Space charge driven resonances in the PS

F. Asvesta

H. Bartosik , H. Damerau, A. Huschauer, Y. Papaphilippou,

SCWG, PS-PSB OP-teams

Machine Studies Working Group

19/10/2018

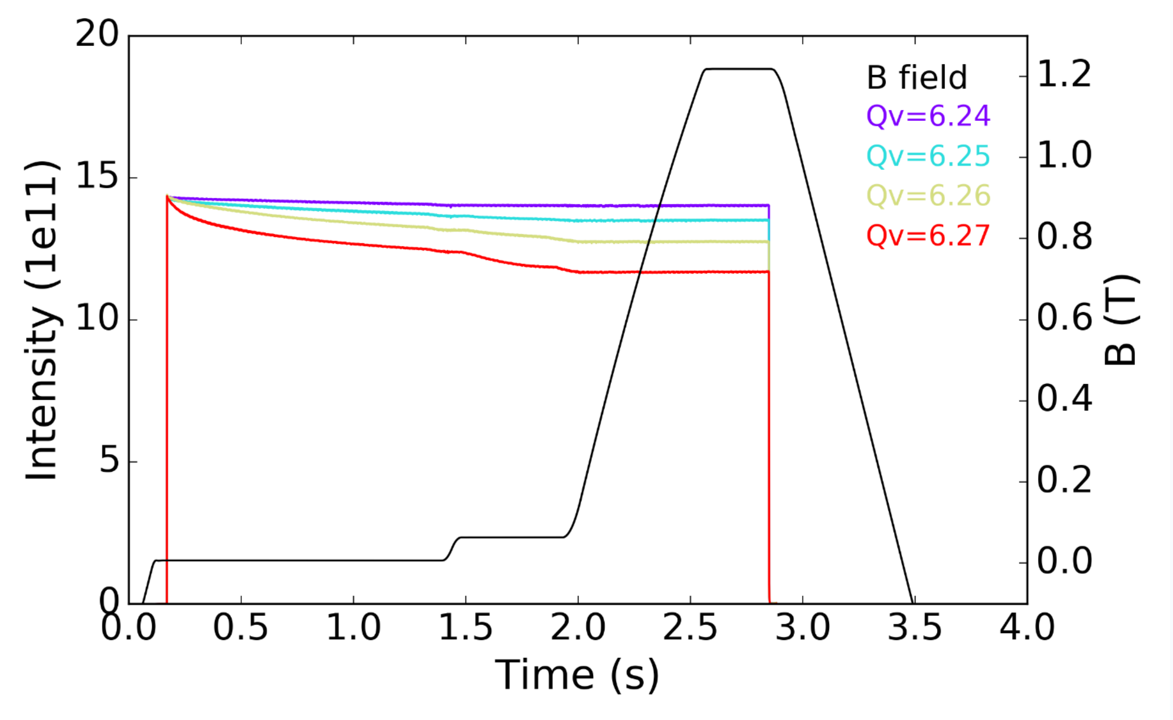
Overview

- Motivation
- Space charge
- Analytical Studies
- Frequency Map Analysis
- Machine Development & Simulation Studies
  - 3rd Order Skew Resonance Compensation
  - Static Tune Scans
    - High Brightness beam
    - Low Brightness beam
- Summary

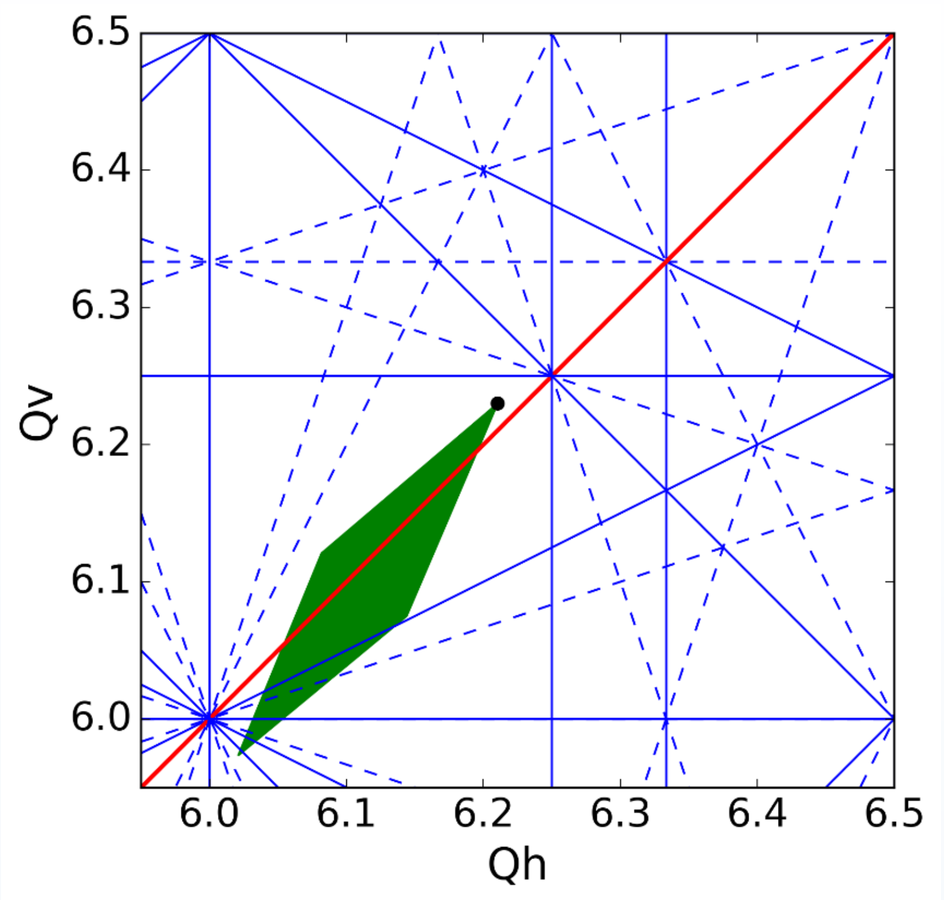
Motivation

Limitations towards the LIU goals for the PS performance connected to space charge:

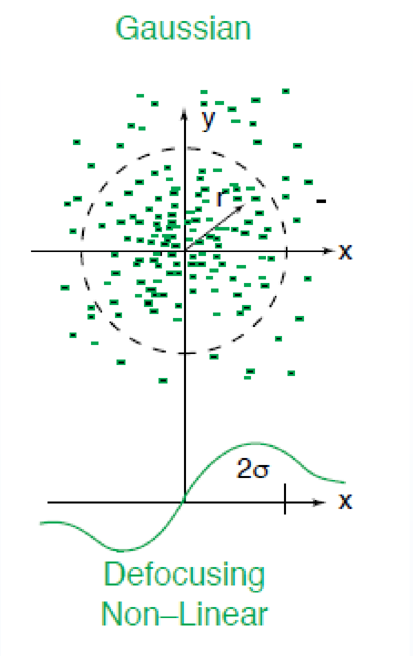
- Vertical integer resonance
- The $Q_v = 6.25$ **8th order structural resonance** (*S. Machida*, *R. Wasef et.al*).



Space charge tune spread in the PS for LHC-type beams.



Space Charge



$$F_r(r) = \frac{\lambda}{2\pi\varepsilon_0\gamma^2}\left(\frac{r}{2\sigma^2} - \frac{r^3}{8\sigma^2} + \cdots\right)$$

<u>Direct Space Charge</u>

⇩

Coulomb forces between the moving particles

⇩

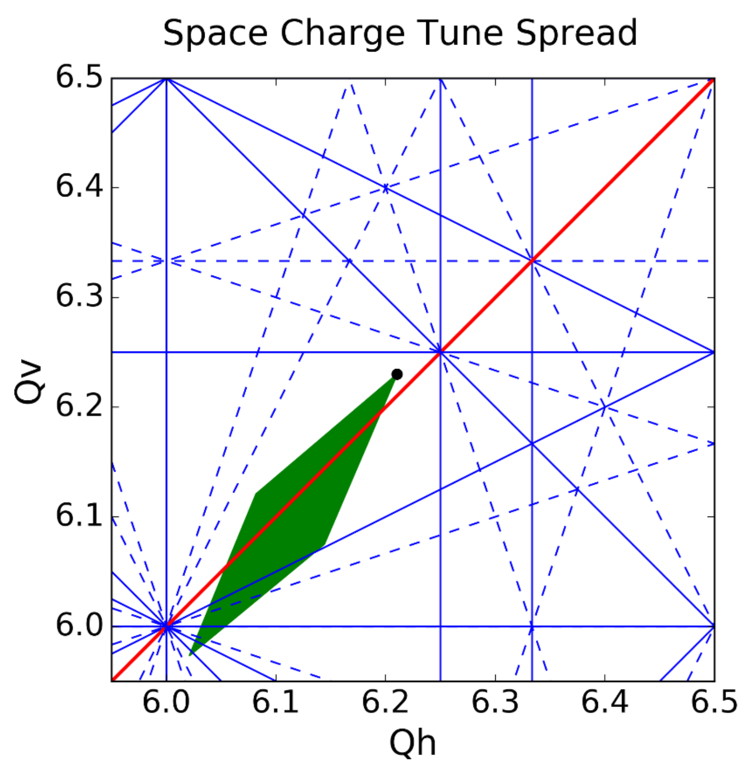
Self-fields that move with the beam

⇩

Non-Linear continuous kick

⇩

<u>Interplay with resonances?</u>



Directly: Drives systematic resonances of even order

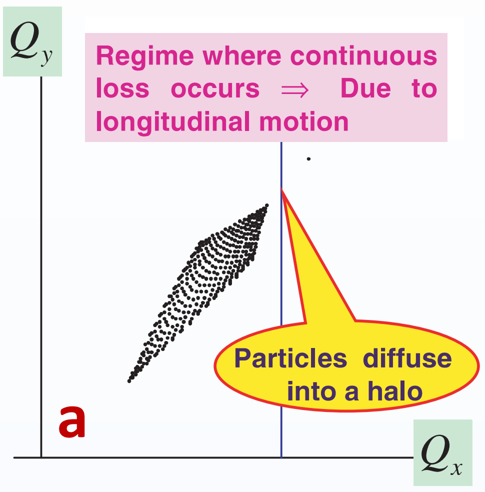
Indirectly

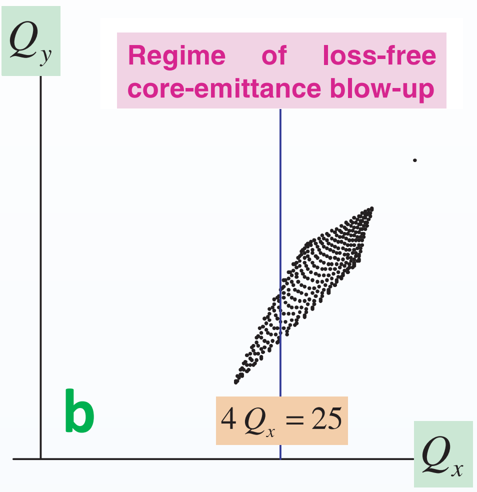
K. Schindl

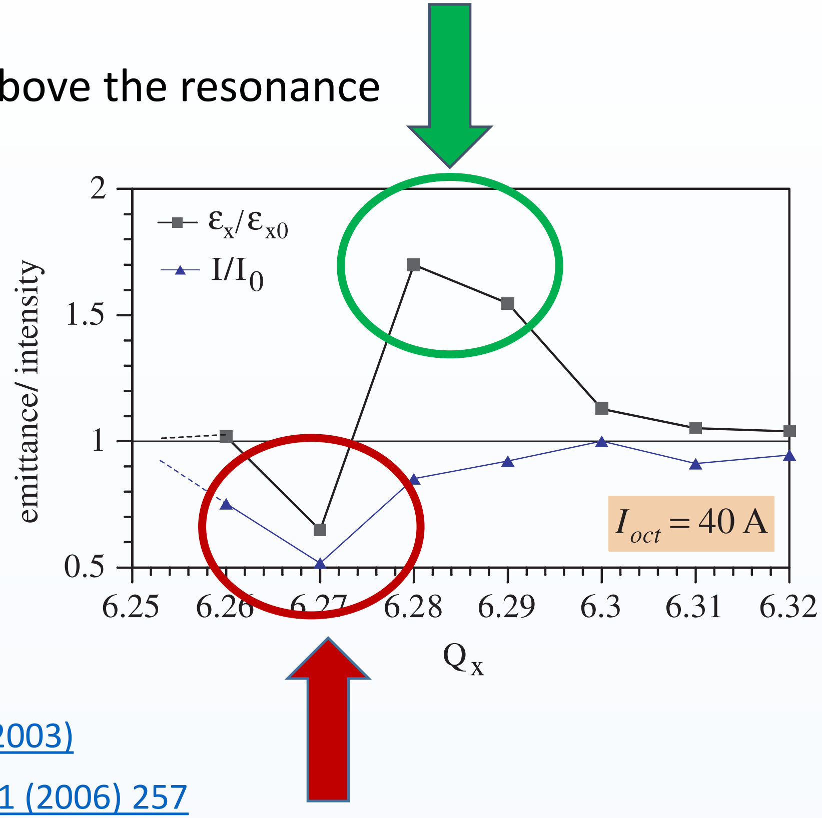
Indirect effect on resonances

Crossing of a known octupolar resonance at $Q_h = 6.25$ in the PS
Two regimes defined:

a) **Beam loss & bunch shortening** for bare machine working points close to or slightly above the resonance
b) **Transverse emittance blow-up** (of the core) further above the resonance



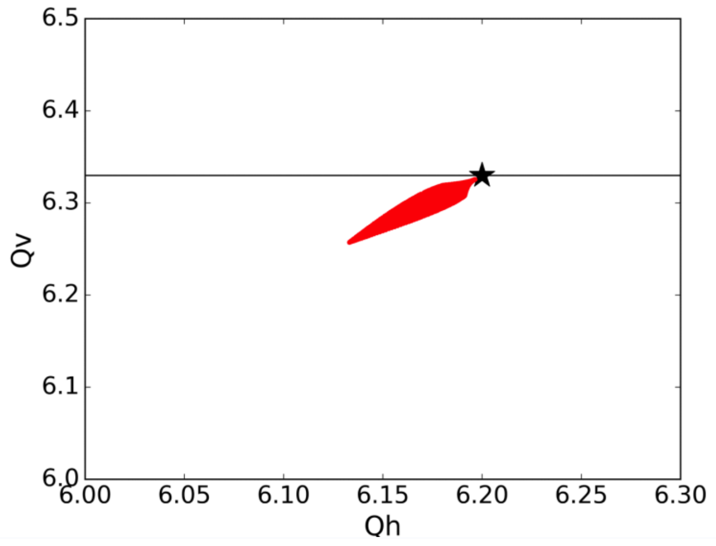




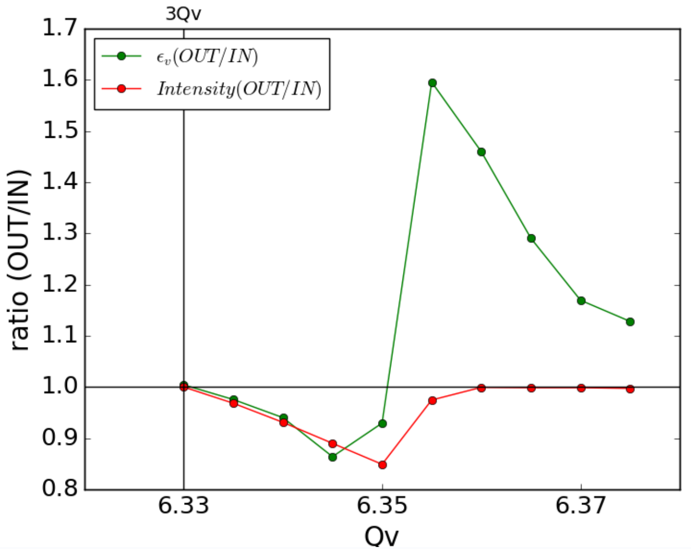
G. Franchetti, M. Giovannozi, I. Hofmann, M. Martini, E. Metral, Phys Rev STAB.6.124201 (2003)

E. Metral, G. Franchetti, M. Giovannozzi, I. Hofmann, M. Martini, R. Steerenberg, NIM A561 (2006) 257

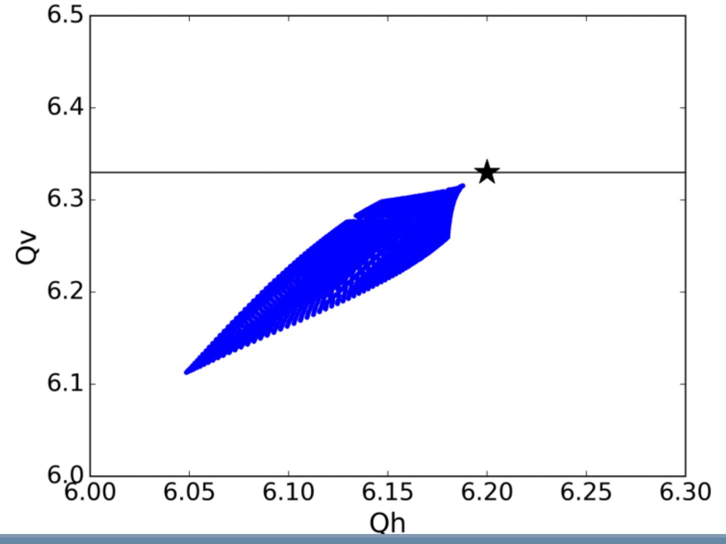
Indirect effect on resonances



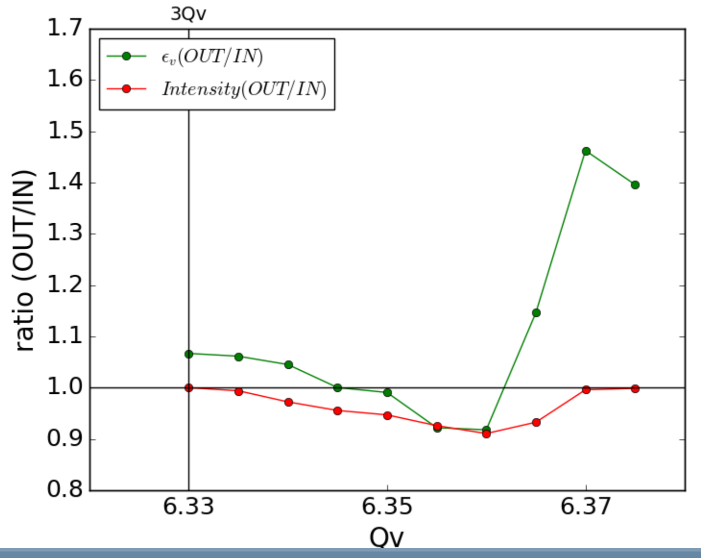
Simulation of the PS lattice in the presence of a skew sextupole exciting the 3rd **order** resonance at $Q_v = 6.33$



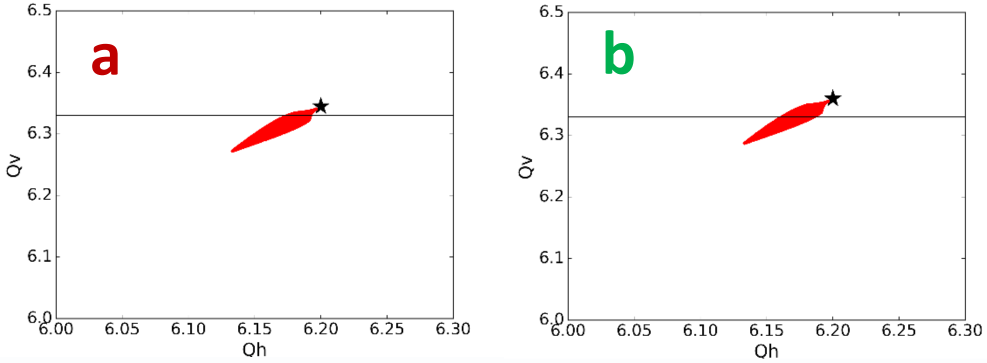
Low Brightness

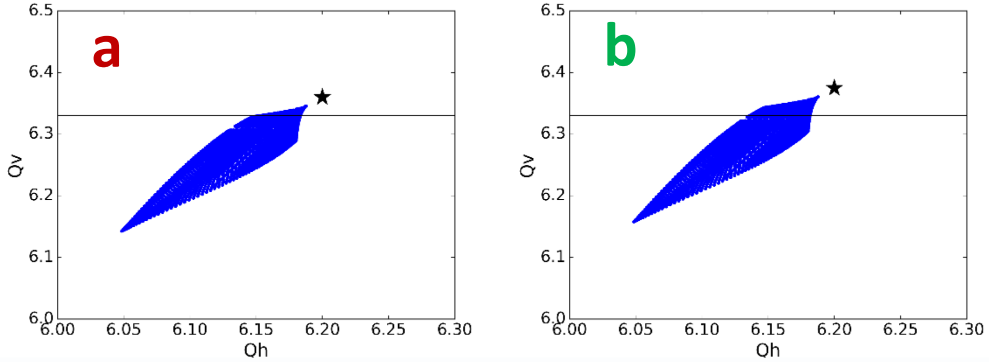


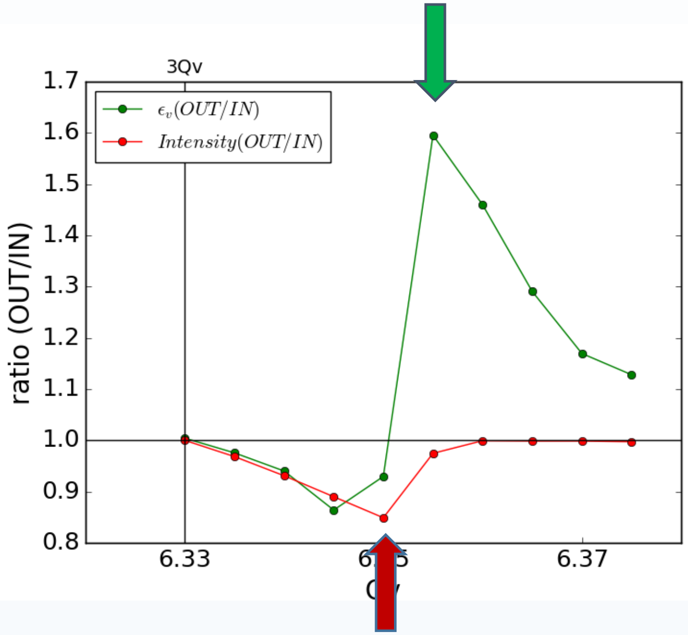
High Brightness



Indirect effect on resonances







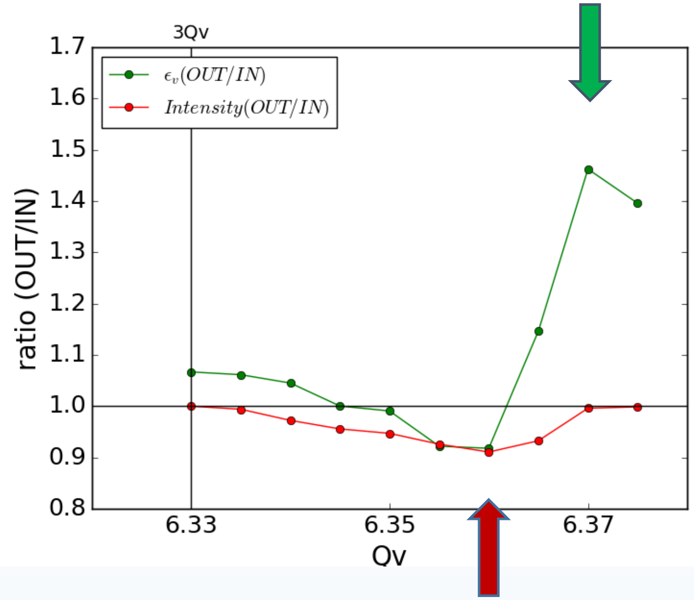
Space charge defines two different regions

a) **Losses regime**

b) **Blow-up regime**

Space charge strength (Brightness) affects:

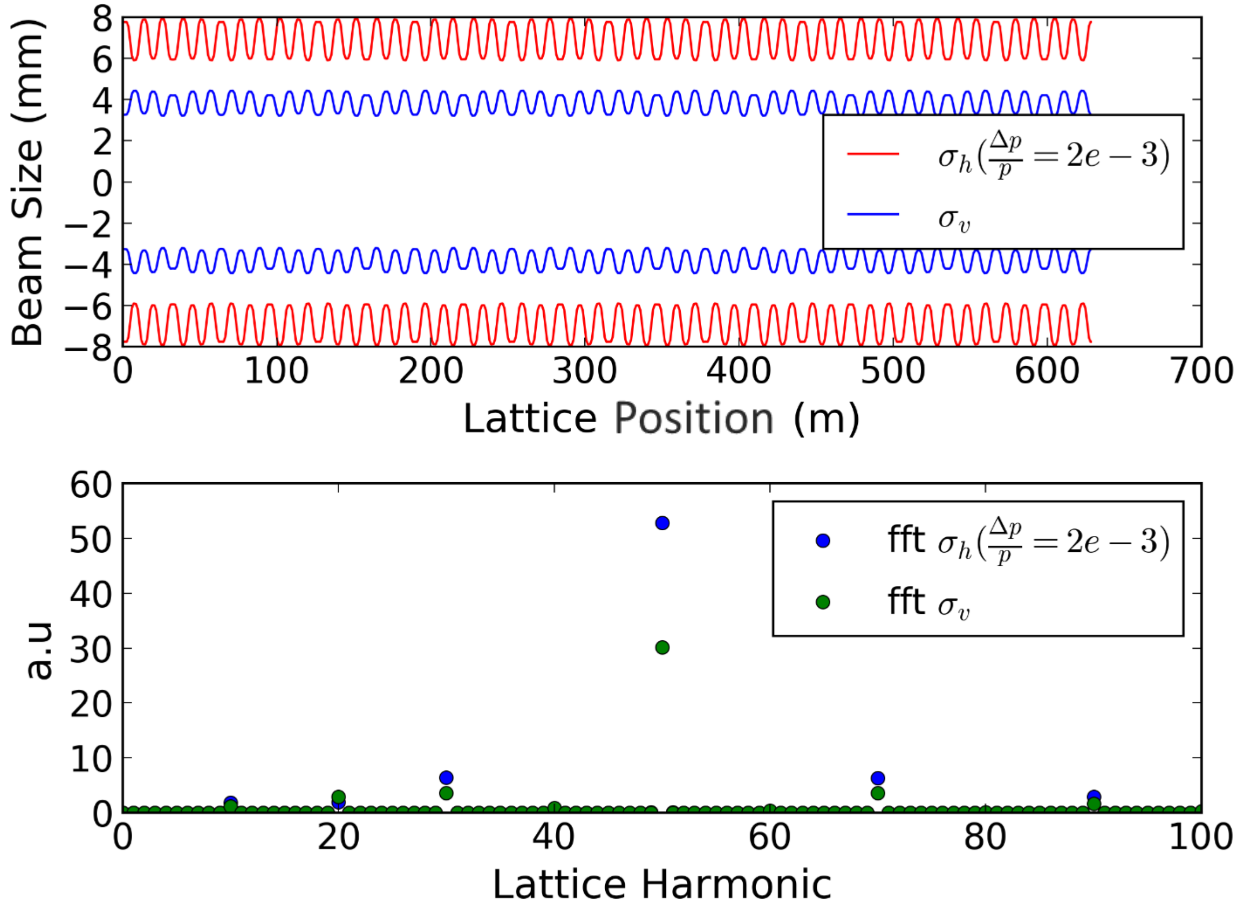
- ***Distance of highest losses from resonance***
- ***Width of resonance effect***
- ***Impact of the resonance on the beam observables***



Direct effect on resonances

The space charge field can be expanded into multipoles giving **all even orders**

$$V_{SC} = -\frac{K_{sc}}{2}\left[\left(\frac{x^2}{\sigma_x(\sigma_x+\sigma_y)}+\frac{y^2}{\sigma_y(\sigma_x+\sigma_y)}\right)\right.$$



Resonance Driving Terms

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

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

Assuming **Gaussian beam** the space charge potential is

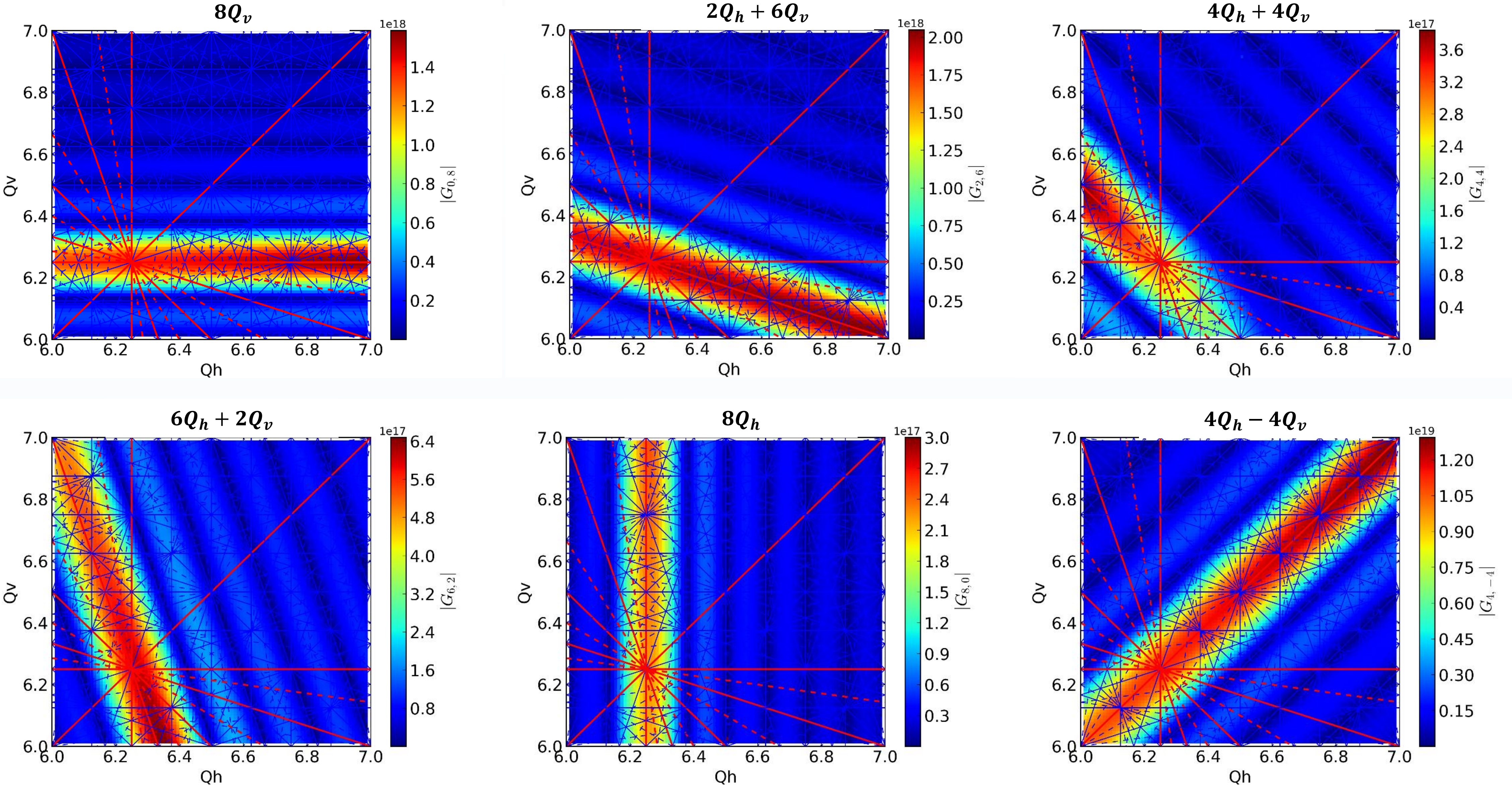
$$V_{sc}(x,y) = \frac{K_{sc}}{2}\int_0^\infty \frac{-1 + e^{-\frac{x^2}{2\sigma_x^2+t}-\frac{y^2}{2\sigma_y^2+t}}}{\sqrt{(2\sigma_x^2+t)\left(2\sigma_y^2+t\right)}}dt$$

Carrying out a Floquet transformation and expanding it in Fourier harmonics we can obtain the **resonance driving terms (RDTs)**.

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

The above have been implemented into a Python module that can be used for any machine and any resonance

Space charge RDTs in the PS (6,7) tune space



Frequency Maps

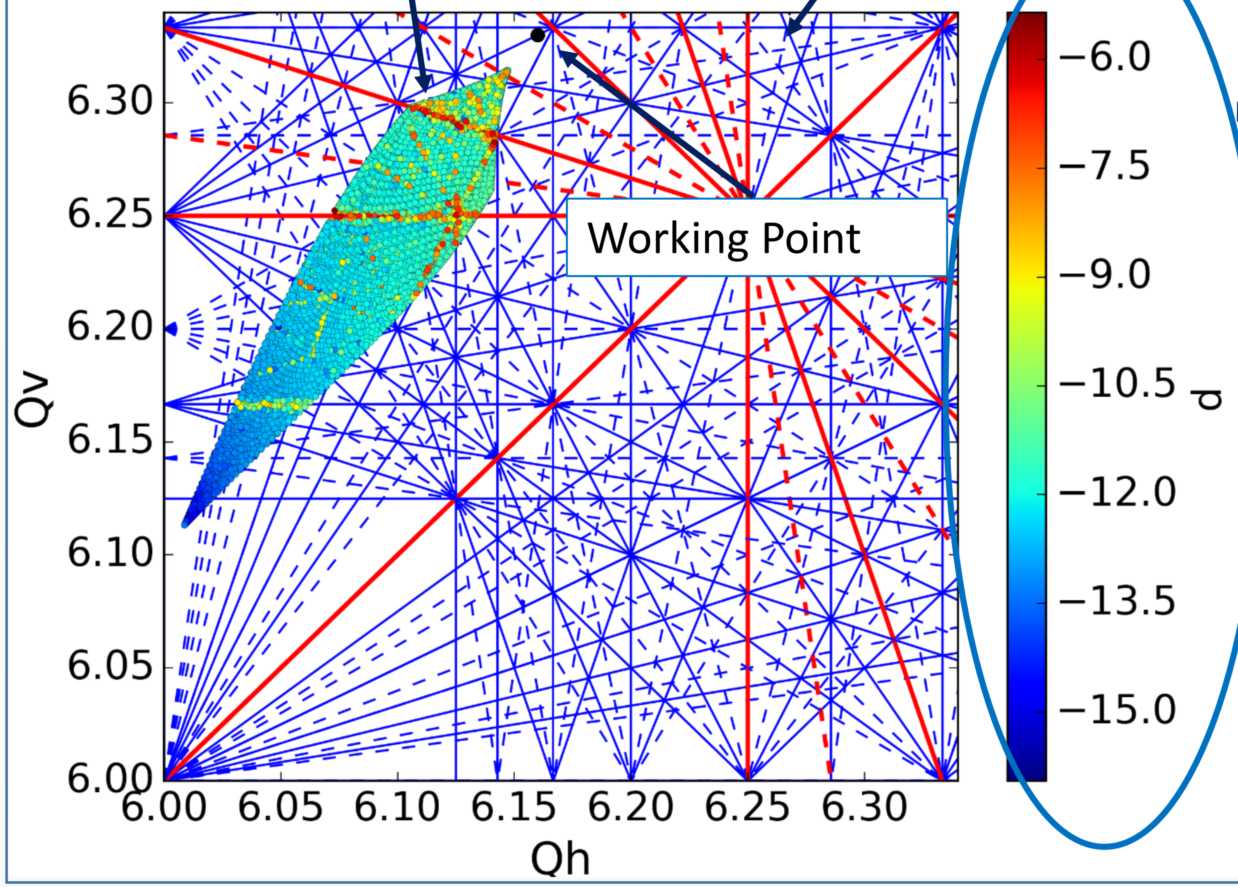
Diffusion: $D = \log\sqrt{\left[(Q_{x2}-Q_{x1})^2 + (Q_{y2}-Q_{y1})^2\right]}$

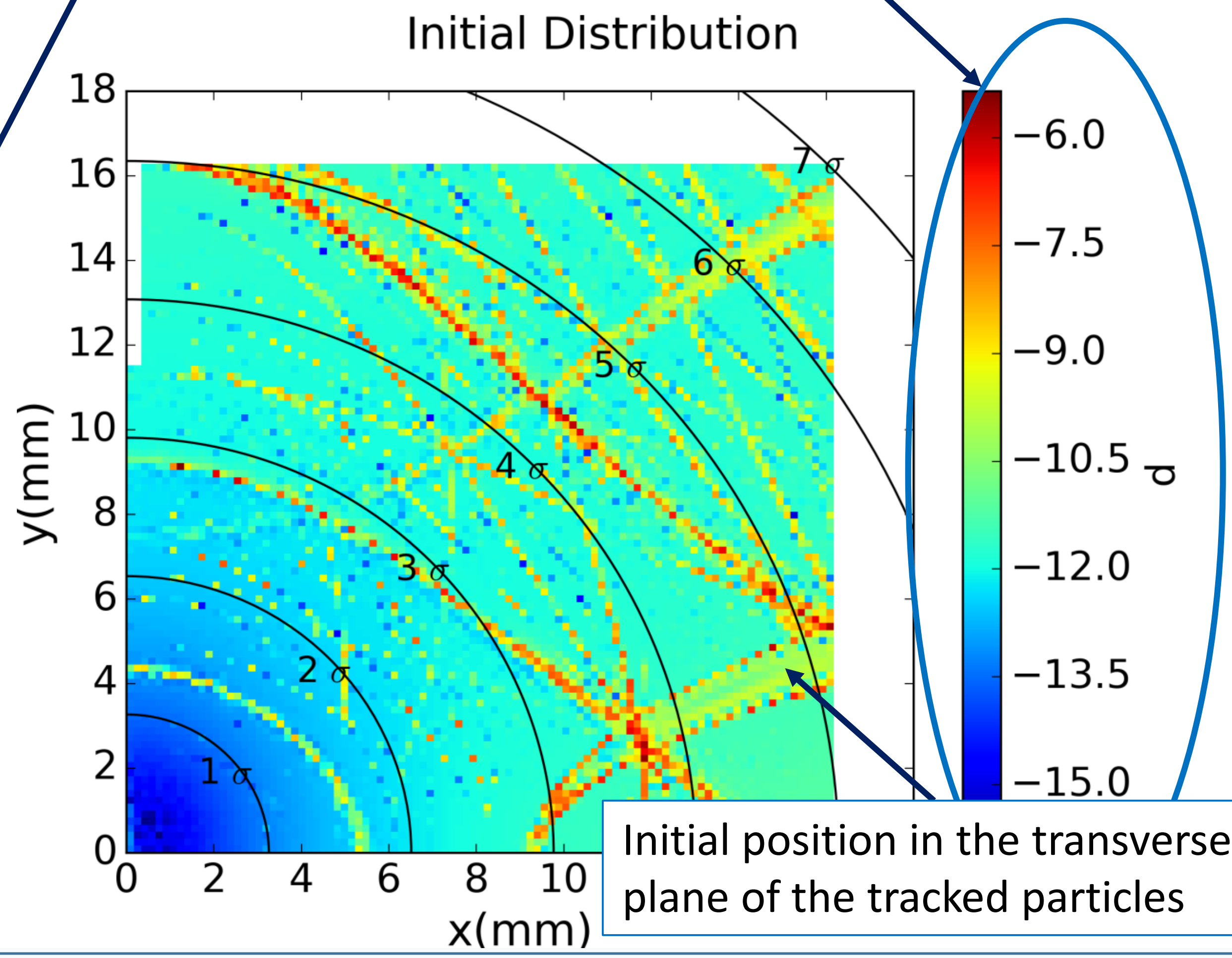
$Q_2, over\ second\ synchrotron\ period$

$Q_1, over\ first\ synchrotron\ period$

Tunes of individual particles calculated over one synchrotron period

Resonance lines up to 8th order





Initial position in the transverse plane of the tracked particles

Machine Development Studies

› **Space charge MD studies at the PS injection plateau**

High brightness beams

- Need to accommodate large tune spreads

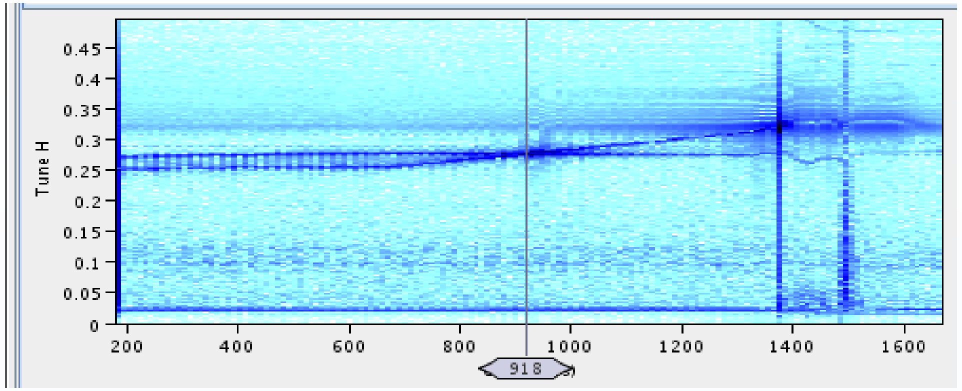
Large storage time of 1.2s

- No losses ($< 5\%$)
- No emittance blow-up ($< 5\%$)

Resonances excited: lattice non-linearities
space charge

Machine Development Studies

- Single Bunch from PSB Ring 3 (INDIV-type)
- Keep the lattice as linear as possible
  - Coupling Corrected (Closest tune approach)
    - Transverse Feedback ON
  - Natural Chromaticity
  - **Compensation of the 3Qy**
    - Naturally excited in the PS

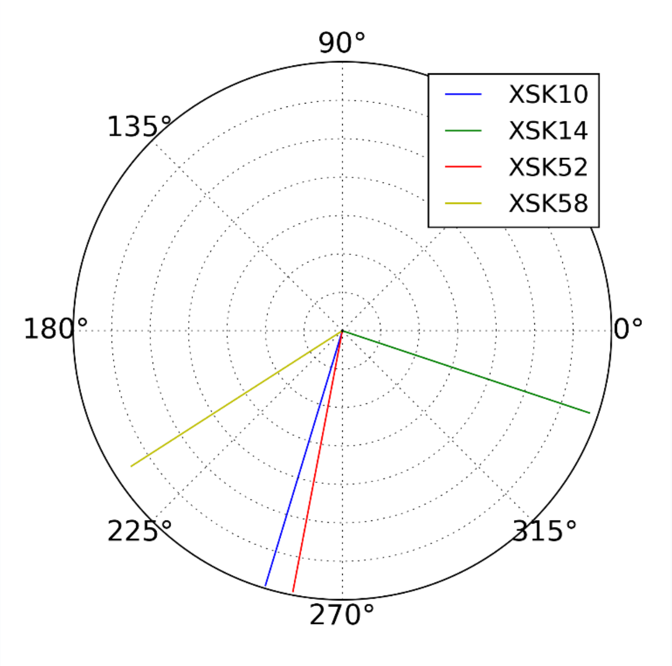


- **Static Tune Scans** to investigate the impact of space charge induced resonances and the space charge tune spread on known resonances (active excitation of the 3Qy)
  - High Brightness
  - Low Brightness

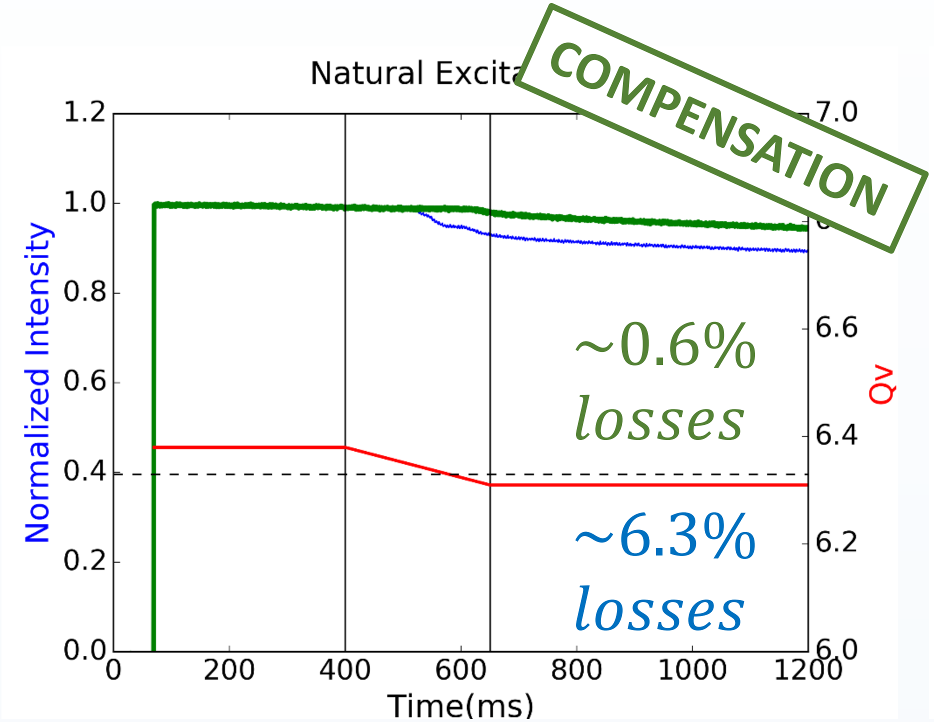
Compensation of the 3Qy

Calculation of the **RDTs** using PTC for the available skew sextupoles.

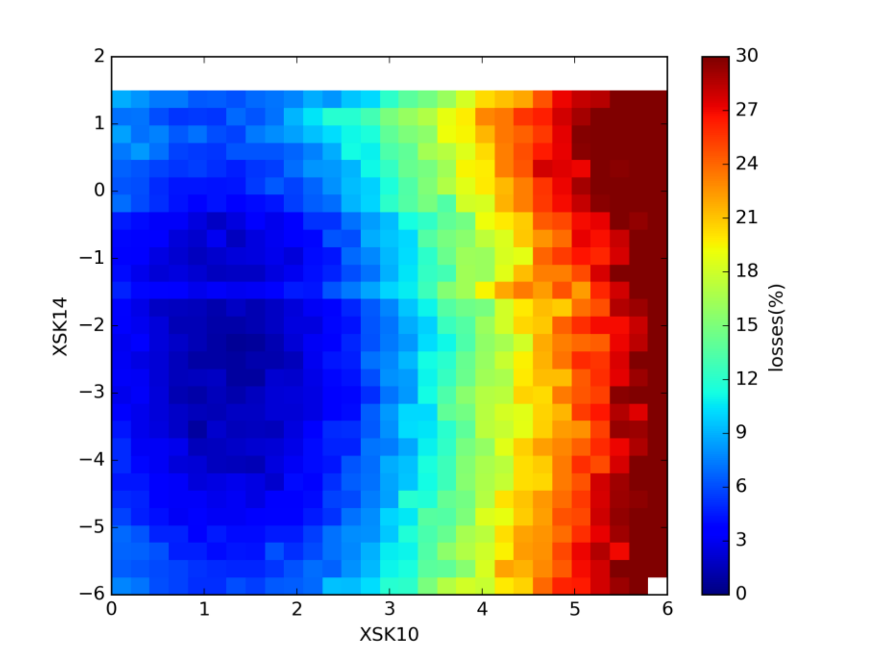
To Identify orthogonal pairs



Dynamic crossing of the resonance

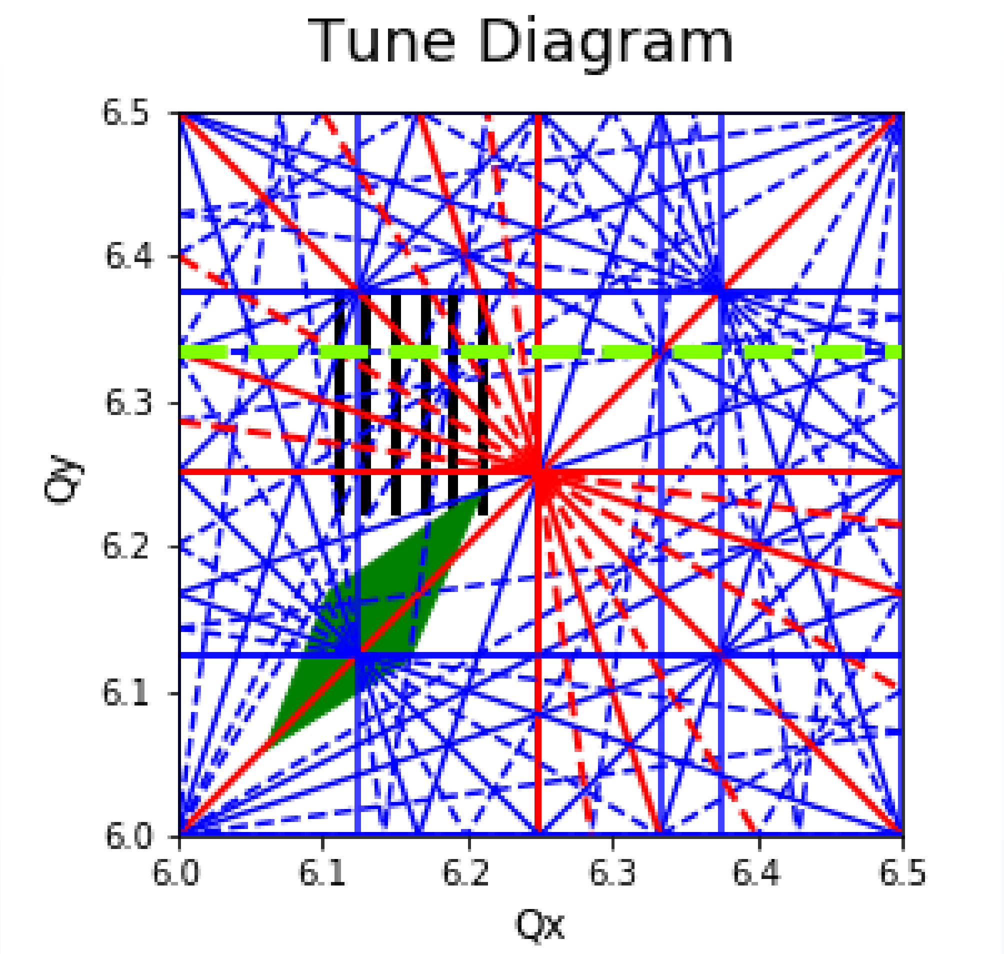


Scan the **skew currents** to minimize the losses



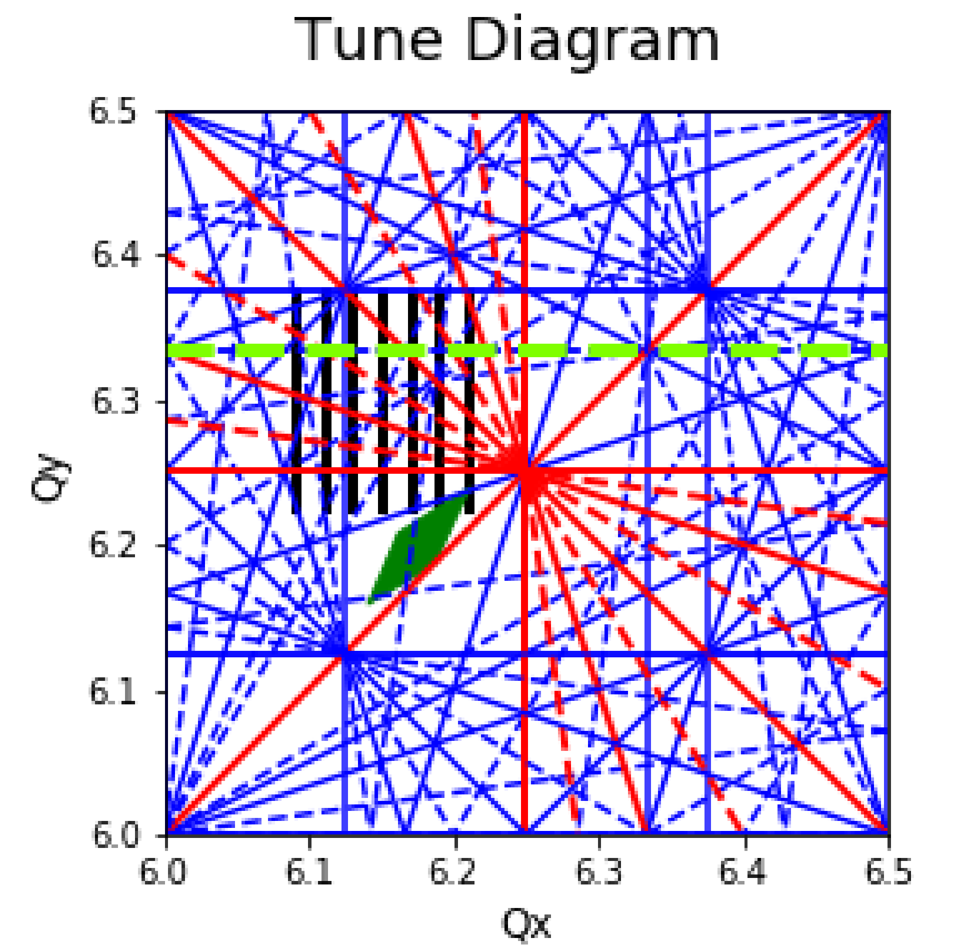
High Brightness

Beam Parameters	
Working Point	$Q_h = 6.11, Q_v = 6.24 - 6.36$ $Q_h = 6.13, Q_v = 6.24 - 6.40$ $Q_h = 6.15\ Q_v = 6.24 - 6.35$ $Q_h = 6.17, Q_v = 6.24 - 6.35$ $Q_h = 6.19, Q_v = 6.24 - 6.35$ $Q_h = 6.21, Q_v = 6.24 - 6.35$
$\Delta p/p_{rms}$	$5.51 * 10^{-4}$
$\varepsilon^n_{h\ IN}$	$5\ mm\ mrad$
$\varepsilon^n_{v\ IN}$	$4\ mm\ mrad$
Intensity	$90 * 10^{10}\ ppb$
Storage time	1.2 s
Space Charge Tune Shift	$\mathbf{dQ_h = 0.15\ dQ_v = 0.18}$



Low Brightness

Beam Parameters	
Working Point	$Q_h = 6.09, Q_v = 6.24 - 6.36$ $Q_h = 6.11, Q_v = 6.24 - 6.36$ $Q_h = 6.13, Q_v = 6.24 - 6.40$ $Q_h = 6.15\ Q_v = 6.24 - 6.35$ $Q_h = 6.17, Q_v = 6.24 - 6.35$ $Q_h = 6.19, Q_v = 6.24 - 6.35$ $Q_h = 6.21, Q_v = 6.24 - 6.35$
$\Delta p / p_{rms}$	$5.51 * 10^{-4}$
$\varepsilon^n_{h\ IN}$	$5\ mm\ mrad$
$\varepsilon^n_{v\ IN}$	$4\ mm\ mrad$
$Intensity$	$45 * 10^{10}\ ppb$
Storage time	$1.2\ s$
Space Charge Tune Shift	$\mathbf{dQ_h = 0.07\ dQ_v = 0.08}$

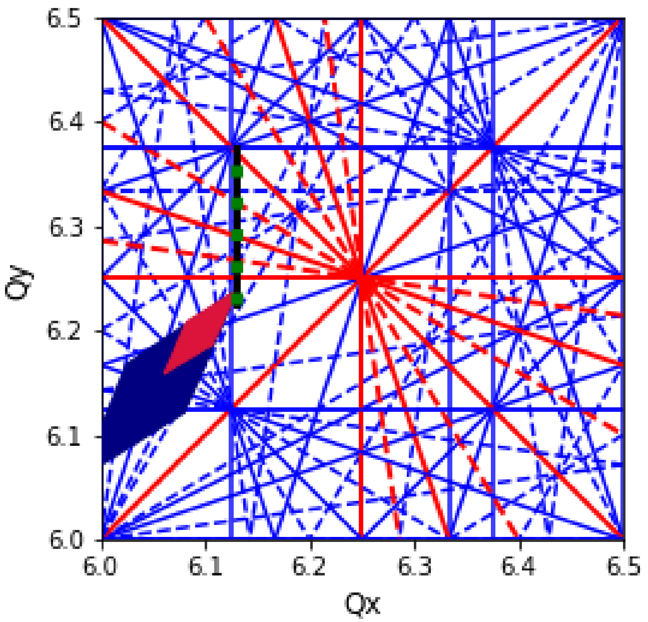


Beam Parameters	
Working Point	$Q_h = 6.13, Q_v = 6.24 - 6.40$
$\Delta p / p_{rms}$	$5.51 * 10^{-4}$
$\varepsilon^n_{h\ IN}$	$5\ mm\ mrad$
$\varepsilon^n_{v\ IN}$	$4\ mm\ mrad$
Intensity	HB: $90 * 10^{10}\ ppb$ LB: $45 * 10^{10}\ ppb$
Storage time	1.2 s
Space Charge Tune Shift	HB: $\boldsymbol{dQ_h = 0.15\ dQ_v = 0.18}$ LB: $\boldsymbol{dQ_h = 0.07\ dQ_v = 0.08}$

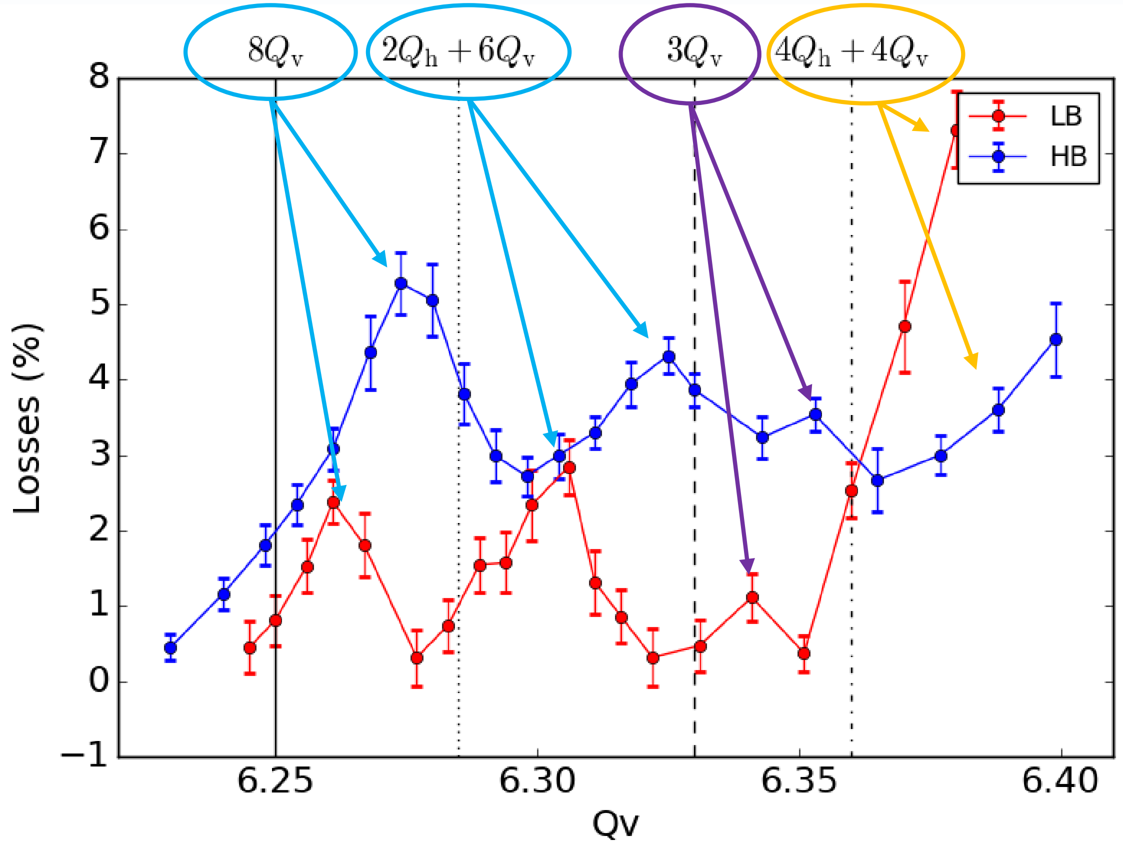
Resonances **excited by Space Charge** show more losses with the High Brightness (HB) beam

Resonance **compensated** using Skew Sextupoles

Resonance that can also be **4th order** normal $(2Q_h + 2Q_v)$ believed to be related to lattice errors
M. Kaitatzi *et al*: MSWG #11



Losses maxima at different locations due to the different space charge tune spreads



Beam Parameters	
Working Point	$Q_h = 6.13, Q_v = 6.24 - 6.40$
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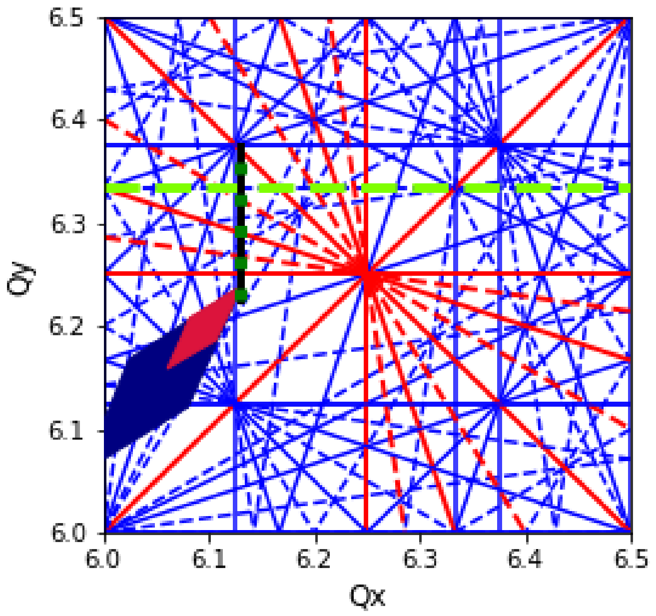
Intensity	HB: $90 * 10^{10}\ ppb$ LB: $45 * 10^{10}\ ppb$
Storage time	1.2 s
Space Charge Tune Shift	HB: $\mathbf{dQ_h = 0.15\ dQ_v = 0.18}$ LB: $\mathbf{dQ_h = 0.07\ dQ_v = 0.08}$

Resonances excited by Space Charge show more losses with the High Brightness (HB) beam

Resonance actively excited using Skew Sextupole

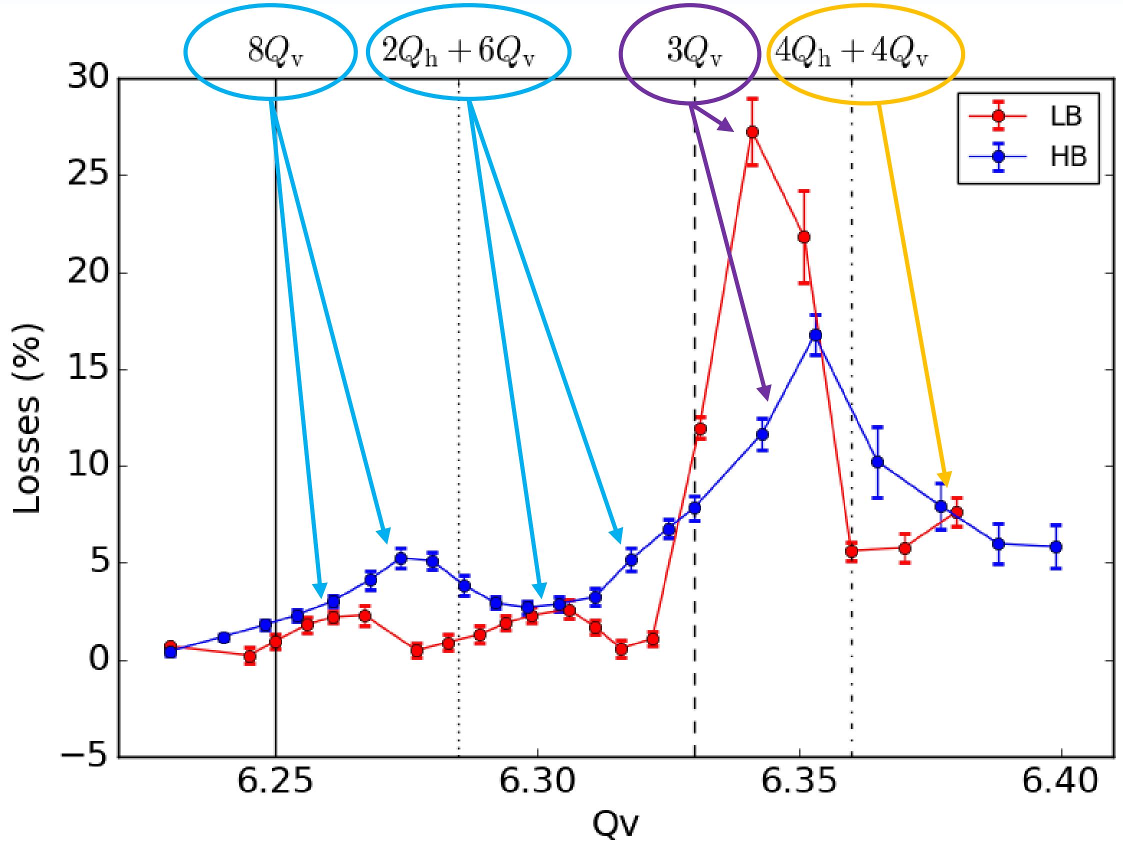
Resonance that can also be 4th order normal $(2Q_h + 2Q_v)$ believed to be related to lattice errors



The losses from the 2Qh+6Qy for the HB beam have merged with the 3Qy

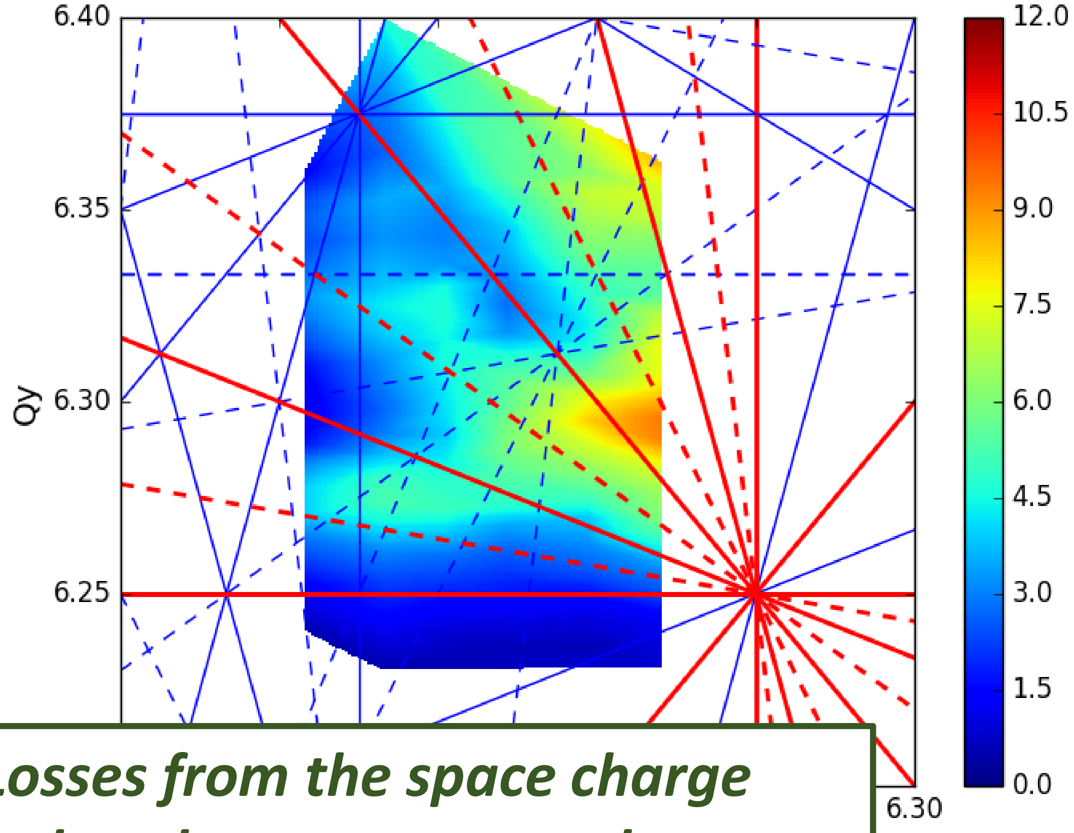
The losses from $8Q_v$ and $2Q_h + 6Q_v$ are not affected by the sextupole

F.Asvesta et.al.



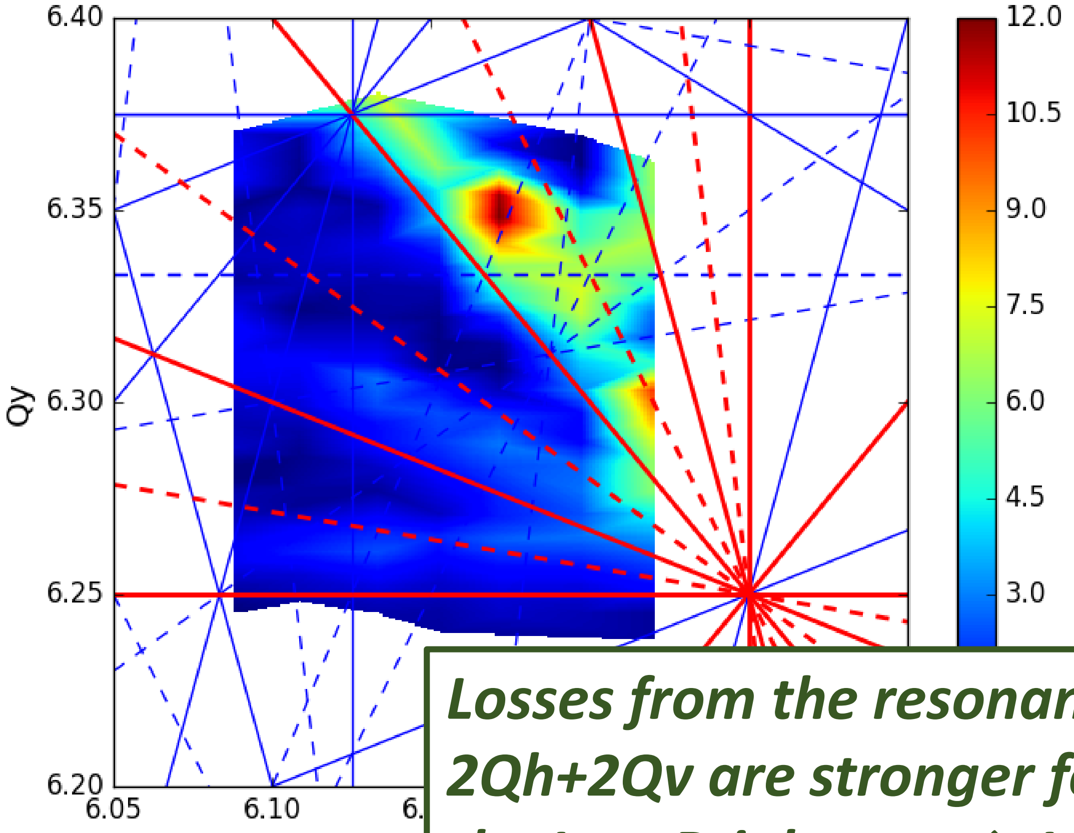
3Qy Compensated (Experimental Data)

High Brightness



Losses from the space charge induced resonances are larger for the High Brightness beam

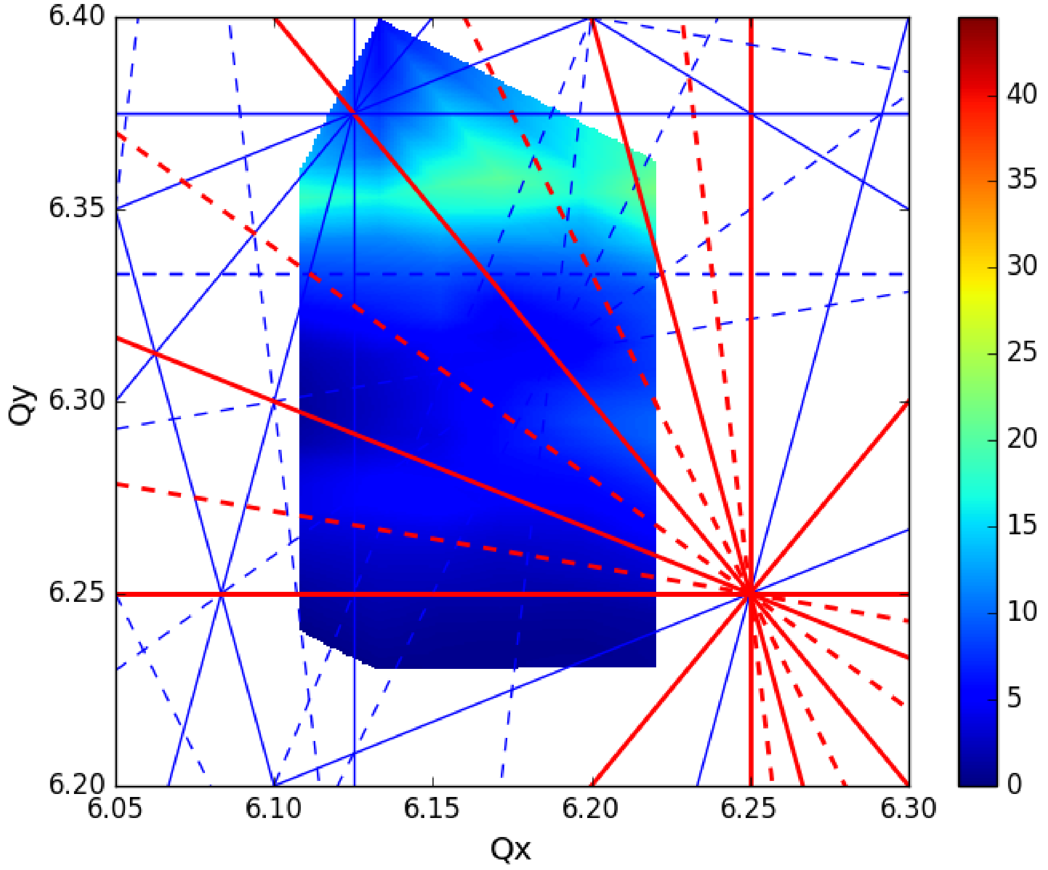
Low Brightness



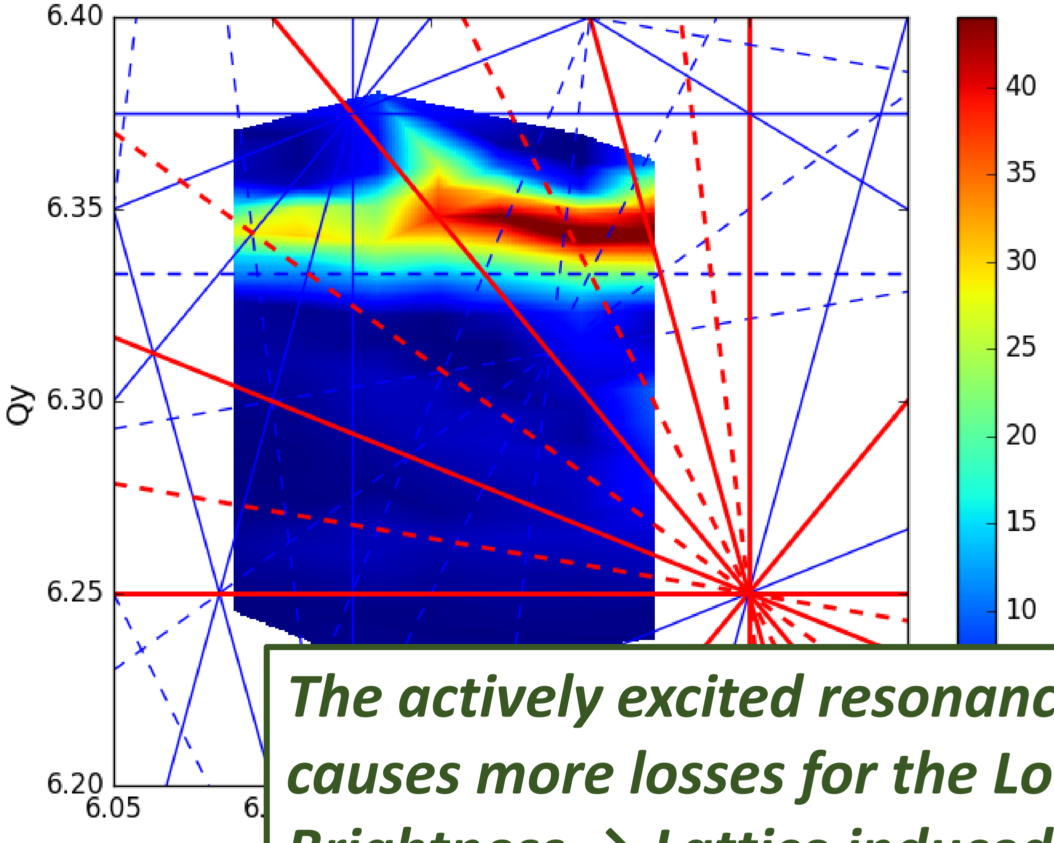
Losses from the resonance 2Qh+2Qv are stronger for the Low Brightness → Lattice errors?

3Qy Excited (Experimental Data)

High Brightness



Low Brightness



The actively excited resonance 3Qv causes more losses for the Low Brightness → Lattice induced resonance

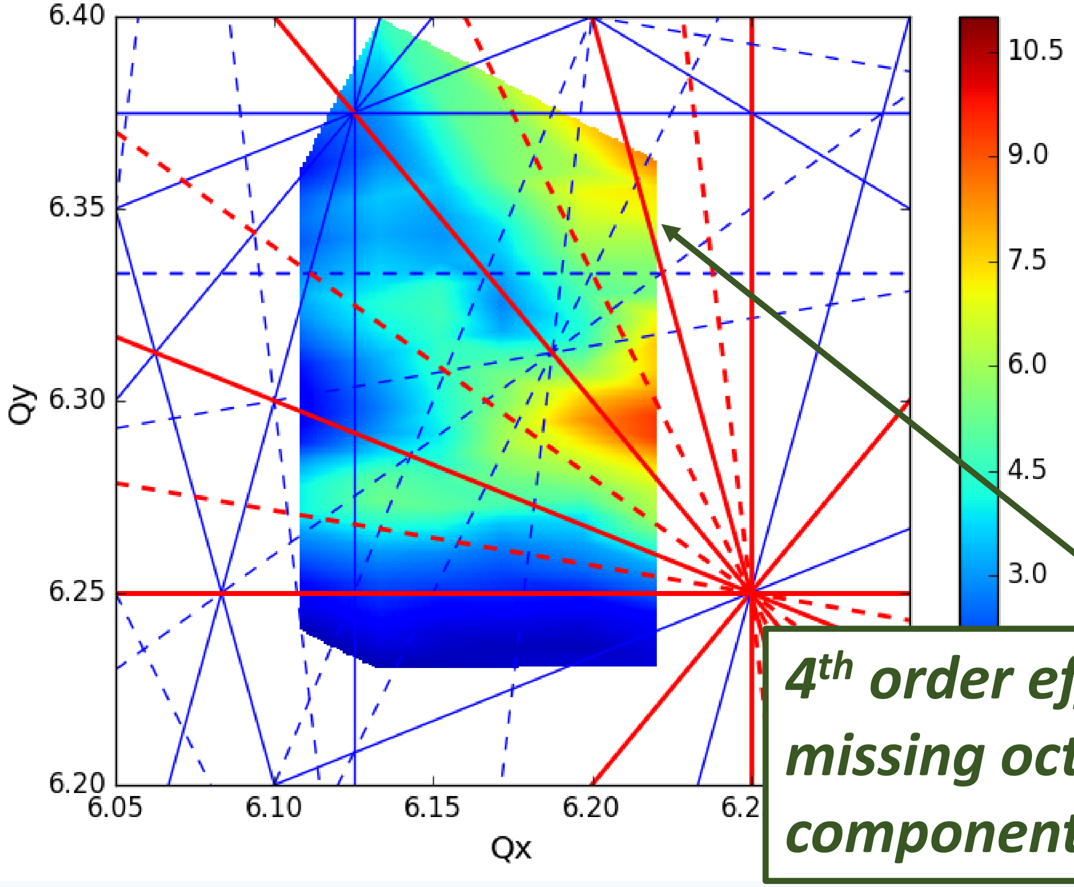
Simulation Studies

- **Non Linear PS Model** from MADx
- Tracking in PyORBIT using PTC **under Space Charge**
- Space charge kick calculated for bi-Gaussian distribution using **Bassetti Erskine** formula
  - Kick calculated using the beam transverse emittances, intensity, ${}^{\Delta\mathrm{p}}/{}_{p_{rms}}$, longitudinal line density and the lattice functions at each location
  - The beam values are updated every 100 turns
  - + Relatively Fast for long term simulations
  - \- Not Self-Consistent

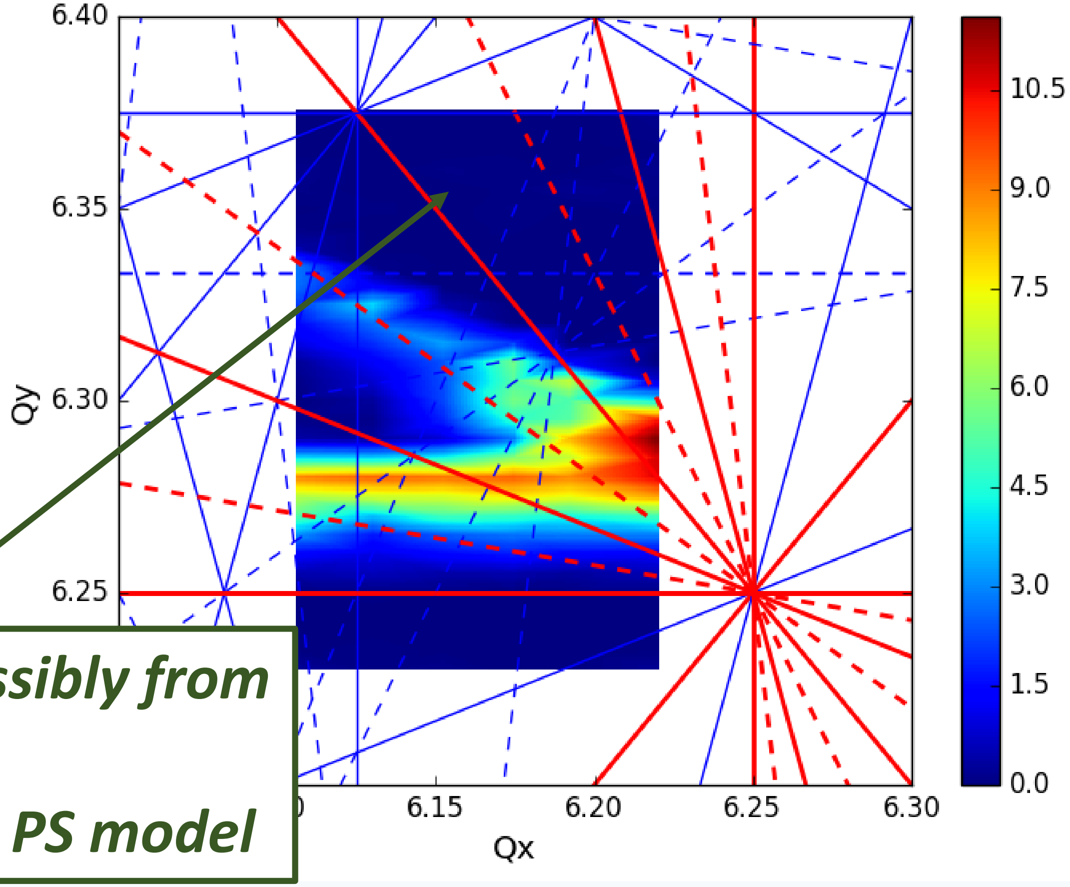
High Brightness

3Qy Compensated

Measurement



Simulation

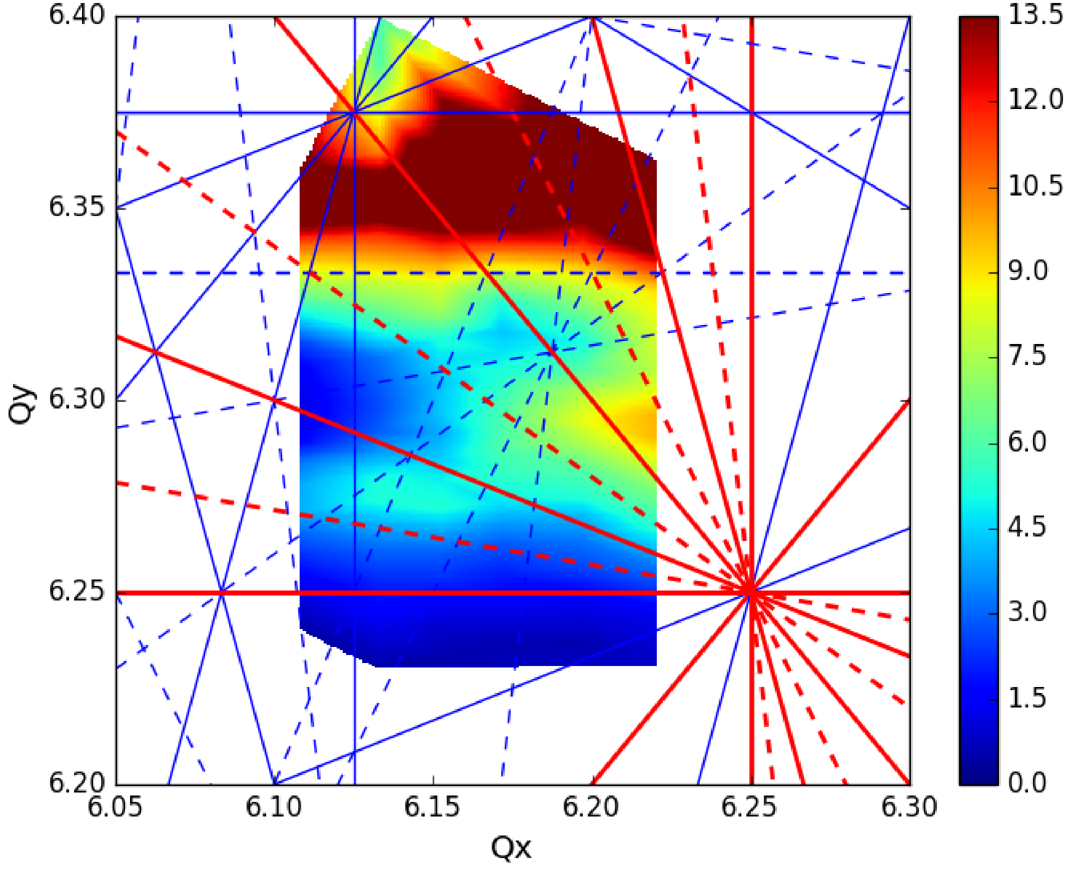


4^{th} order effect possibly from missing octupolar components in the PS model

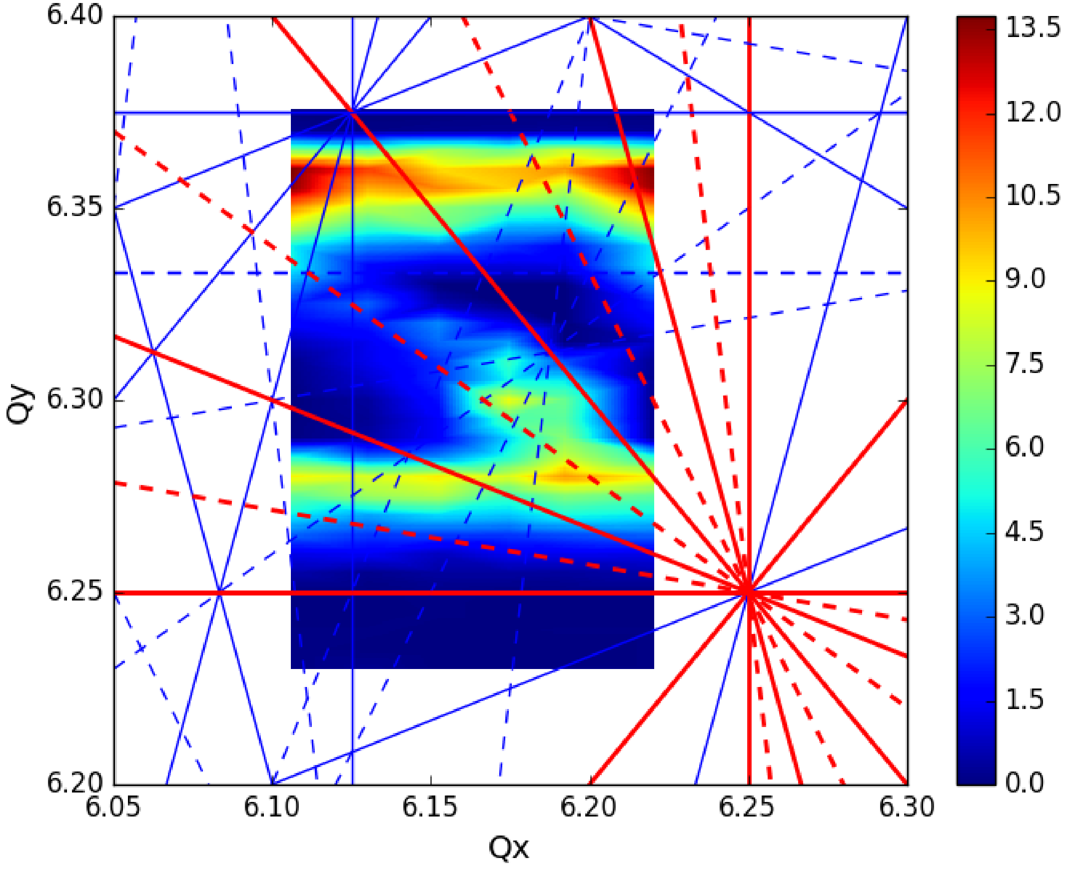
High Brightness

3Qy Excited

Measurement



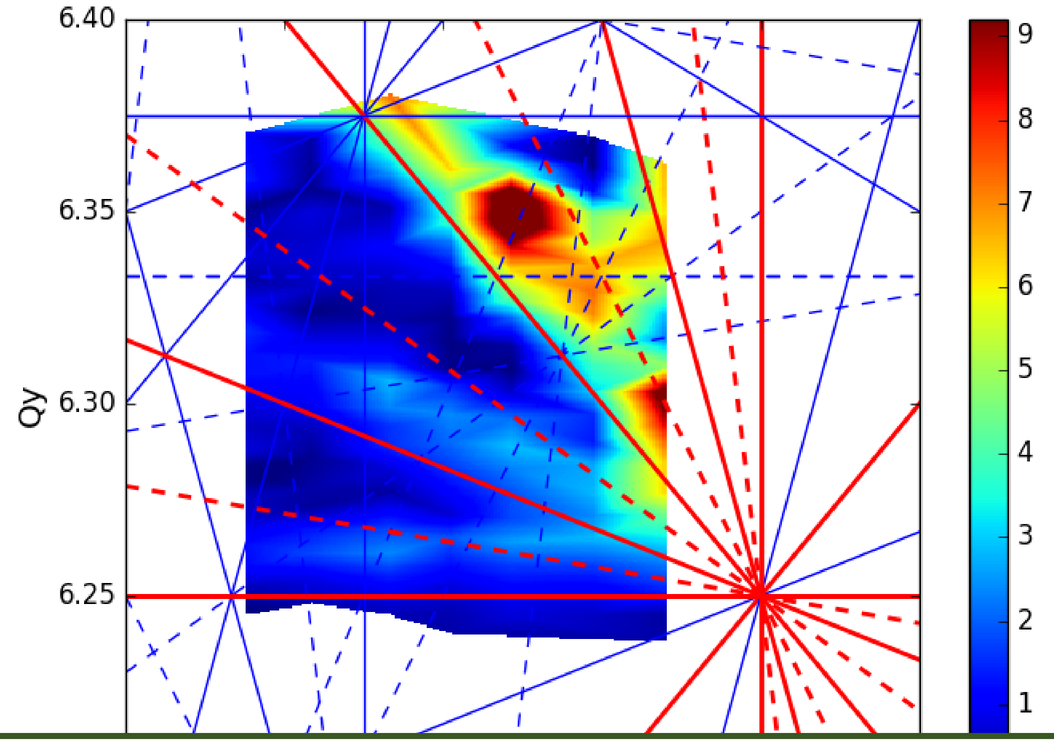
Simulation



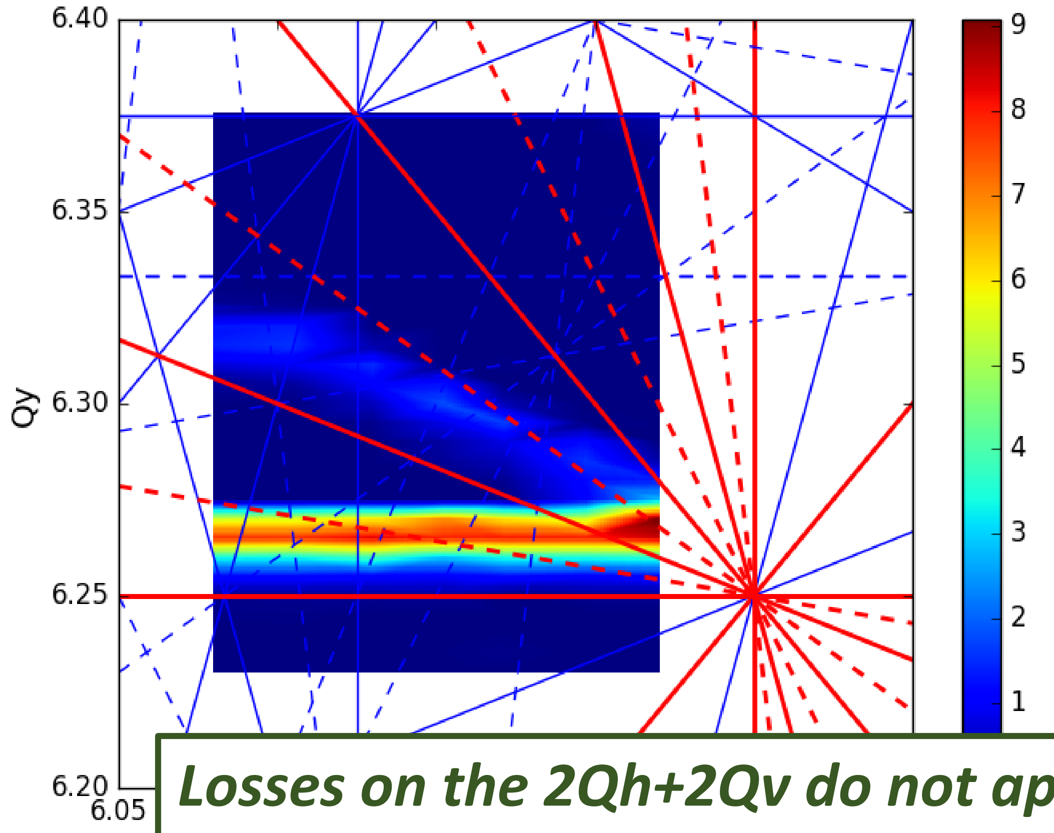
Low Brightness

3Qy Compensated

Measurement



Simulation



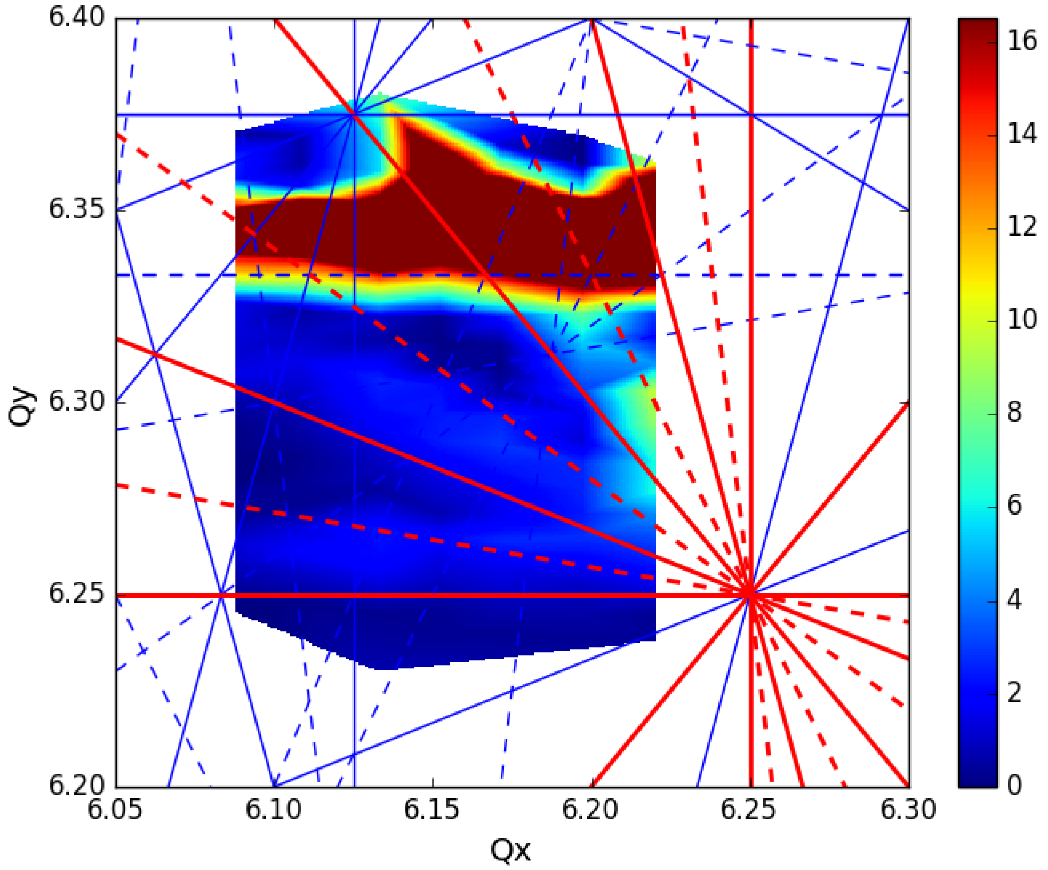
Losses on the 8Qv appear stronger in simulation Maybe affected from the same unknown components in the PS Lattice?

Losses on the 2Qh+2Qv do not appear in simulation due to unknown Octupolar components in the PS Lattice

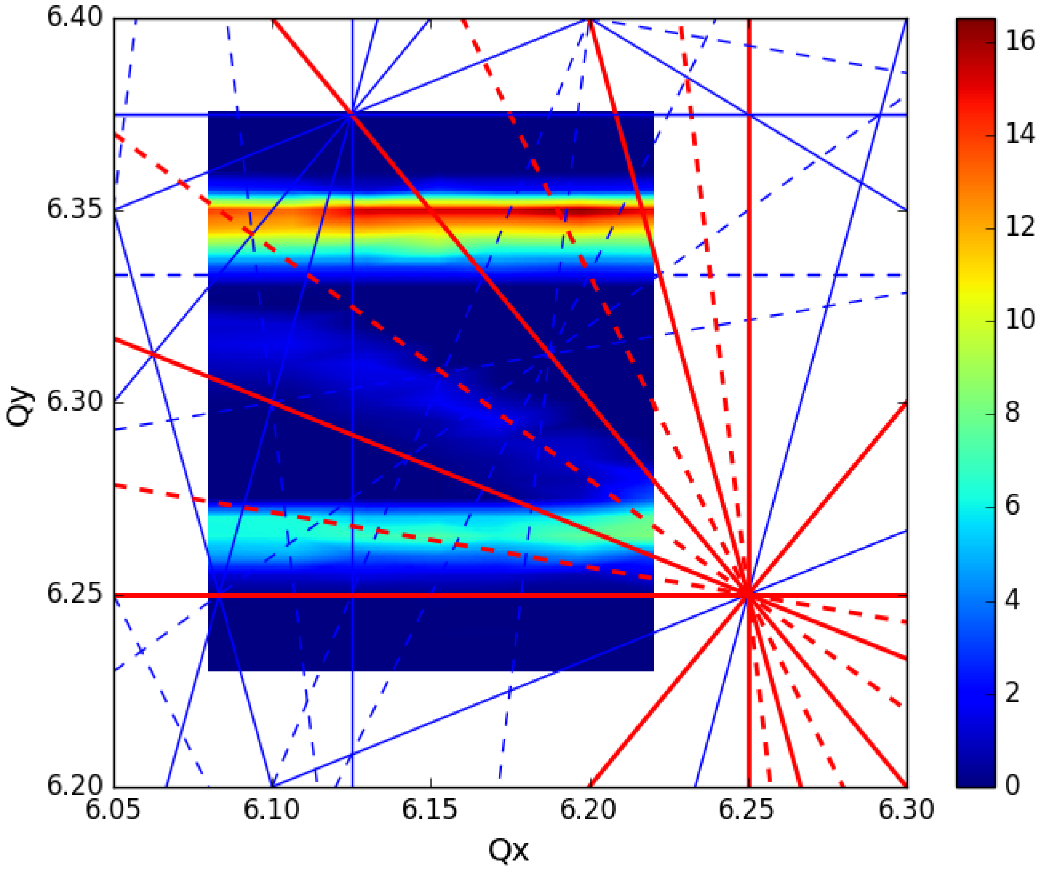
Low Brightness

3Qy Excited

Measurement



Simulation



Summary & Outlook

- Machine Studies
  - The effect of the **8th order structural** resonances $8Q_v$ and $2Q_h + 6Q_v$ has been studied in terms of **losses**
  - The resonance $3Q_v$, naturally excited in the PS, has been **compensated** using skew sextupoles
  - The 4th order $2Q_h + 2Q_v$ seems to be also excited
- Simulation Studies
  - Simulations including space charge **qualitatively agree** with the measurements
  - To get better agreement it seems that we are **missing non-linear components** in the lattice
- Further MD studies
  - Tune scans using an even **lower brightness** beam
  - Tune scans using **coasting** beam
  - **Measure** the higher order **RDTs** in the BBQ

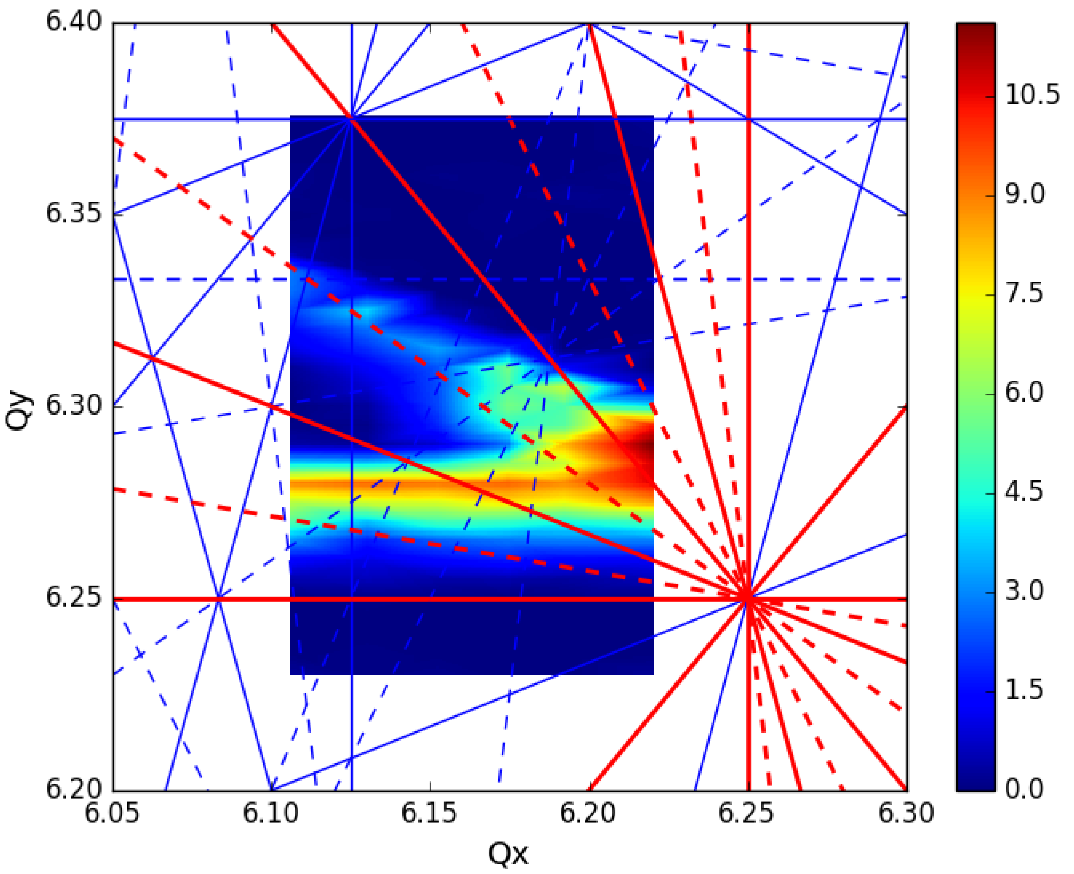
Thank you for your attention

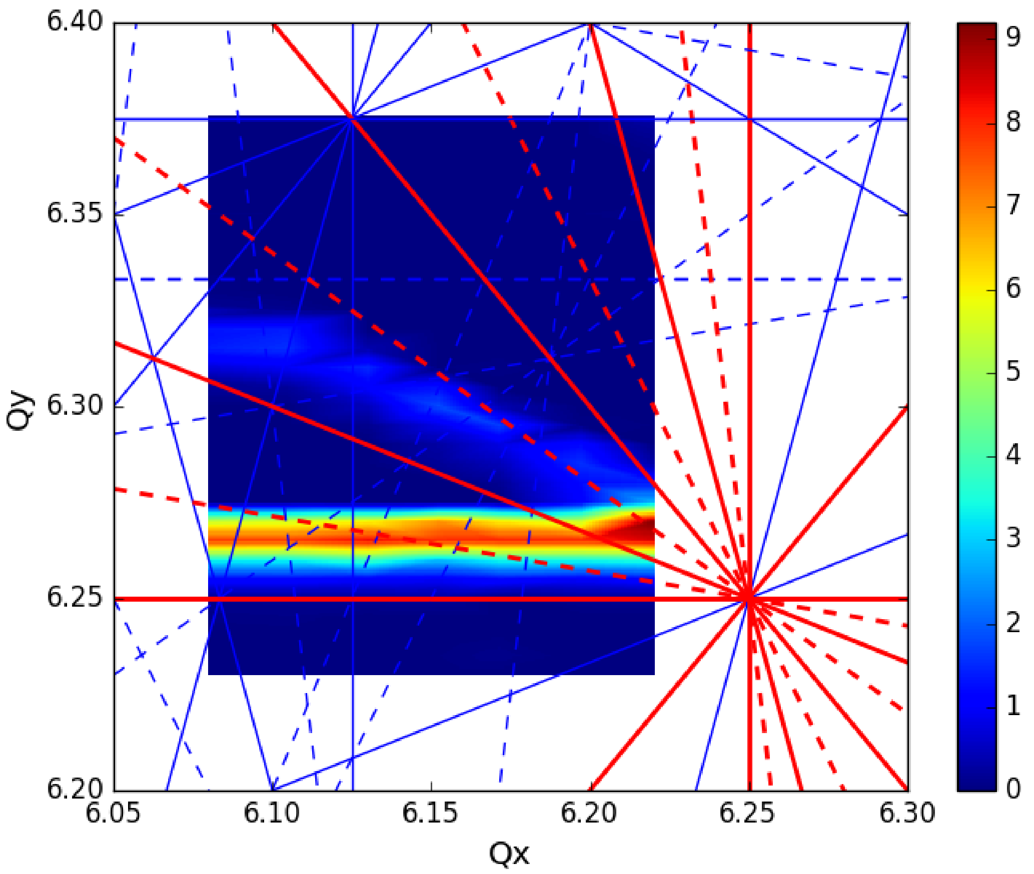
Back up

Simulation

3Qy Compensated

High Brightness	***Low Brightness***

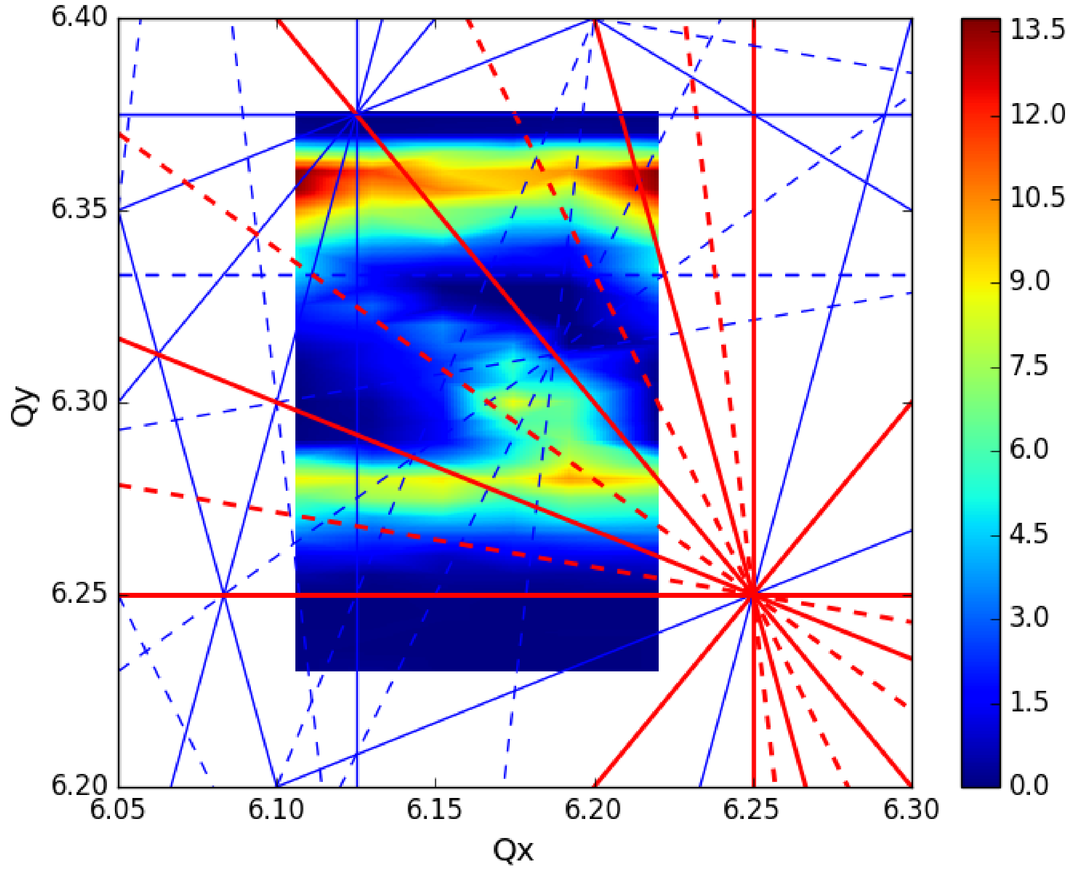




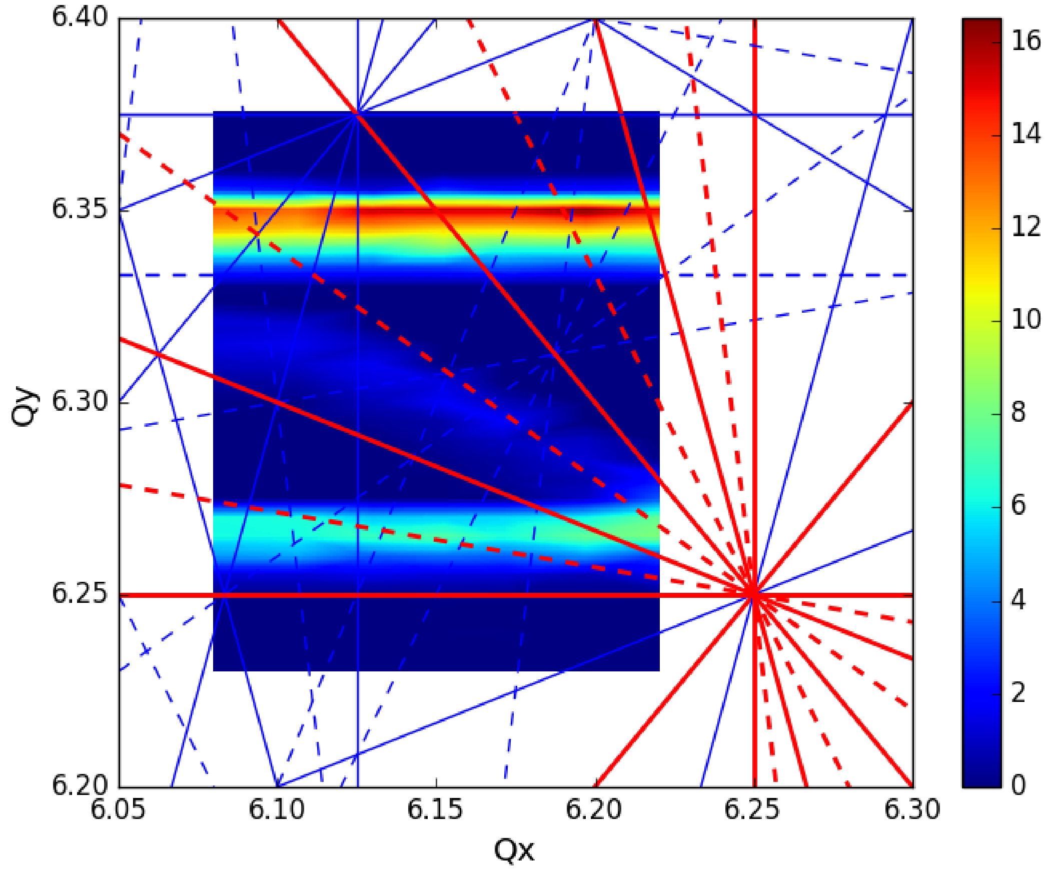
Simulation

3Qy Excited

High Brightness

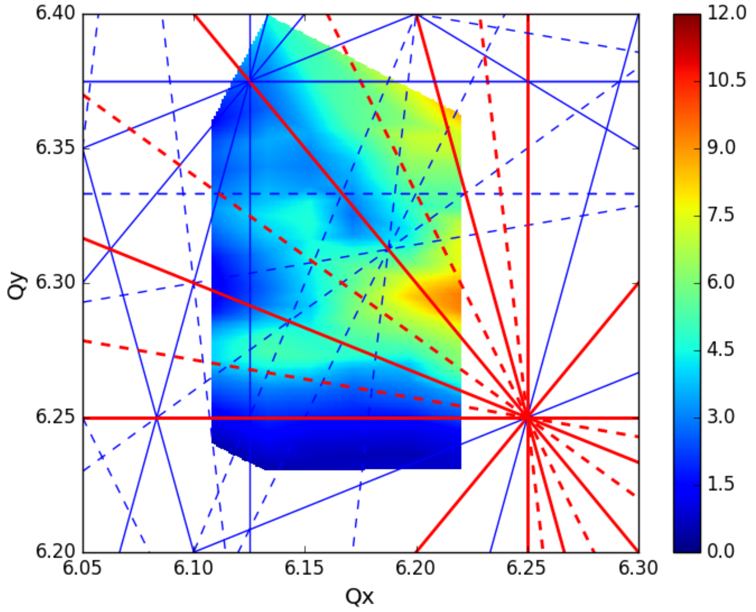


Low Brightness

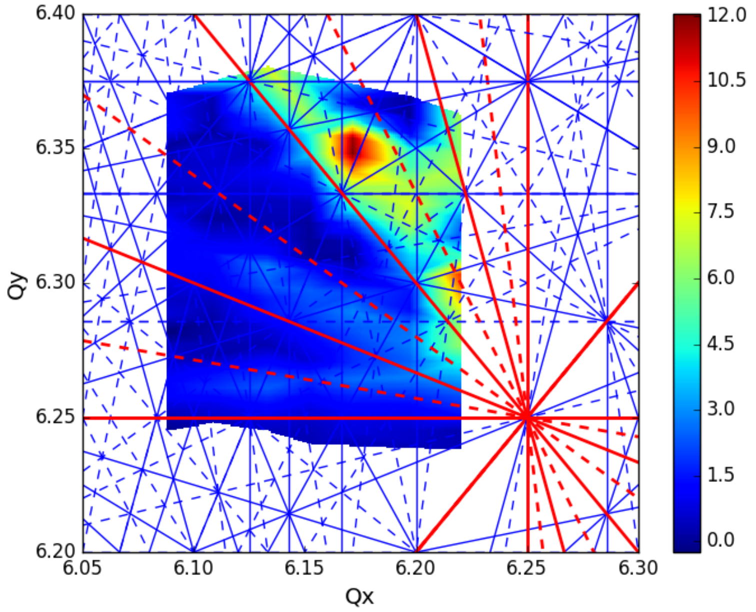


3Qy Compensated

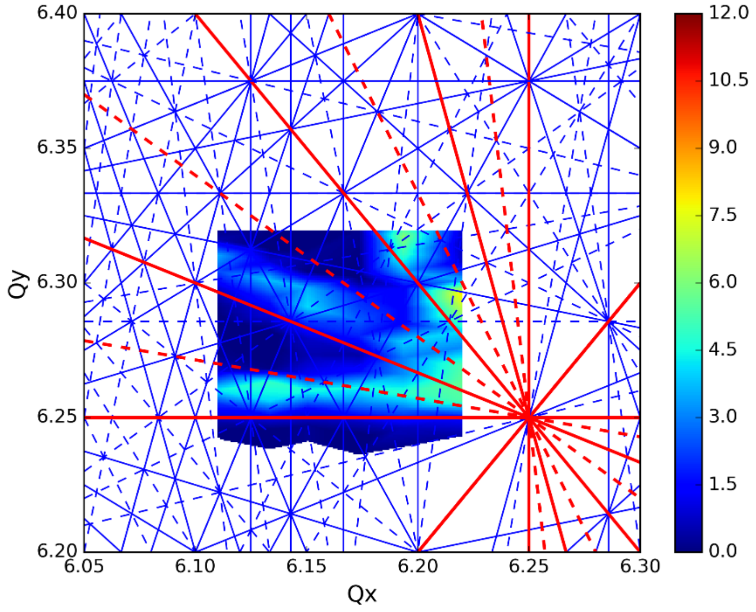
High Brightness



Low Brightness

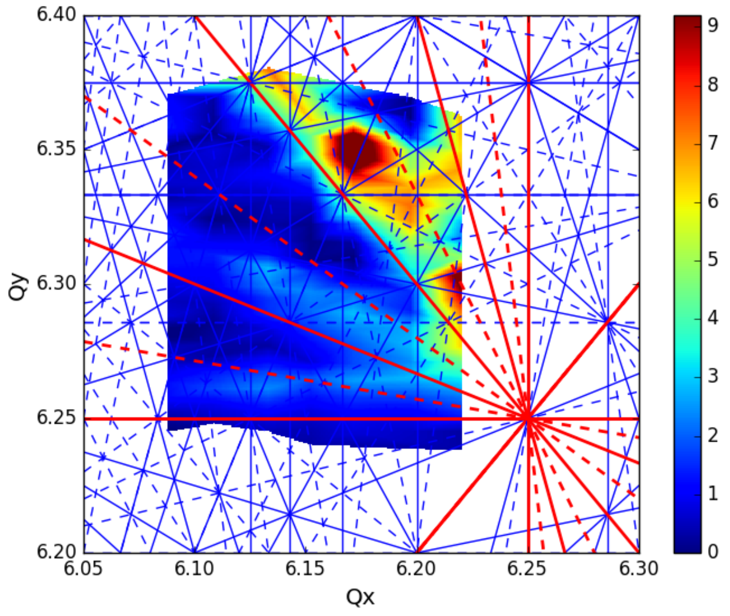


"Lower Brightness"



Low Brightness

Measurement



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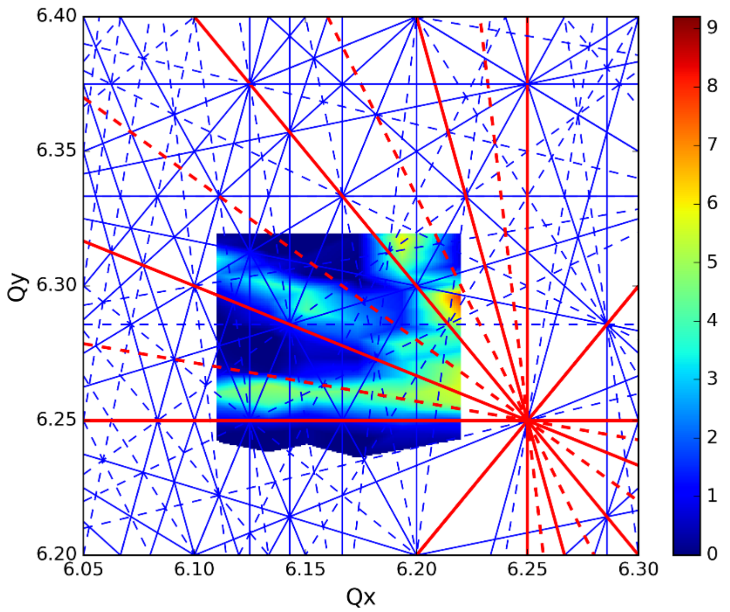
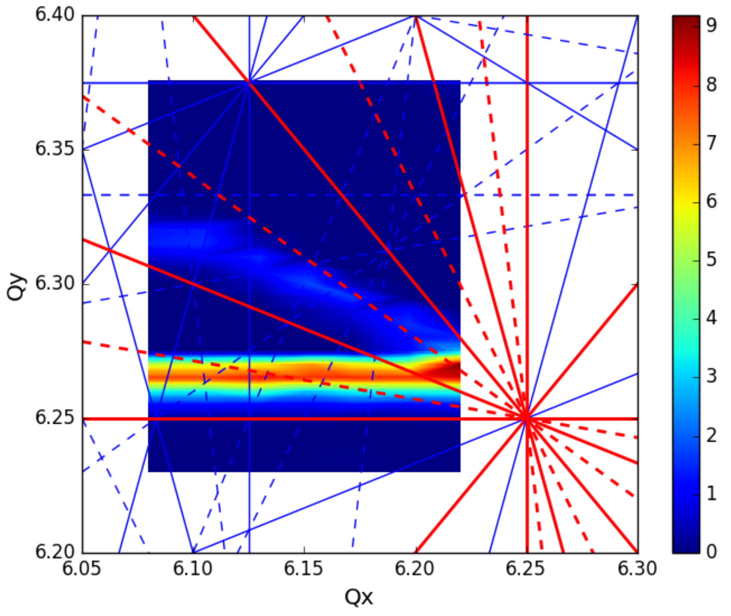


Simulation



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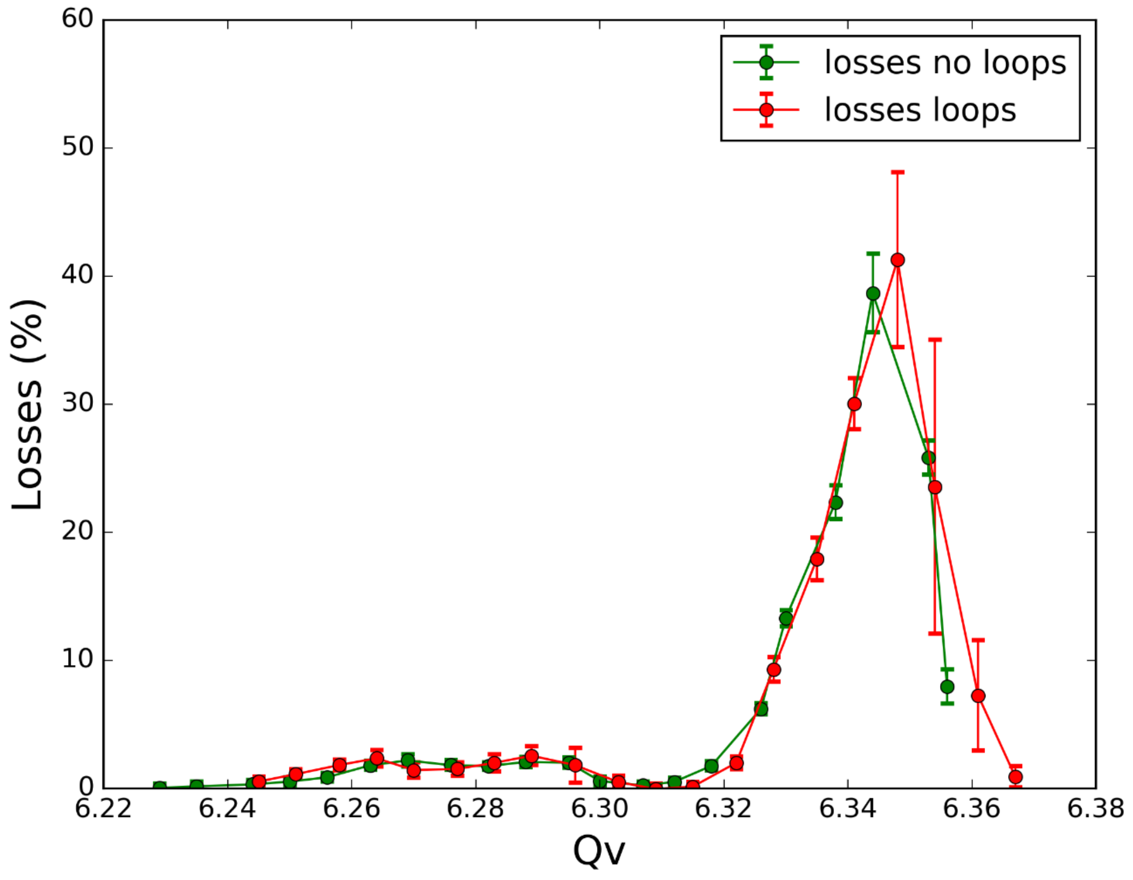

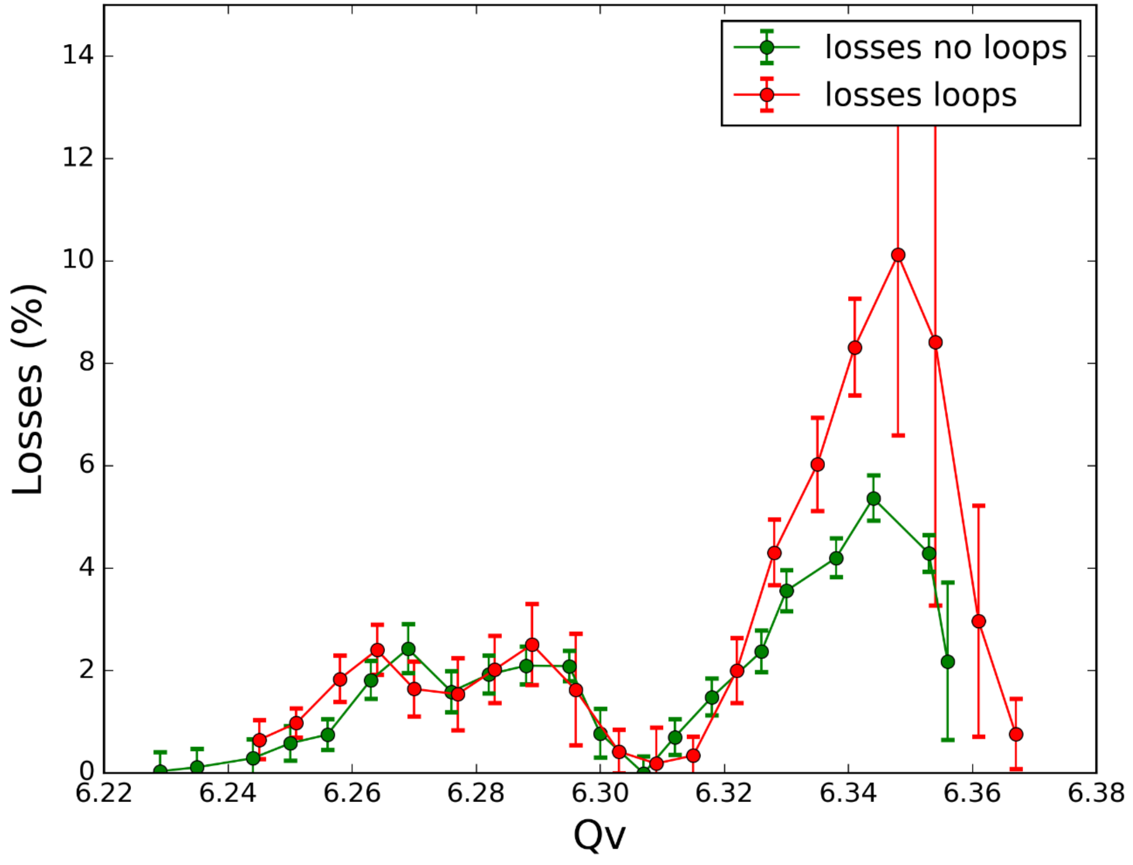

Frequency Maps

Tracking off-momentum particles under the influence of space charge using the Py-ORBIT Frozen model

- More particles trapped by the resonances due to the periodic crossing