Resonance Compensation for High Intensity and High Brightness Beams in the CERN PSB

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ABSTRACT

Resonance studies have been conducted during the recommissioning of the CERN Proton Synchrotron Booster (PSB) following the implementation of the LHC Injectors Upgrade (LIU) project. In particular, resonance identification through so-called loss maps has been applied on all four rings of the PSB, revealing various resonances up to fourth order. In a second step, compensation schemes for the observed resonances were developed using a combination of analytical methods, experimental data and machine learning tools. These resonance compensation schemes have been deployed in operation to minimize losses for reaching high intensity and high brightness, thereby achieving the target brightness for the LHC-type beams.

Brightness Limitation

LIU targets

2×brightness + ↑ intensity

LHC Beams Physics Beyond Collider & other physics users

Space charge effects

during LIU:

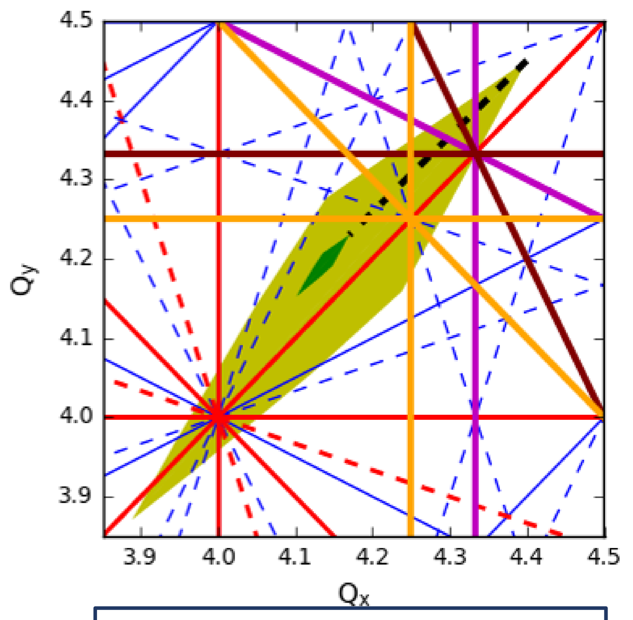
→ increased injection energy

→ injection scheme (H⁻) + β-beating (~5 ms)

- Still **incoherent tune spread at injection** > - 0.5
  → High tunes at Injection [4.4/4.45]
- Small **incoherent tune spread at extraction**
  → Optimized extraction tunes [4.17/4.23]

✓**Dynamic tunes** along the cycle

→ *Resonances Overlapped & Crossed in operations*



3rd Order Normal
3rd Order Skew
4th Order Normal
+ 2nd Order normal (to test higher tunes)

Resonance Identification

Dynamic tune scans

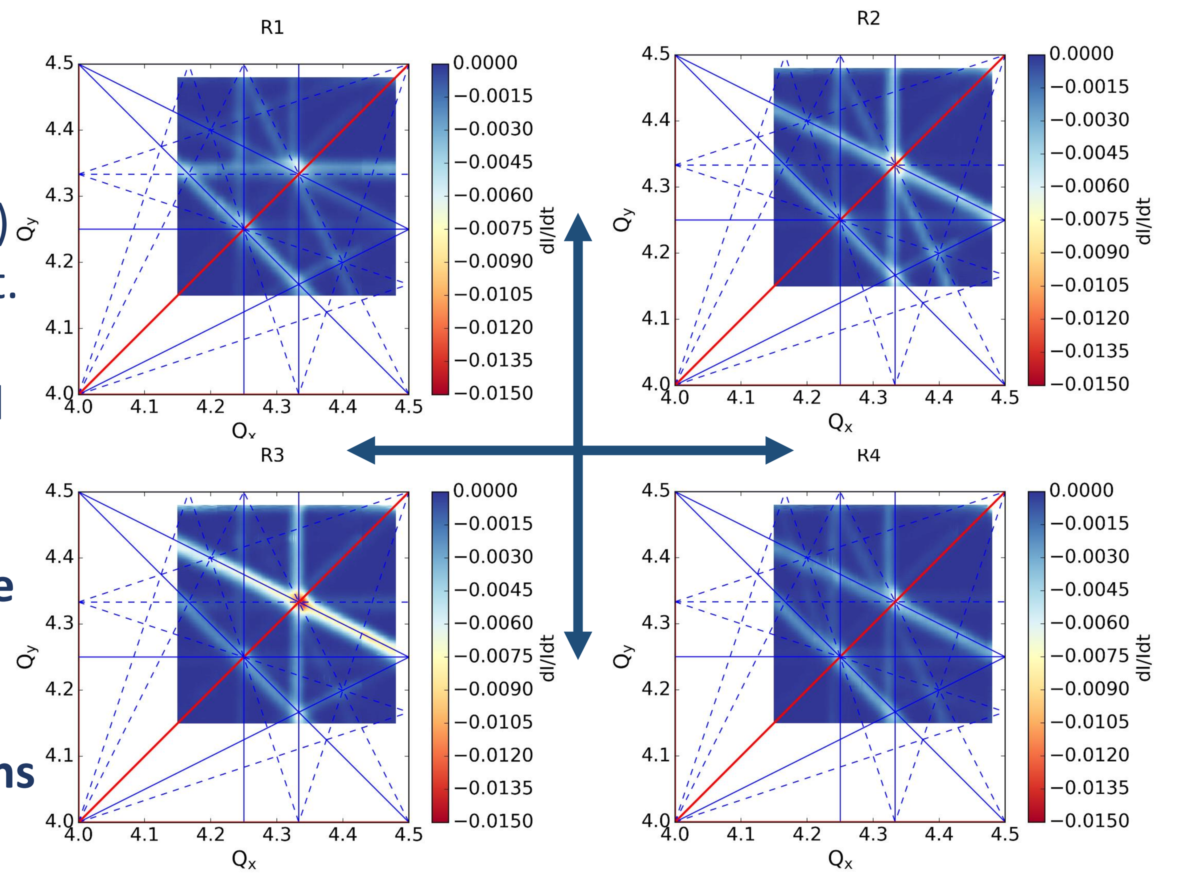
One tune (Q_x *or* Q_y) is varying during C350-700ms from $[4.15-4.48]$ (and vice versa) while the other is kept constant.

The resonances can be seen through the loss rate calculated from the intensity curve

→ **Loss Map**

The study is done on a **flat cycle** with a **low brightness** beam ($\Delta Q_x \approx \Delta Q_y \approx -0.035$)

Results : average of **all directions**



→ Resonances **up to 4th order** can be seen in **all rings**

→ **3rd order normal** resonances are stronger in **R2, R3 & R4**

→ **3rd order skew** resonances are stronger in **R1**

→ **4th order normal** resonances are strong in **all rings**

2nd order normal (half integer) in all rings → omitted

Resonance Compensation

Vertical half Integer

$2Q_y = 9$:

Q_y ramped: [4.45-4.55] in [400-500 ms]

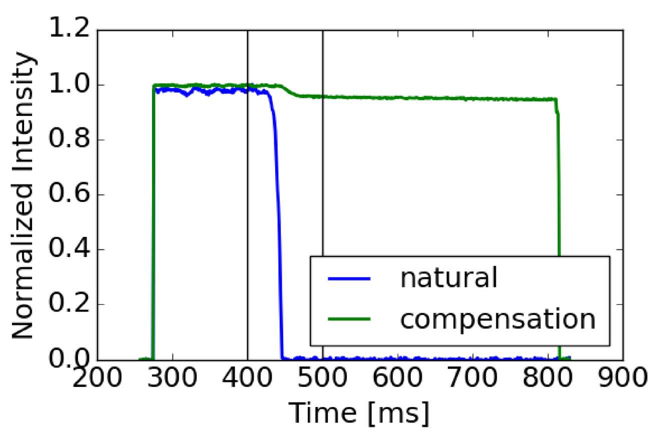
→ **full beam lost**

Identification of suitable correctors (PTC)

Varied currents (experimentally)

Partial compensation:

→ **5% beam loss**

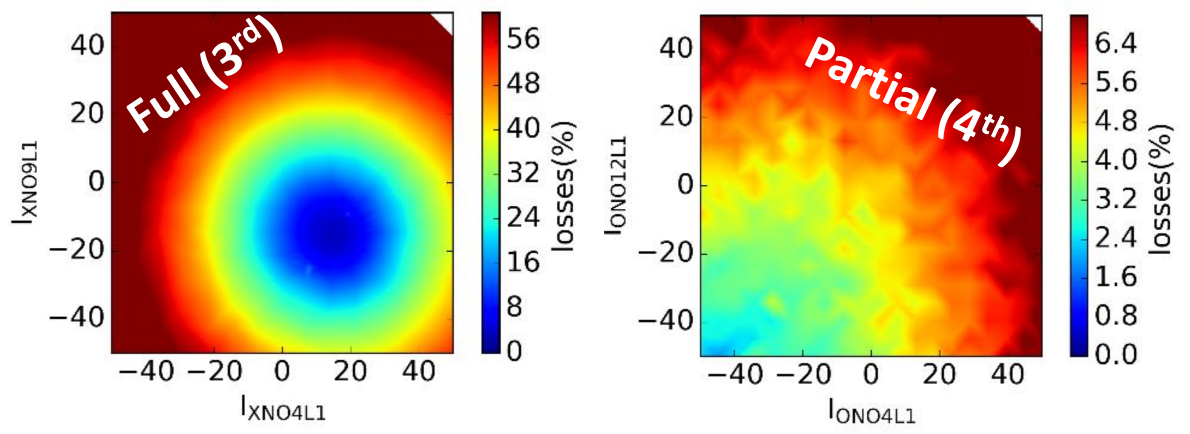


High order resonances

For each resonance:

- Resonances dynamically crossed
- Identified **suitable correctors**
- **Varied currents** experimentally
- **Losses** monitored for all configurations

✓**Individual resonance compensation**



Investigating global corrections:

Using PTC and the MADX model where the resonances are crossing each other:

- Calculate the RDTs of the resonances based on the compensation values
- Calculate the RDTs of each available magnet for all resonances of interest

Analytically estimated global solutions

E.g. 3rd order normal resonance

$$\begin{bmatrix} Re[RDT^{sext1}_{3Qx}] & Re[RDT^{sext2}_{3Qx}] & Re[RDT^{sext3}_{3Qx}] & Re[RDT^{sext4}_{3Qx}] \\ Im[RDT^{sext1}_{3Qx}] & Im[RDT^{sext2}_{3Qx}] & Im[RDT^{sext3}_{3Qx}] & Im[RDT^{sext4}_{3Qx}] \\ Re[RDT^{sext1}_{Qx+2Qy}] & Re[RDT^{sext2}_{Qx+2Qy}] & Re[RDT^{sext3}_{Qx+2Qy}] & Re[RDT^{sext4}_{Qx+2Qy}] \\ Im[RDT^{sext1}_{Qx+2Qy}] & Im[RDT^{sext2}_{Qx+2Qy}] & Im[RDT^{sext3}_{Qx+2Qy}] & Im[RDT^{sext4}_{Qx+2Qy}] \end{bmatrix} \times \begin{bmatrix} F_{k\,sext1} \\ F_{k\,sext2} \\ F_{k\,sext3} \\ F_{k\,sext4} \end{bmatrix} = \begin{bmatrix} Re[RDT^{meas}_{3Qx}] \\ Im[RDT^{meas}_{3Qx}] \\ Re[RDT^{meas}_{Qx+2Qy}] \\ Im[RDT^{meas}_{Qx+2Qy}] \end{bmatrix}$$

Global solutions 3rd & 4th normal

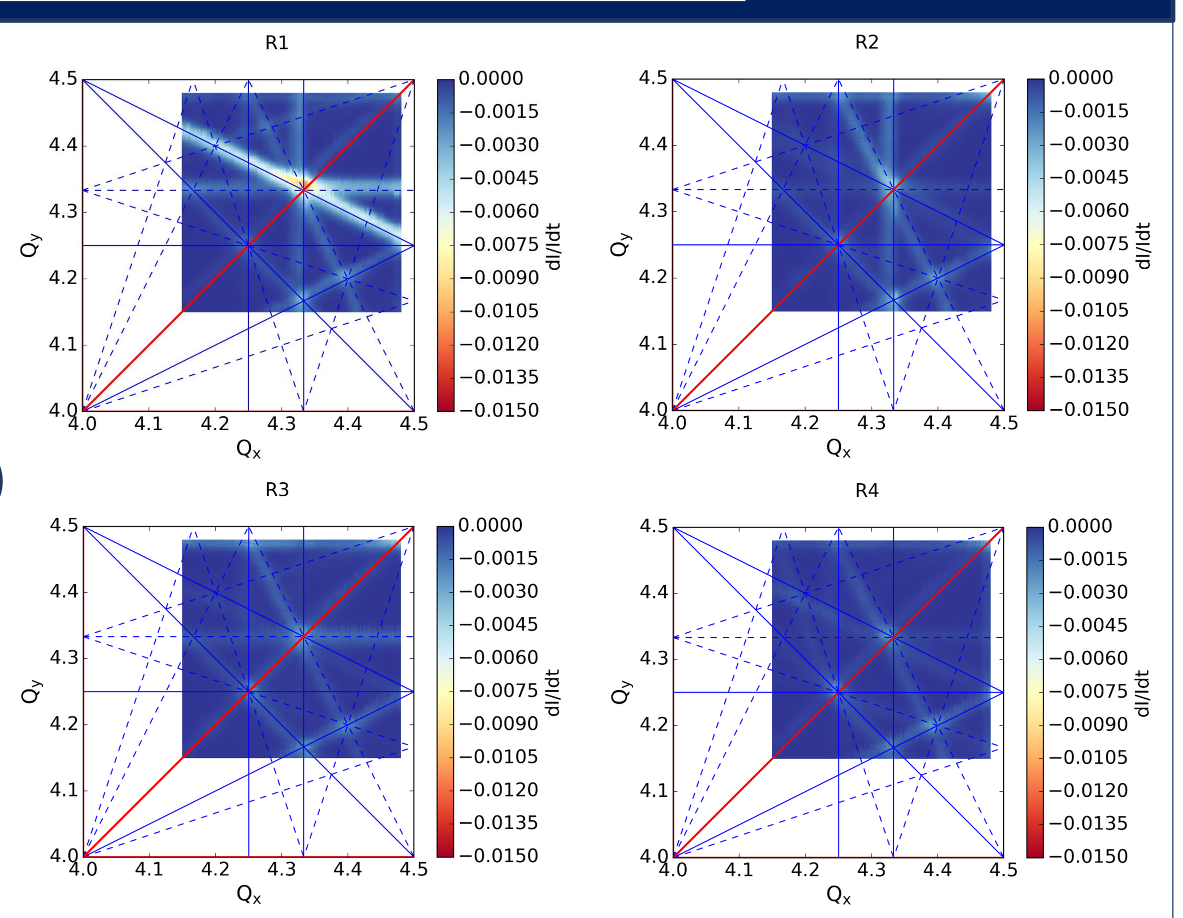
Analytically (normal sextupoles/3rd) & experimentally (normal octupoles/4th) estimated corrections applied:

✓**Significant suppression of targeted resonances**

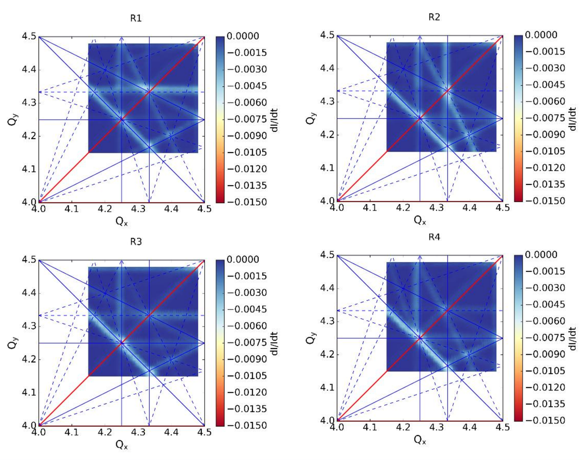
✓**In R2, no global correction for 3rd order was found (current limitations)**

✓**No global correction for 3rd order skew (limited correctors)**

✓**In R1, 3rd order normal resonances appear enhanced**



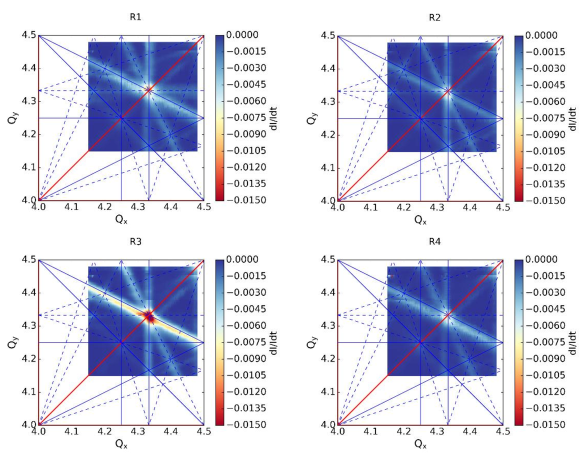
Global solutions 3rd or 4th normal



Targeting each order alone:

✓**Compensation in all rings**

✓**Enhanced 3rd order with Octupoles**



Optimization tools

→**Optimization Framework** GeOFF

- Fast convergence for individual resonances
- Flexible to add extra corrector magnets either for investigations of individual resonances or global settings

✓**Better compensation** for cases of cross-talk & partial compensation

✓**Global settings** for all rings

CONCLUSION

Resonance studies were conducted in the PSB during the commissioning period after the upgrade in the frame of the LIU project. The identification studies revealed resonances up to 4th order in all rings, that were observed for the first time. Compensation schemes allowing for global compensation of the resonances were developed through extensive experimental and analytical studies. Refinement of the schemes with optimizer tools provides a better compensation for all resonances and contributes to higher brightness and intensity for the PSB users.

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