



# PSB: Q4Q3 optics

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2/07/2018

# Overview

- › Introduction
  - Resonances
  - Space charge
  - Resonance Driving Terms
- › Q4Q4
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- › Resonance Driving Terms
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  - Q4Q3
- › Experimental Set-up
- › Summary

# Resonances

Resonances can be excited due to linear errors or multipolar field components in the machine.

Depending on the field component that drives the resonance we can have both skew and normal resonances.

For example a skew quadrupole will drive a 2<sup>nd</sup> order resonance (coupling resonance)

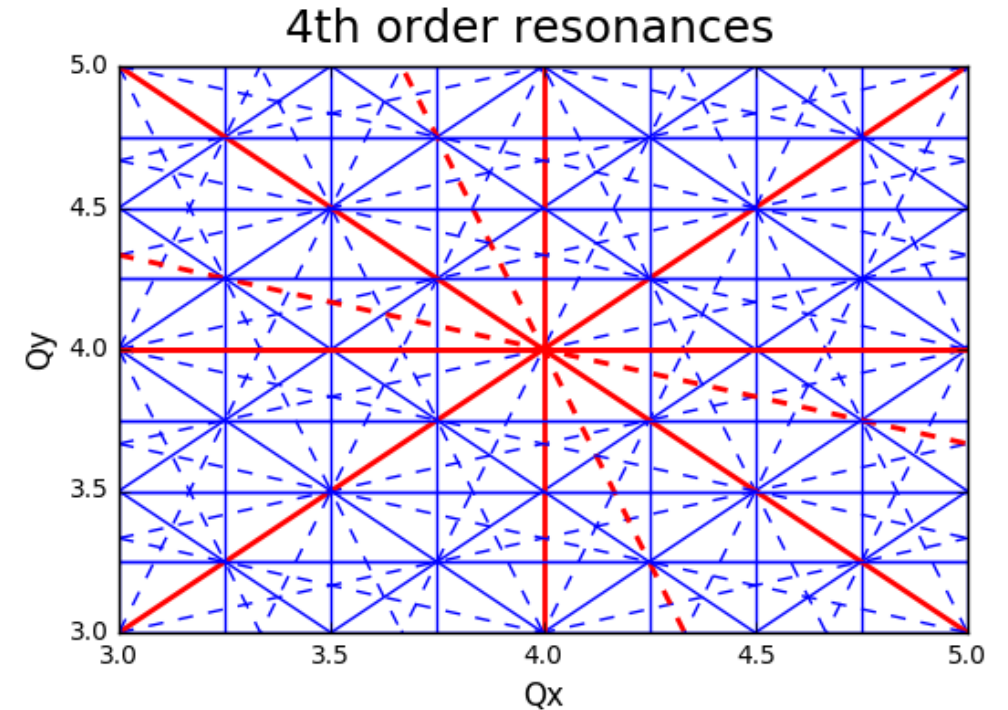
The resonance condition for given vertical and horizontal tunes is:

$$mQ_x + nQ_y = l, \quad \text{where: } m, n \text{ and } l \text{ integers}$$

If  $l$  is equal to a multiple of the periodicity of the machine's lattice, the resonance is called systematic.

For the PSB case:

$$l = 16$$



	Systematic	Non Systematic
Skew		
Normal		

# Space Charge

## Direct Space Charge

Coulomb forces between the moving particles

Self-fields that move with the beam

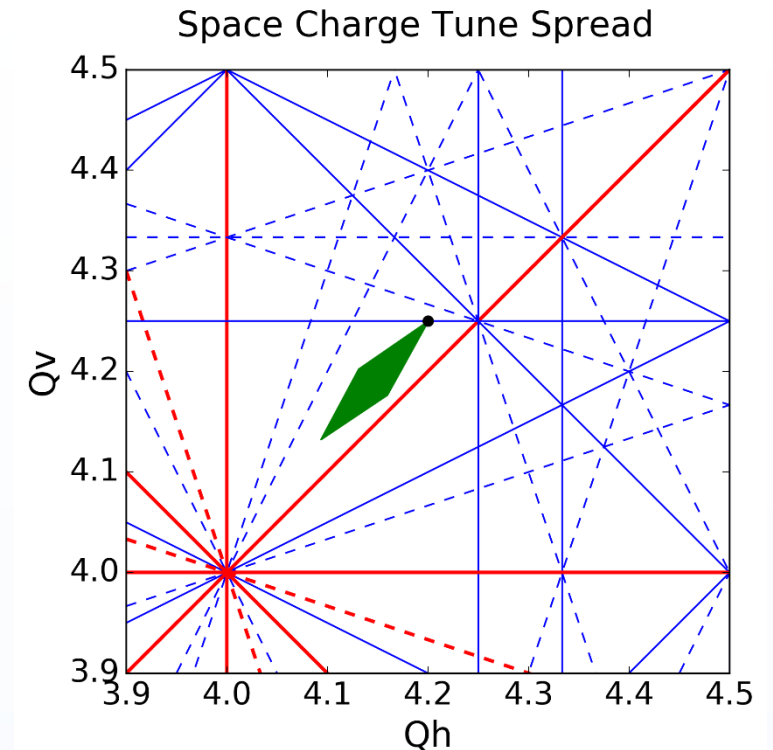
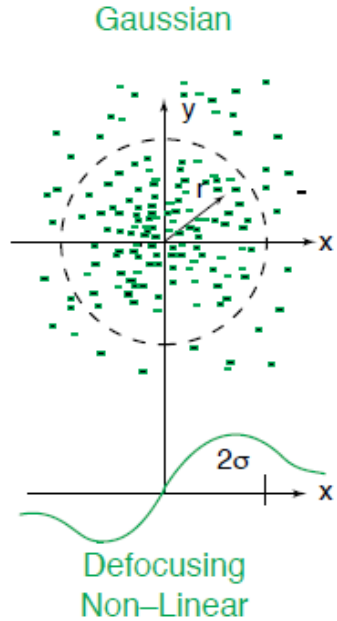
Non-Linear **continuous** kick

Interplay with resonances?

Directly

Indirectly

Drives **systematic resonances**  
of **even** order



# Resonance Driving Terms

- The Hamiltonian in the presence of the space charge force becomes

$$H = \frac{1}{2} (K_1 x^2 + K_2 y^2 + p_x^2 + p_y^2) + V_{sc}$$

Magnetic fields gradients    Perturbing potential

- Assuming Gaussian beam the space charge potential is:

$$V_{sc}(x, y) = \frac{K_{sc}}{2} \int_0^\infty \frac{-1 + e^{-\frac{x^2}{2\sigma_x^2+t} - \frac{y^2}{2\sigma_y^2+t}}}{\sqrt{(2\sigma_x^2+t)(2\sigma_y^2+t)}} dt$$

- Expanding this potential all even orders are present

- Up to 4<sup>th</sup> order it yields:

$$-\frac{K_{sc}}{2} \left[ \left( \frac{x^2}{\sigma_x(\sigma_x + \sigma_y)} + \frac{y^2}{\sigma_y(\sigma_x + \sigma_y)} \right) - \left( \frac{(2\sigma_x + \sigma_y)x^4}{12\sigma_x^3(\sigma_x + \sigma_y)^2} + \frac{(2\sigma_y + \sigma_x)y^4}{12\sigma_y^3(\sigma_x + \sigma_y)^2} + \frac{x^2 y^2}{2\sigma_x \sigma_y (\sigma_x + \sigma_y)^2} \right) \right]$$

# Resonance Driving Terms

- Carrying out Floquet transformation we can express the potential as

$$V_{sc}(x, y) \rightarrow V_{sc}(J_x, J_y, \psi_x, \psi_y, \theta)$$

- For a given resonance:

$$V_{sc}(J_x, J_y, \psi_x, \psi_y, \theta)_{m,n,l} \approx \sum |G_{m,n,l}| J_x^{m/2} J_y^{n/2} \cos(m\psi_x + n\psi_y - l\theta + \chi_{m,n,l})$$

- Expanding this potential in Fourier harmonics around the machine the resonance strength and phase can be estimated:

$$G_{m,n,l} e^{j\chi_{m,n,l}} \approx \frac{1}{4\pi} \int V_{sc\,m,n,l} \beta_x^{m/2} \beta_y^{n/2} e^{j(m\varphi_x + n\varphi_y - mQ_x - nQ_y + l\theta)} ds$$

# Resonance Driving Terms

- The above have been implemented into a python script for any machine any resonance
- Input:
  - Resonance order
  - Working point
  - MADx twiss files
  - Beam parameters (Intensity, Emittances,  $\Delta p/p$  etc.)
- Output:
  - Amplitude and phase of the resonance strength

*G.Guignard, CERN 76-06 (1976)*

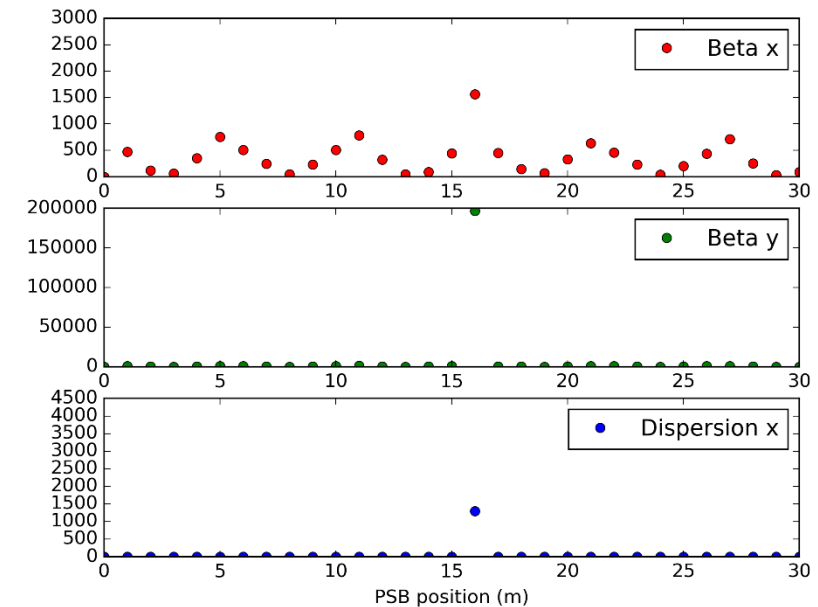
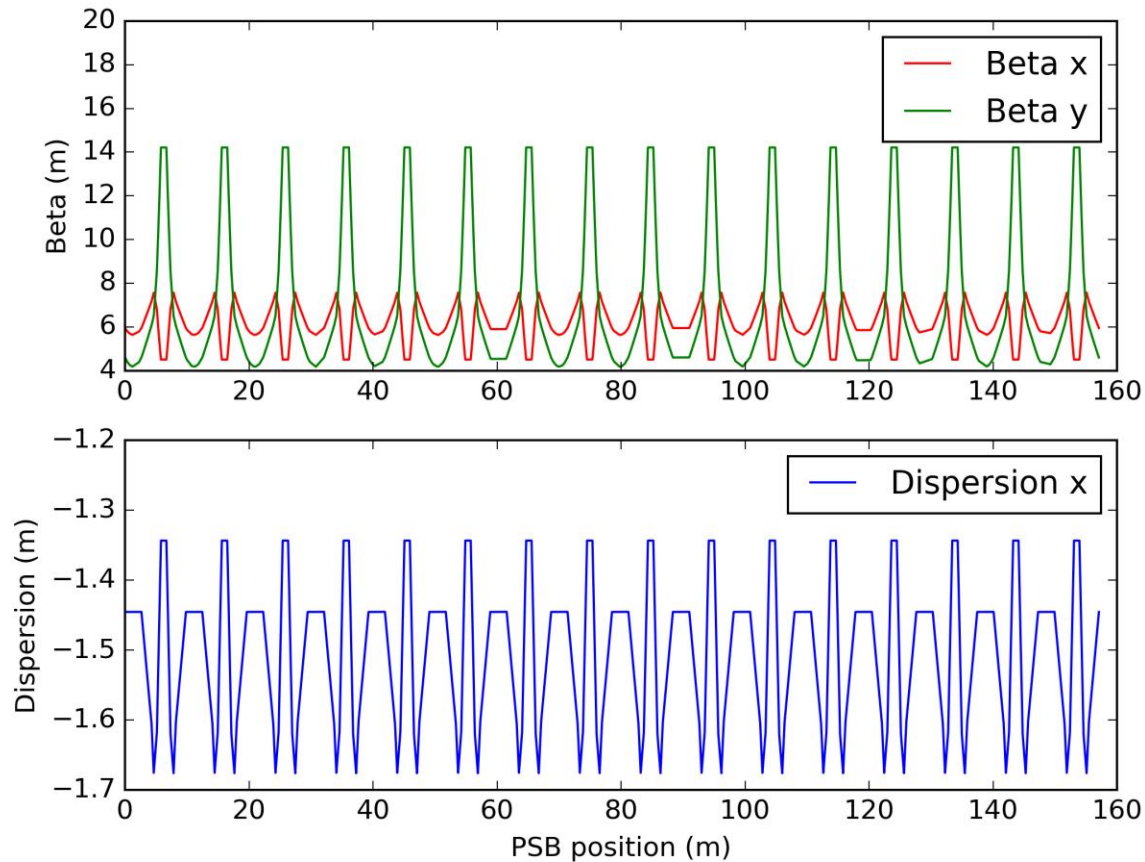
*S.Machida, Space-charge-induced resonances in a synchrotron, Nuclear Instruments and Methods in Physics Research A (1997)*

*S.Y.Lee et.al, Emittance growth mechanisms for space charge dominated beams in fixed field alternating gradient and proton driver rings, New Journal of Physics 8 (2006)*

*S.Y.Lee, Accelerator Physics 3<sup>rd</sup> Edition (2012)*

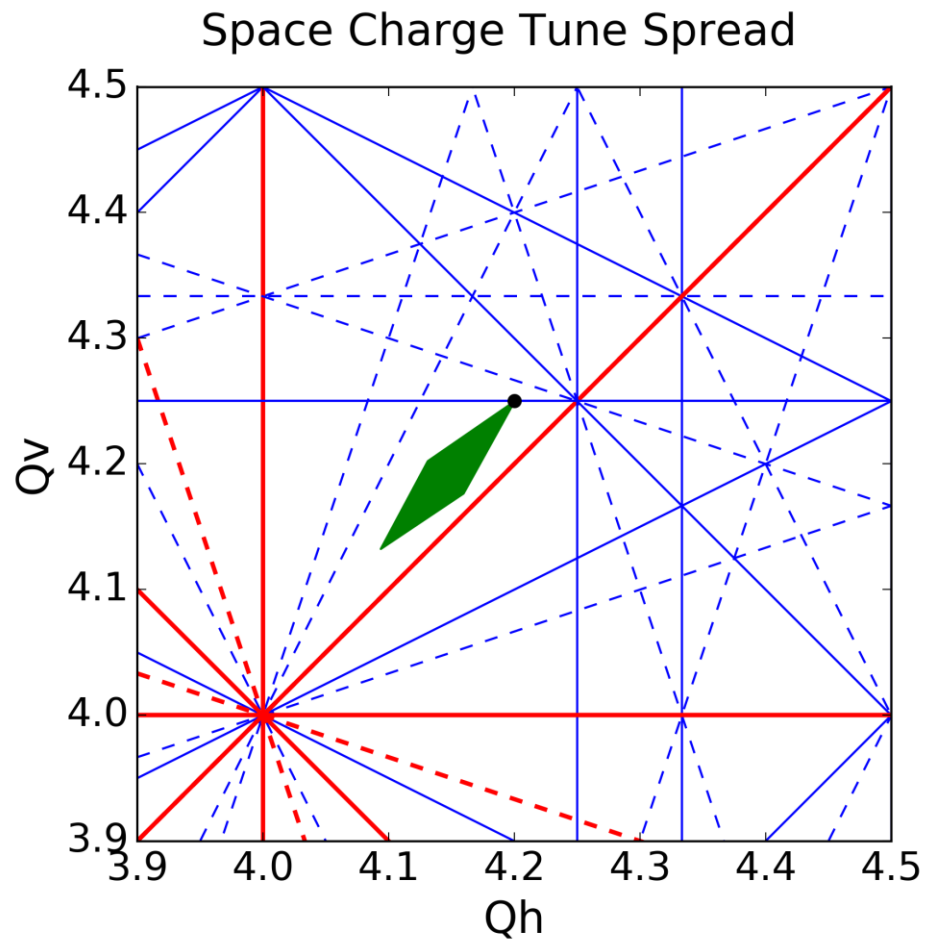
# PSB Q4Q4: Optics

Current Optics of the PSB at  $Q_h = 4.2$  and  $Q_v = 4.25$   
The lattice functions have a “strong” 16<sup>th</sup> harmonic





# PSB Q4Q4: Space Charge Considerations



Tune spread calculated for a round beam at the plateau of:  
 $E = 160 \text{ MeV}$  (Injection energy after LS2)

With:

$$e_x \cong e_y \cong 2 \text{ mm mrad}$$

$$\text{Intensity} \cong 100e10 \text{ ppb}$$

$$\text{Bunchlength} = 500\text{ns}$$

$$\Delta p / p_{rms} = 1.5e - 3$$

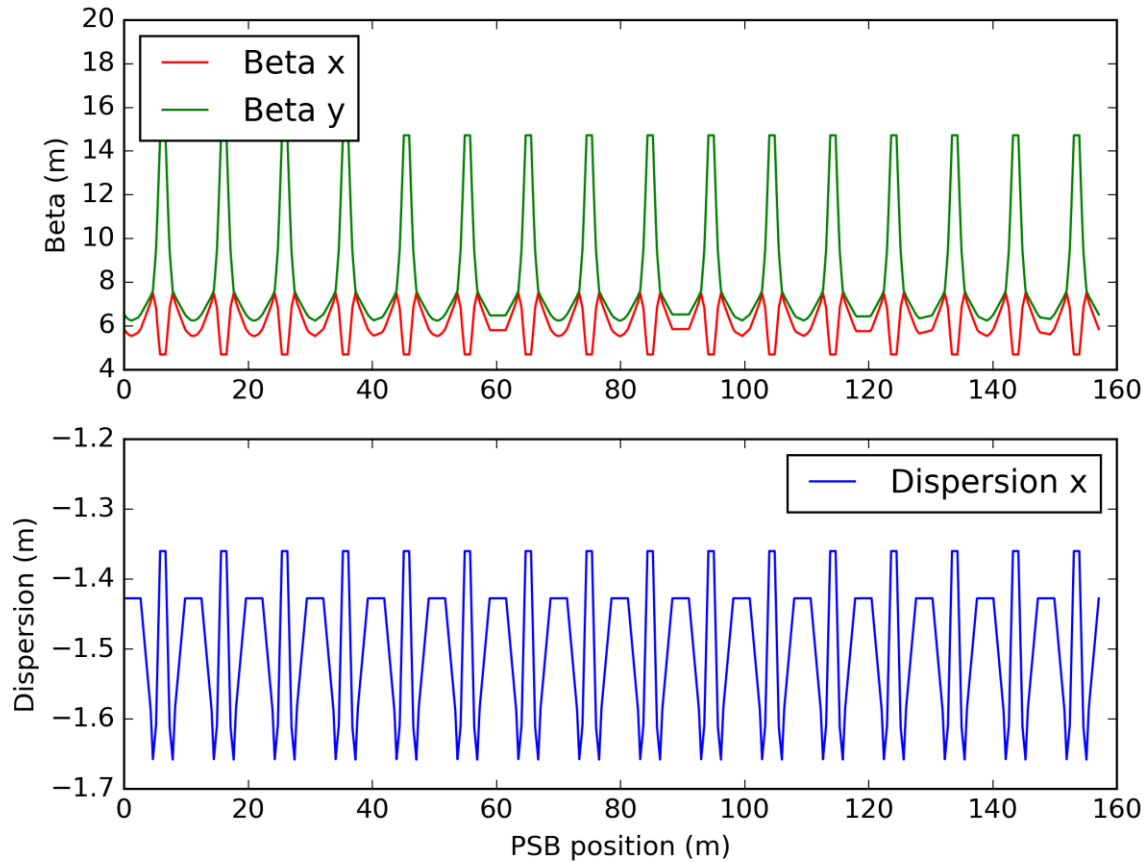
Assuming a periodicity of 16 for the lattice **4<sup>th</sup> order systematic resonances** are observed at  $4Q_v, 4Q_h = 16$

$$\text{and } 2Q_h - 2Q_v = 0$$

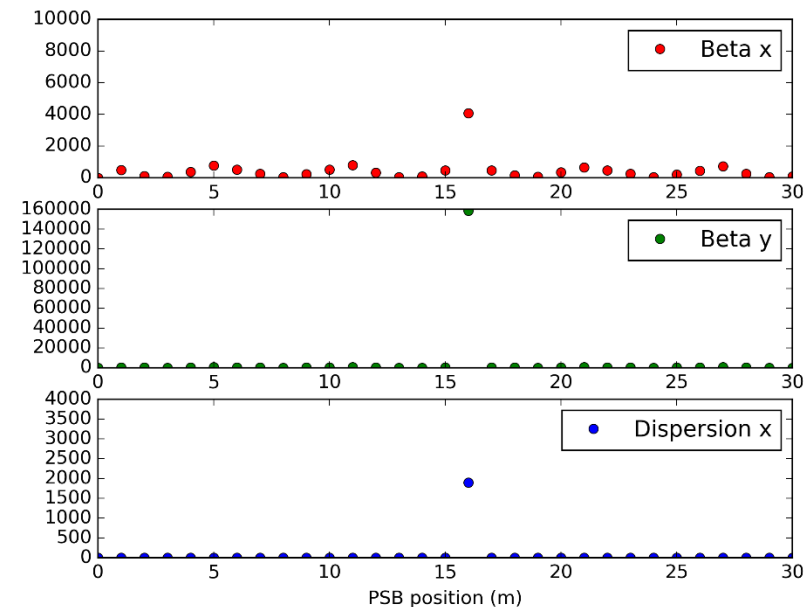
Those resonances could be further excited by space charge since they are of even order

***could a change of the Integer tune improve the available tune space?***

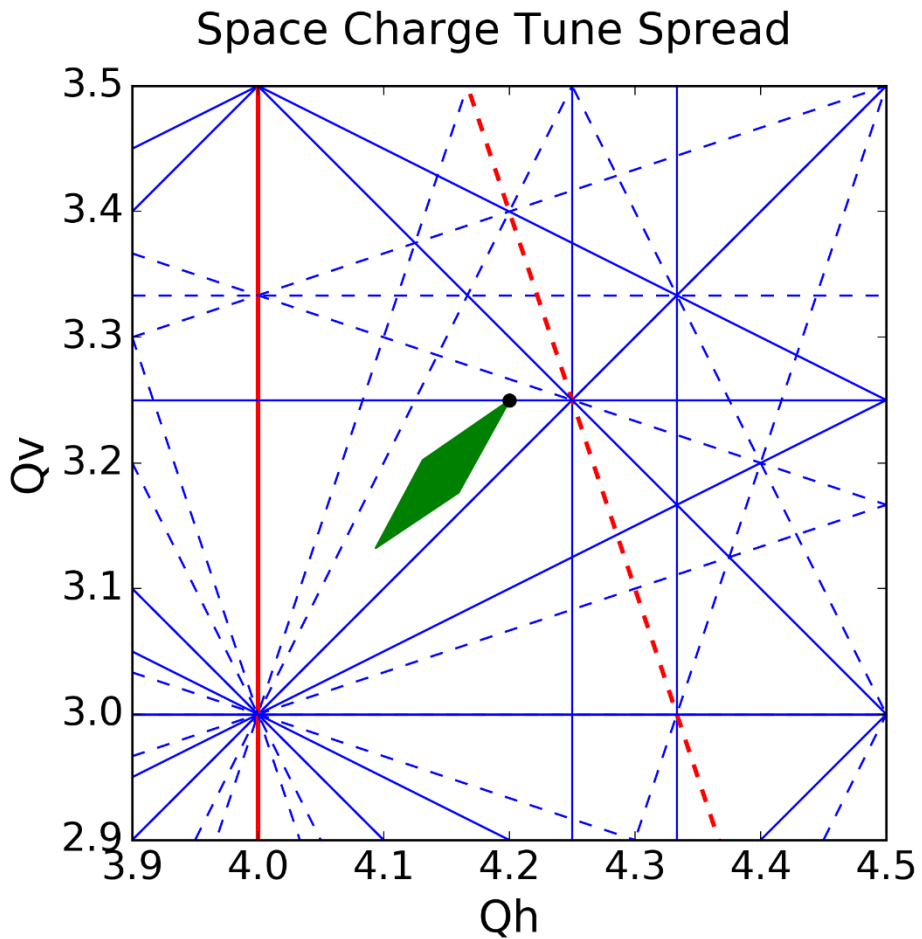
# PSB Q4Q3: Optics



Alternative working point optics of the PSB after changing the vertical integer tune at  $Q_h = 4.2$  and  $Q_v = 3.25$   
The lattice functions have again a “strong” 16<sup>th</sup> harmonic



# PSB Q4Q3: Space Charge Considerations



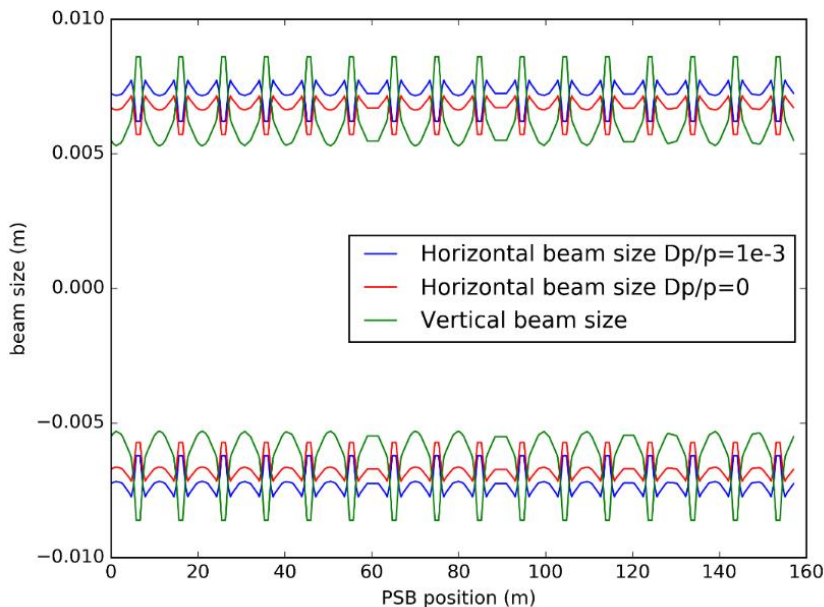
Tune spread calculated for the same beam injected at the new tunes of  $Q_h = 4.2$  and  $Q_v = 3.25$

Only one **4<sup>th</sup> order systematic resonance** is observed at  $4Q_h = 16$

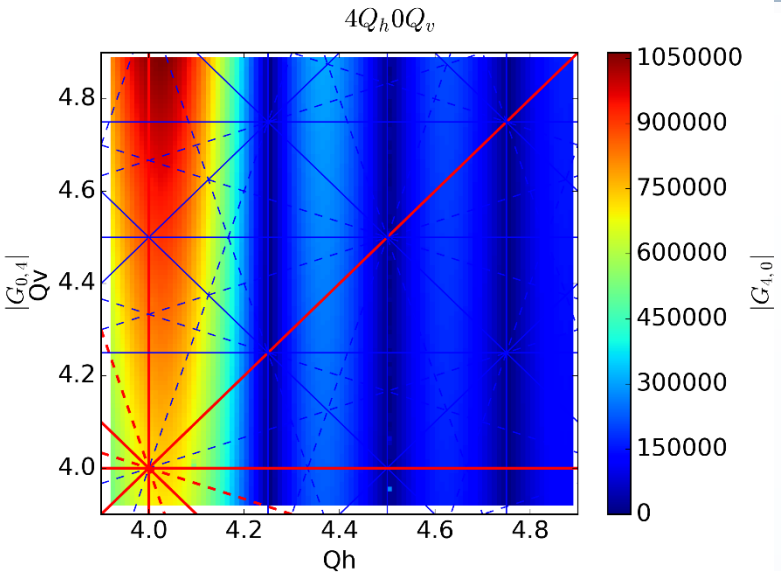
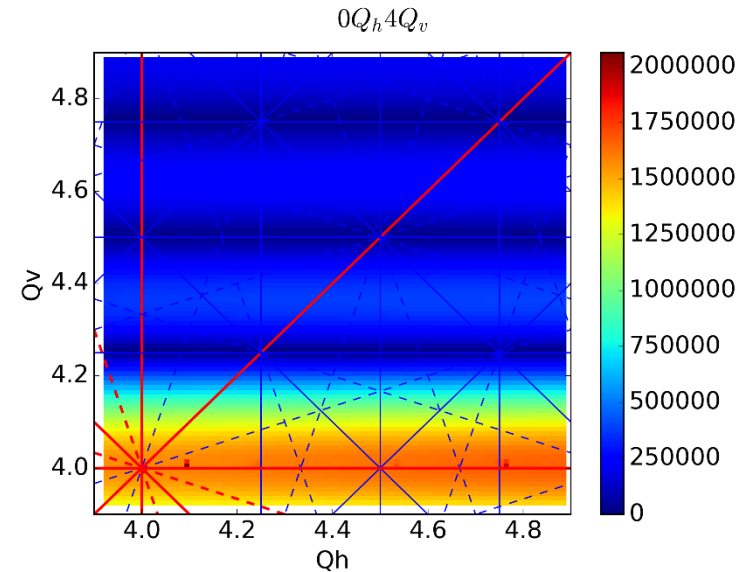
The vertical integer and the coupling in this case should not be excited by space charge since they should be suppressed by the lattice periodicity.

# PSB Q4Q4: Resonance Driving Terms

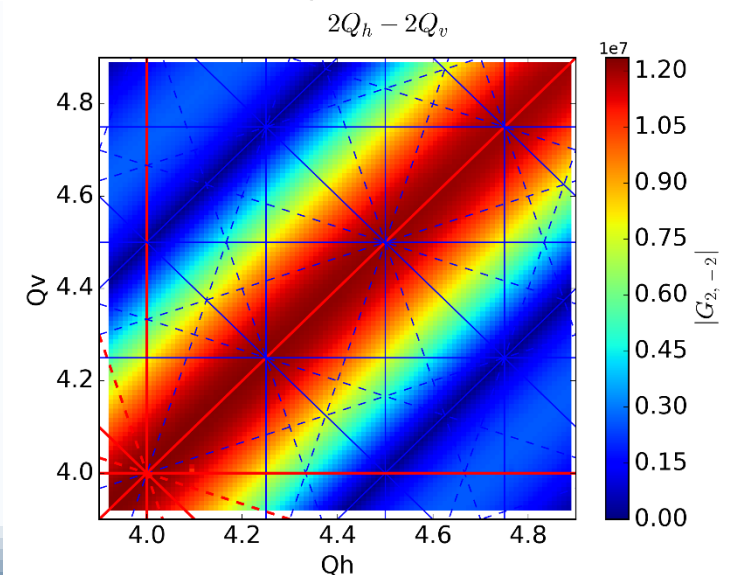
Calculation of the RDTs for the 4<sup>th</sup> order resonances coming from the space charge potential of a Gaussian beam. The beam size modulation even after including the dispersive component has the same periodicity as the lattice functions



7/2/2018



*Clear excitation of the 4<sup>th</sup> order **systematic** resonances from space charge. The non-systematic resonances are **suppressed**.*



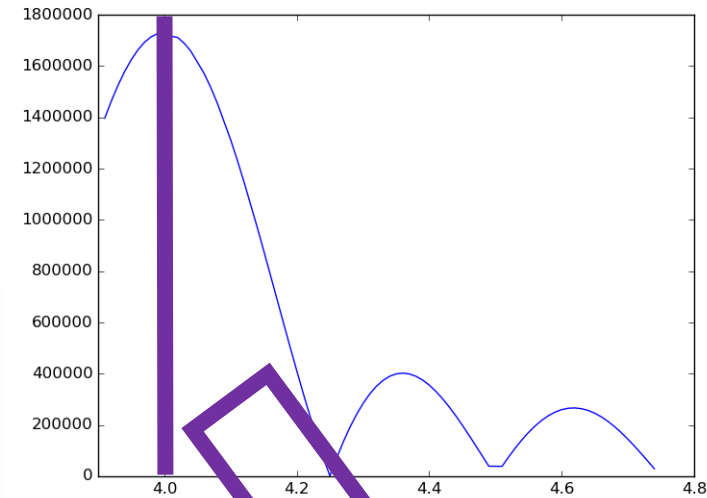
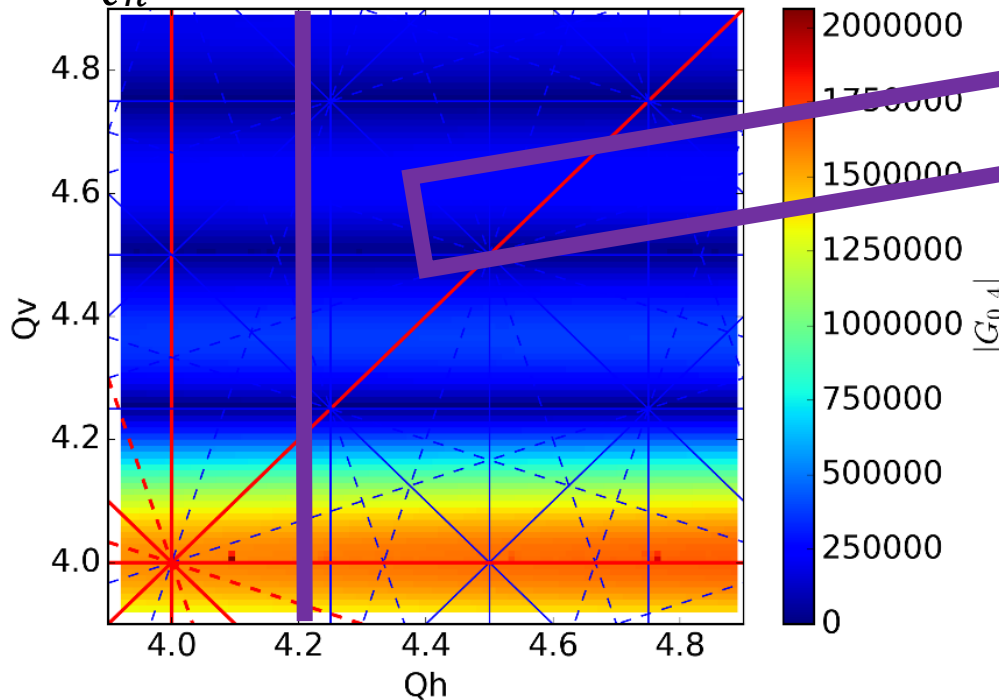
Foteini Asvesta

# PSB Q4Q4: Resonance Driving Terms

Following the driving term on a single line of the grid

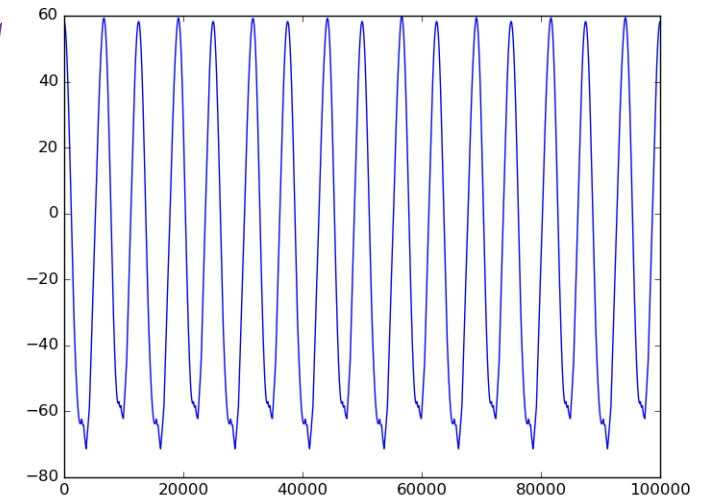
$$Q_h = 4.2$$

$$0Q_h4Q_v$$



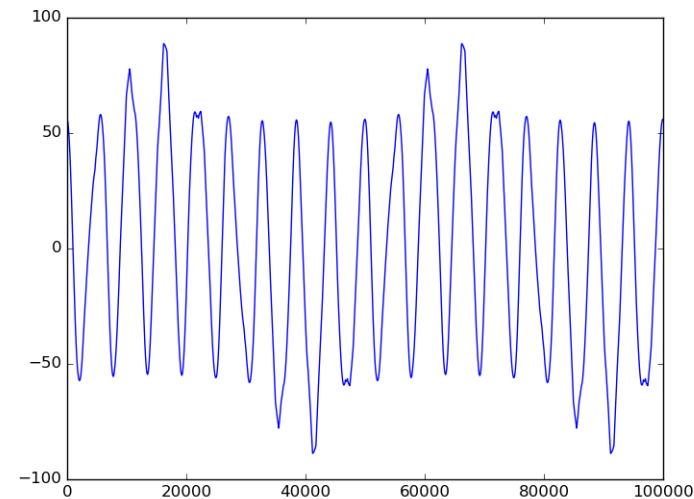
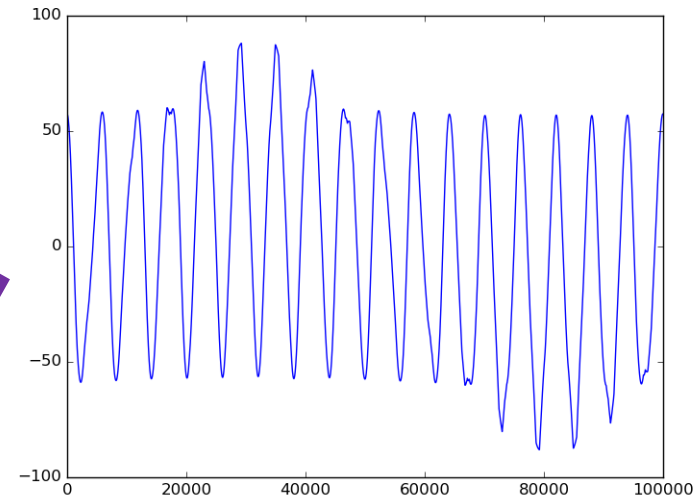
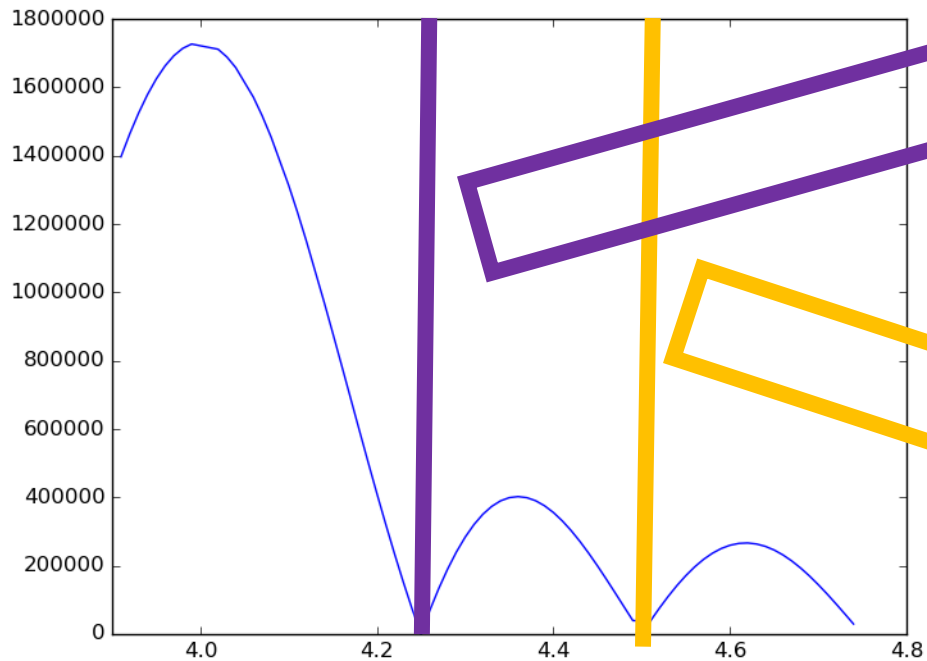
Following the driving term along the ring for the maximum excitation at  $Q_v = 4$

The driving term is adding up along the ring



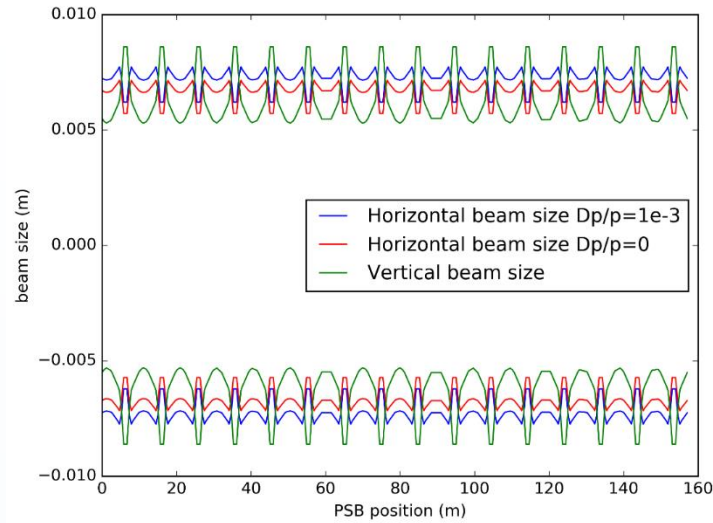
# PSB Q4Q4: Resonance Driving Terms

Following the driving term along the ring for the minima of excitation at  $Q_v = 4.25$  and  $Q_v \cong 4.5$

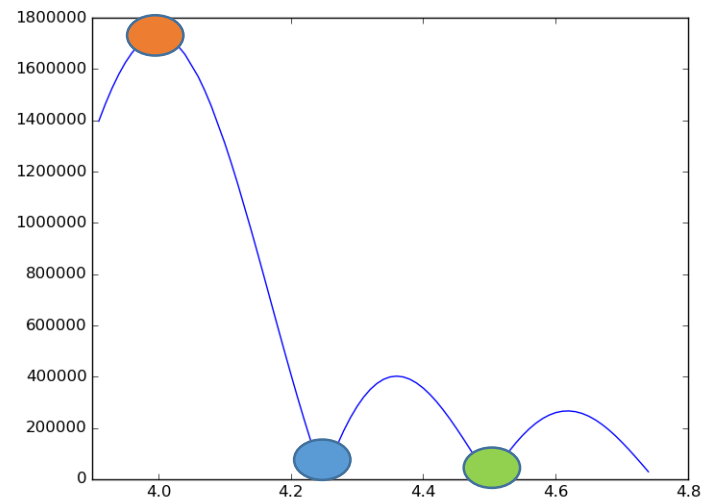
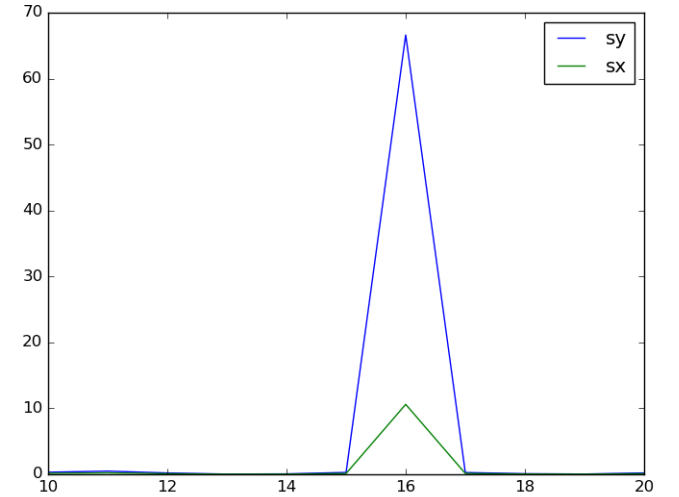


The driving term is cancelling out along the lattice since it does not have the same periodicity

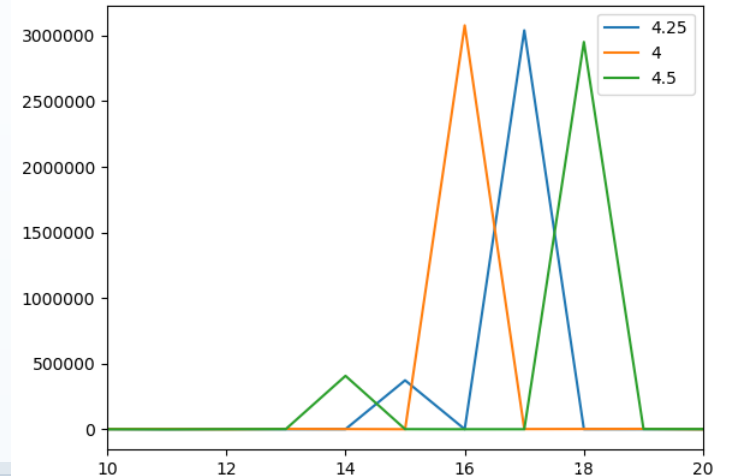
# PSB Q4Q4: Resonance Driving Terms



Fourier Analysis of the beam size



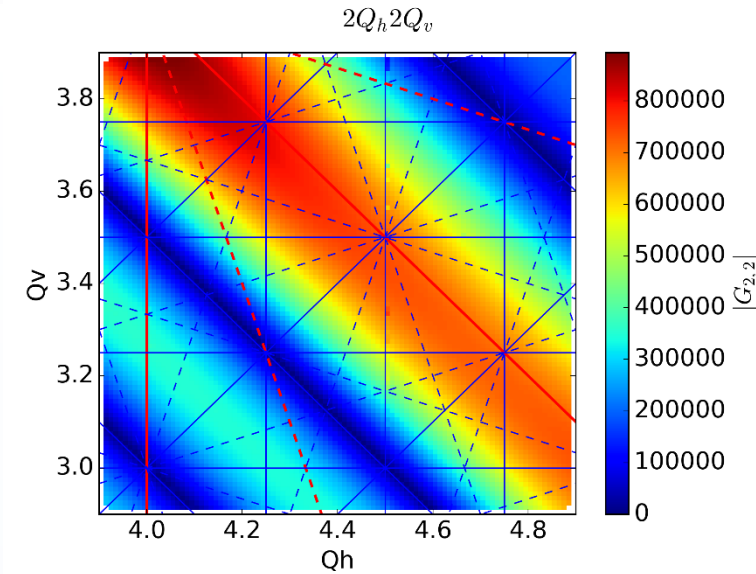
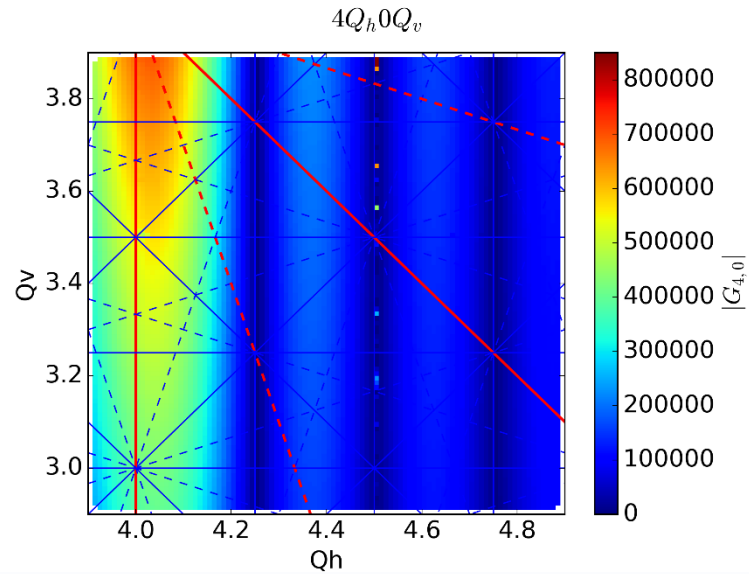
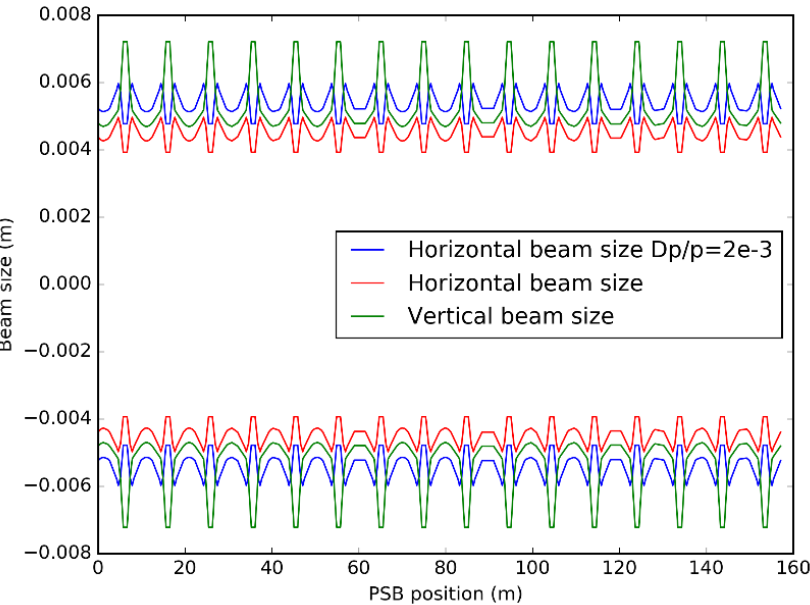
Fourier Analysis of the rdt along the ring





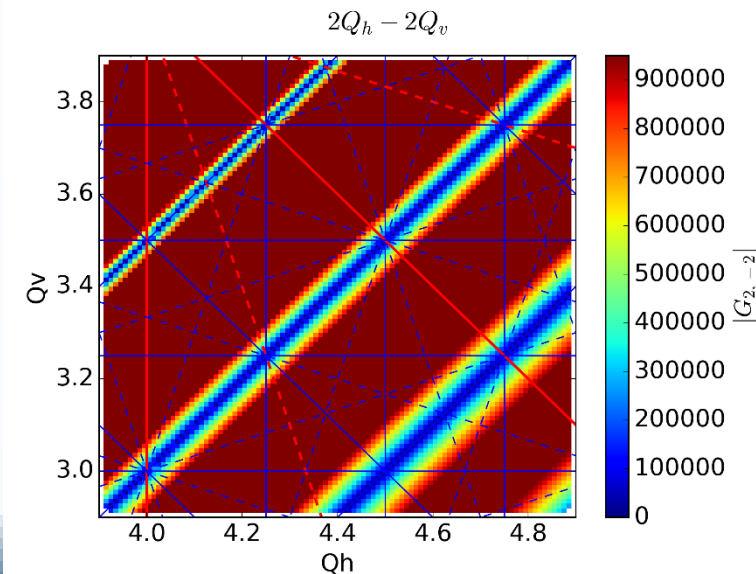
# PSB Q4Q3: Resonance Driving Terms

Calculation of the RDTs for the 4<sup>th</sup> order resonances coming from the space charge potential of a Gaussian beam. The beam size modulation even after including the dispersive component has the same periodicity as the lattice functions



*The coupling resonance is suppressed since it's not systematic in this configuration*

*Could this be seen in MDs?*





# Experimental Set-up

Machine Development studies are ongoing in the PSB in an effort to check the Montague resonance, which should be excited in the Q4Q4 but not in the Q4Q3 configuration

## ***1. Can we inject in the Q4Q3?***

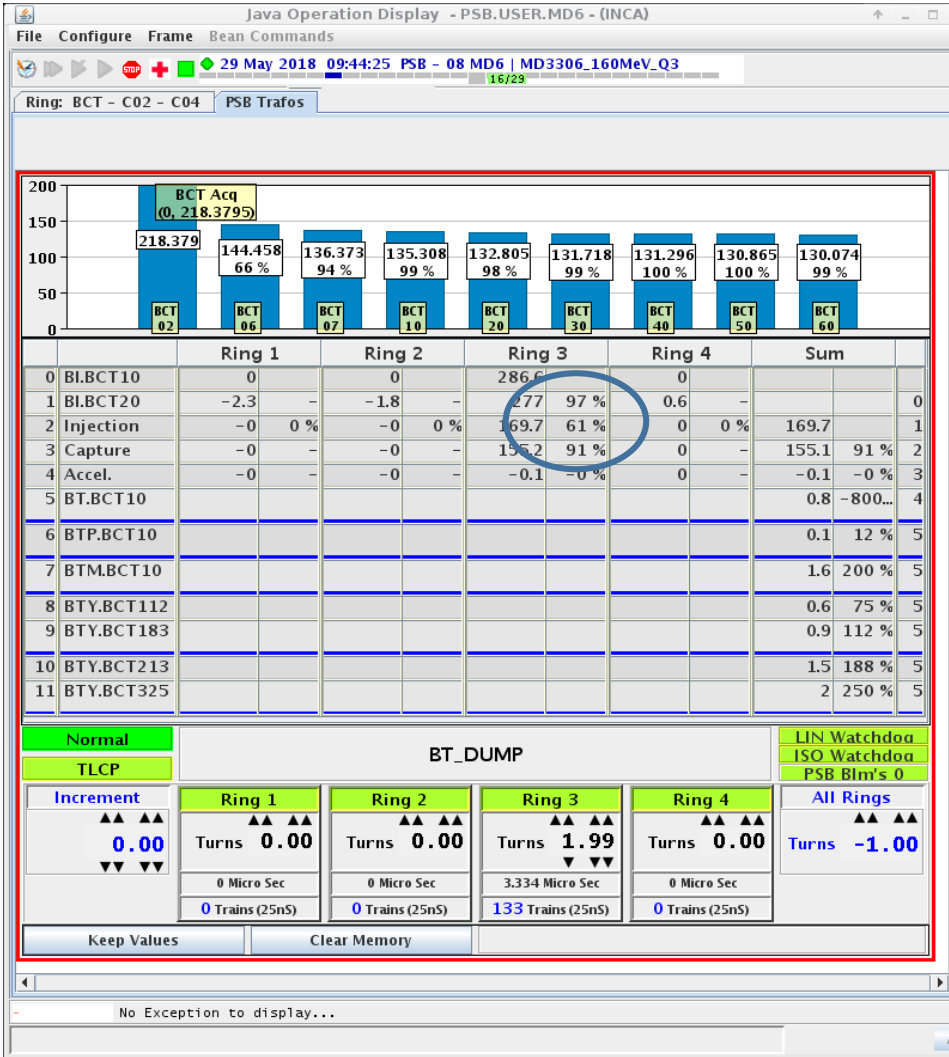
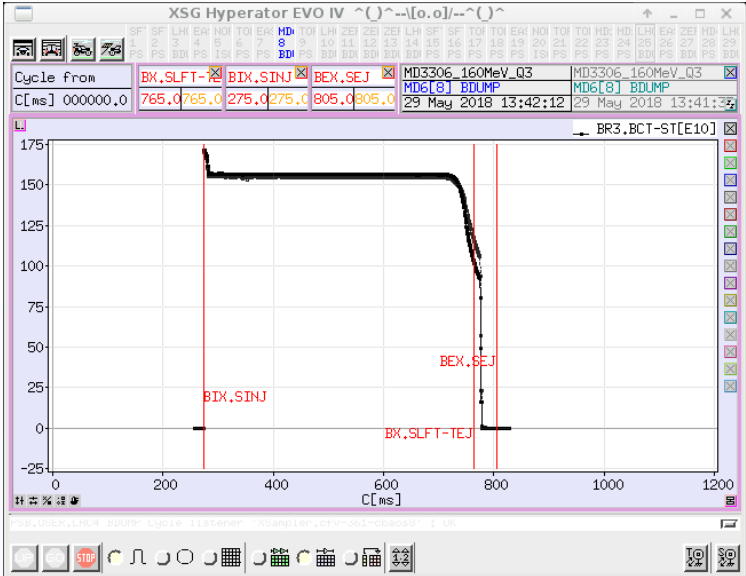
# Experimental Set-up

Injecting in the Q4Q3 Optics after optimizations

Injection efficiency → 61%

Capture → 91%

No Losses in the plateau of 160MeV that we are interested in (400-600ms)



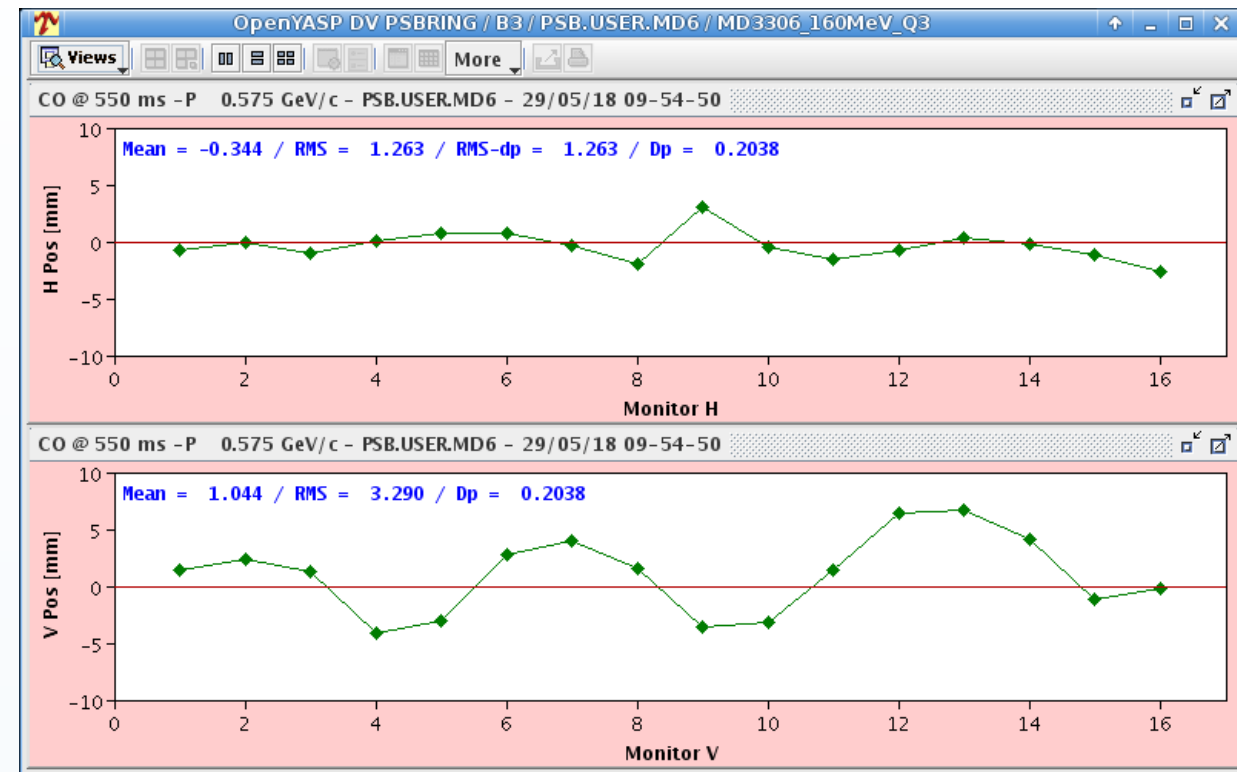
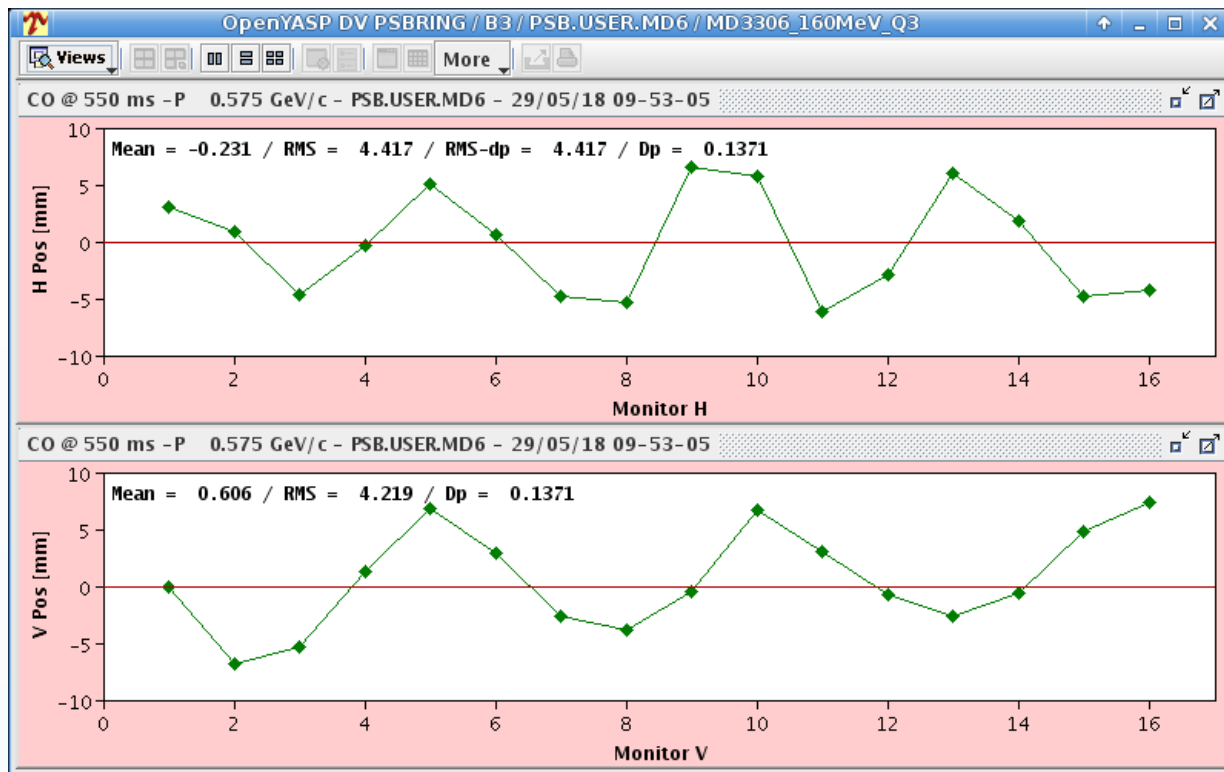
# Experimental Set-up

Machine Development studies are ongoing in the PSB in an effort to check the Montague resonance, which should be excited in the Q4Q4 but not in the Q4Q3 configuration

- 1. Can we inject in the Q4Q3?***
- 2. Is the Integer of the Vertical Tune 3?***

# Experimental Set-up

Checking the Orbit without and with the orbit correctors we clearly see the 3 peaks in the vertical plane hinting at the integer tune.



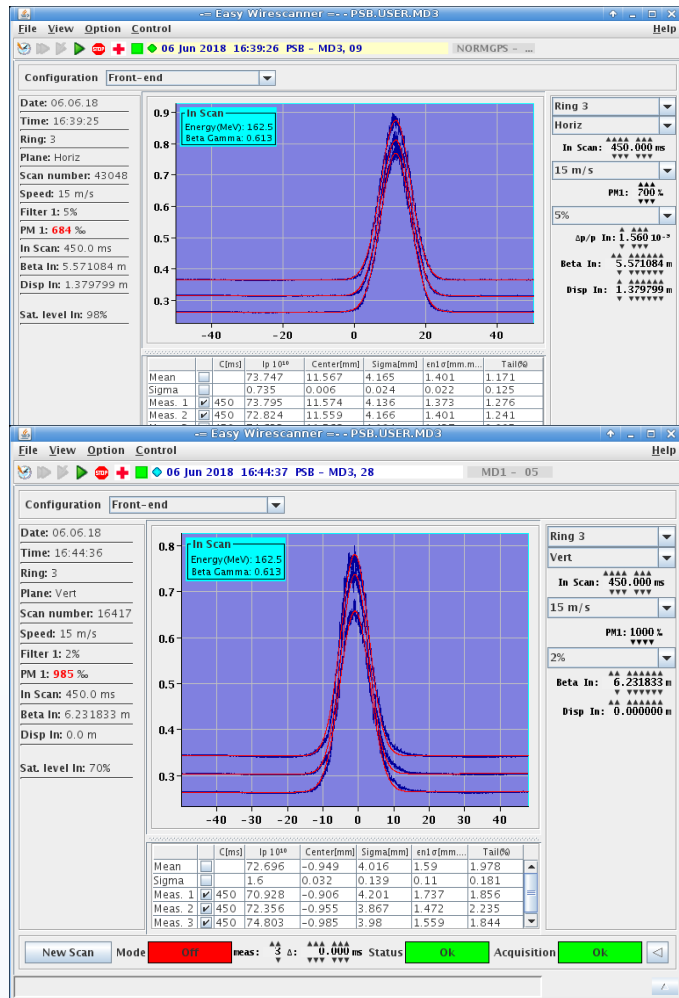
# Experimental Set-up

Machine Development studies are ongoing in the PSB in an effort to check the Montague resonance, which should be excited in the Q4Q4 but not in the Q4Q3 configuration

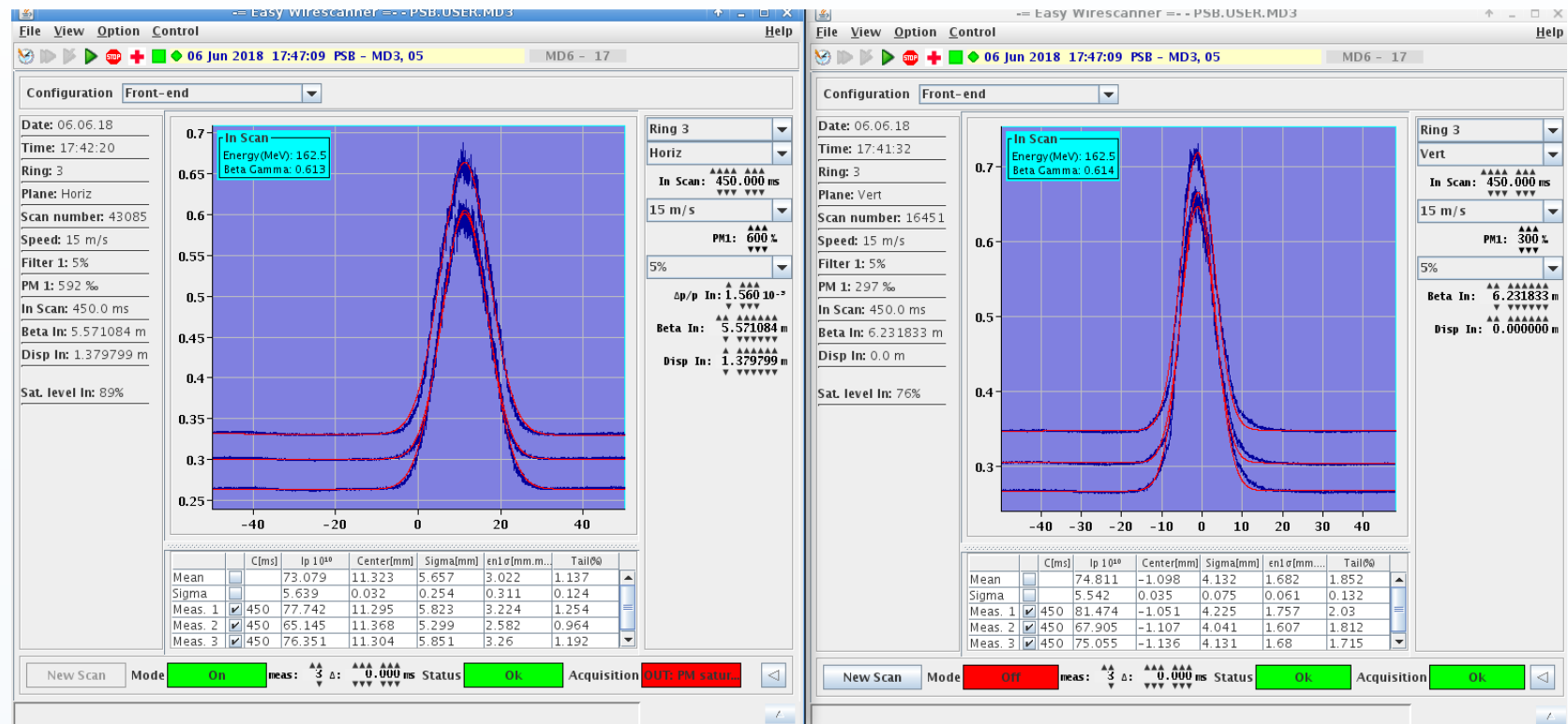
- 1. Can we inject in the Q4Q3?***
- 2. Is the Integer of the Vertical Tune 3?***
- 3. Can we produce flat beams to be able to see the emittance exchange while crossing the coupling?***

# Experimental Set-up

Starting from round beam



Working point moved close to the integer at injection to blow up the beam at one plane producing a flatter beam

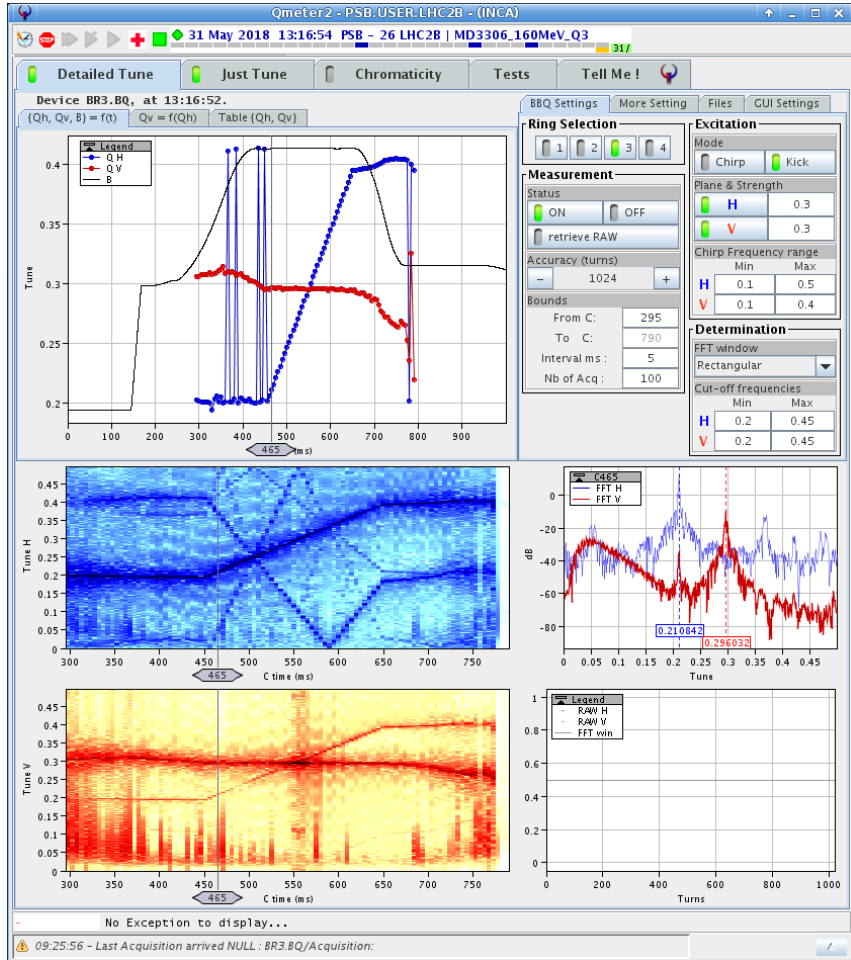


# Experimental Set-up

Machine Development studies are ongoing in the PSB in an effort to check the Montague resonance, which should be excited in the Q4Q4 but not in the Q4Q3 configuration

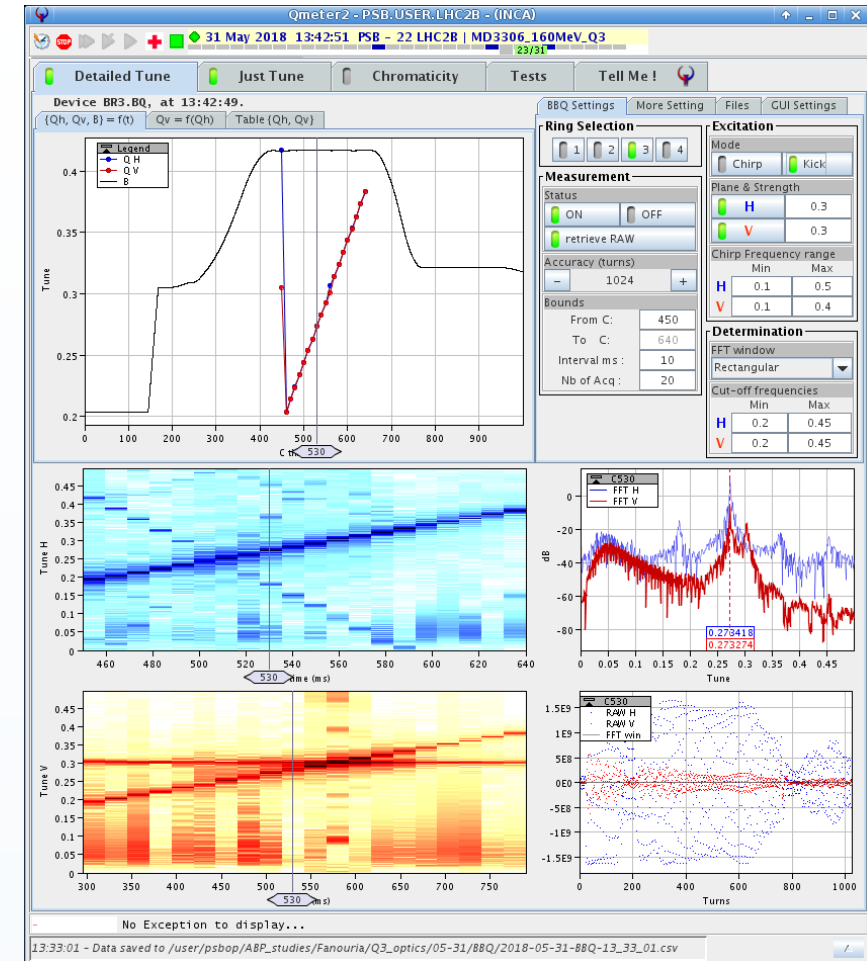
- 1. Can we inject in the Q4Q3?***
- 2. Is the Integer of the Vertical Tune 3?***
- 3. Can we produce flat beams to be able to see the emittance exchange while crossing the coupling?***
- 4. Can the coupling be sufficiently corrected to test whether space charge is the main reason for the excitation?***

# Machine Development Studies



Even though the tunes can be crossed using the closest tune approach we always observe horizontal tune in the spectrum of the vertical and most of the times as the main peak

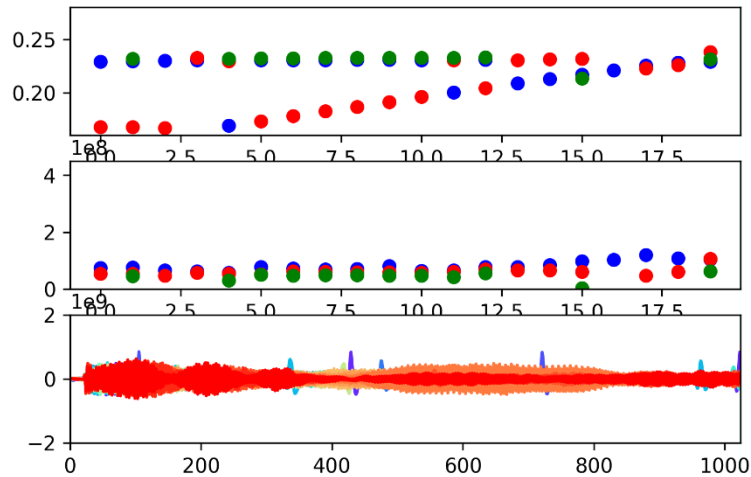
**Further optimizations needed**





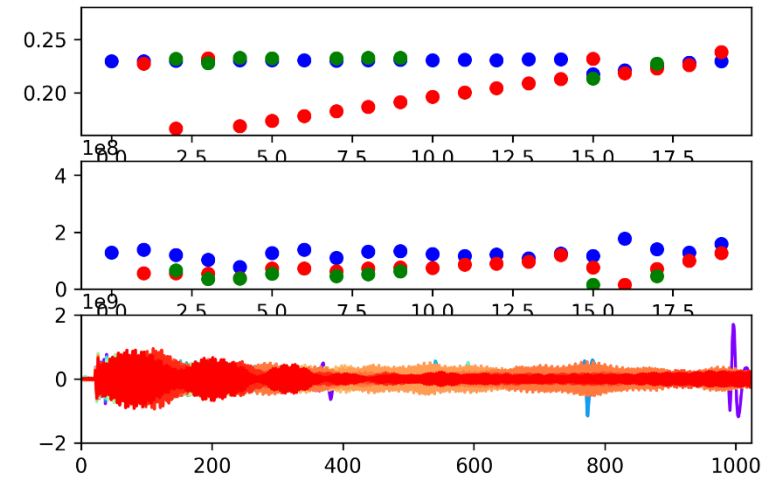
# Machine Development Studies

Skew= -2.796757221221924

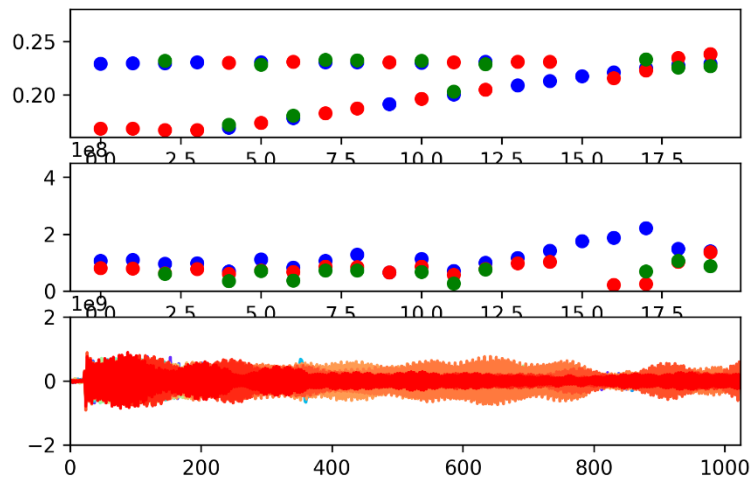


Tunes and Amplitudes required from the analysis of the horizontal raw data

Skew= -0.17762774229049683

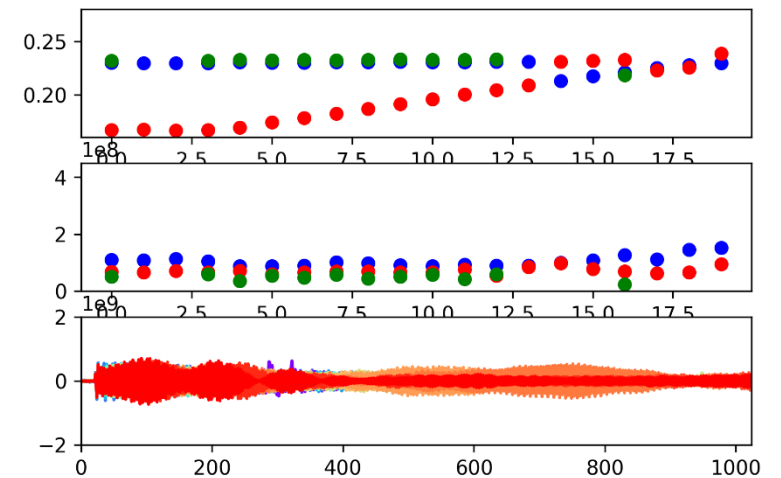


Skew= 0.34158968925476074



The vertical tune is always present in the horizontal data spectrum with comparable amplitudes regardless of the current in the Skew Quads

Skew= 3.7427167892456055



# Machine Development Studies

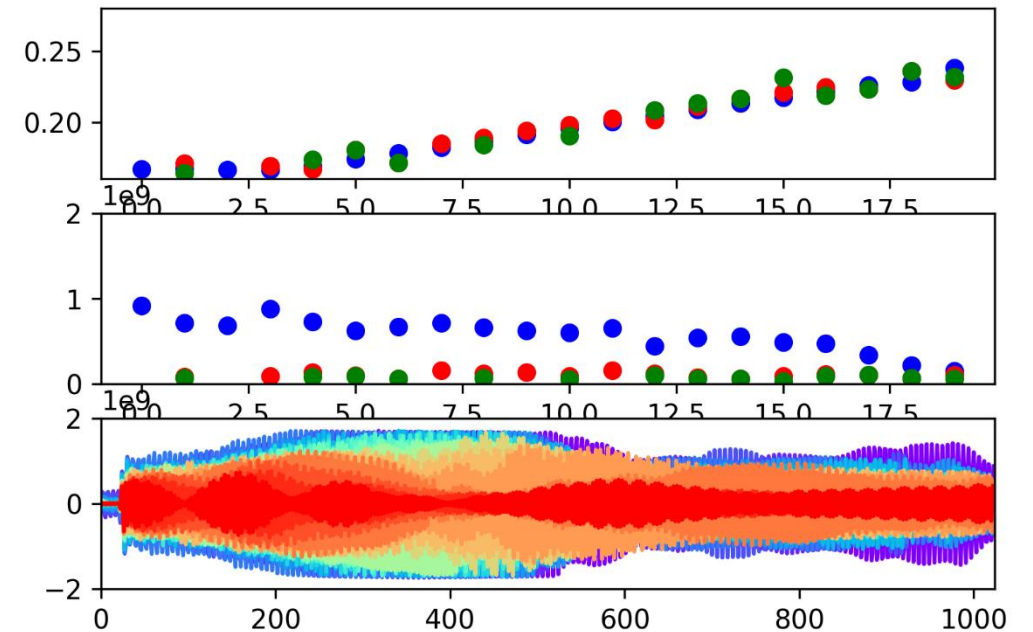
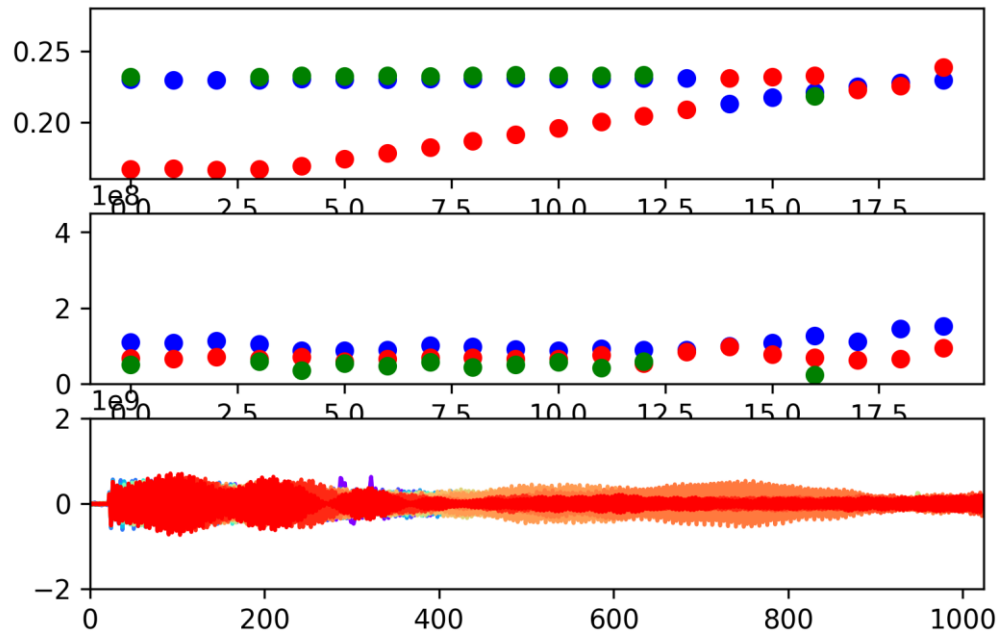
Tunes and Amplitudes required from the analysis of the **horizontal** raw data

Tunes and Amplitudes required from the analysis of the **vertical** raw data

Skew= 3.7427167892456055

Repeat measurement exciting each plane individually

Skew= 3.7427167892456055



# Summary

Space charge analytical studies have shown that the alternative tune configuration for the PSB at the Q4Q3 could be beneficial regarding the 4<sup>th</sup> order resonances.

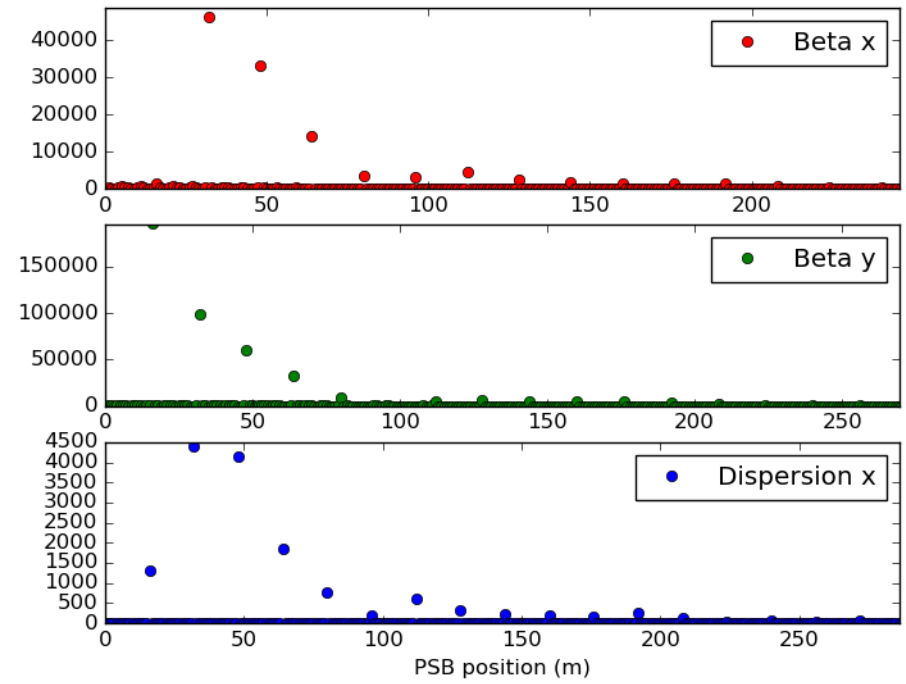
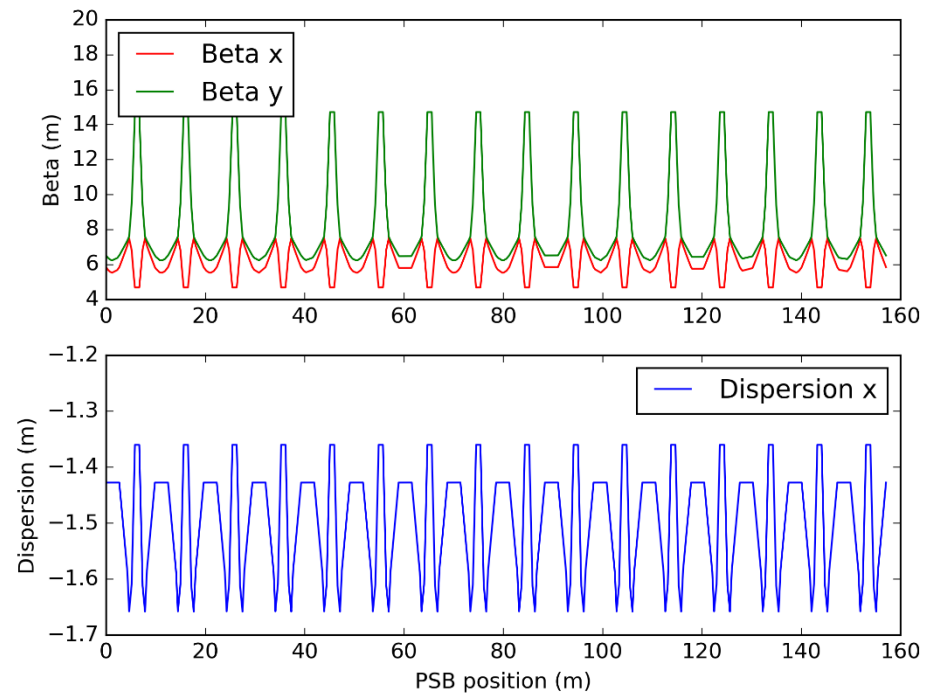
Setting up of the experimental studies for the space charge induced resonances in the new configurations is ongoing.

The first test will be the study of the Montague resonance in both optics (Q4Q4 and Q4Q3) once the setup is complete

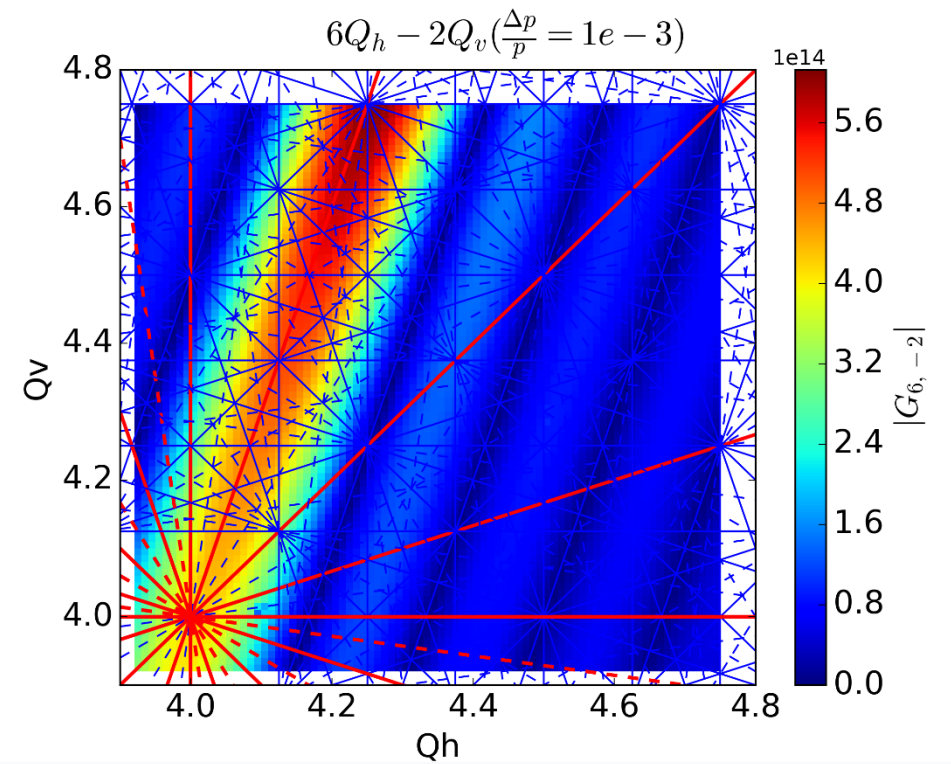
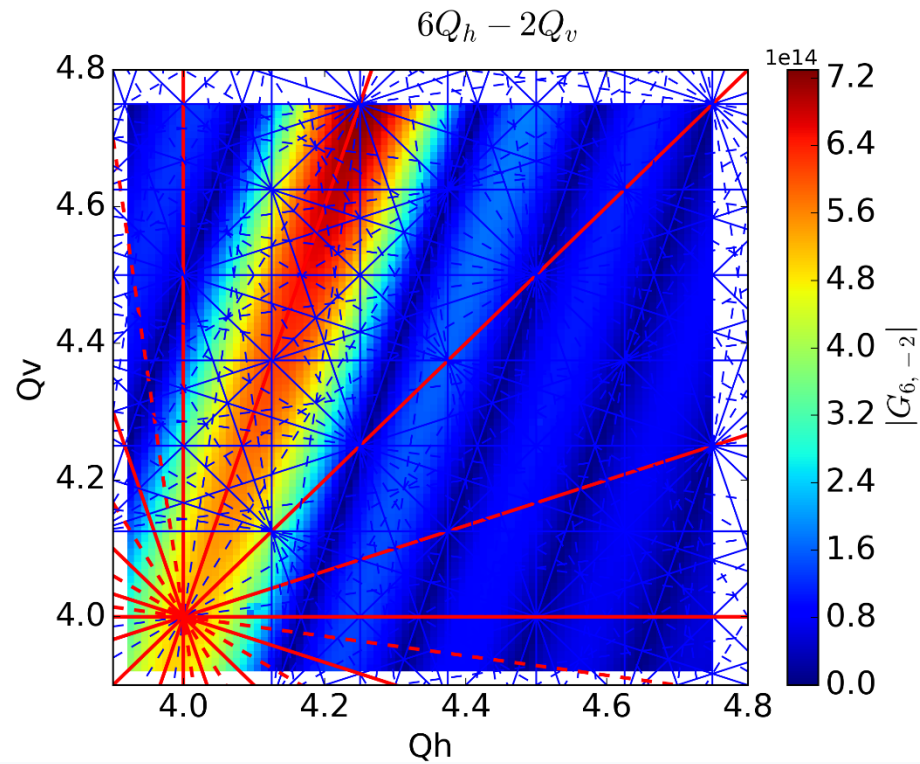
*To be continued.....*

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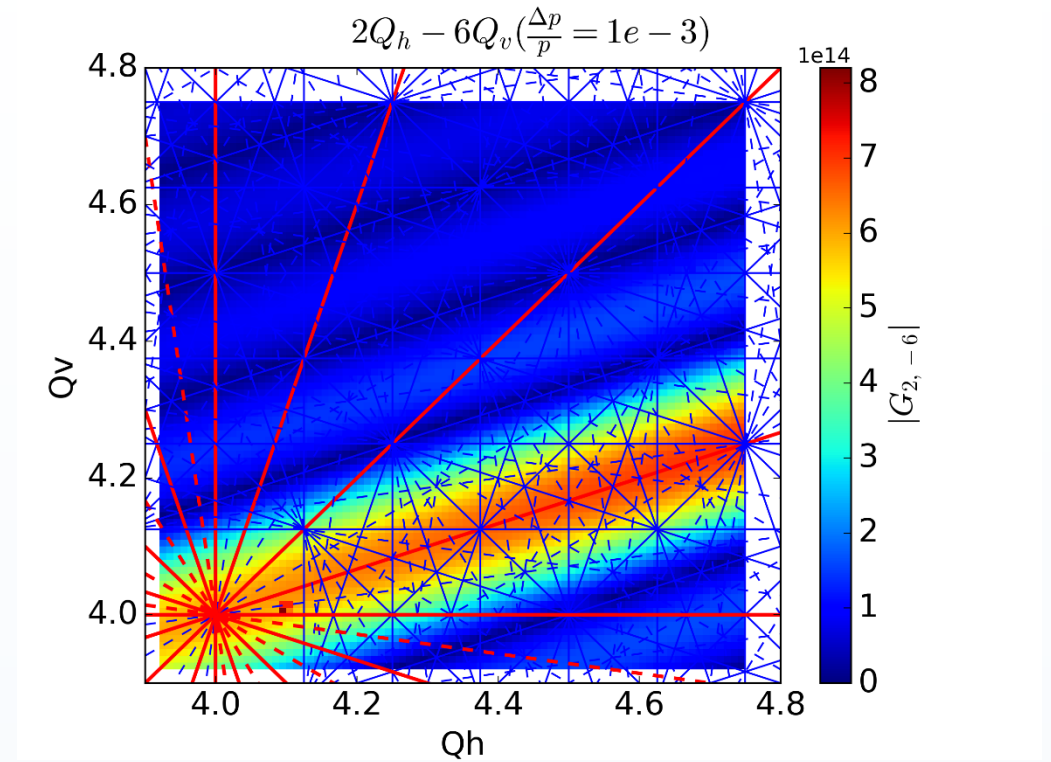
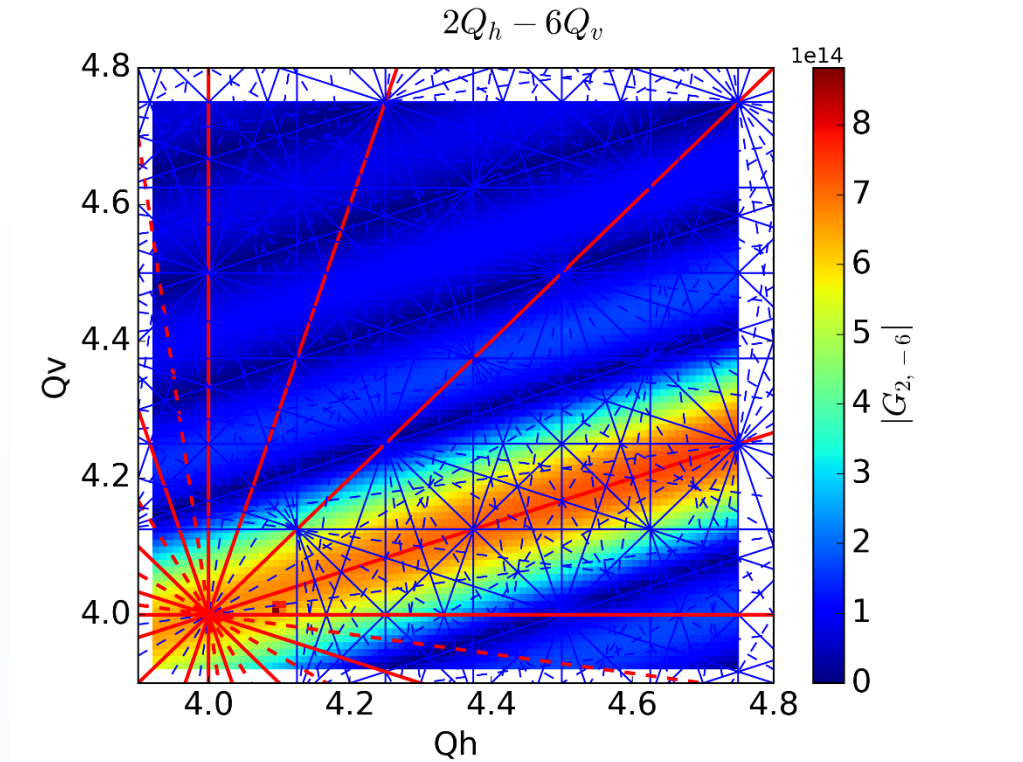
Back up



# 8<sup>th</sup> order

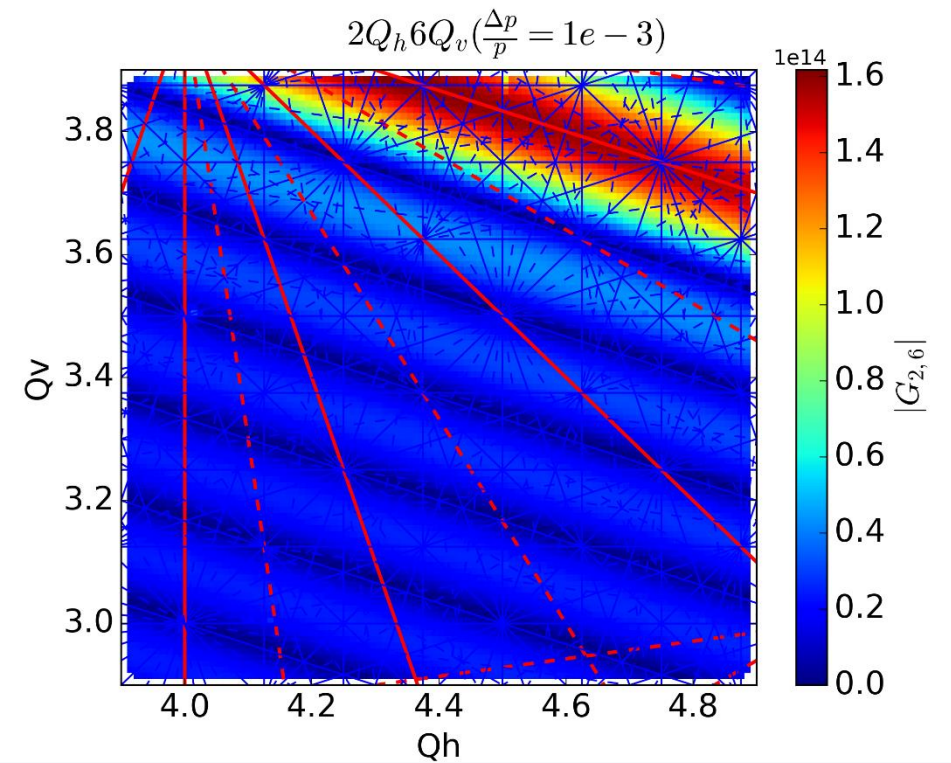
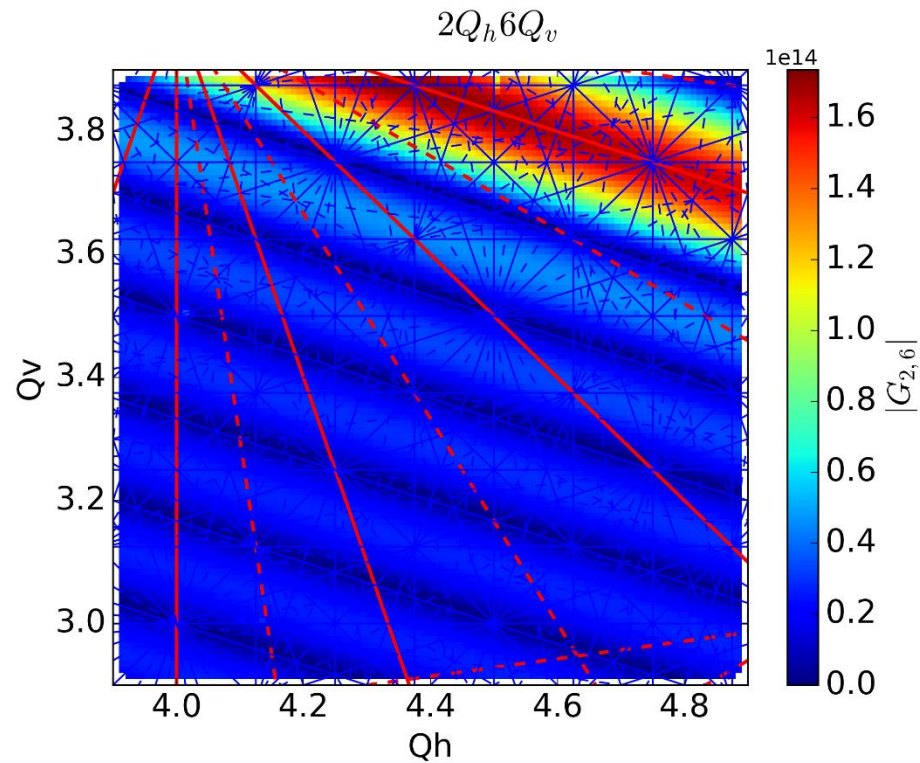


# 8<sup>th</sup> order





# 8<sup>th</sup> order





# 8<sup>th</sup> order

