects of different optics: footprints

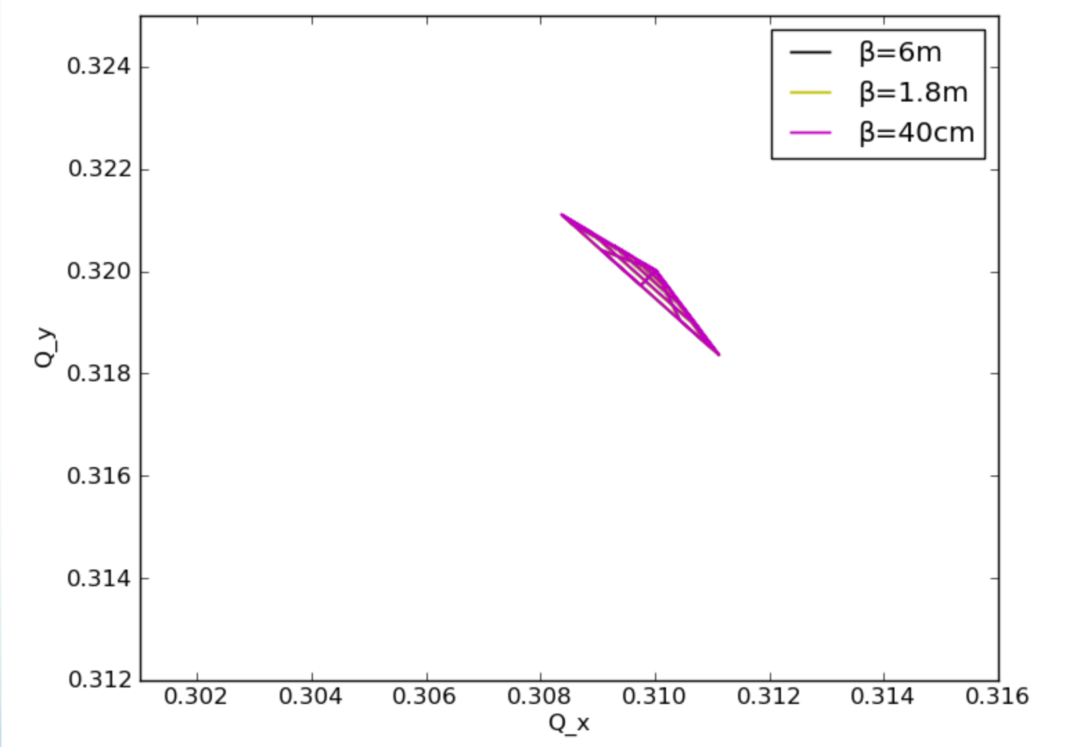
➢ Negative LOF



Effects of different optics: footprints

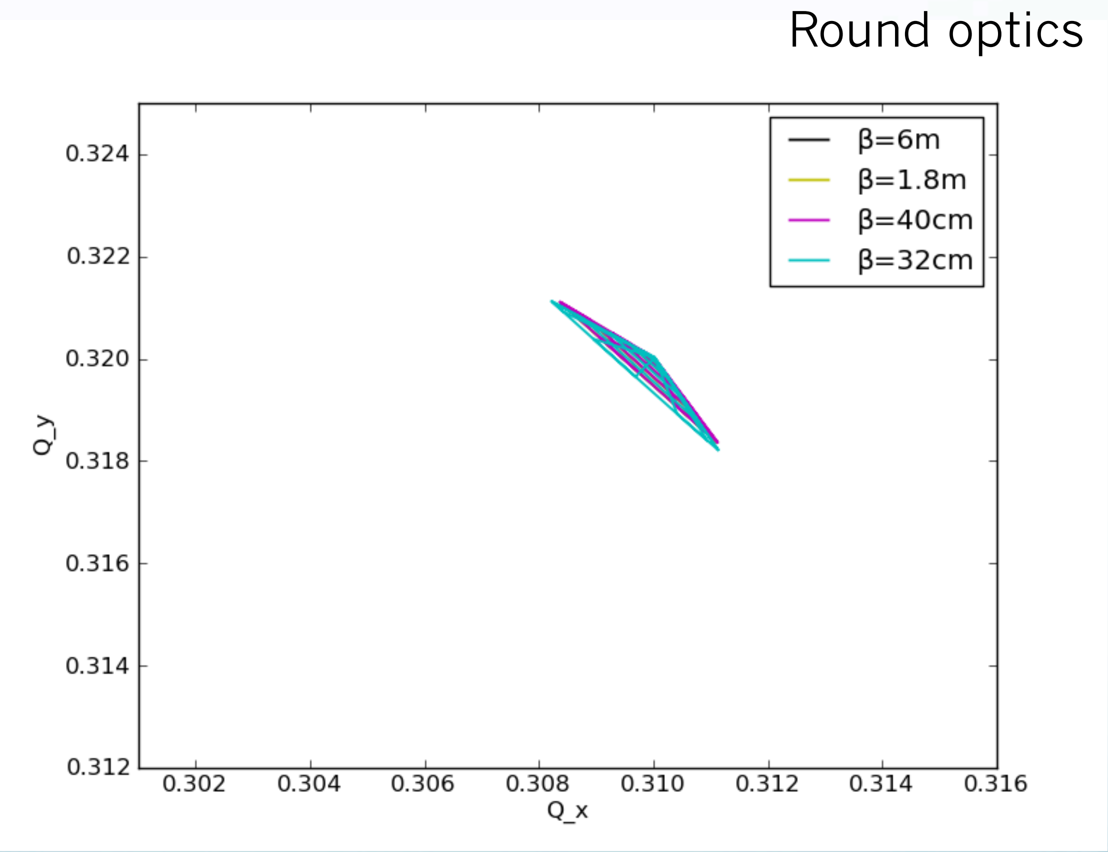
- Negative LOF

Round optics



Effects of different optics: footprints

- Negative LOF



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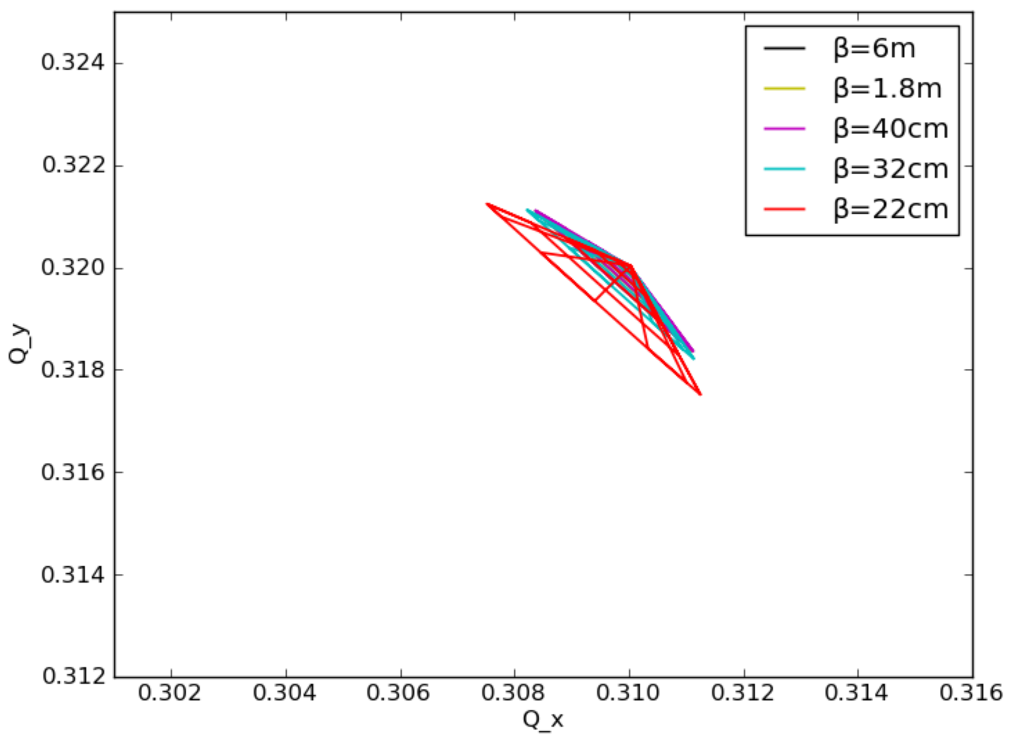

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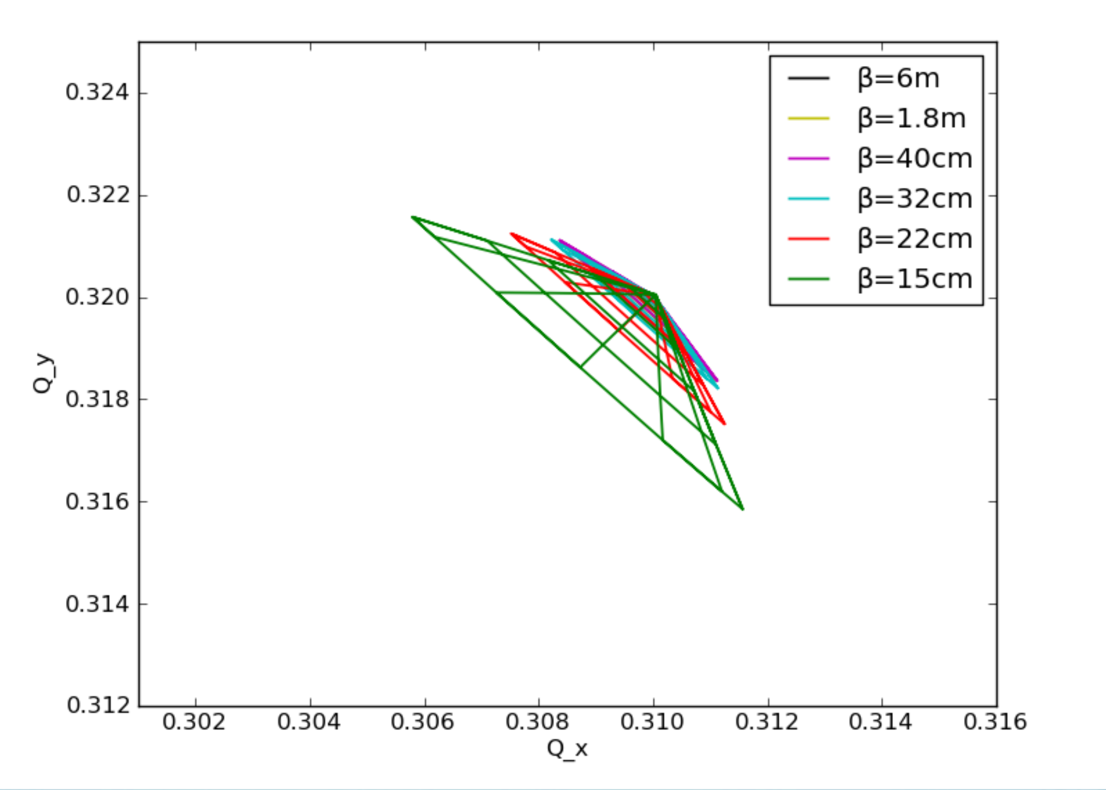
Round optics



Effects of different optics: footprints

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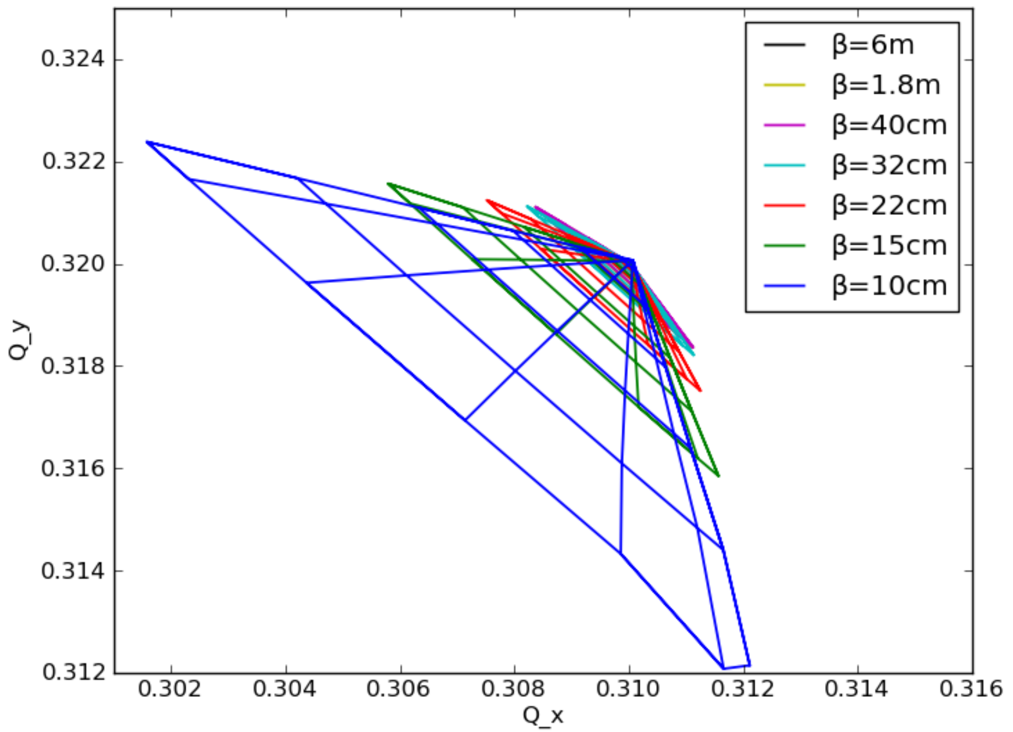
Round optics

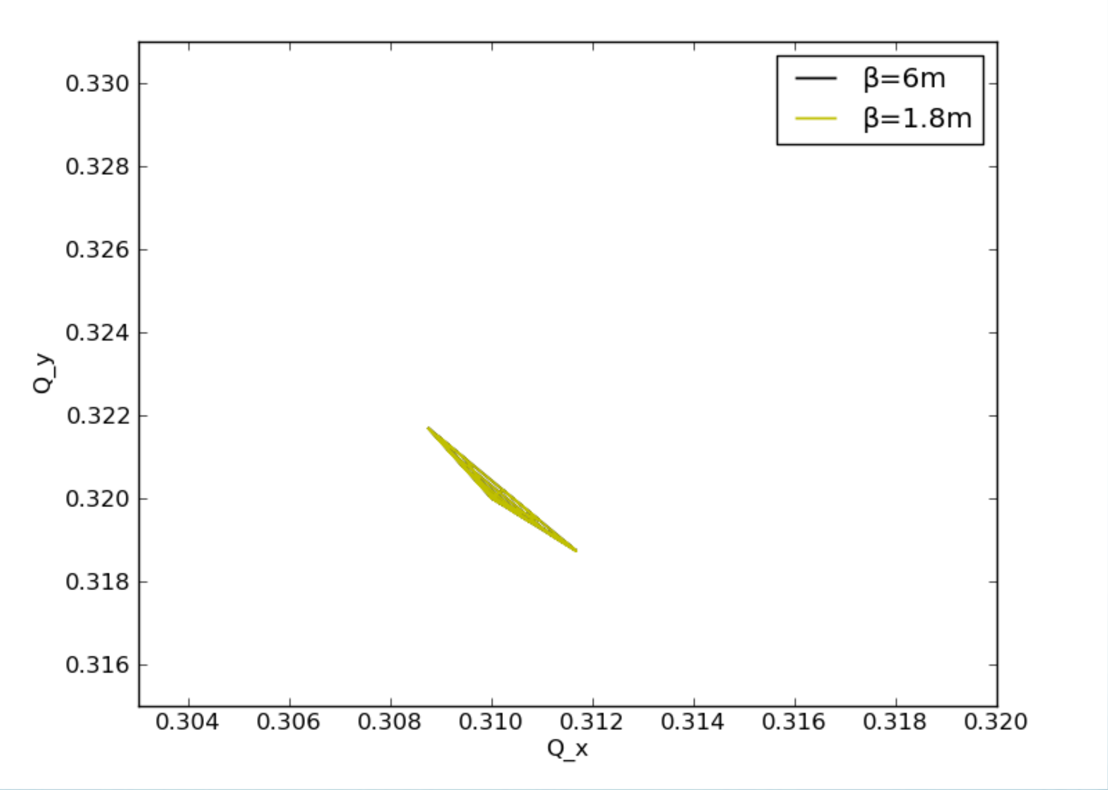


Below β*=40 cm, the beta function in the arc start to increase and accordingly the octupole spread thanks to ATS part!

Effects of different optics: footprints

- Positive LOF

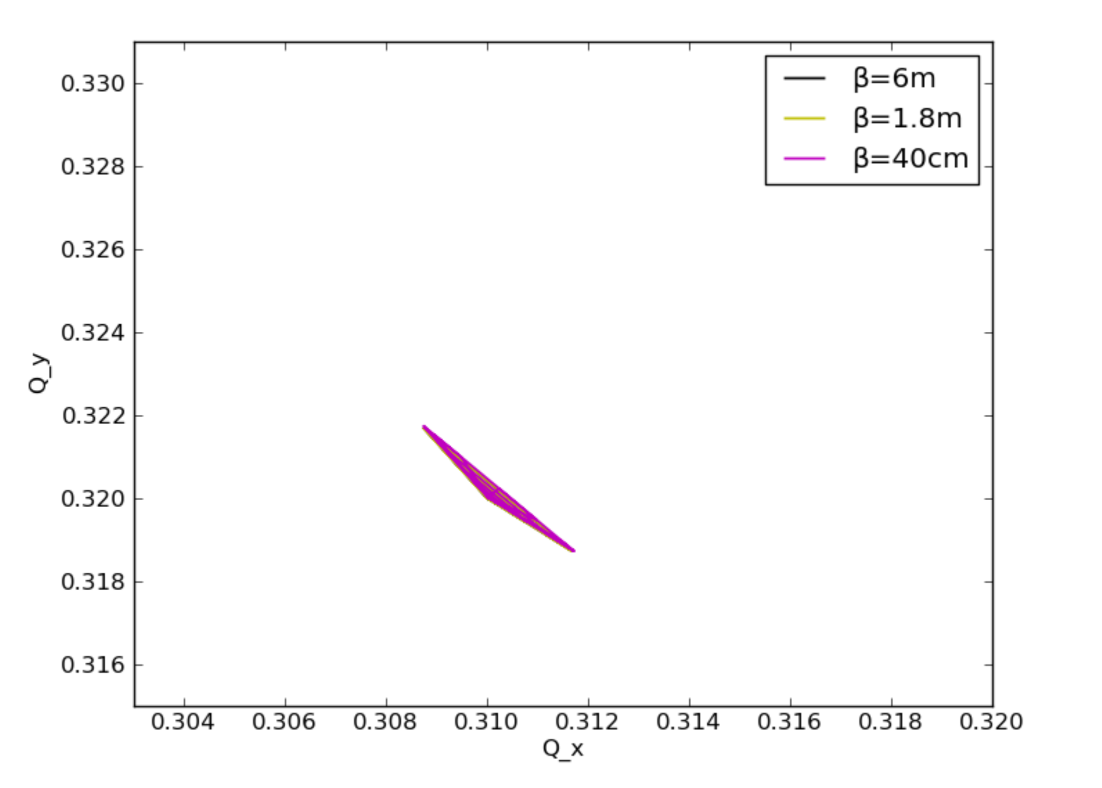
Round optics



Effects of different optics: footprints

- Positive LOF

Round optics



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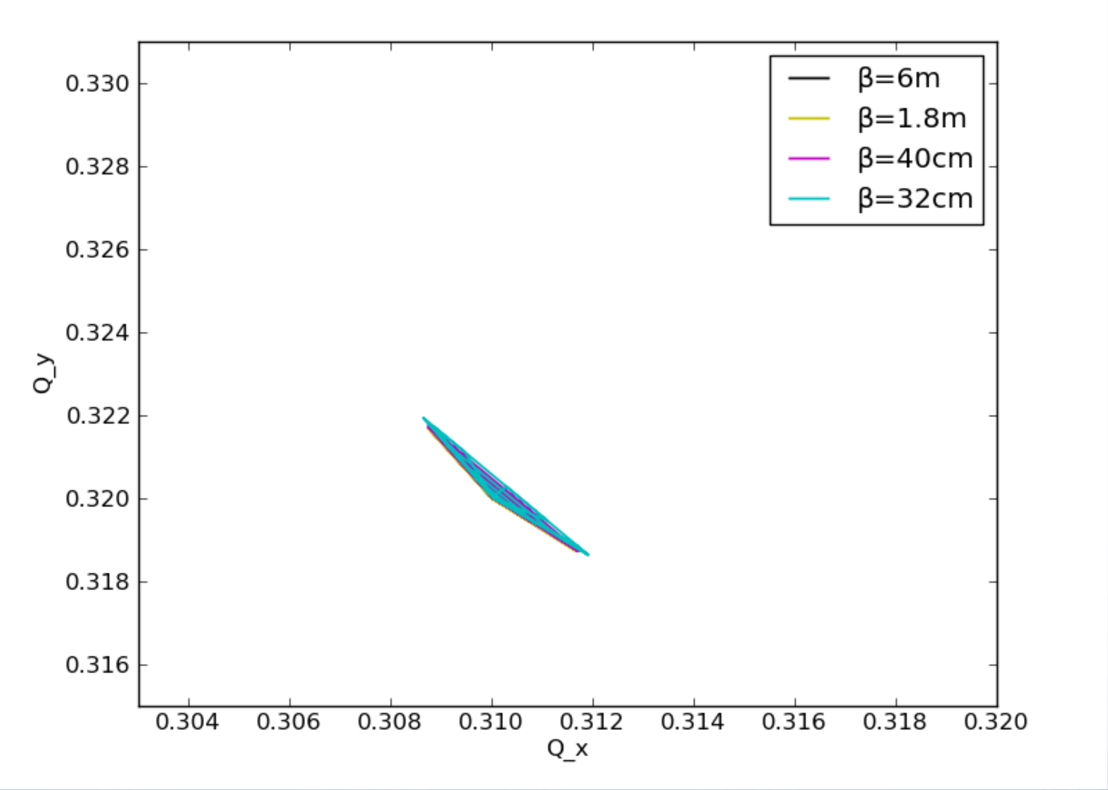
Round optics



Effects of different optics: footprints

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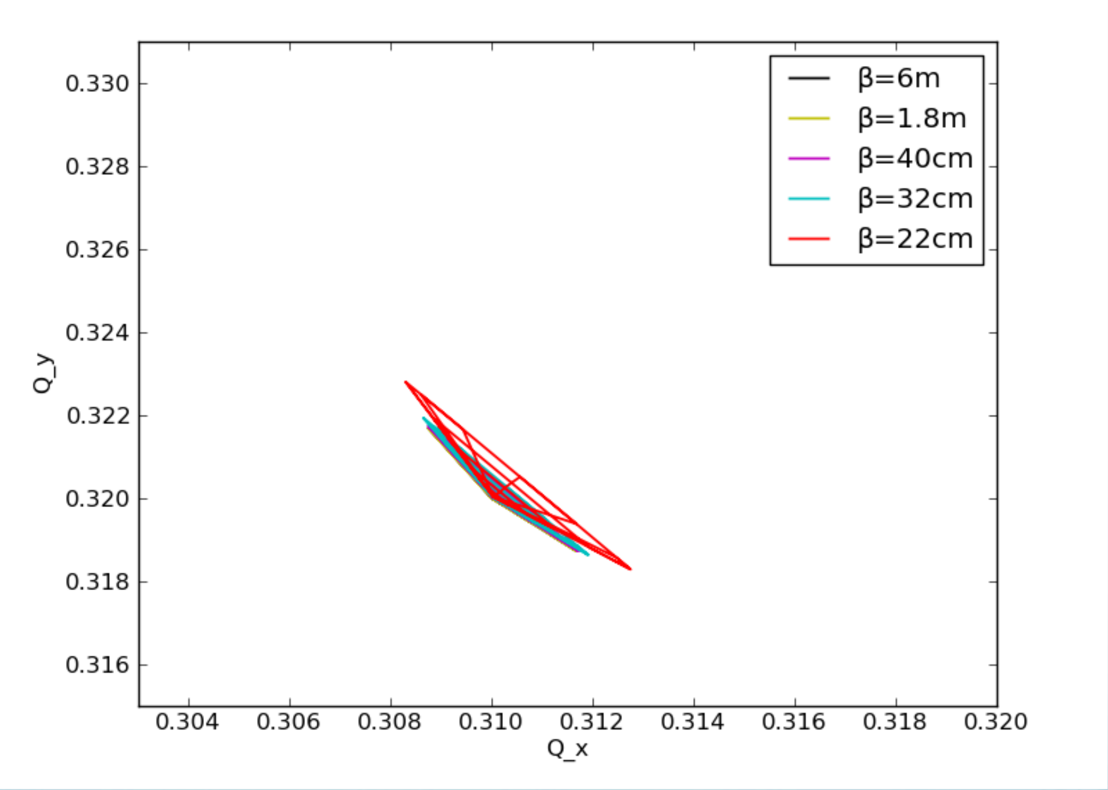

Effects of different optics: footprints

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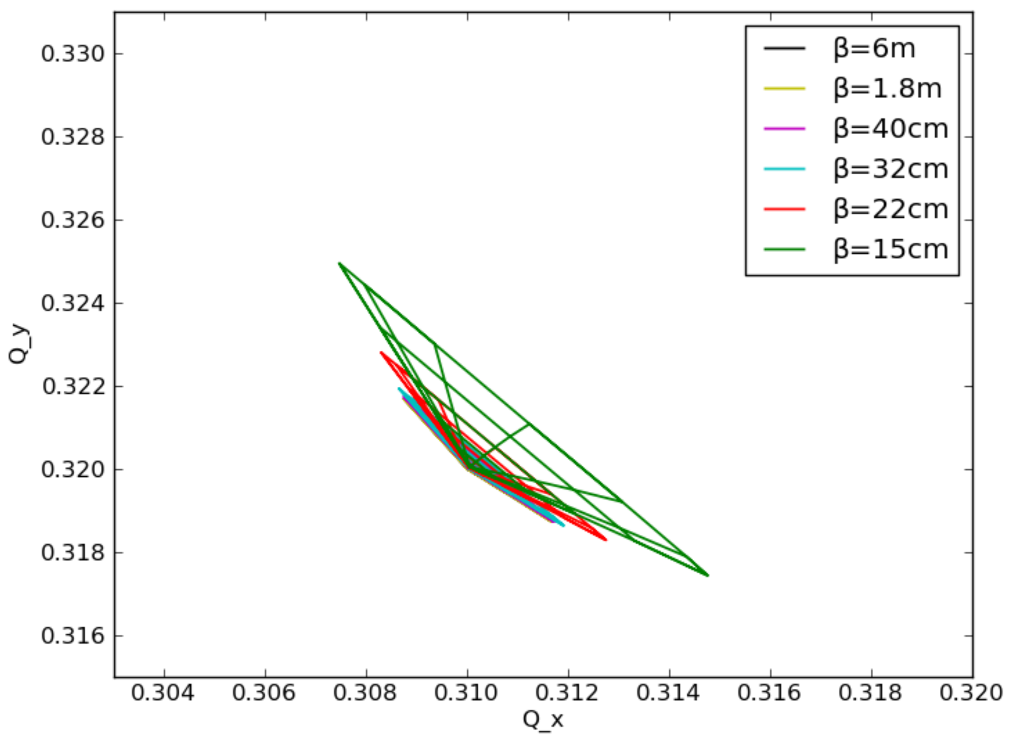
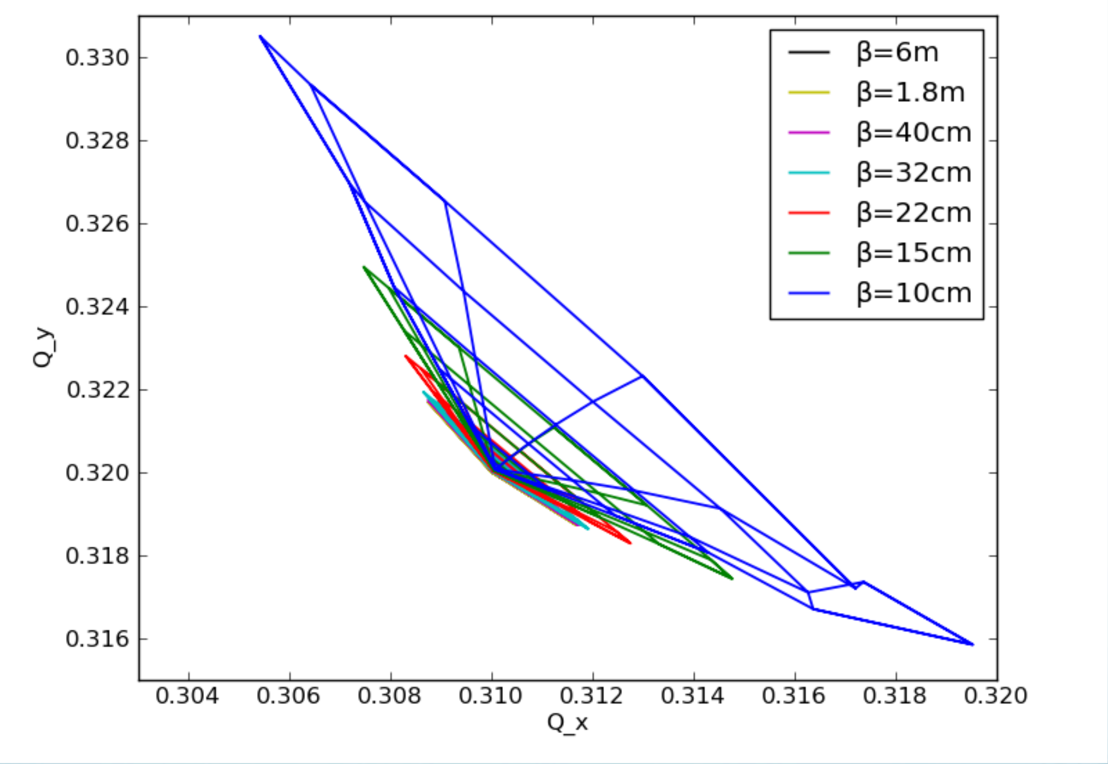


Effects of different optics: footprints

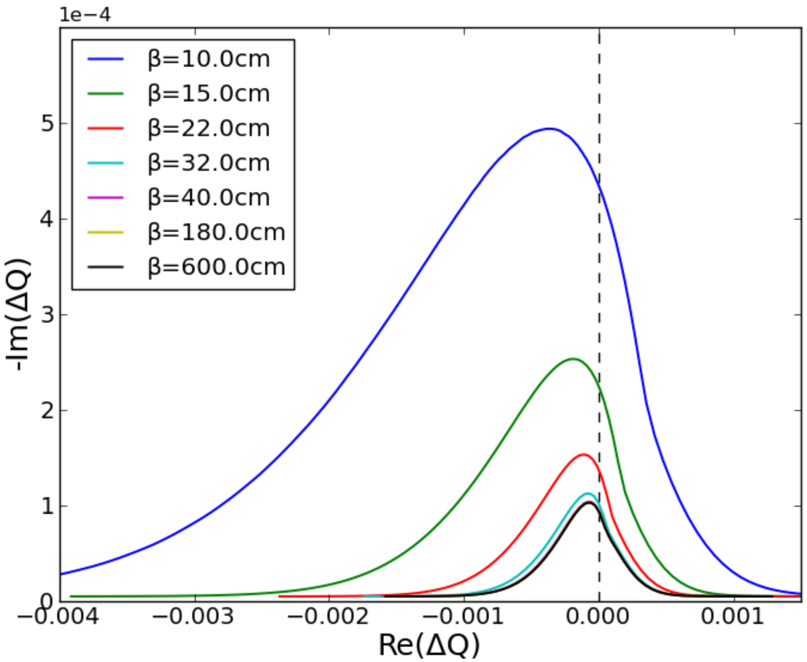
- Positive LOF

Round optics

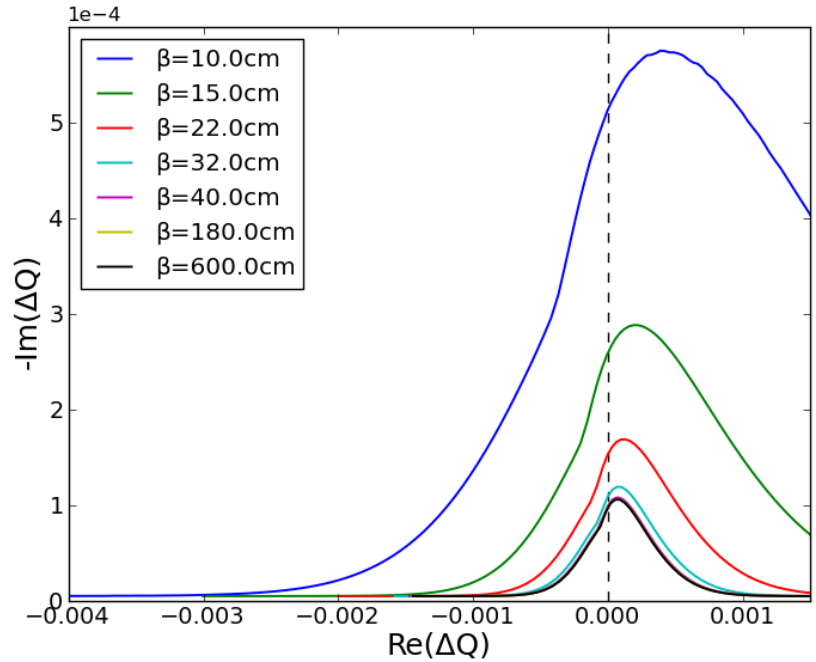


Effects of different optics: stability diagrams

Negative LOF



Positive LOF

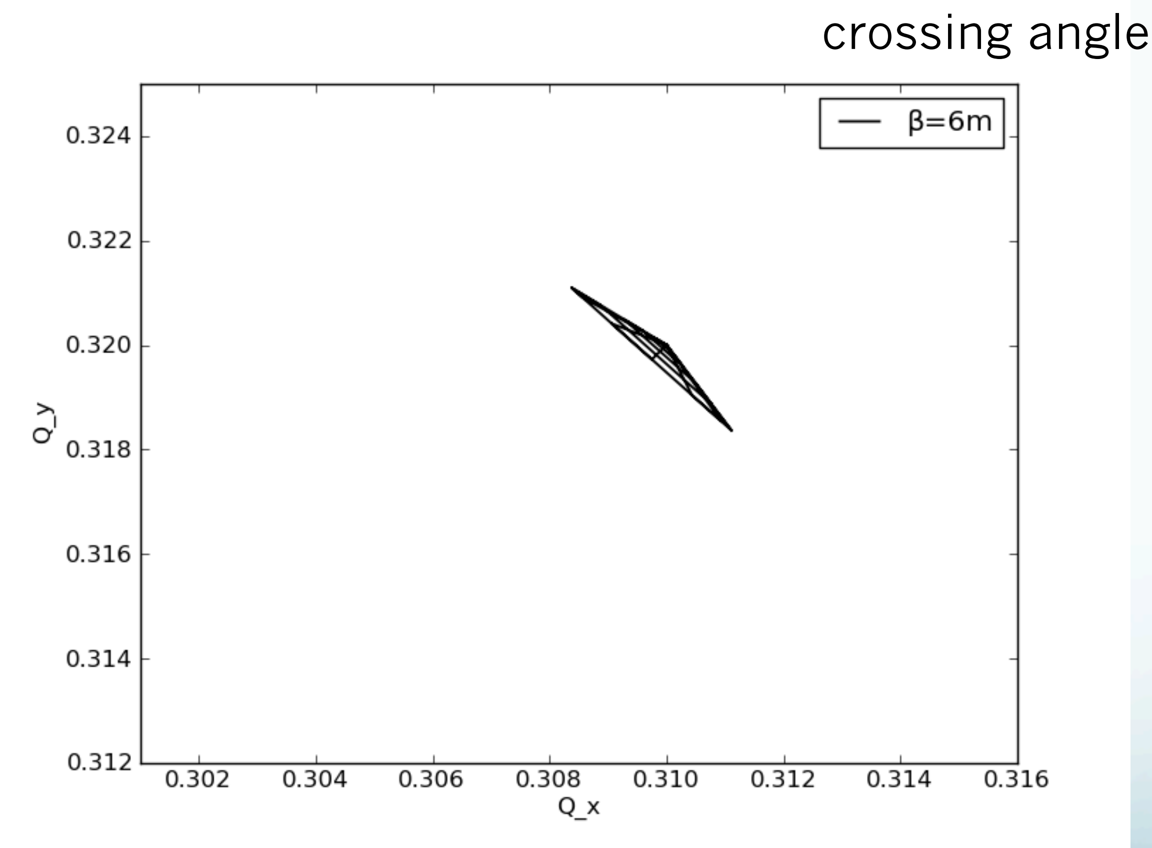


From β^*=32cm SD start to increase due to the larger tune spread provided by the octupoles

Effects of different optics + beam beam LR: footprints

- Negative LOF

IP1 and IP5 only
crossing angle of 590 μrad



Effects of different optics + beam beam LR: footprints

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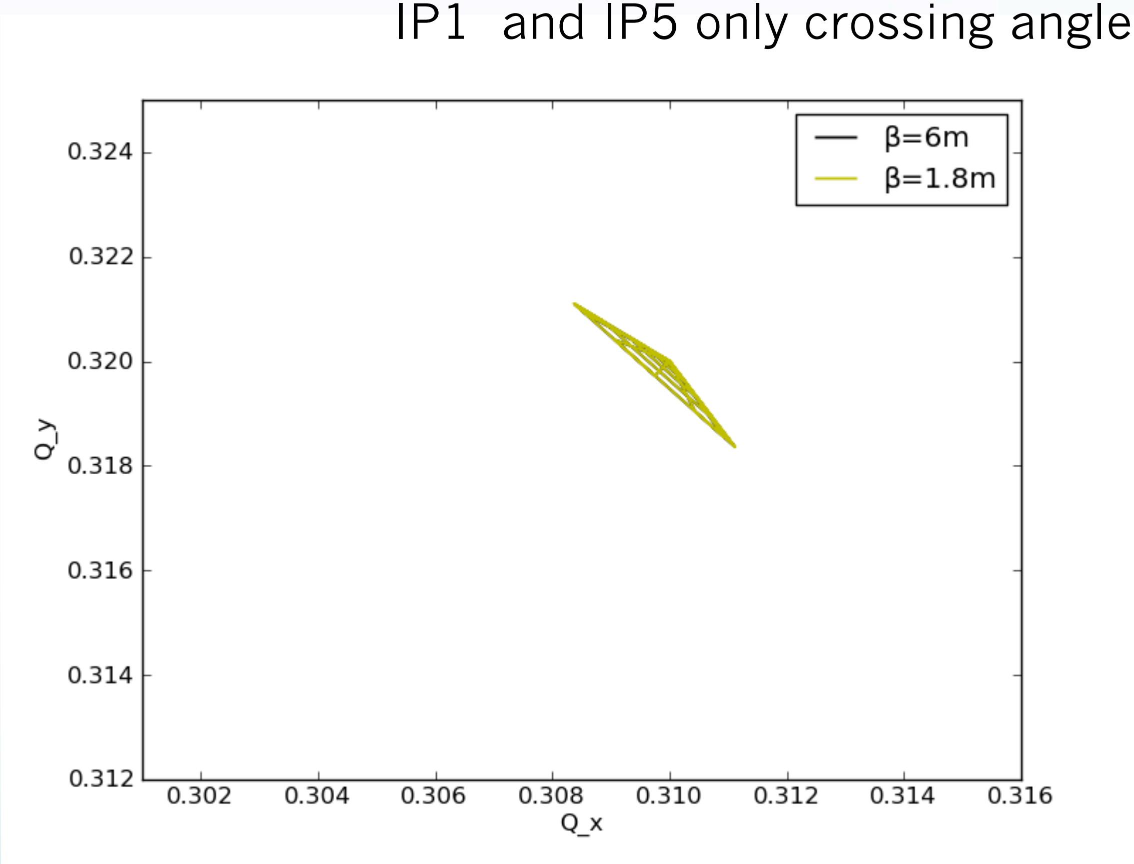
IP1 and IP5 only crossing angle of 590 μrad

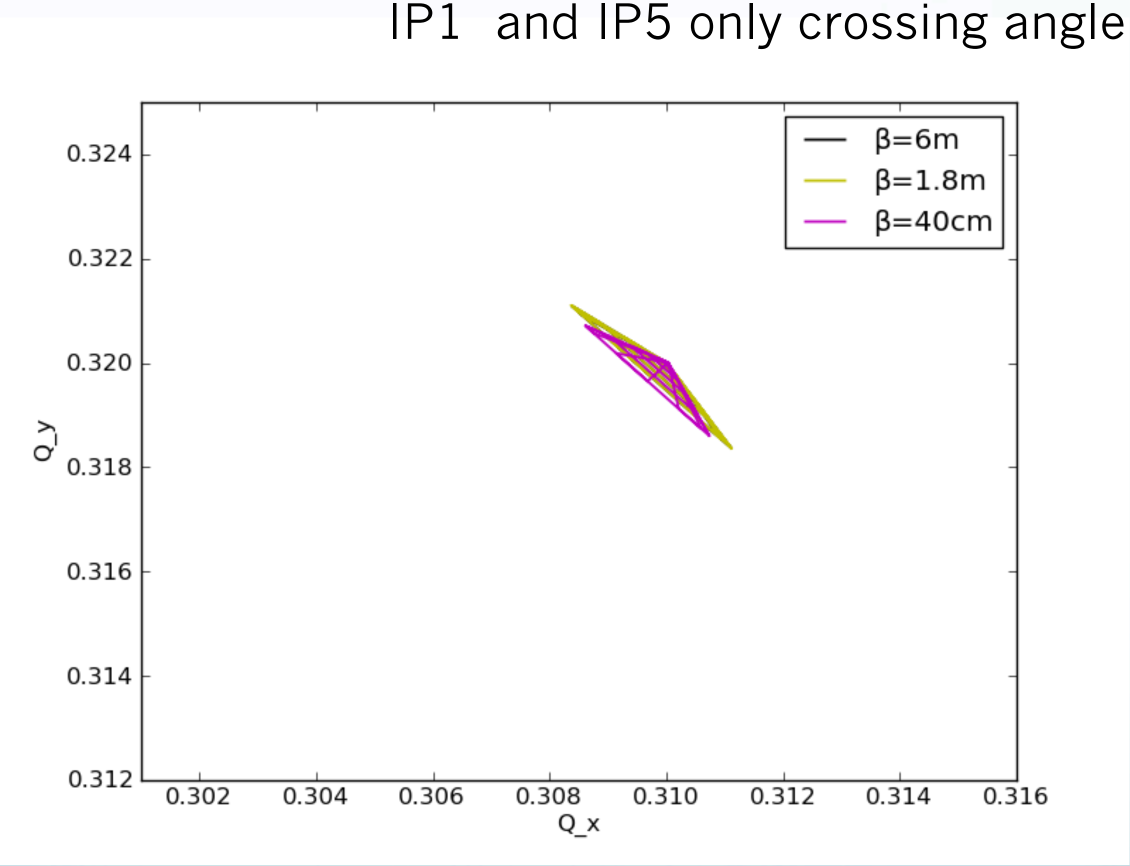


Beam-beam long range effects reduces the tune spread of octupoles during betatron squeeze (as also seen by S. Fartoukh for LHC run 1)

Effects of different optics + beam beam LR: footprints

- Negative LOF

IP1 and IP5 only crossing angle of 590 μrad



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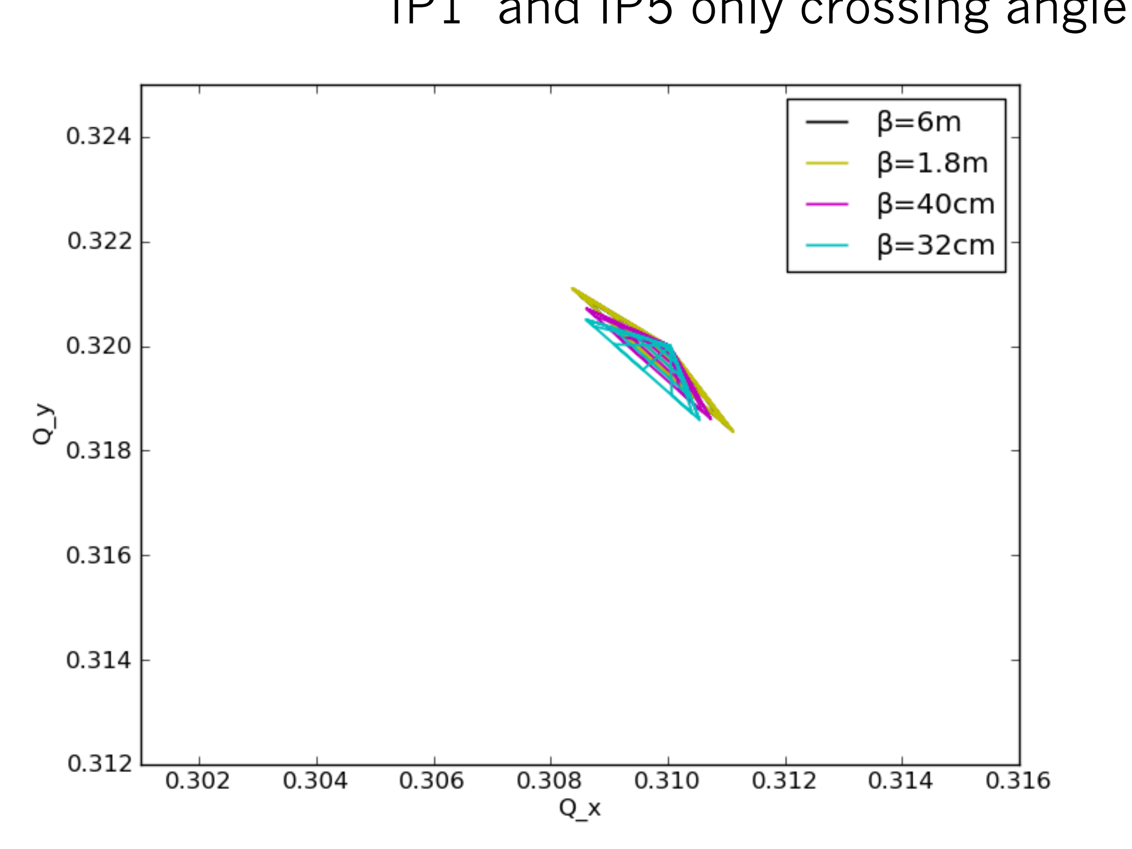

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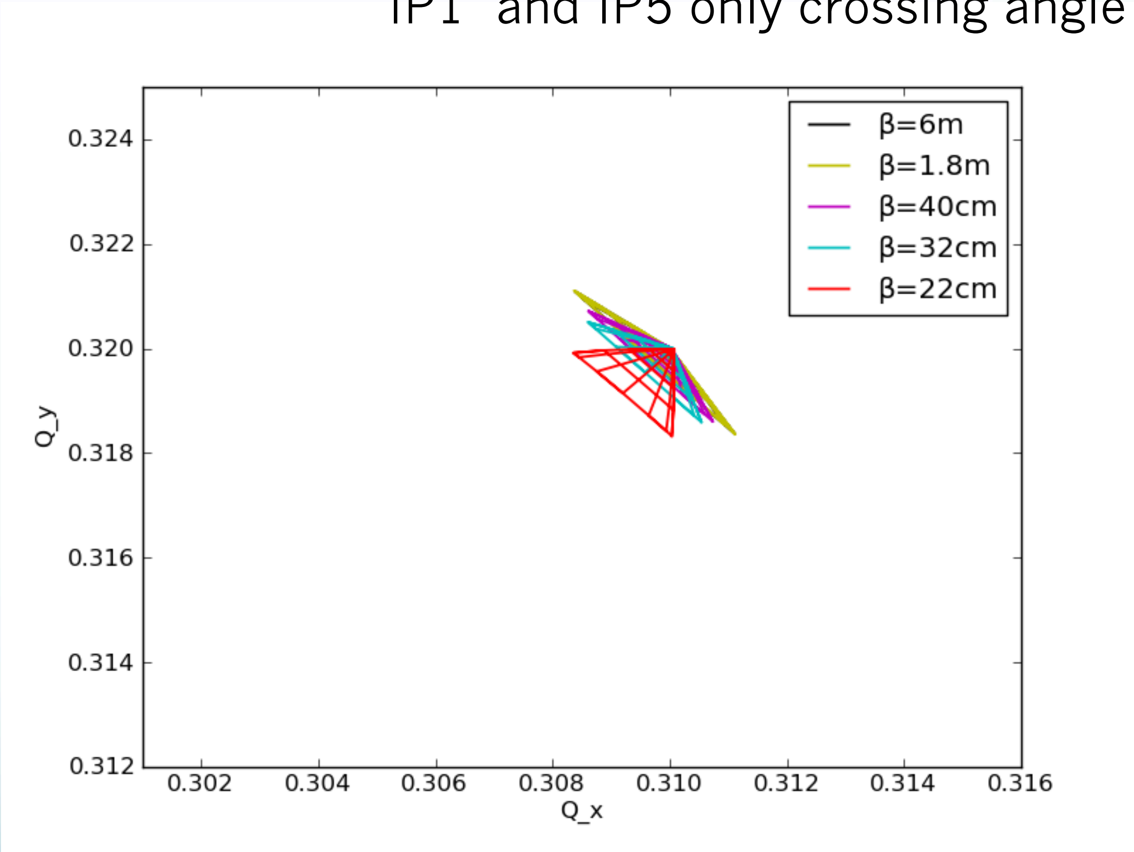

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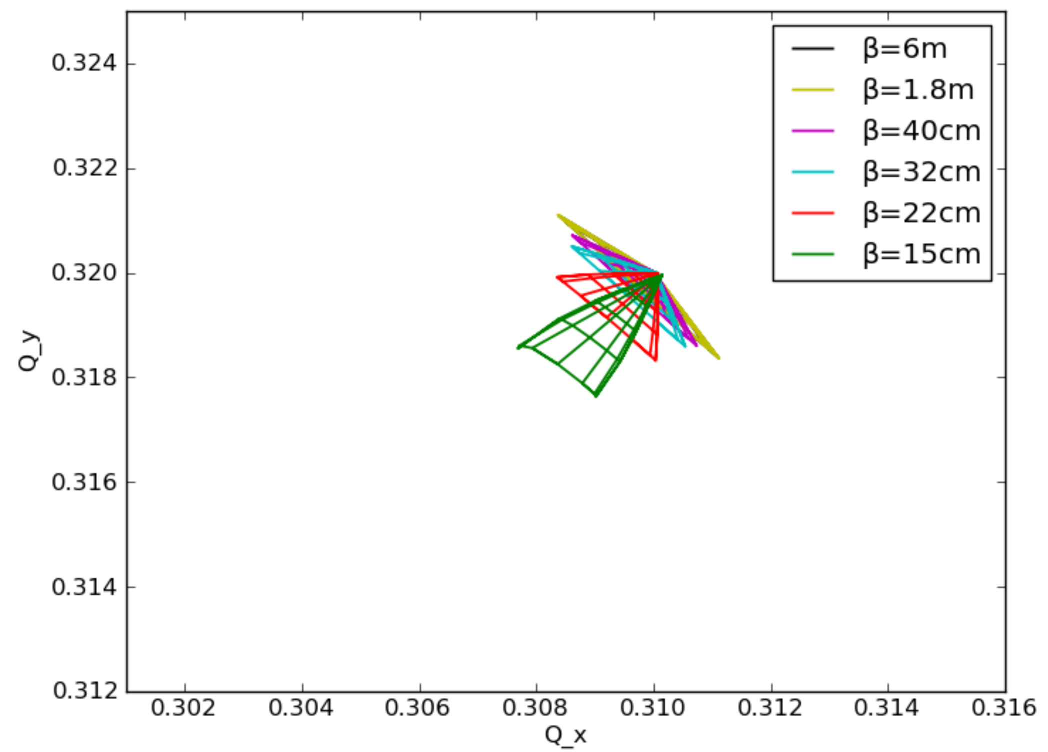
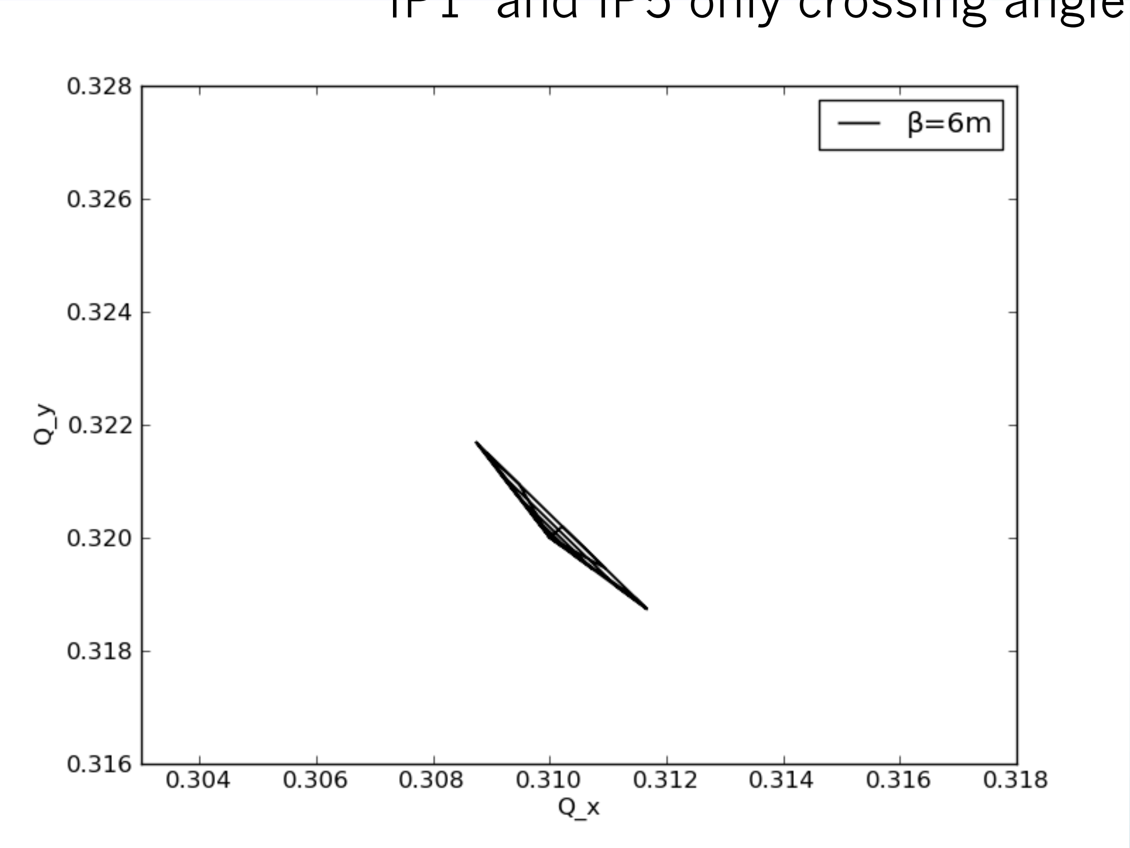


But it is not like for LHC case!

Effects of different optics + beam beam LR: footprints

- Positive LOF

IP1 and IP5 only crossing angle of 590 μrad



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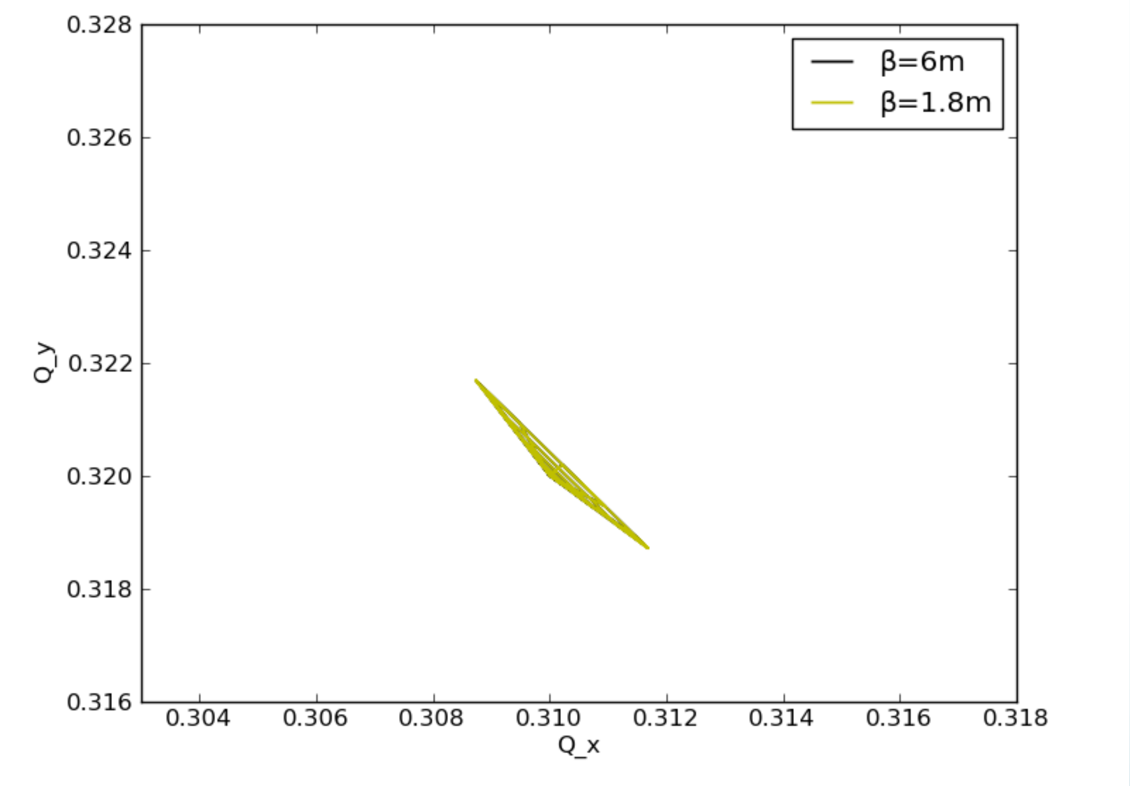

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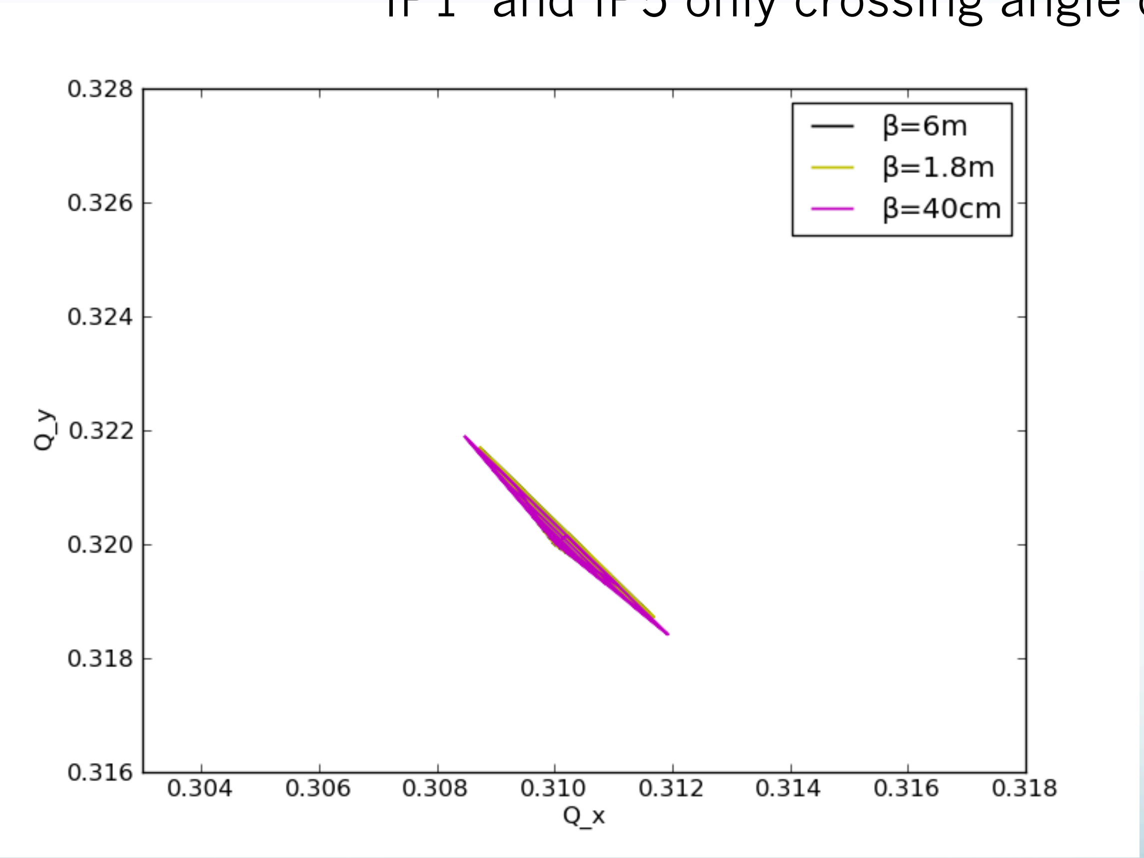

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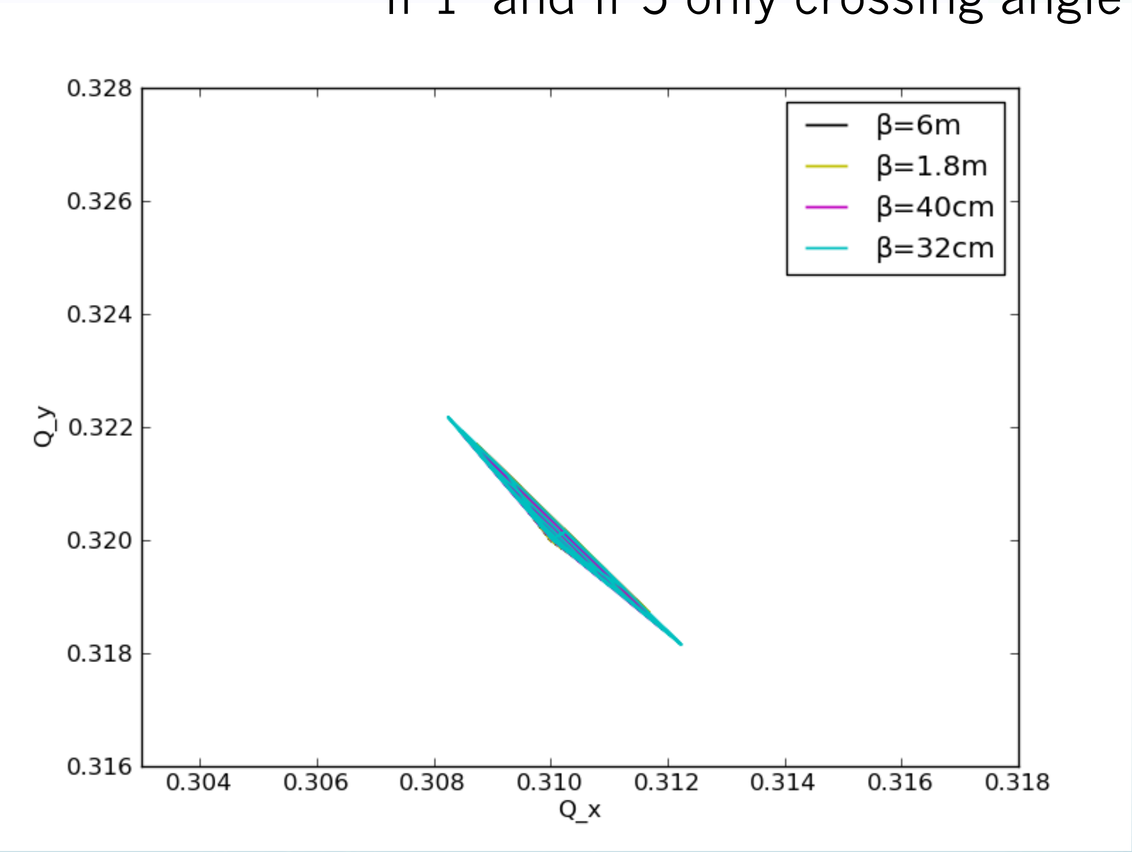

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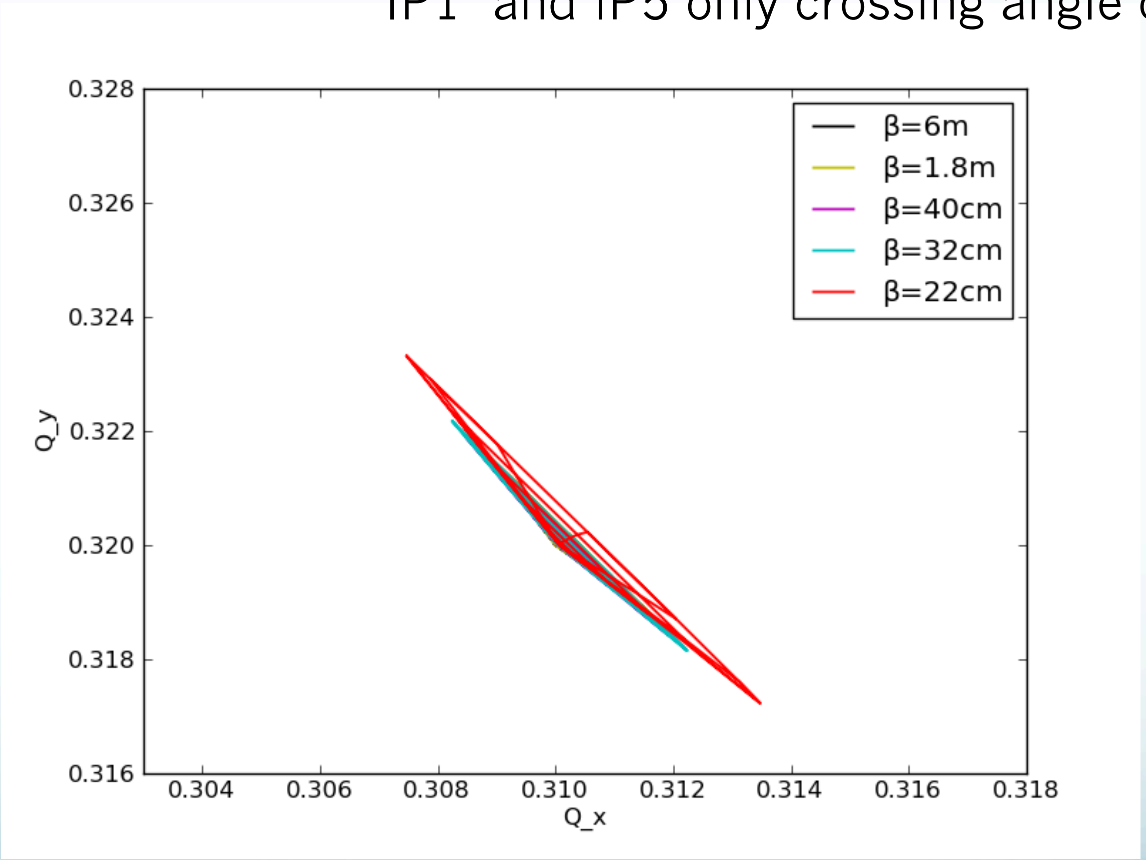

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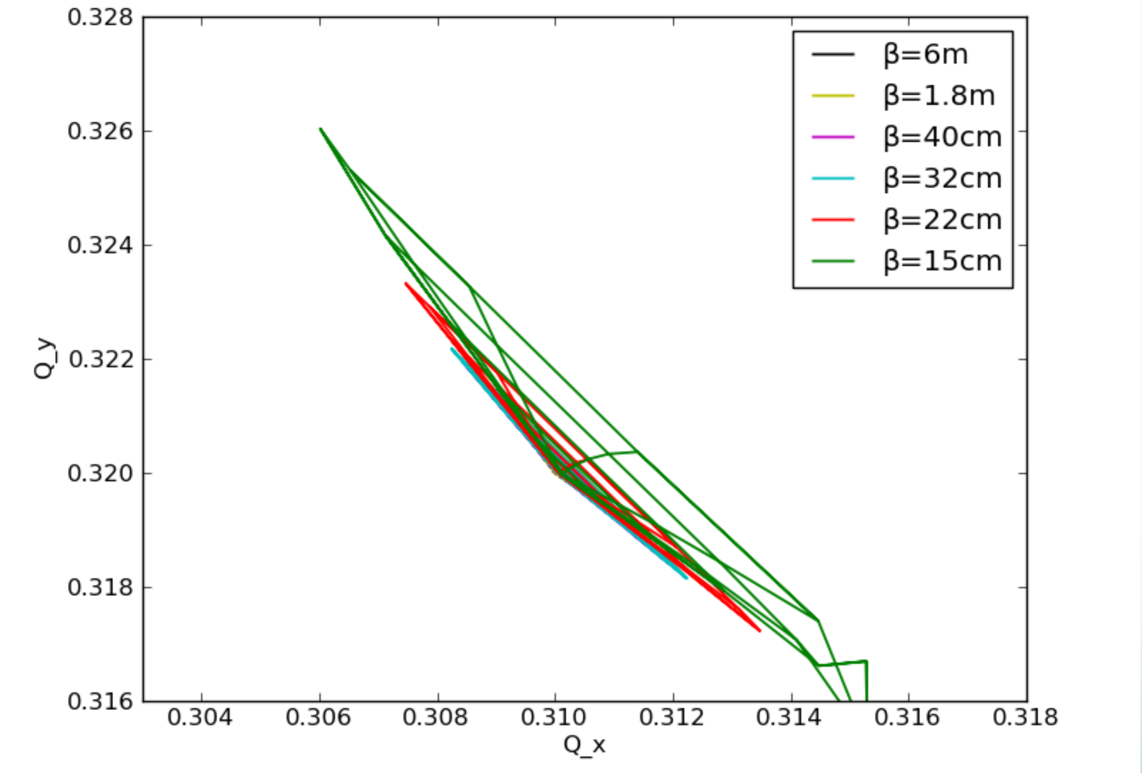

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Betatron Squeeze

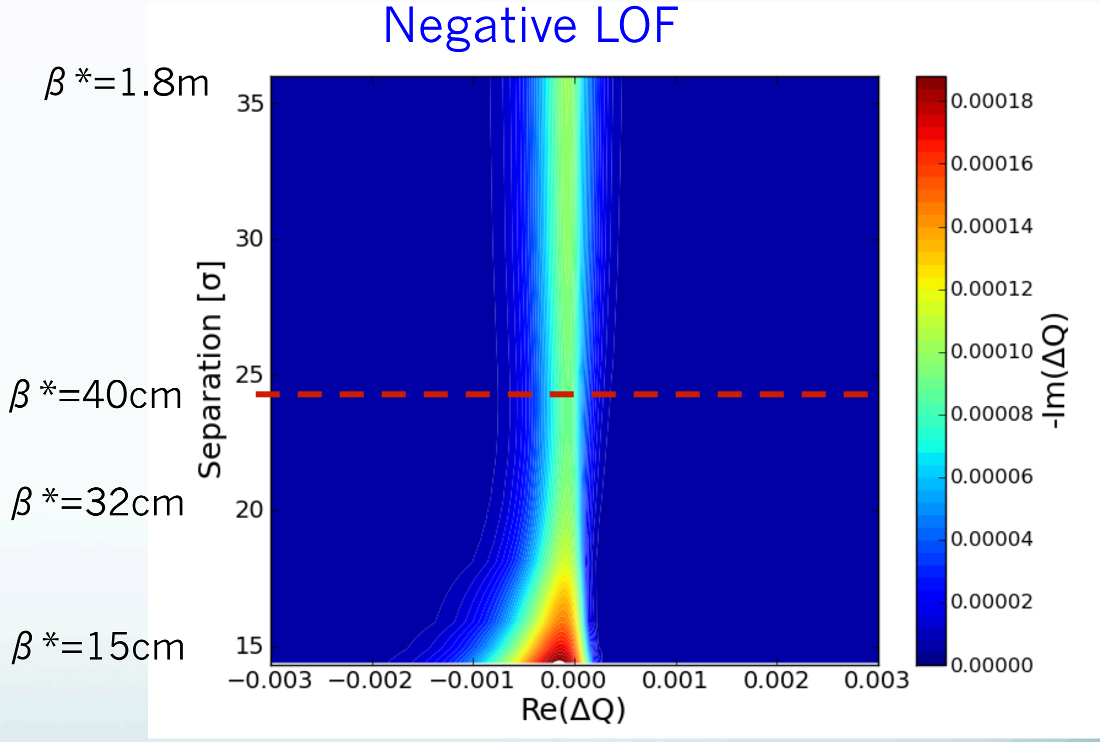
Evolution of the betatron squeeze with LR beam beam

LR beam-beam in IP1 and IP5 **I=2.2e11 ppb ε =2.5 µm**

Long range slightly reduce the SD

At 22 σ the β in the arcs increases and compensates LR effects

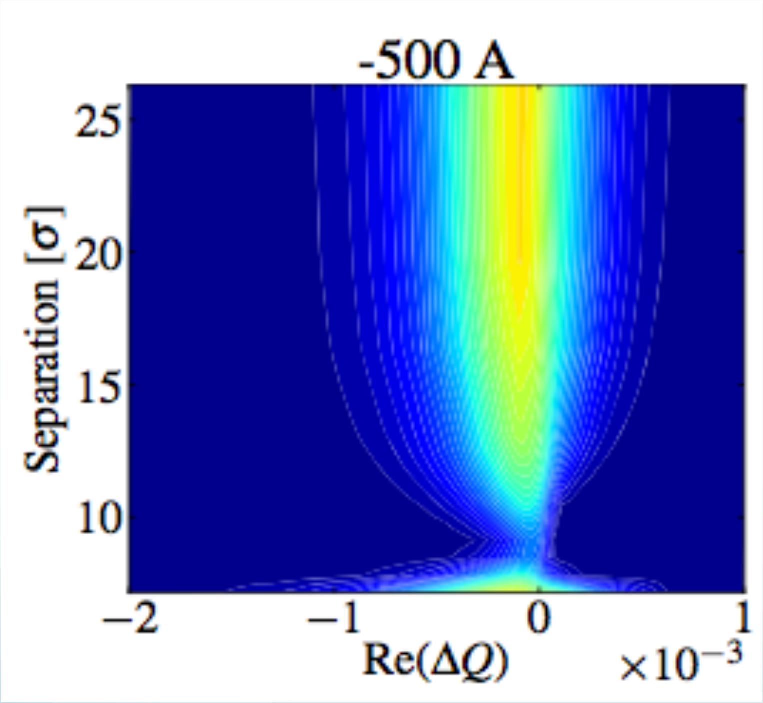
The SD keep increasing below β^*=32cm



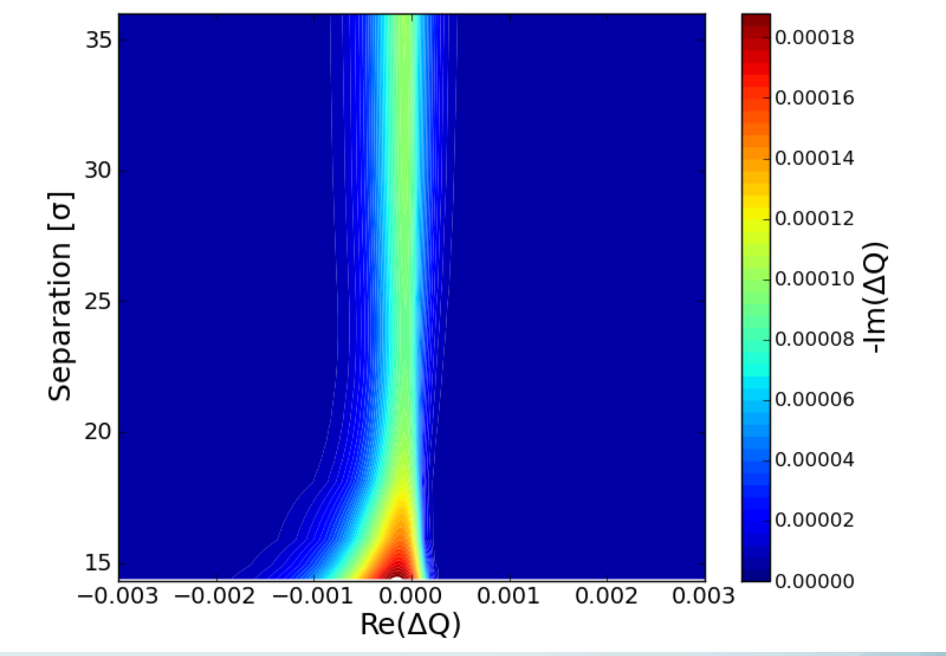
HL-LHC vs LHC

Evolution of the betatron squeeze with LR beam beam

LR beam-beam in IP1 and IP5



Negative LOF



Betatron Squeeze

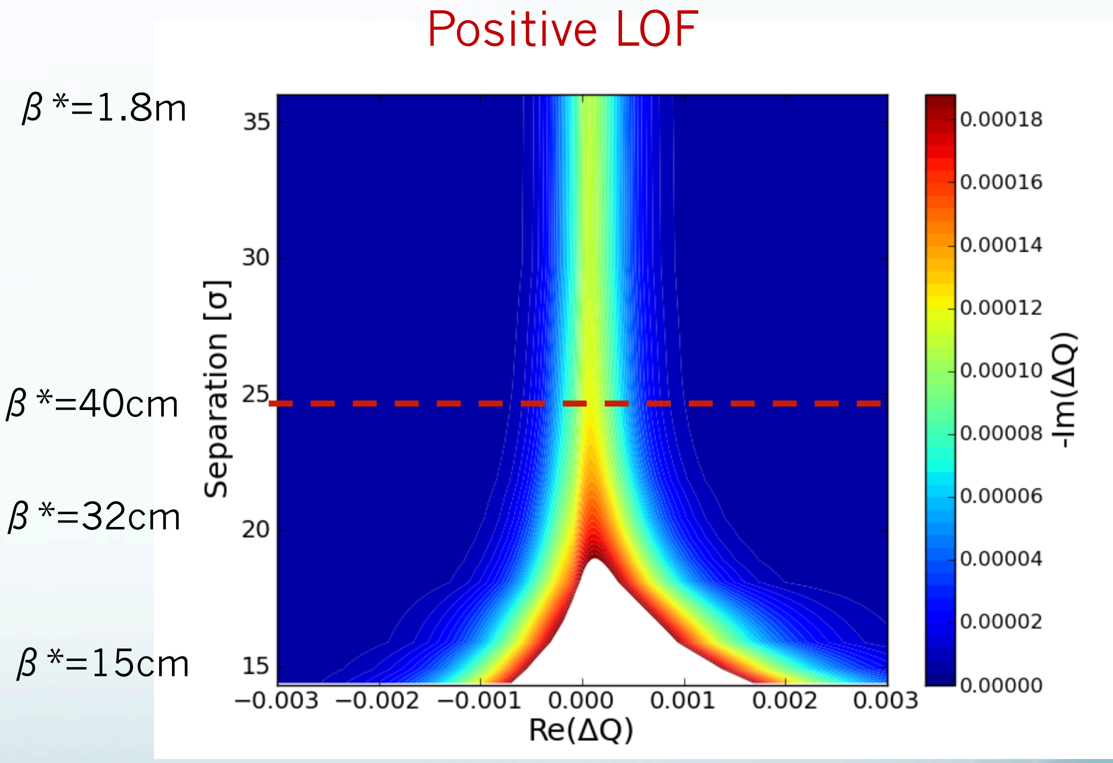
Evolution of the betatron squeeze with LR beam beam

LR beam-beam in IP1 and IP5

I=2.2e11 ppb   ε =2.5 μm

LR add up to the octupoles contribution

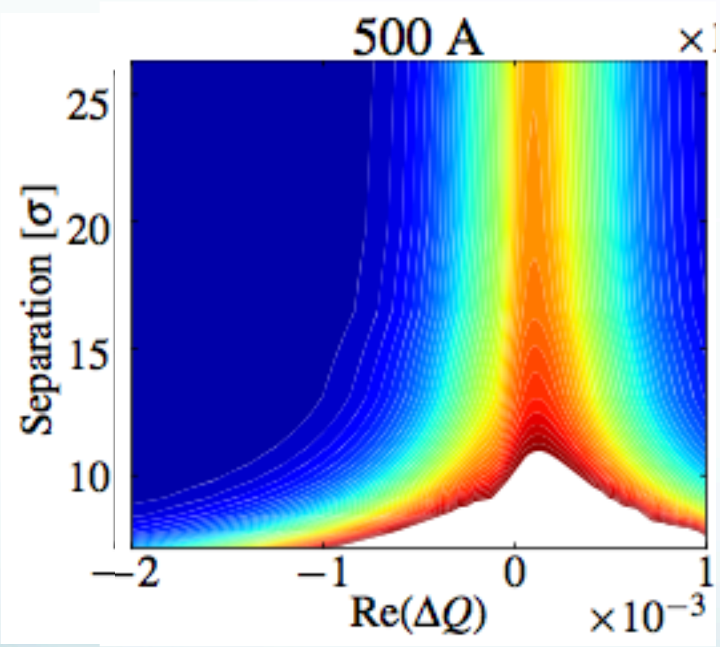
At 22σ the β in the arcs increase and add up with LR



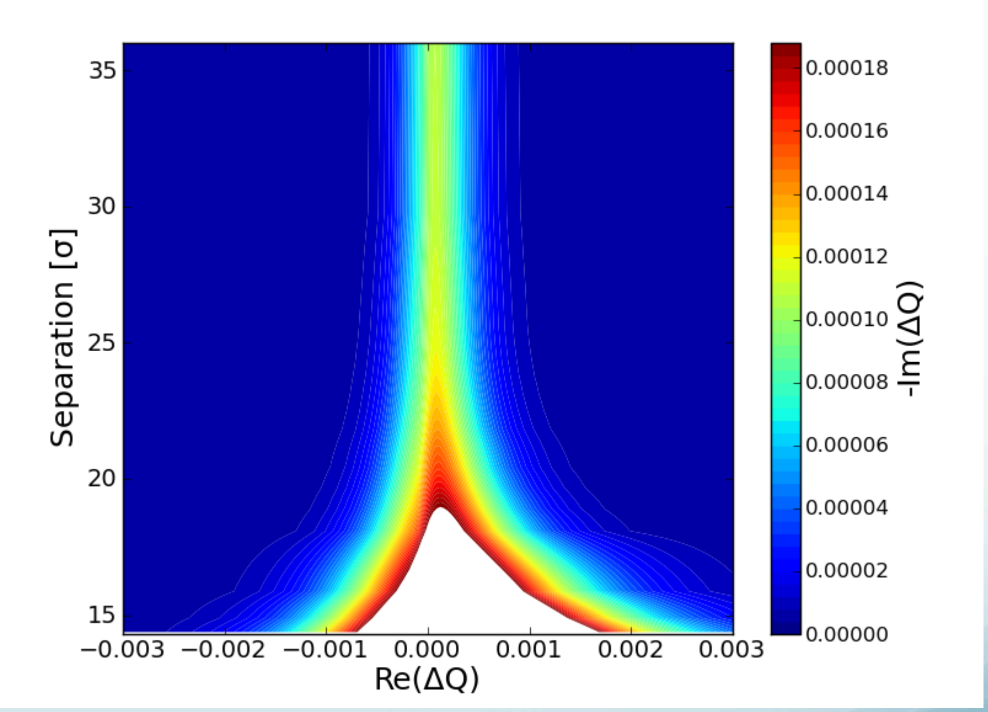
HL-LHC vs LHC

Evolution of the betatron squeeze with LR beam beam

LR beam-beam in IP1 and IP5



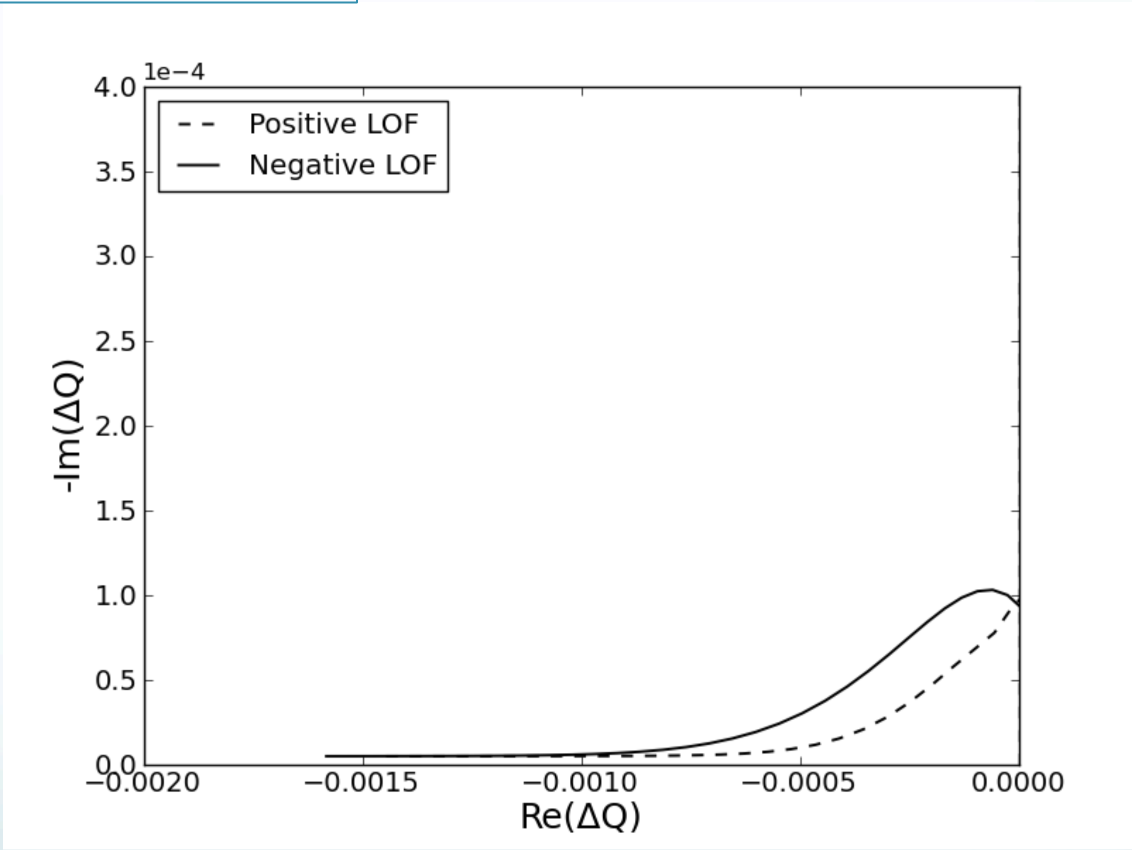
Positive LOF



As in LHC the SD increase during the squeeze

SD evolution during the β-squeeze

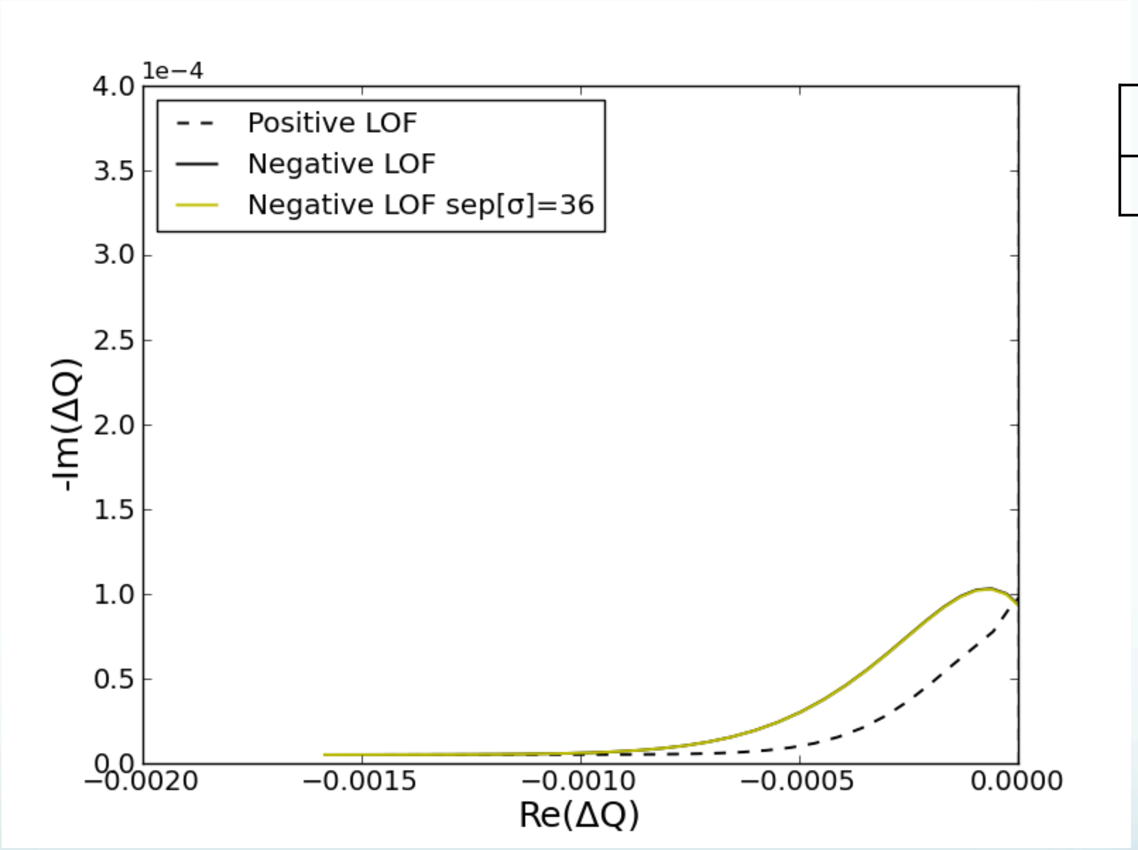
Octupoles only, single beam



- Negative polarity preferred for single beam

SD evolution during the β -squeeze

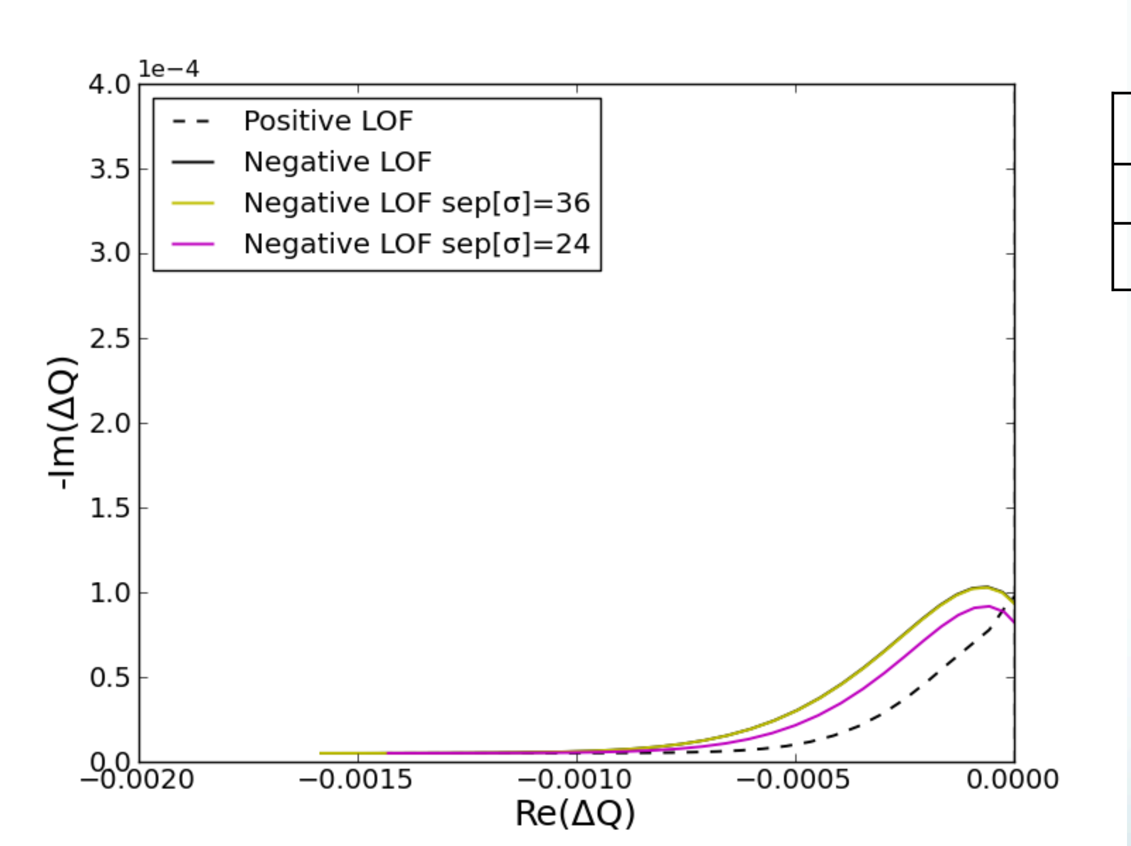
LR beam-beam added



β [m]	Sep [σ]
1.8	36

SD evolution during the β-squeeze

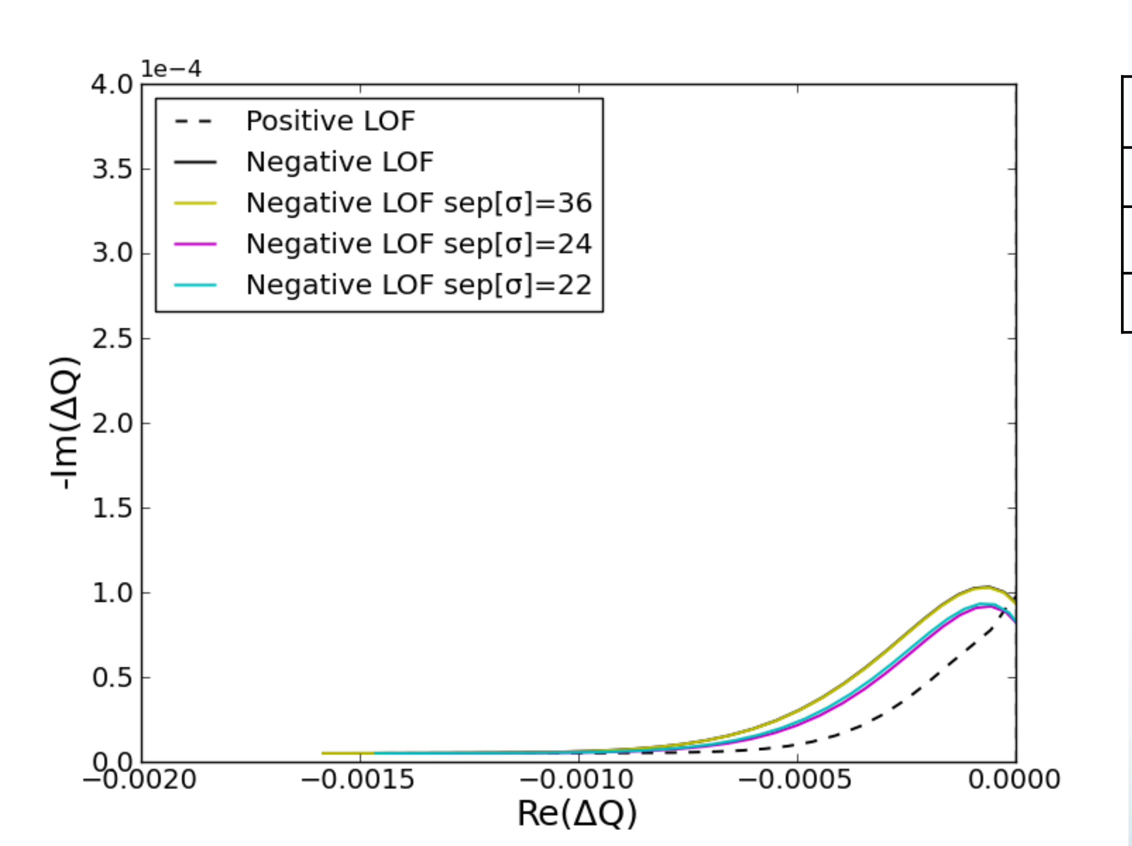
LR beam beam added



β [m]	Sep [σ]
1.8	36
0.40	24

SD evolution during the β -squeeze

LR beam beam added

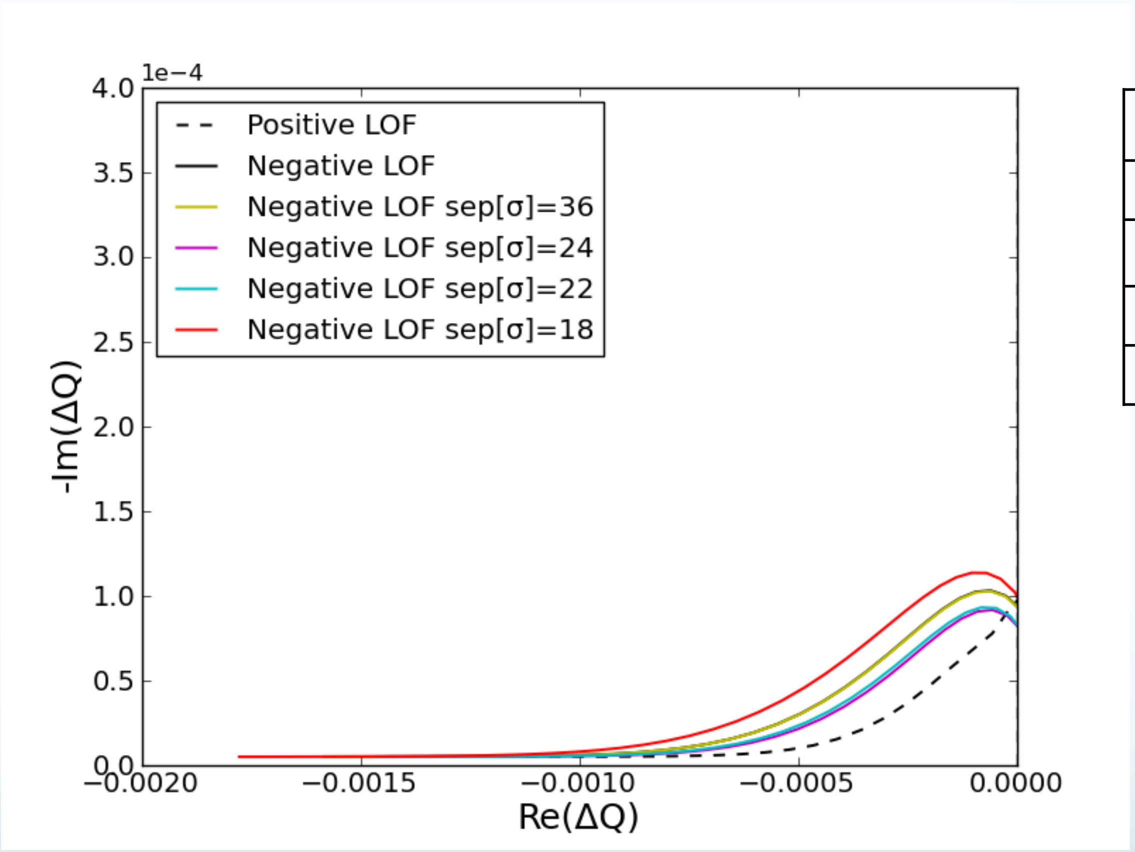


β [m]	Sep [σ]
1.8	36
0.40	24
0.32	22

- At 22σ the ATS optics takes action and the SD starts to increase despite the LR contribution

SD evolution during the β-squeeze

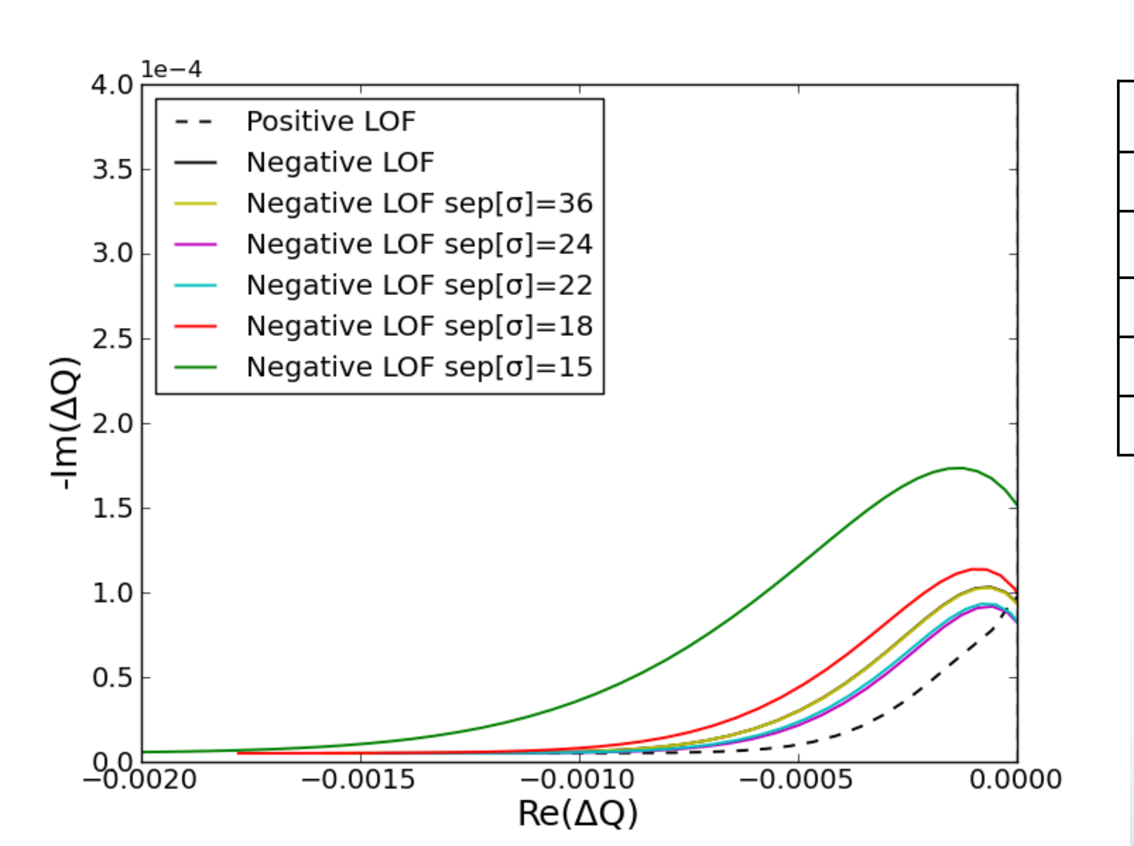
LR beam beam added



β [m]	Sep [σ]
1.8	36
0.40	24
0.32	22
0.22	18

SD evolution during the β-squeeze

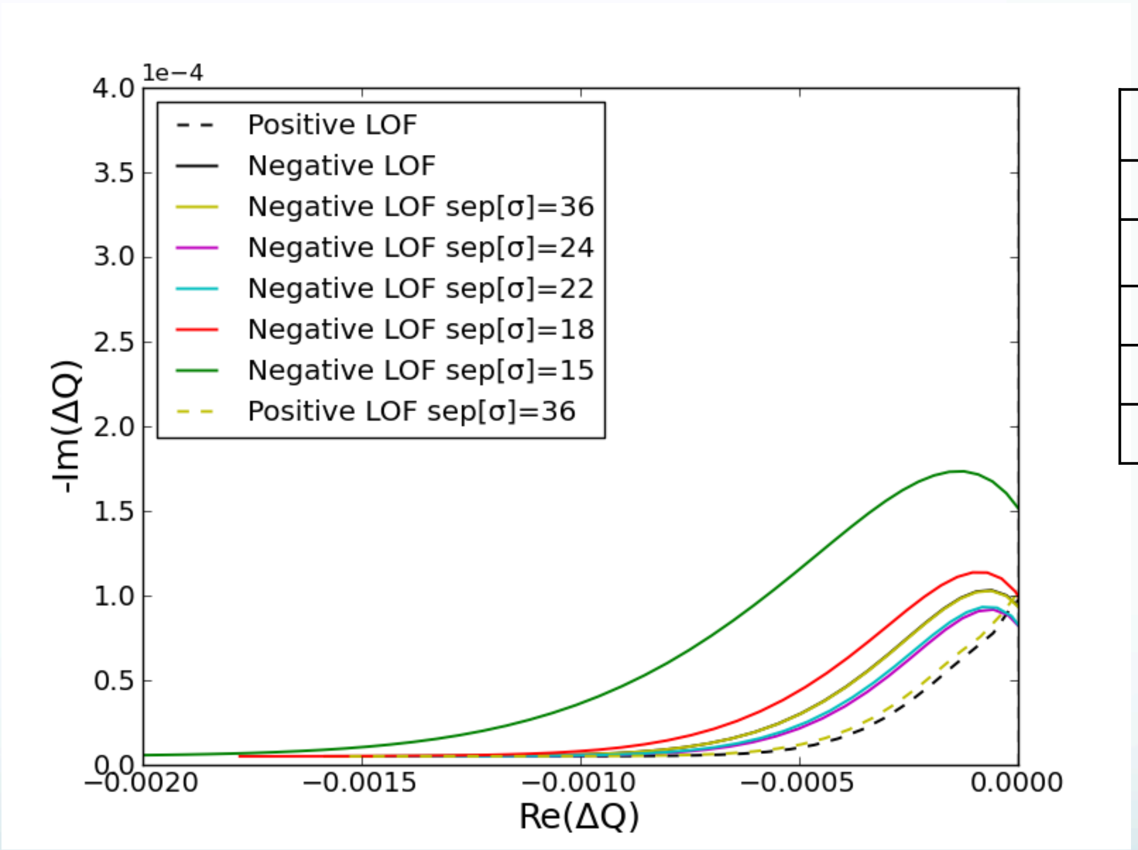
LR beam beam added



β [m]	Sep [σ]
1.8	36
0.40	24
0.32	22
0.22	18
0.15	15

SD evolution during the β-squeeze

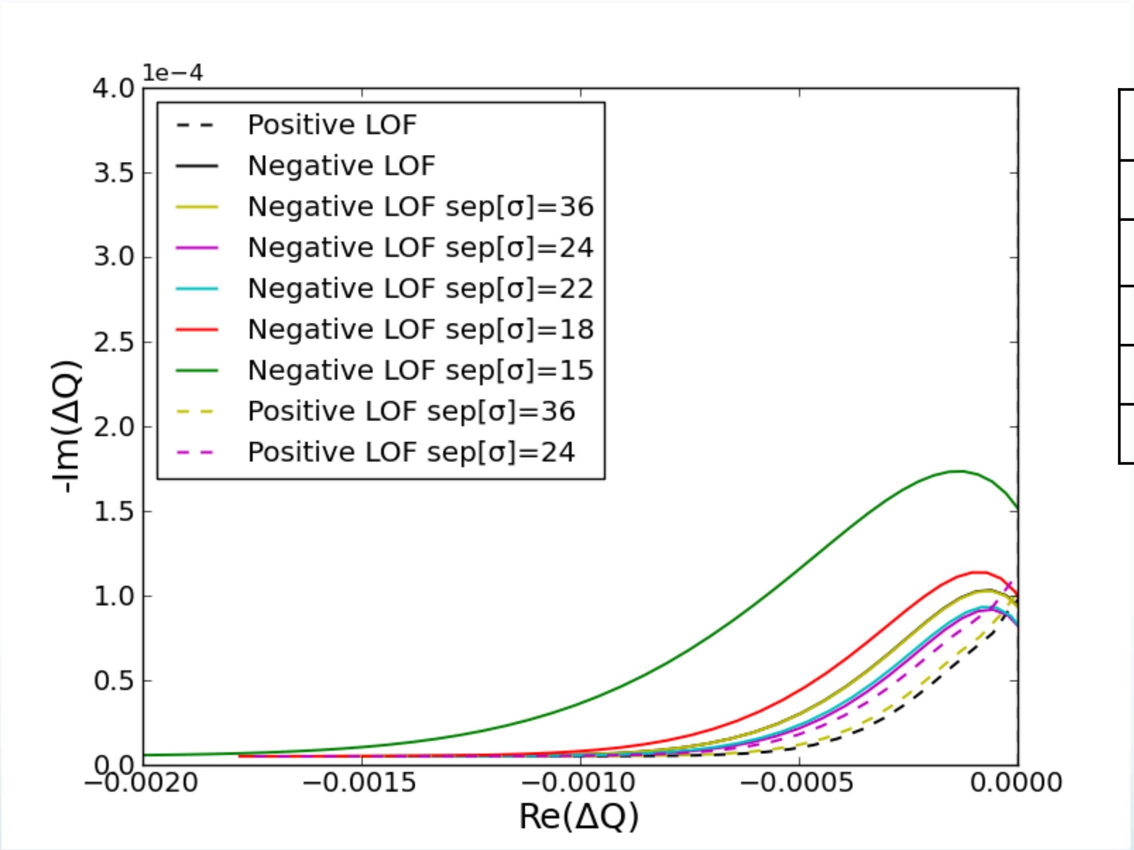
LR beam beam added



β [m]	Sep [σ]
1.8	36
0.40	24
0.32	22
0.22	18
0.15	15

SD evolution during the β -squeeze

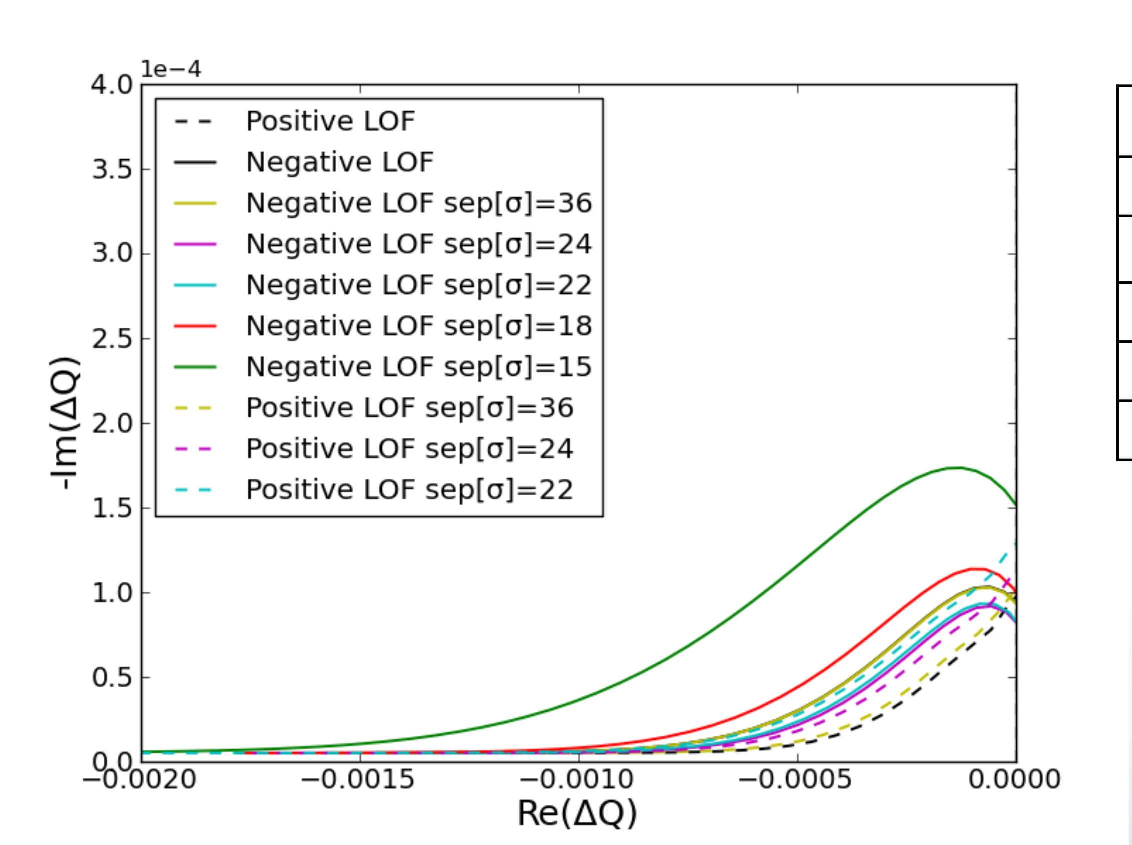
LR beam beam added



β [m]	Sep [σ]
1.8	36
0.40	24
0.32	22
0.22	18
0.15	15

SD evolution during the β-squeeze

LR beam beam added

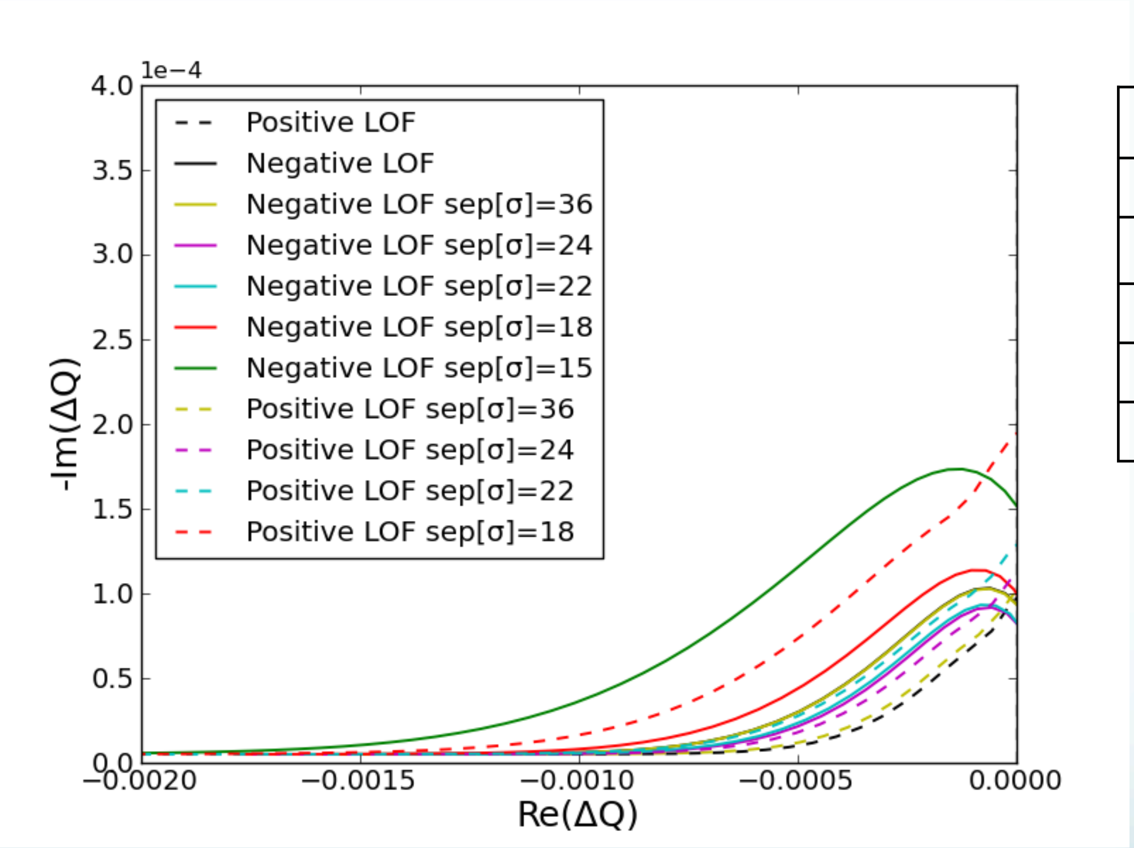


β [m]	Sep [σ]
1.8	36
0.40	24
0.32	22
0.22	18
0.15	15

- At 22 σ equal SD for positive/negative LOF

SD evolution during the β-squeeze

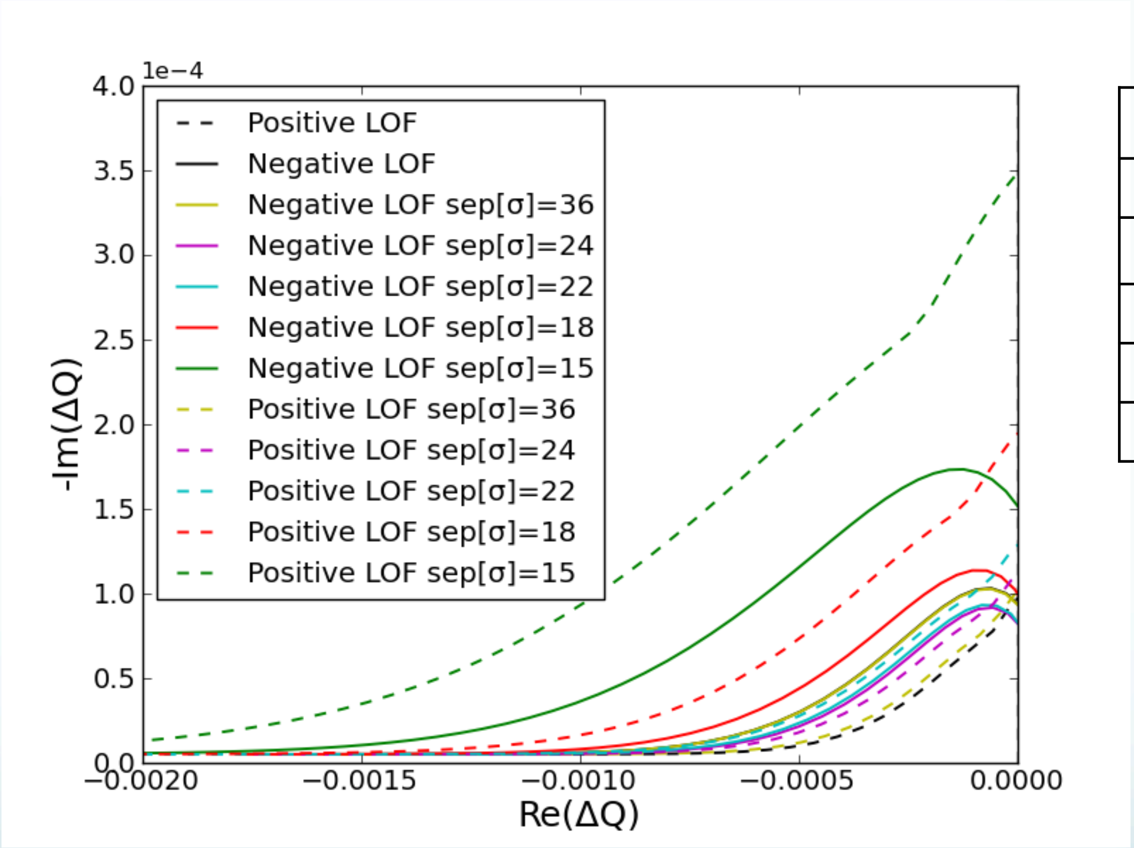
LR beam beam added



β [m]	Sep [σ]
1.8	36
0.40	24
0.32	22
0.22	18
0.15	15

SD evolution during the β -squeeze

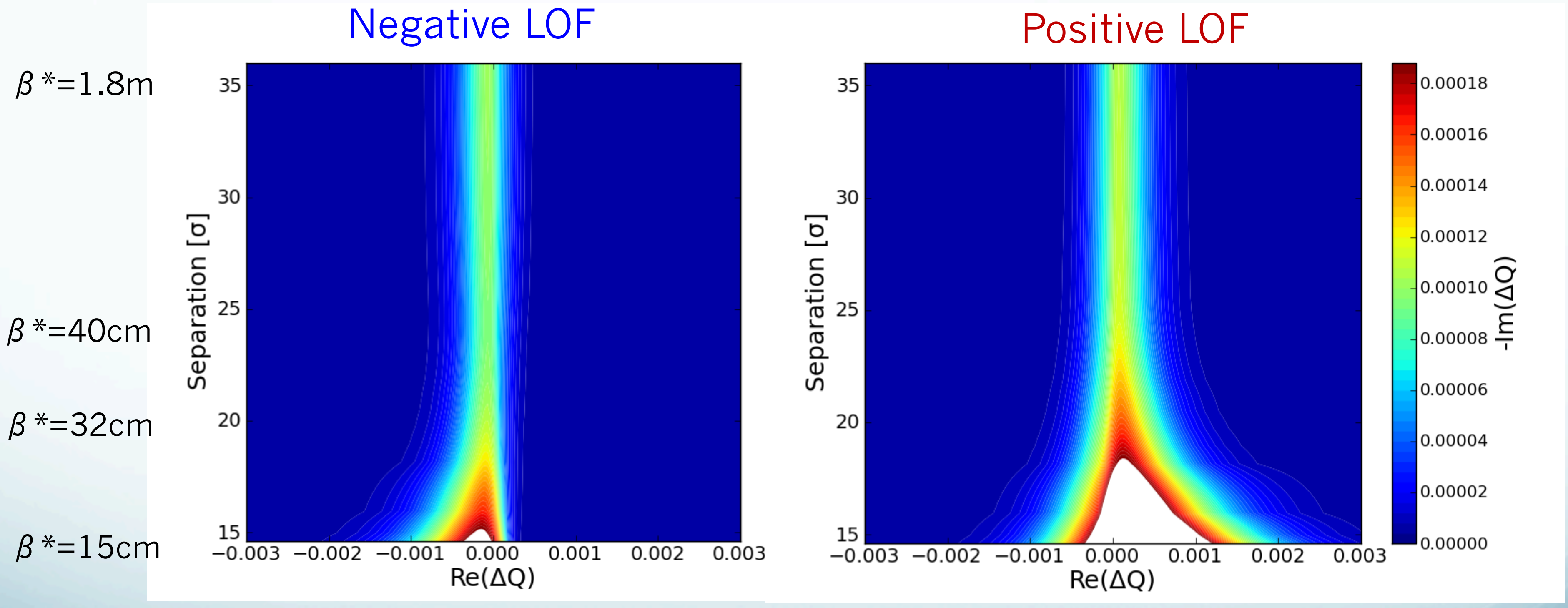
LR beam beam added



β [m]	Sep [σ]
1.8	36
0.40	24
0.32	22
0.22	18
0.15	15

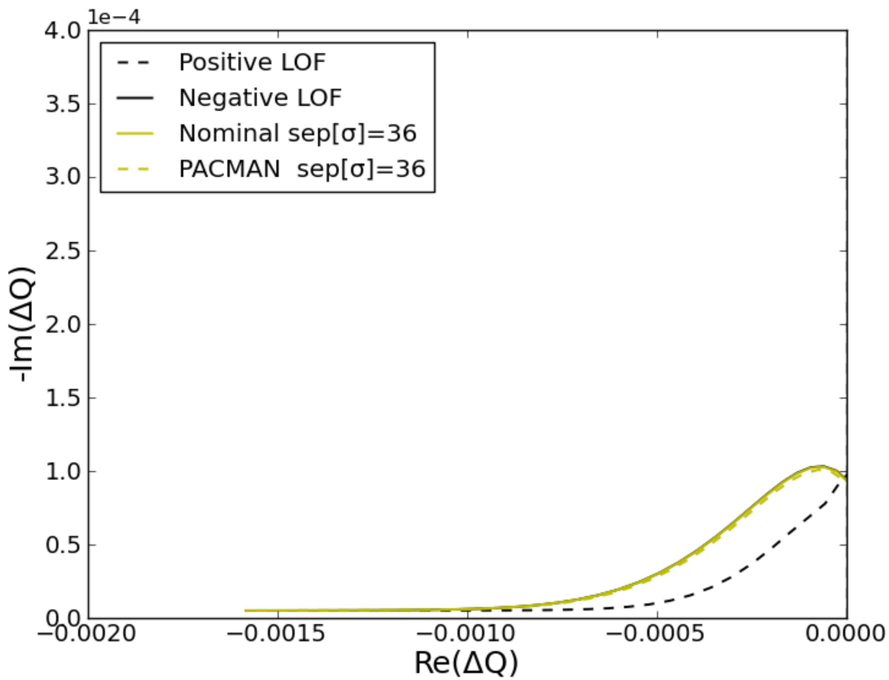
Betatron squeeze for HL-LHC optics: PACMAN bunches

Evolution of the betatron squeeze with LR beam beam for PACMAN bunches

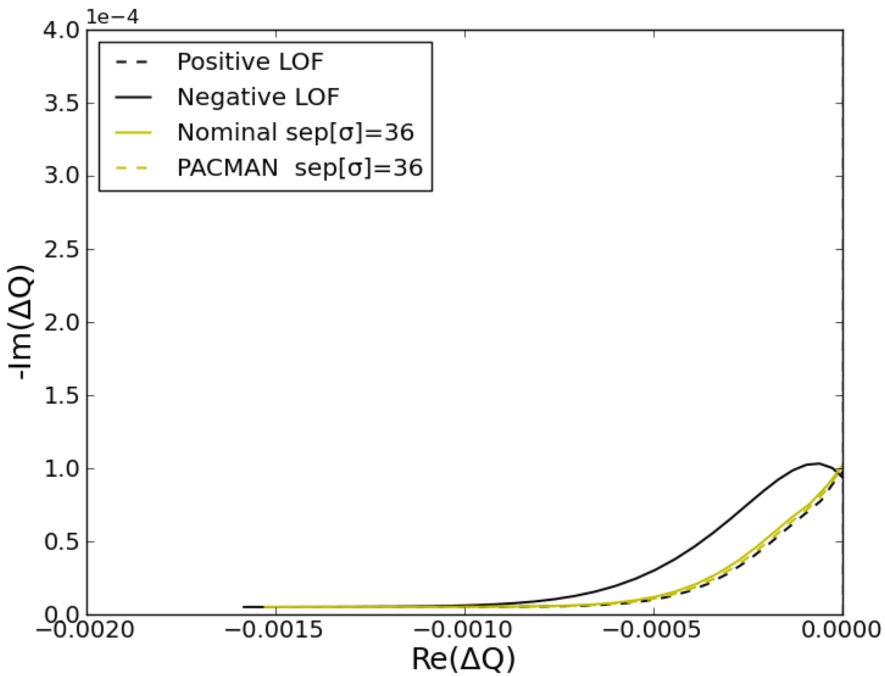


Stability Diagrams for PACMAN bunches

Negative LOF



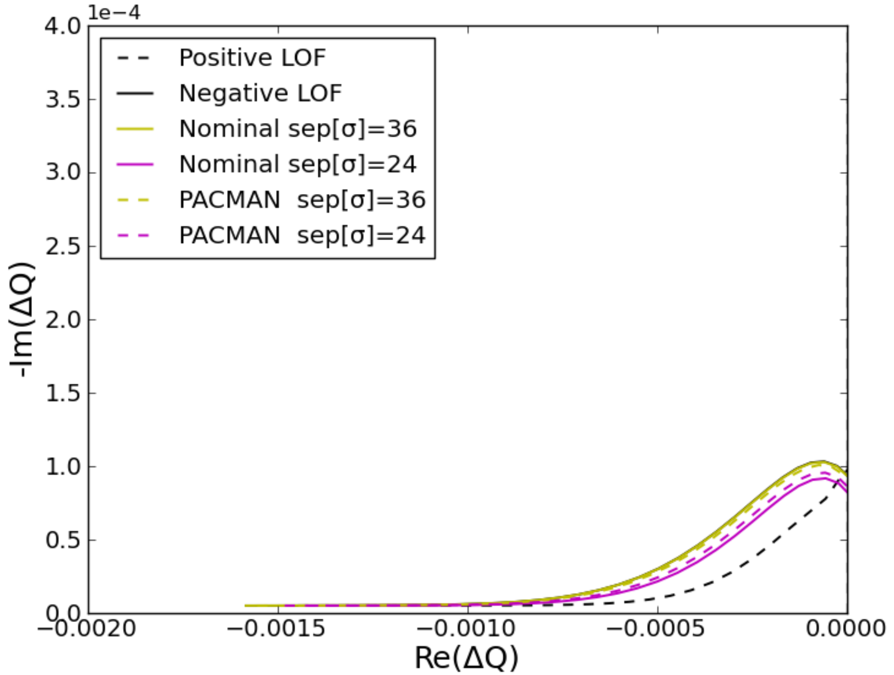
Positive LOF



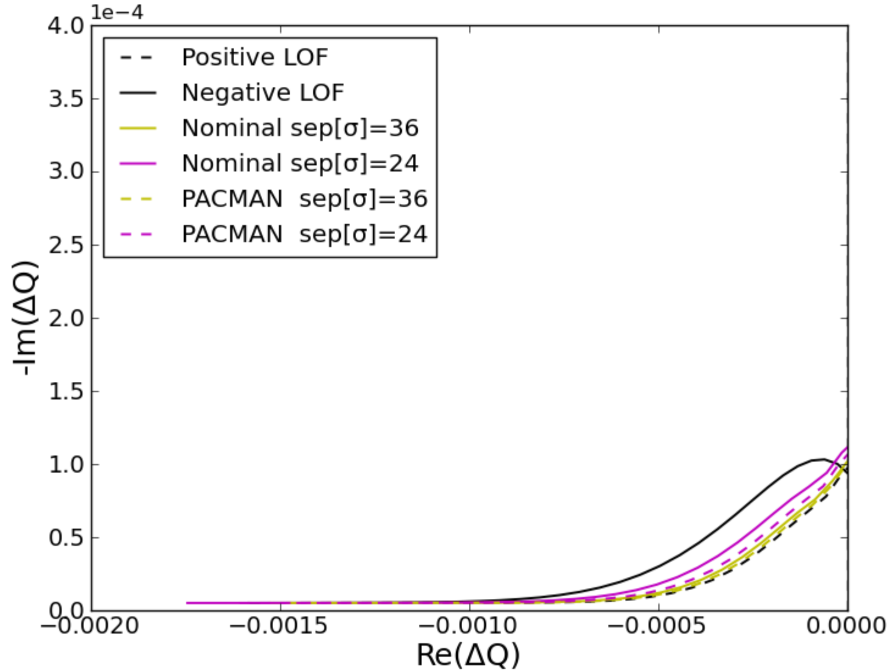
PACMAN bunches: greater SD in case of negative polarity

Stability Diagrams for PACMAN bunches

Negative LOF



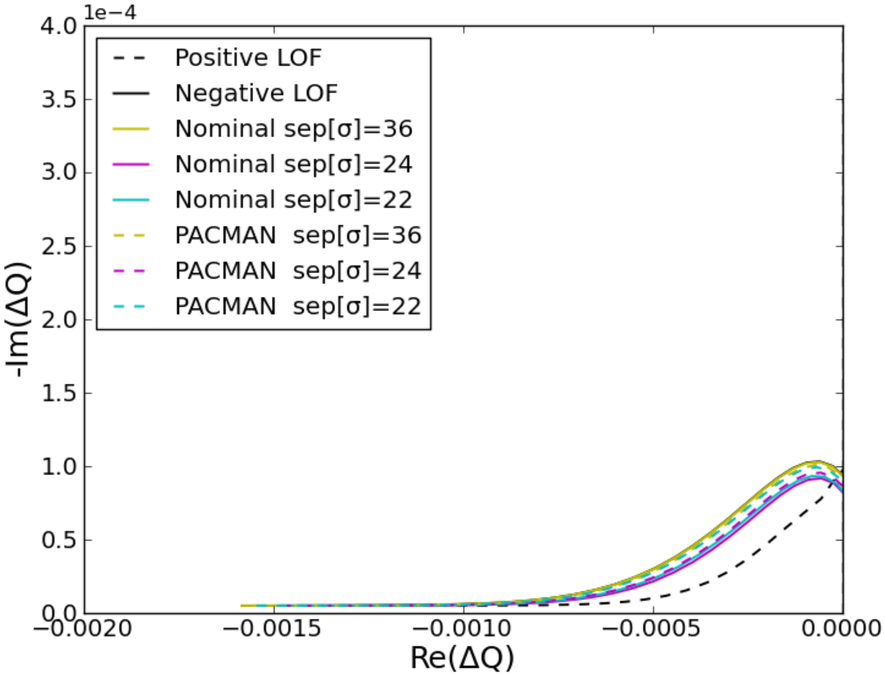
Positive LOF



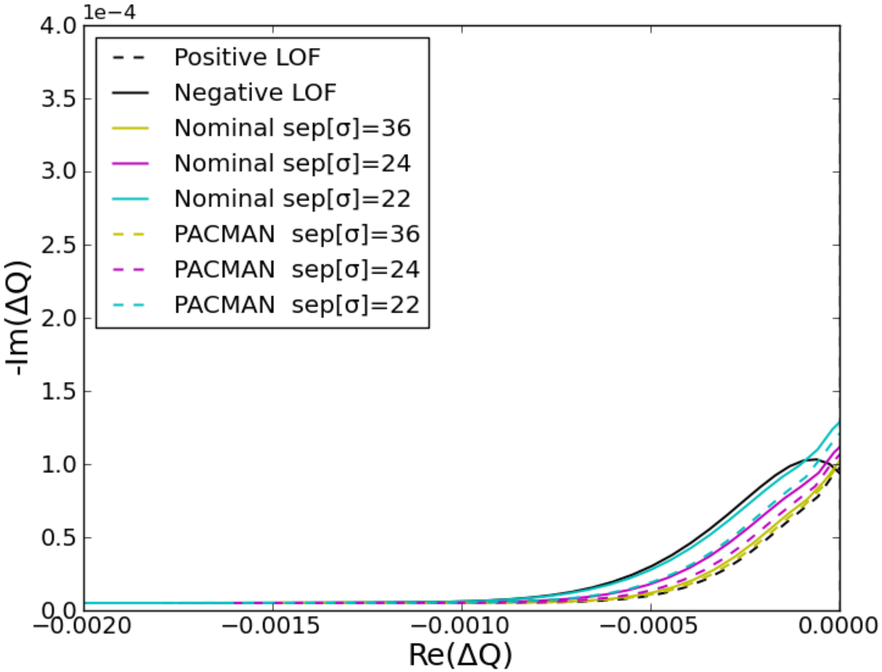
PACMAN bunches: greater SD in case of negative polarity

Stability Diagrams for PACMAN bunches

Negative LOF



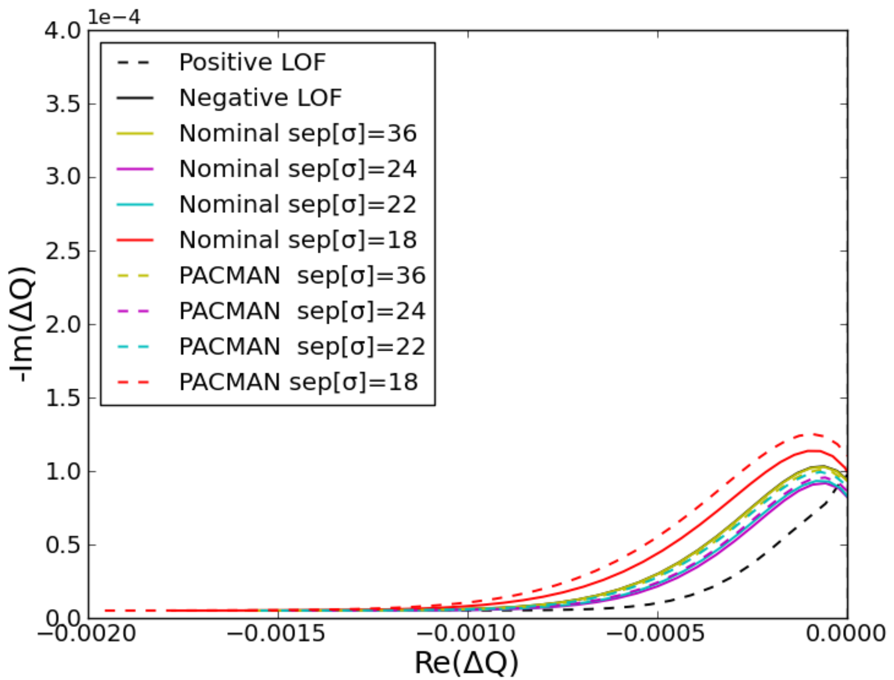
Positive LOF



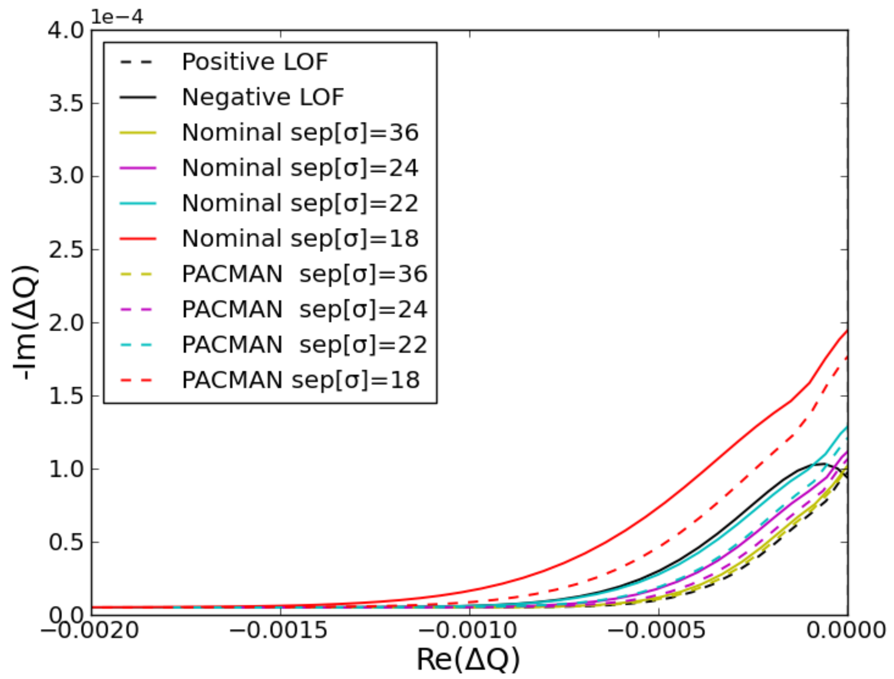
PACMAN bunches: greater SD in case of negative polarity

Stability Diagrams for PACMAN bunches

Negative LOF



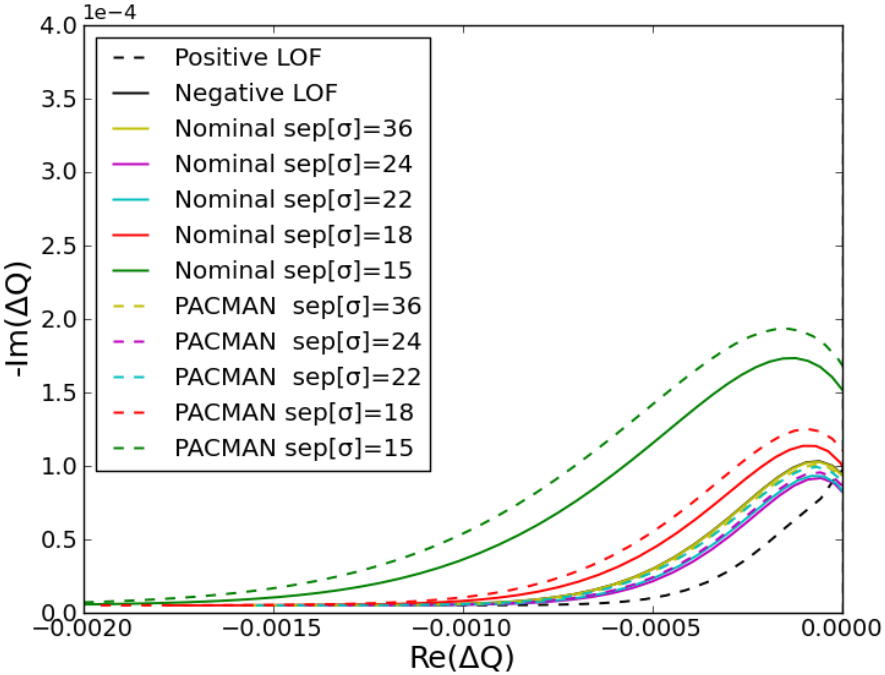
Positive LOF



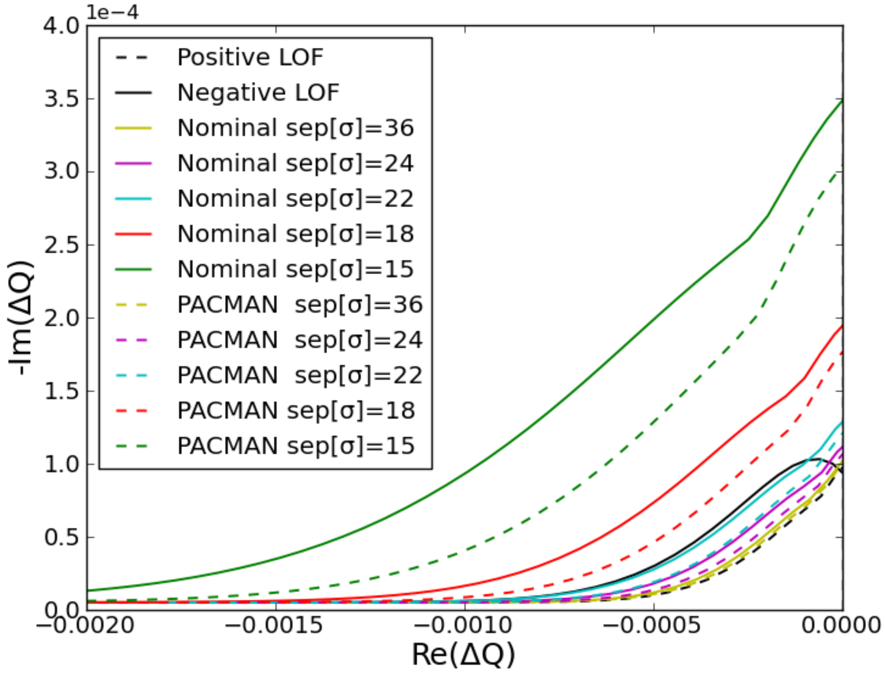
PACMAN bunches: greater SD in case of negative polarity

Stability Diagrams for PACMAN bunches

Negative LOF



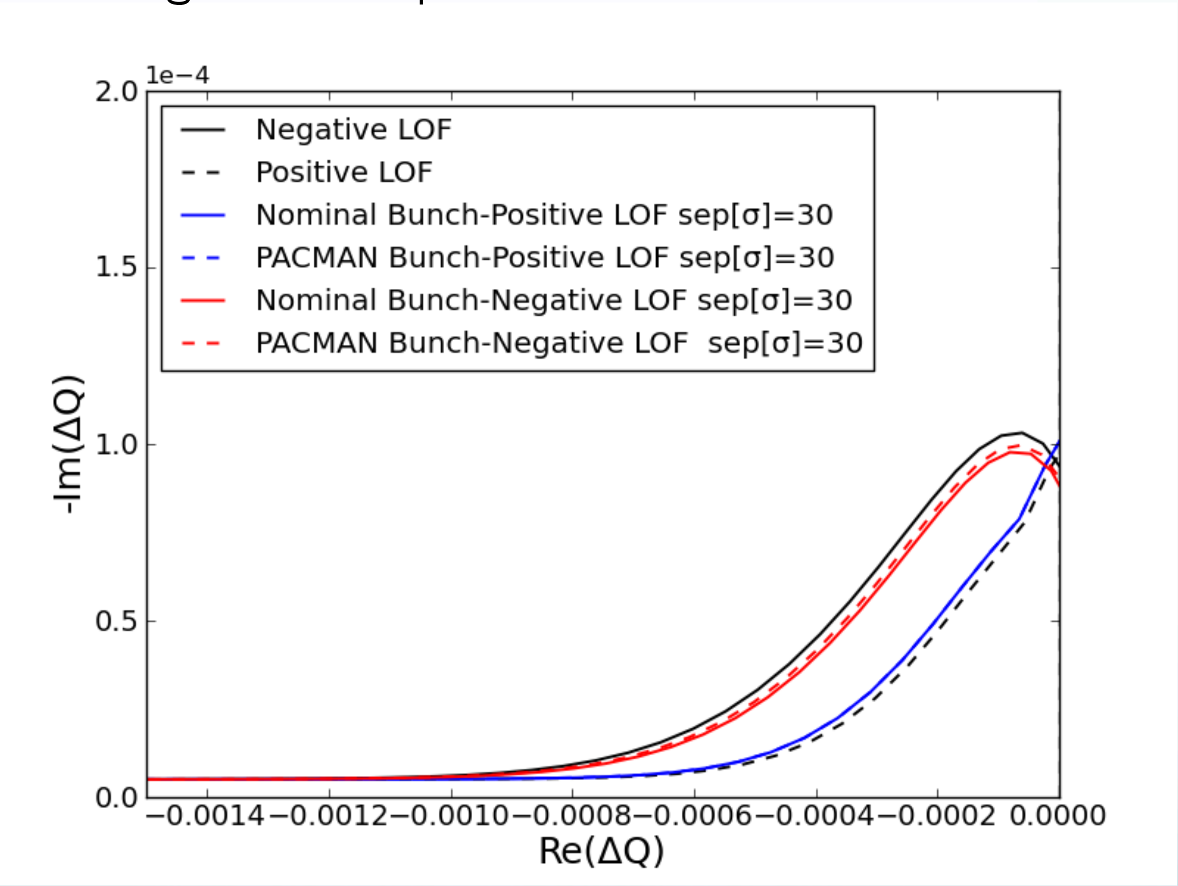
Positive LOF



PACMAN bunches: greater SD in case of negative polarity

Stability Diagrams for Baseline scenario

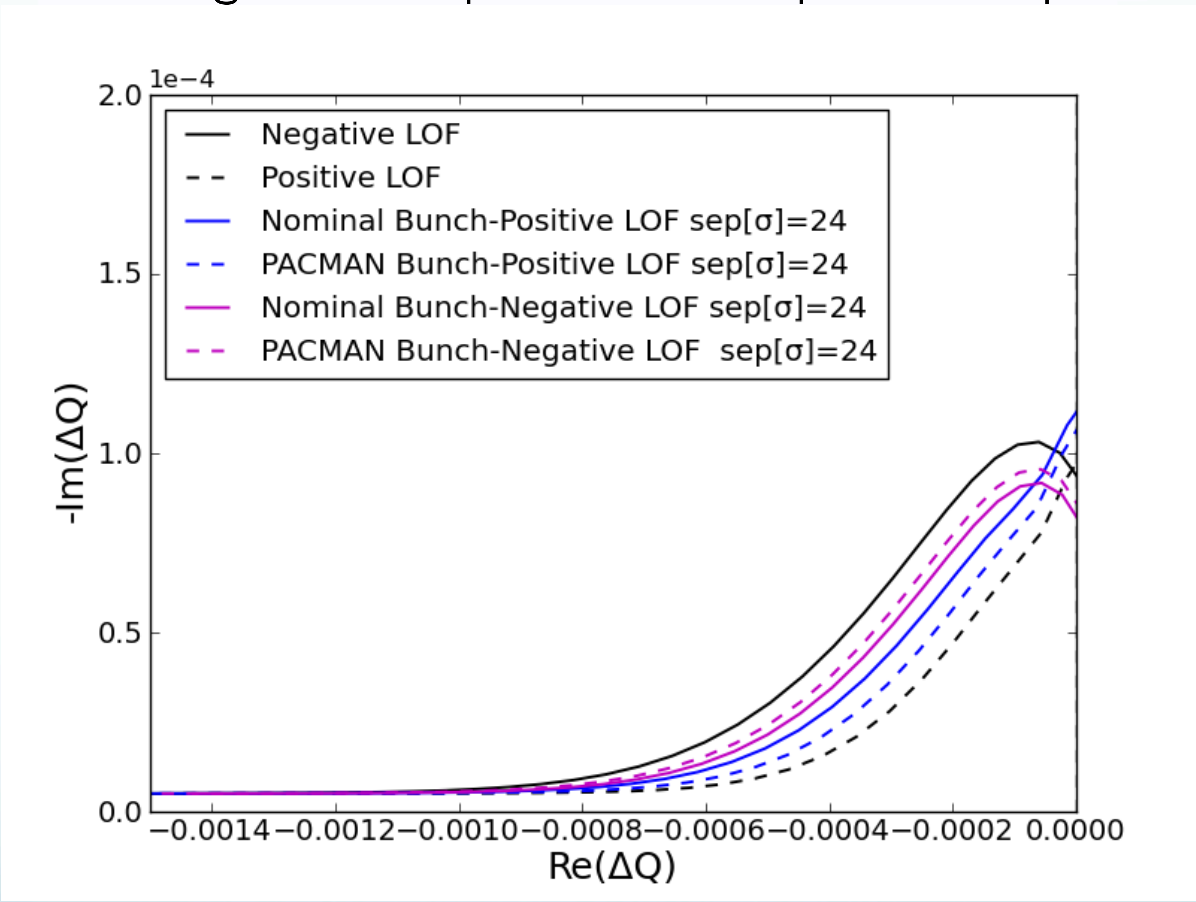
Baseline scenario negative LOF preferred



β [m]	Sep [σ]
0.60	30

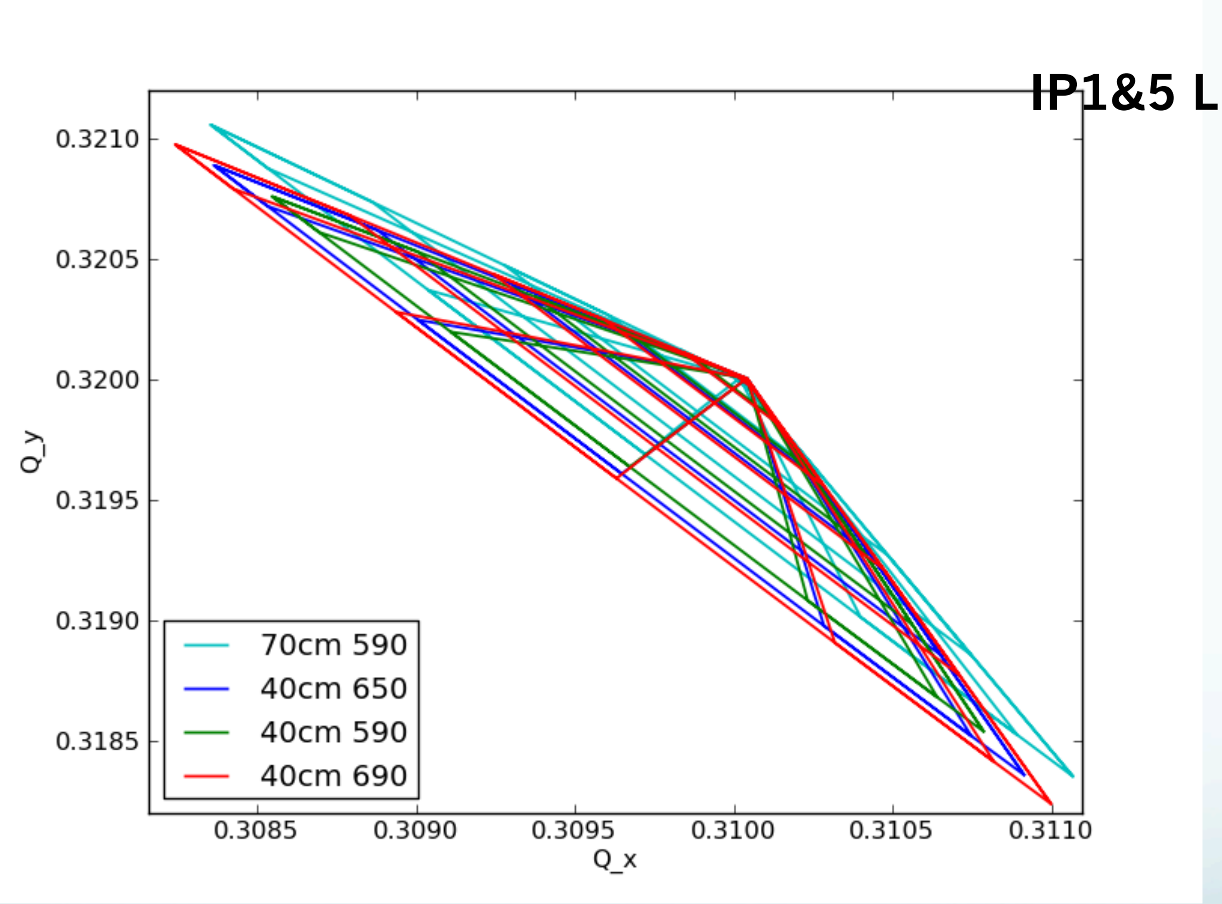
Stability Diagrams for Ultimate scenario

Ultimate scenario negative LOF preferred/comparable to positive LOF



β [m]	Sep [σ]
0.40	24

Can we compensate the reduction with stronger effect of Octupoles?



IP1&5 LRs + Octupoles

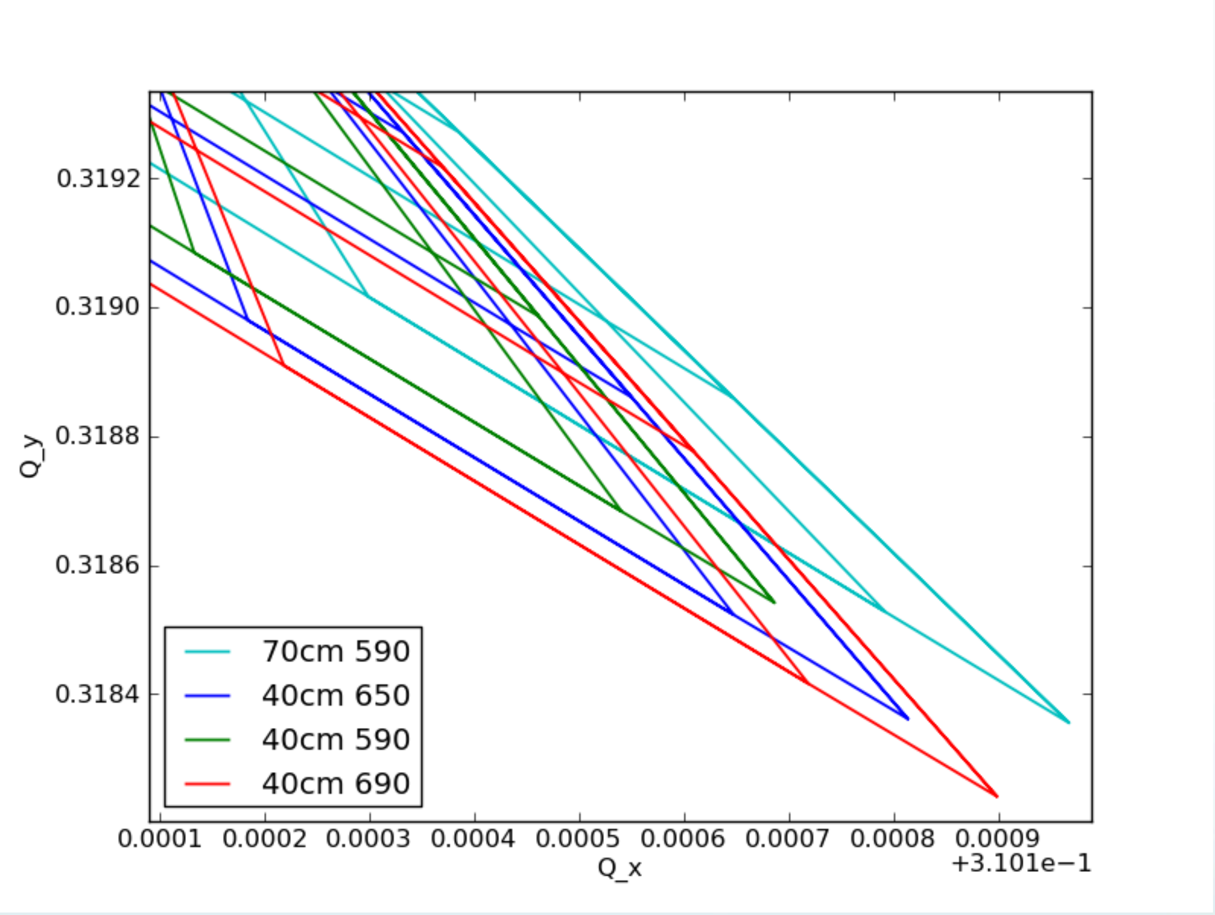
We increase current in Octupoles

Landau Damping, Dynamic Aperture and Octupoles in LHC

J. Gareyte, J.P. Koutchouk and F. Ruggiero

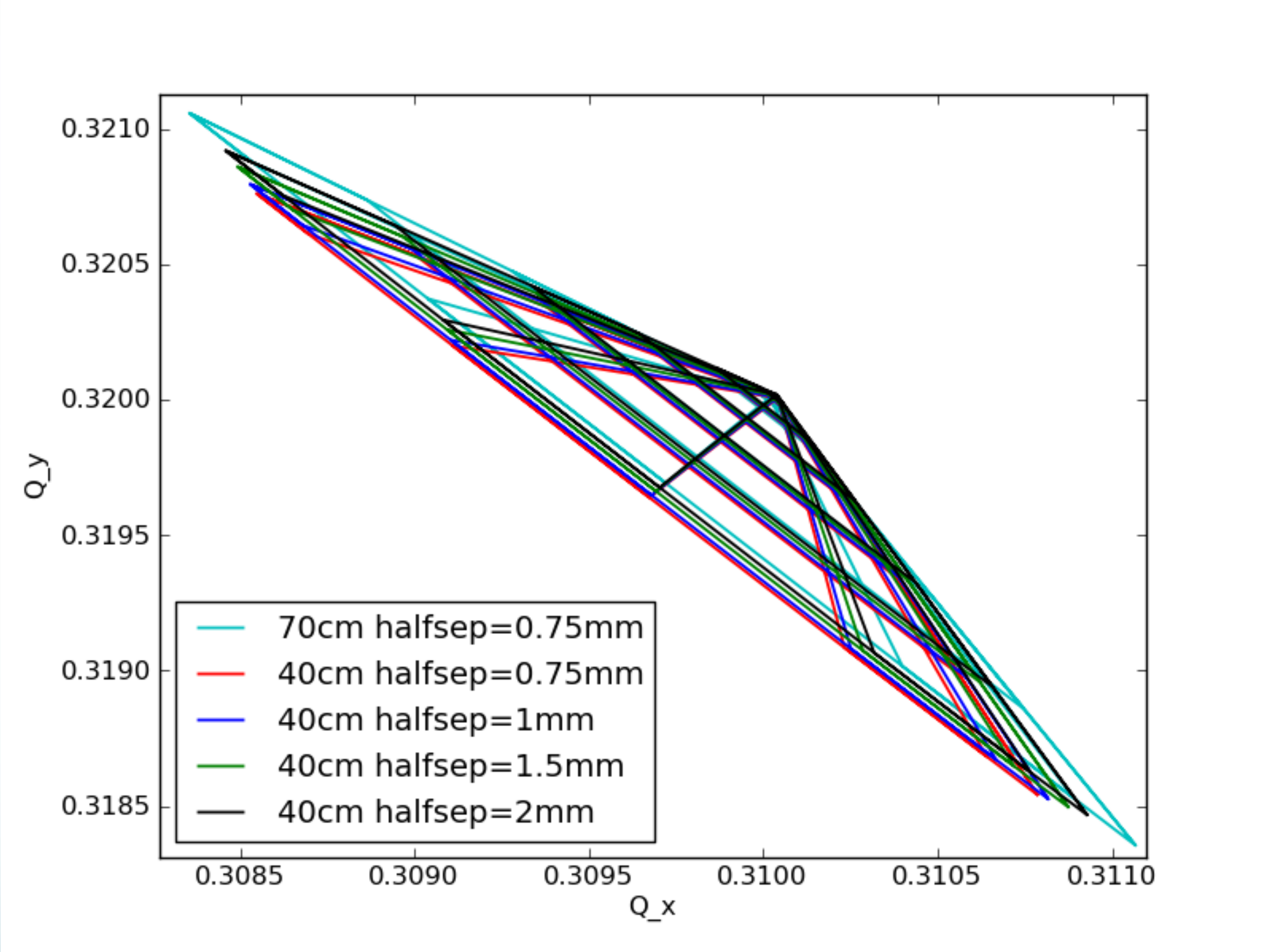
$$\Delta Q_x = \left[\frac{3}{8\pi}\int \beta_x^2 \frac{O_3}{B\rho}\,ds\right] J_x - \left[\frac{3}{8\pi}\int 2\beta_x\beta_y \frac{O_3}{B\rho}\,ds\right] J_y,$$

Can we compensate the reduction with stronger effect of Octupoles?



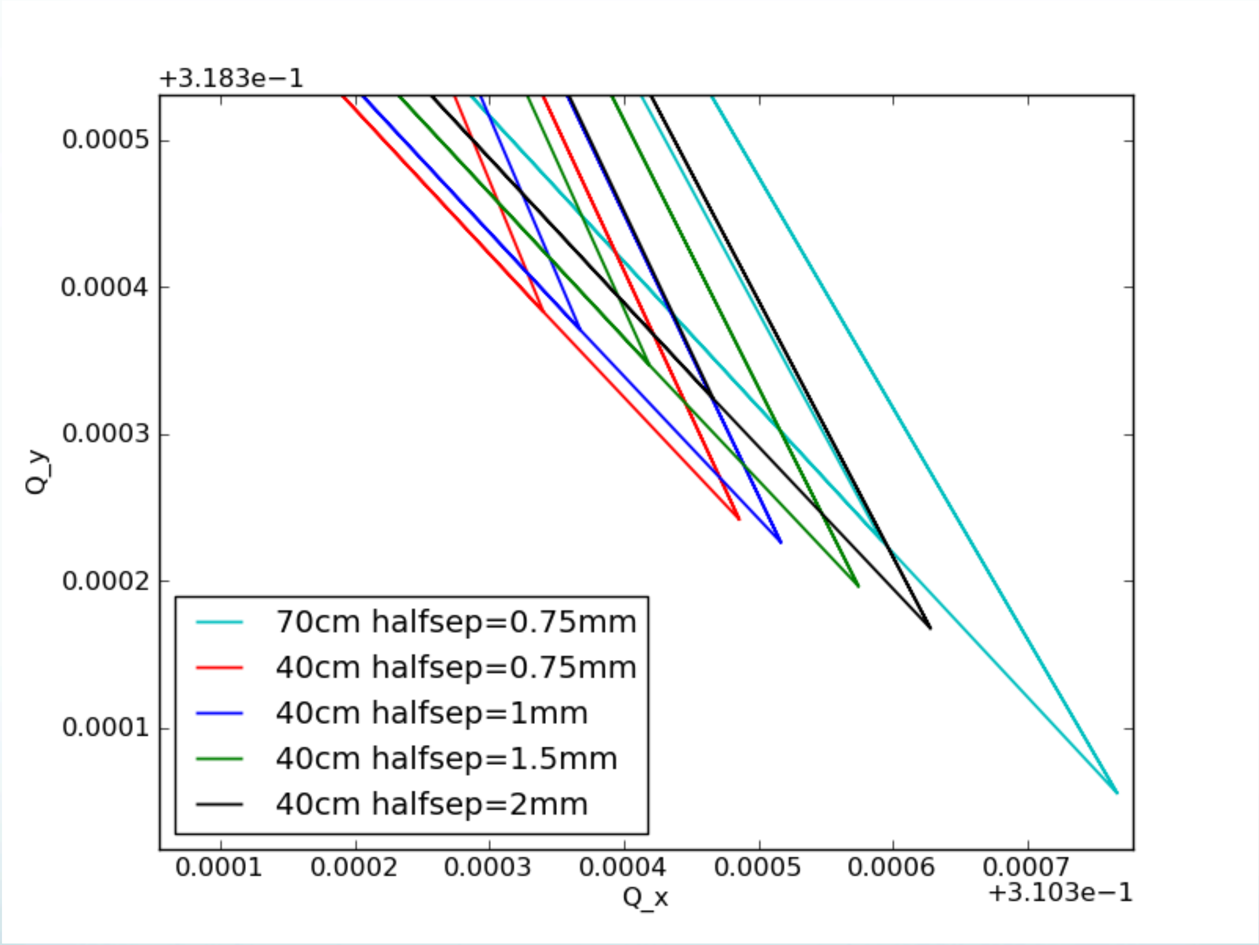
To reduce differences in Octupole spread to 10^{-4} we will need a factor 17% more in current 690 A → **8% more betas in arcs at 40 cm** (should arrive linearly from 70 cm beta*). Is this feasible?

Can we compensate the reduction with weaker LRs?



To reduce differences in Octupole spread to 10^{-4} we will need a factor 17% more in current 690 A → 8% more betas in arcs at 40 cm

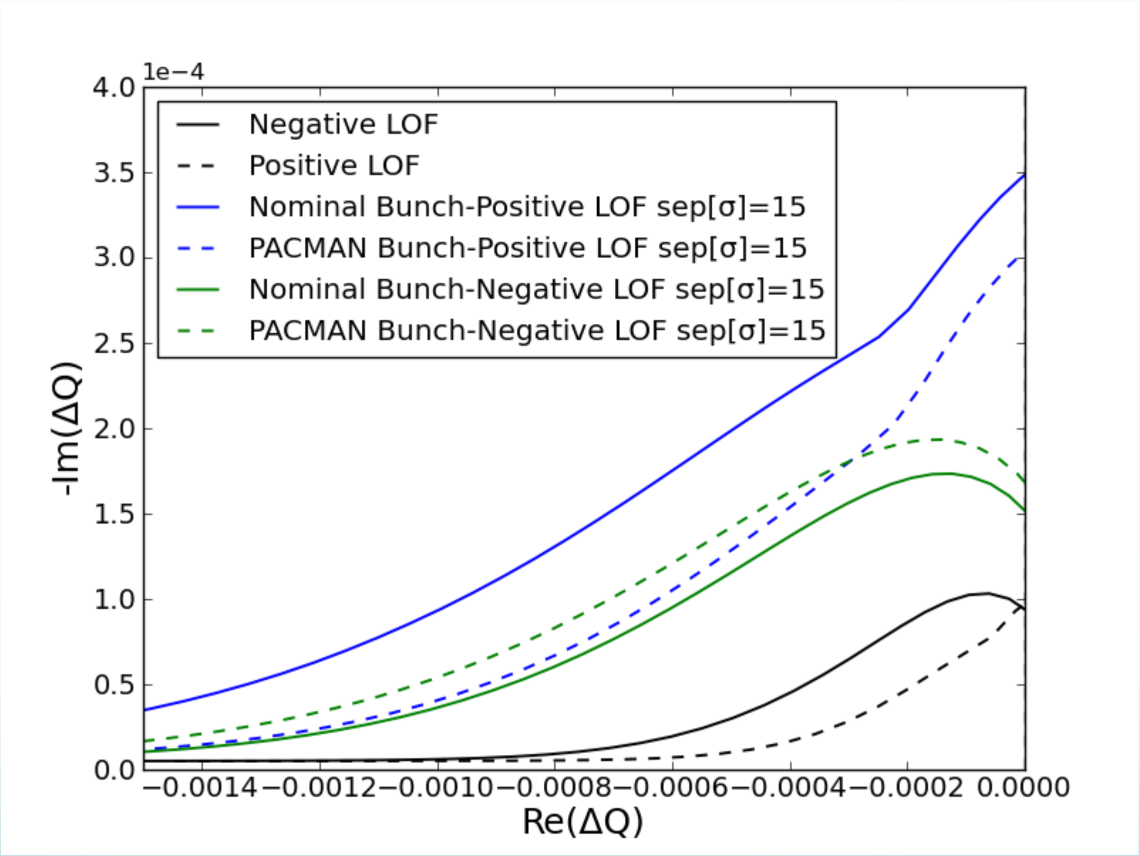
Can we compensate the reduction with weaker LRs?



Less effective (acts only on LRs close to IP)but still can help.
We can reduce to half the variation with a half separation of 2mm at 40 cm beta*. Is this feasible?

Stability Diagrams for Full Squeeze

Full squeeze positive LOF preferred

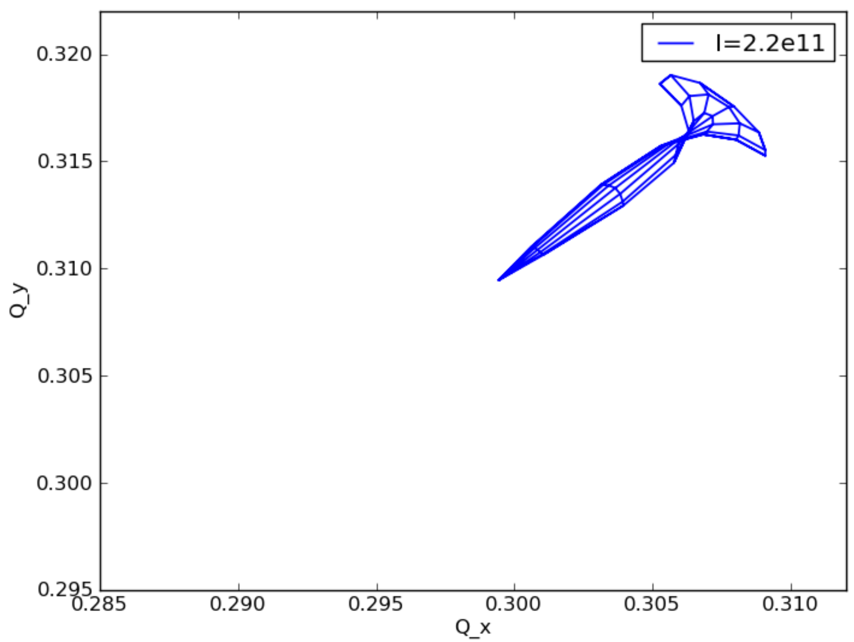


β [m]	Sep [σ]
0.15	15

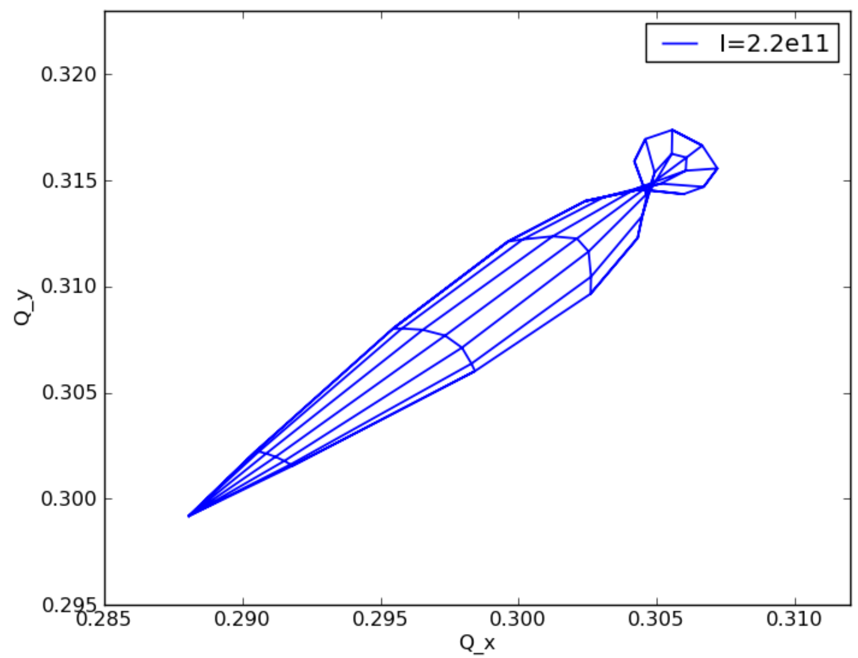
Crab crossing head-on: footprint

- Negative LOF

β^*=15cm optics



1 H-O I=2.2e11 ppb

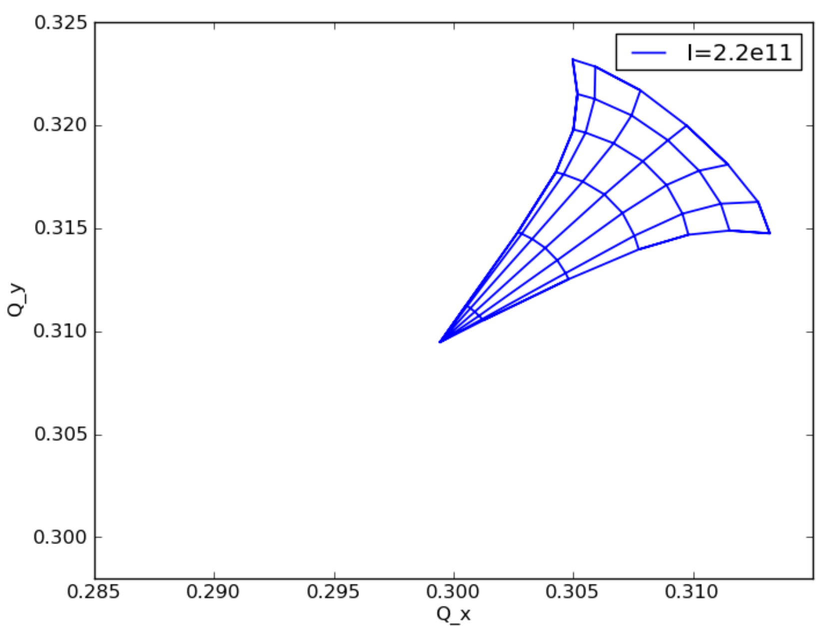


2 H-O I=2.2e11 ppb

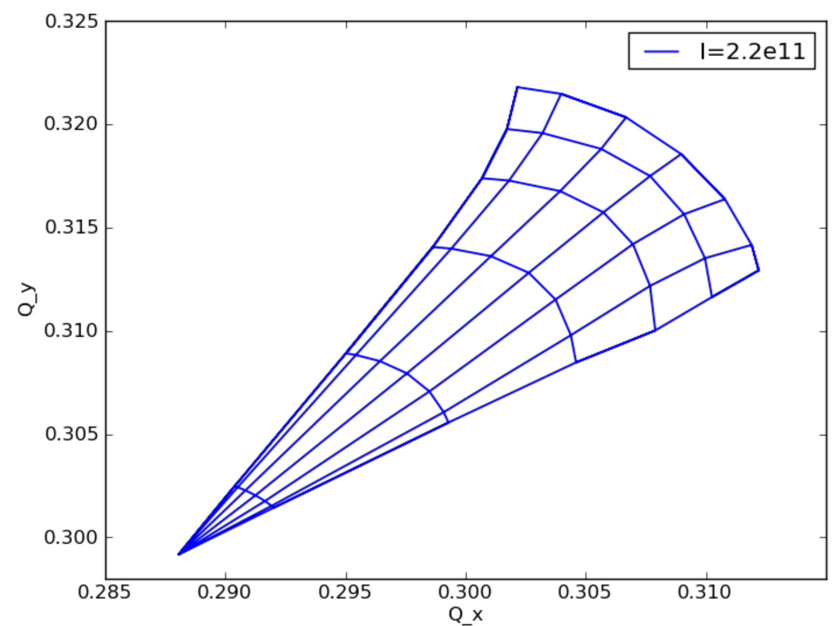
Crab crossing head-on: footprint

- Positive LOF

β^*=15cm optics



1 H-0 I=2.2e11

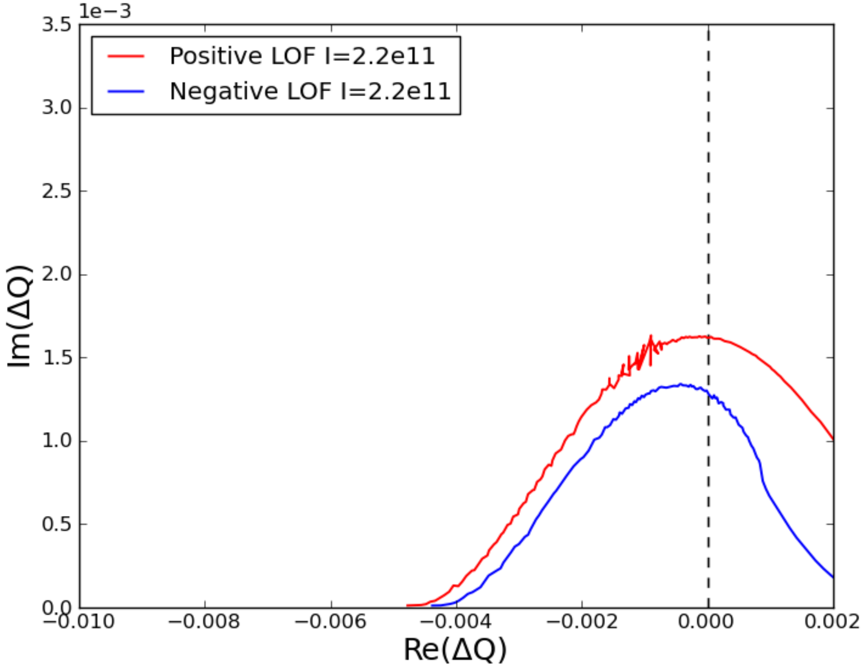


2 H-0 I=2.2e11

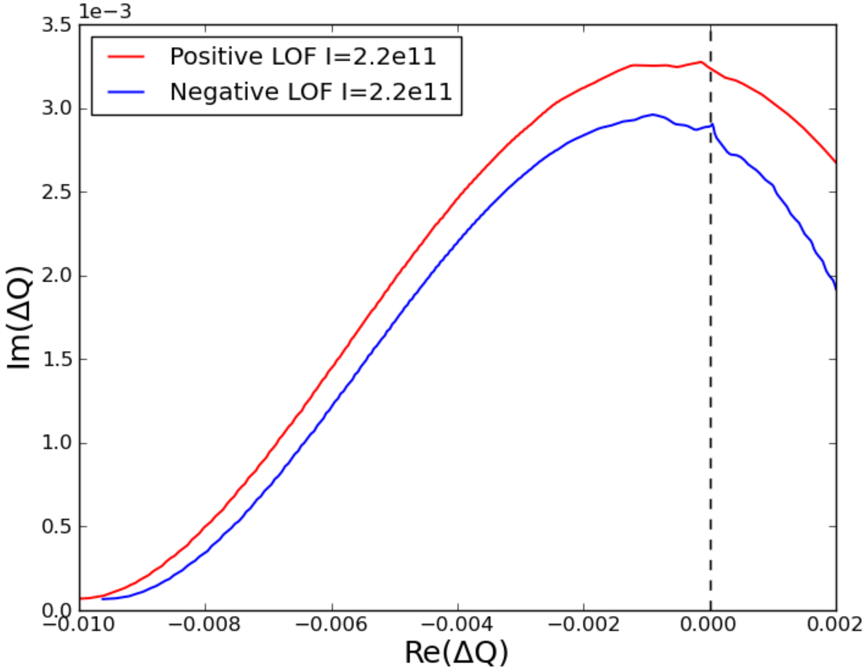
Crab crossing head-on: stability diagrams

β *=15cm optics

1 H-O I=2.2e11 ppb



2 H-O I=2.2e11 ppb



Ongoing work, to study SD H-O collision for different ATS optics (octupoles contribution)

Summary and Outlook

- **At flat top** (single beam) negative polarity preferred to positive for optic with β^*=60cm

- **ATS optics** β^*=15cm gives larger SD thanks to large β function in the arcs
  - SD gets larger for β^*<40cm
  - Sextupole non-linearities adds to positive polarity creating asymmetry positive-negative LOF: **can we reduce this contribution?**

- **BB LR:**
  - Negative LOF reduces SD till β^*>40cm
  - Positive LOF increases SD at any β^*

- **For Negative LOF** larger β in the arcs compensates LR reduction increasing SD for β^*<40cm.
  - **Can we have larger betas in arcs to compensate reduction?**
- **Positive polarity of Octupoles reduces by 2 σ DA → presentation after Easter on chromaticity and octupoles effect**

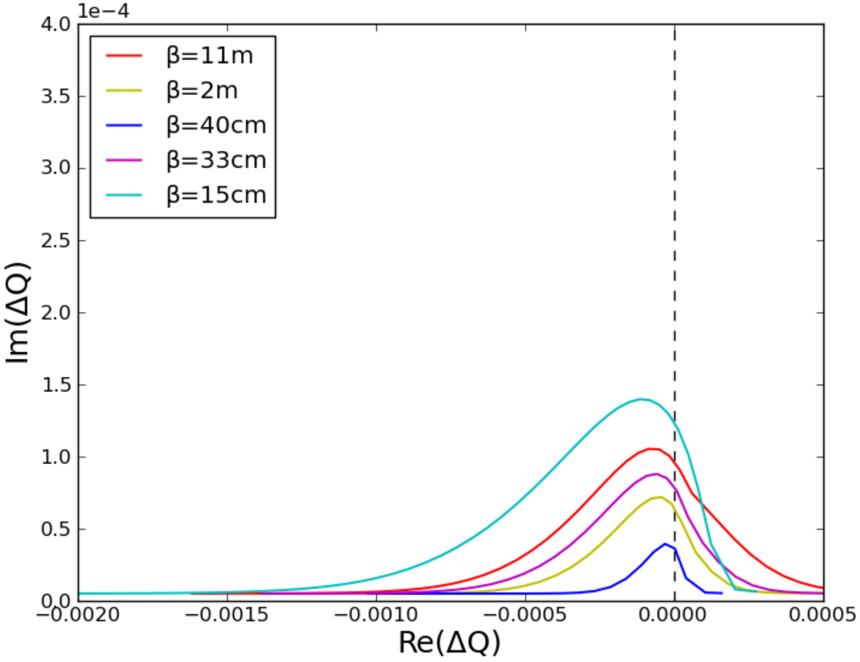
Summary

HL-LHC V1.0 optics	**Positive LOF**	**Negative LOF**
Single beam β*=6m	**Smaller SD than Negative**	**Preferred**
Baseline scenario ~65 cm β*	**Smaller SD than Negative**	**Preferred**
Ultimate scenario ~40 cm β*	**Smaller SD than Negative**	**Preferred Reduction can be solved with 8% more betas in arc (and/or larger sep)**
Full squeeze ~15 cm β*	**SD increases during the full squeeze**	**To avoid reduction collide needed at ~70 cm or apply larger betas and or sep**

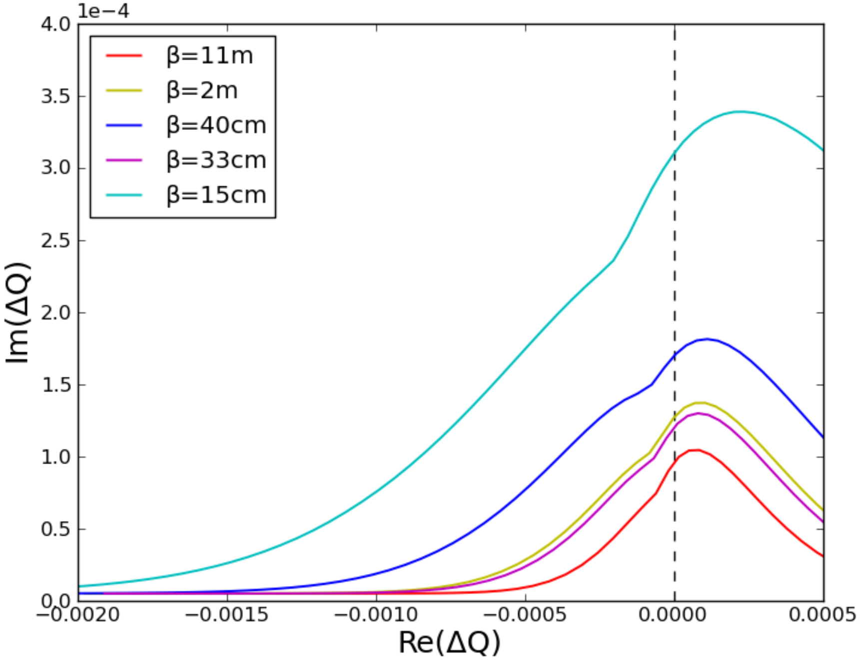
Backup slide

Effects of different optics+beam beam LR: stability diagrams

➢ Negative LOF



➢ Positive LOF



For 2m β^* the crossing angle was set to 80μrad in the optics file

Contents

- **ATS optics:** footprint
  stability diagrams
  effects of non-linearities

- **Optics effect study:** footprint with different β^* optics and beam-beam LR
  stability diagrams for different β^* optics and LR

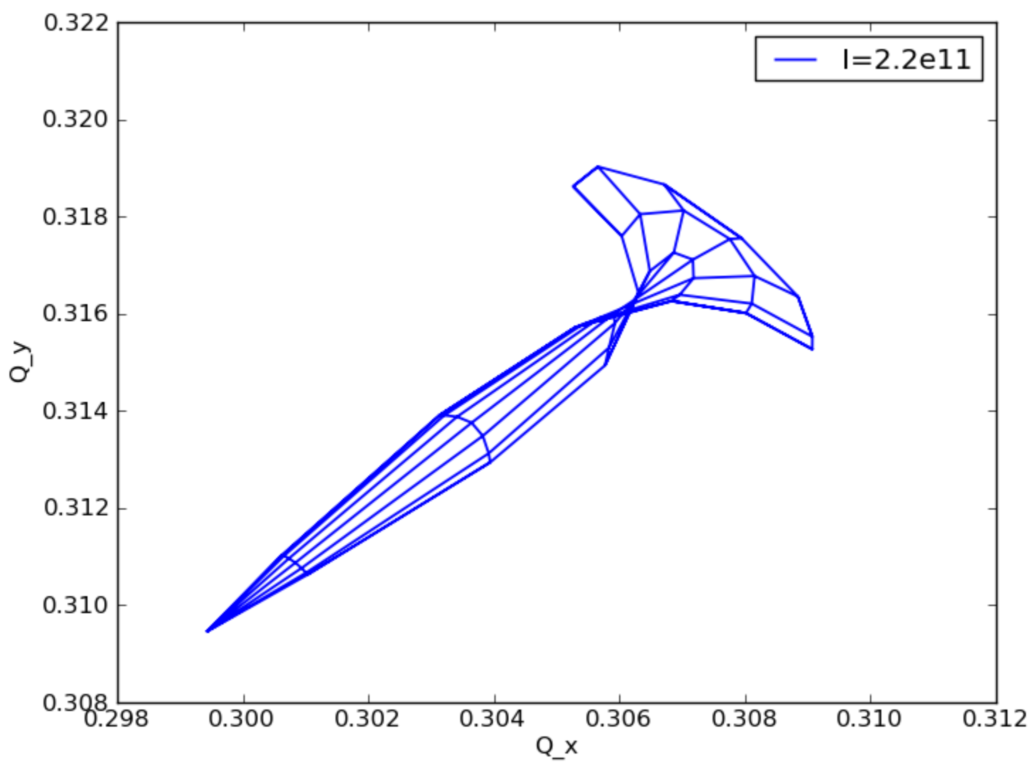
- **Betatron : squeeze** stability diagrams with LR+optics
  Nominal and PACMAN bunch comparison

- **BB head-on:** footprint vs beam intensity
  stability diagrams

- **Summary and Outlook**

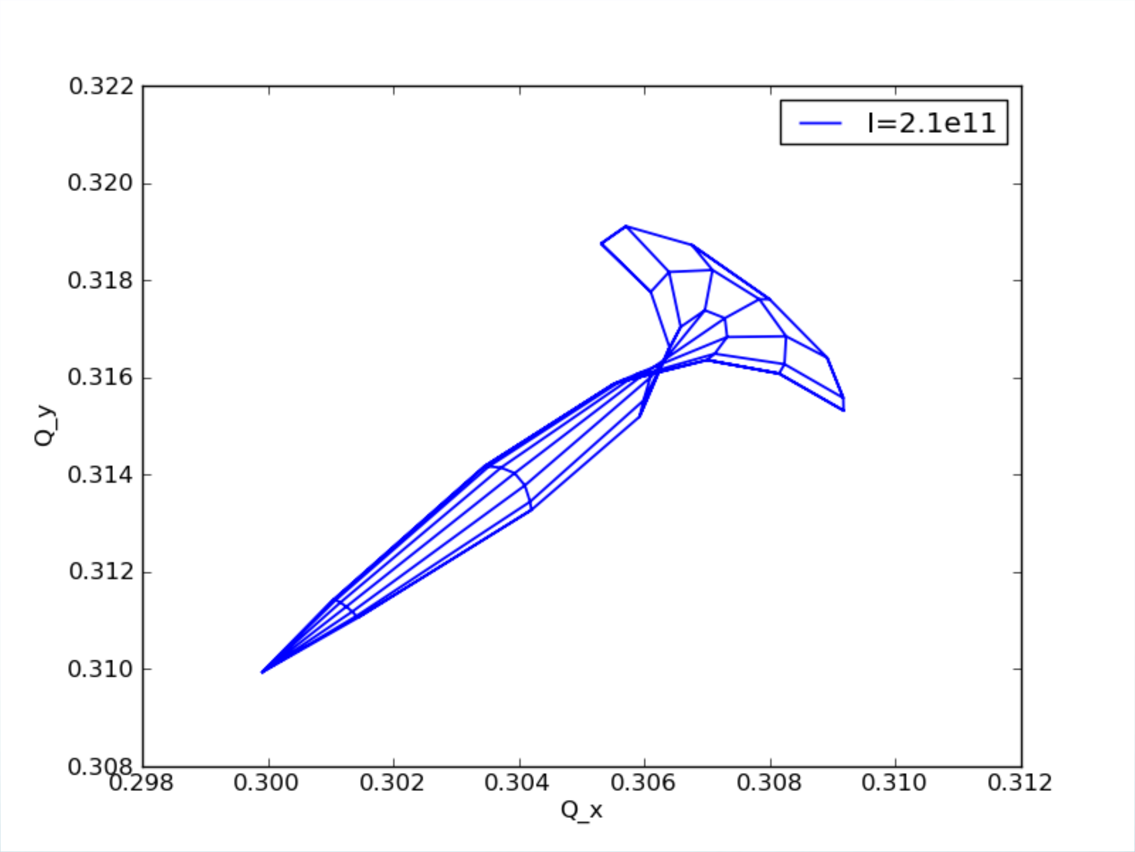
Crab crossing head-on: footprint evolution in function of beam intensity

- Negative LOF



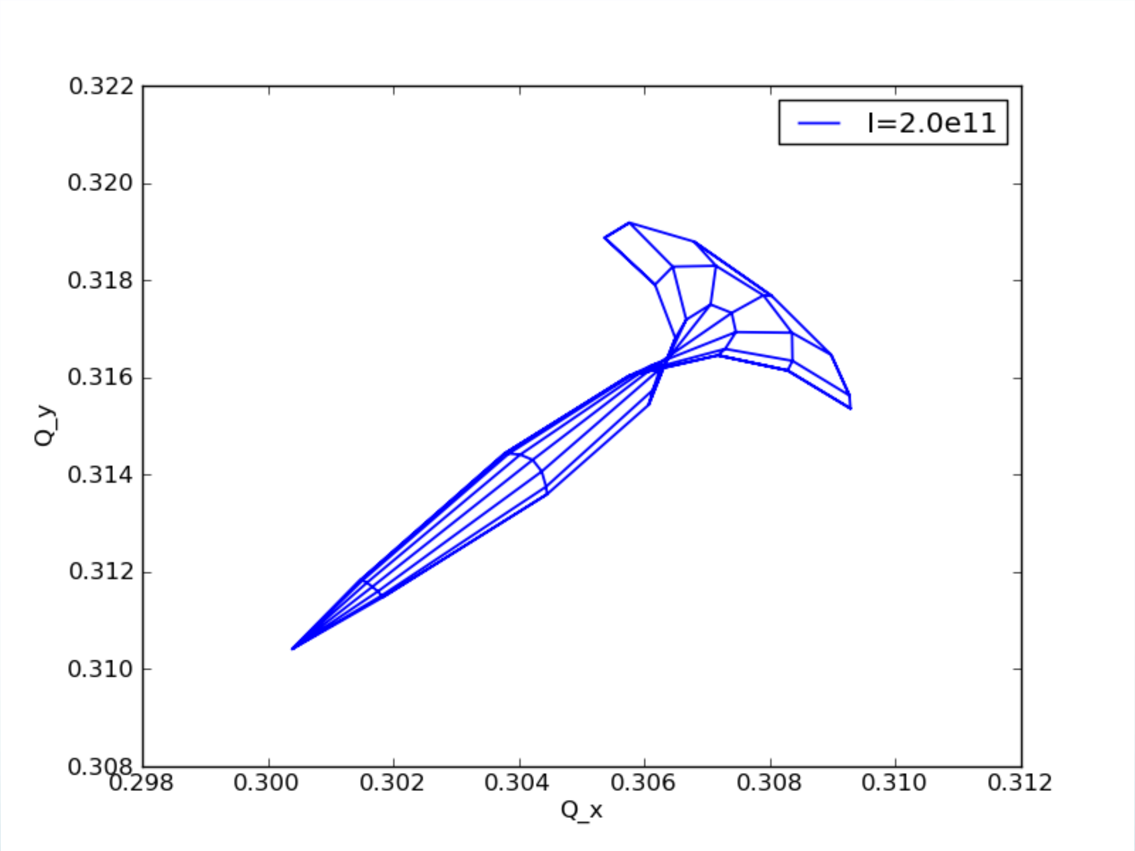
Crab crossing head-on: footprint evolution in function of beam intensity

- Negative LOF



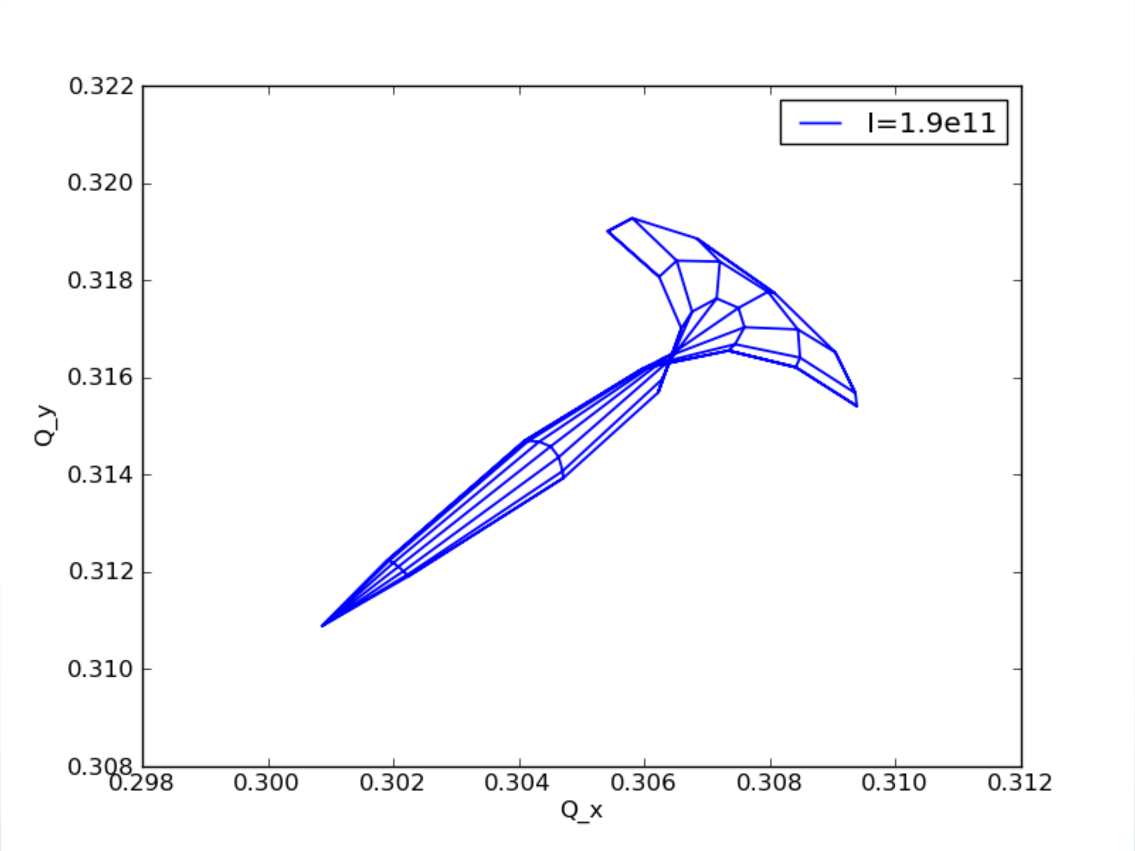
Crab crossing head-on: footprint evolution in function of beam intensity

- Negative LOF



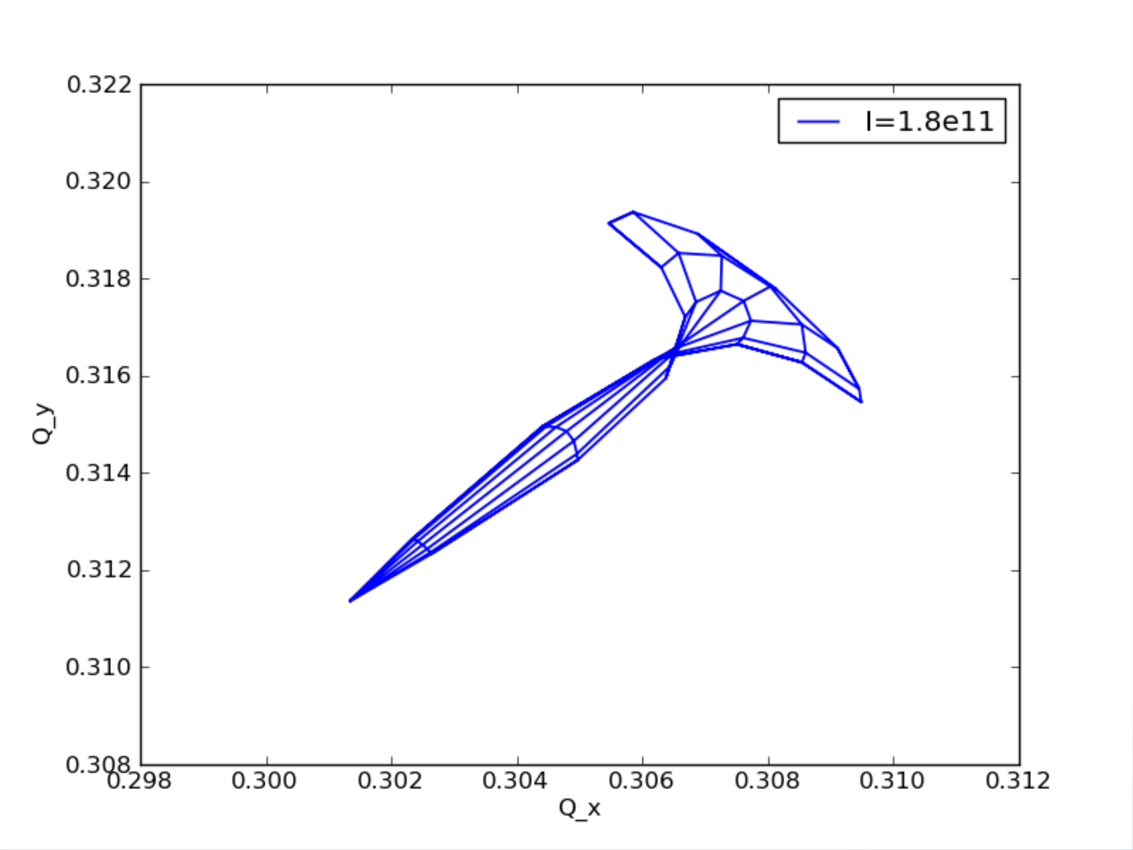
Crab crossing head-on: footprint evolution in function of beam intensity

- Negative LOF



Crab crossing head-on: footprint evolution in function of beam intensity

- Negative LOF



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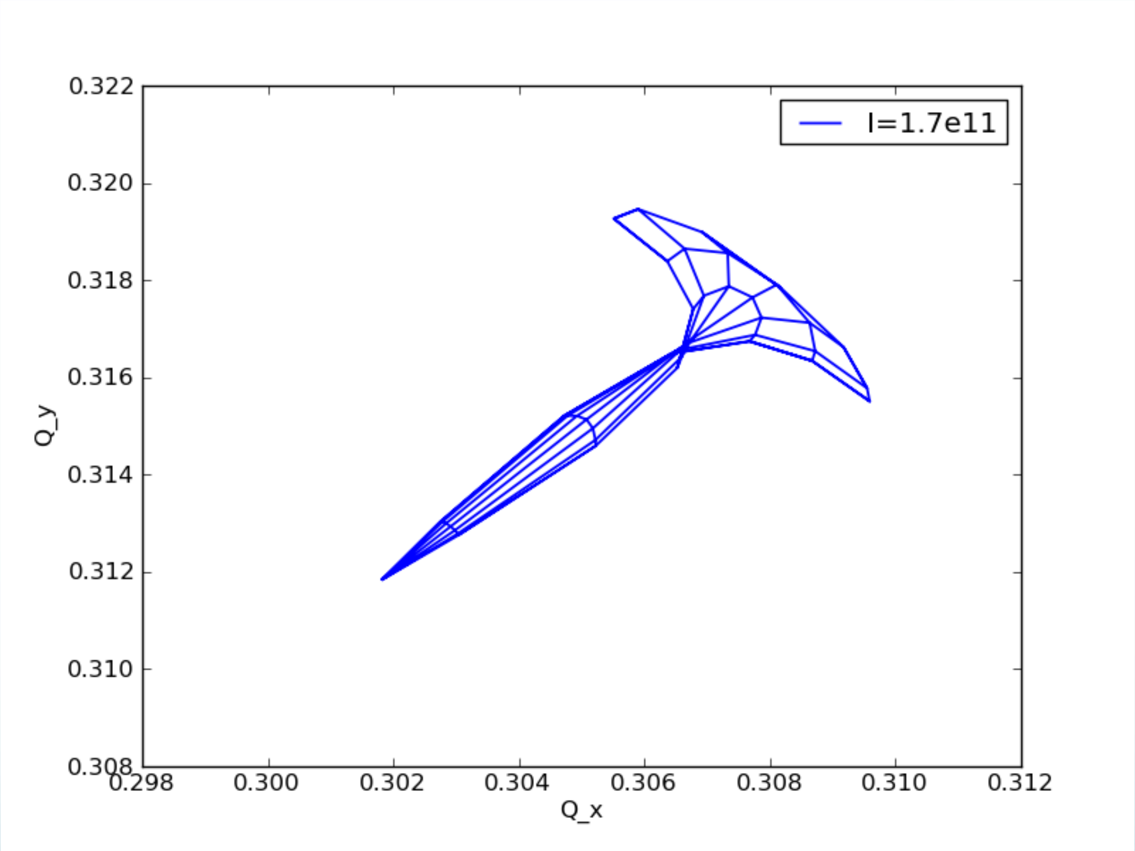
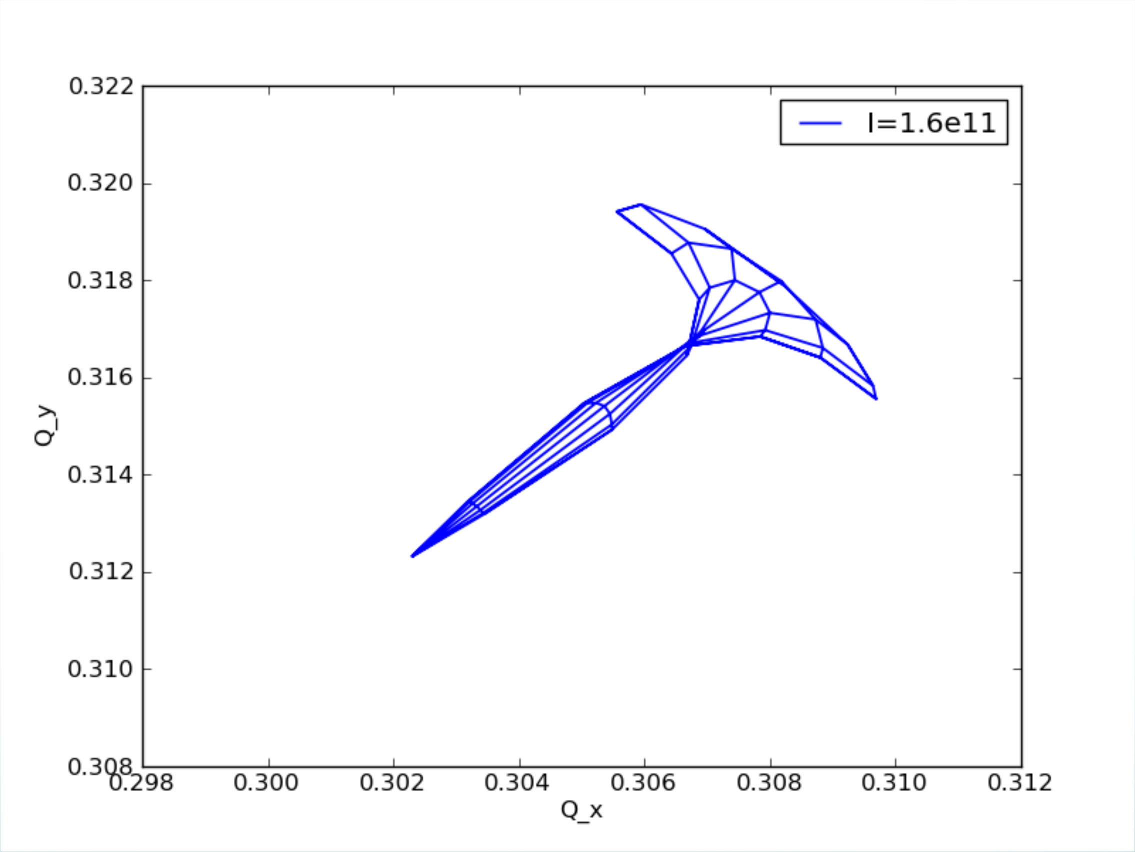


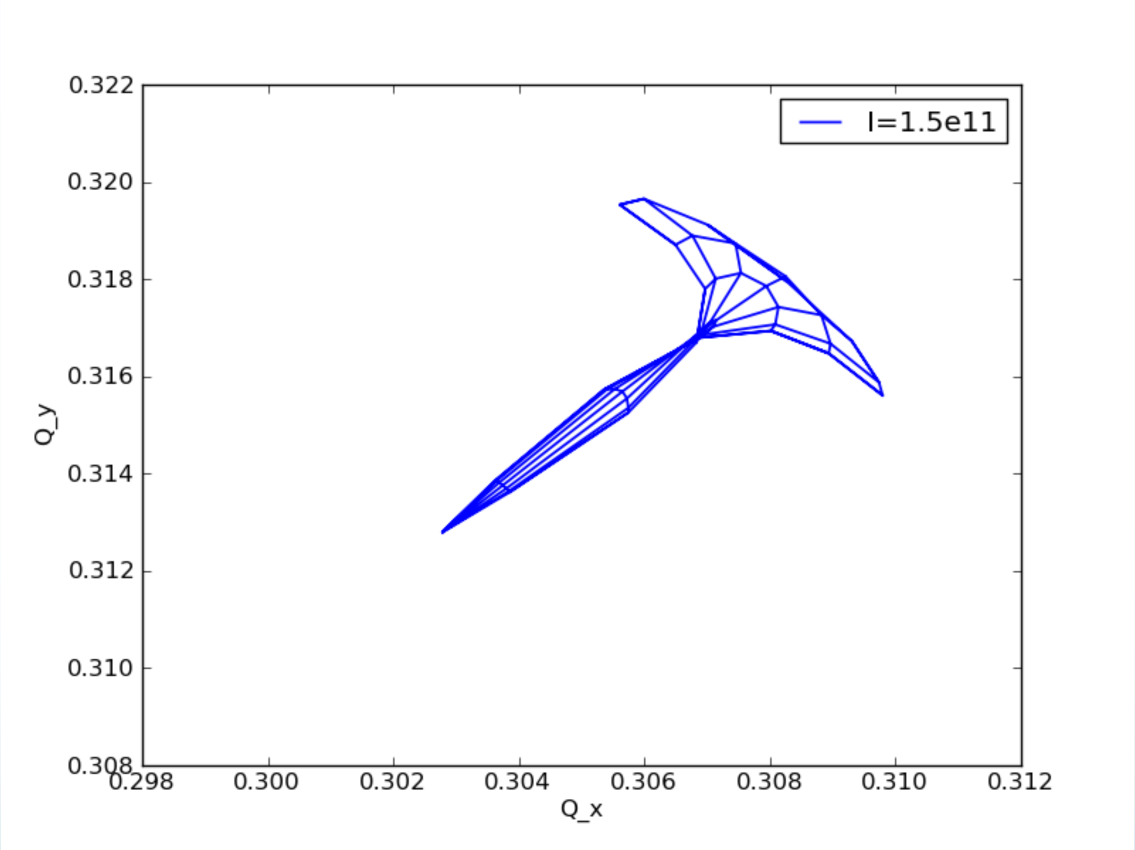
Crab crossing head-on: footprint evolution in function of beam intensity

- Negative LOF



Crab crossing head-on: footprint evolution in function of beam intensity

- Negative LOF



Crab crossing head-on: footprint evolution in function of beam intensity

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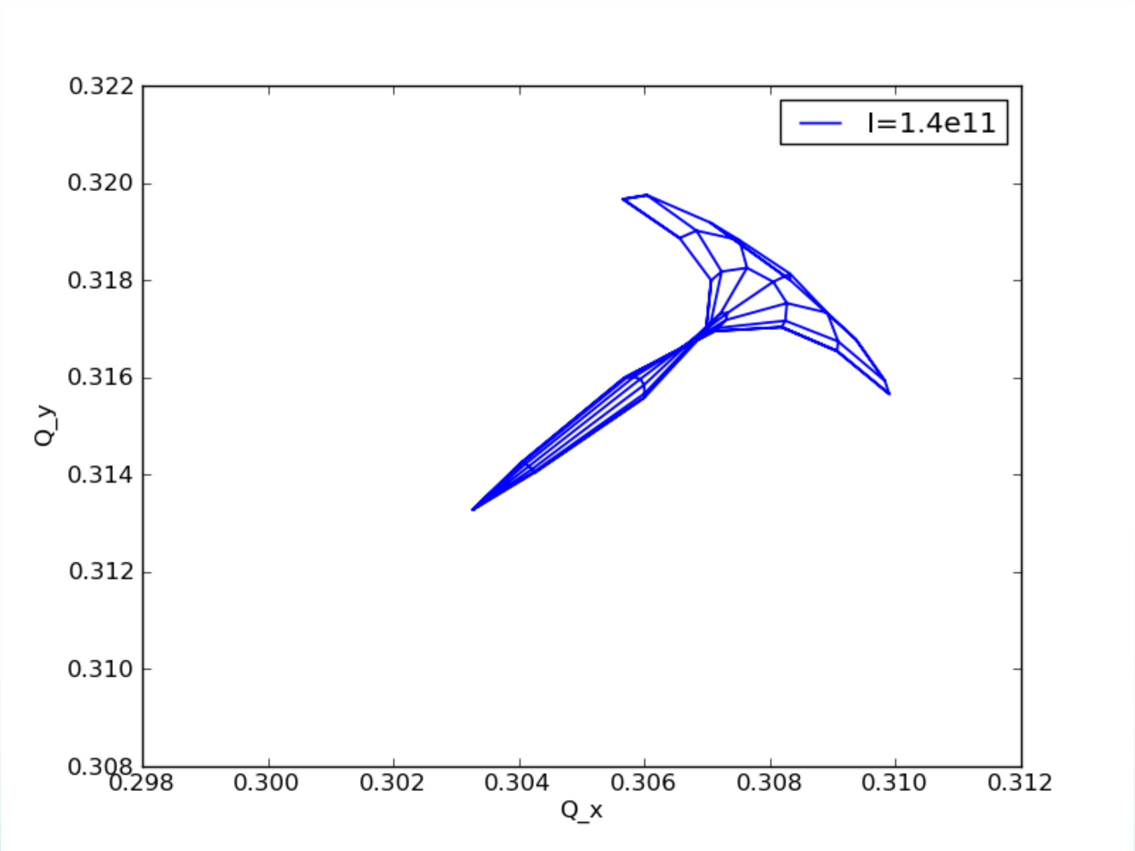

Crab crossing head-on: footprint evolution in function of beam intensity

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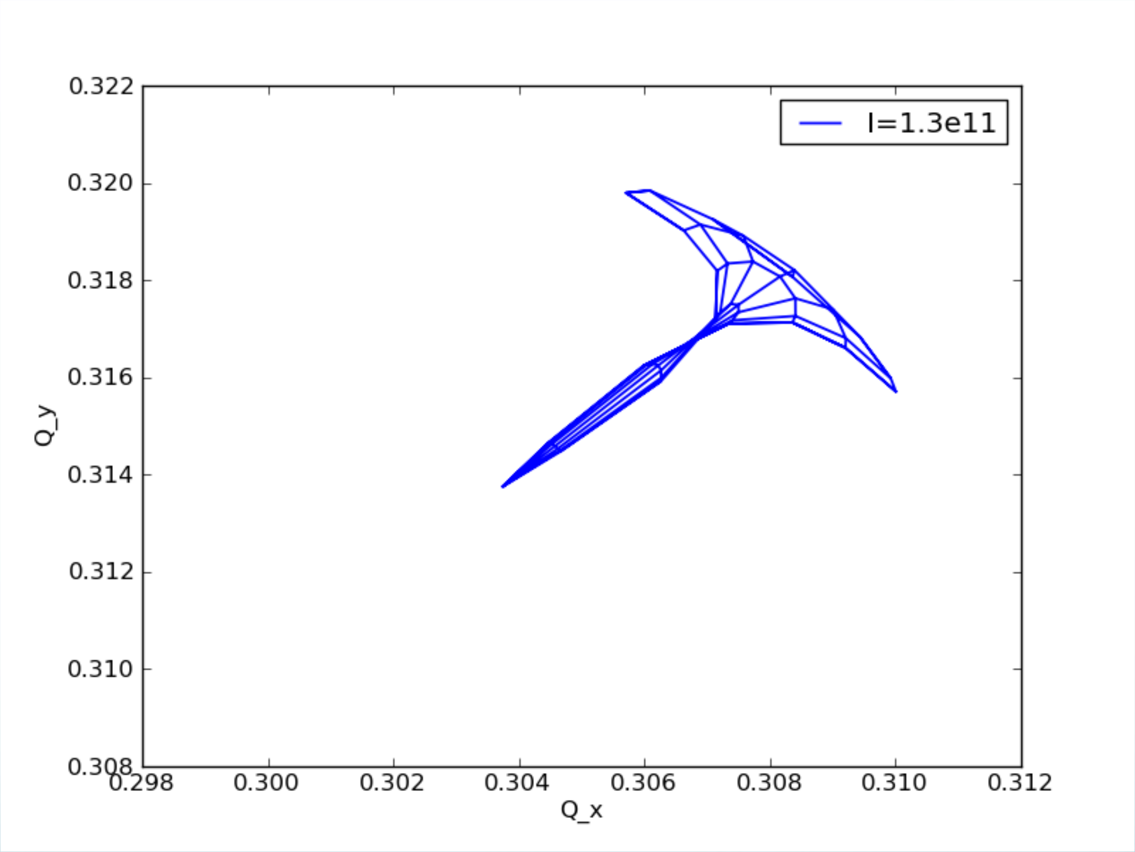

Crab crossing head-on: footprint evolution in function of beam intensity

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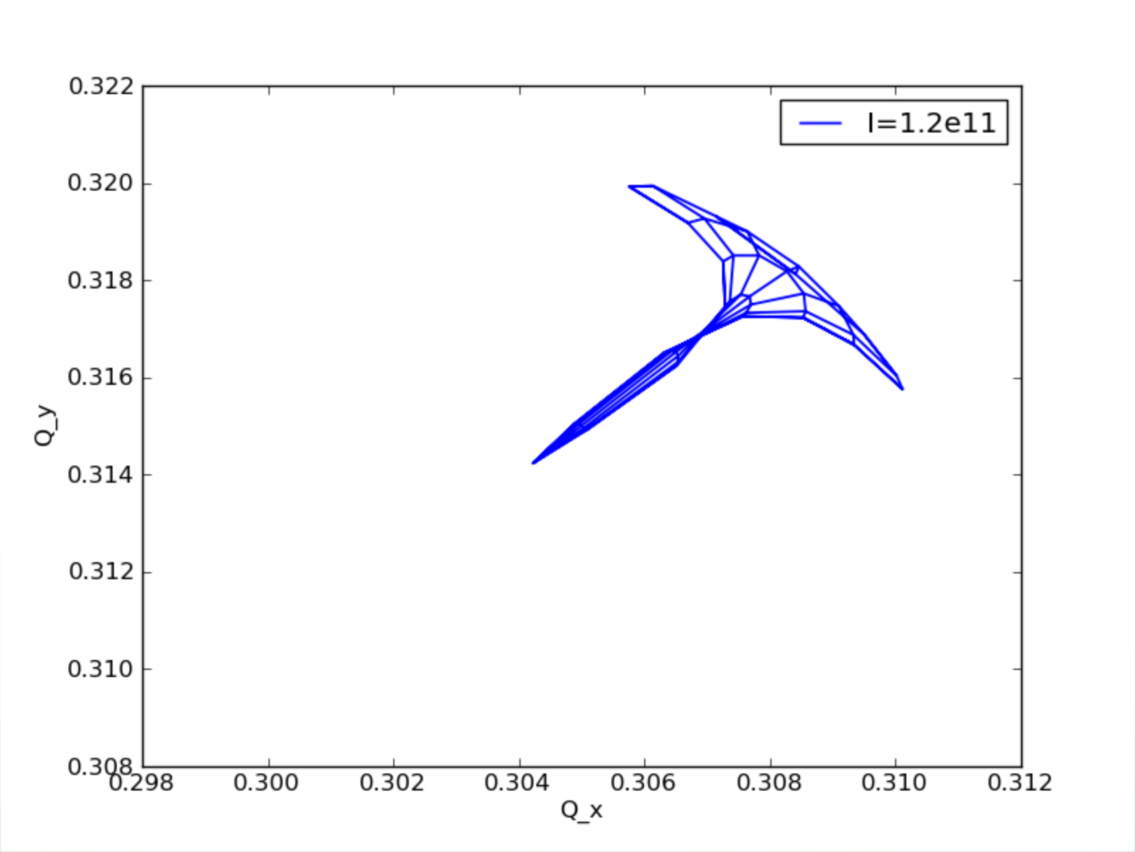
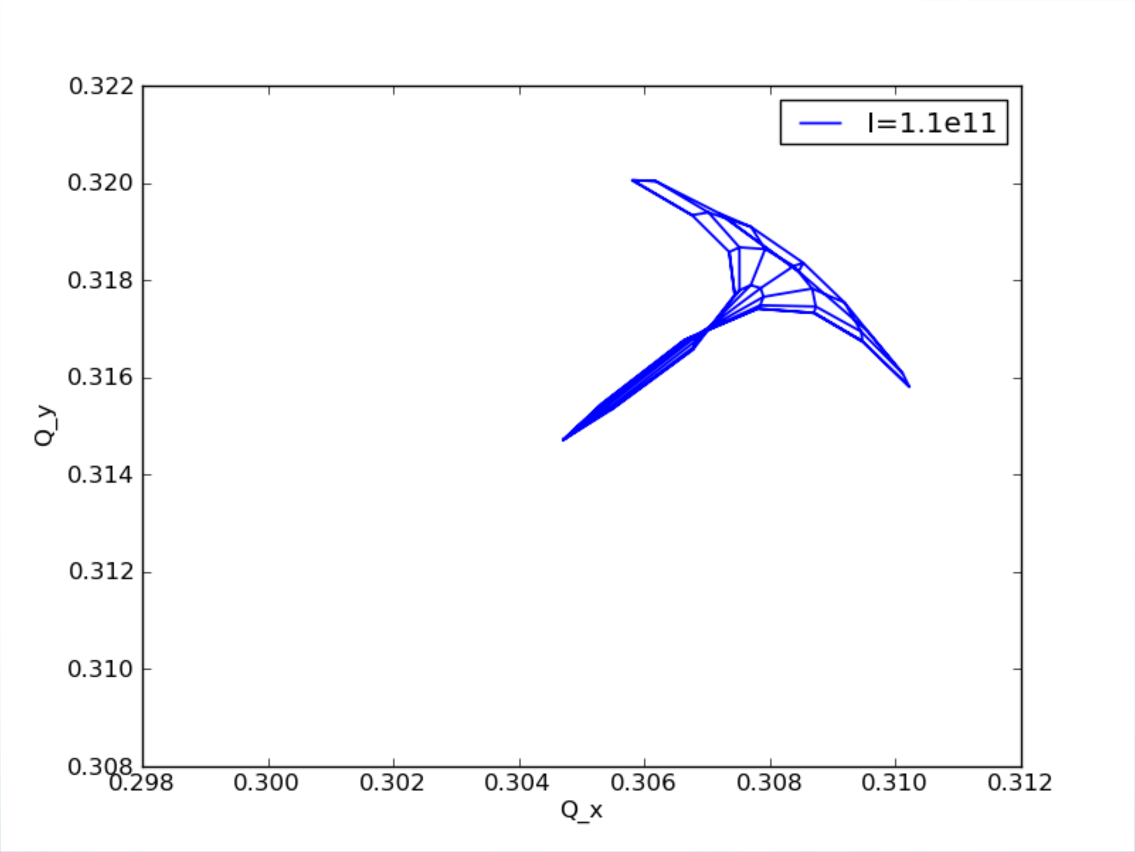


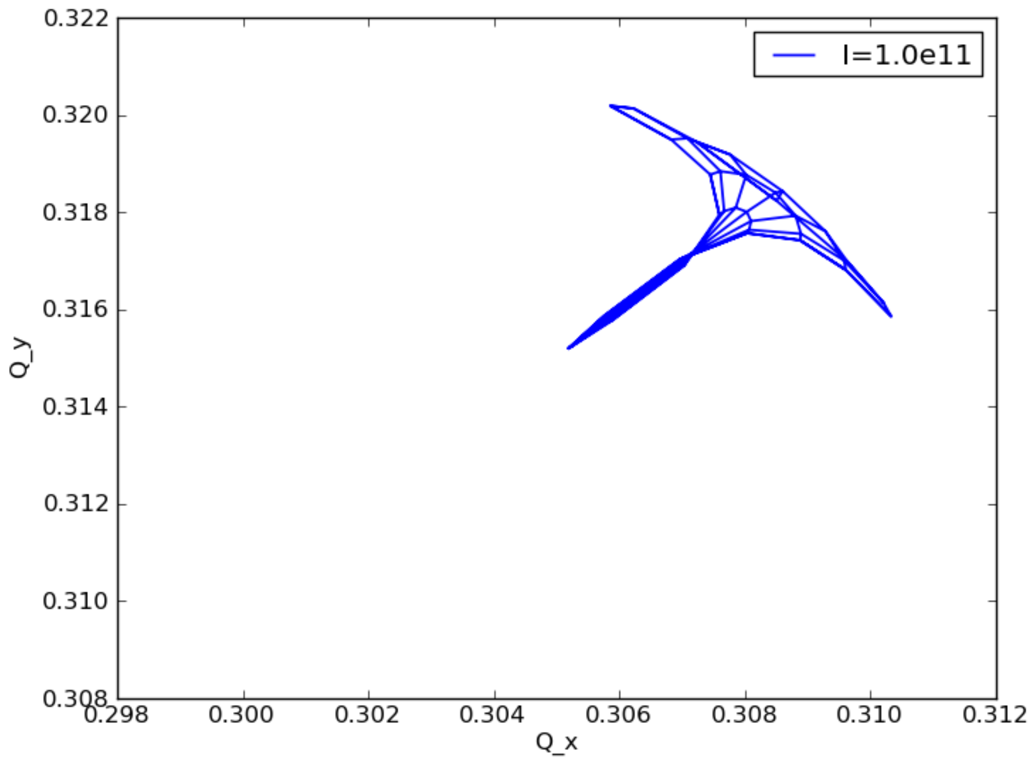
Crab crossing head-on: footprint evolution in function of beam intensity

- Negative LOF



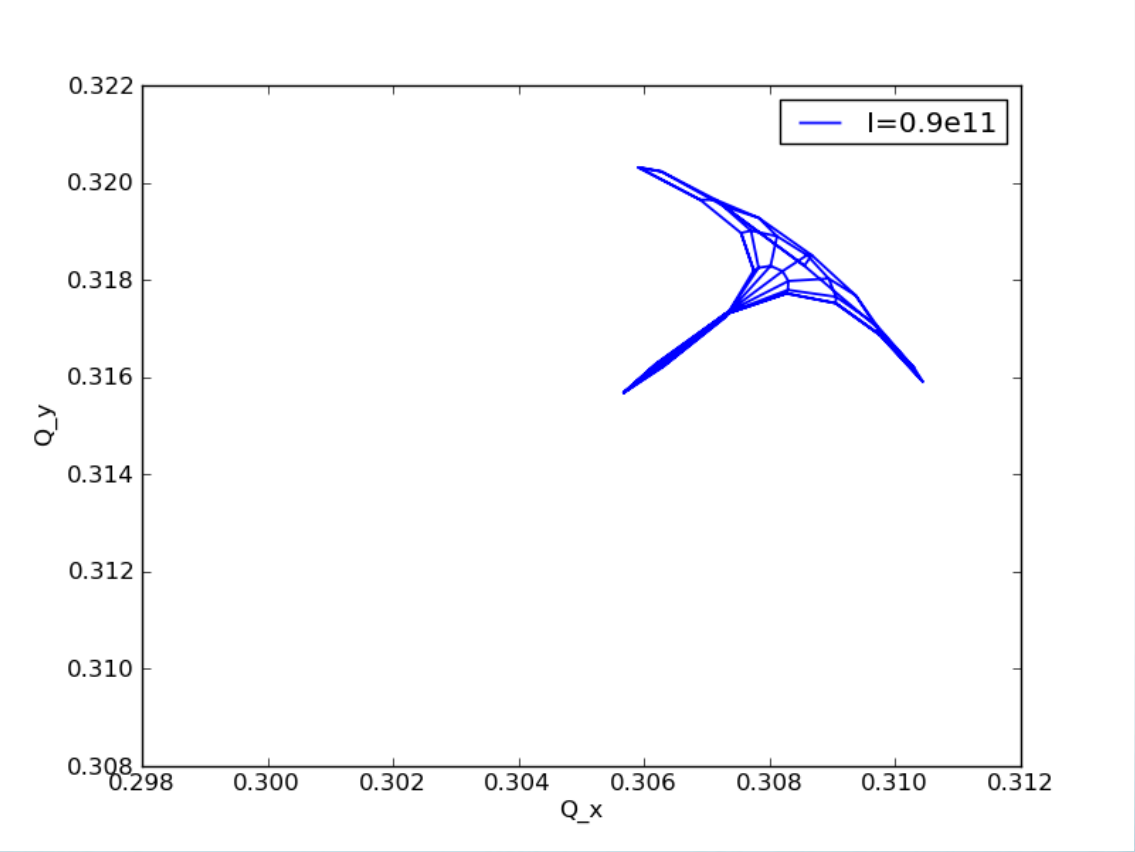
Crab crossing head-on: footprint evolution in function of beam intensity

- Negative LOF



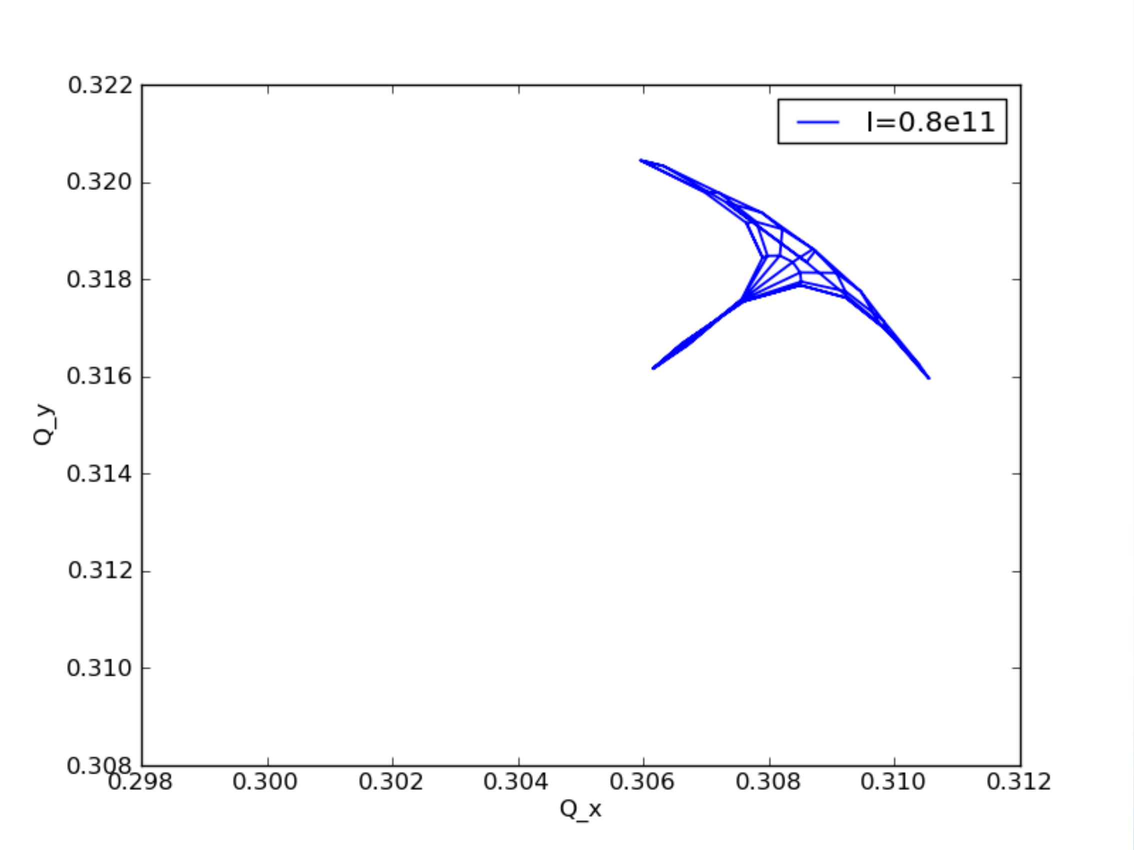
Crab crossing head-on: footprint evolution in function of beam intensity

- Negative LOF



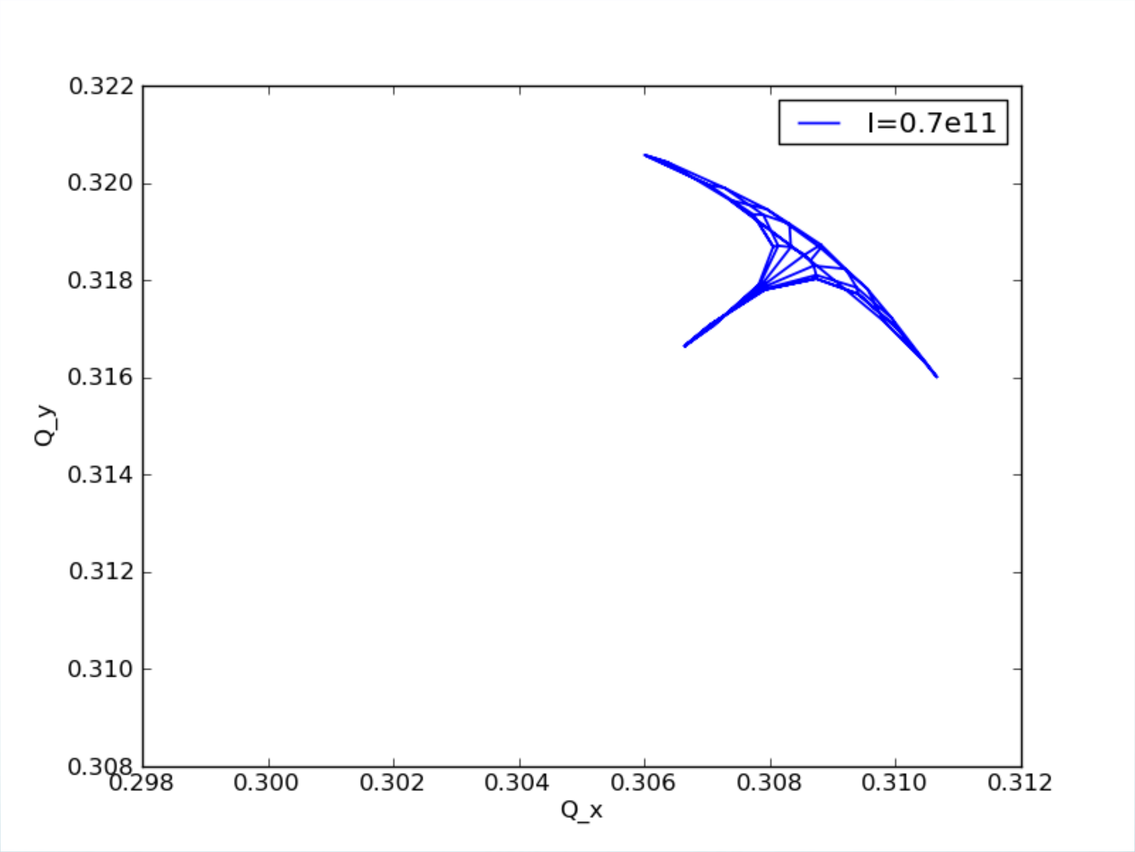
Crab crossing head-on: footprint evolution in function of beam intensity

- Negative LOF



Crab crossing head-on: footprint evolution in function of beam intensity

- Negative LOF



Crab crossing head-on: footprint evolution in function of beam intensity

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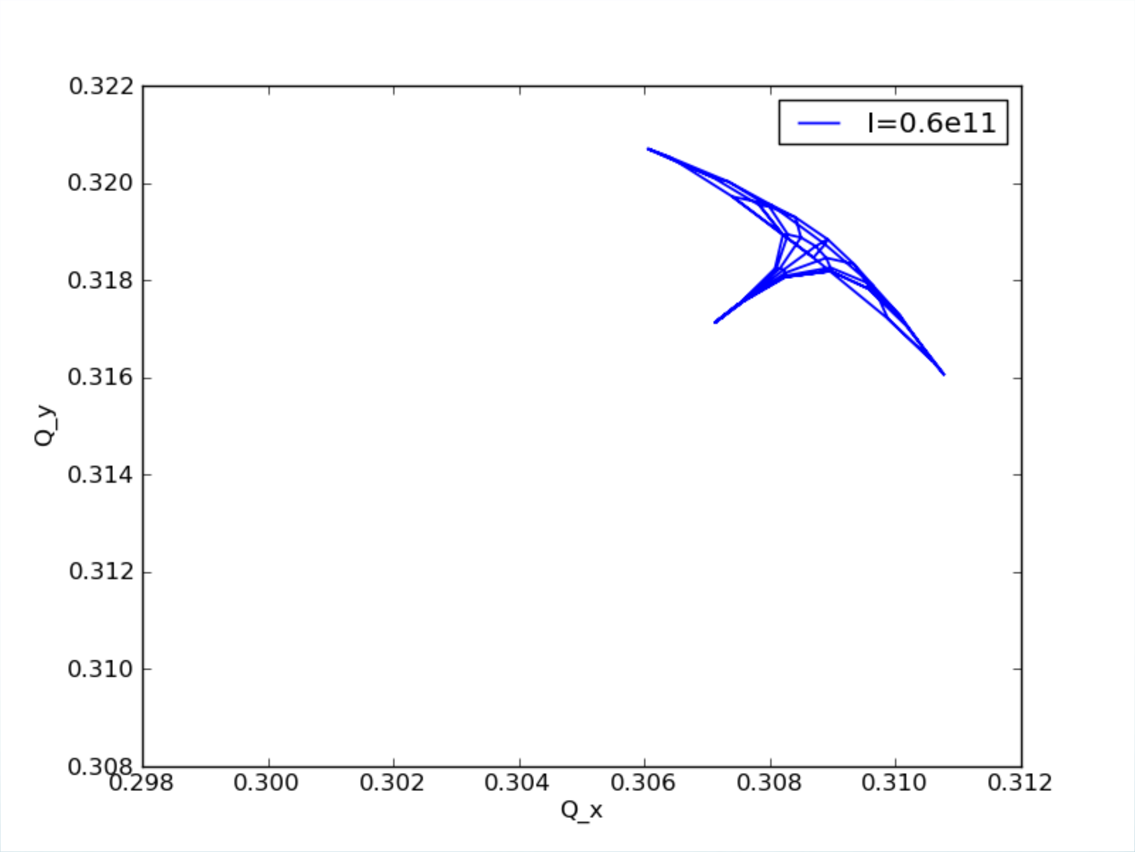
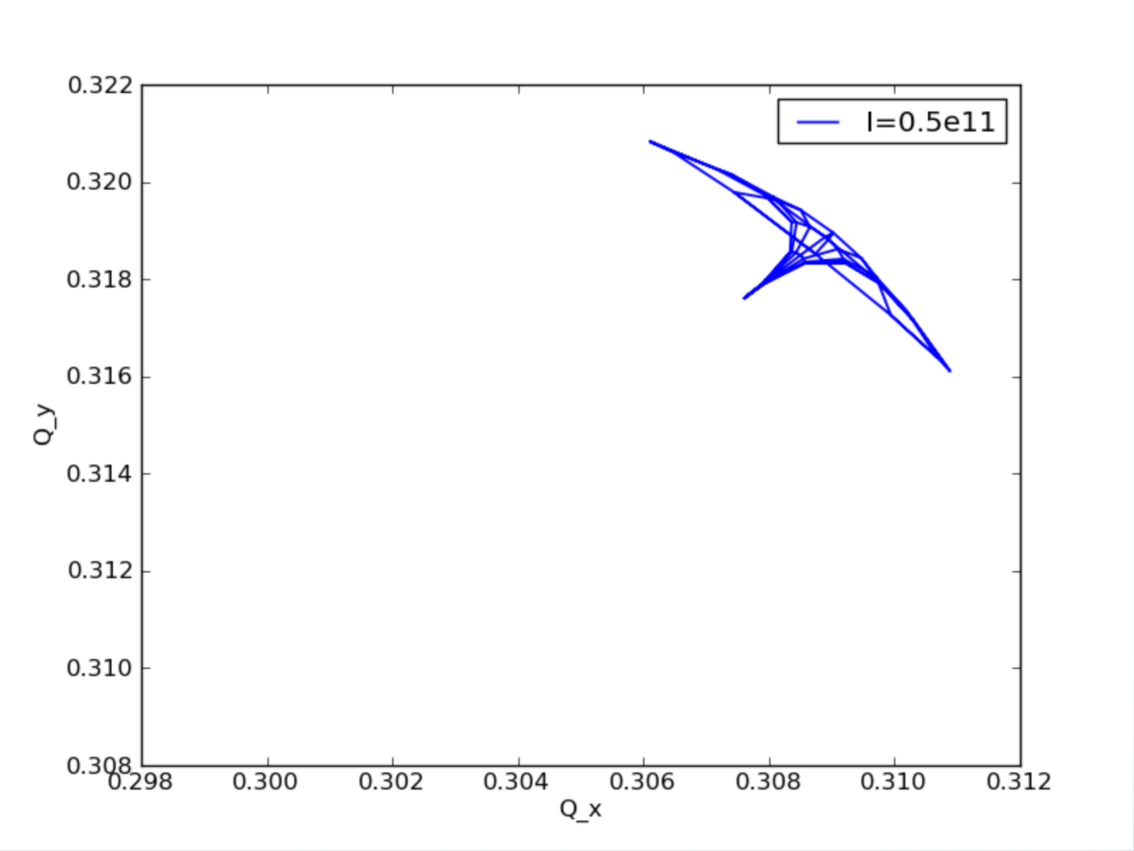


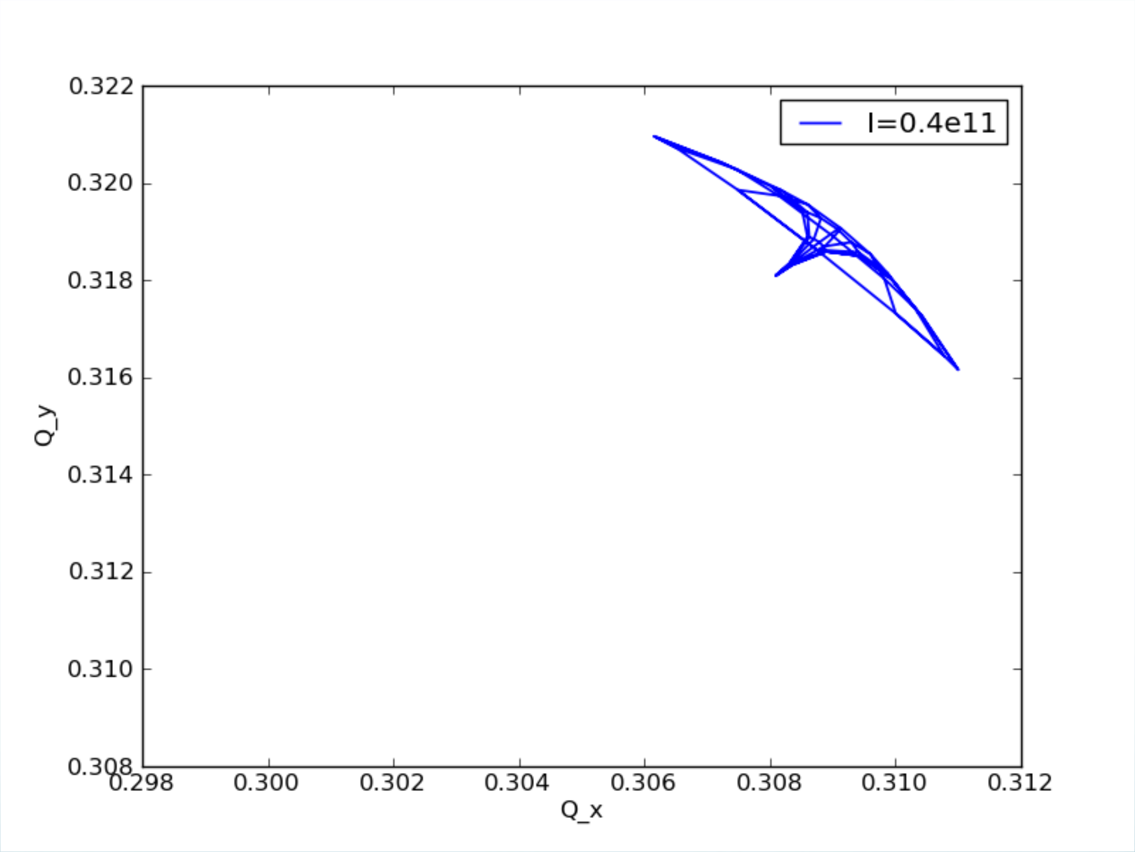
Crab crossing head-on: footprint evolution in function of beam intensity

- Negative LOF



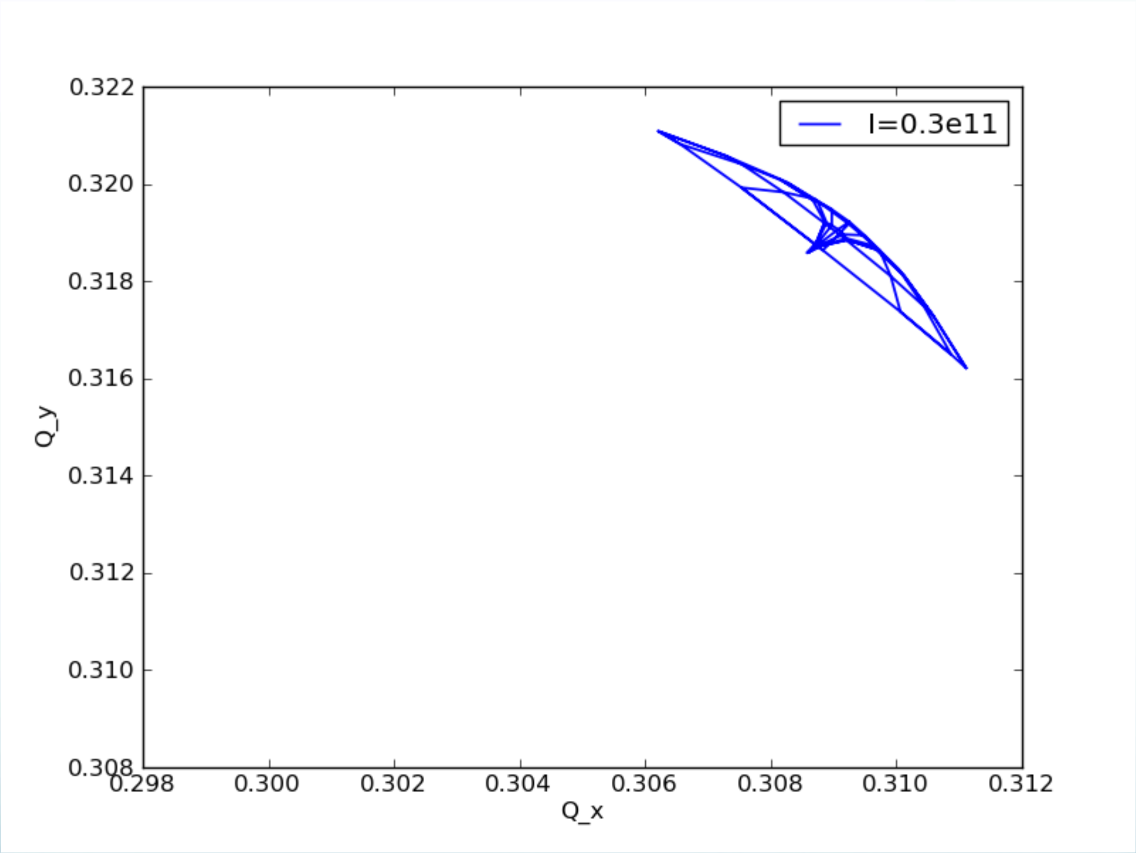
Crab crossing head-on: footprint evolution in function of beam intensity

- Negative LOF



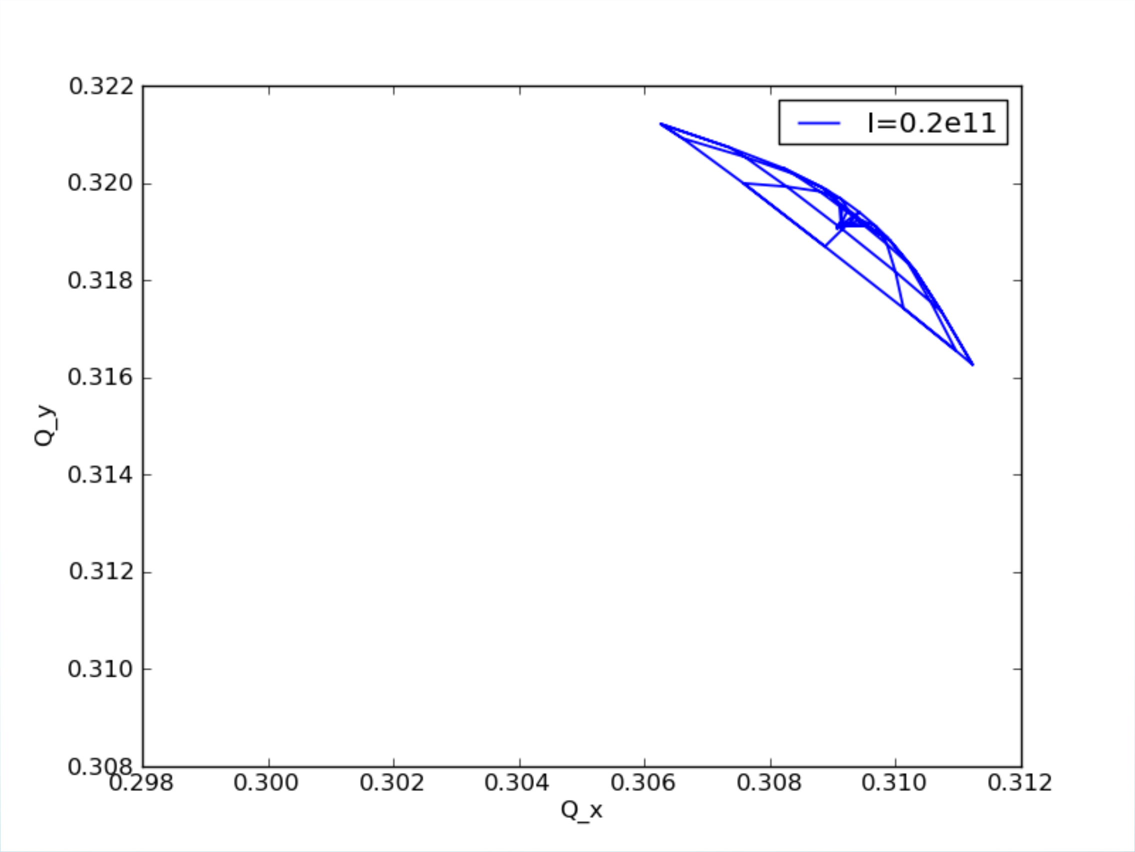
Crab crossing head-on: footprint evolution in function of beam intensity

- Negative LOF



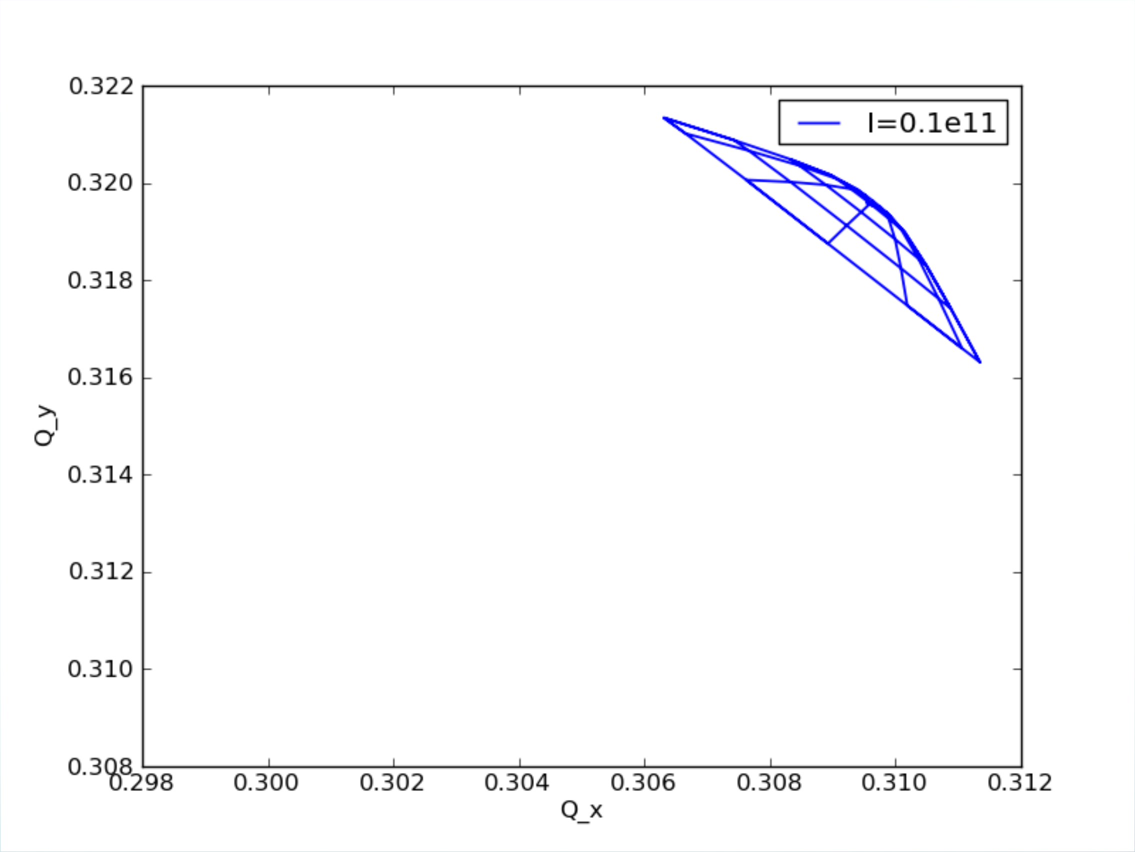
Crab crossing head-on: footprint evolution in function of beam intensity

- Negative LOF



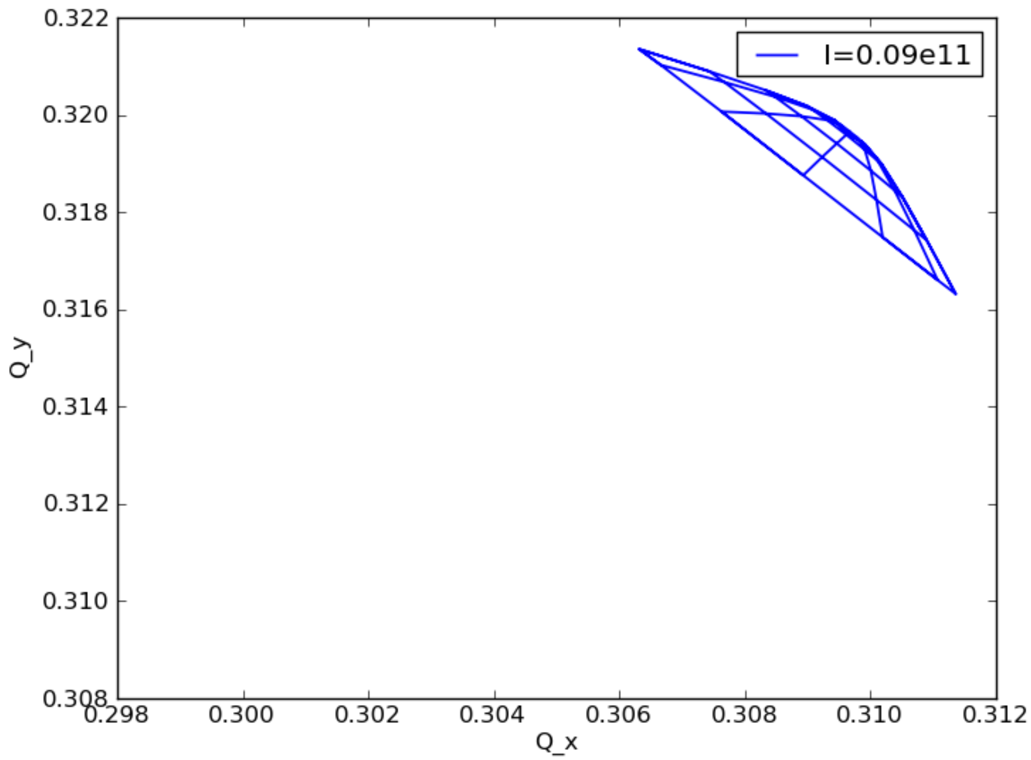
Crab crossing head-on: footprint evolution in function of beam intensity

- Negative LOF



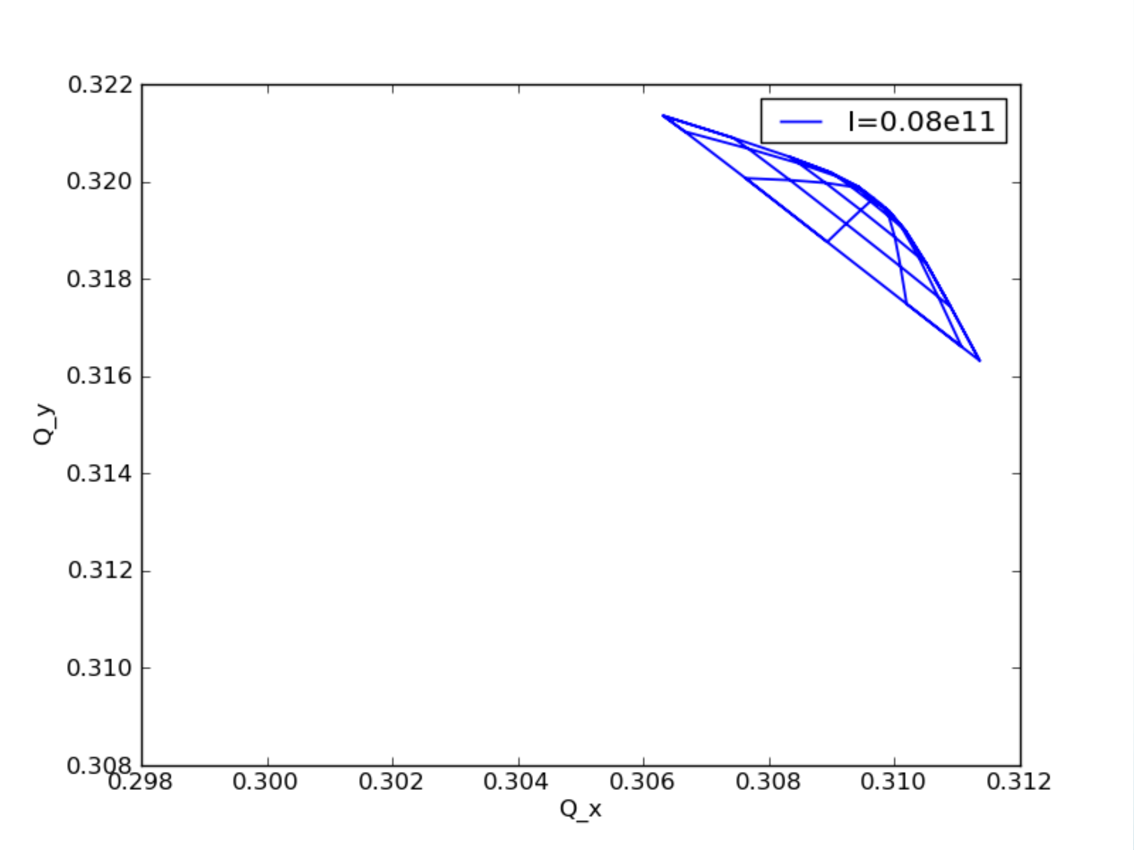
Crab crossing head-on: footprint evolution in function of beam intensity

- Negative LOF



Crab crossing head-on: footprint evolution in function of beam intensity

- Negative LOF



Crab crossing head-on: footprint evolution in function of beam intensity

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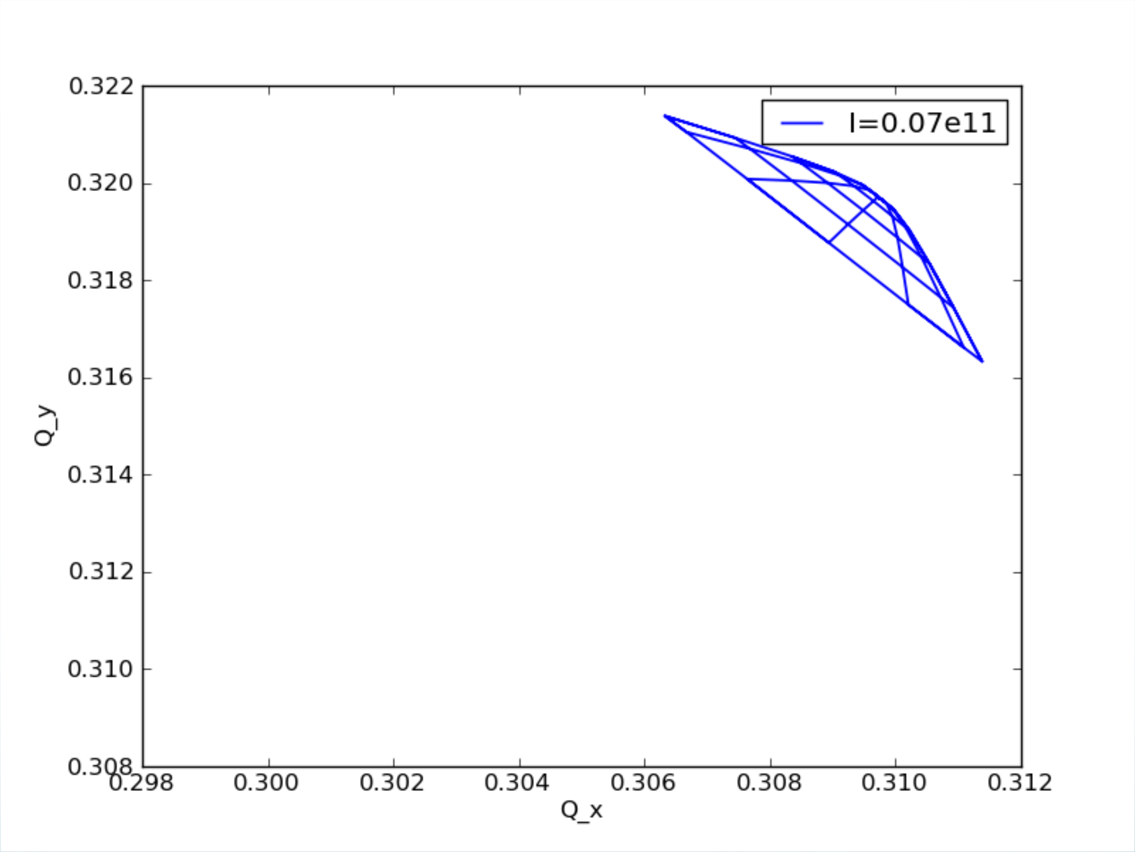

Crab crossing head-on: footprint evolution in function of beam intensity

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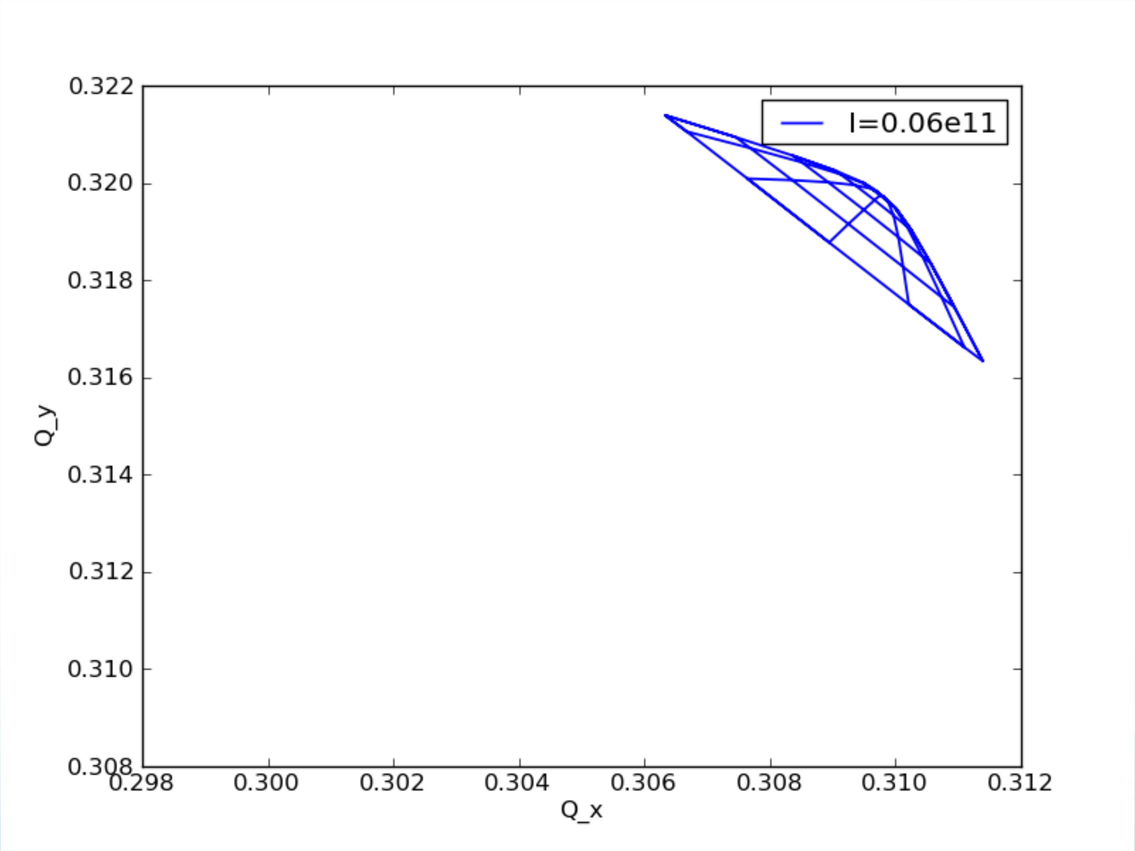
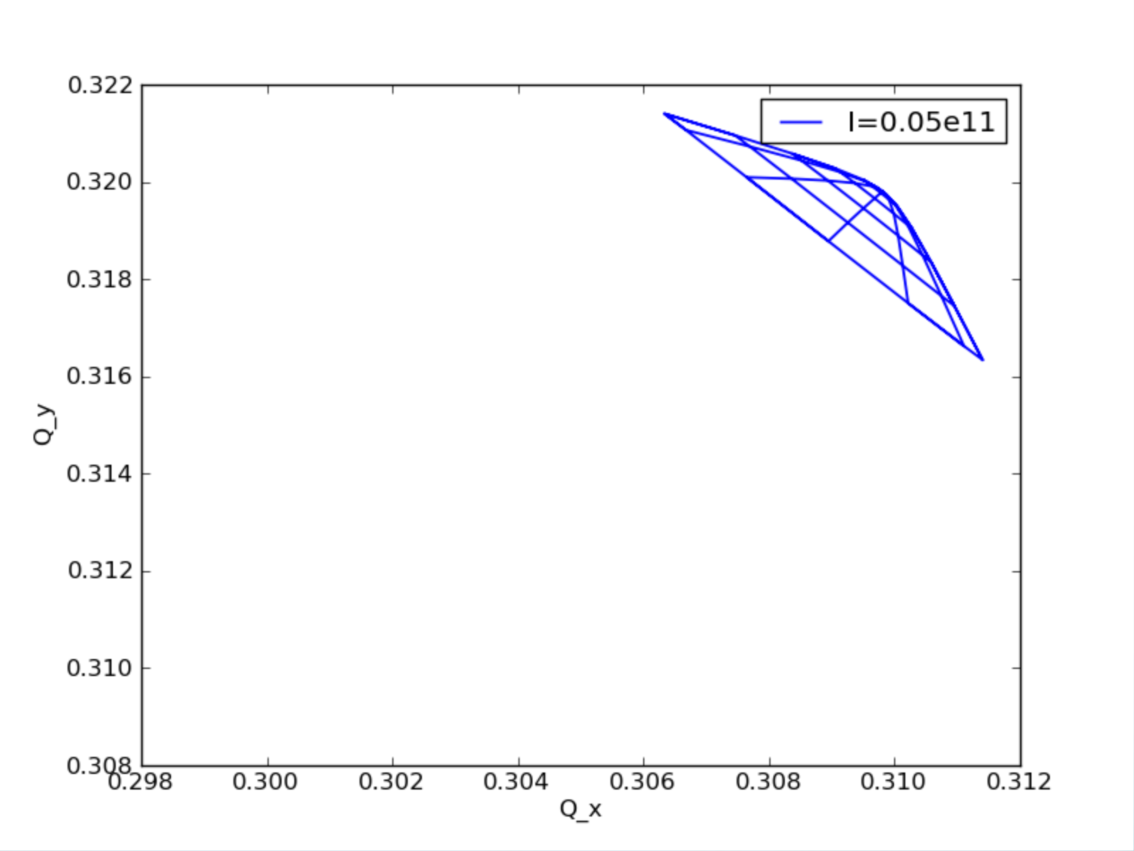


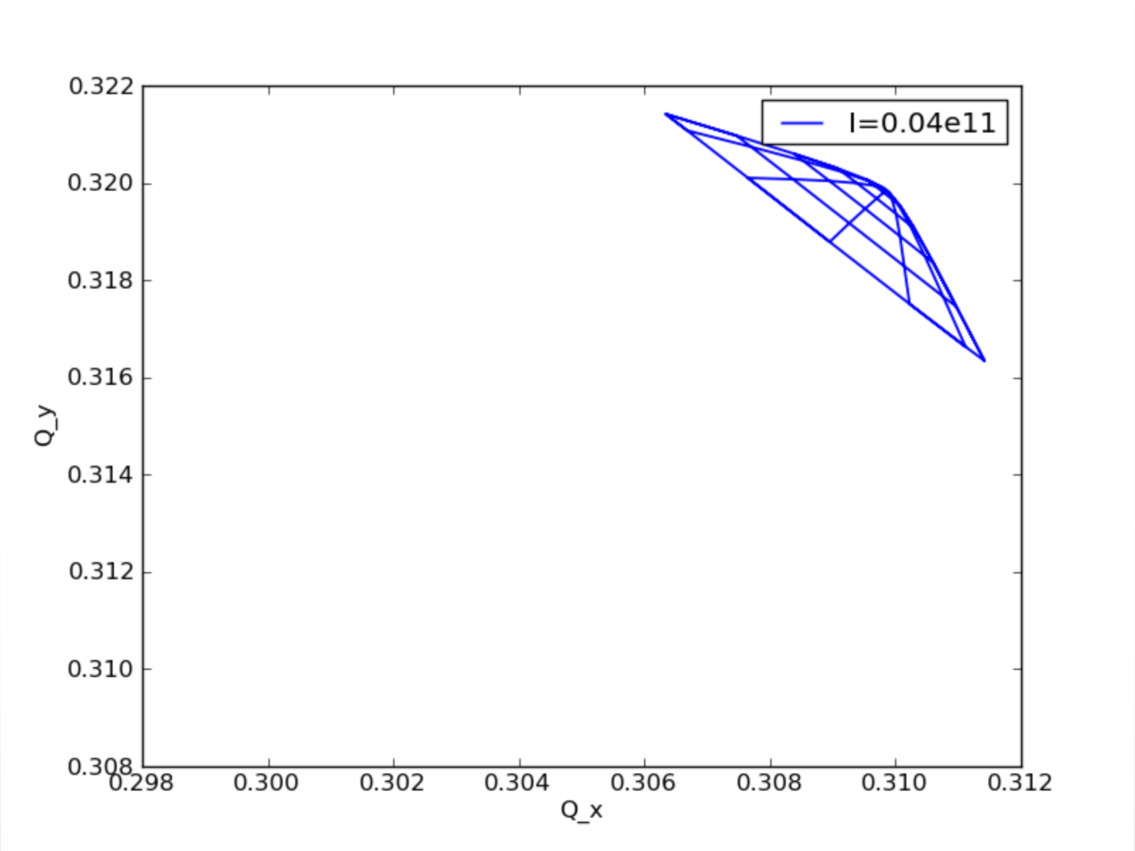
Crab crossing head-on: footprint evolution in function of beam intensity

- Negative LOF



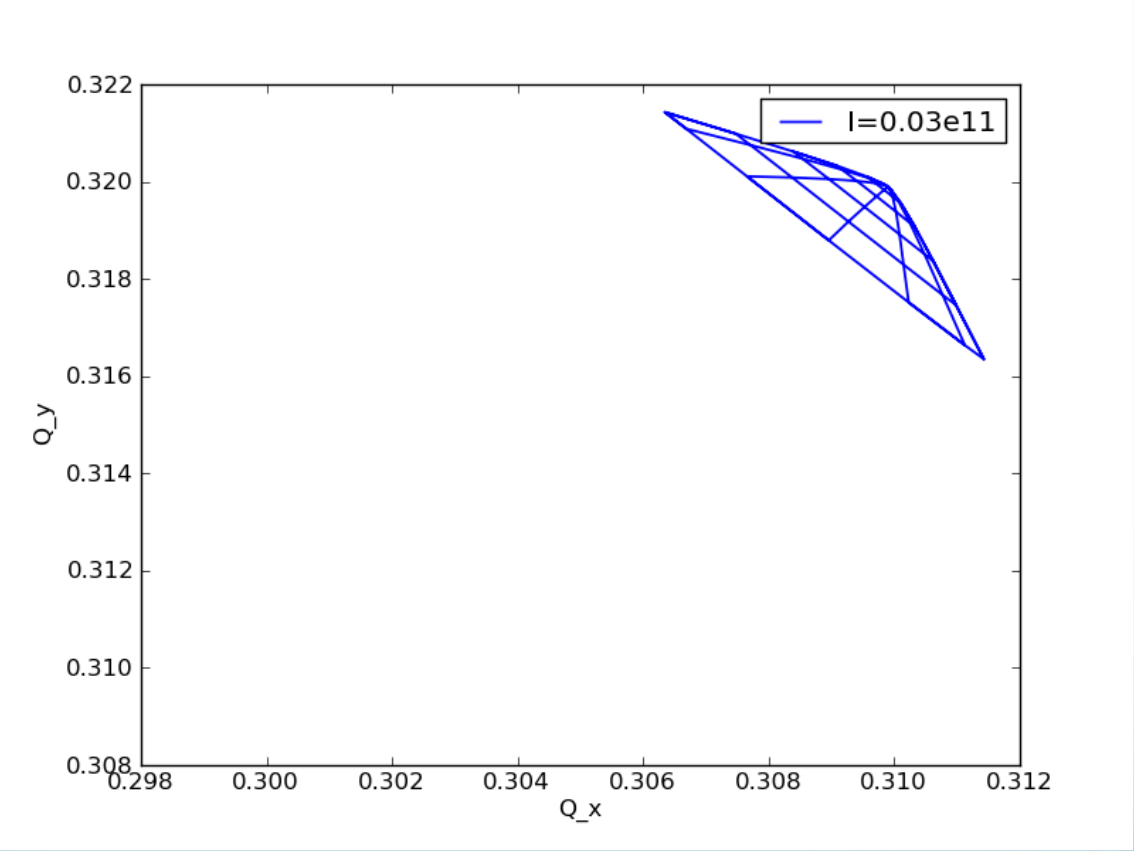
Crab crossing head-on: footprint evolution in function of beam intensity

- Negative LOF



Crab crossing head-on: footprint evolution in function of beam intensity

- Negative LOF



Crab crossing head-on: footprint evolution in function of beam intensity

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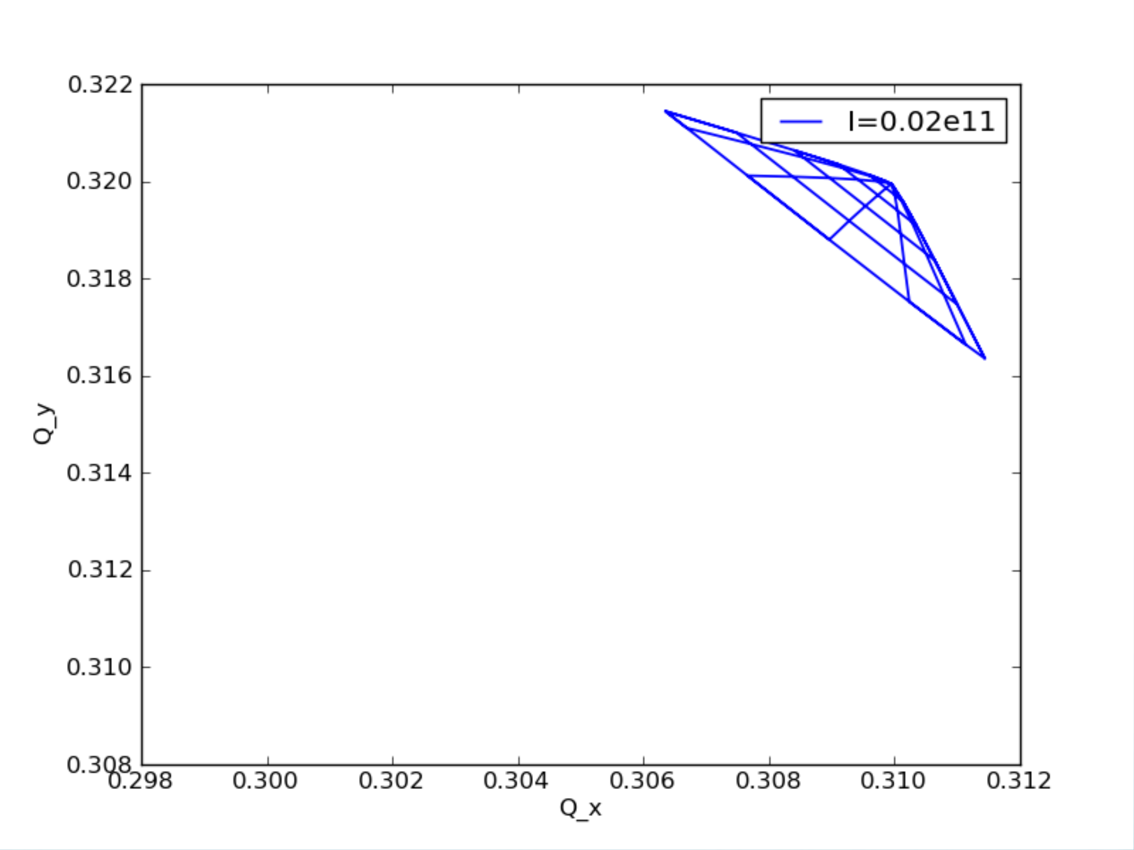
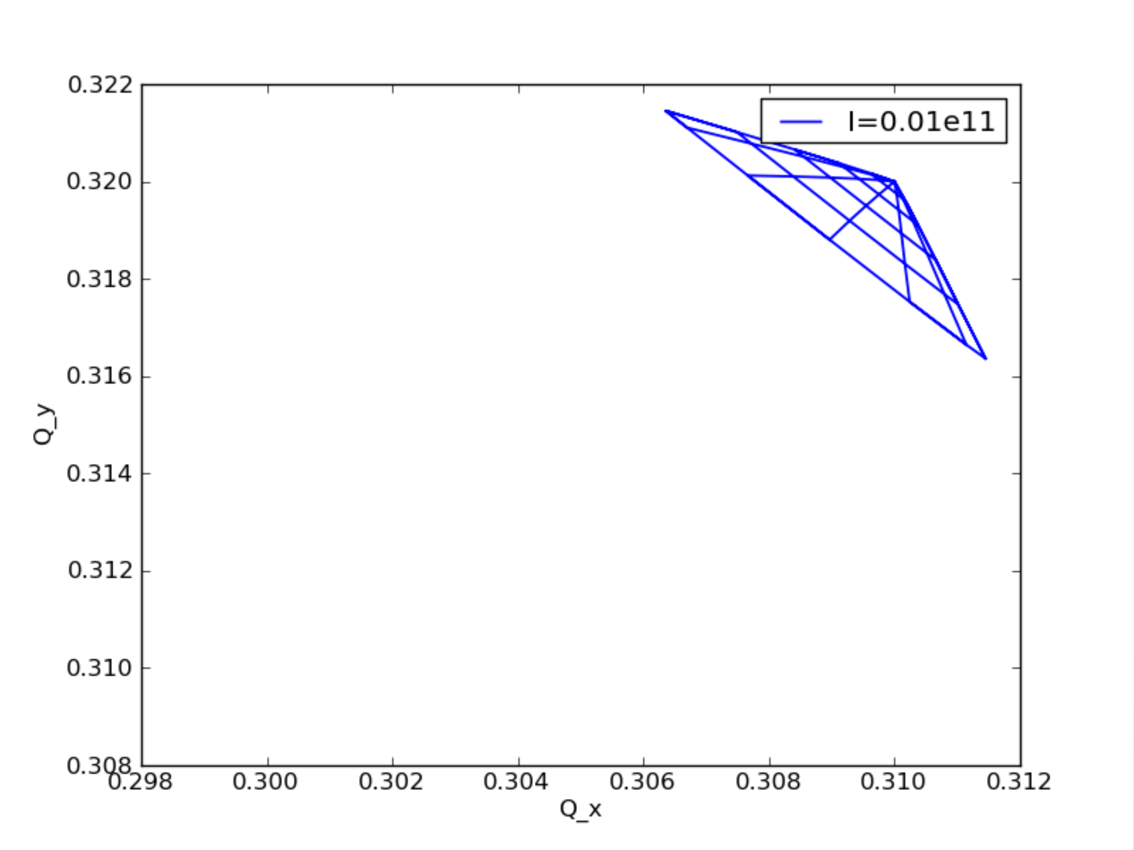


Crab crossing head-on: footprint evolution in function of beam intensity

- Negative LOF



Crab crossing head-on: footprint evolution in function of beam intensity

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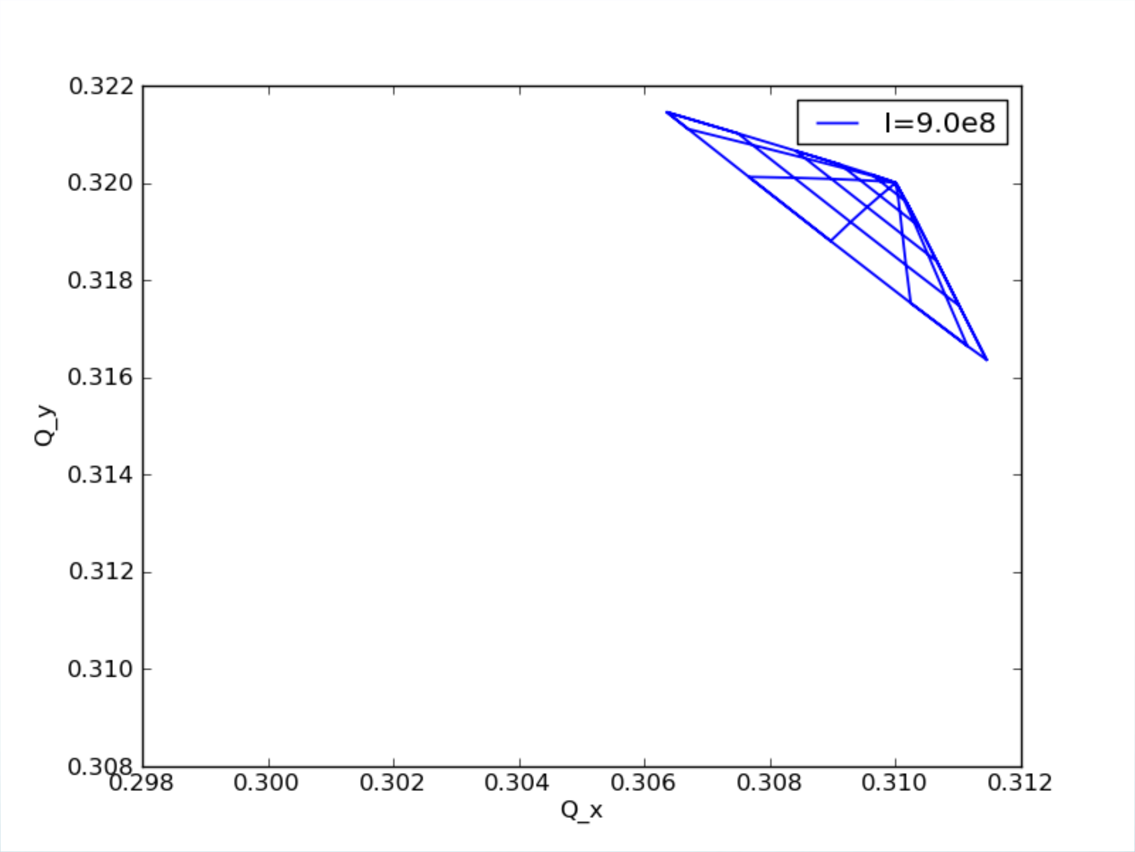

Crab crossing head-on: footprint evolution in function of beam intensity

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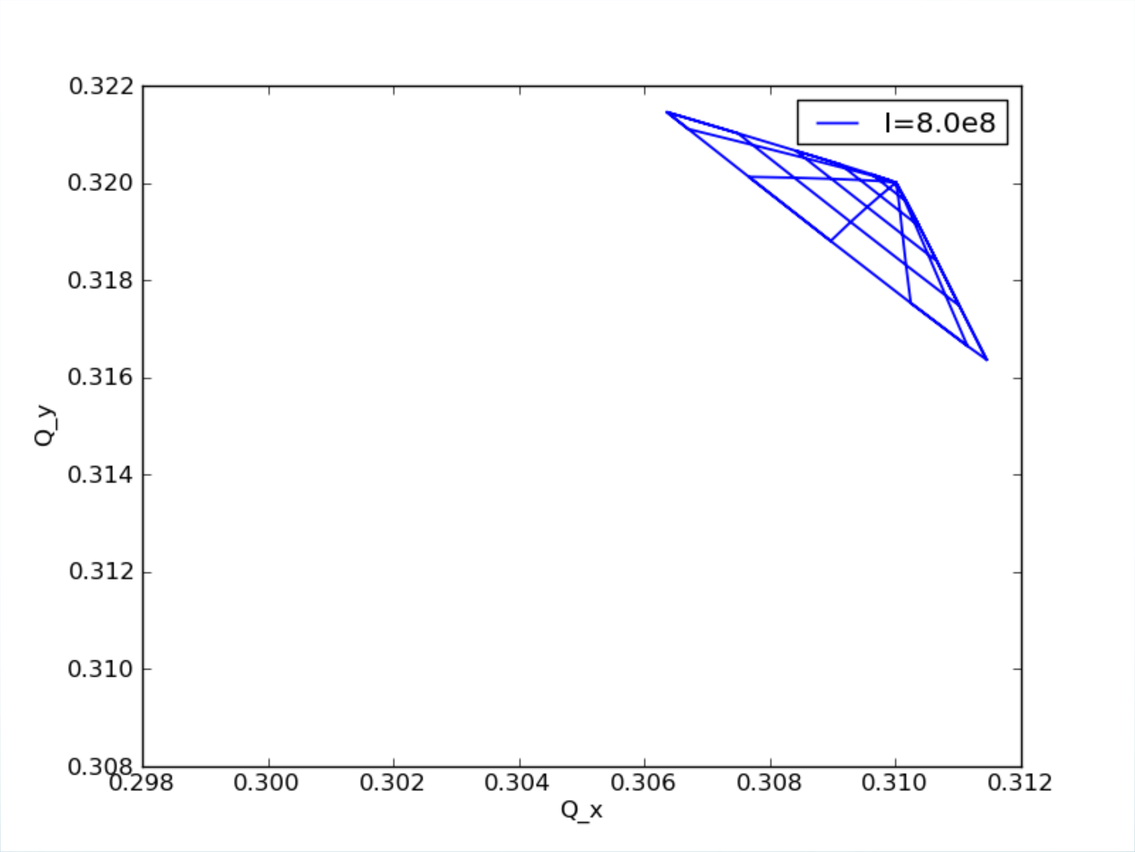

Crab crossing head-on: footprint evolution in function of beam intensity

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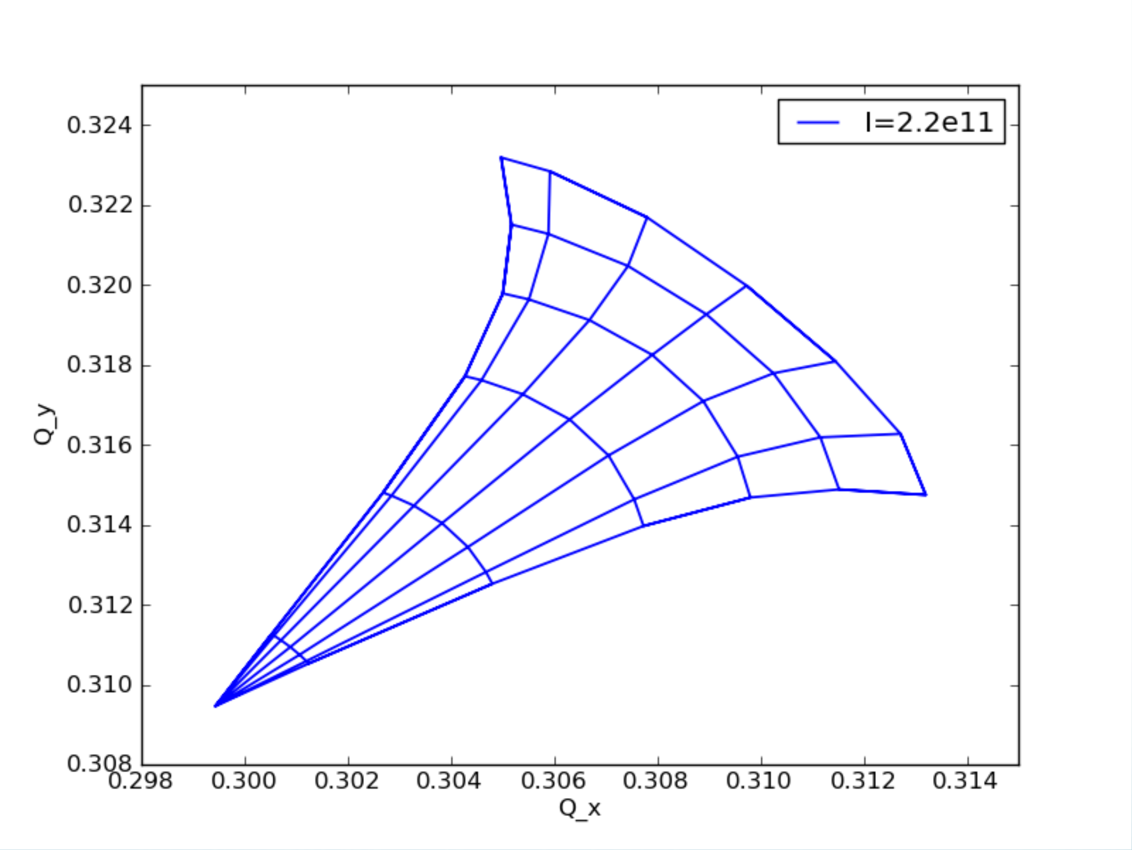

Crab crossing head-on: footprint evolution in function of beam intensity

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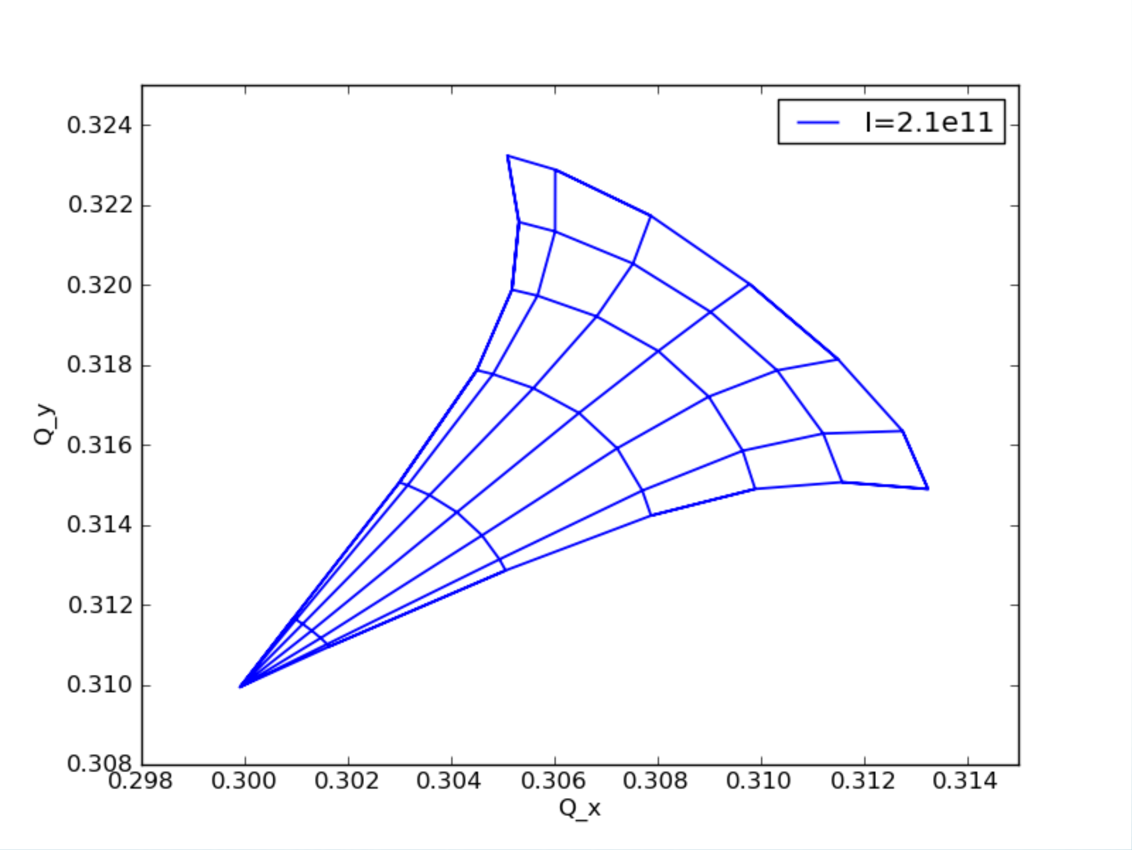

Crab crossing head-on: footprint evolution in function of beam intensity

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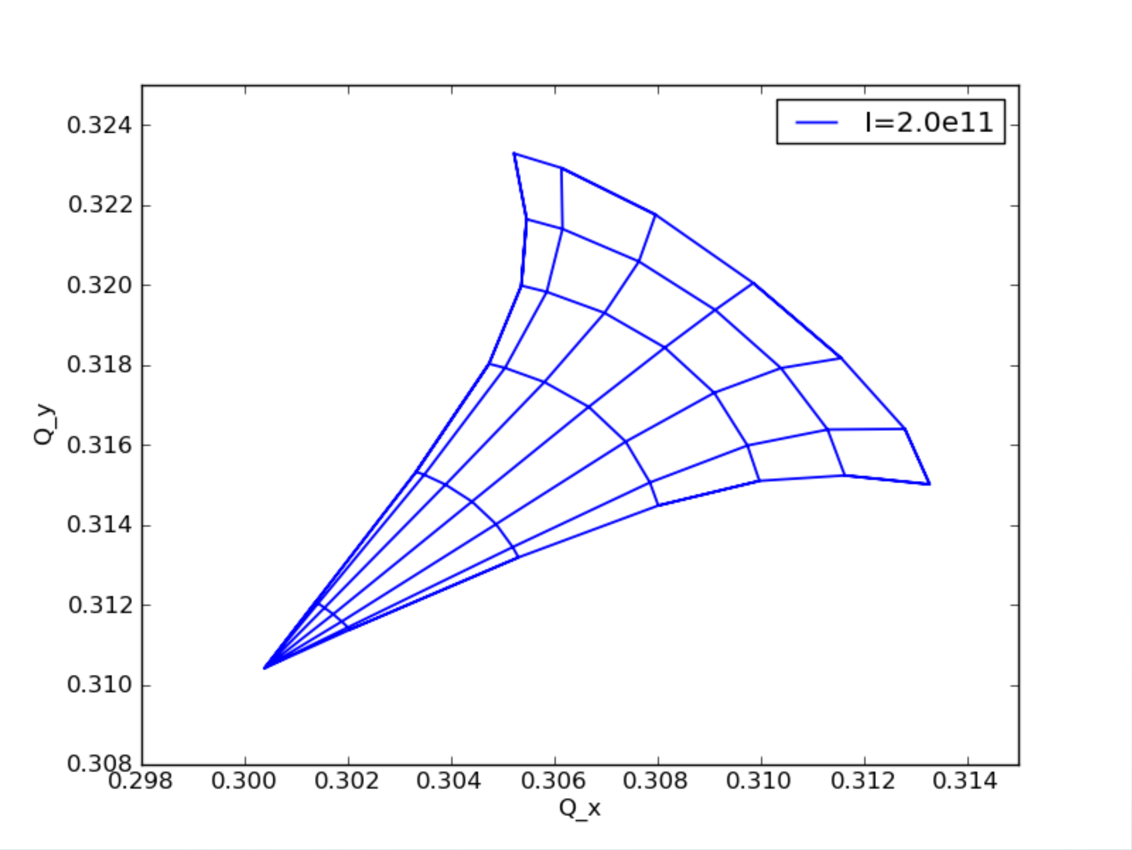

Crab crossing head-on: footprint evolution in function of beam intensity

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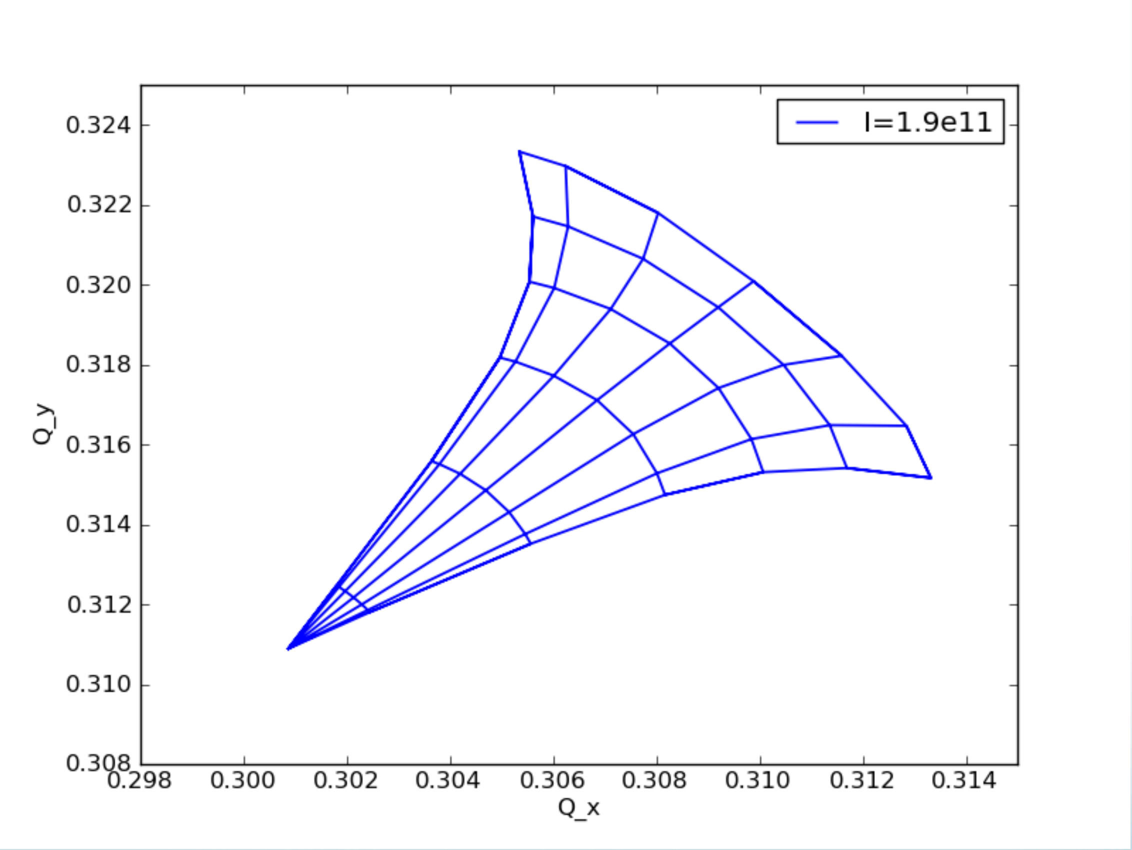

Crab crossing head-on: footprint evolution in function of beam intensity

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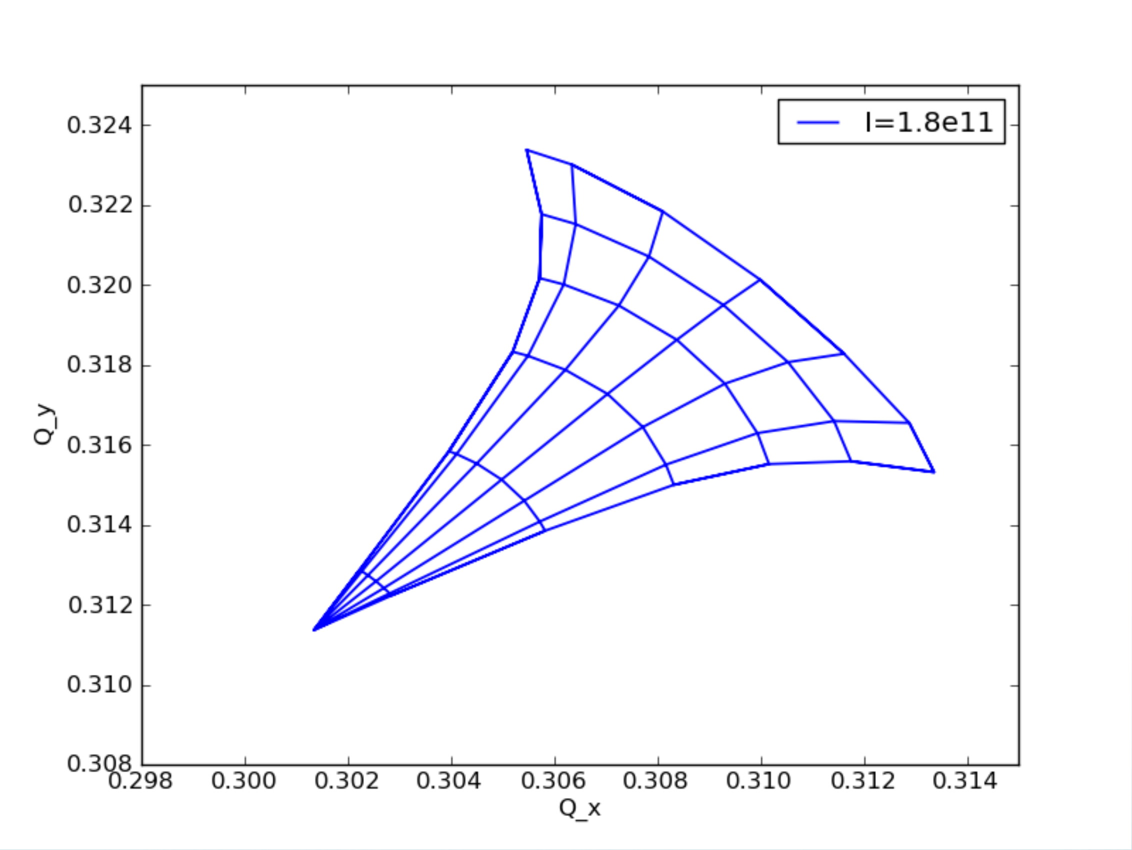

Crab crossing head-on: footprint evolution in function of beam intensity

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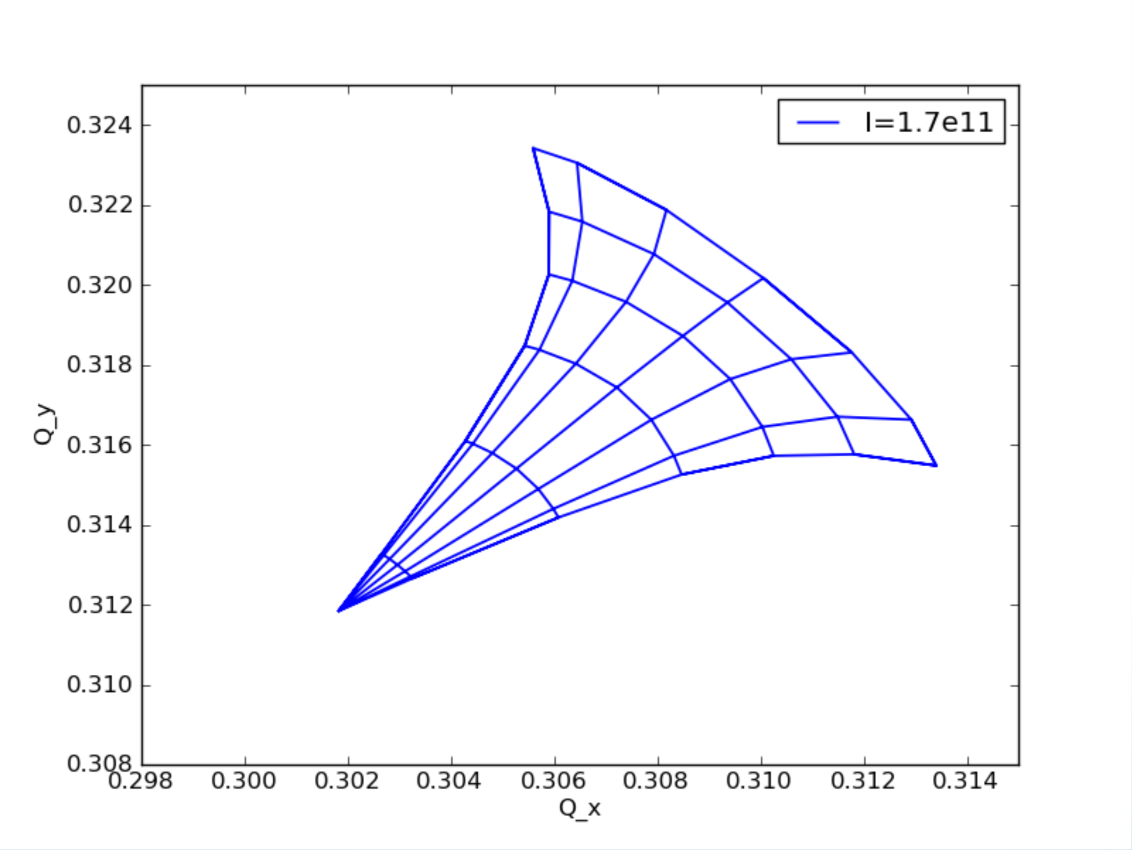

Crab crossing head-on: footprint evolution in function of beam intensity

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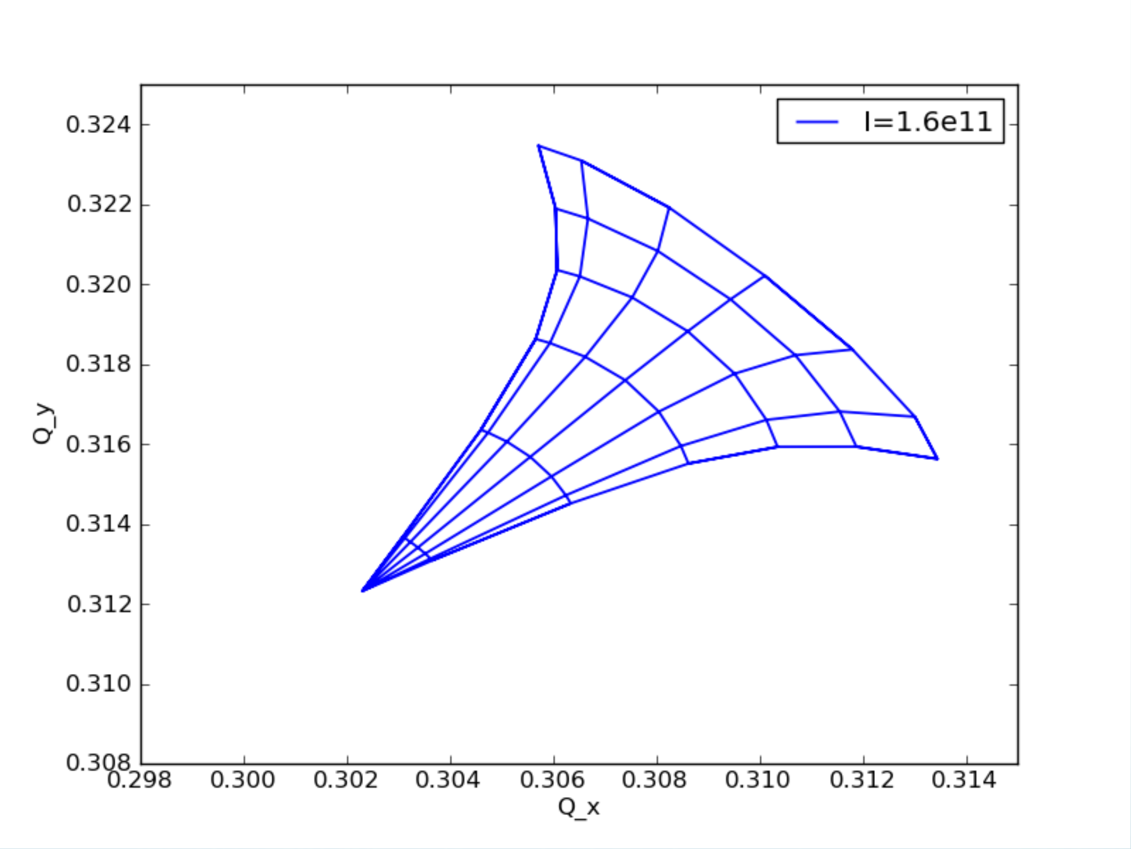

Crab crossing head-on: footprint evolution in function of beam intensity

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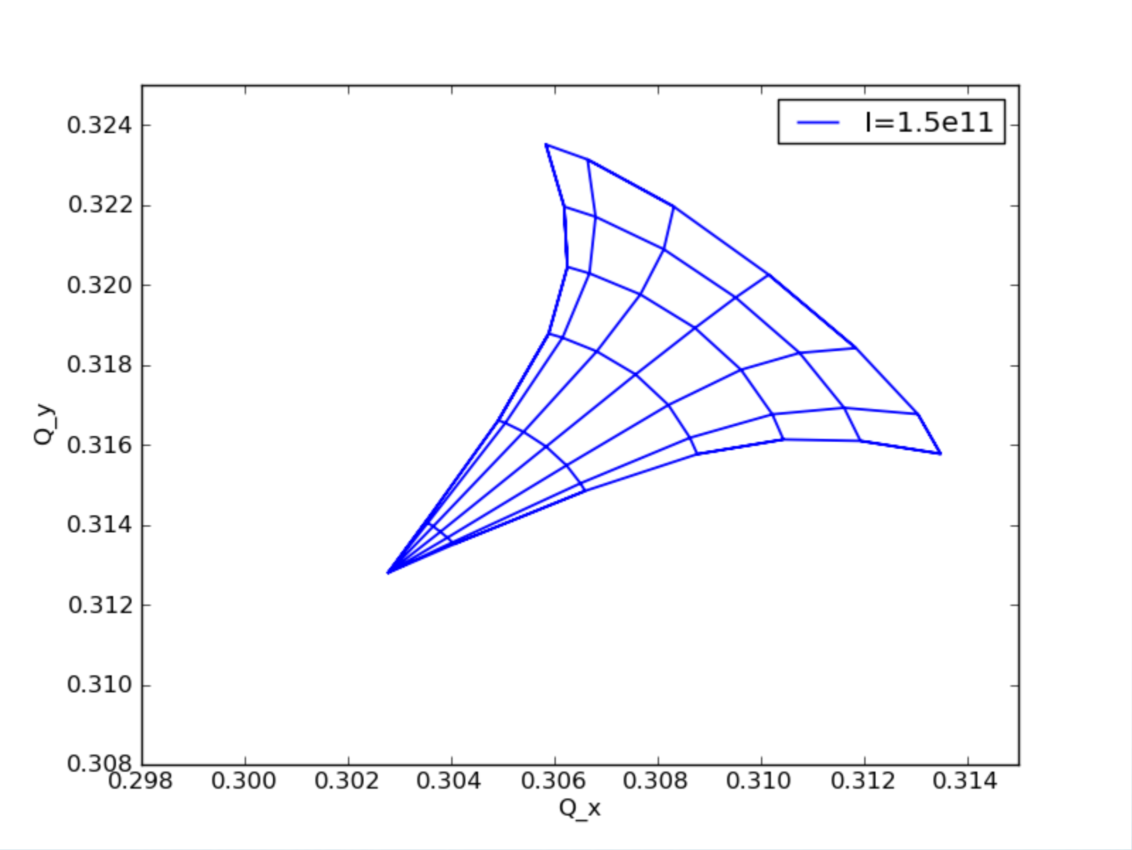

Crab crossing head-on: footprint evolution in function of beam intensity

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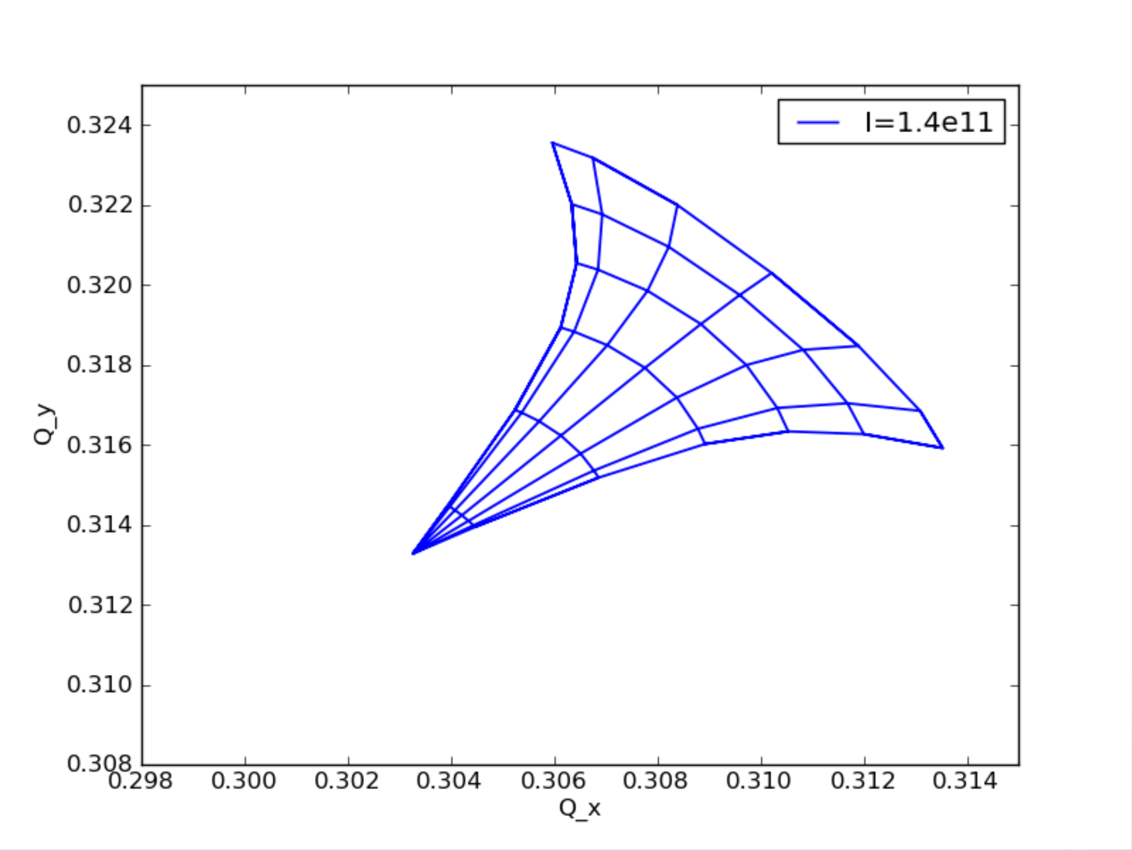

Crab crossing head-on: footprint evolution in function of beam intensity

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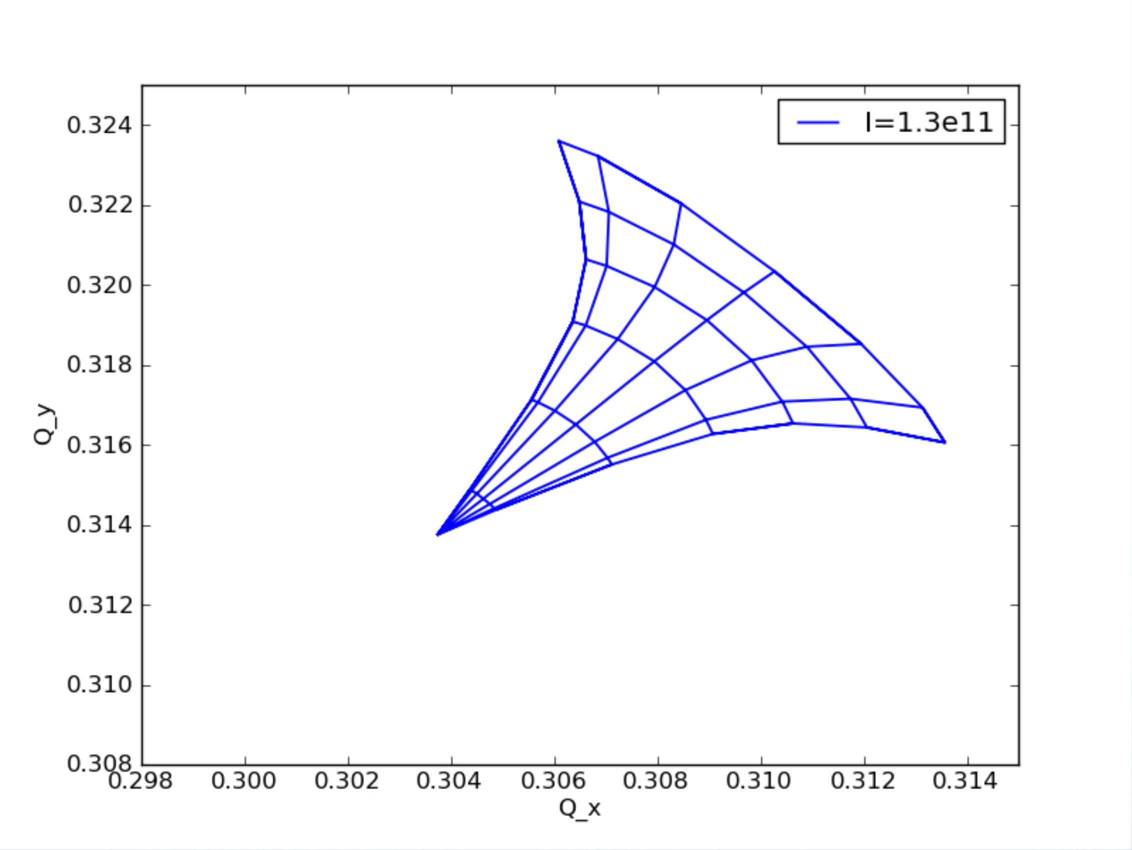

Crab crossing head-on: footprint evolution in function of beam intensity

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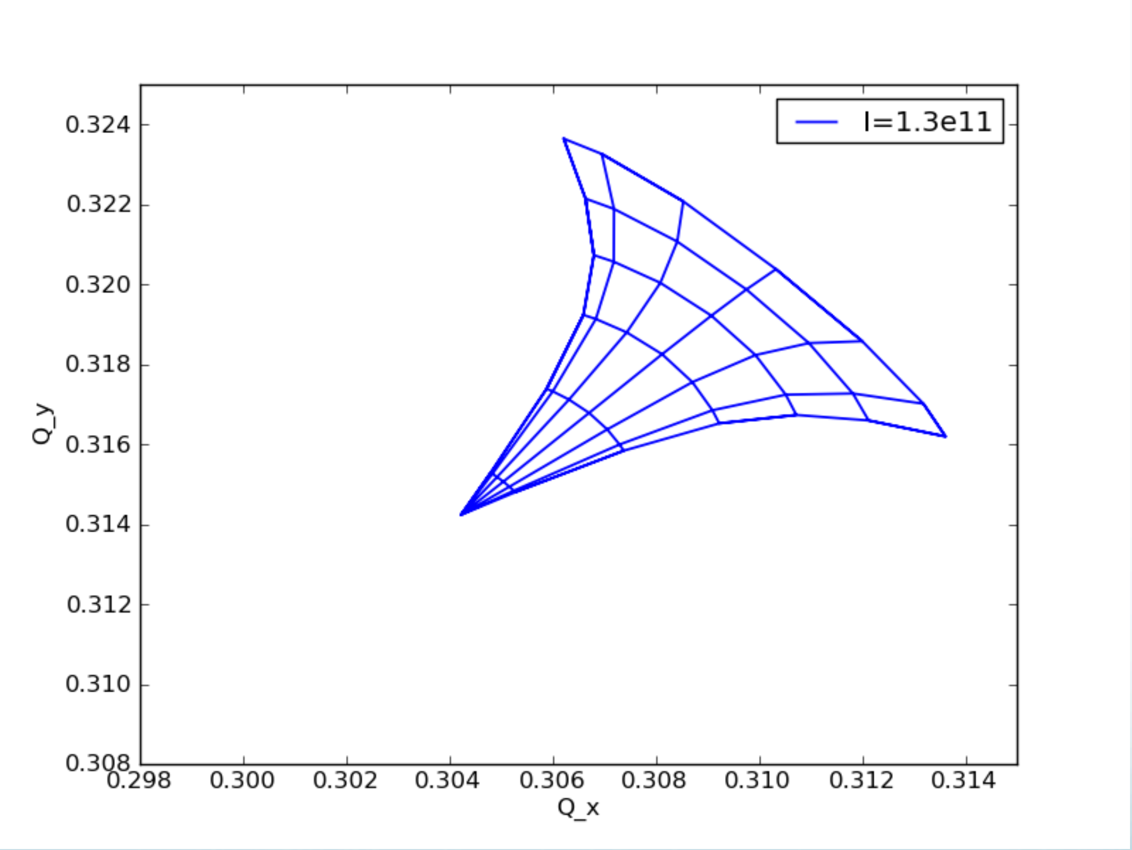

Crab crossing head-on: footprint evolution in function of beam intensity

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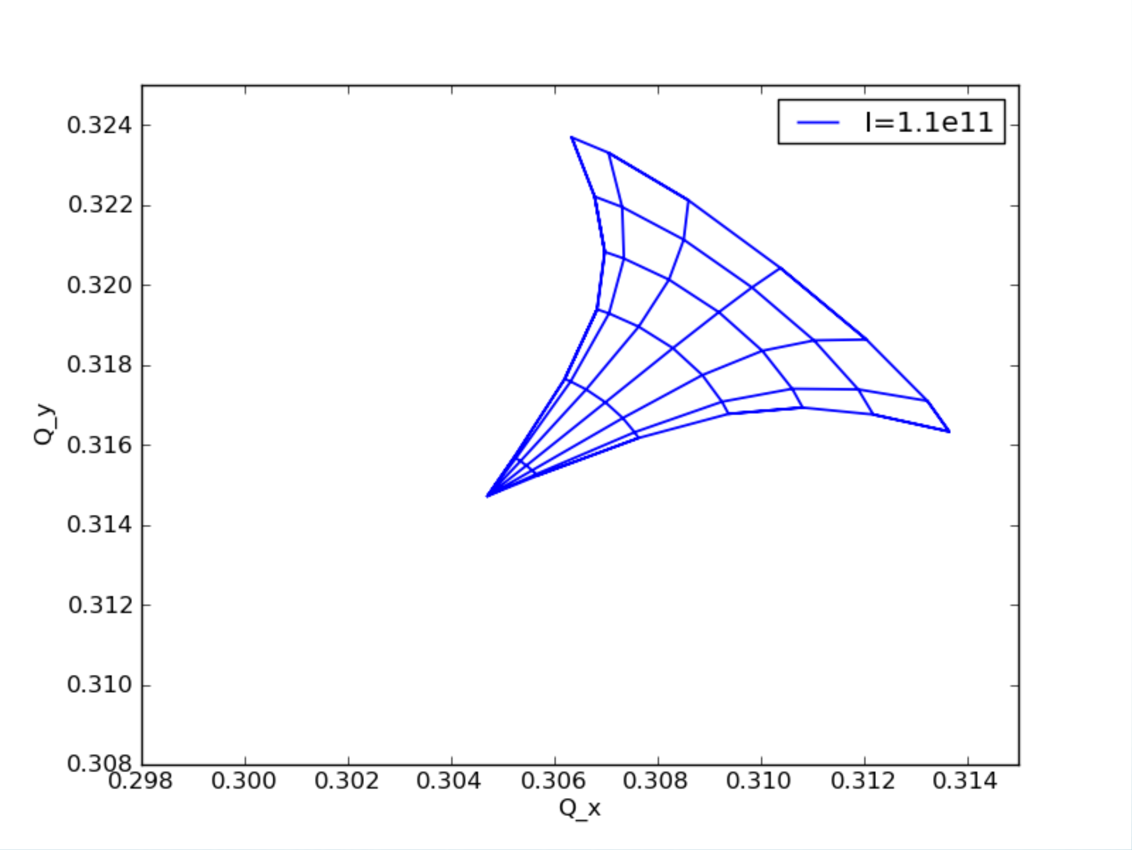
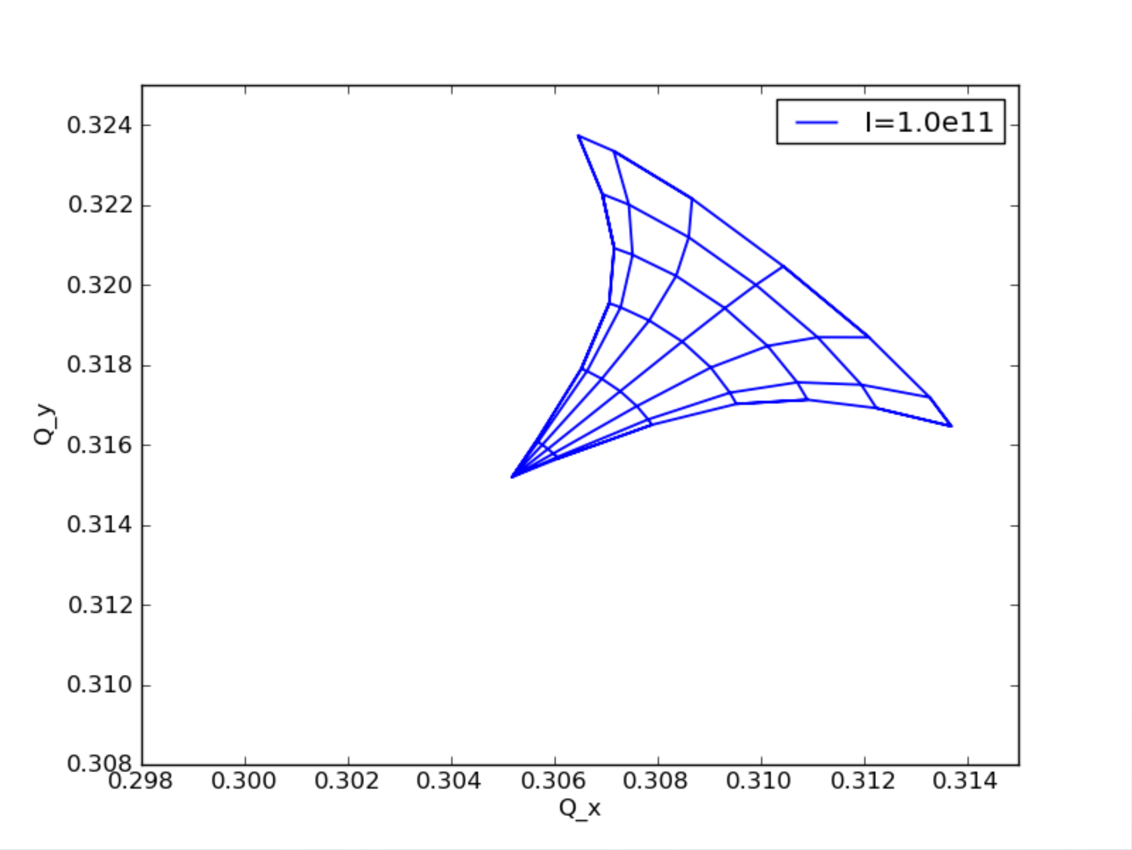


Crab crossing head-on: footprint evolution in function of beam intensity

- Positive LOF



Crab crossing head-on: footprint evolution in function of beam intensity

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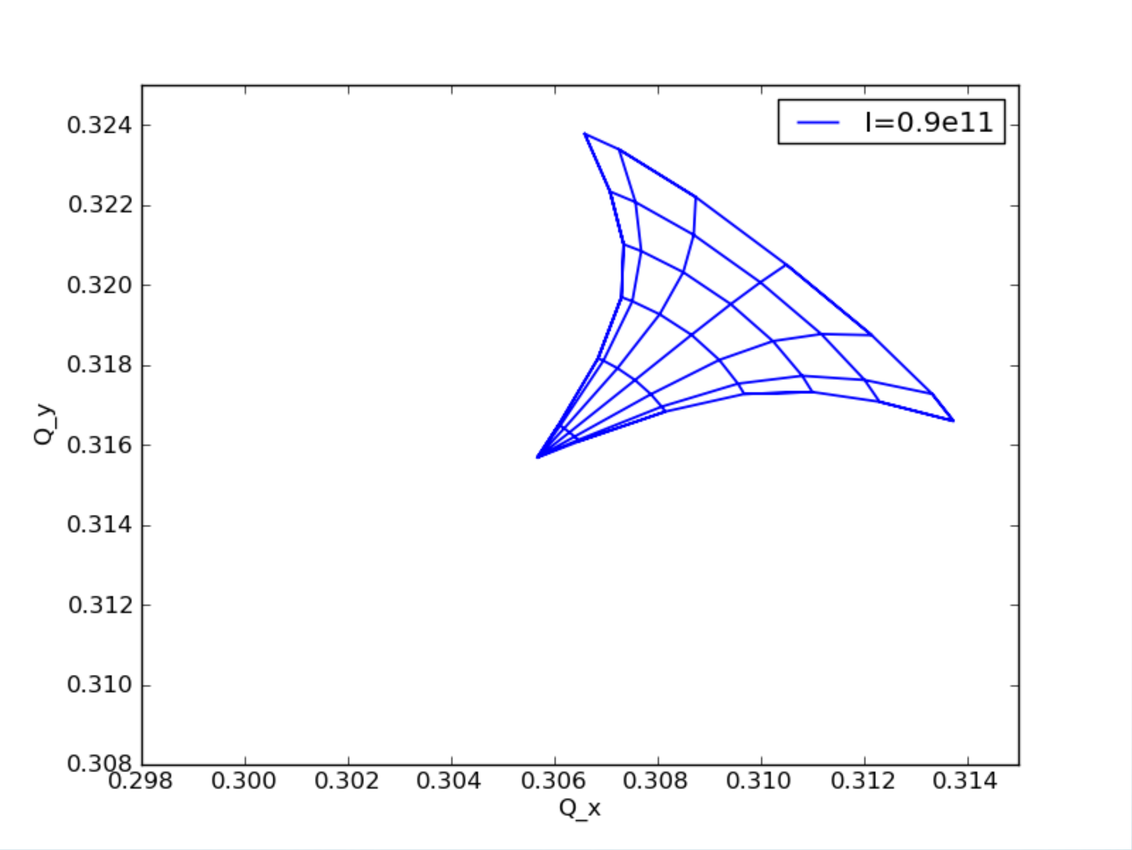

Crab crossing head-on: footprint evolution in function of beam intensity

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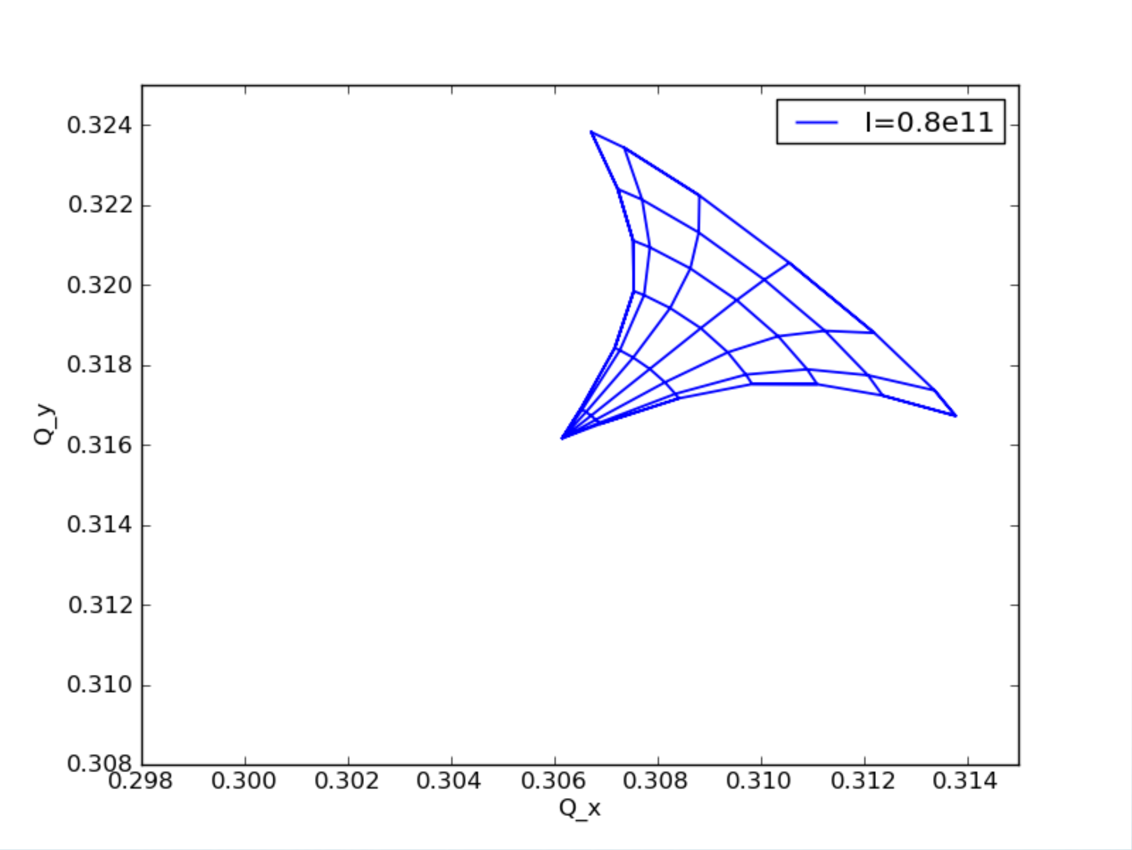

Crab crossing head-on: footprint evolution in function of beam intensity

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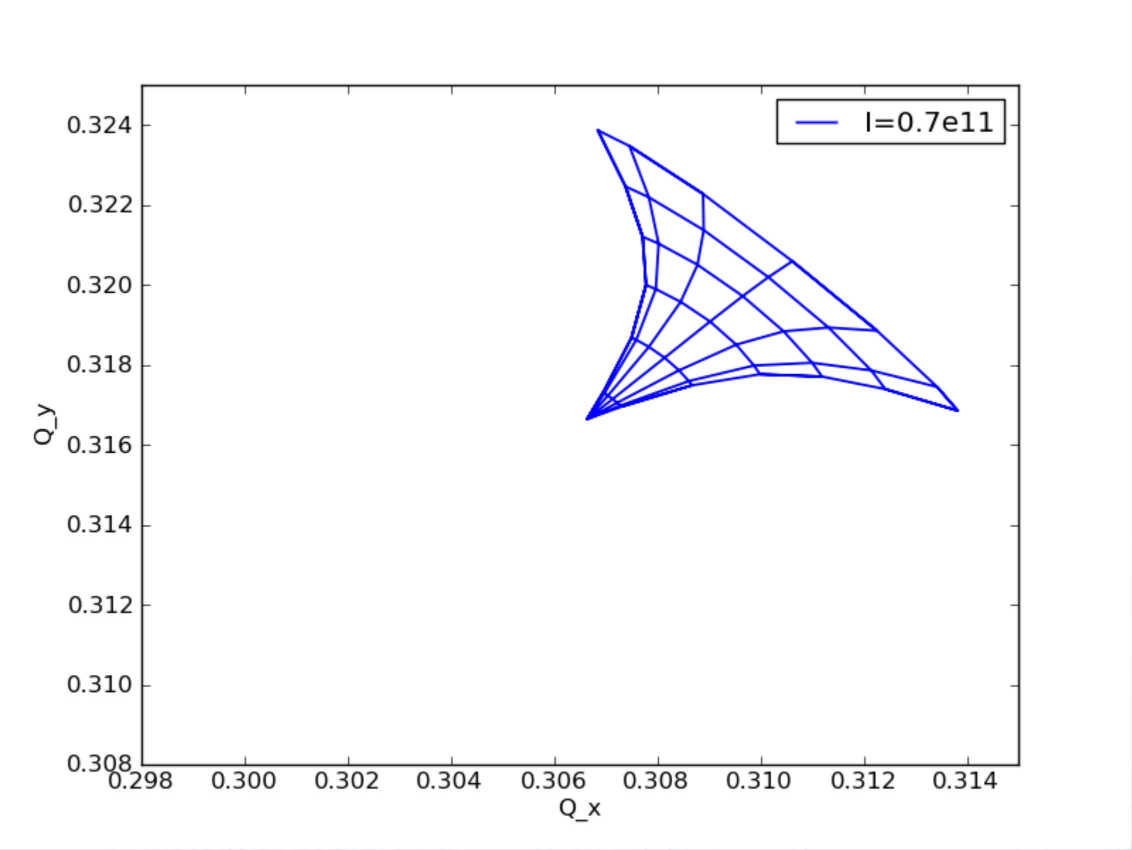

Crab crossing head-on: footprint evolution in function of beam intensity

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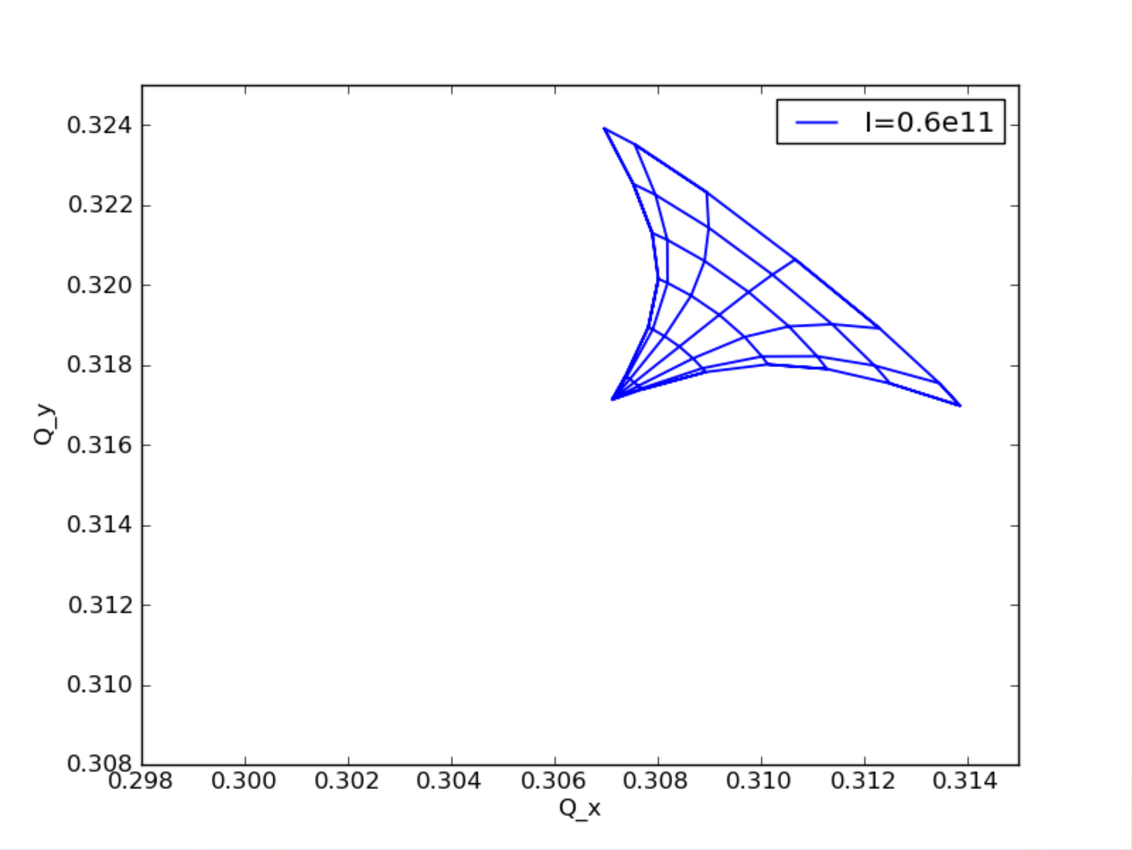

Crab crossing head-on: footprint evolution in function of beam intensity

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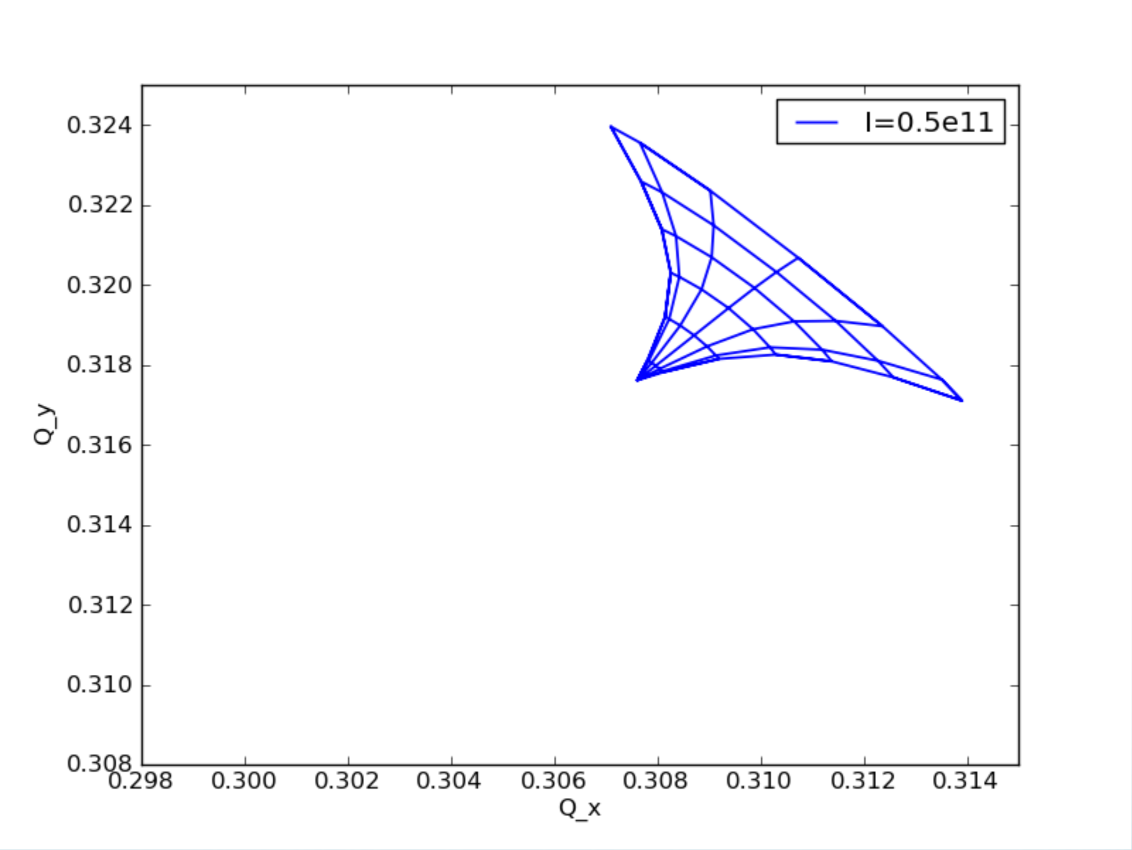

Crab crossing head-on: footprint evolution in function of beam intensity

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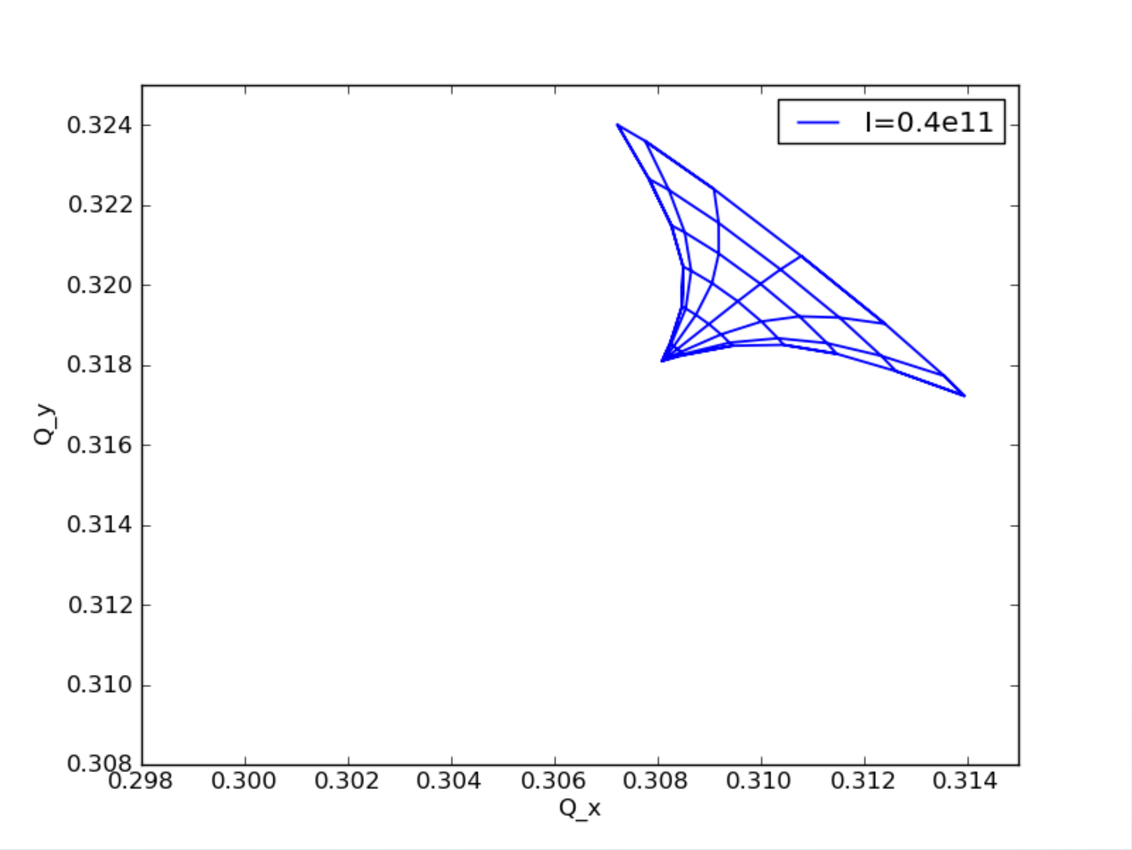

Crab crossing head-on: footprint evolution in function of beam intensity

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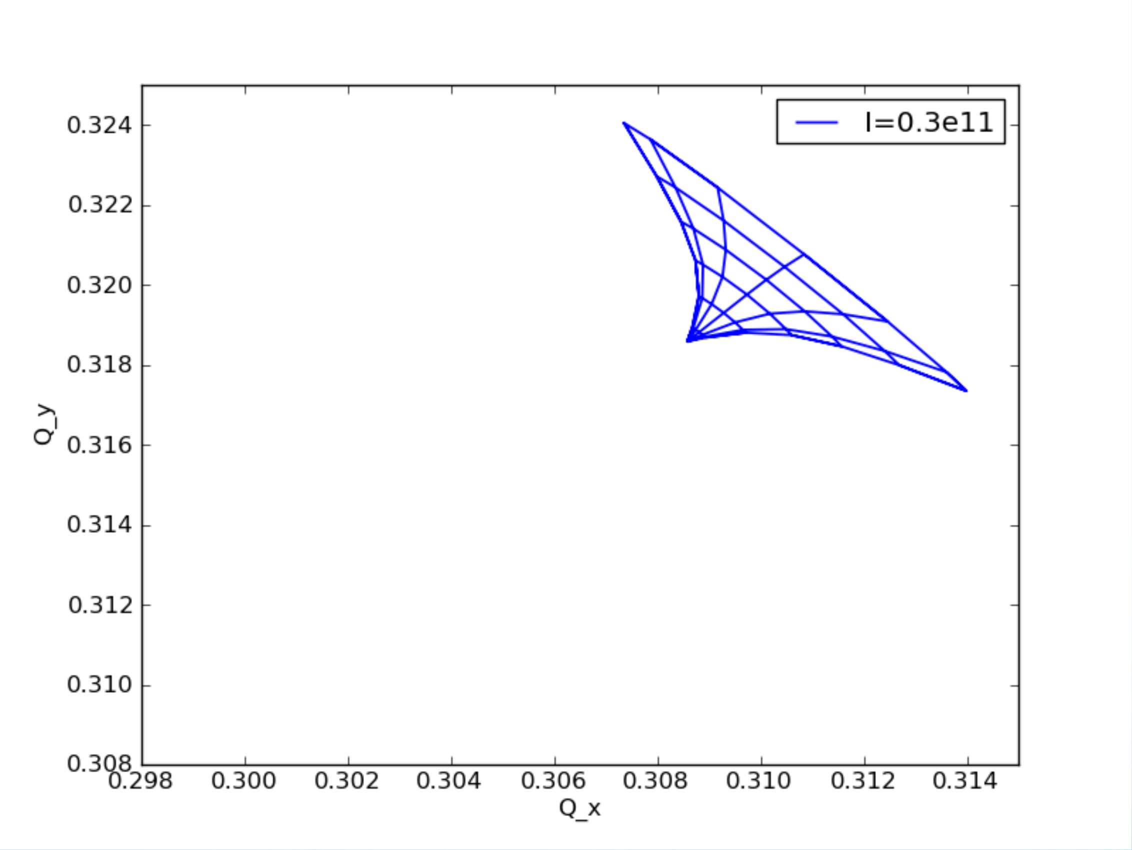

Crab crossing head-on: footprint evolution in function of beam intensity

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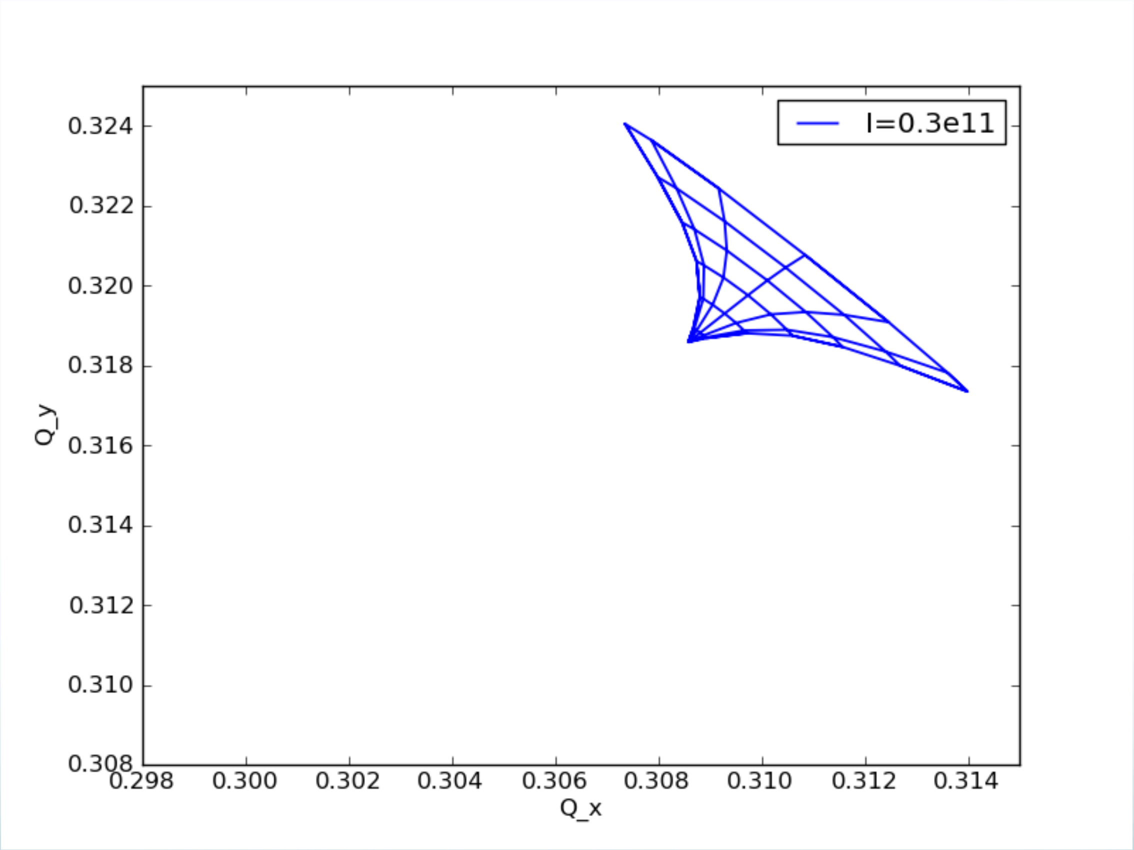

Crab crossing head-on: footprint evolution in function of beam intensity

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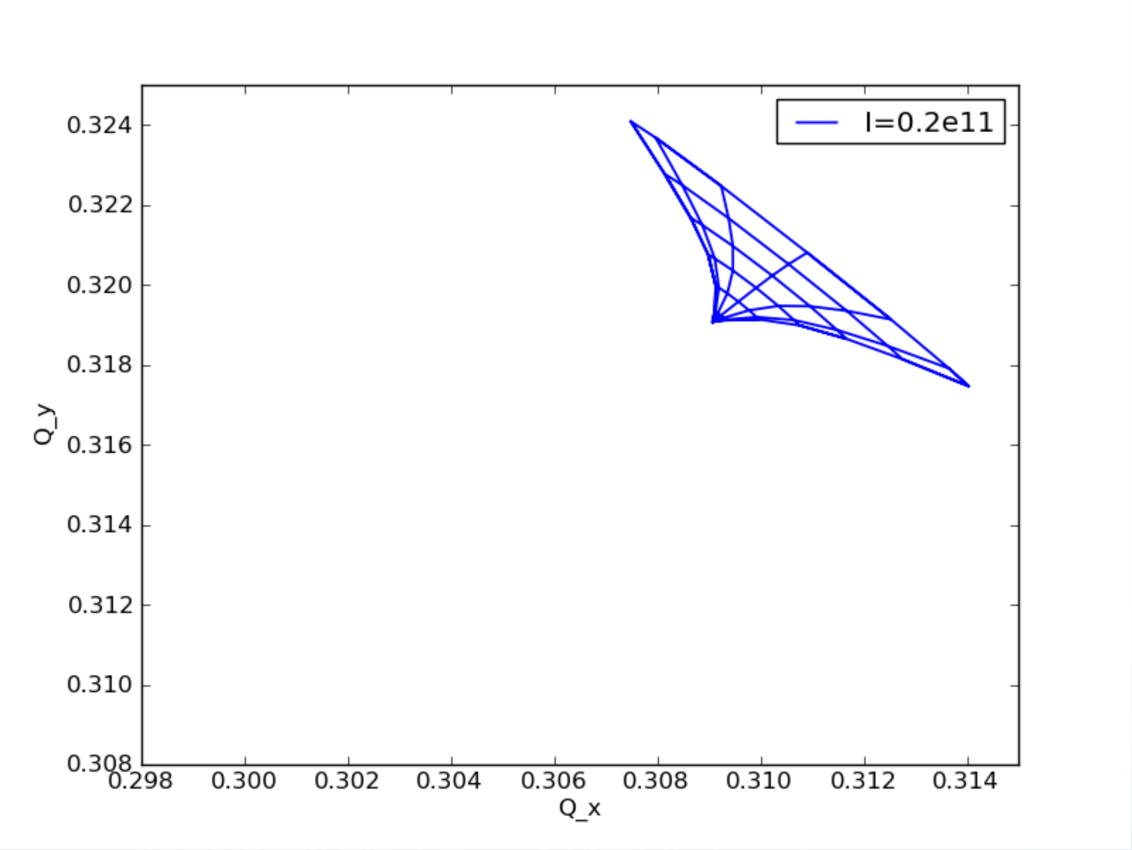
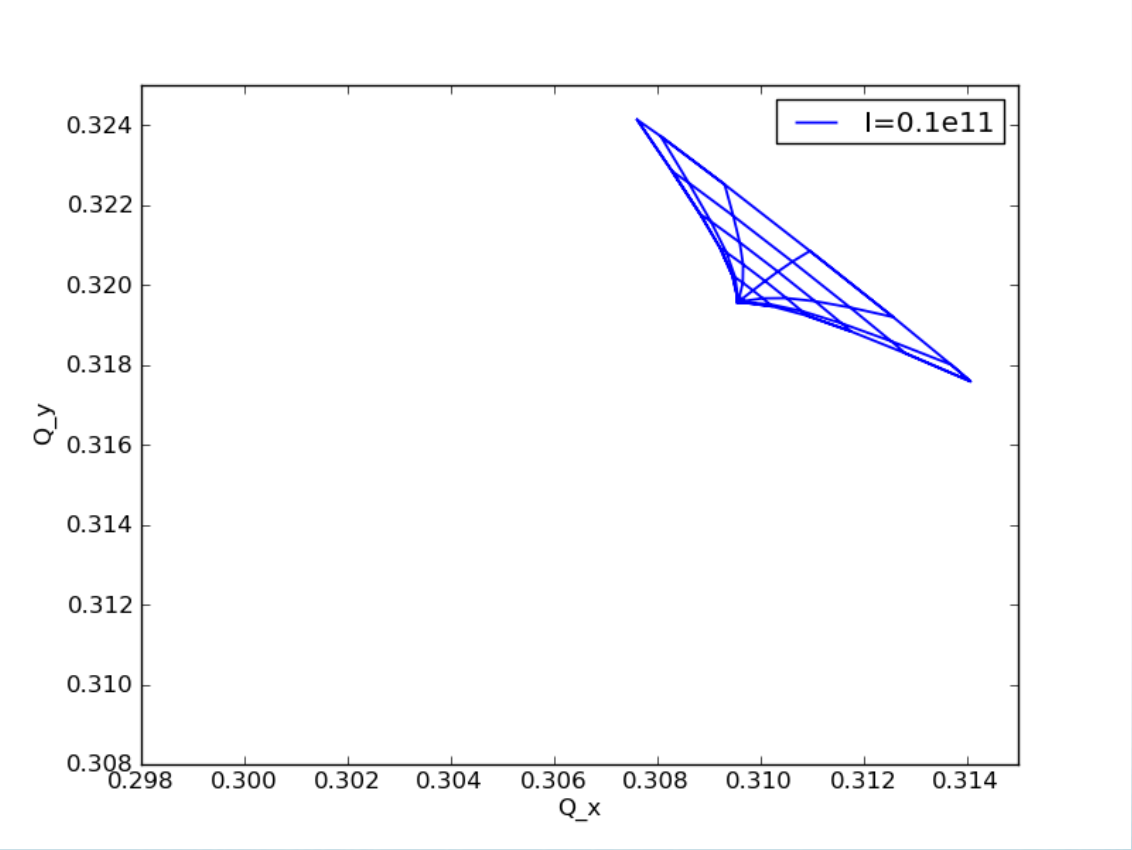


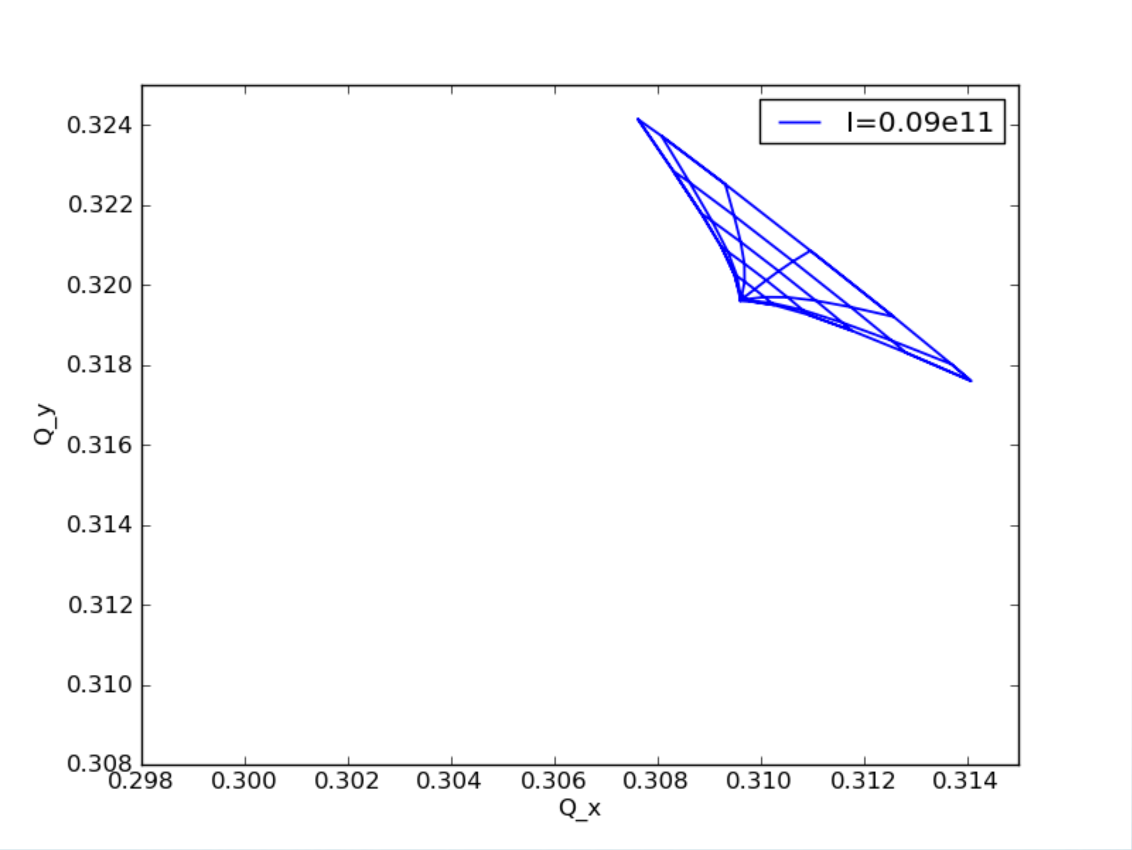
Crab crossing head-on: footprint evolution in function of beam intensity

- Positive LOF



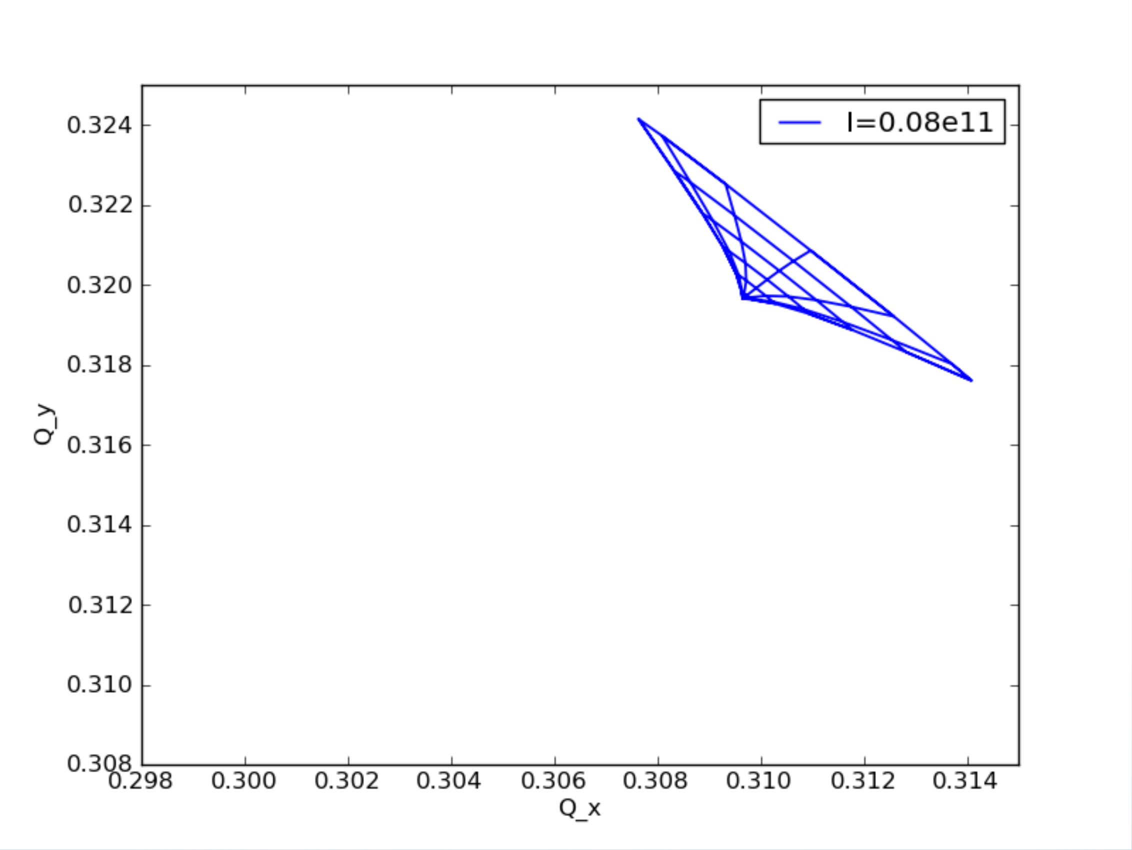
Crab crossing head-on: footprint evolution in function of beam intensity

- Positive LOF



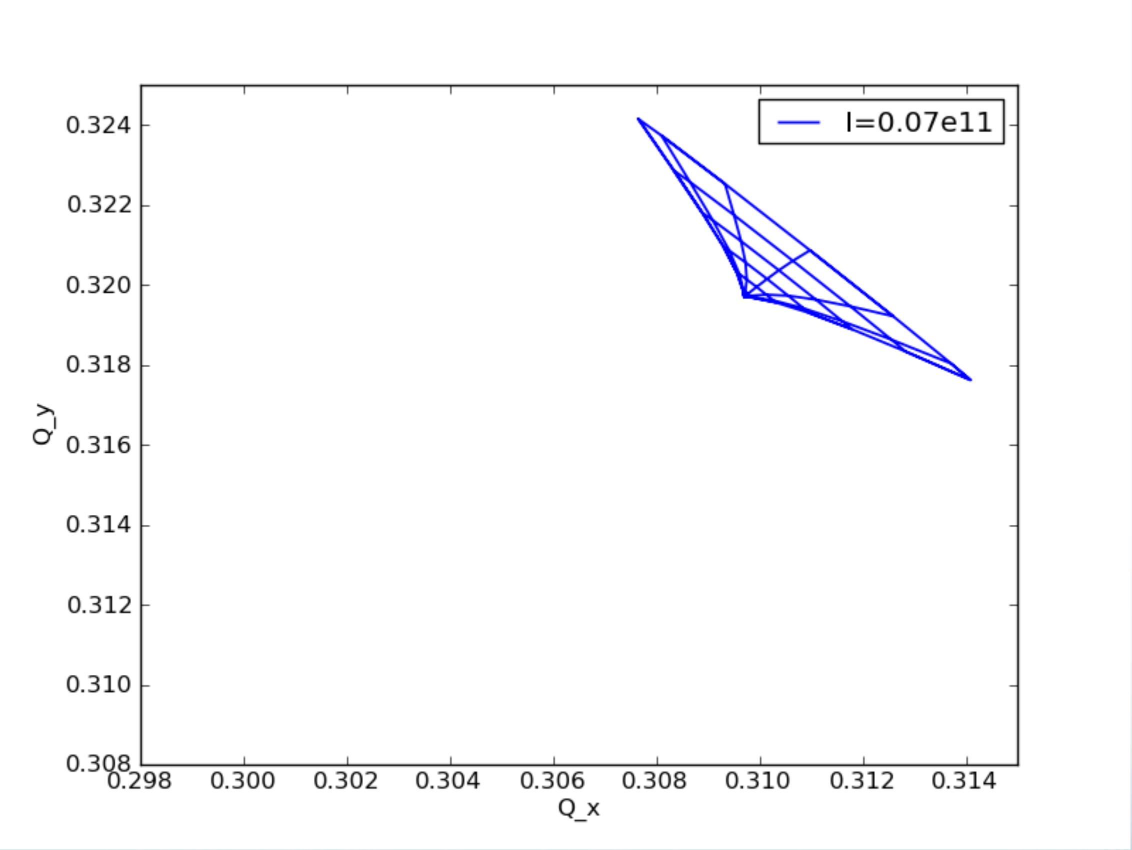
Crab crossing head-on: footprint evolution in function of beam intensity

- Positive LOF



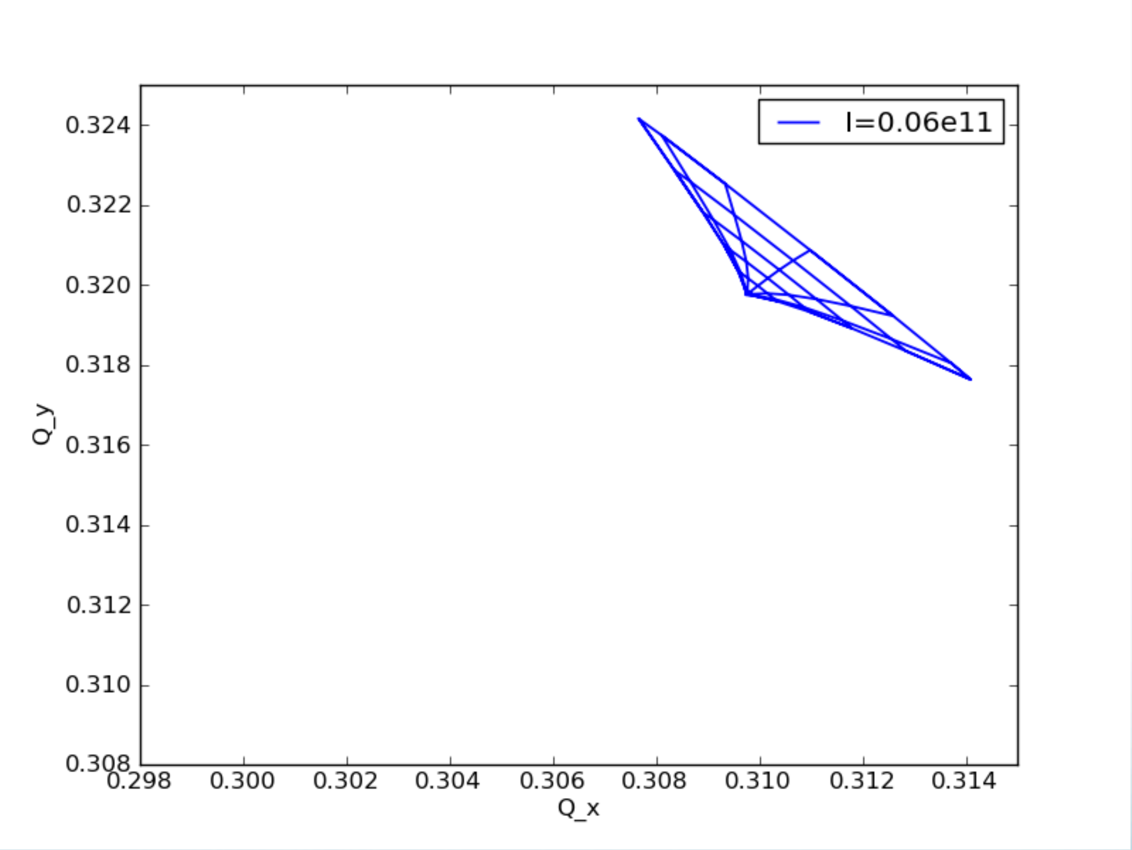
Crab crossing head-on: footprint evolution in function of beam intensity

- Positive LOF



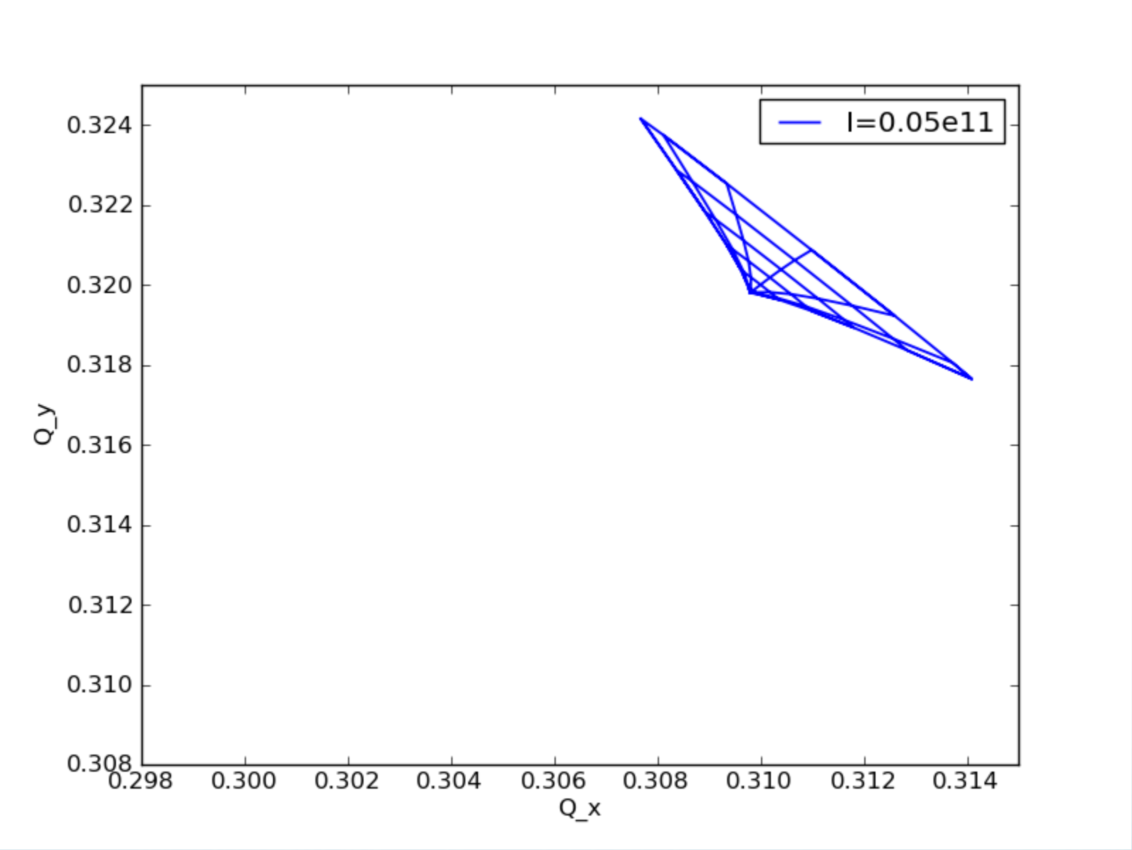
Crab crossing head-on: footprint evolution in function of beam intensity

- Positive LOF



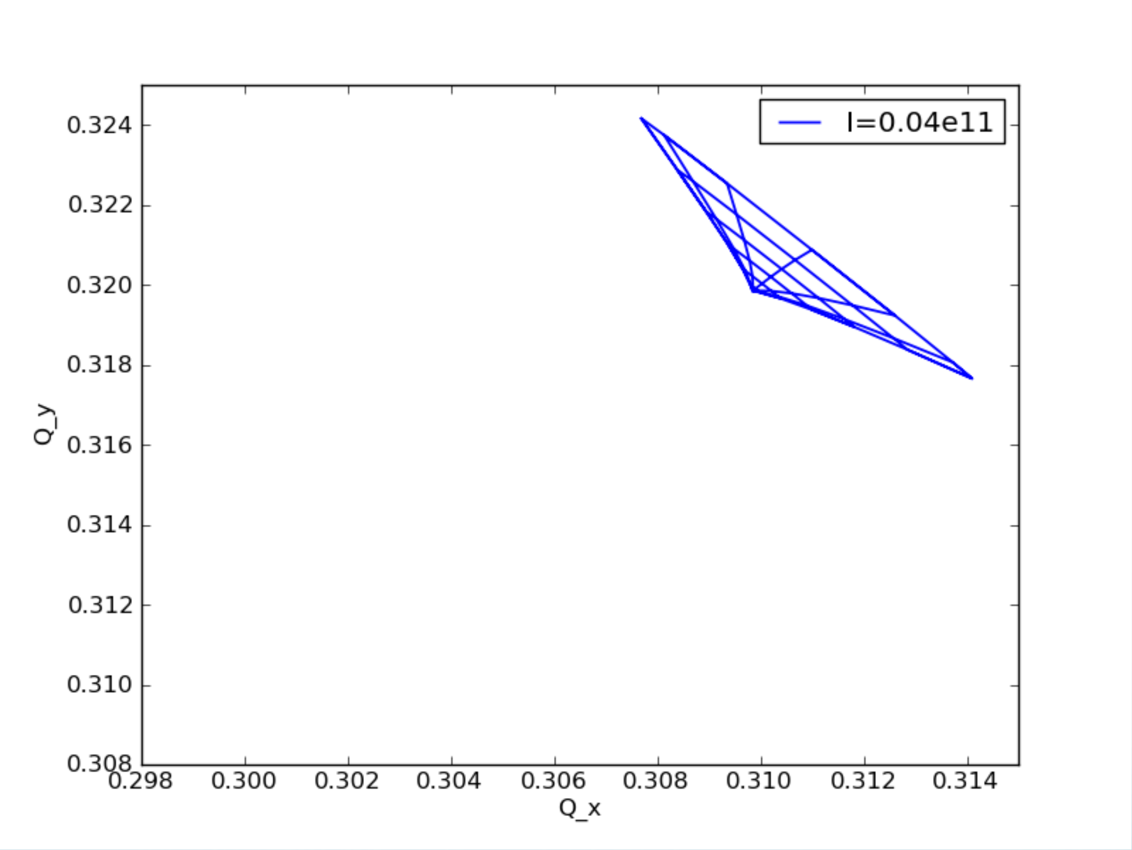
Crab crossing head-on: footprint evolution in function of beam intensity

- Positive LOF



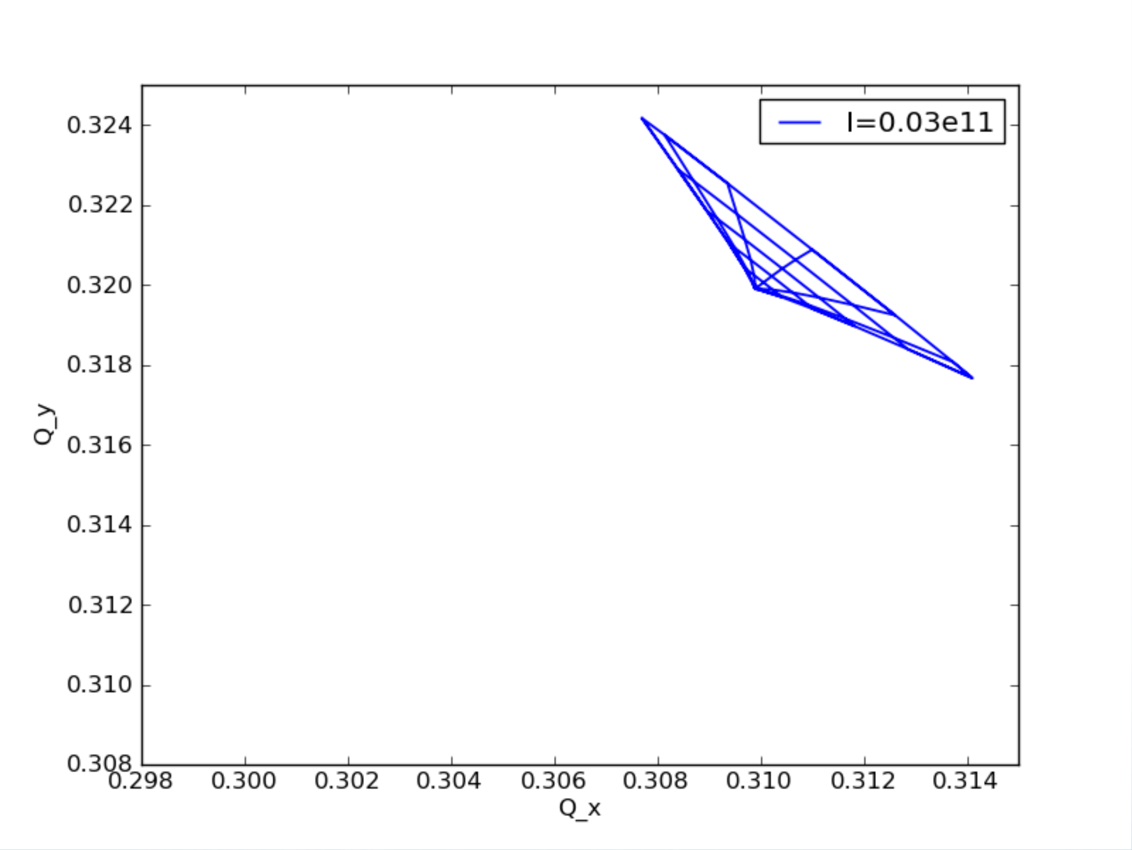
Crab crossing head-on: footprint evolution in function of beam intensity

- Positive LOF



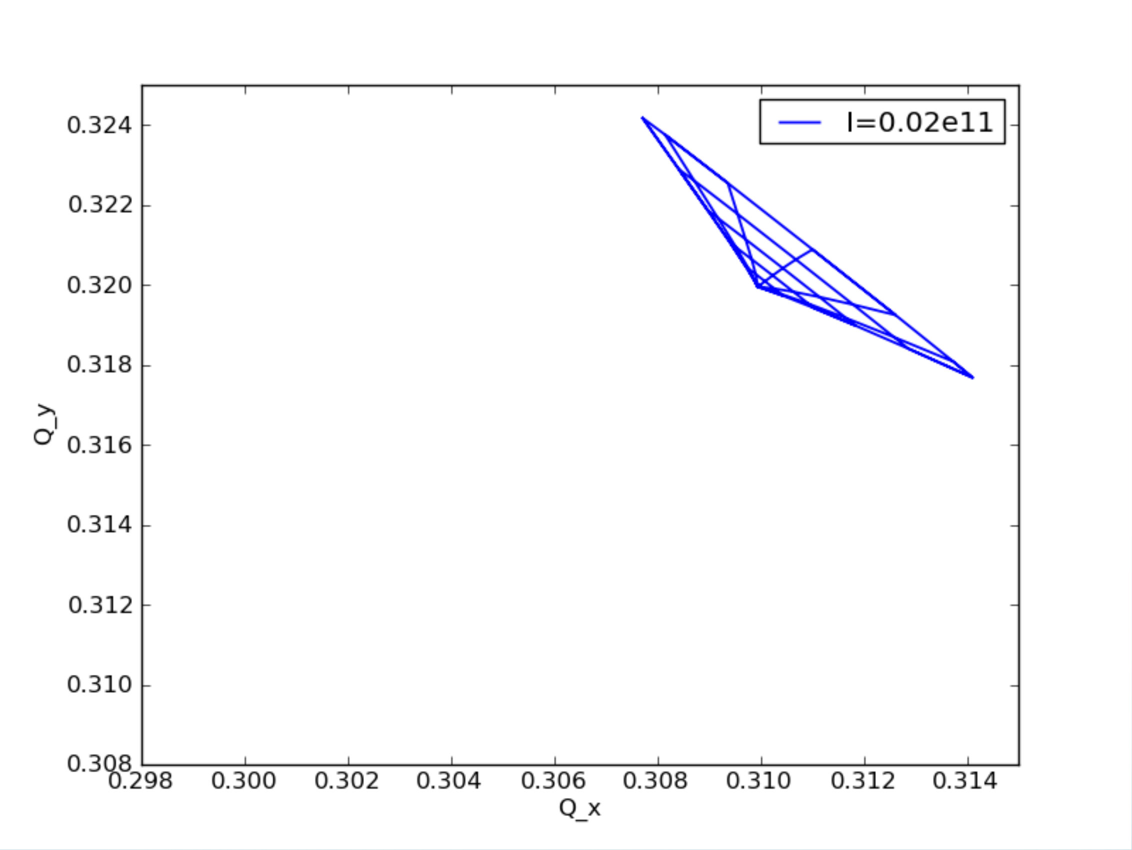
Crab crossing head-on: footprint evolution in function of beam intensity

- Positive LOF



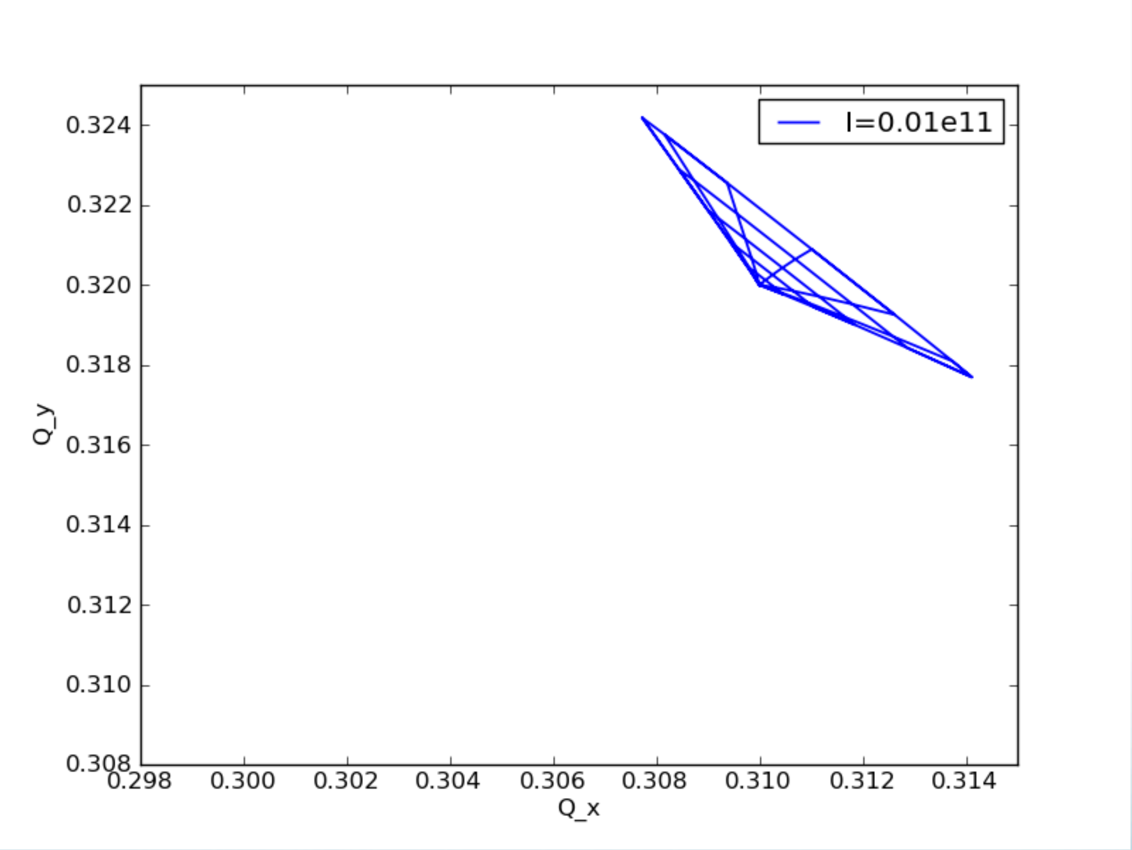
Crab crossing head-on: footprint evolution in function of beam intensity

- Positive LOF



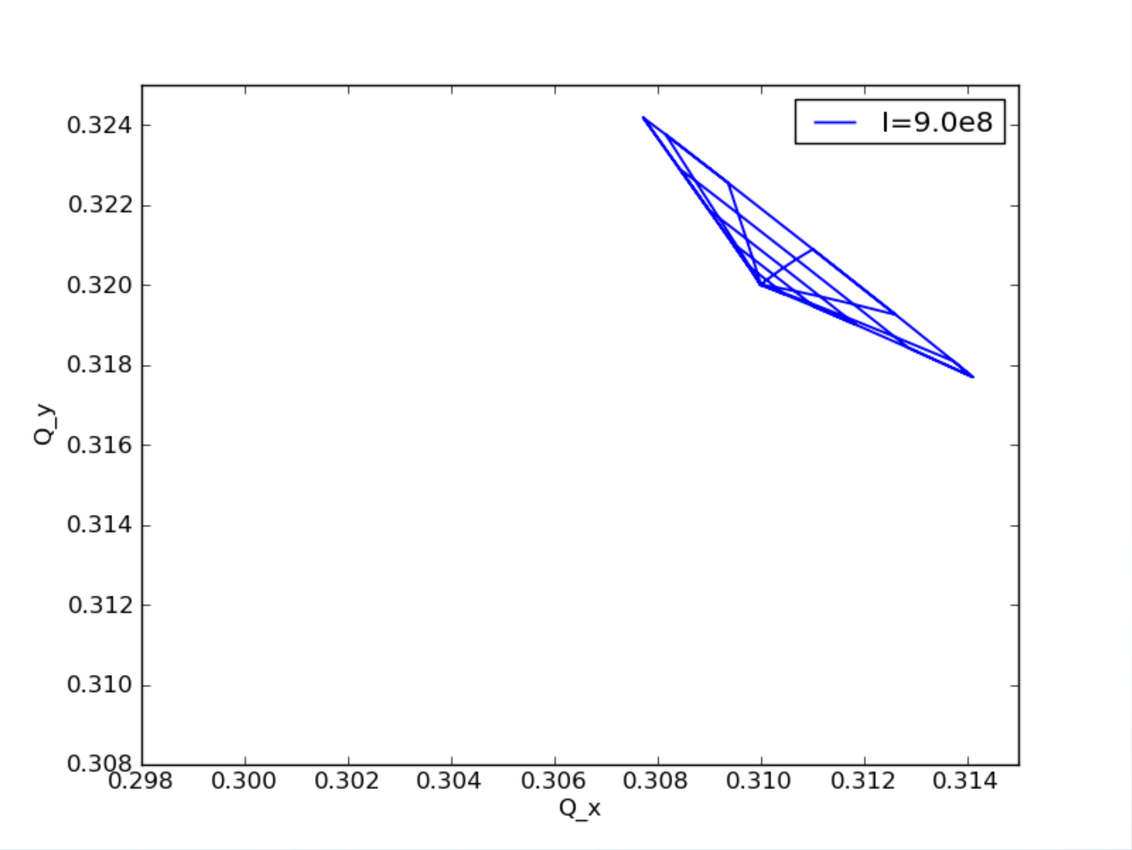
Crab crossing head-on: footprint evolution in function of beam intensity

- Positive LOF



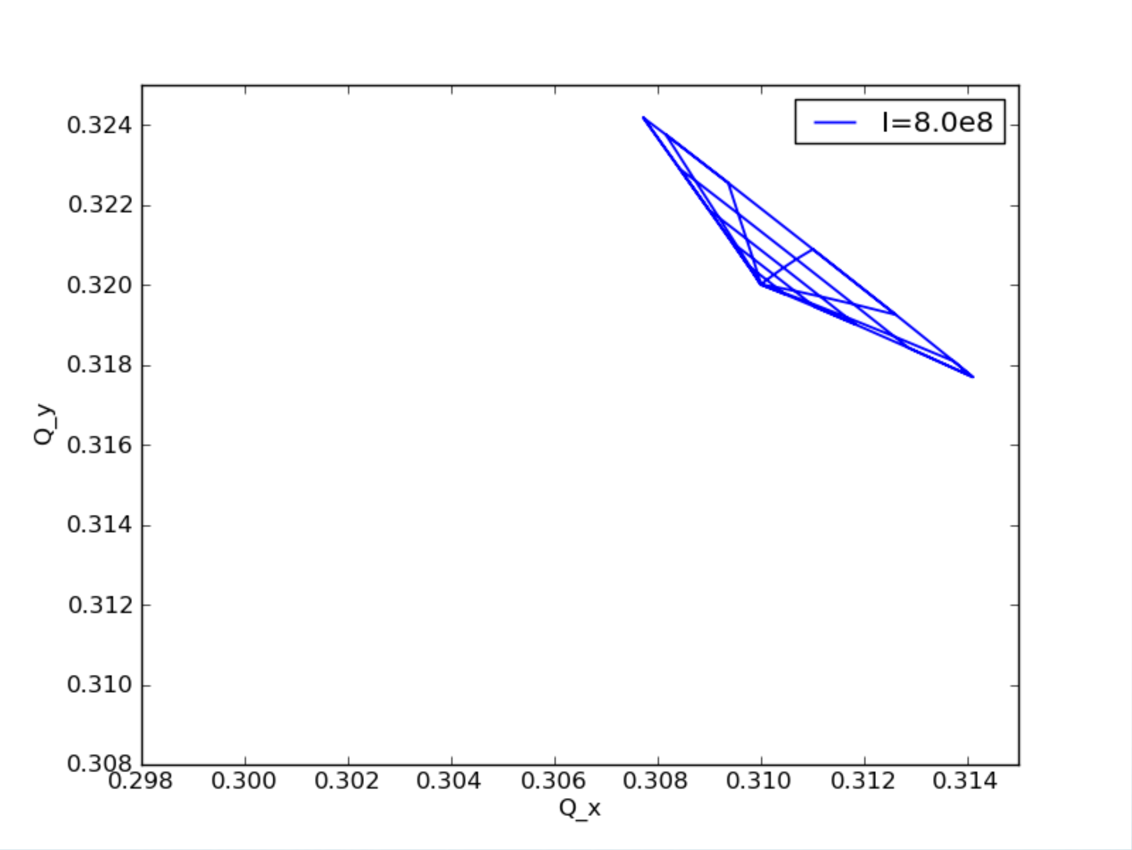
Crab crossing head-on: footprint evolution in function of beam intensity

- Positive LOF



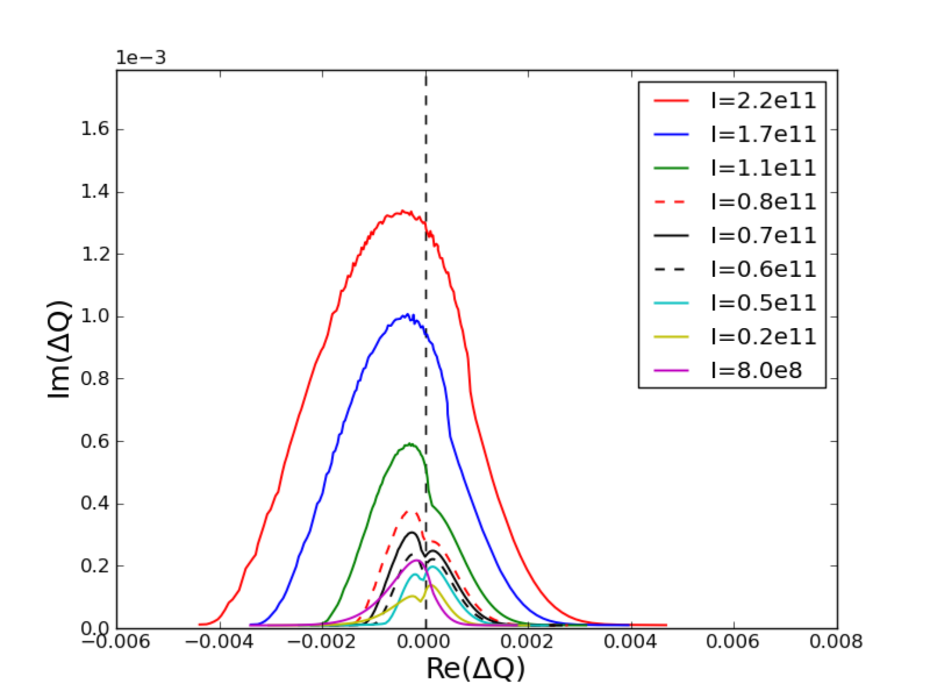
Crab crossing head-on: footprint evolution in function of beam intensity

- Positive LOF



Crab crossing head-on: stability diagrams in function of the beam intensity

Negative LOF



Positive LOF