LHC Injectors Upgrade

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Identification and compensation of resonances in the CERN Proton Synchrotron

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Space Charge 2013

Acknowledgements

The PS/PSB operations crew

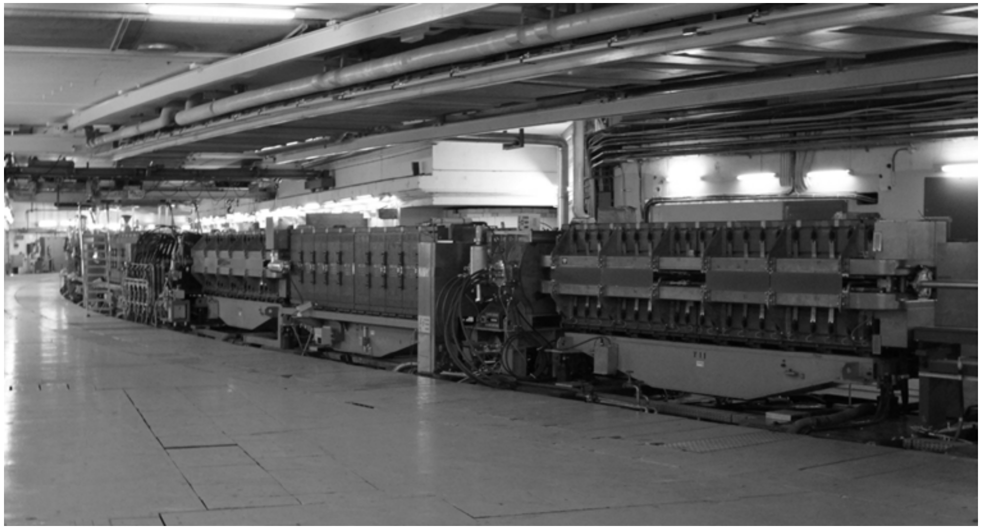
CERN

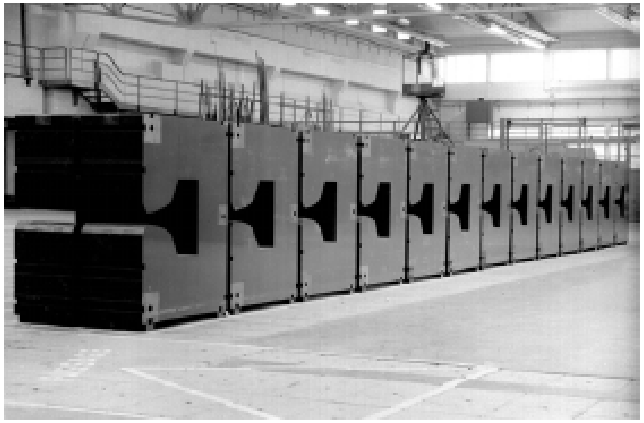
Overview

- The main magnets of the CERN PS
- Control of the working point
- Identification of dangerous resonances
- Compensation of resonances
- Conclusion

The main magnets of the CERN PS

- Machine circumference: $2\pi \cdot 100$ m
- **100 main magnets**
- **1 reference unit** to allow access during operation
- First machine to apply the alternating gradient principle → **combined function** magnets
- Each unit composed of 10 blocks, 5 providing focusing, 5 defocusing
- Working point of the machine is determined by the dipole field → **bare tune** of the beam





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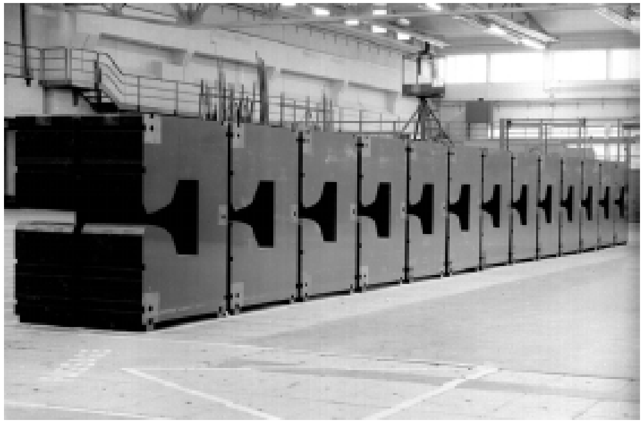
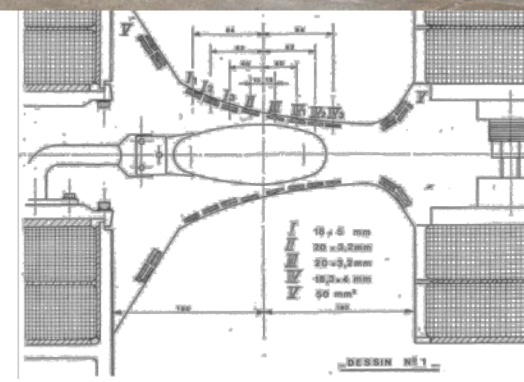
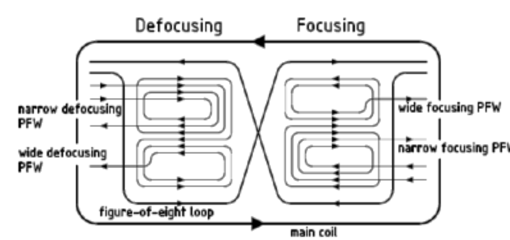


Control of the working point





Courtesy M. Juchno

Two different ways of controlling the tune

- **Low Energy Quadrupoles** (LEQ)
  - RMS current limited to 10 A
  - 2 families: focusing/defocusing
  - used from injection at E_k=1.4 GeV up to 3.5 GeV

- **Pole Face Windings** (PFW) and **Figure of 8 Loop** (F8L)
  - in total **5 circuits** to control tunes, linear chromaticities and (in theory) one of the second order chromaticities
  - PFW positioned on the main magnet pole
  - for operational beams narrow and wide circuits of F and D powered in series
  - F8L crosses between the magnet half units

Control of the working point

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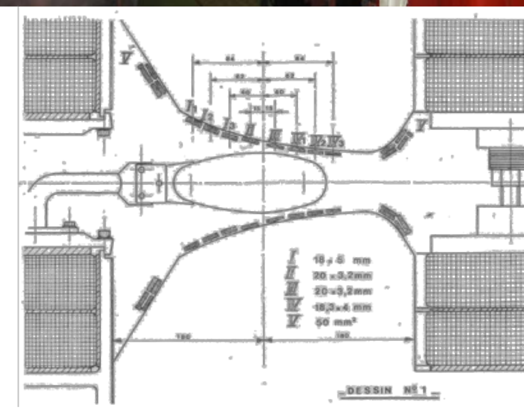

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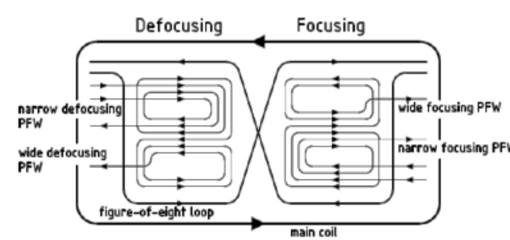

Control of the working point

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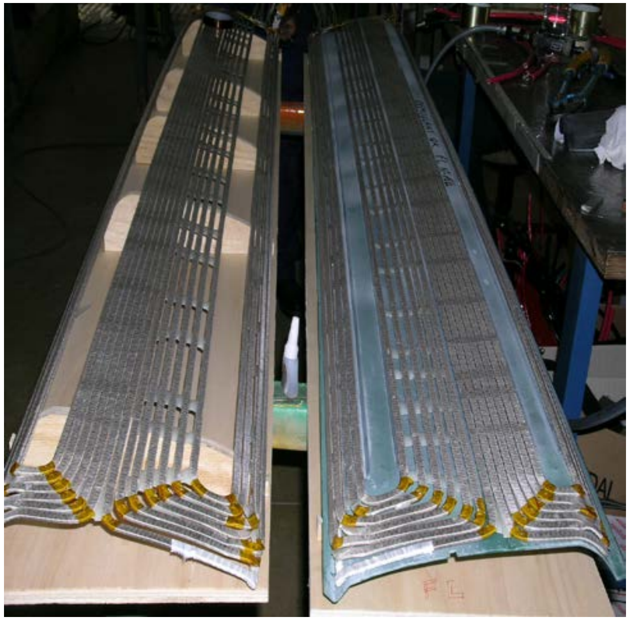
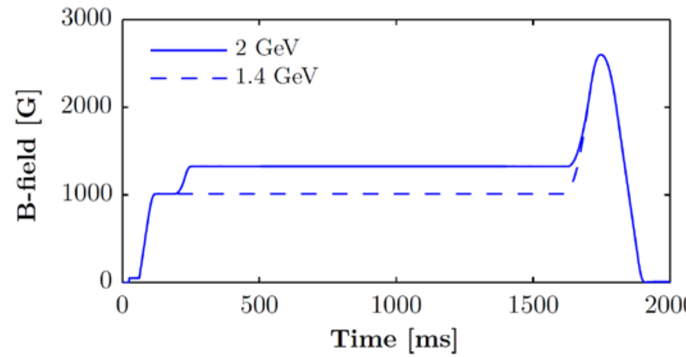
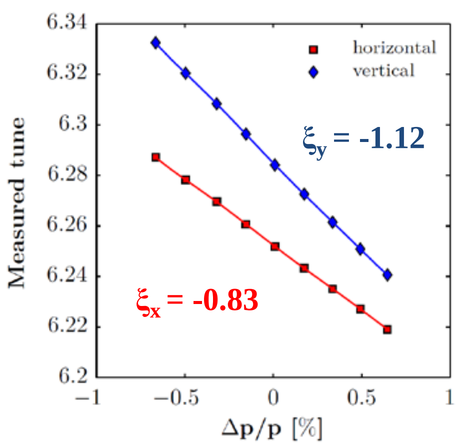


Control of the working point

Measurements were mainly carried out at the future injection energy of **2 GeV** (plateau > 1 sec)



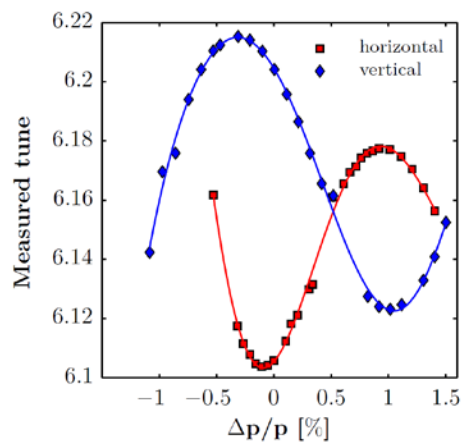
Bare machine
no LEQ, no PFW



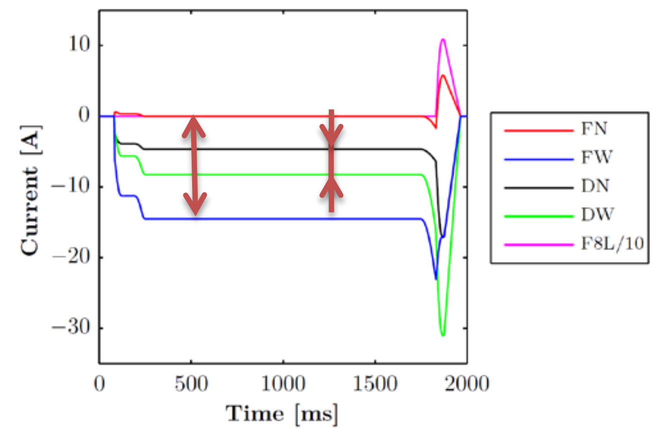
very linear behaviour

LEQ don't influence linearity

PFW

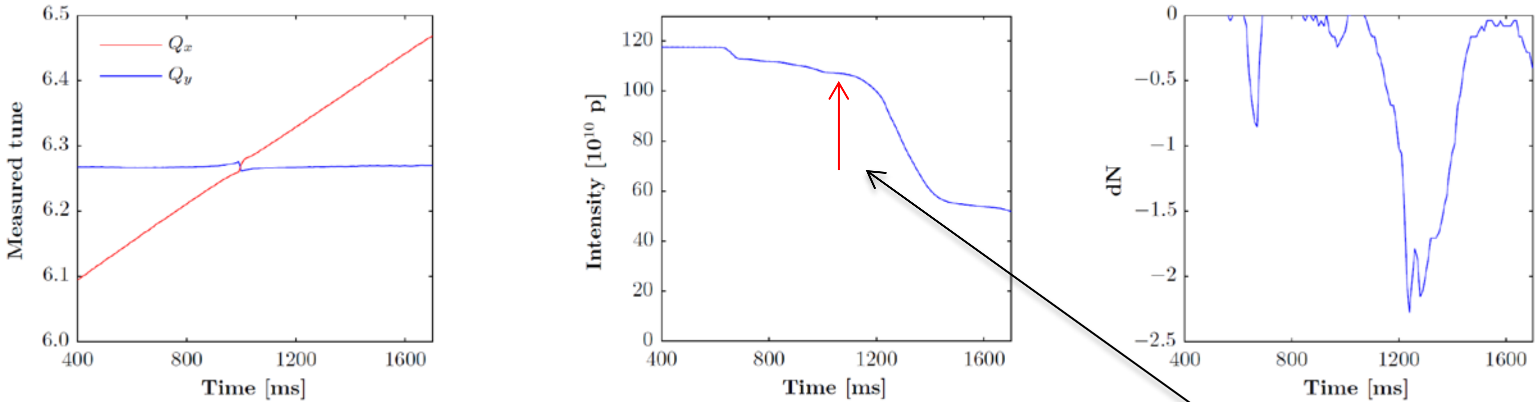


significant alteration of linear machine



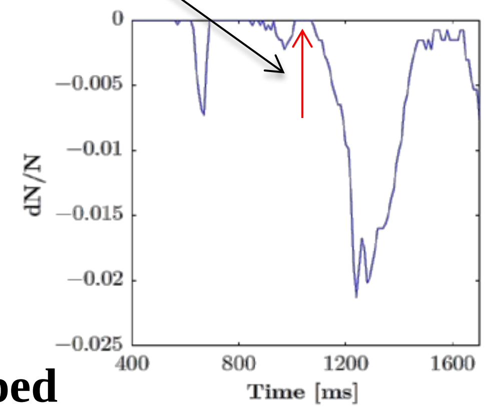
unbalanced narrow and wide circuits

Identification of dangerous resonances



<u>Measurement concept</u>

- technique first used by G. Franchetti et al.[*] at GSI in 2004
- only **beam loss** considered to identify resonances → **large** normalized transverse **emittances** ($\varepsilon_{x1\sigma} \approx$ 10 mm·mrad, $\varepsilon_{y1\sigma} \approx$ 8 mm·mrad), **small tune spread** ($\Delta Q_x \approx -0.05$, $\Delta Q_y \approx -0.07$)
- **tune** in one plane kept **constant**, in the other dynamically **ramped**
- intensity recorded
- **derivative** calculated
- each peak **normalized** by intensity before the respective resonance



[*]A benchmarking experiment in SIS18 for dynamic aperture induced beam loss, GSI-Acc-Note-2004-05-001

Identification of dangerous resonances

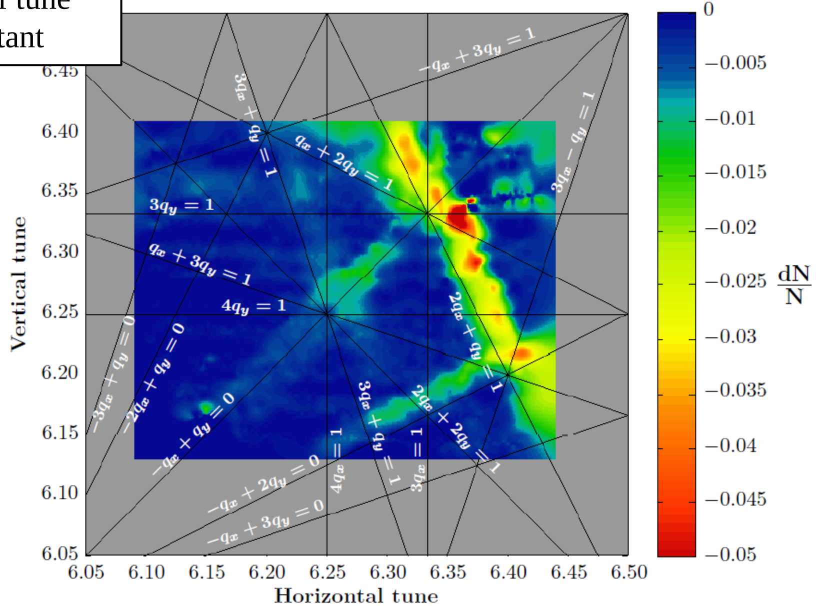
- all steps repeated for different constant tune
- **interpolation** of whole set of data on equidistant grid
- **color scaling** informs about losses

estimated tune spread:
$\Delta Q_x \approx -0.05$, $\Delta Q_y \approx -0.07$

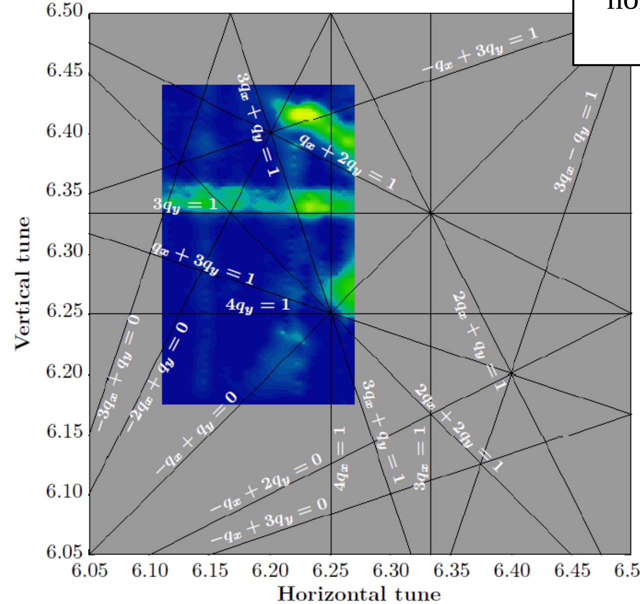
<u>First measurement at 1.4 GeV</u>

LEQ active to control the tunes

vertical tune constant



horizontal tune constant



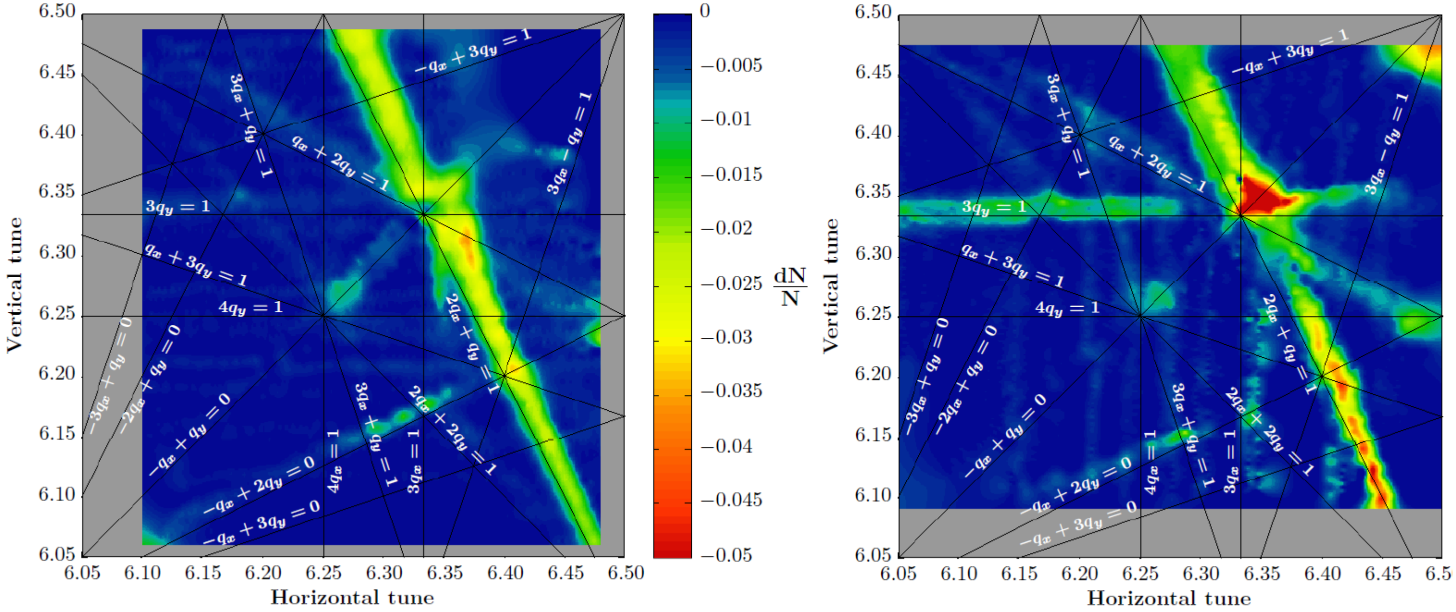
strongest observed resonance: $2q_x+q_y=1$

important for machine operation: $3q_y=1$

Identification of dangerous resonances

Measurements with **PFW** at 2 GeV

- only 4 out of the 5 available circuits powered → F8L fixed to 0 A **(4 current mode)**
- accessible area in the tune diagram much larger than with LEQ

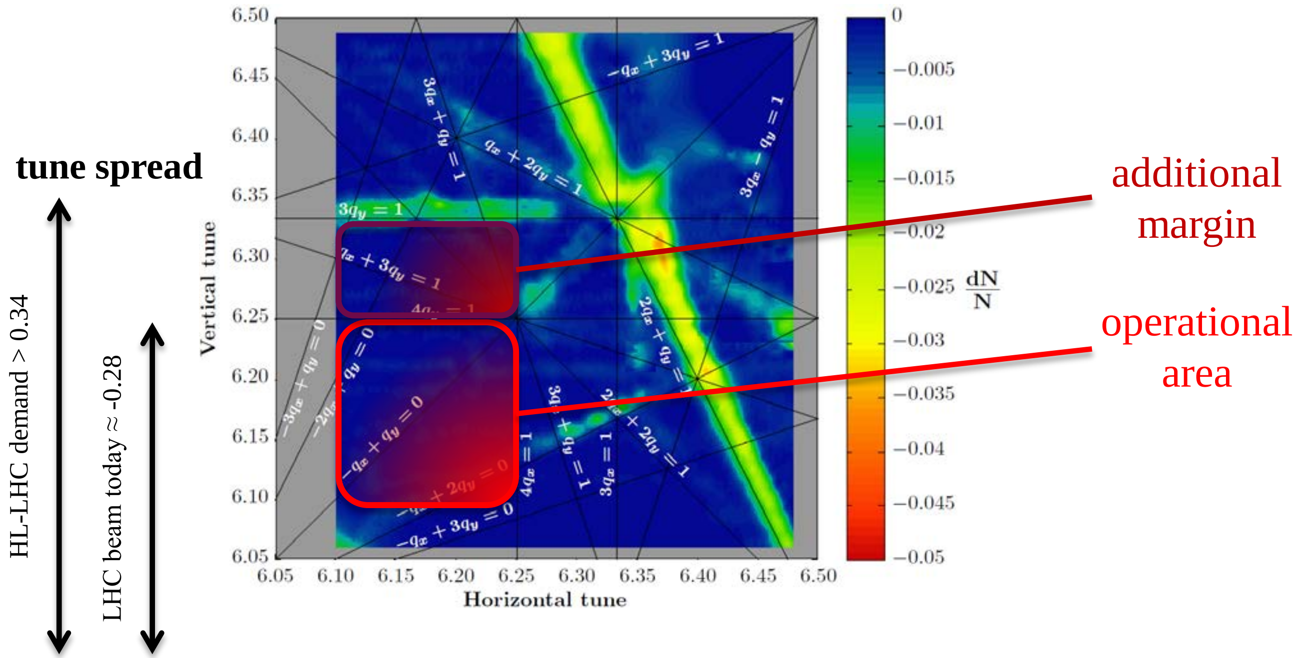


same resonances excited as in measurements on previous slide

→ **no additional excitation by PFW**

Identification of dangerous resonances

Combination of both scans



- measurements suggest possibility to increase working point
- but even then: available area not large enough to accommodate HL-LHC beam → **resonance compensation**

Compensation of resonances

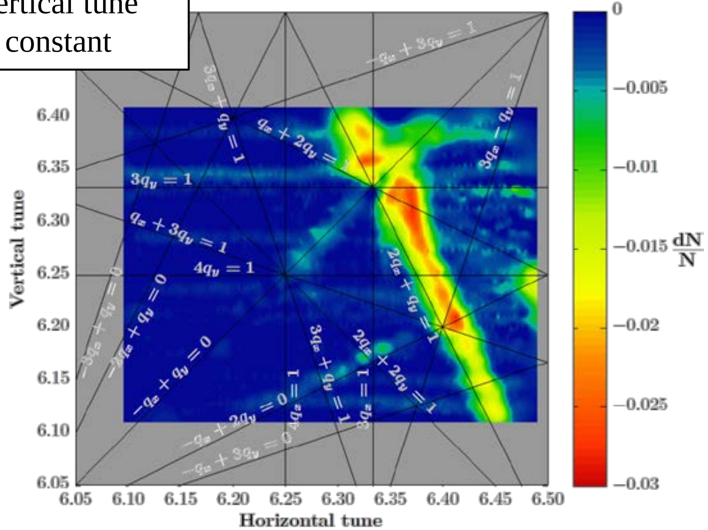
- resonances excited by the bare machine → **effect of the main magnets**
- simulation campaign to obtain **magnetic errors** due to **mechanical tolerances of the yoke** and **alignment tolerances of the main coil, PFW, F8L**
- errors implemented in **MAD** and **PTC** is then used to calculate **driving terms** of the resonances and the corresponding **correction currents**
- cause of this errors not completely understood (contribution of **fringe fields**, fields in the **junctions** between the single blocks of the main magnet,…)
- resonances $3q_y=1$ and $2q_x+q_y=1$ are caused by **skew sextupolar components** of the magnetic field
- installation of **4 skew sextupoles** (independent power supplies)

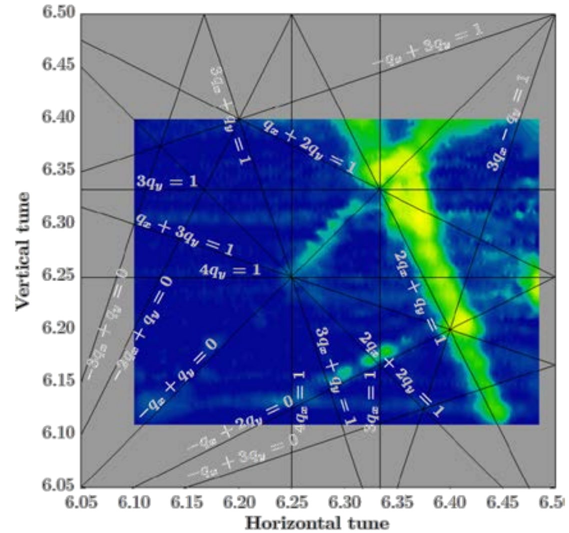
Compensation of resonances

before

after

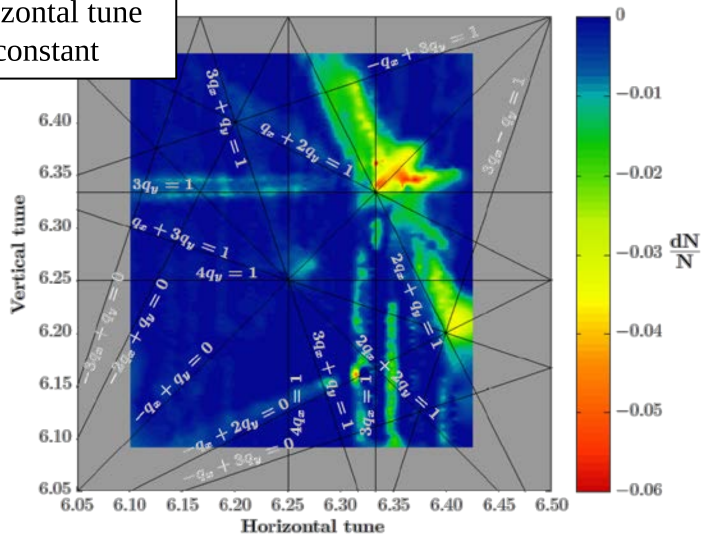
vertical tune constant



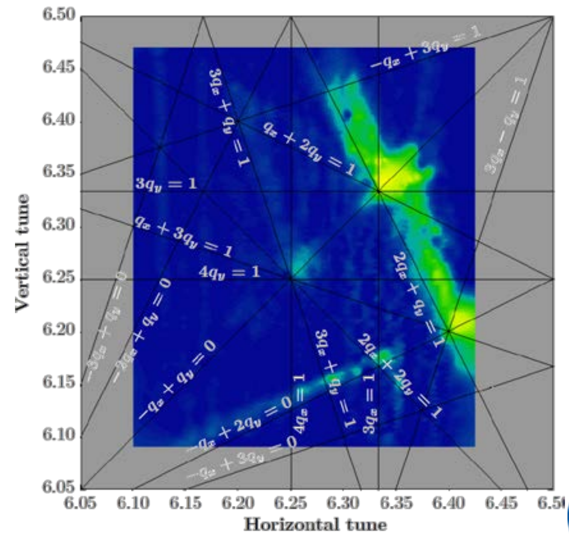


Compensation of $3q_y=1$

horizontal tune constant



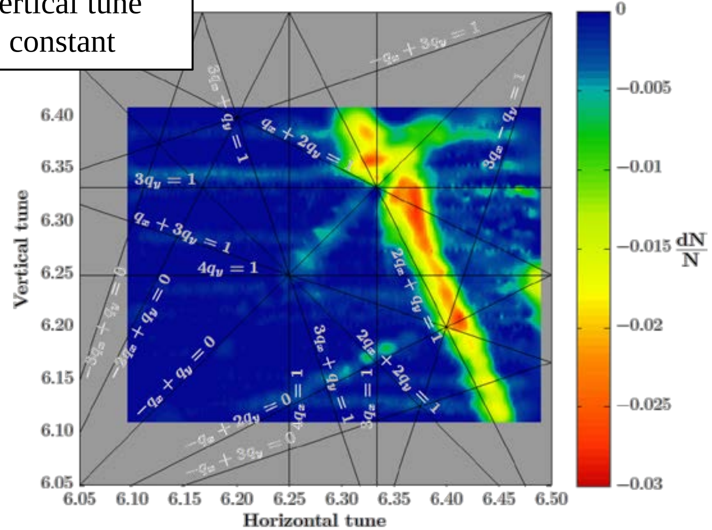
additionally: reduction of $2q_x+q_y=1$

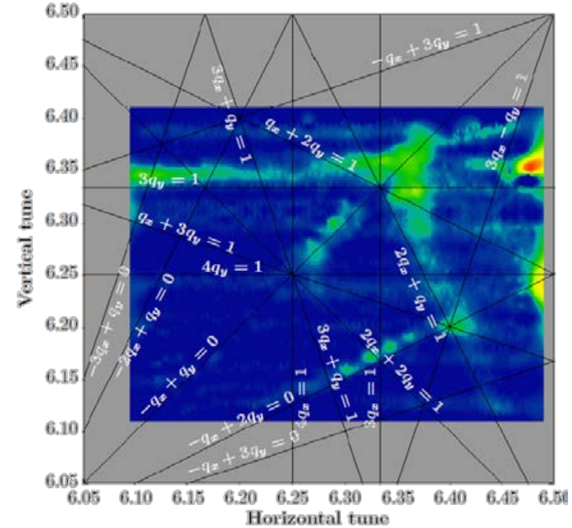


Compensation of resonances

before | **after**

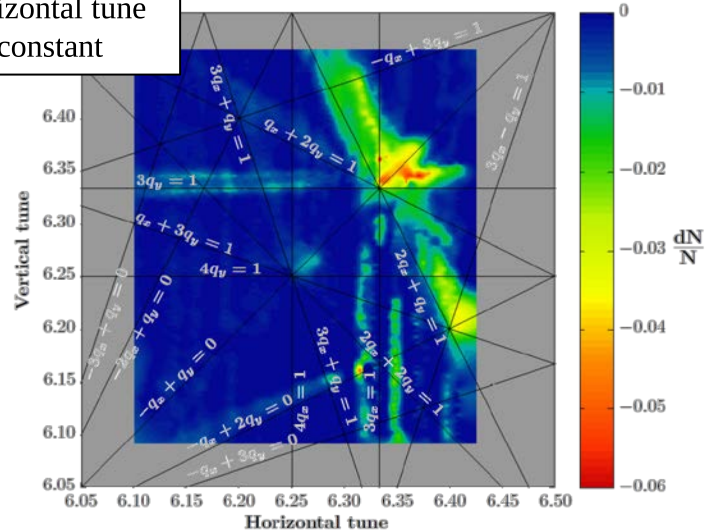
vertical tune constant



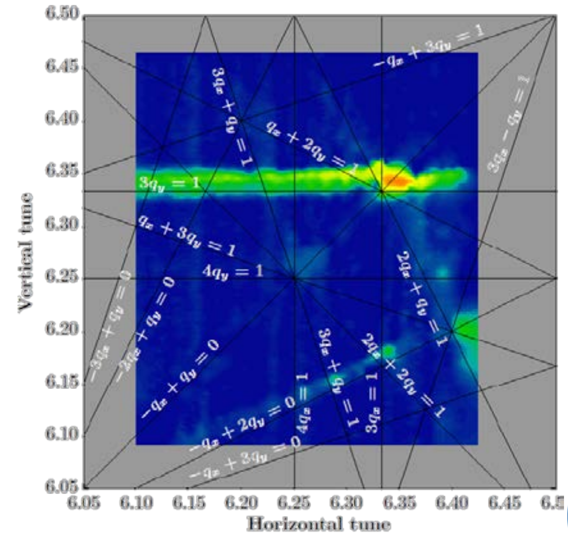


Compensation of $2q_x+q_y=1$

horizontal tune constant

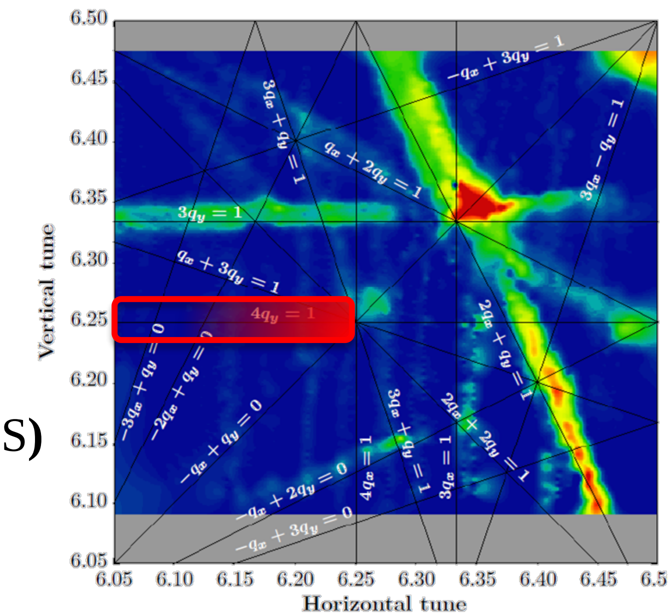


$3q_y=1$ is clearly enhanced



Conclusion

- suggested by the presented measurements: the resonance **$3q_y$=1** constitutes the **major limit** for increasing the space charge tune spread
- resonance **compensation successfully** implemented
- ready for **tune spreads** in the order of HL-LHC **(> -0.3)**?
  → unfortunately **NOT**!
- resonance **$4q_y$=1** not found to be excited by the magnetic errors, **BUT** seems to be **excited by space charge**
  (see talk of R. Wasef, Space charge studies in the CERN PS**)**
- additional **compensation scheme with octupoles** to be studied



LHC Injectors Upgrade

THANK YOU FOR YOUR ATTENTION!

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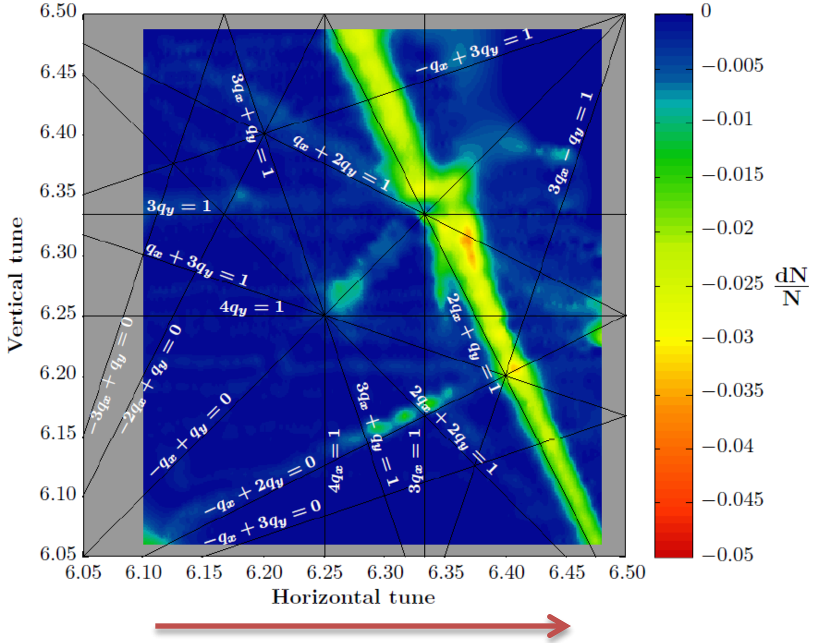
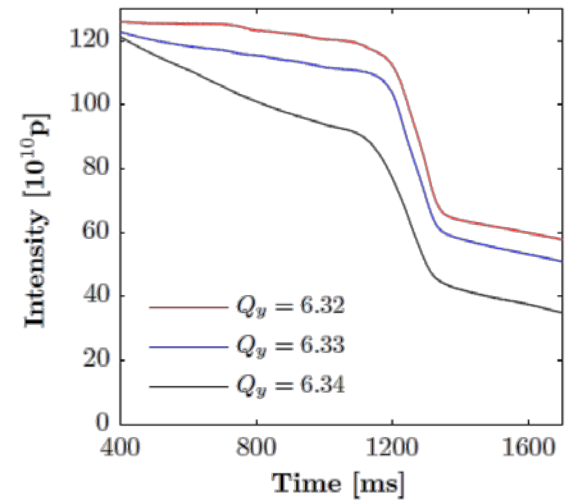
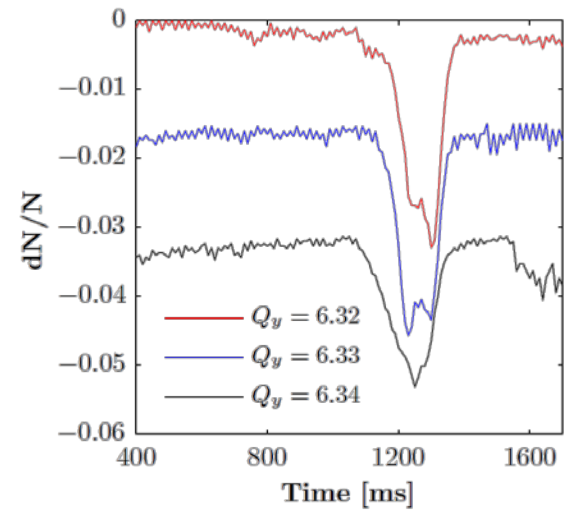
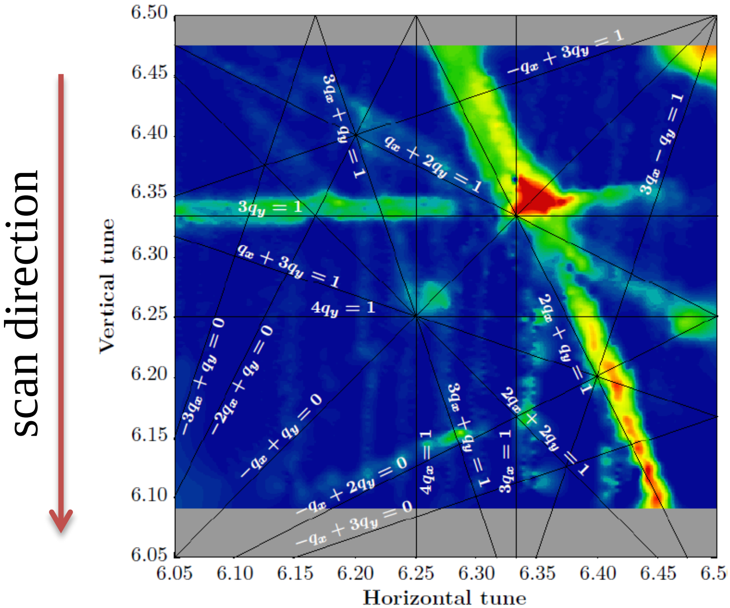
Backup

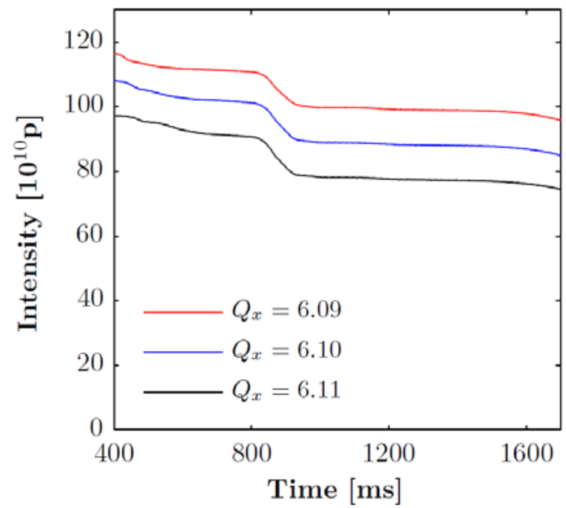


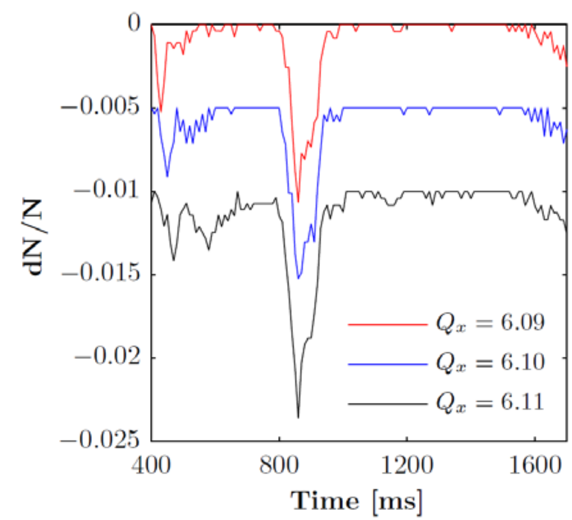
scan direction





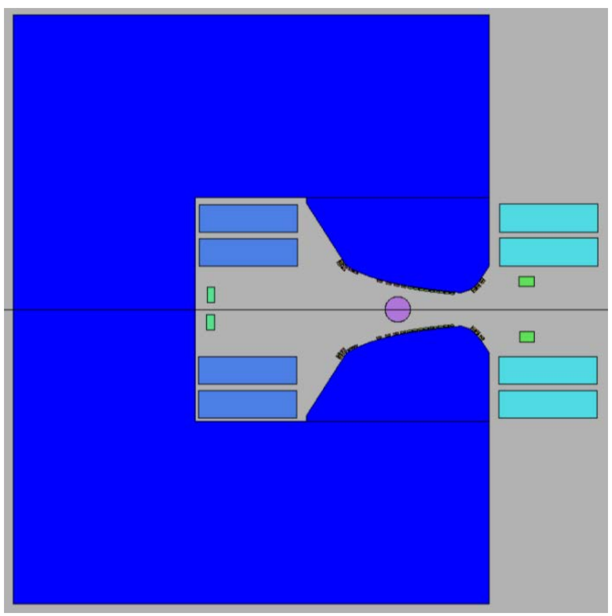

scan direction
Vertical tune
Horizontal tune
6.05
6.10
6.15
6.20
6.25
6.30
6.35
6.40
6.45
6.50
6.5
$3q_y = 1$
$q_x + 3q_y = 1$
$4q_y = 1$
$q_x + 2q_y = 1$
$3q_x + q_y = 1$
$-q_x + 3q_y = 1$
$3q_x - q_y = 1$
$2q_x + q_y = 1$
$2q_x + 2q_y = 1$
$3q_x + q_y = 1$
$3q_x = 1$
$4q_x = 1$
$-3q_x + q_y = 0$
$-2q_x + q_y = 0$
$-q_x + q_y = 0$
$-q_x + 2q_y = 0$
$-q_x + 3q_y = 0$

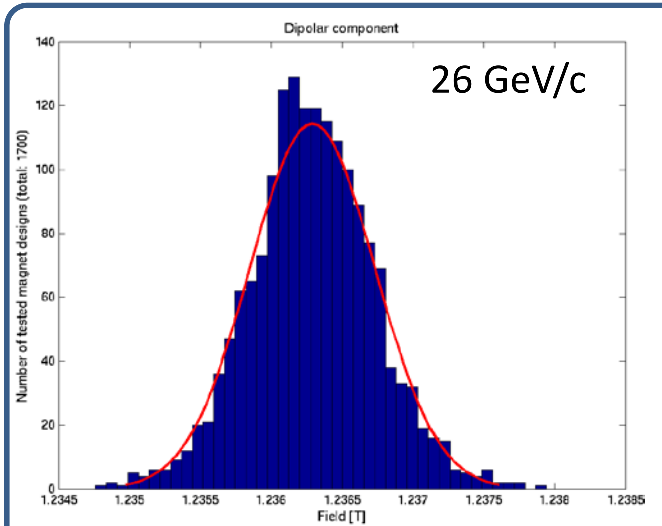

Intensity [10^{10}p]
Time [ms]
0
20
40
60
80
100
120
400
800
1200
1600
$Q_x = 6.09$
$Q_x = 6.10$
$Q_x = 6.11$


dN/N
Time [ms]
0
−0.005
−0.01
−0.015
−0.02
−0.025
400
800
1200
1600
$Q_x = 6.09$
$Q_x = 6.10$
$Q_x = 6.11$

IV. Resonance compensation

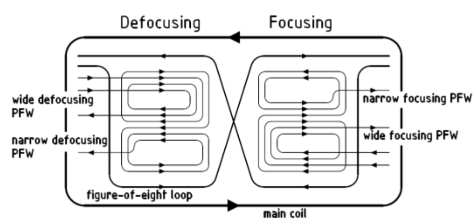
- 2D calculation including Gaussian distribution of the position of the coils and the shape of the iron with up to 22 DOFs per magnet (OPERA)
- 1000 models per magnet type and current level have to be calculated (<1 d with advanced and additional licenses, before 10 d)
- Performed for momentum of 2.14 GeV/c, 2.78 GeV/c, 14 GeV/c, 26 GeV/c

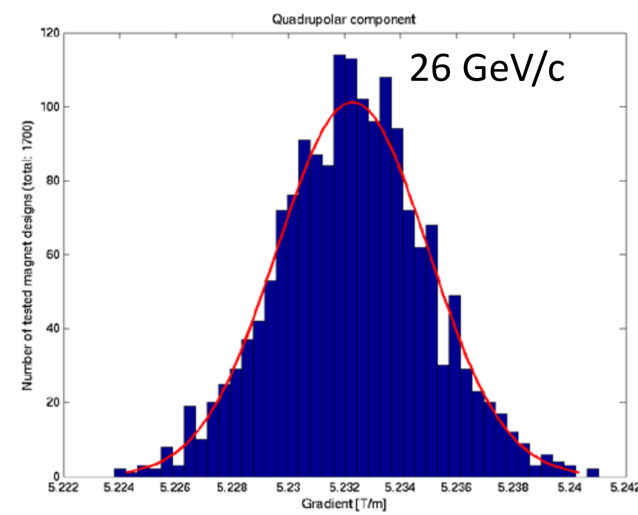




Coils can be displaced, no rotation:
Main coils (2 x 4 DOFs), σ = 3 mm
F8 (2 x 4 DOFs), σ = 1 mm
PFW (2 x 2 DOFs), σ = 0.7 mm

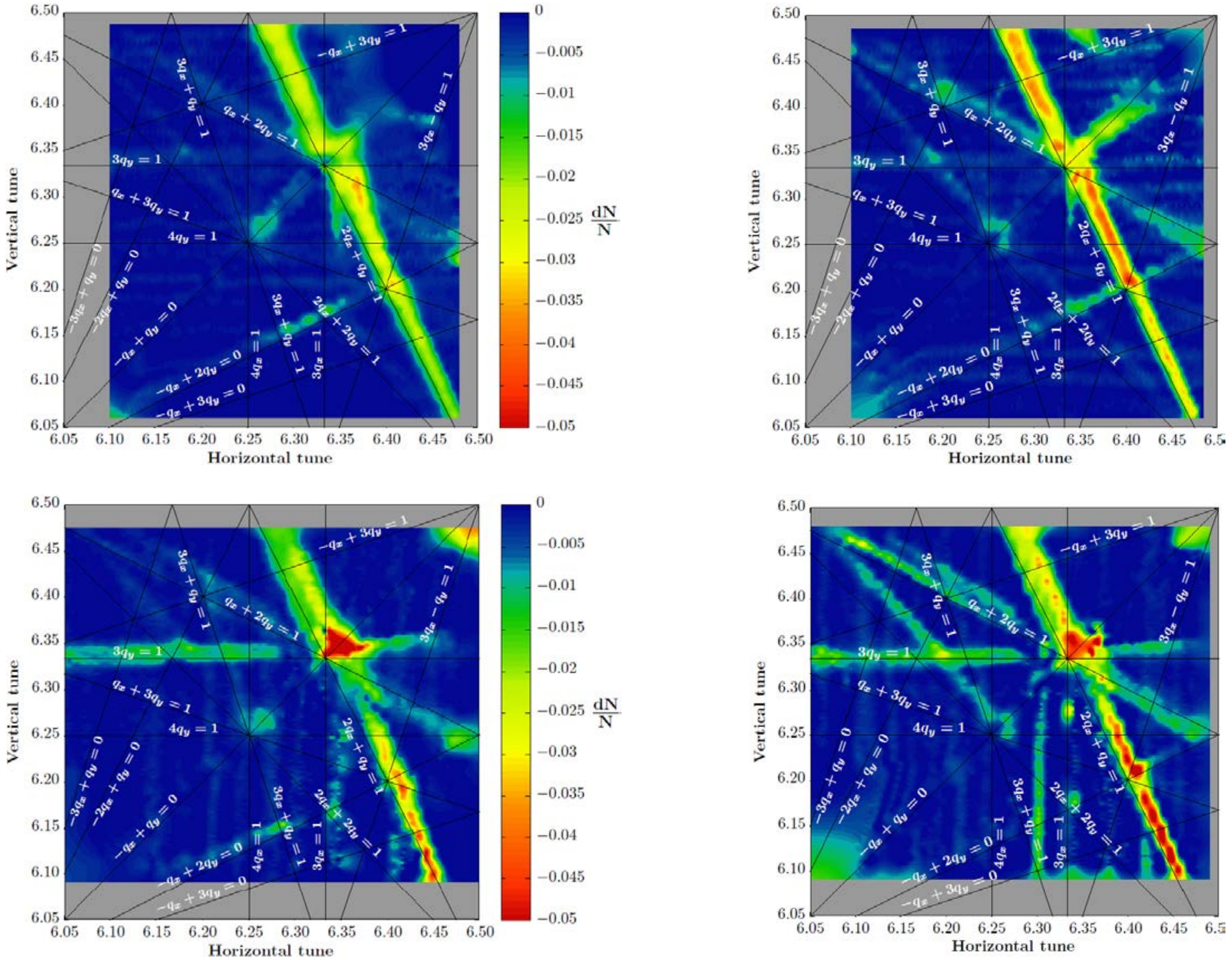
Iron is displaced in y-direction, σ = 0.02/3 mm





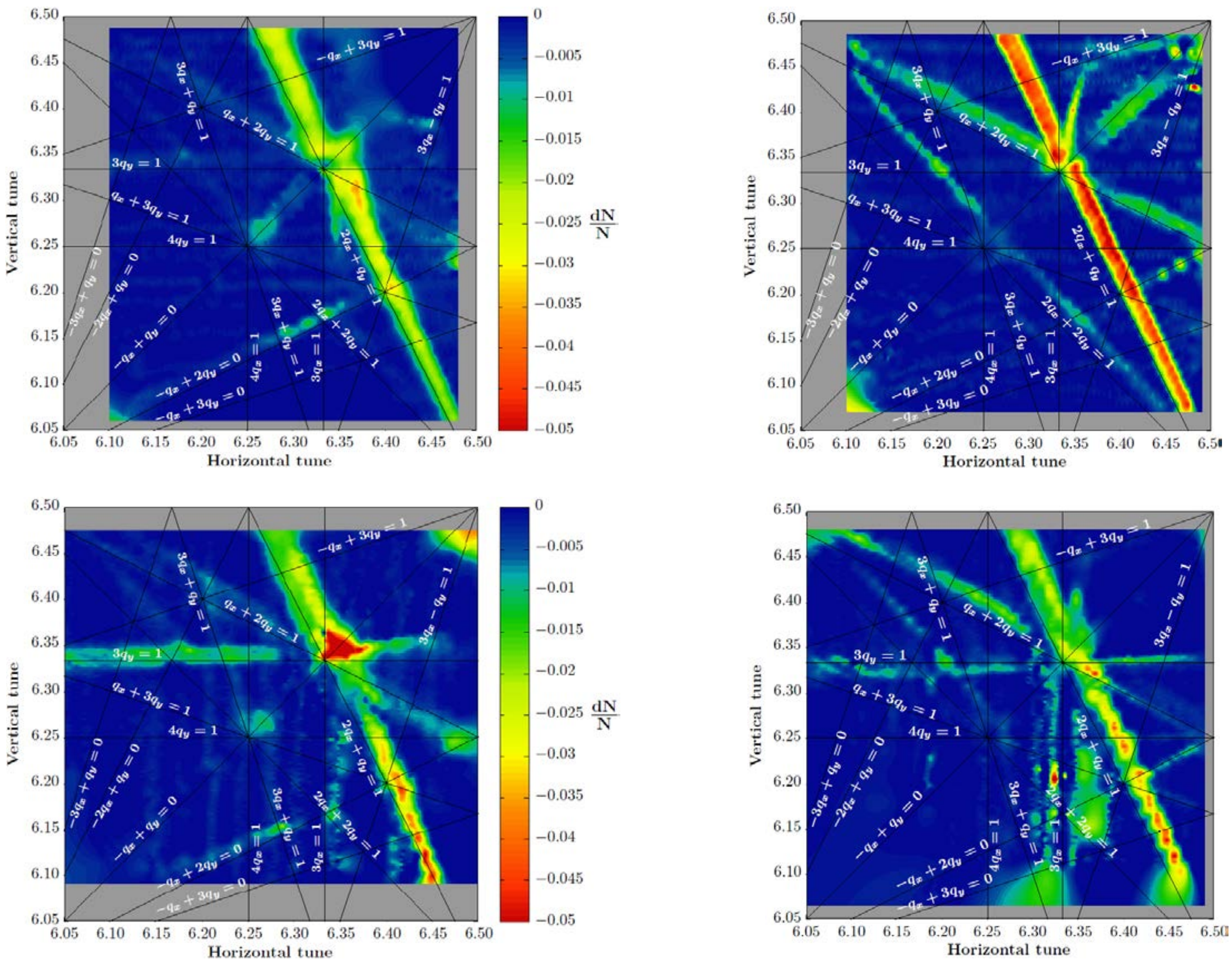
Chromaticity correction – horizontal plane

Changing from $\xi_x = -0.83$ to $\xi_x = -0.2$

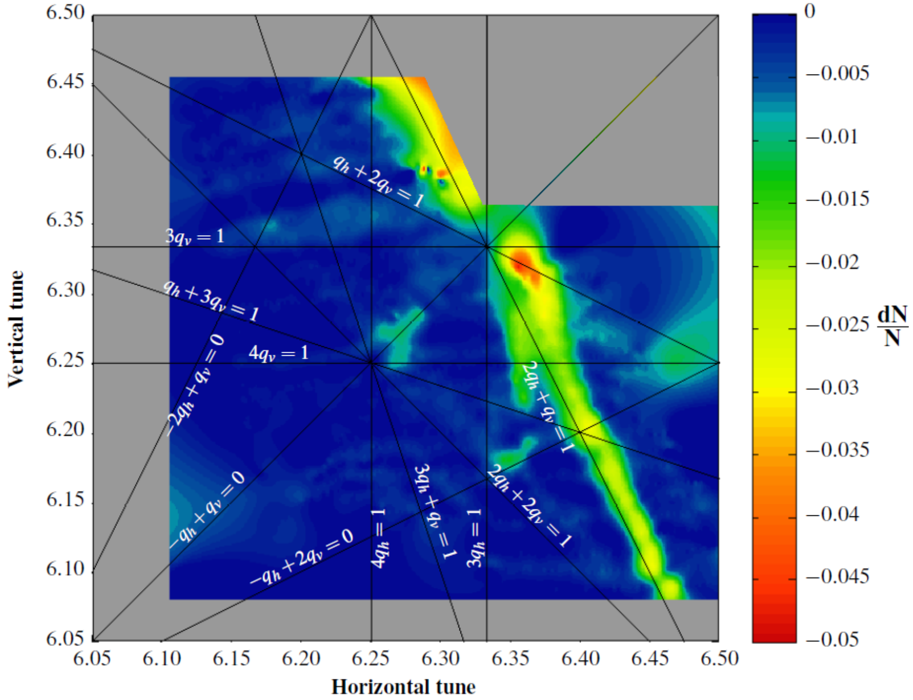


Chromaticity correction – both planes

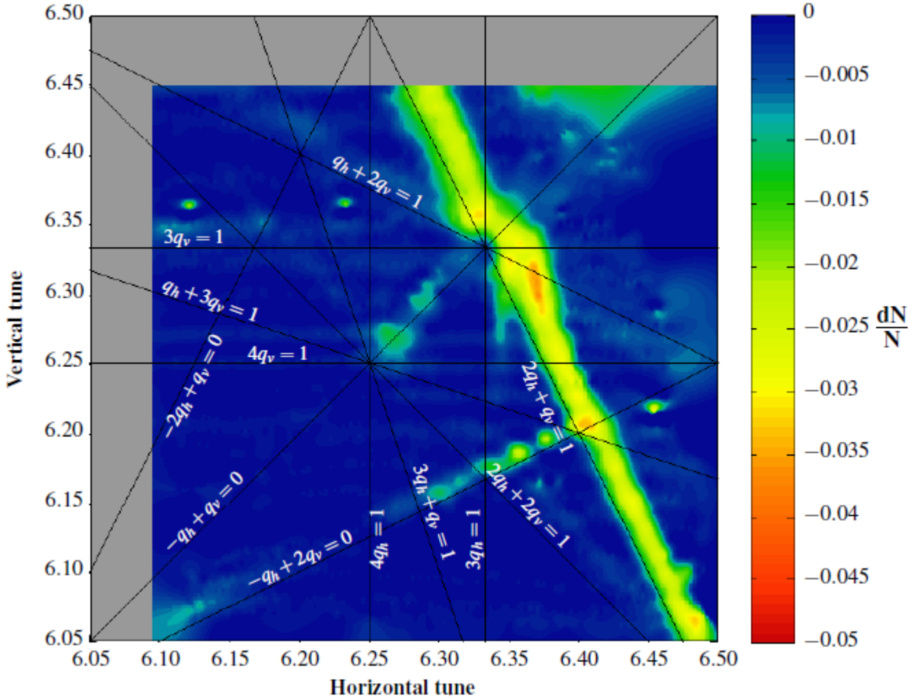
Changing from $\xi_x = -0.83$ and $\xi_y = -1.12$ to $\xi_x = \xi_y = -0.2$



Tune Diagrams for fixed N

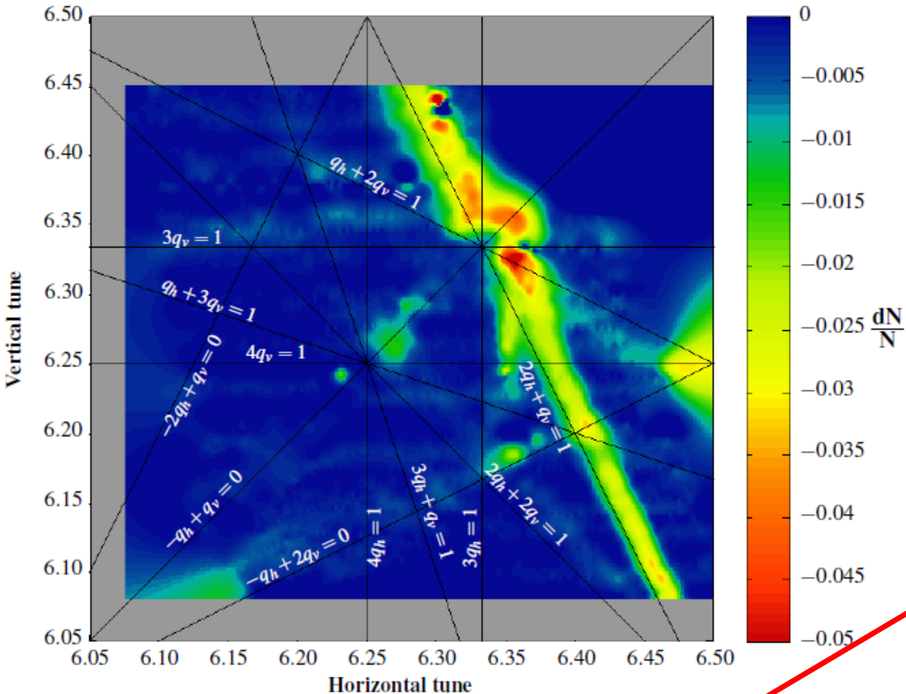


fixed DN



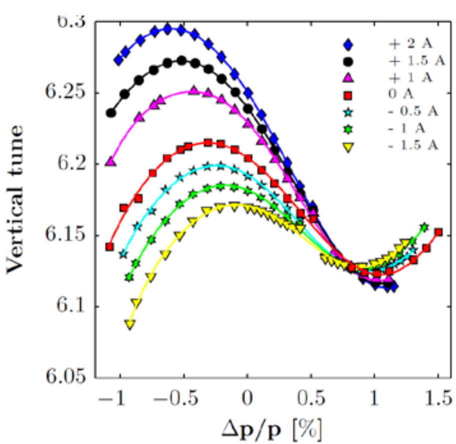
fixed FN

Tune Diagrams for fixed W



fixed DW

additional resonances visible,
highest losses
→
influence of narrow windings



fixed FW