Simulating the wire compensation of LHC long-range beam-beam effects

T. Rijoff, F. Zimmermann, R. Steinhagen

Acknowledgements:

- S. Fartoukh
- G. Sterbini
- R. De Maria
- U. Dorda
- C. Zannini
- G. Iadarola
- E. Benedetto

Outline

Wire comp.
Stability
Tune

Longtudinal B
Longtudinal P
Transv & Curr

Best res.
First prop.
Cross. Angle
Wire Shape

Conclusions

Next Steps
Adds
Formulas
Optics par

Main Concepts
- The wire compensator
- Stability Analysis
- Tune Analysis

Studied Cases
- Longitudinal best solution
- Longitudinal prototype solution
- Transversal position and current

Results
- Best results
- First proposal
- Crossing angle Analysis
- Wire Shape

Conclusions

Appendix
- Next steps
- Additional results
- Formulas
- Analyzed cases, parameters summary

Main Concepts

LHC

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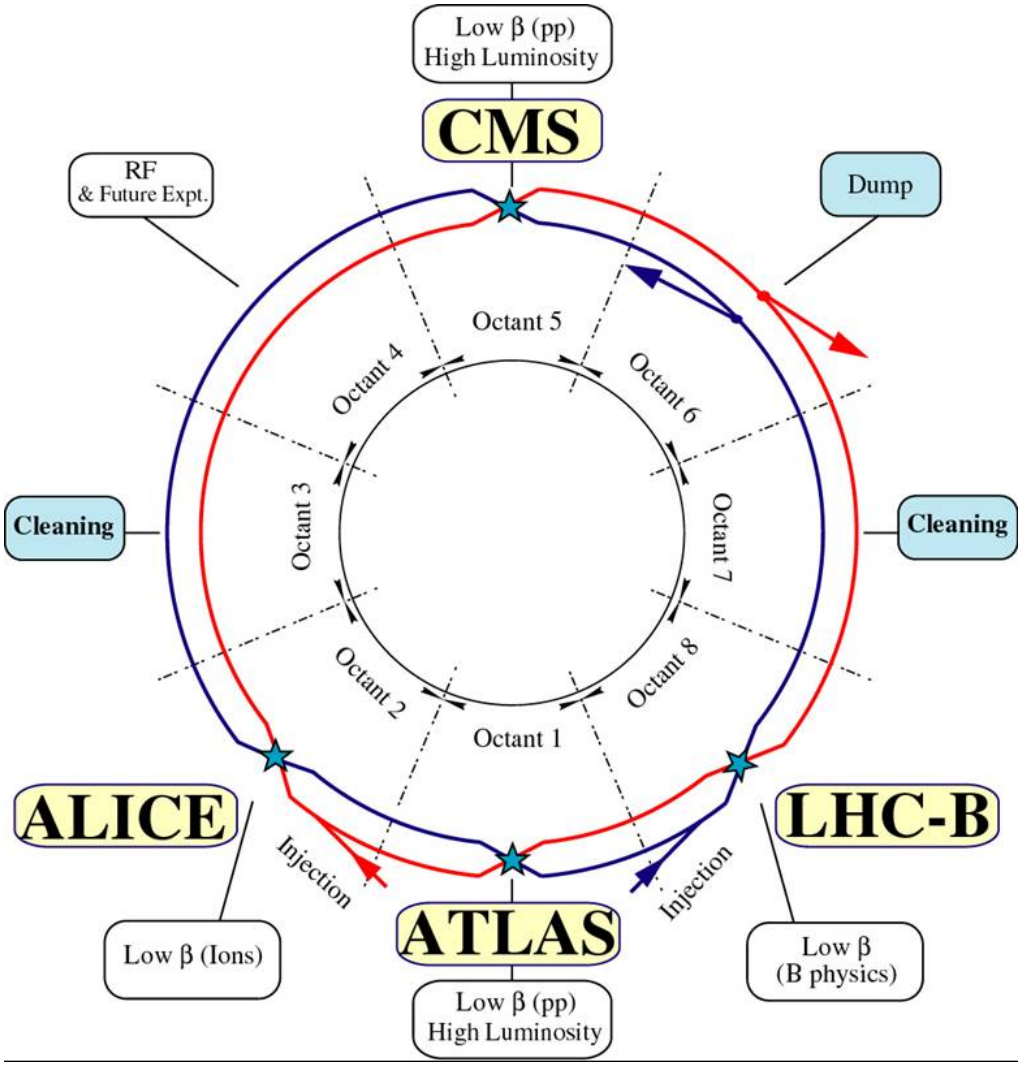

Ring of 27 Km
4 Interaction points (IP)

Wire compensation at the 2 main **Interaction Points**:
IP1 ATLAS
IP5 CMS

Nominal Luminosity :
10^{34} cm^{-2} s^{-1}

Nominal Energy :
7 TeV

The Wire Compensator

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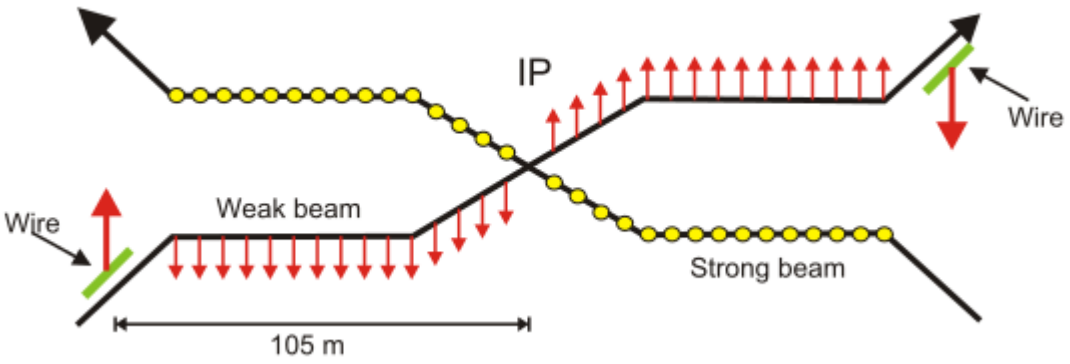
Compensate long range beam beam with a wire

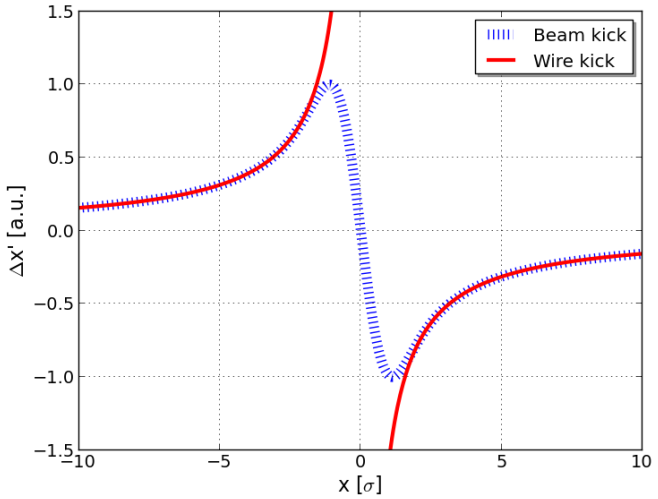


Motivation:

Head On: at IP beams collision
Long Range: electromagnetic beam beam interaction out the IP

In our analysis

HOLR -> Head On at IP1 and IP5
16 Long Range before IP
16 Long Range after IP



Simulation tools

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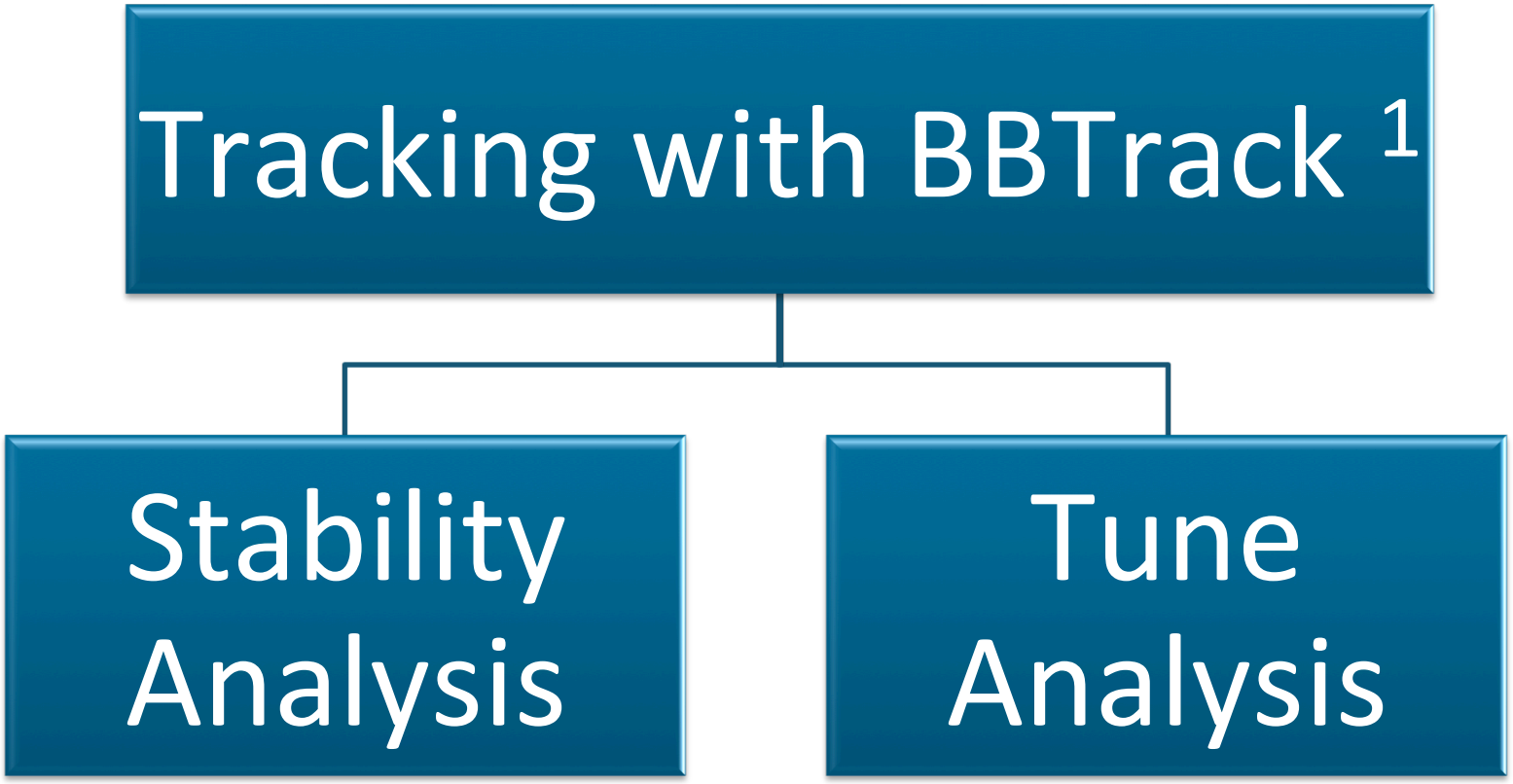

1) Fortran 90 code developed by U. Dorda

Stability Analysis

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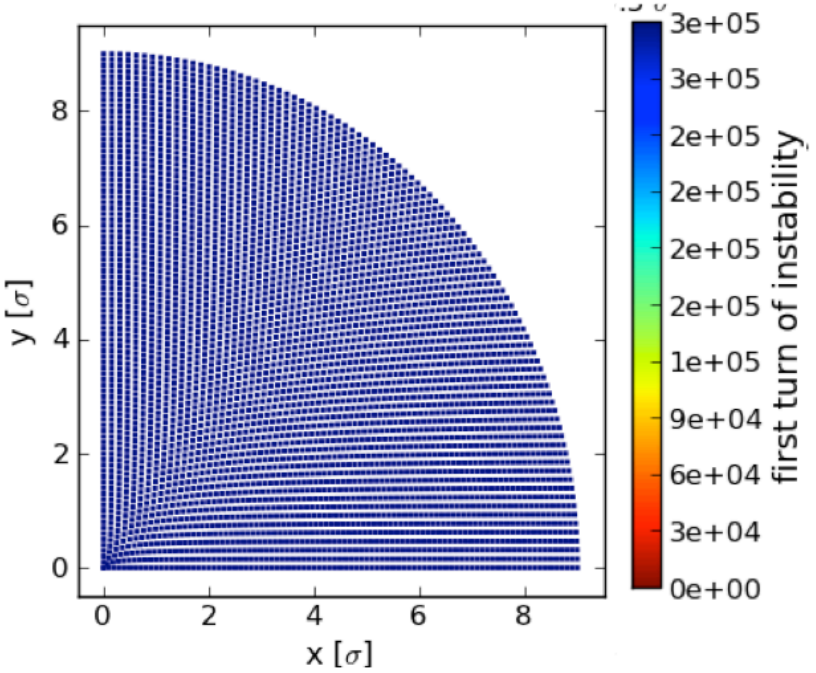

- More than 4000 particles with max radius [0,9] σ
- Tracked for at least 300.000 turns
- Particles set unstable when λ[j] > 2.8
- Color emphasizes the turn where particle become instable

λ[j] = Lyapunov coefficient at turn j

Stability Analysis: Lyapunov

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Lyapunov coefficient: rates of divergence of nearby trajectories in phase space

definition

$$\lambda = \lim_{N\to\infty} \lim_{d(0)\to 0} \frac{1}{N} \log \frac{d(N)}{d(0)}$$

d(N) = distance between trajectories at turn N

Used in the code

$$\lambda[j] = \frac{\left\langle d_r[\frac{j}{2} : j]\right\rangle - \left\langle d_r[0 : \frac{j}{2}]\right\rangle}{\left\langle d_r[\frac{j}{4} : \frac{3j}{4}]\right\rangle} \geq 2.8$$

d_r = normalized distance in 4 dim

Lyapunov Criterion: Check

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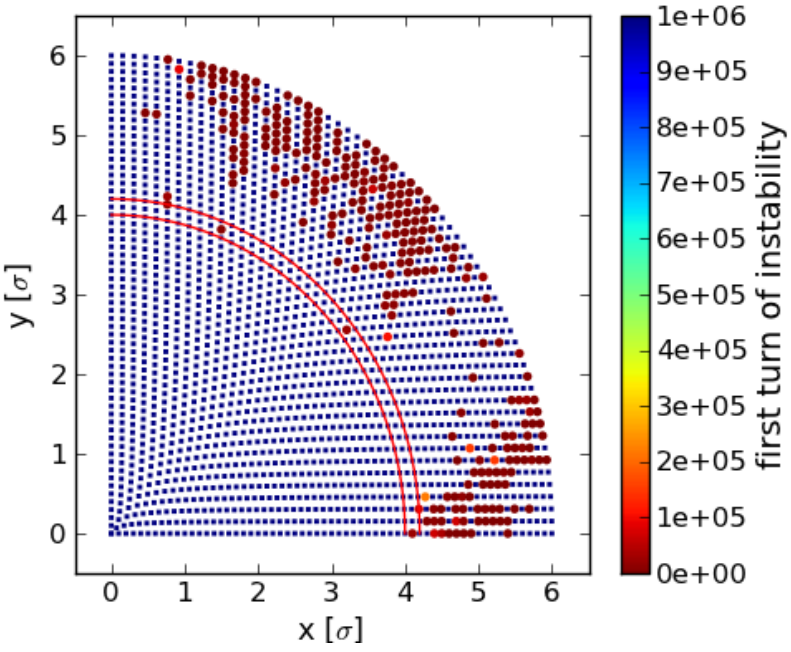
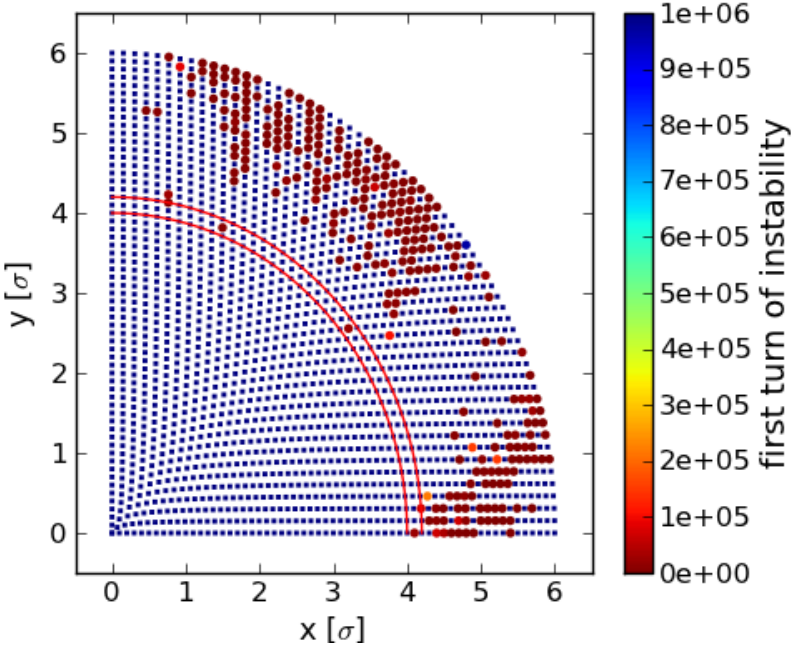
Criterion stable increasing the number of turns!

600.000 turns



1.000.000 turns



Head On + Long Range – crossing angle 6.3 σ

Lyapunov Criterion: Check

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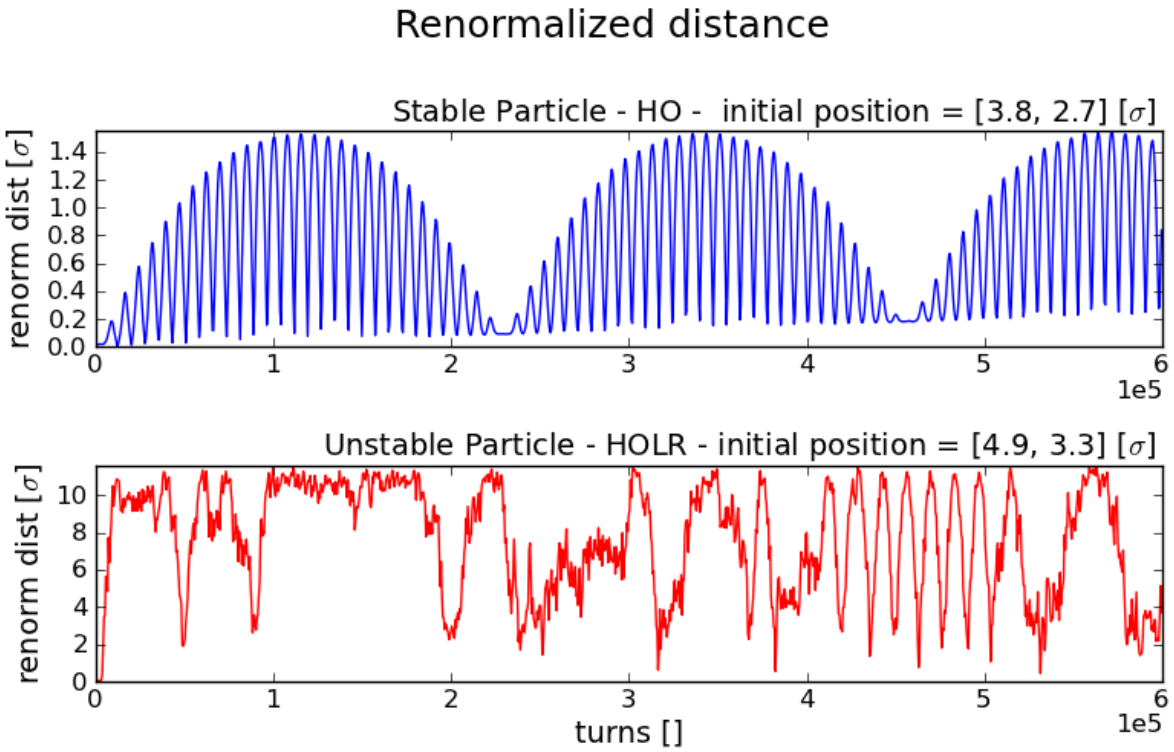
Criterion confirmed by direct observation for some cases



Tune Analysis

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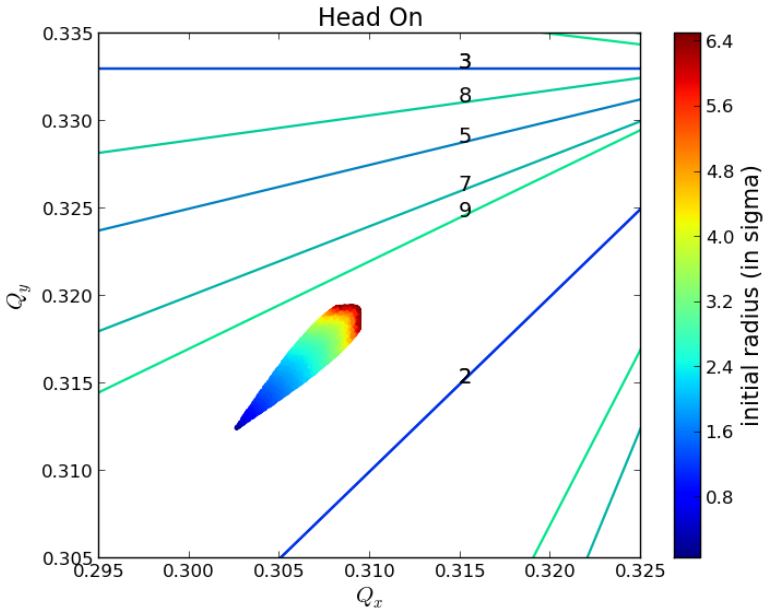

- Tracked between 1.000 and 10.000 particles (depend on the test performed)
- Calculated the tune
- Verified if the fractional part of the tune touches resonance lines

Studied Cases

Requirements

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Requirements for a good compensation

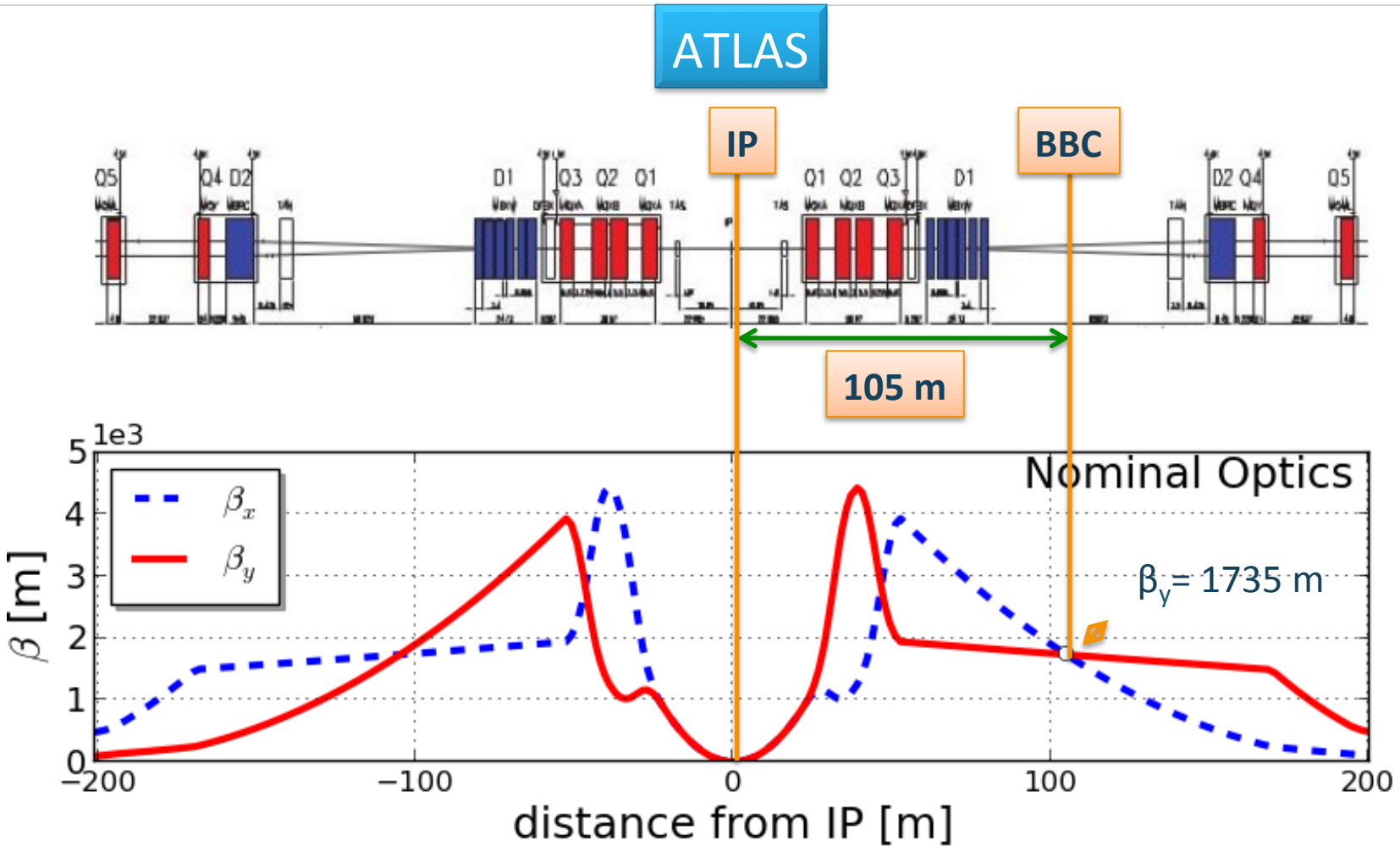
$\beta_x = \beta_y$ at each IP or $\beta_y(IP1) = \beta_x(IP5)$ $\beta_x(IP1) = \beta_y(IP5)$

$\beta_{x,y}$ (1) Big enough

$\Delta\mu_{x,y}$ (2) Small enough

1. $\beta_{x,y}$ = Betatron function
2. $\Delta\mu_{x,y}$ = phase advance between the average LRBB and the wire position

Best Solution: BBC



1. J.P. Koutchouk's note: CERN-SL-2001-048-BI

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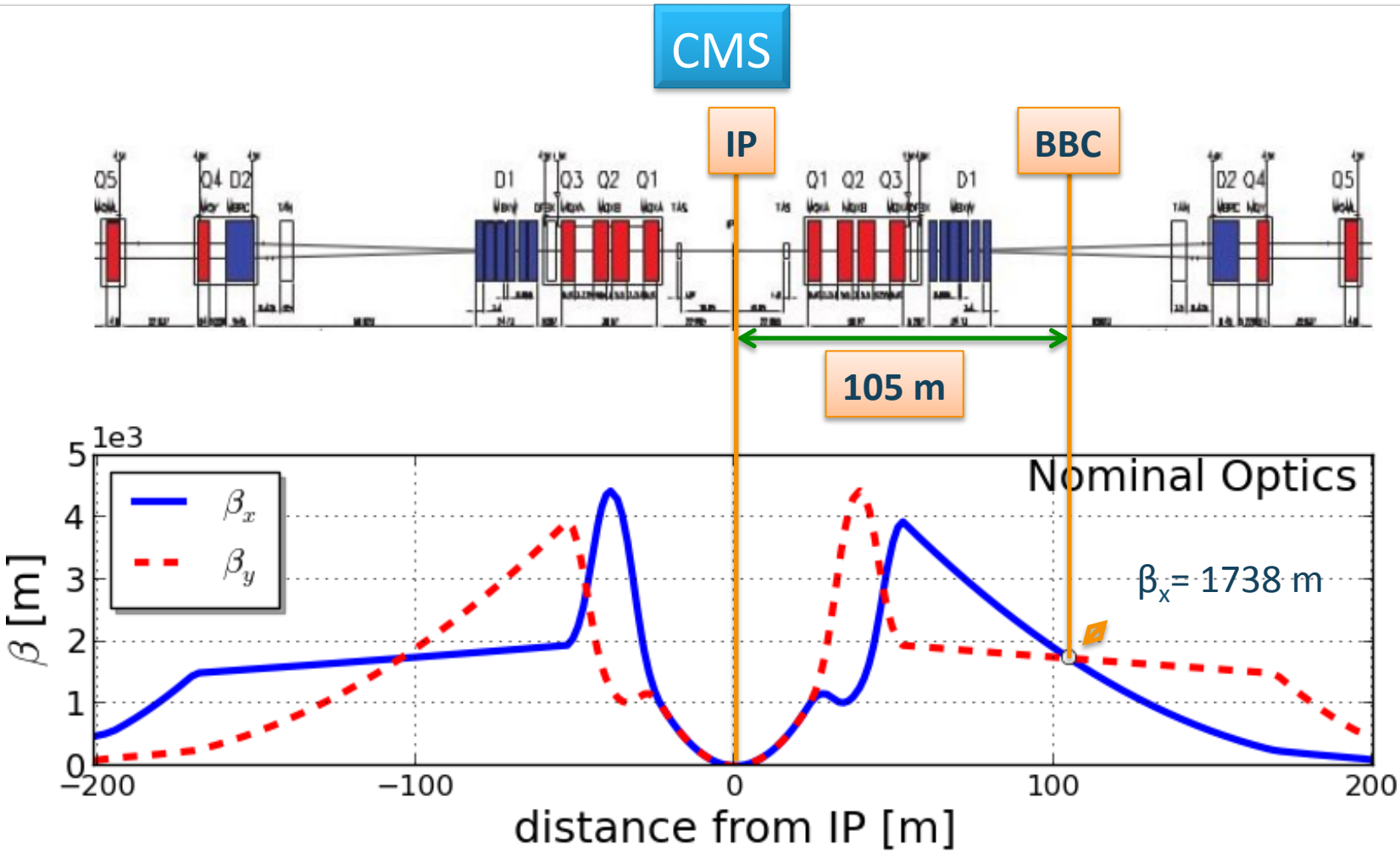

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Prototype solutions

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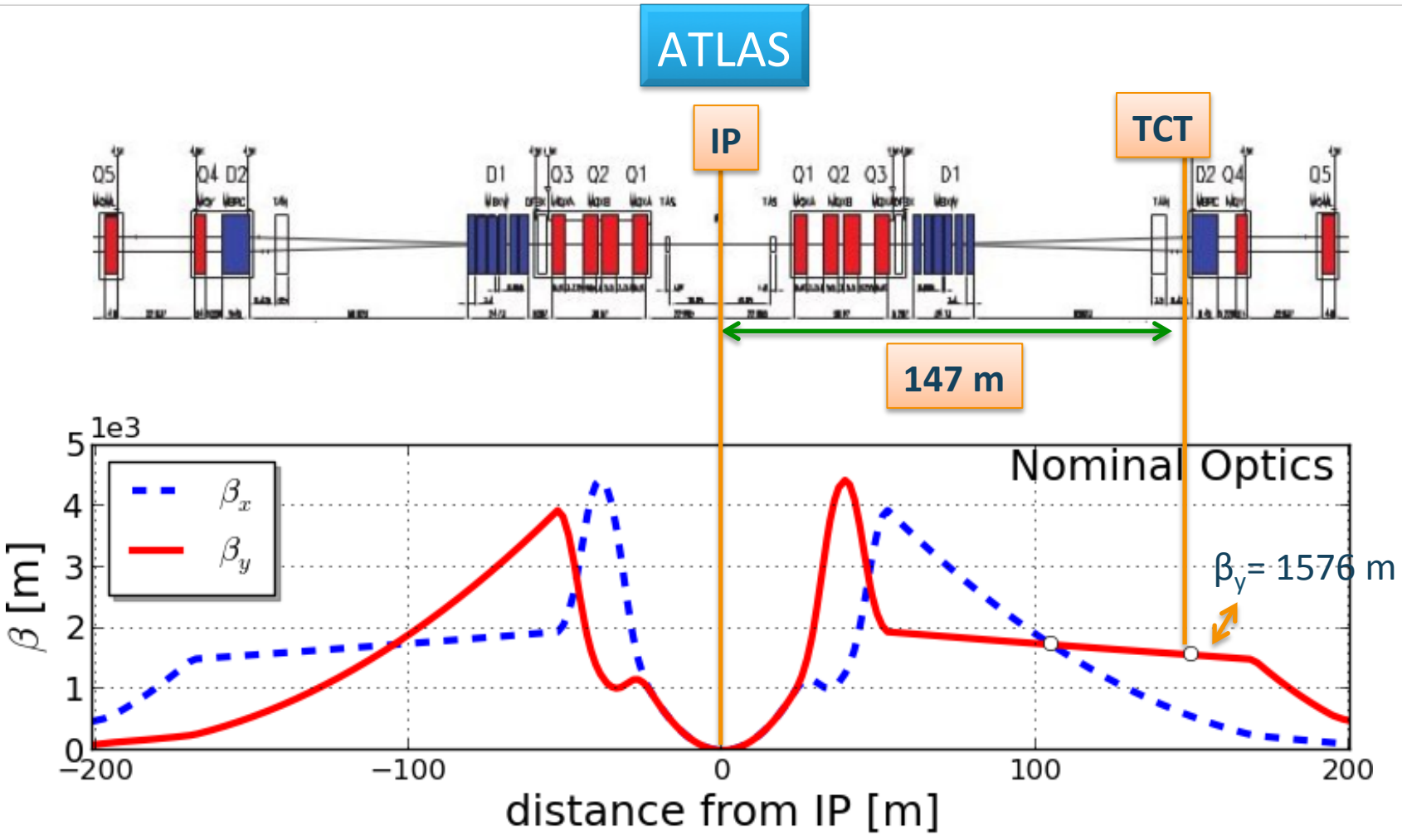
BBC location not available for LS1

Different solutions analized, best for:
Wire in the shadow of TCT

- Using nominal optics (with β= 0.55m at IP):
  - 147 m after IP1
  - 147 m before IP5
- Using a modified optics [1] (with β= 0.60m at IP):
  - 147 m before IP1 and IP5

1) Courtesy of S. Fartoukh

Prototype: TCT Nominal Optics



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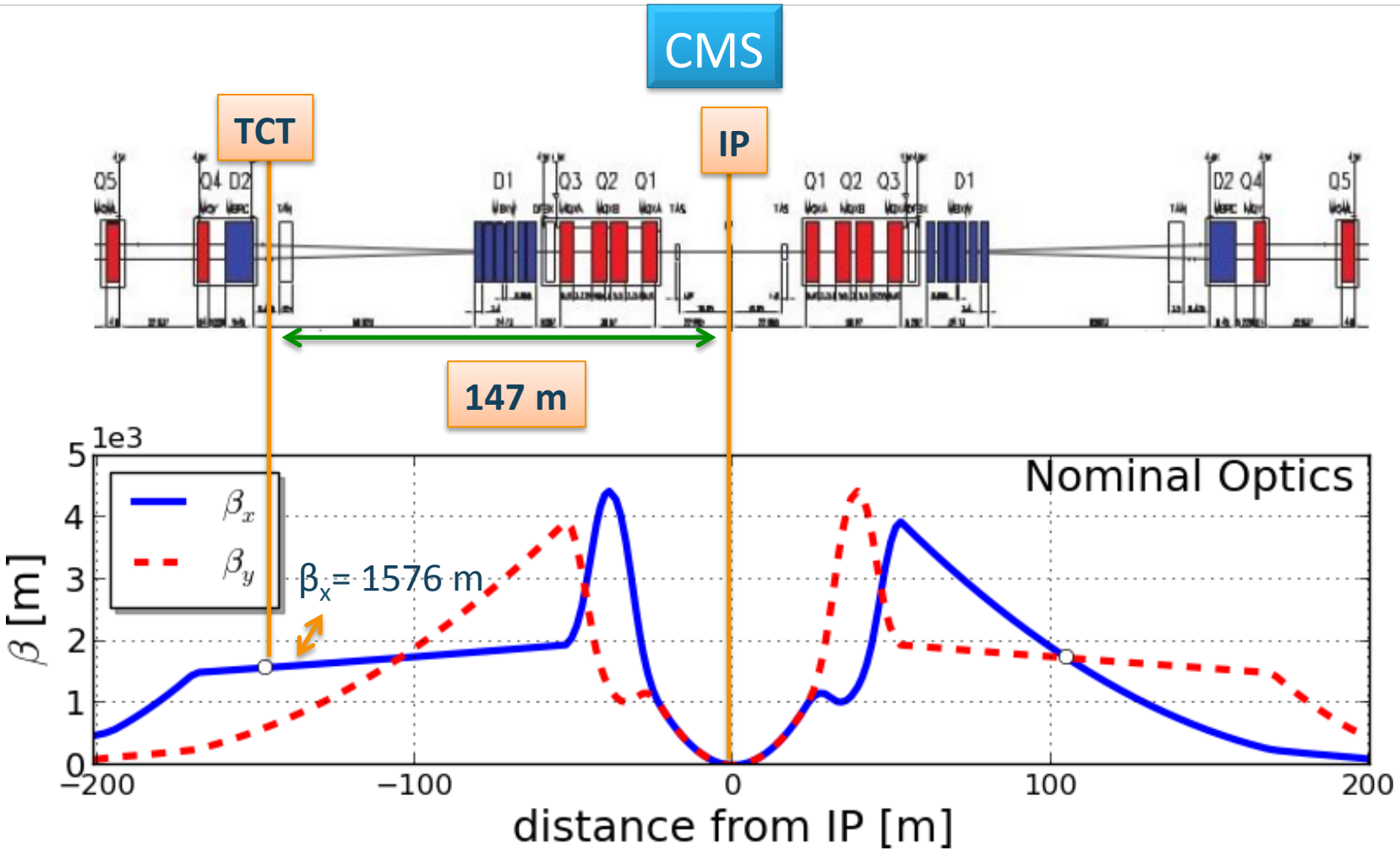
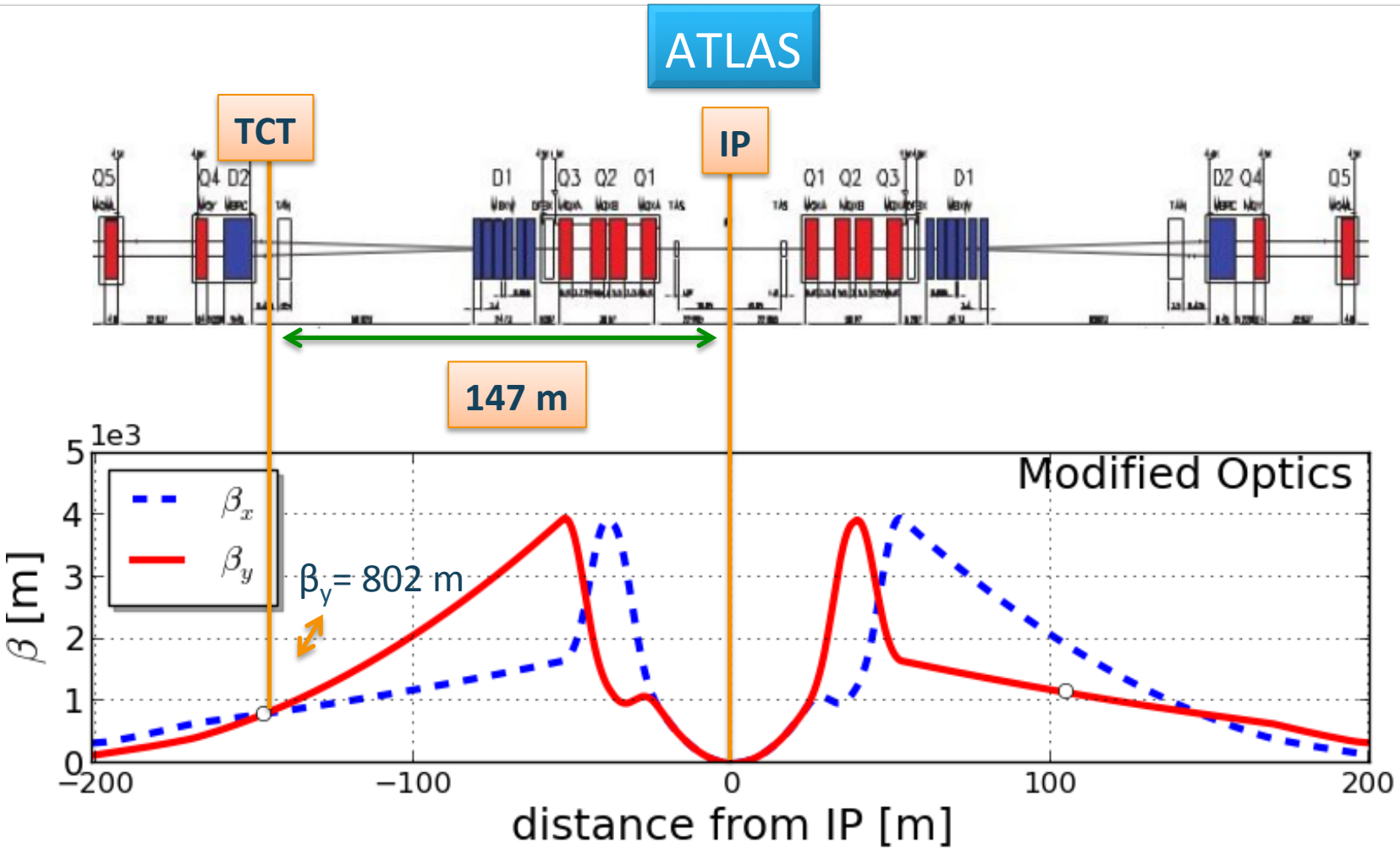


Prototype: TCT Modified Optics



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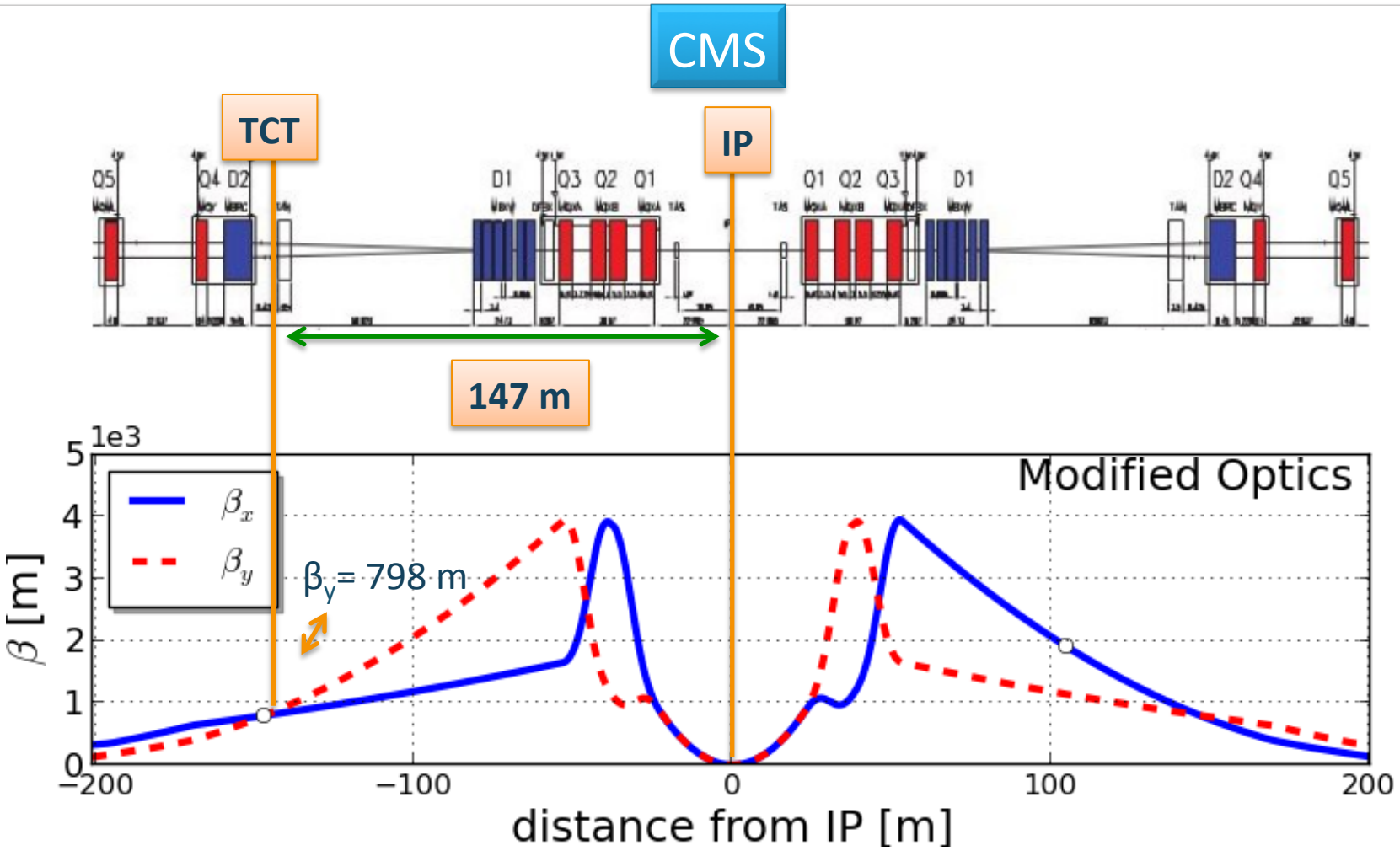

Analyzed Cases Summary

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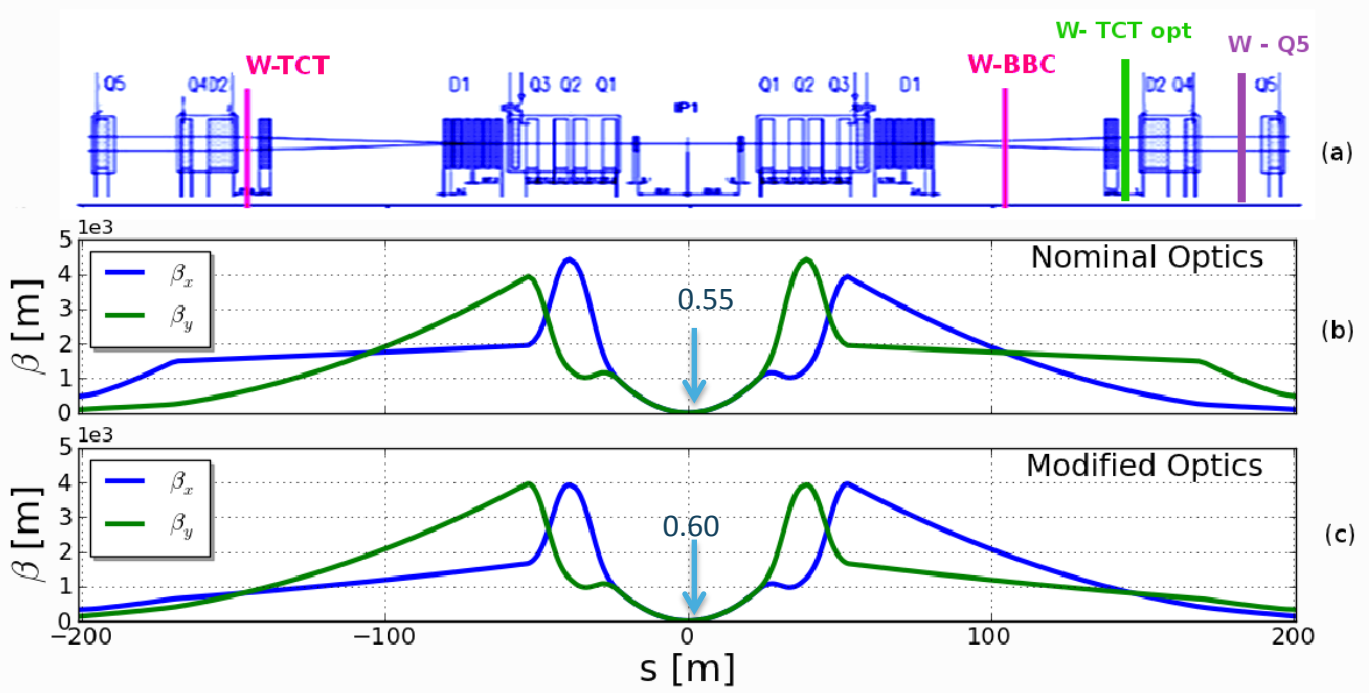

Wire position	BBC	TCT	TCT opt
from IP1 [m]	105	-147	150
from IP5 [m]	105	-147	-147

Q5
199
199

In all the cases Δμ is not a problem (see appendix)

Wire Position and Current

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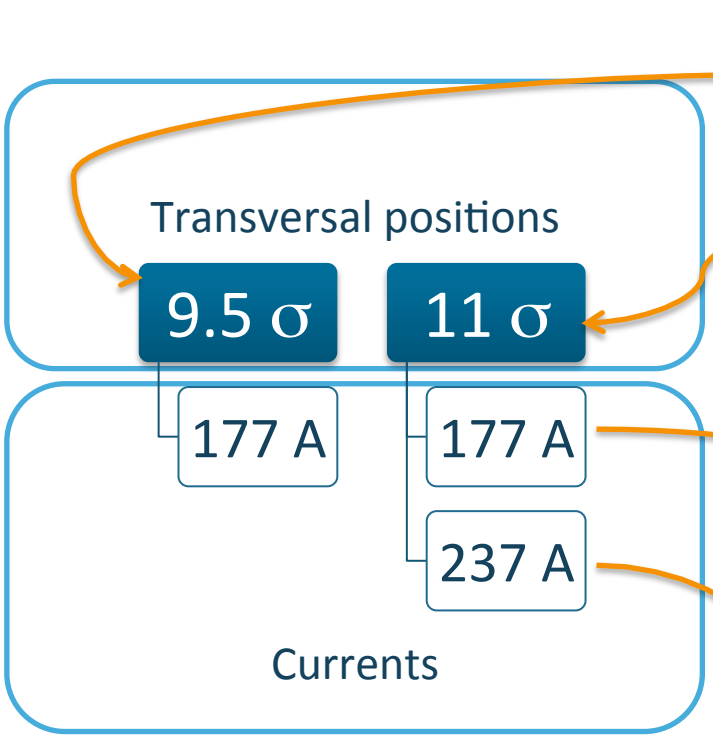

Average long range beam-beam distance

Prototype proposal

$$I_{opt} = \frac{n_{LR} c e N_b}{L_w}$$

$$I_{d_2} = I_{d_1} \left(\frac{d_2}{d_1} \right)^2$$

σ ≈ 9 10^{-4} m at wire position

Transversal position analysis

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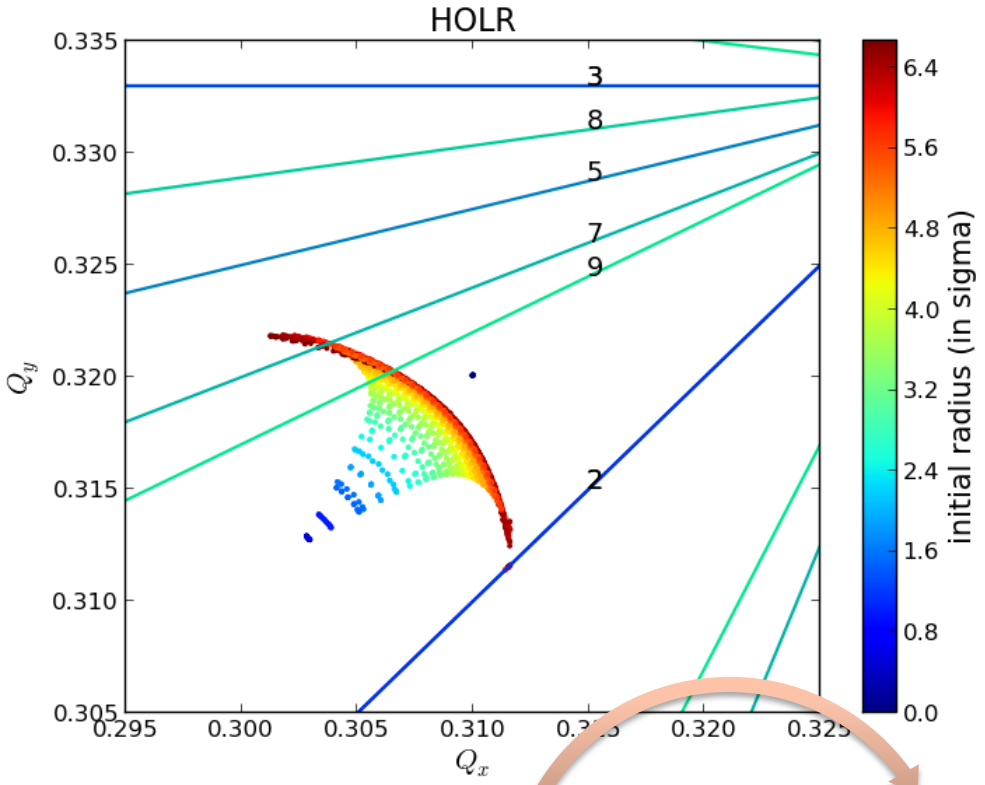

- Small compensation

θ > 11 σ

- Best compensation

θ = 9.5 σ

- Dangerous effects

θ < 9 σ

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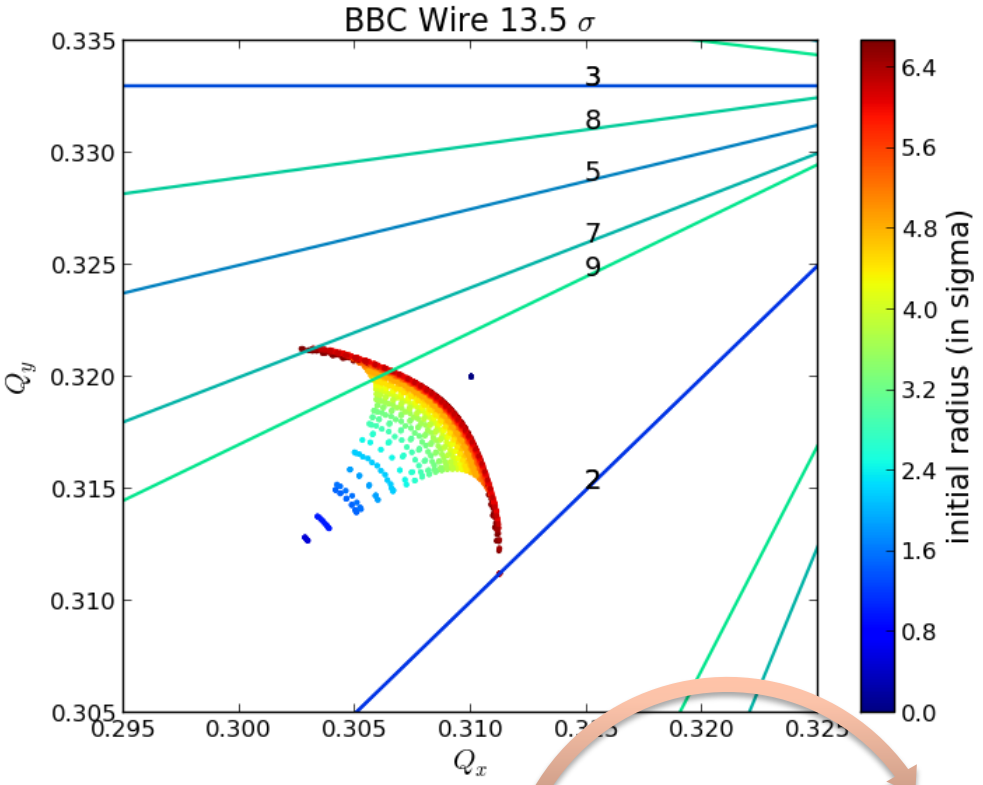

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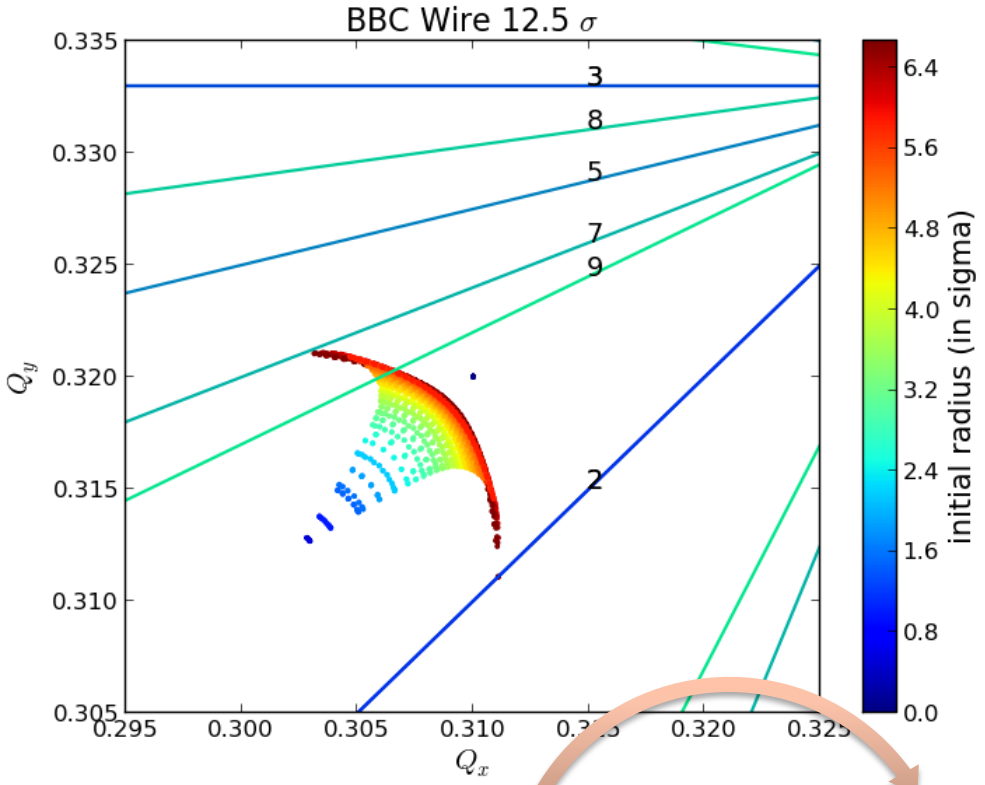

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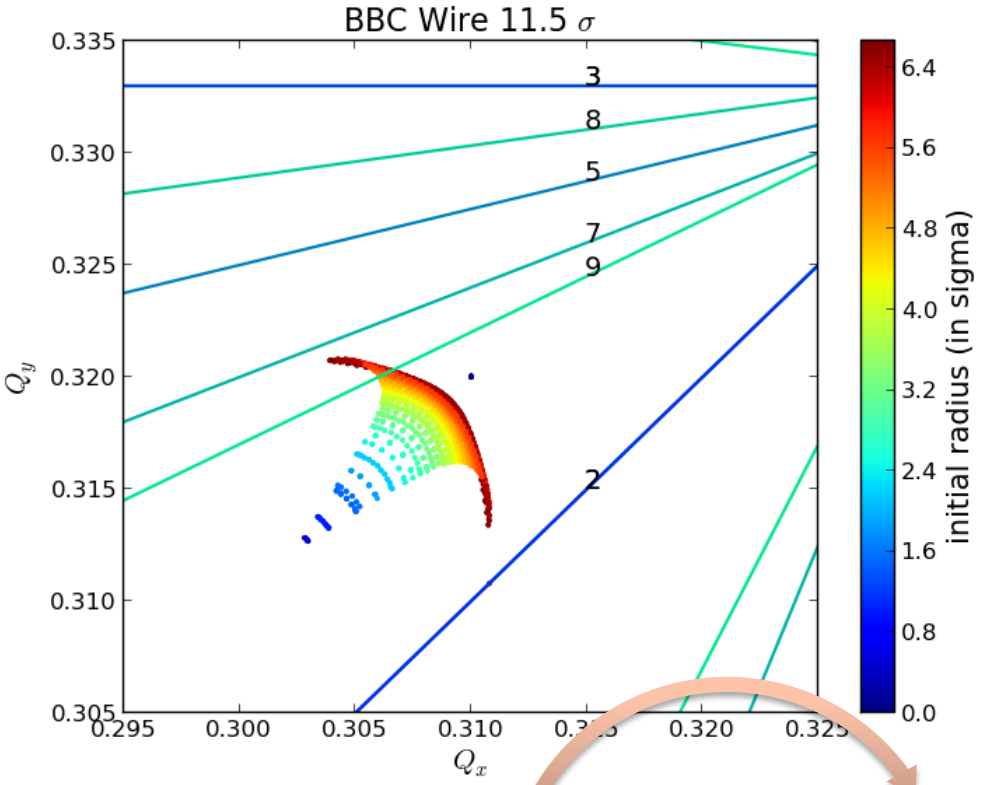

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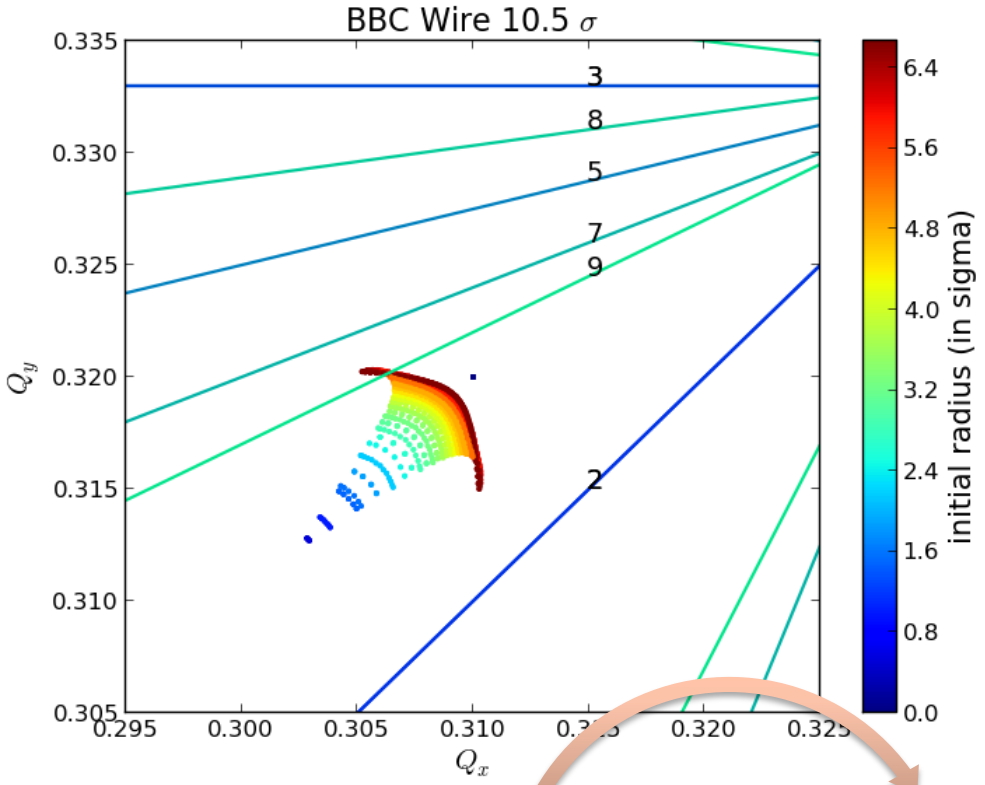

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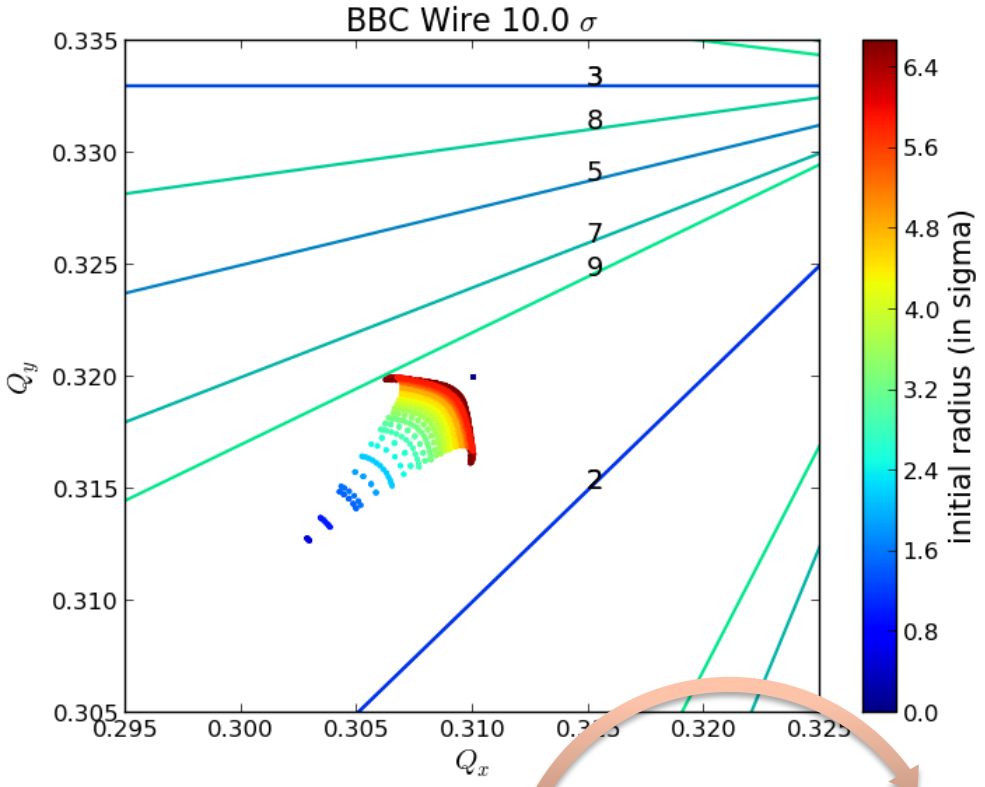

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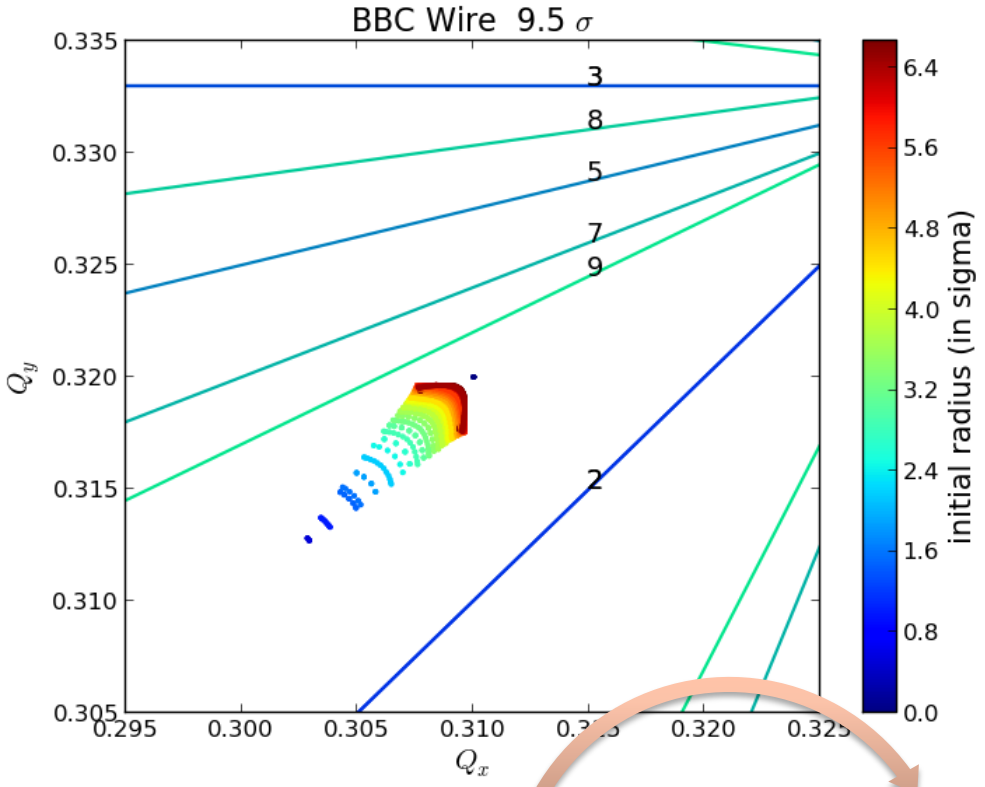

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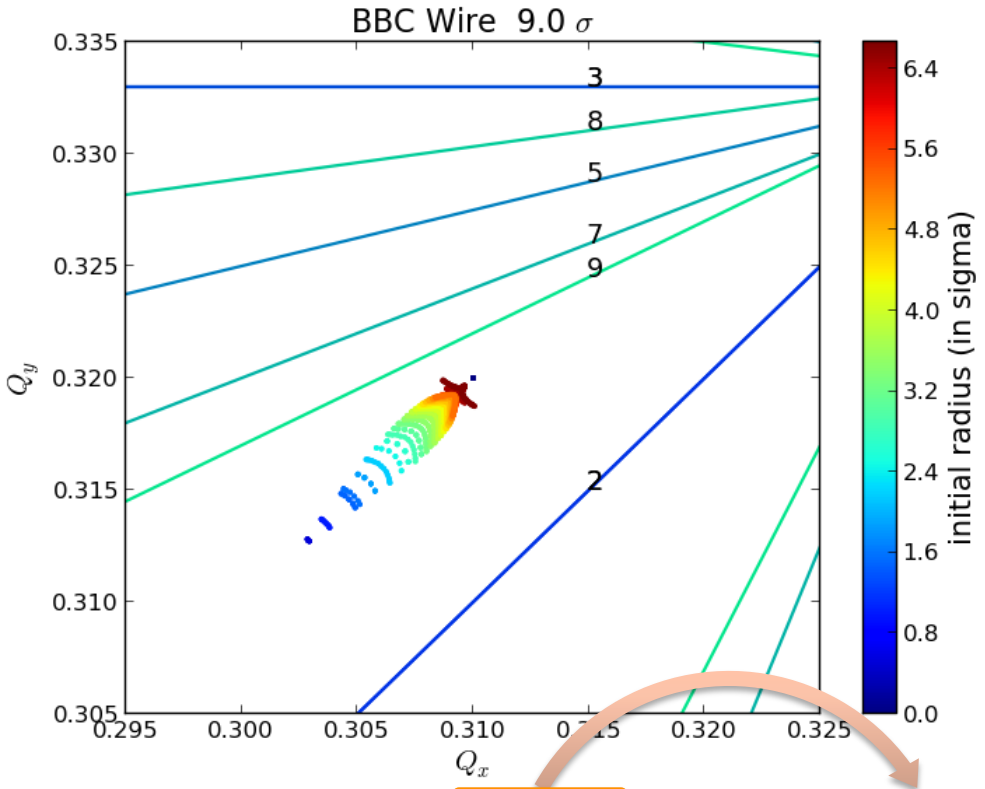

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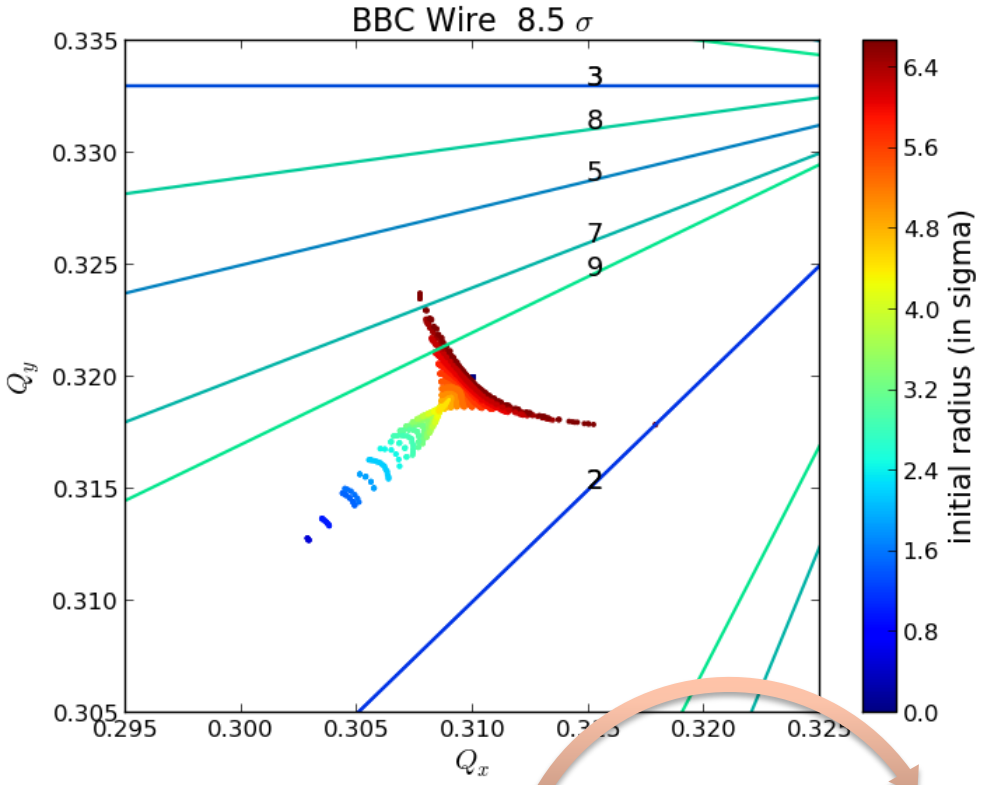

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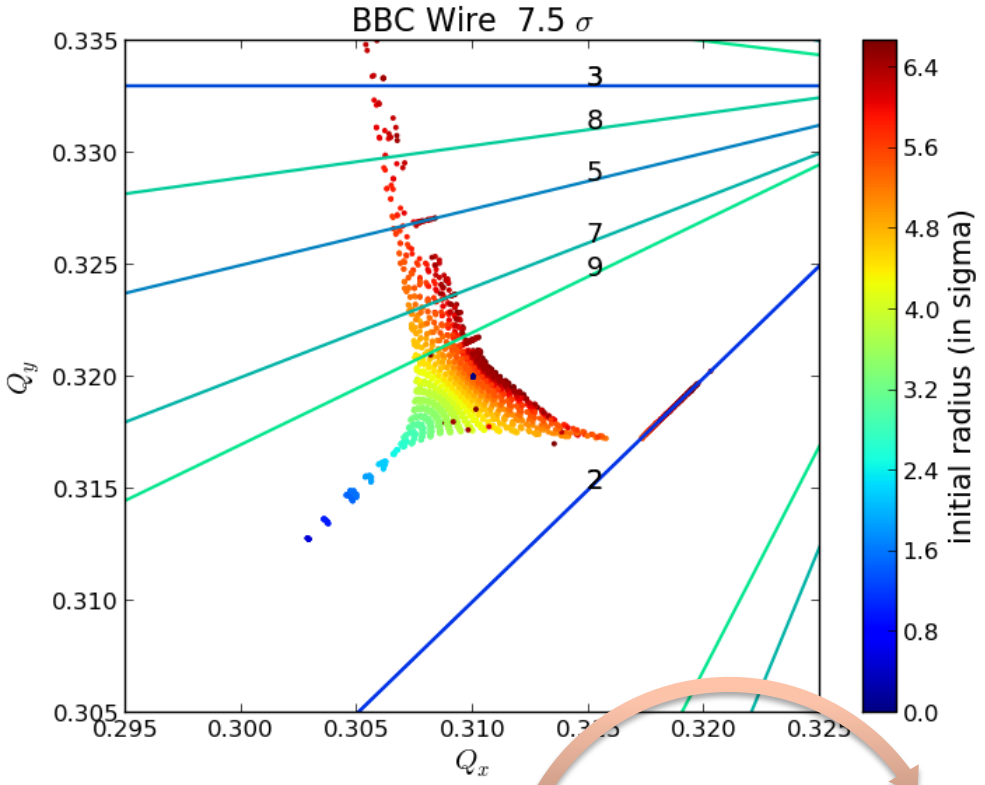

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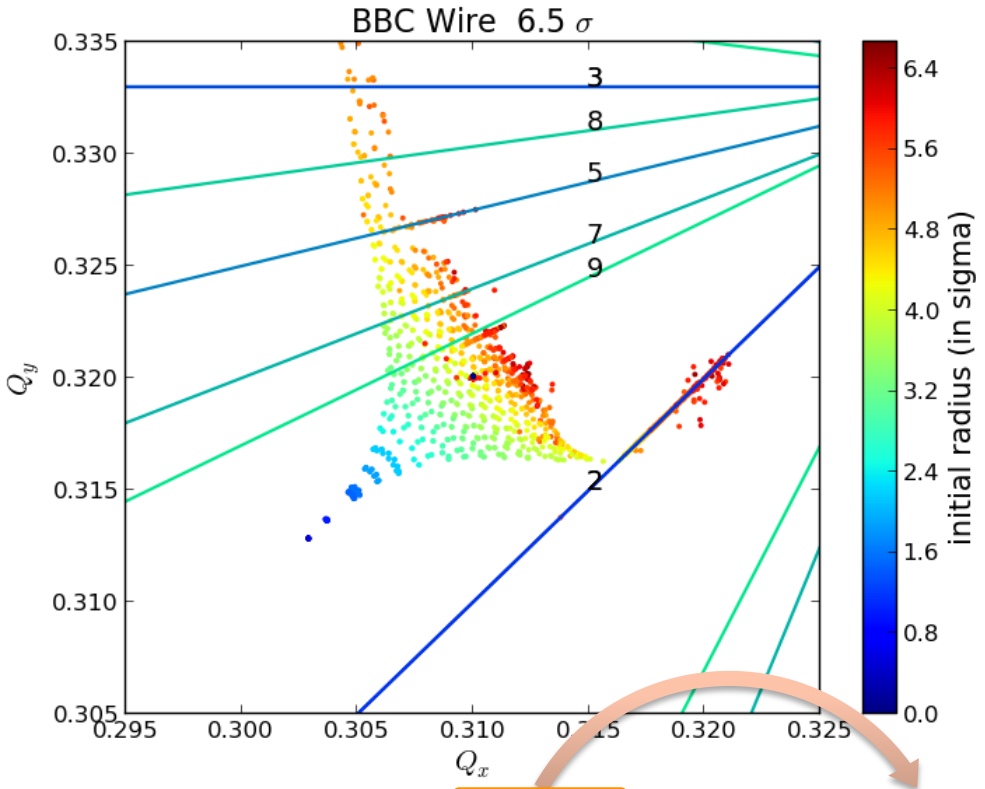

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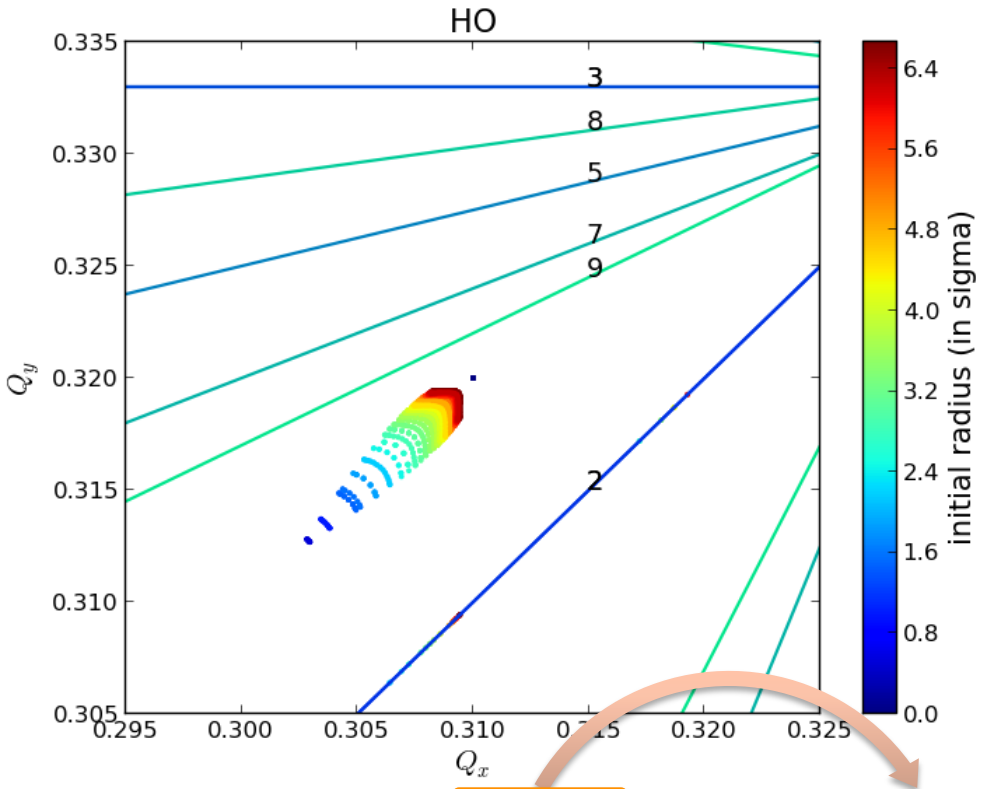

- No resonance touched

I > 130 A

I = 177 A

- Almost equal HO

- No significant improvement

I > 177 A

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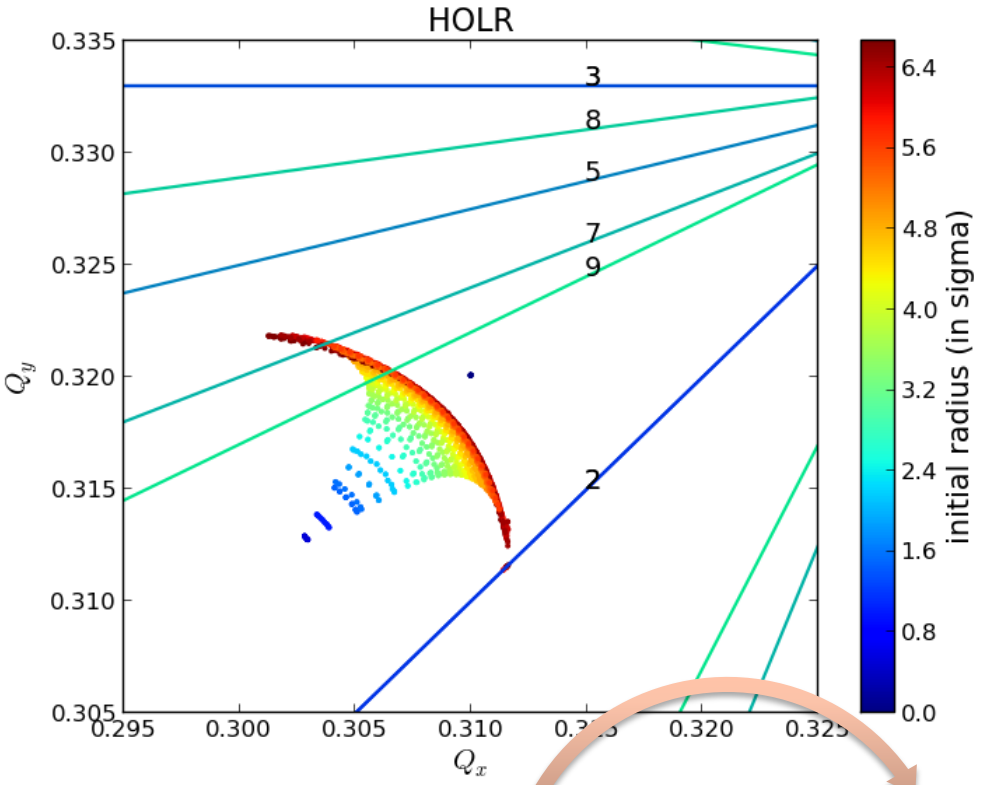

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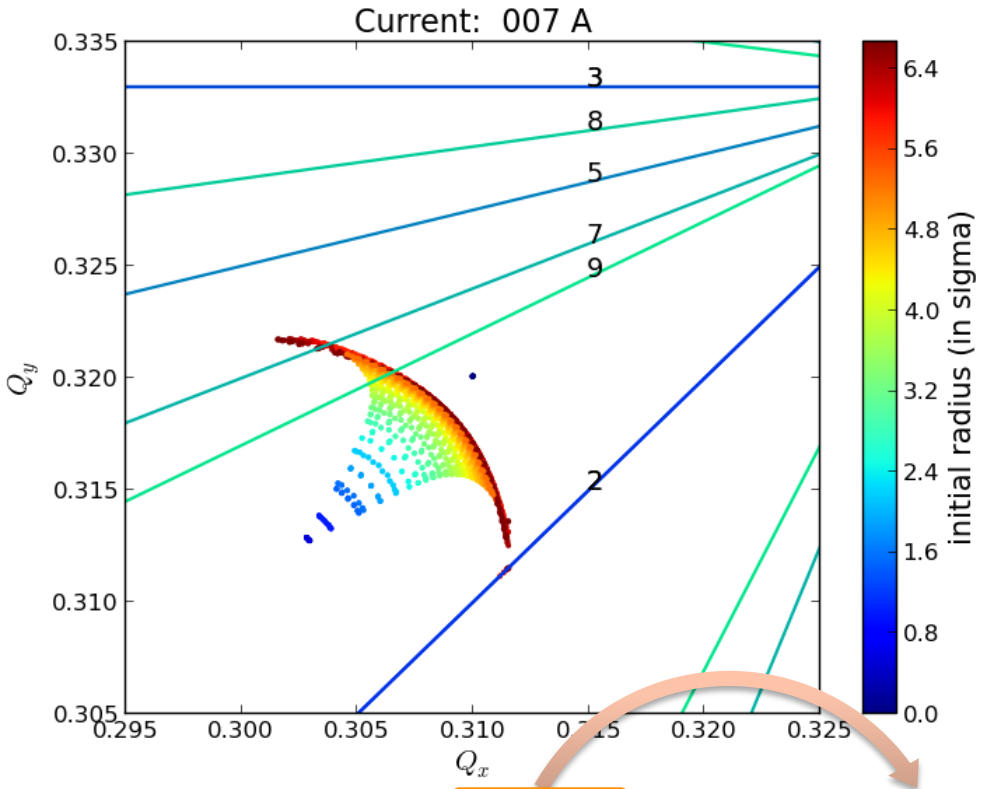

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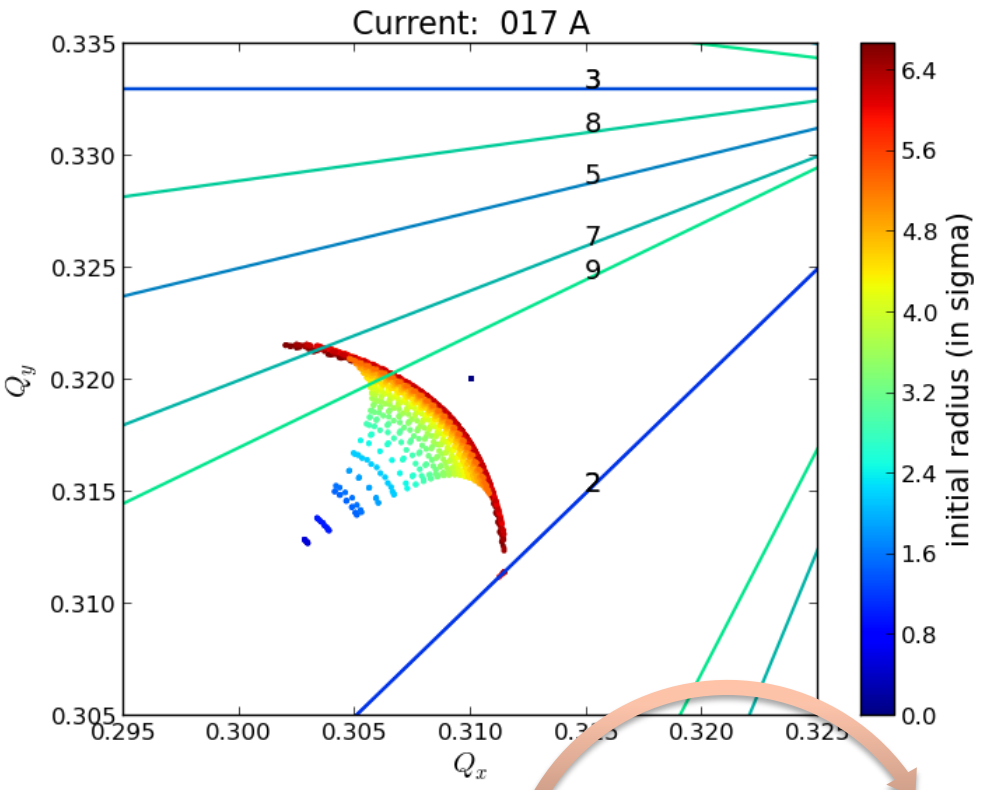
Best res.
First prop.
Cross. Angle
Wire Shape

Conclusions

Next Steps
Adds
Formulas
Optics par



- No resonance touched

I > 130 A

I = 177 A

- Almost equal HO

- No significant improvement

I > 177 A

Current analysis

Wire comp.
Stability
Tune

Longtudinal B
Longtudinal P
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Next Steps
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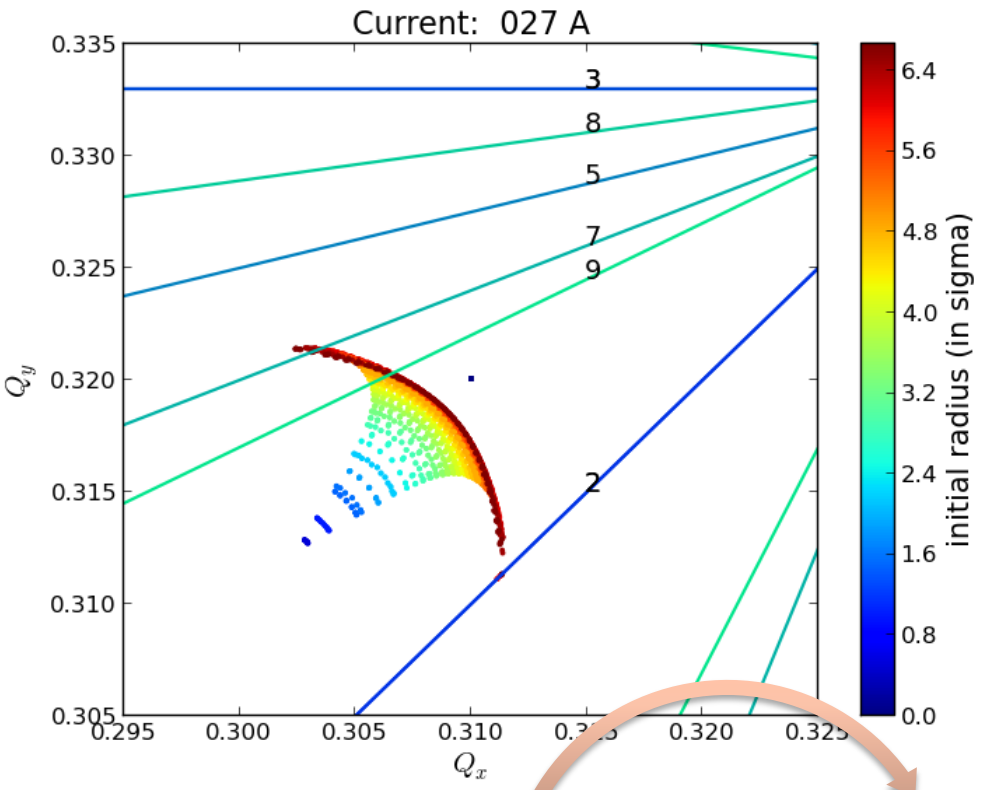

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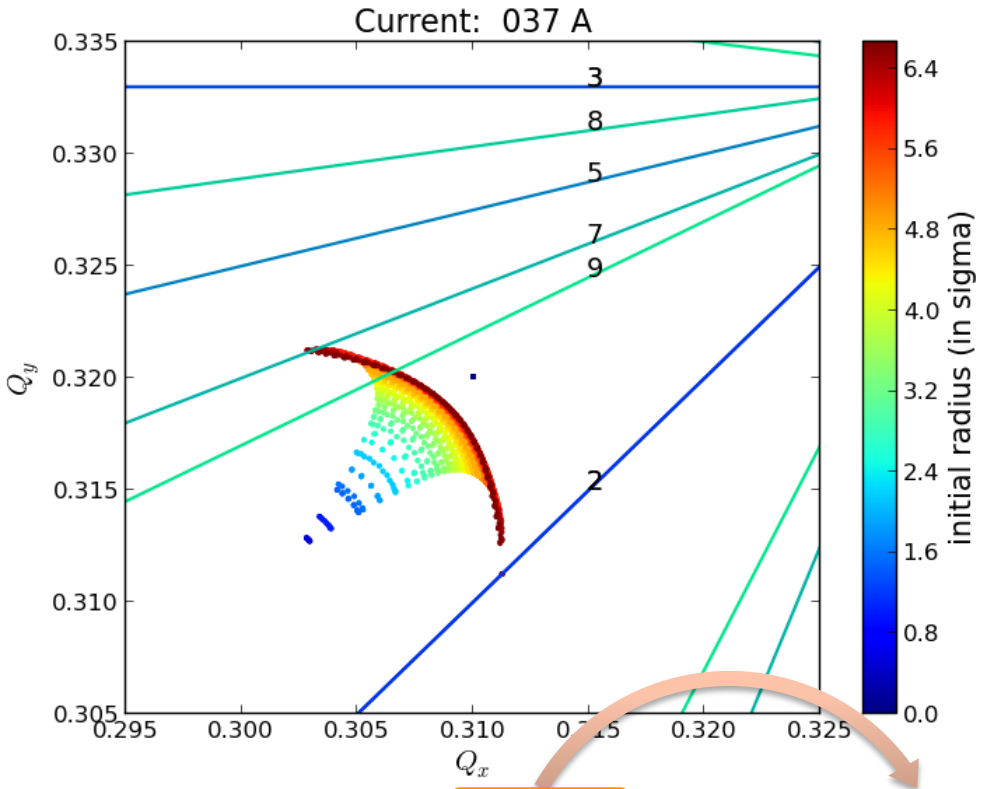
Optics par



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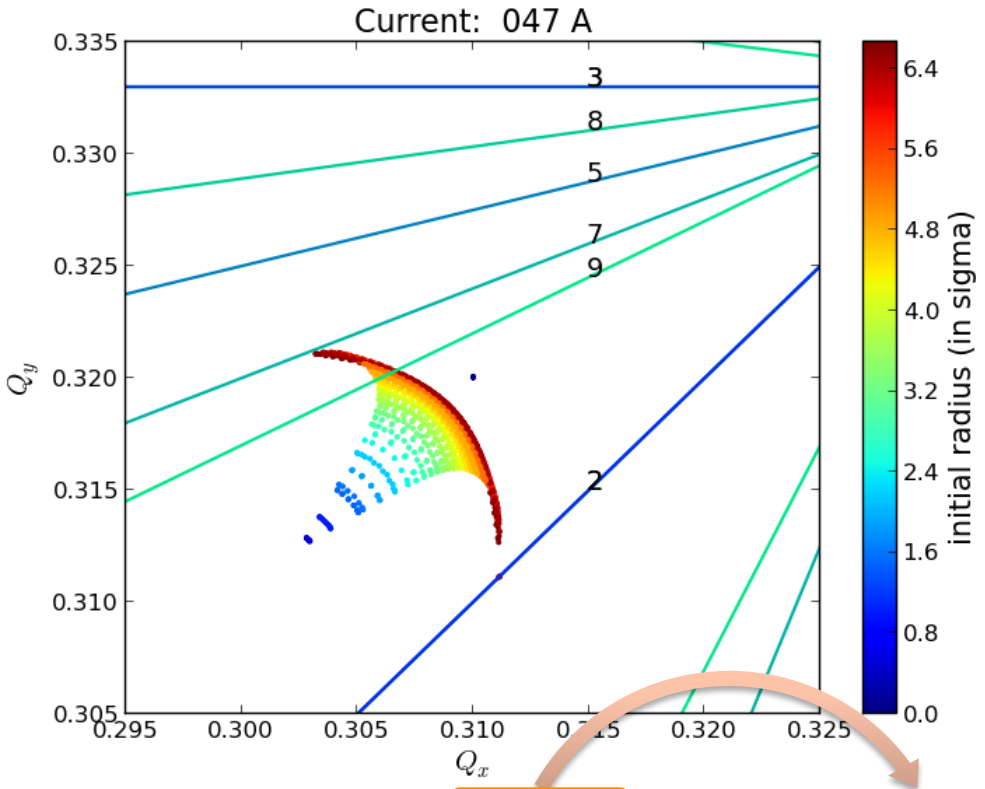

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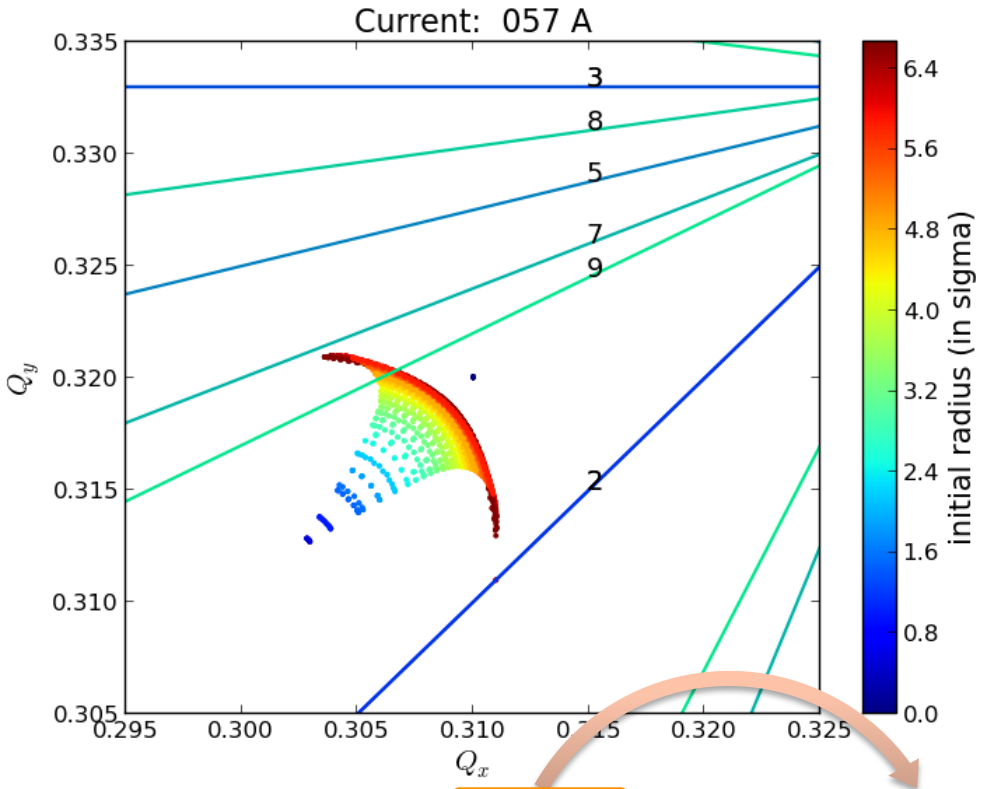

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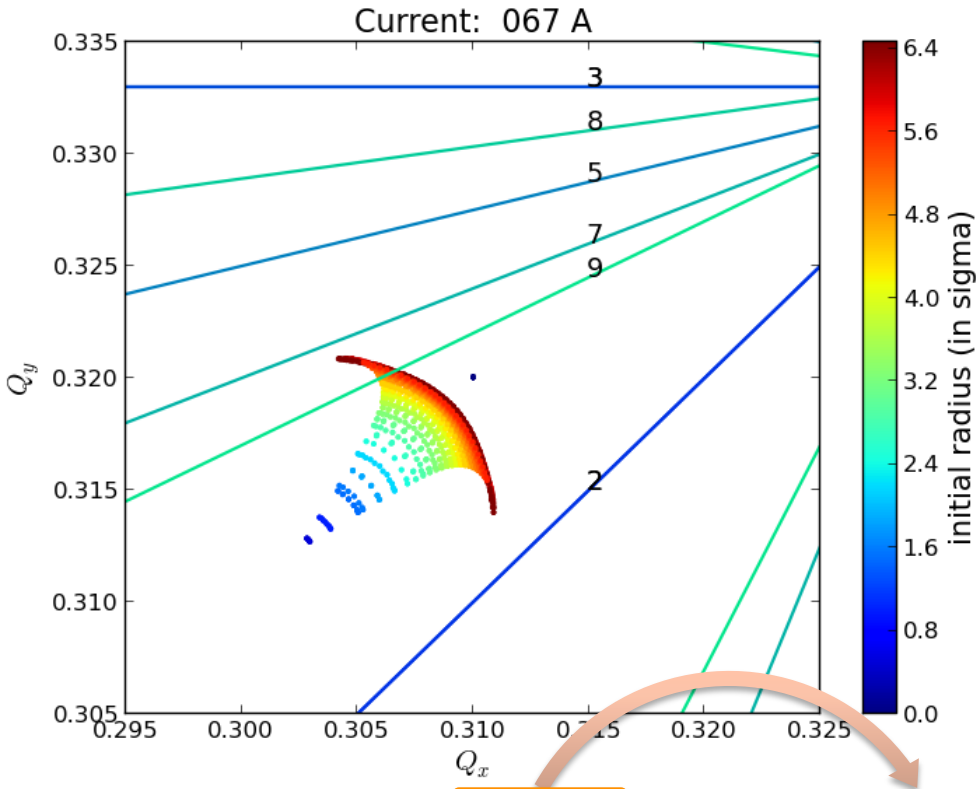

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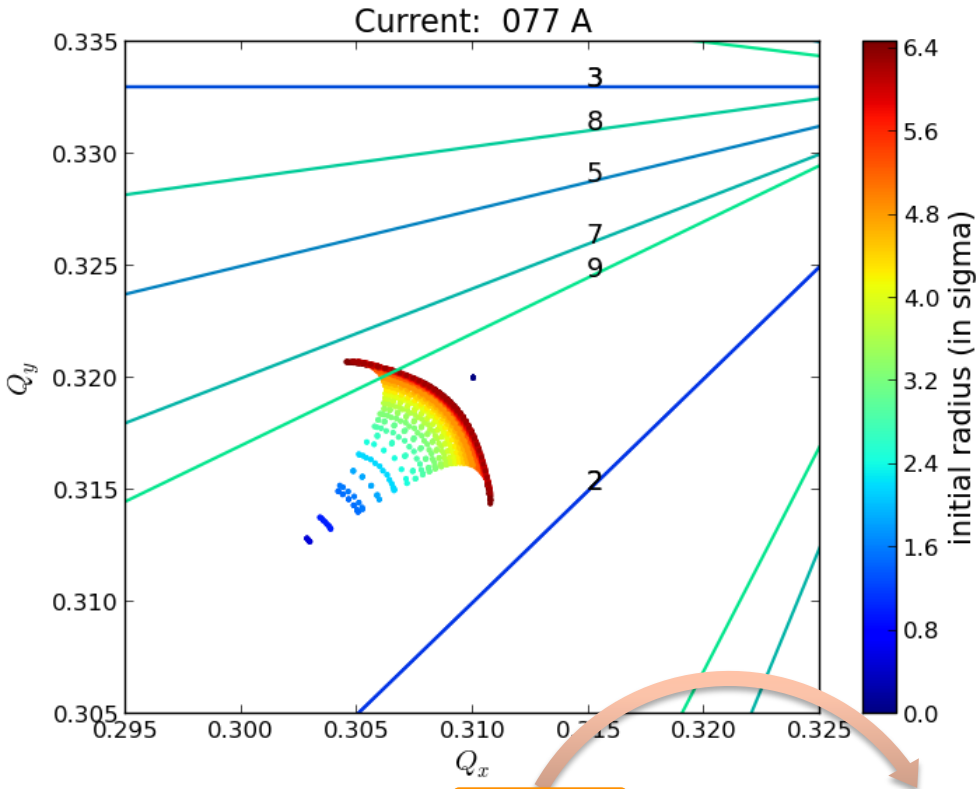

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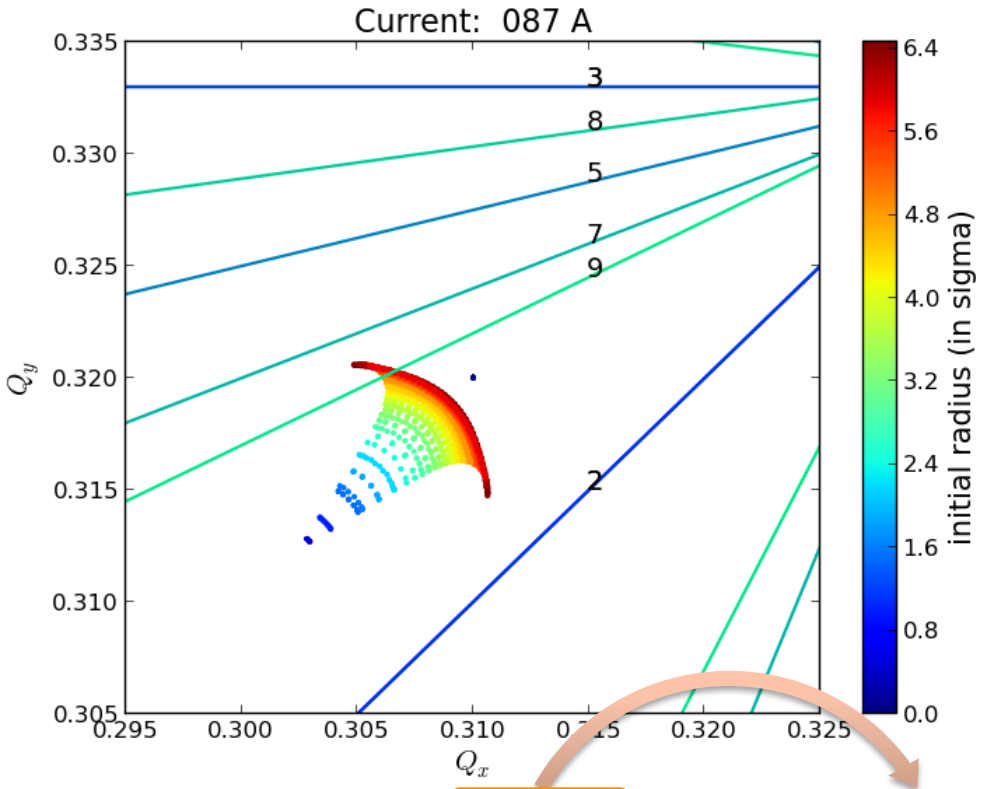

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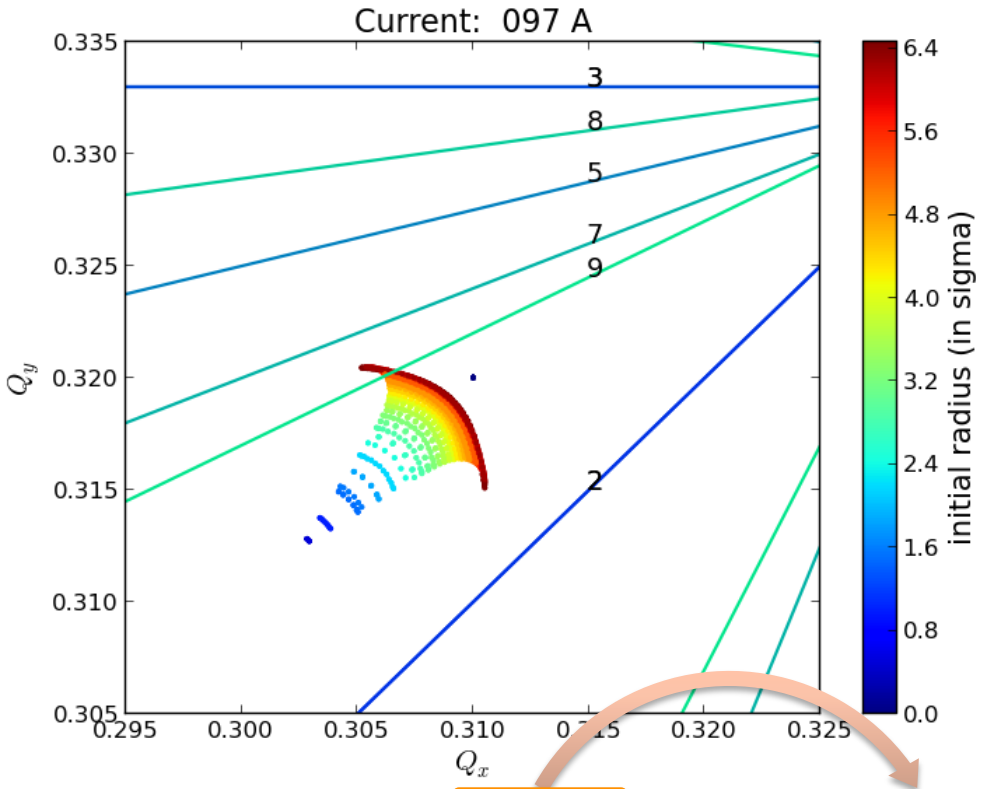

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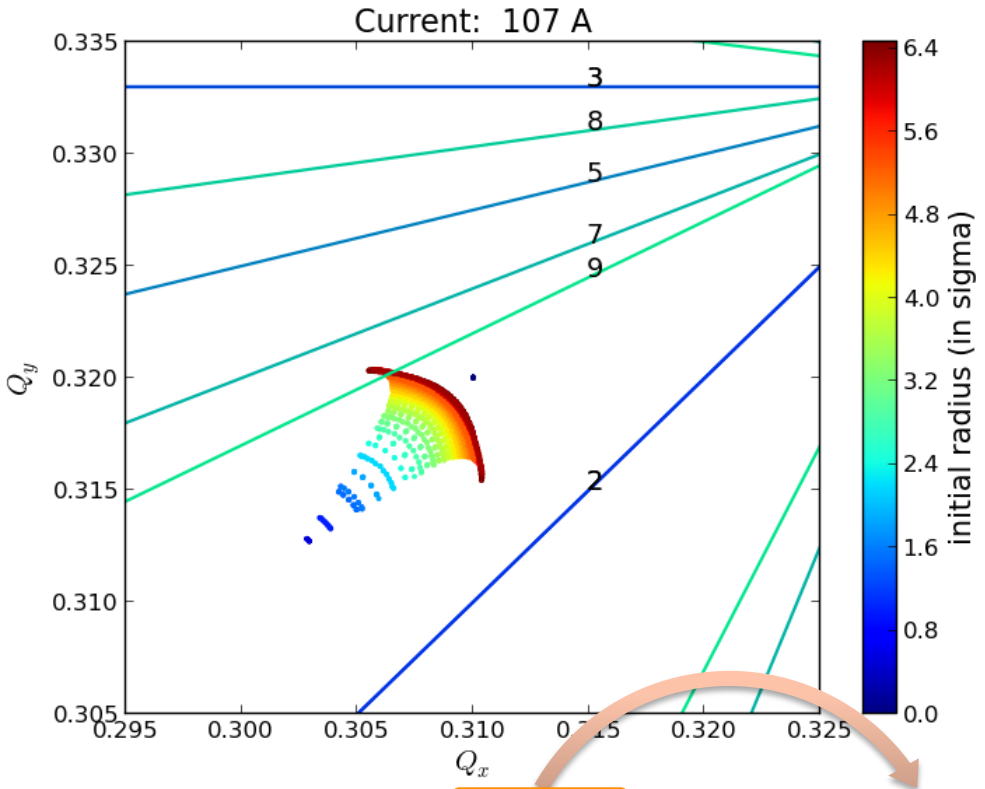

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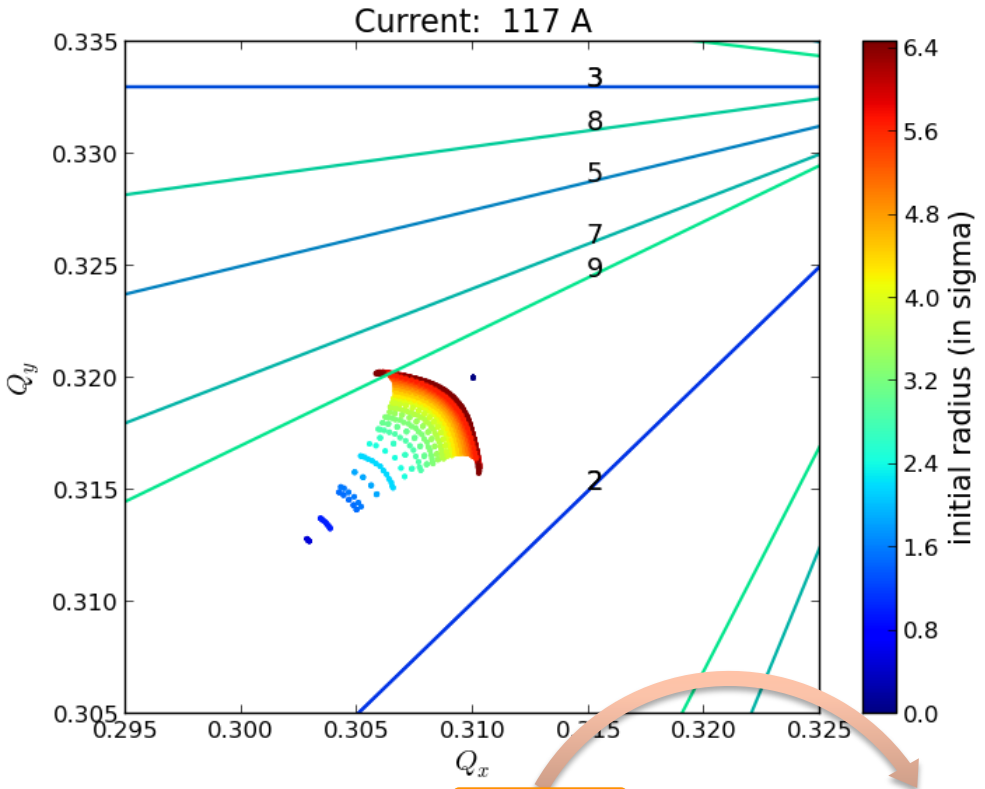

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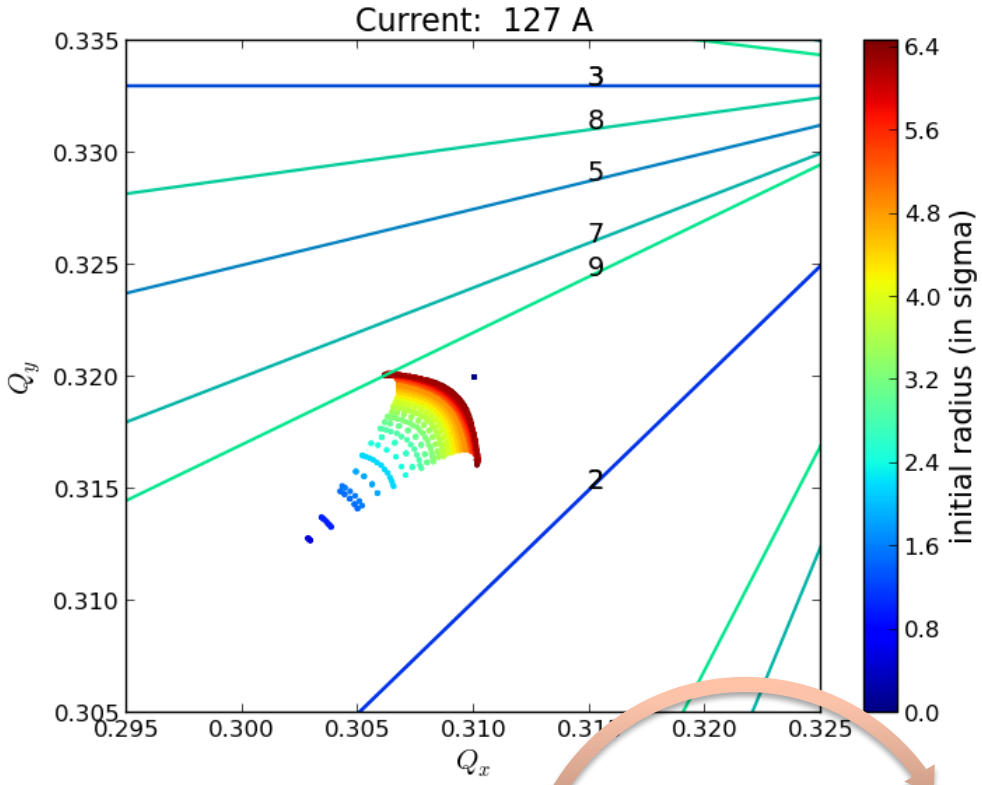

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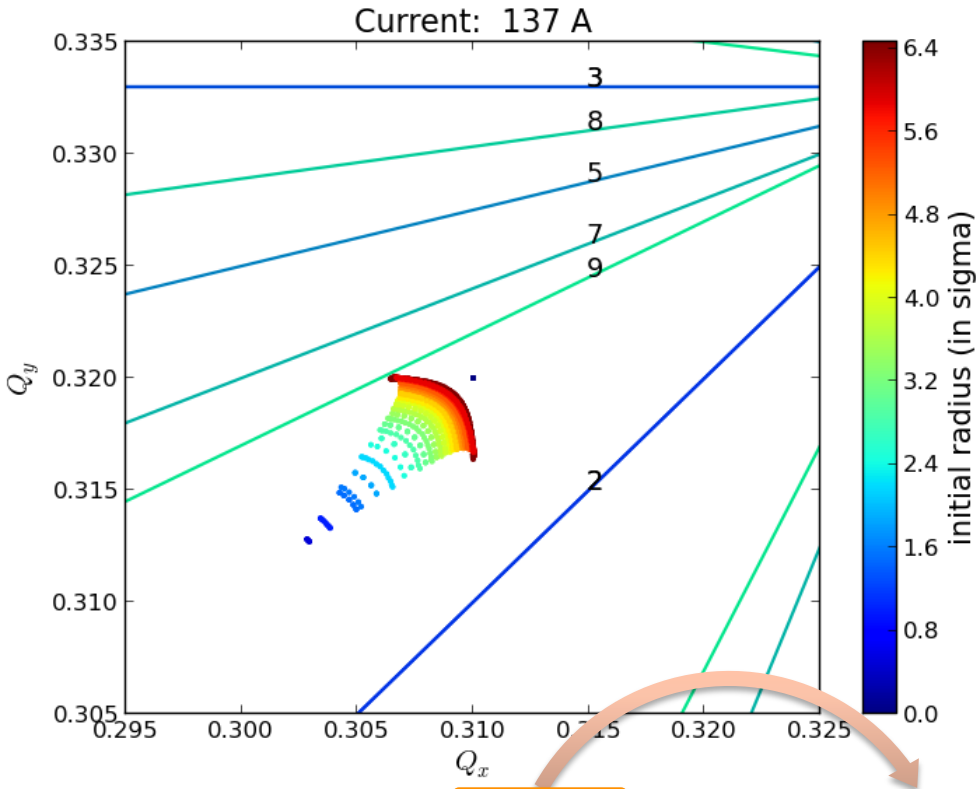

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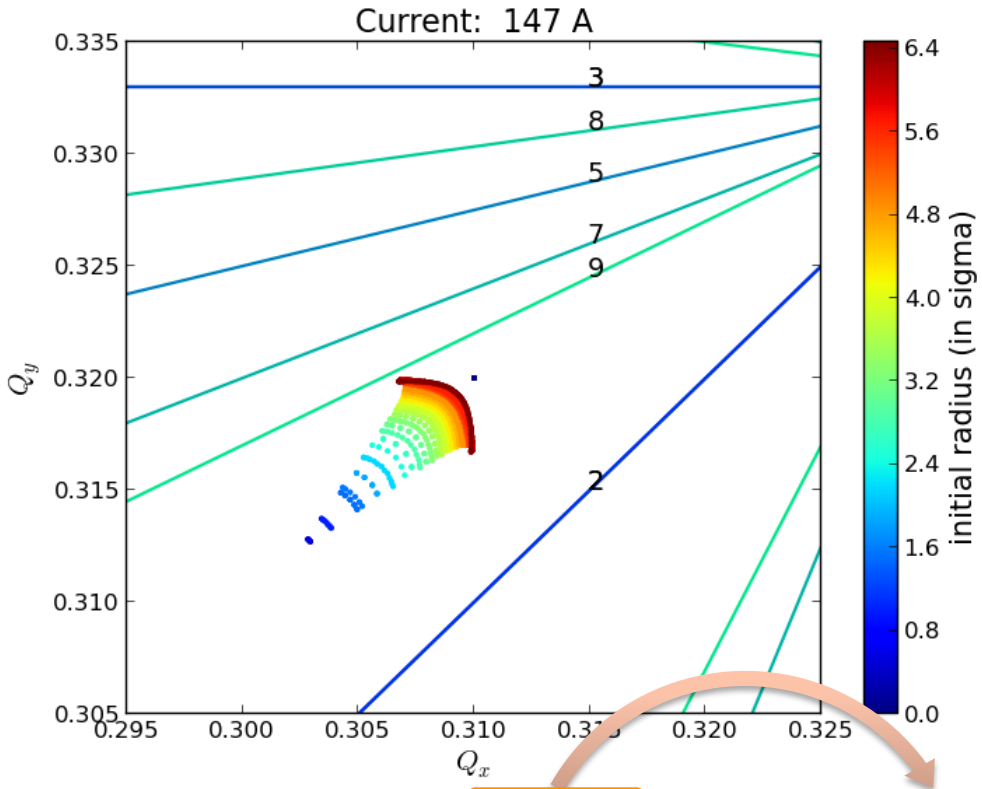

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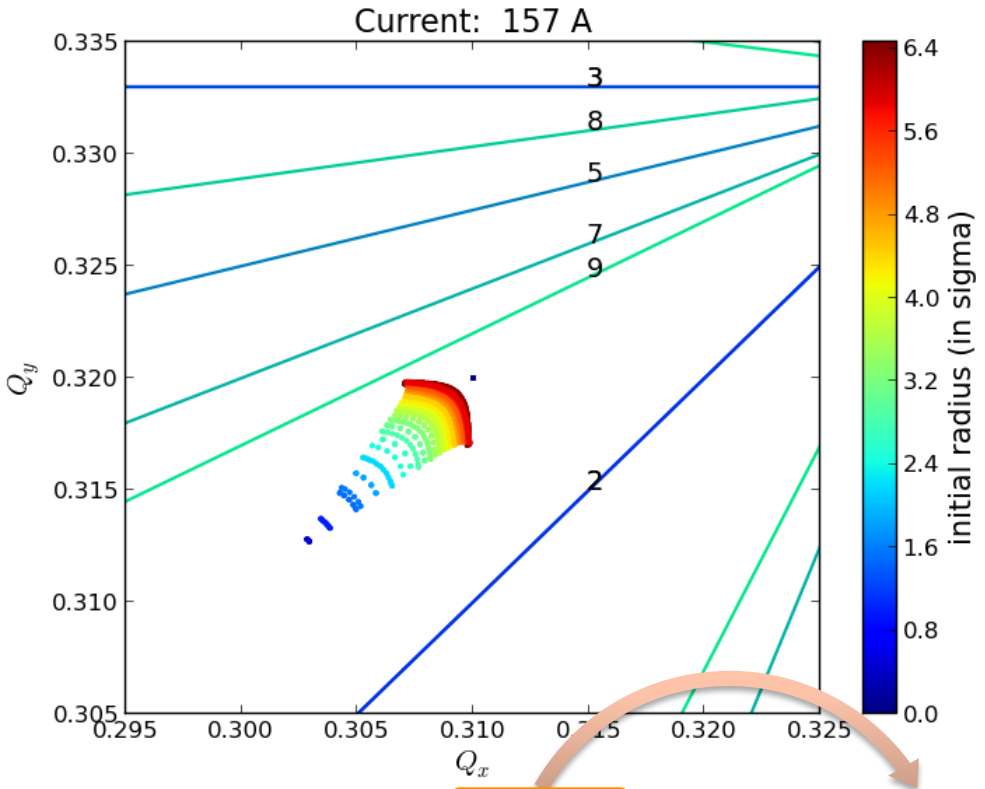

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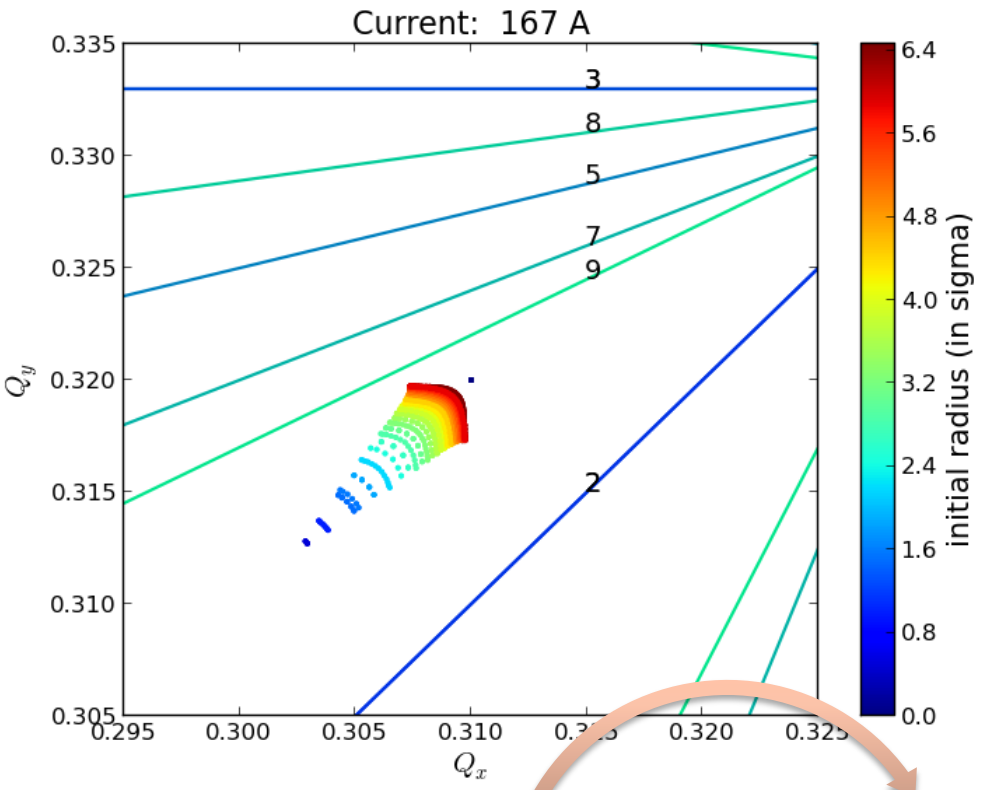

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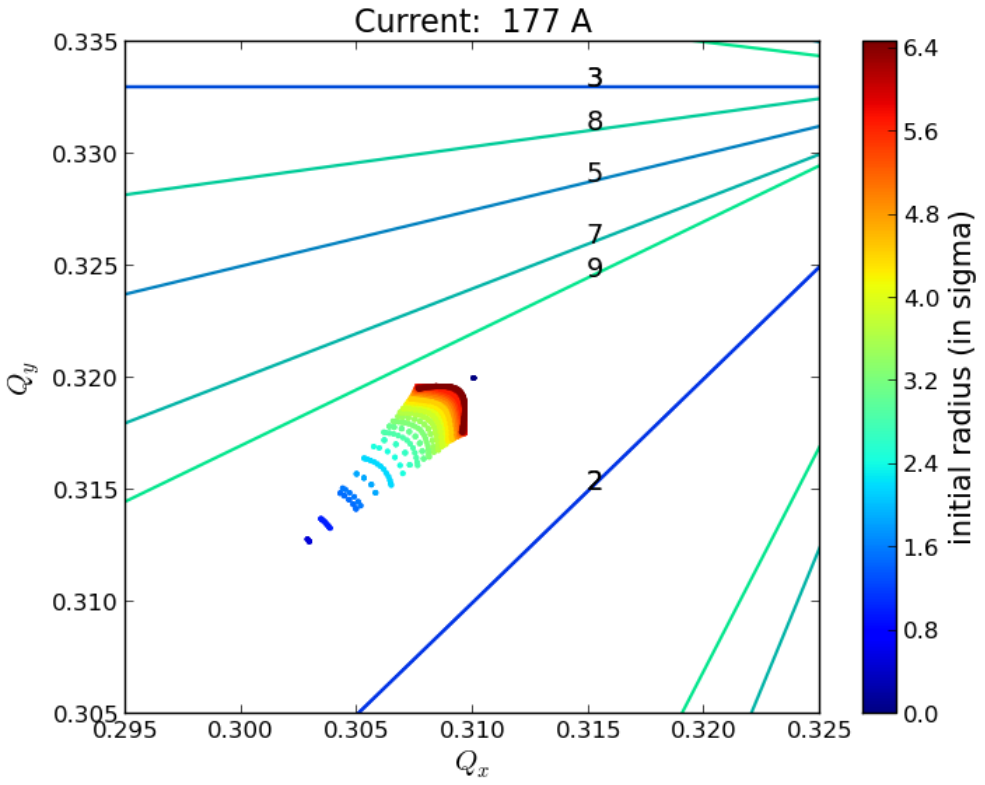

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Longtudinal P
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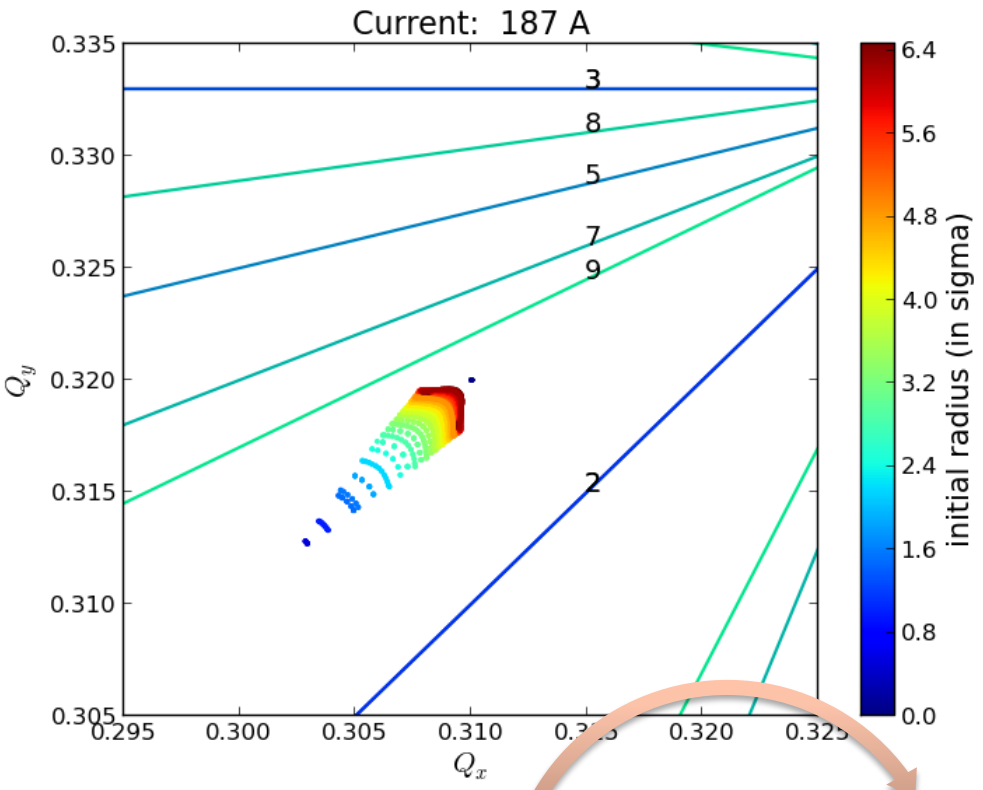
Optics par



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Longtudinal B
Longtudinal P
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First prop.
Cross. Angle
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Conclusions

Next Steps
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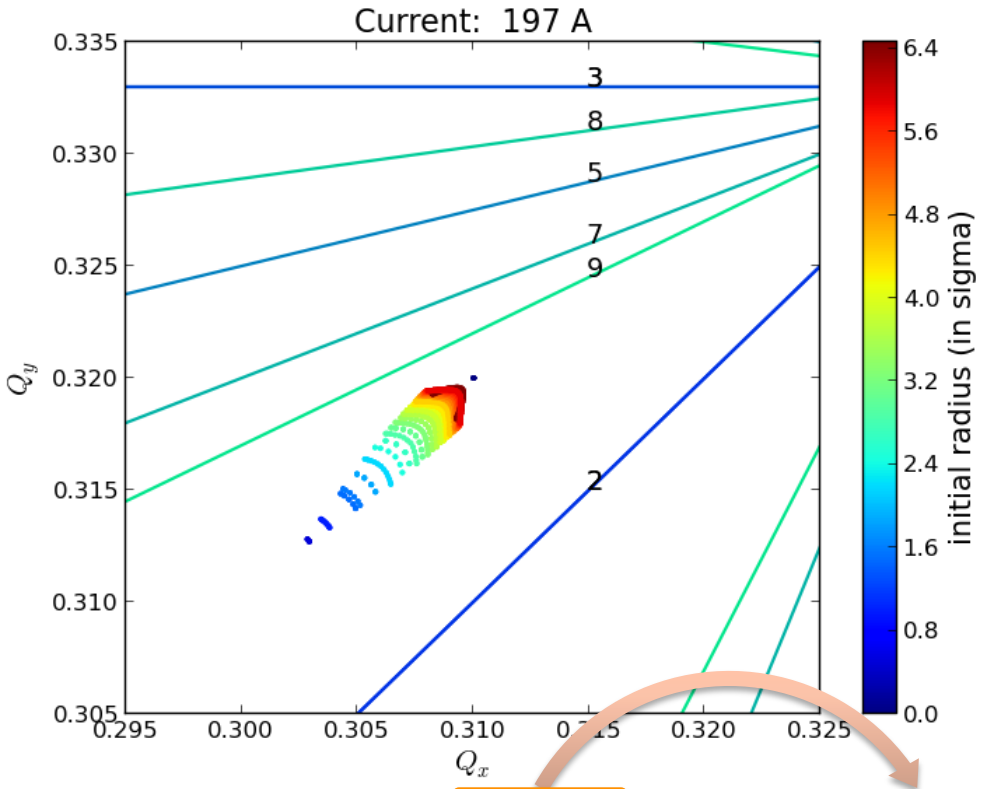
Formulas
Optics par



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Current analysis

Wire comp.
Stability
Tune

Longtudinal B
Longtudinal P
Transv & Curr

Best res.
First prop.
Cross. Angle
Wire Shape

Conclusions

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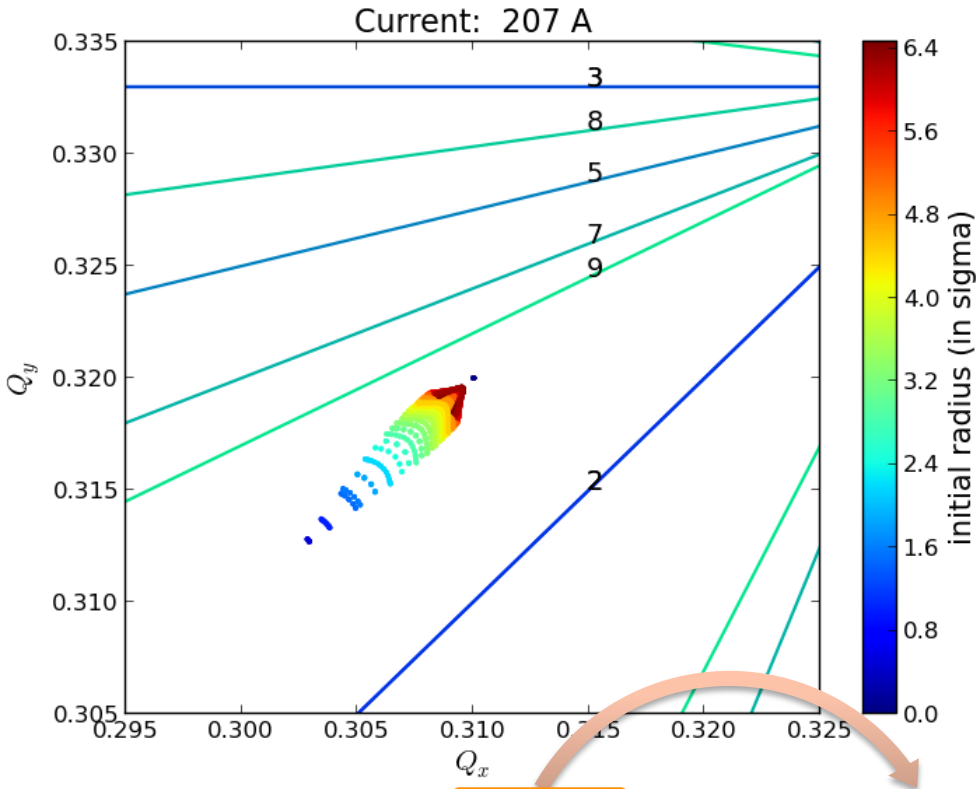
Adds
Formulas
Optics par



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I > 177 A

Results

Best Tune results

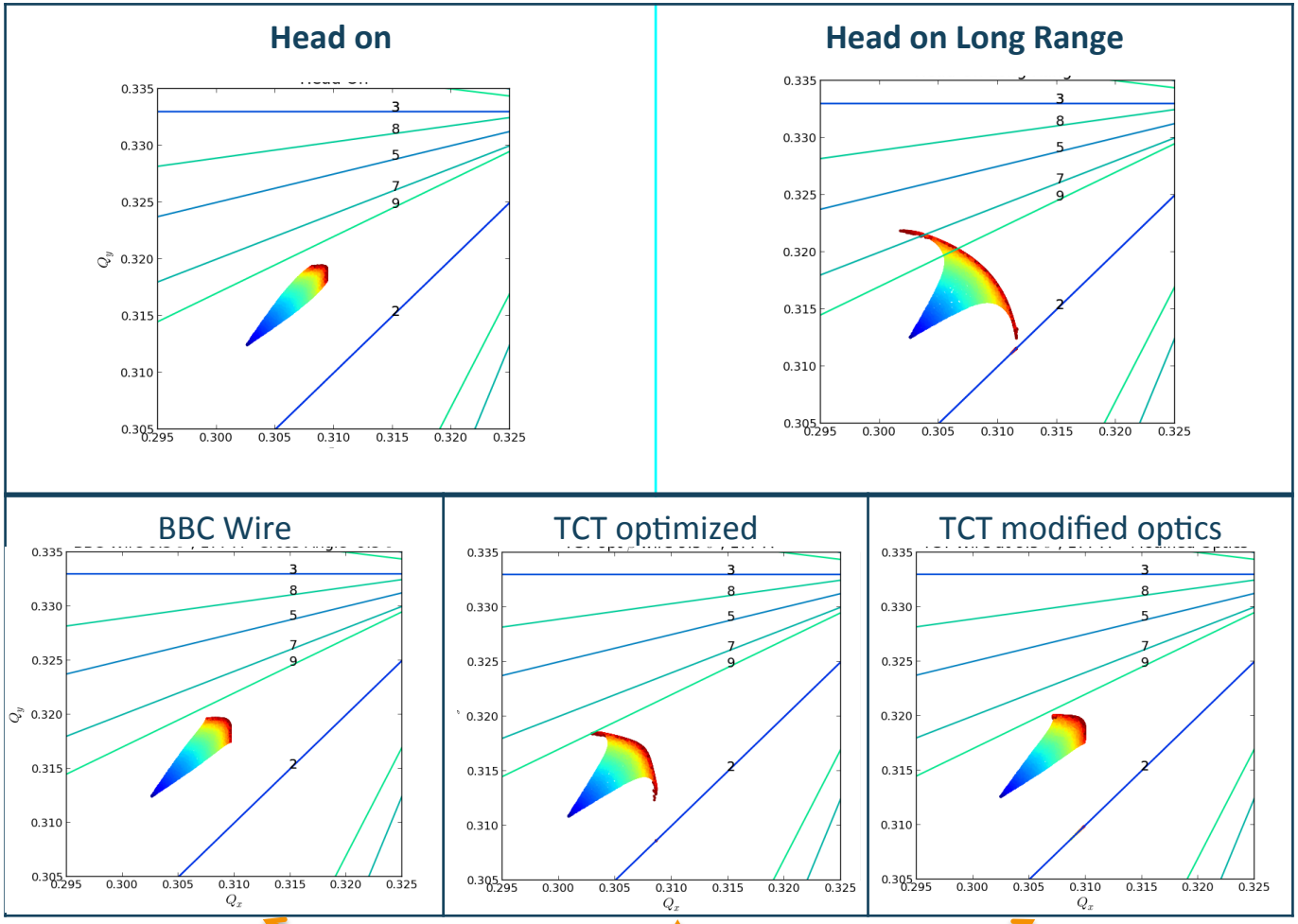
Wire comp.
Stability
Tune

Longtudinal B
Longtudinal P
Transv & Curr

Best res.
First prop.
Cross. Angle
Wire Shape

Conclusions

Next Steps
Adds
Formulas
Optics par



Wire at 9.5 σ – 177 A

Best Stability results

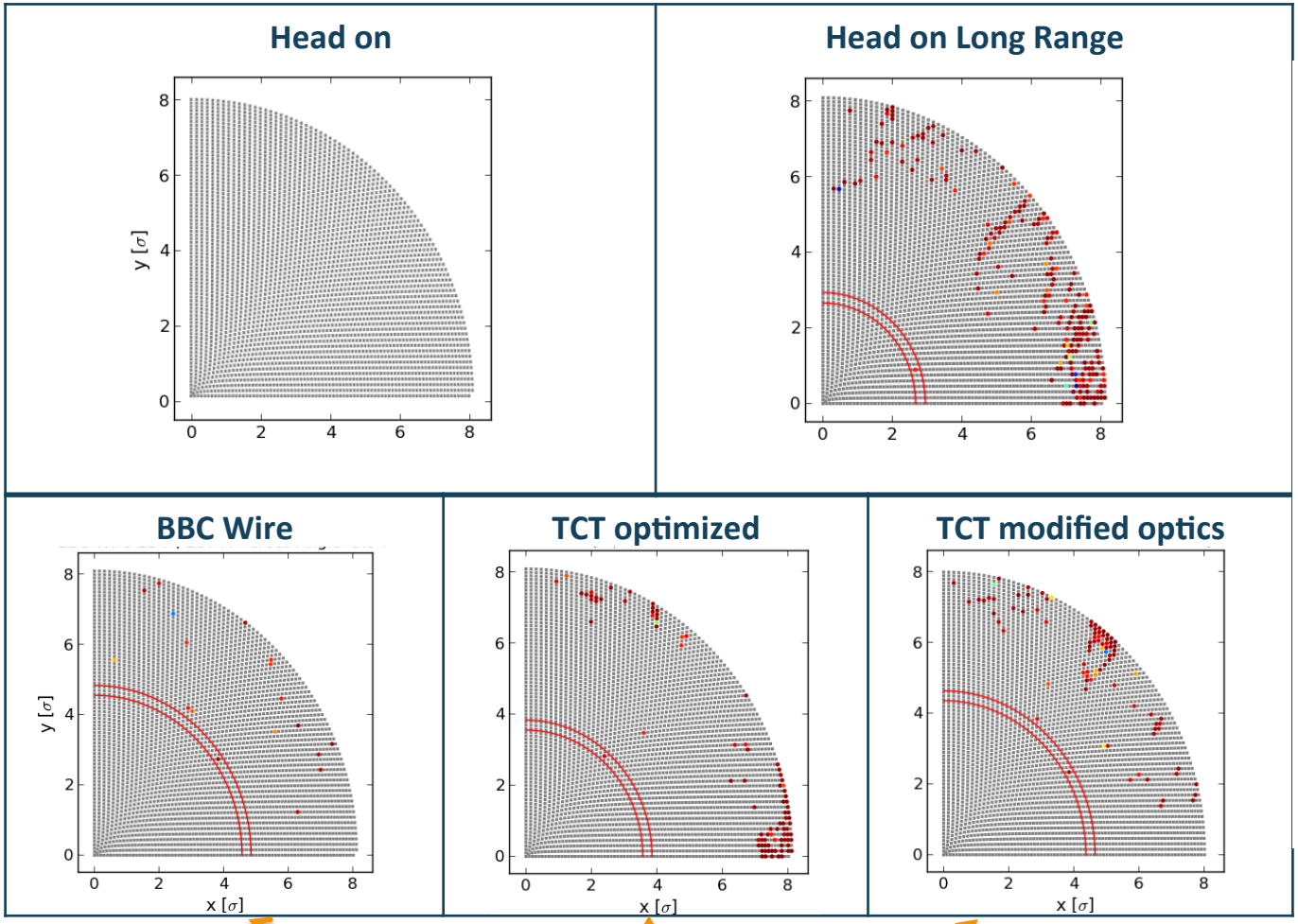
Wire comp.
Stability
Tune

Longtudinal B
Longtudinal P
Transv & Curr

Best res.
First prop.
Cross. Angle
Wire Shape

Conclusions

Next Steps
Adds
Formulas
Optics par



Wire at 11 σ – 237 A

First proposal

Wire comp.
Stability
Tune

Longtudinal B
Longtudinal P
Transv & Curr

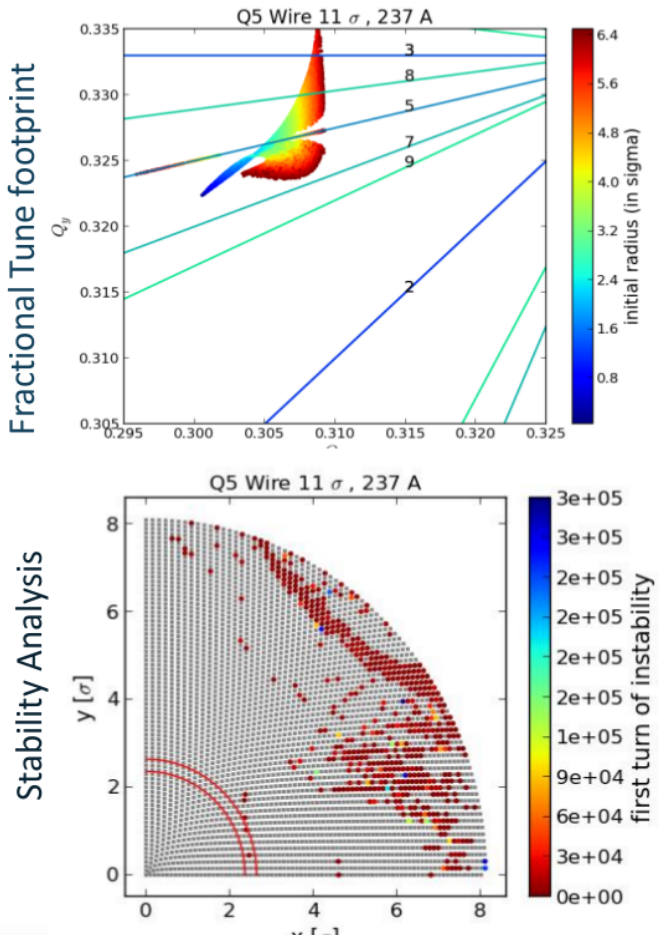
Best res.
First prop.
Cross. Angle
Wire Shape

Conclusions

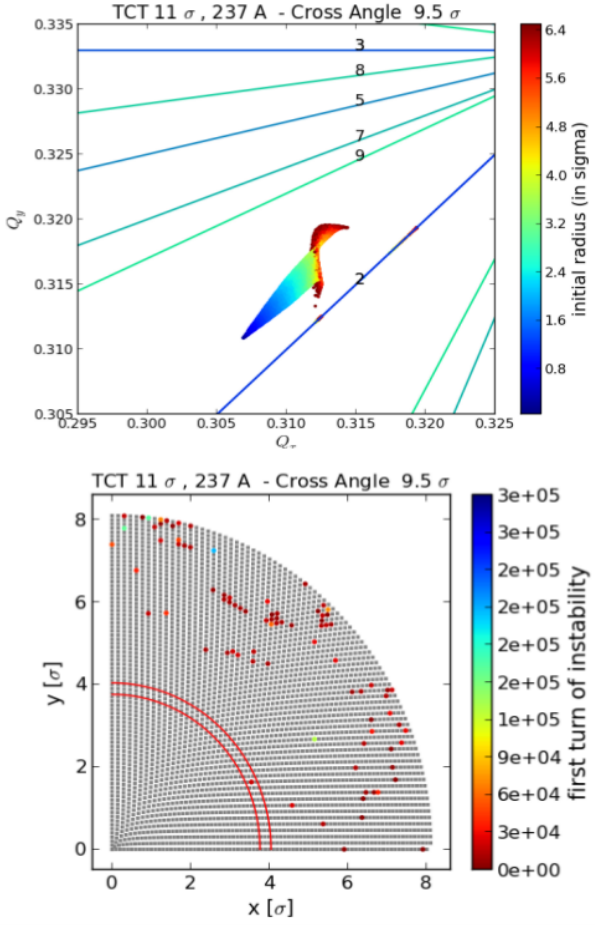
Next Steps
Adds
Formulas
Optics par

Highlights

Q5 wire 11 σ 237 A



TCT wire 11 σ 237 A



Tune Analysis Crossing Angle

Wire comp.
Stability
Tune

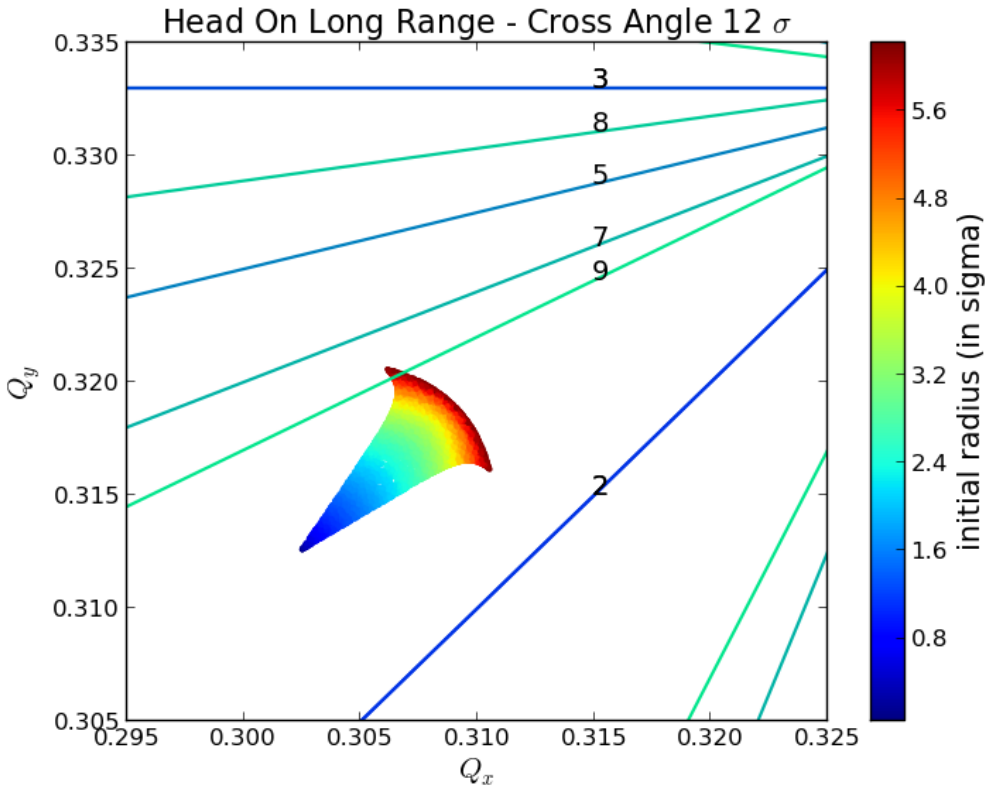
Longtudinal B
Longtudinal P
Transv & Curr

Best res.
First prop.
Cross. Angle
Wire Shape

Conclusions

Next Steps
Adds
Formulas
Optics par

Head On Long Range Dependency from Crossing Angle



Tune Analysis Crossing Angle

Wire comp.
Stability
Tune

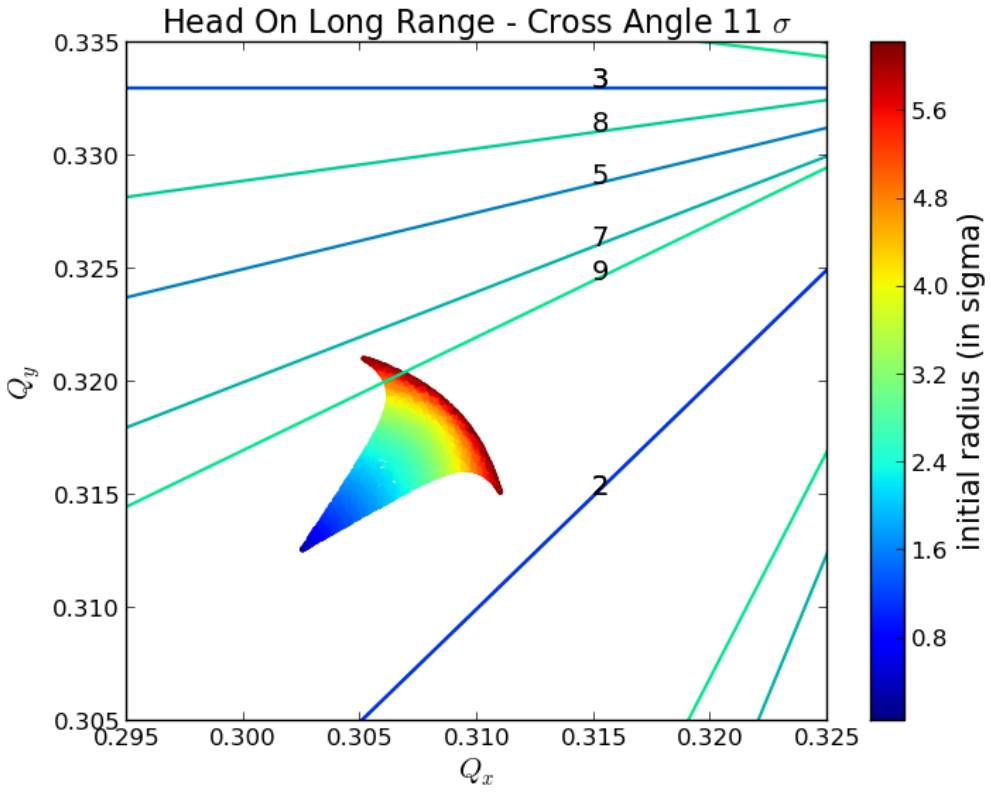
Longtudinal B
Longtudinal P
Transv & Curr

Best res.
First prop.
Cross. Angle
Wire Shape

Conclusions

Next Steps
Adds
Formulas
Optics par

Head On Long Range Dependency from Crossing Angle



Tune Analysis Crossing Angle

Wire comp.
Stability
Tune

Longtudinal B
Longtudinal P
Transv & Curr

Best res.
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Cross. Angle
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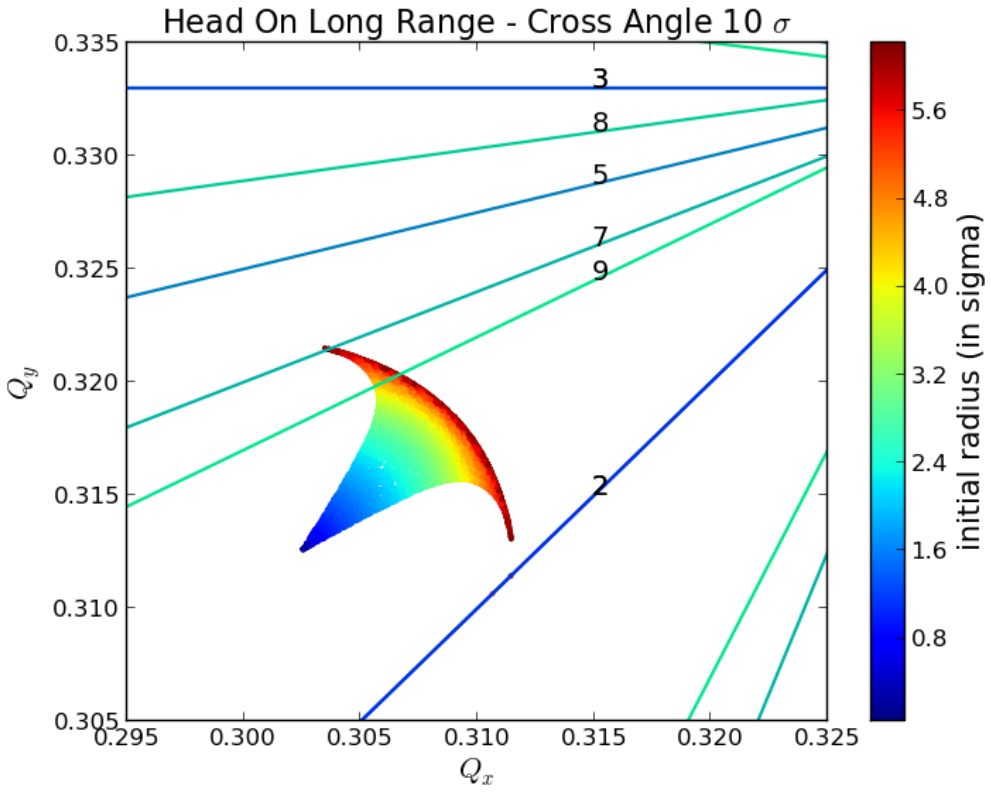
Next Steps
Adds
Formulas
Optics par

Head On Long Range Dependency from Crossing Angle



Tune Analysis Crossing Angle

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Tune

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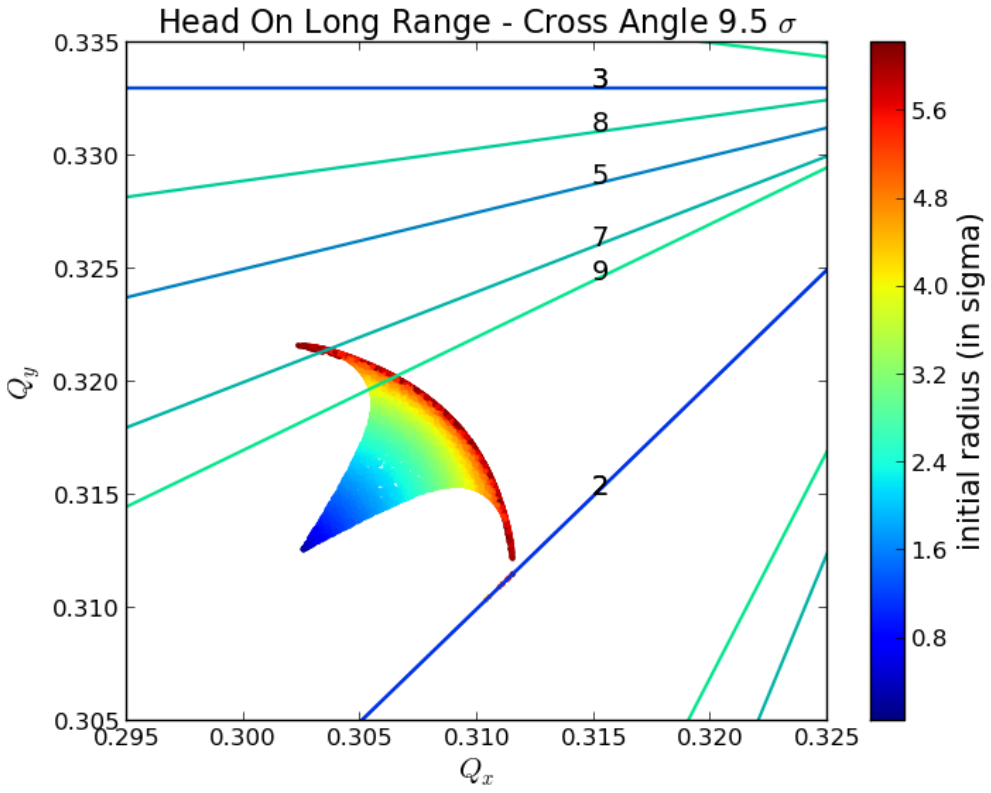

Tune Analysis Crossing Angle

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Tune

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Transv & Curr

Best res.
First prop.
Cross. Angle
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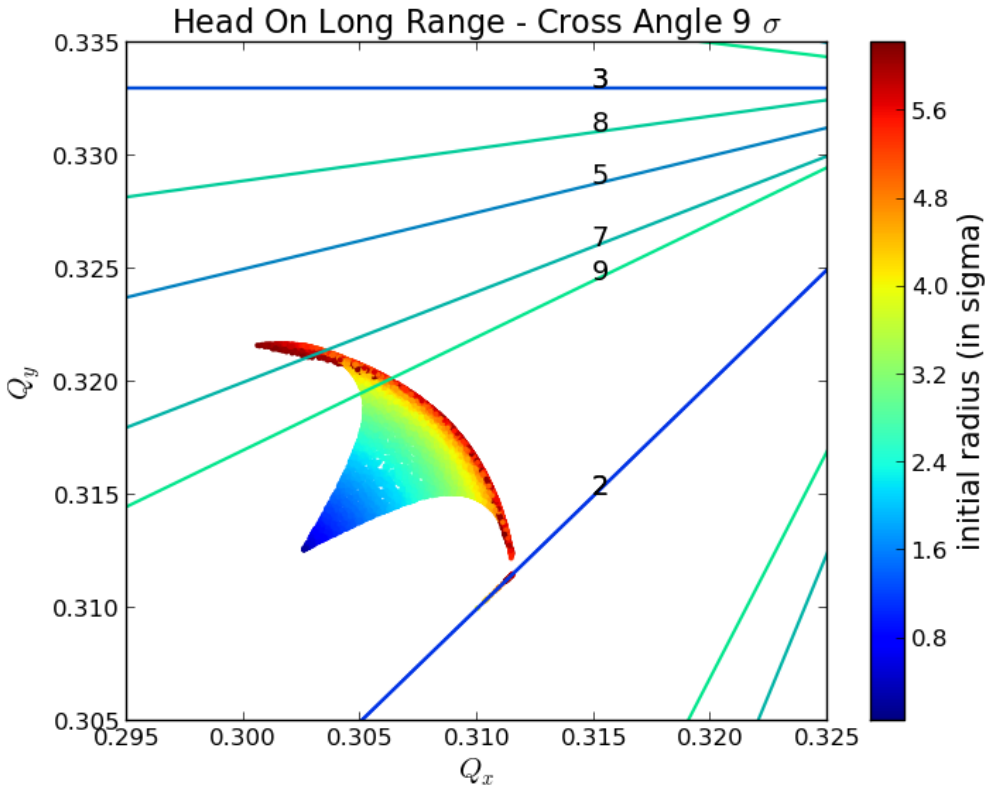
Adds
Formulas
Optics par

Head On Long Range Dependency from Crossing Angle



Tune Analysis Crossing Angle

Wire comp.
Stability
Tune

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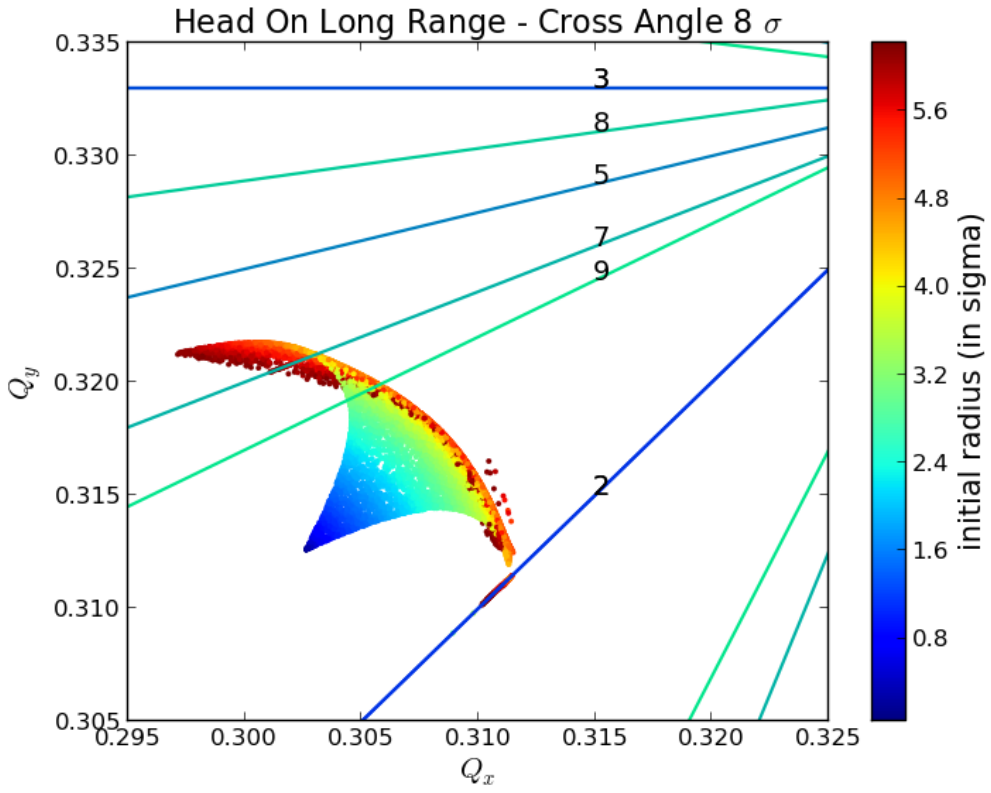
Longtudinal P
Transv & Curr

Best res.
First prop.
Cross. Angle
Wire Shape

Conclusions

Next Steps
Adds
Formulas
Optics par

Head On Long Range Dependency from Crossing Angle



Tune Analysis Crossing Angle

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Tune

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Longtudinal P
Transv & Curr

Best res.
First prop.
Cross. Angle
Wire Shape

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Next Steps
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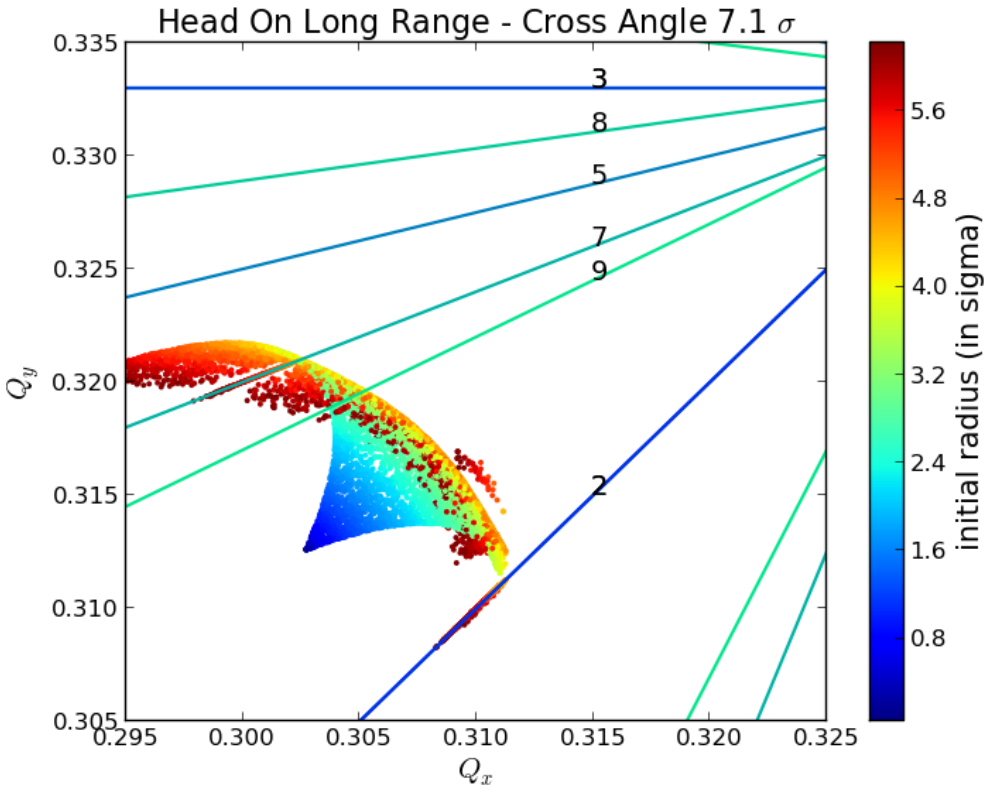
Formulas
Optics par

Head On Long Range Dependency from Crossing Angle



Tune Analysis Crossing Angle

Wire comp.
Stability
Tune

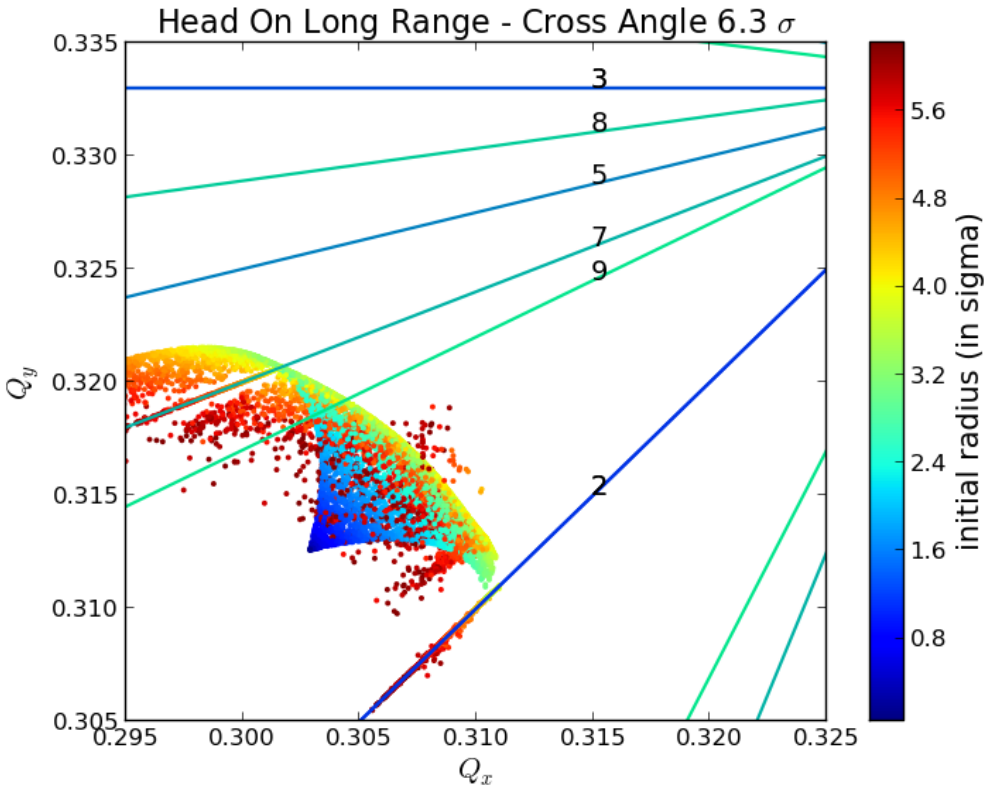
Longtudinal B
Longtudinal P
Transv & Curr

Best res.
First prop.
Cross. Angle
Wire Shape

Conclusions

Next Steps
Adds
Formulas
Optics par

Head On Long Range Dependency from Crossing Angle



Cross. angle dep.: Tune

Wire comp.
Stability
Tune

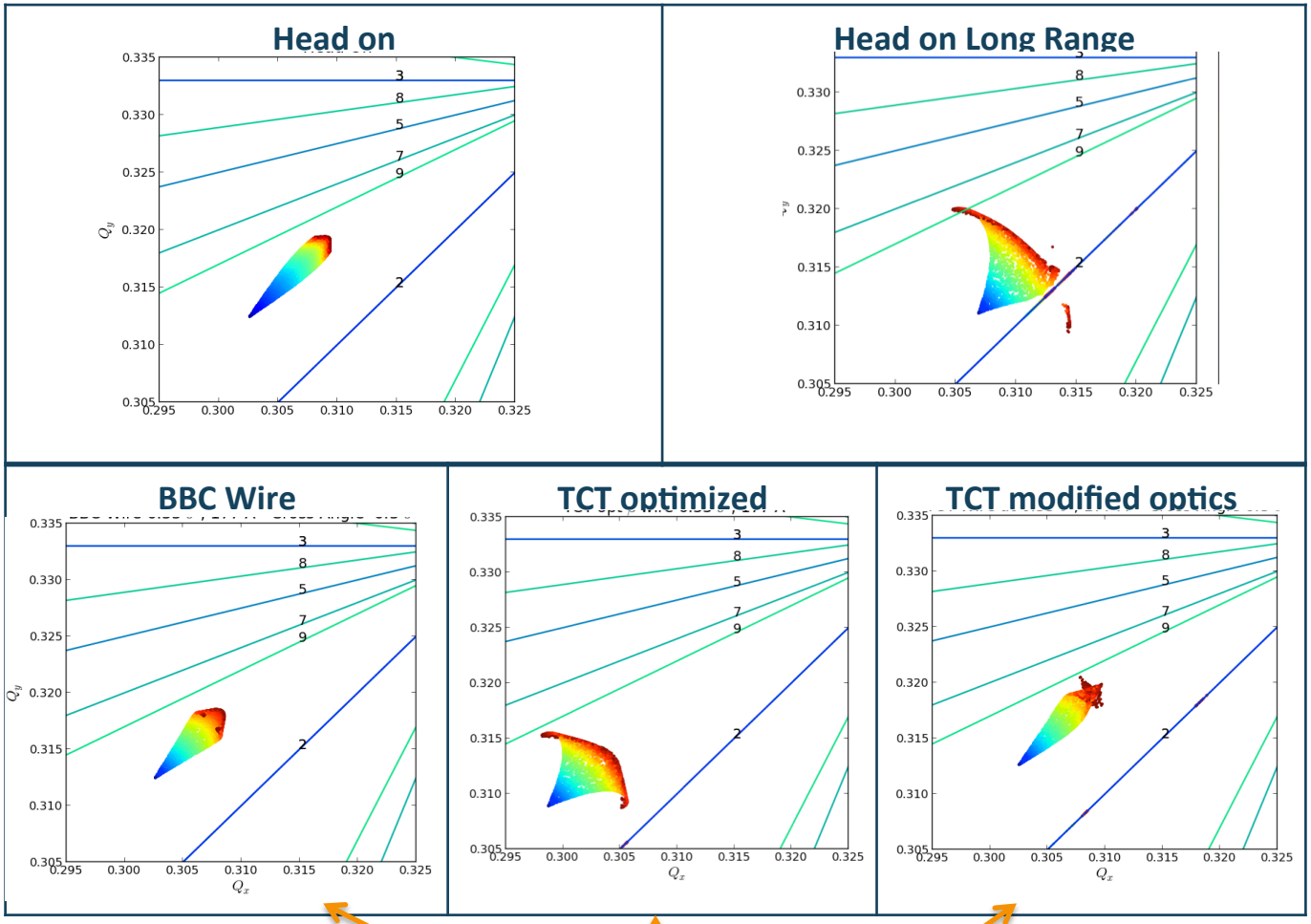
Longtudinal B
Longtudinal P
Transv & Curr

Best res.
First prop.
Cross. Angle
Wire Shape

Conclusions

Next Steps
Adds
Formulas
Optics par

Crossing Angle 6.3 σ



Cross. angle dep.: stability

Wire comp.
Stability
Tune

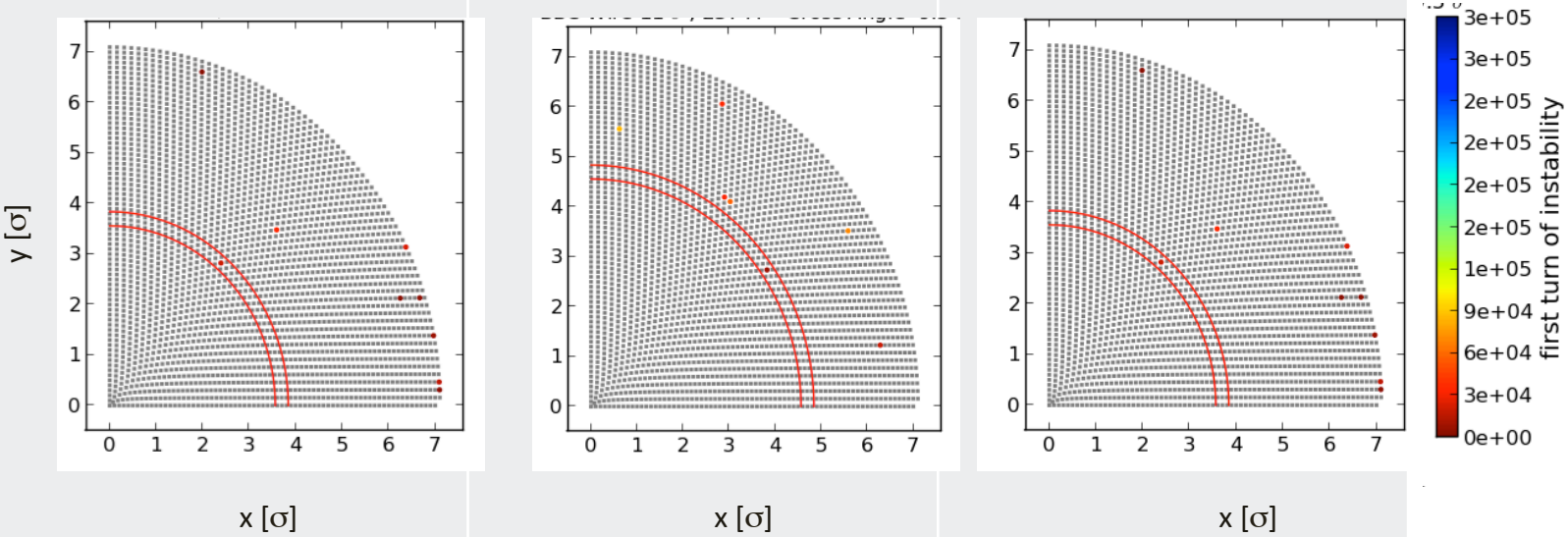
Longtudinal B
Longtudinal P
Transv & Curr

Best res.
First prop.
Cross. Angle
Wire Shape

Conclusions

Next Steps
Adds
Formulas
Optics par

Cross Angle 12 σ	Cross Angle 9.5 σ	
HOLR	**BBC** 237 A 11σ	**TCT optimized** 237 A 11σ



12 σ without wire ⟷ 9.5 σ with the wire

Cross. angle dep.: stability

Wire comp.
Stability
Tune

Longtudinal B
Longtudinal P
Transv & Curr

Best res.
First prop.
Cross. Angle
Wire Shape

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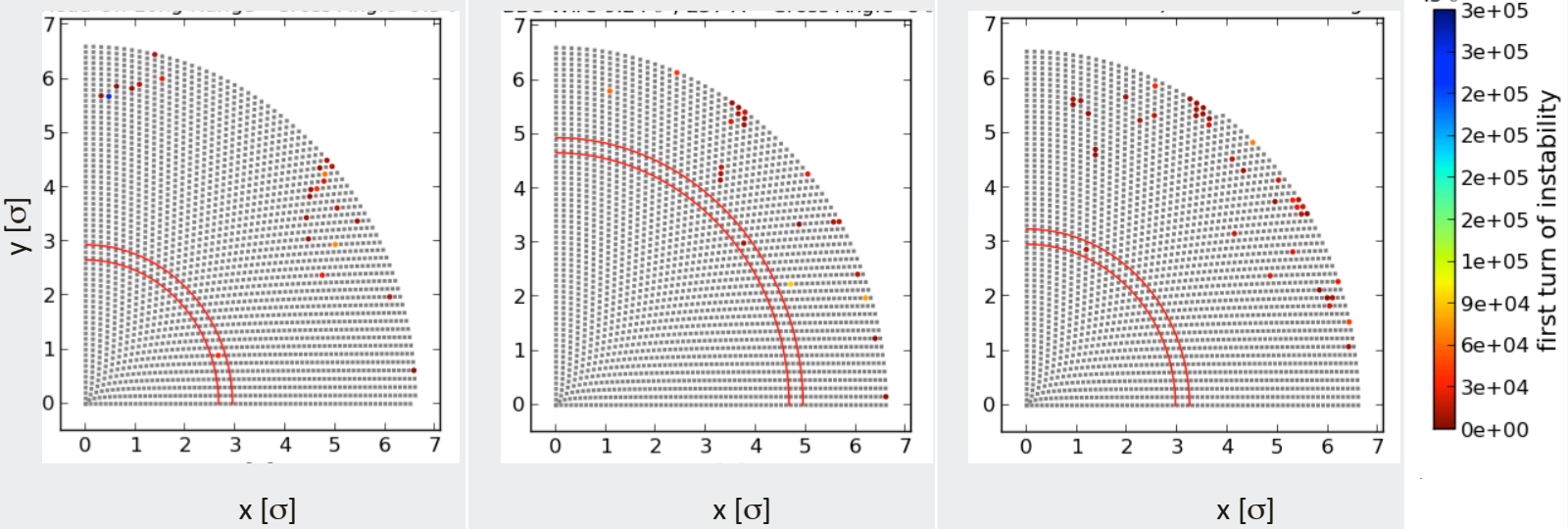
Cross Angle 9.5 σ	Cross Angle 8 σ	
HOLR	**BBC** 237 A 9.24σ	**TCT modified optics** 237 A 9.24σ



9.5 σ without wire ⟷ 8 σ with the wire

Wire shape

Wire comp.
Stability
Tune

Longtudinal B
Longtudinal P
Transv & Curr

Best res.
First prop.
Cross. Angle
Wire Shape

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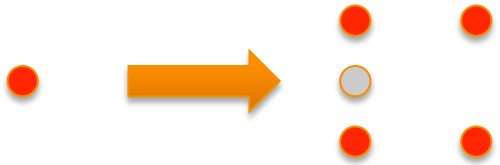
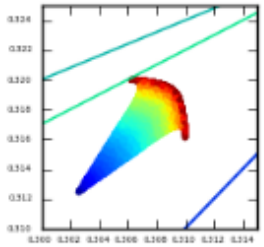
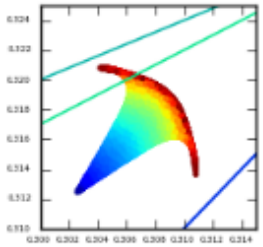
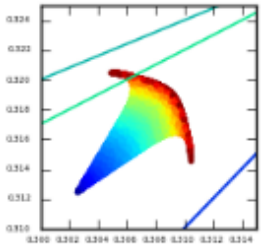
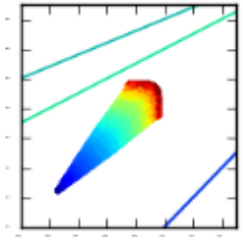
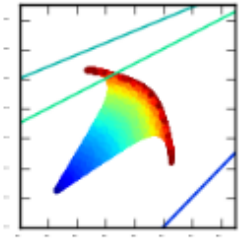
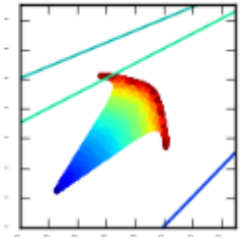


1mm

Footprint Summary			
Test	177 A 9.5 σ	177 A 11 σ	237 A 11 σ
Square Wire			
Pencil like wire			

Wire shape

Wire comp.
Stability
Tune

Longtudinal B
Longtudinal P
Transv & Curr

Best res.
First prop.
Cross. Angle
Wire Shape

Conclusions

Next Steps
Adds
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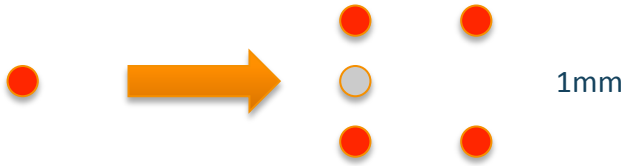
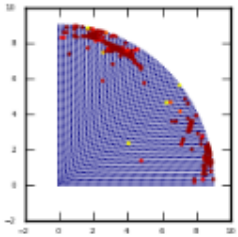
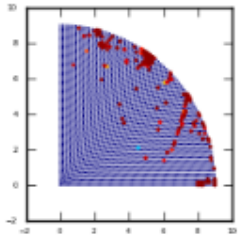
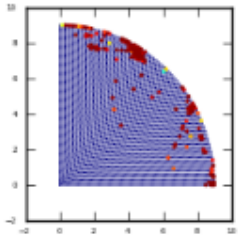
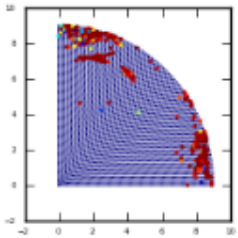
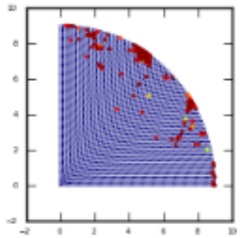
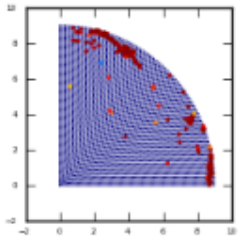
Optics par



Stability Summary

Test	177 A 9.5 σ	177 A 11 σ	237 A 11 σ
Square Wire			
Pencil like wire			

Conclusions

Conclusions

Wire comp.
Stability
Tune

Longtudinal B
Longtudinal P
Transv & Curr

Best res.
First prop.
Cross. Angle
Wire Shape

Conclusions

Next Steps
Adds
Formulas
Optics par

- ✓ We studied a possible compensation of long range beam beam effects in LHC with a DC wire compensator
- ✓ We analyzed the tune and stability for different configurations
  - ✓ Wire Longitudinal positions
  - ✓ Wire Transverse position
  - ✓ Wire Current
  - ✓ LHC optics
- ✓ From tune analysis
  - ✓ best transverse location 9.5 σ with current 177 A
- ✓ From stability analysis
  - ✓ best transverse location 11 σ with current 237 A
- ✓ Longitudinally, best compensation at BBC location
- ✓ Promising results also at TCT opt β or TCT with modified optics

- ✓ Varying the crossing angle we see that wire compensator allows to reduce crossing angle of 1-2 σ maintaining the same stable region
- ✓ Wire shape (sqare vs pencil like) doesn't affect our results

Thank you!

Appendix

Next Steps

Wire comp.
Stability
Tune

Longtudinal B
Longtudinal P
Transv & Curr

Best res.
First prop.
Cross. Angle
Wire Shape

Conclusions

Next Steps
Adds
Formulas
Optics par

- Mechanical feasibility (compatibility tests)
- Impact of wire-in-jaw on machine impedance
- Beam cleaning performance simulations
- Wire-in-jaw robustness simulations
- Prototype installation and integration

Tune results for best Stab

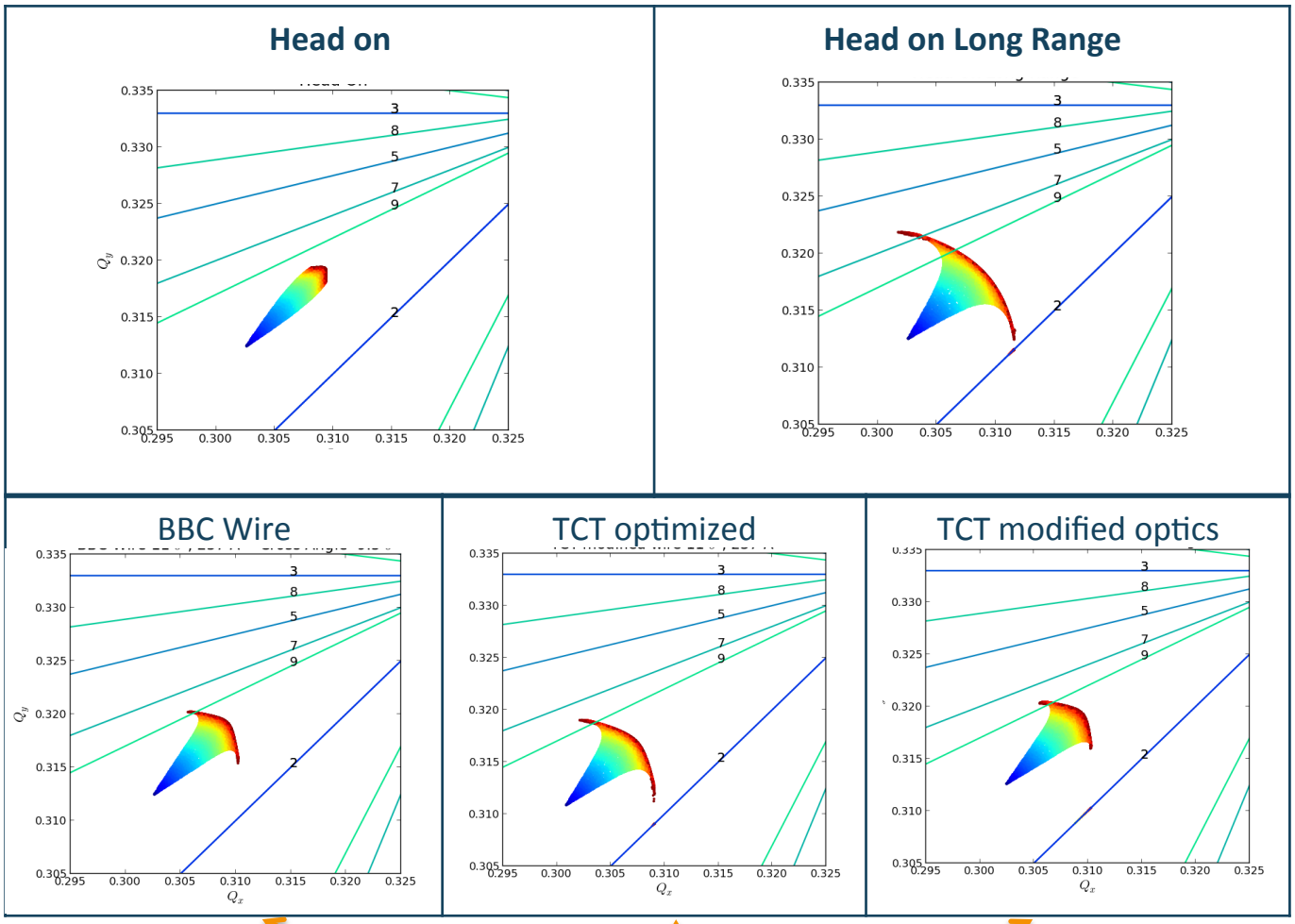
Wire comp.
Stability
Tune

Longtudinal B
Longtudinal P
Transv & Curr

Best res.
First prop.
Cross. Angle
Wire Shape

Conclusions

Next Steps
Adds
Formulas
Optics par



Wire Linear Tune Shift

Wire comp.
Stability
Tune

Longtudinal B
Longtudinal P
Transv & Curr

Best res.
First prop.
Cross. Angle
Wire Shape

Conclusions

Next Steps
Adds
Formulas
Optics par

$$\Delta Q_x = -\frac{\mu_0 L_w I_w}{2\pi B_d \rho}\frac{\beta_x}{4\pi}\left(-\frac{2d\,x_w^2}{\left(d\,x_w^2+d\,y_w^2\right)^2}+\frac{1}{d\,x_w^2+d\,y_w^2}\right)$$

$$\Delta Q_y = -\frac{\mu_0 L_w I_w}{2\pi B_d \rho}\frac{\beta_y}{4\pi}\left(-\frac{2d\,y_w^2}{\left(d\,x_w^2+d\,y_w^2\right)^2}+\frac{1}{d\,x_w^2+d\,y_w^2}\right)$$

$$d^2 = x_w^2 + y_w^2$$

μ_0 = free permeability
L_w = wire length
I_w = wire current
$B_d\rho$ = magnetic rigidity
$\beta_{x,y}$=betatron function
(x_w , y_w) = wire coordinates

Round beam – horizontal cross

Long range kick

$$\Delta x' = -\frac{2Nr_0}{\gamma}\frac{x-d}{r^2}\left(1-\exp\left(\frac{r^2}{2\sigma^2}\right)\right)$$

$$\Delta y' = -\frac{2Nr_0}{\gamma}\frac{y}{r^2}\left(1-\exp\left(\frac{r^2}{2\sigma^2}\right)\right)$$

$$r^2 = (x-d)^2 + y^2$$

Wire kick

$$\Delta x' = -\frac{2Nr_0}{\gamma}\frac{x-x_w}{r_w^2}$$

$$\Delta y' = -\frac{2Nr_0}{\gamma}\frac{y-y_w}{r_w^2}$$

$$r_w^2 = x^2 + y^2$$

N = nbr protons
r_0 = classical radius
d = distance between beams centers
σ = standard deviation

Renormalized distance

Wire comp.
Stability
Tune

Longtudinal B
Longtudinal P
Transv & Curr

Best res.
First prop.
Cross. Angle
Wire Shape

Conclusions

Next Steps
Adds
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Optics par

$$x_r = \frac{x}{\sigma_x}$$

$$x_r' = x' \sqrt{\frac{\beta_x}{\varepsilon_x}} + x \frac{\alpha_x}{\sigma_x}$$

$$y_r = \frac{y}{\sigma_y}$$

$$y_r' = y' \sqrt{\frac{\beta_y}{\varepsilon_y}} + y \frac{\alpha_y}{\sigma_y}$$

$$d_r(j) = \left(\left(x_{r,1}(j) - x_{r,2}(j) \right)^2 + \left(x_{r,1}'(j) - x_{r,2}'(j) \right)^2 + \left(y_{r,1}(j) - y_{r,2}(j) \right)^2 + \left(y_{r,1}'(j) - y_{r,2}'(j) \right)^2 \right)$$

Analyzed Cases Summary

Wire comp.
Stability
Tune

Longtudinal B
Longtudinal P
Transv & Curr

Best res.
First prop.
Cross. Angle
Wire Shape

Conclusions

Next Steps
Adds
Formulas
Optics par

test	ip	βx [m]	β_y [m]	$\Delta\mu_x$ [2 π]	$\Delta\mu_y$ [2 π]
BBC	1	1738	1735	0.25	0.25
	5	1739	1735	0.25	0.25
TCT optimized	1	559	1576	0.25	0.25
	5	1576	607	-0.26	-0.26
TCT mod optics	1	801	802	-0.26	-0.26
	5	798	794	-0.26	-0.26
TCT	1	1577	615	-0.26	-0.26
	5	1576	607	-0.26	-0.26
Q5	1	106	503	0.26	0.26
	5	106	503	0.26	0.26