Tune scans in the PSB

Presented by Andrea Santamaría García

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CERN

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Introduction

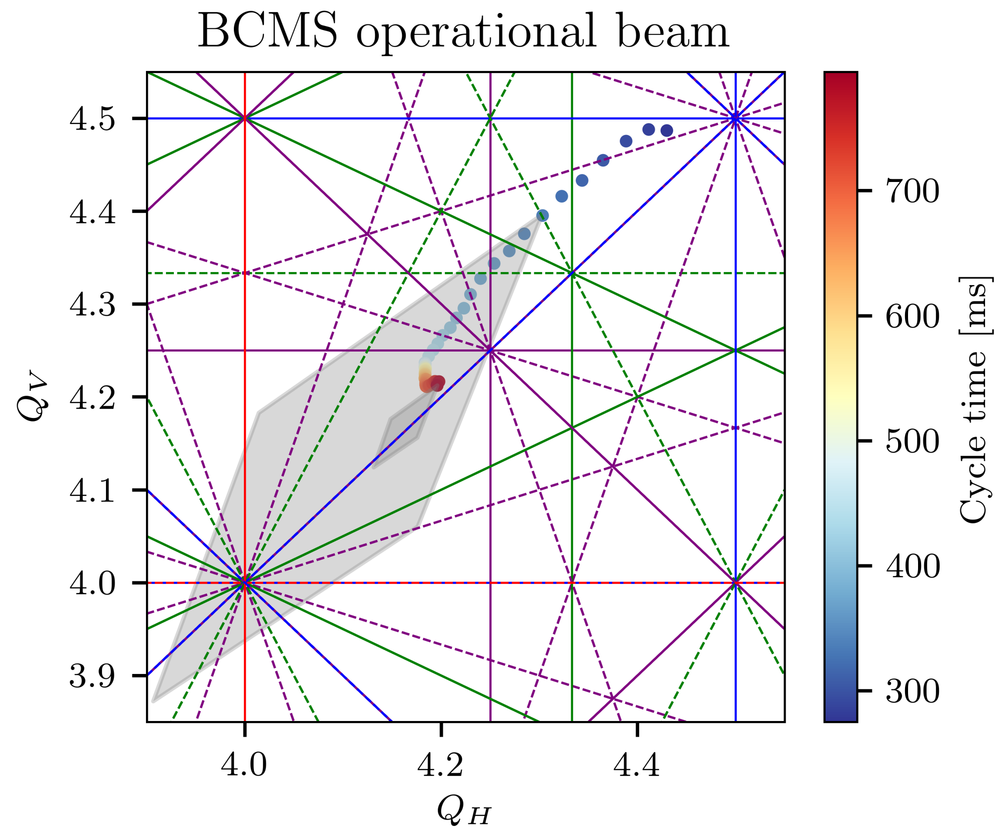
A large **incoherent space charge tune spread** at injection (50 MeV) currently limits the brightness* of the beams in the PSB

At ctime = 330 ms (~82 MeV):

- $\varepsilon_{x,y} \approx$ 1 um.rad
- Bunch length ≈ 700 ns
- Momentum spread ≈ 2e-3
- Intensity ≈ 70e10 protons
- Gamma relativistic = 1.087
- dQx, dQy = (0.396, 0.524)

At ctime = 795 ms (~1.4 GeV):

- $\varepsilon_{x,y} \approx$ 1 um.rad
- Bunch length ≈ 144 ns
- Momentum spread ≈ 9.41e-4
- Intensity ≈ 70e10 protons
- Gamma relativistic = 2.47
- dQx, dQy = (0.0648, 0.0881)



- Space charge tune spread calculated with: /eos/project/l/liu/Toolbox/Tune_diagram.py
- Explanation here (A. Oeftiger)

*Bunch intensity per transverse emittance

Introduction

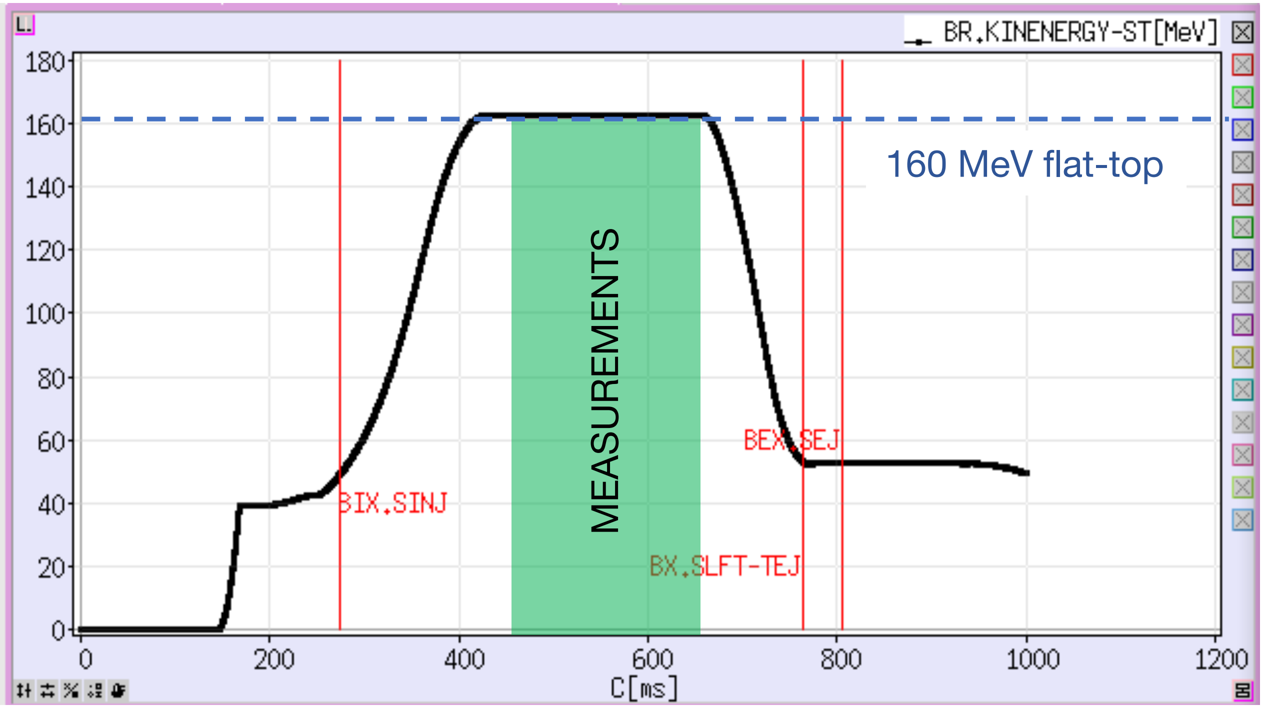
The new PSB injection at 160 MeV will allow to double the intensity, but the space charge tune spread will remain comparable to the previous one.

- A single particle in a perfect machine will oscillate with the tunes (Qx, Qy).
- Field errors and magnet imperfections give kicks to the particles, which can be added coherently for certain tune combinations.
- These resonant conditions happen when **$m\,Q_x + n\,Q_y = p$** (where $m, n, p \in \mathbb{Z}$).
- Hitting a betatron resonance causes emittance growth and particle losses, which leads to the degradation of the beam brightness.
- Due to the large space charge tune spreads at the PSB injection, many resonances are crossed.

In view if the LIU upgrade, studies were carried out to identify the resonances currently present in the bare machine at 160 MeV

MD3034 set-up

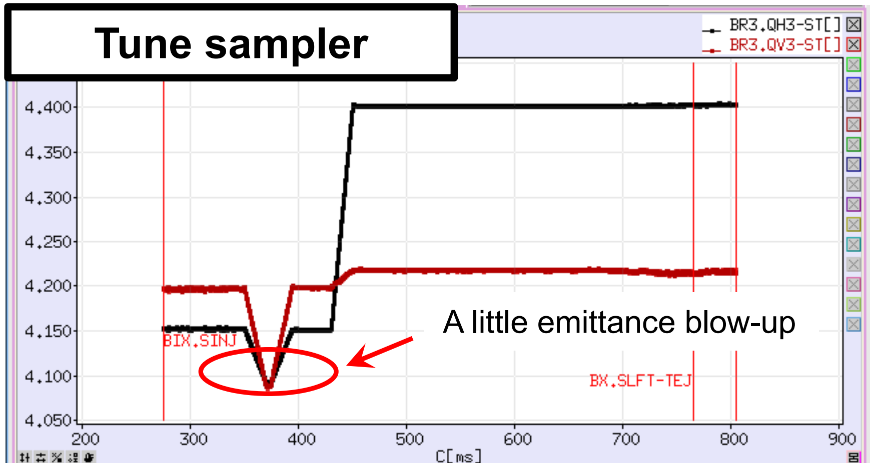
- A clone of **MD_BetaBeat_160MeV** was used (set-up this year).
- Almost natural chromaticity of $\xi_x = -0.9$, $\xi_y = -1.4$ (residual $I_{GSXNOHO}$ = ~10 A).

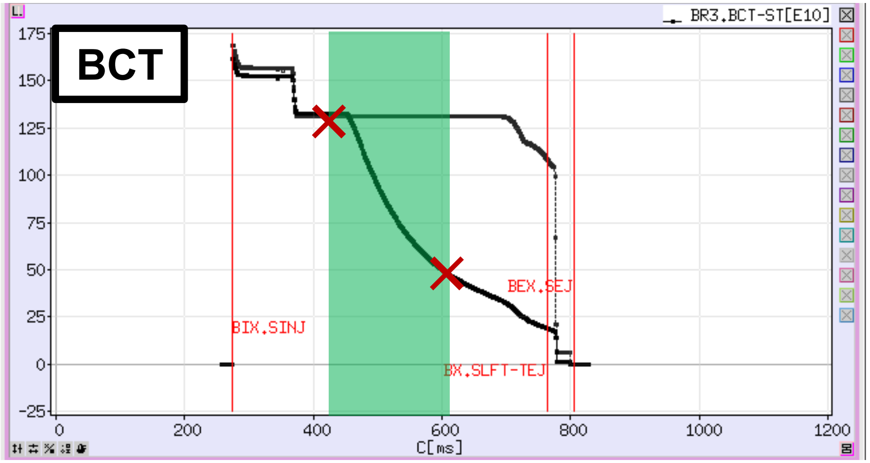


Static tune scans

Static tune scans

- A **static tune scan** consists of measuring the beam losses induced by maintaining the beam at a specific working point (Qx, Qy).
- The initial working point was set to (4.15, 4.20), which corresponds to a lossless region in the tune diagram and good injection efficiency.





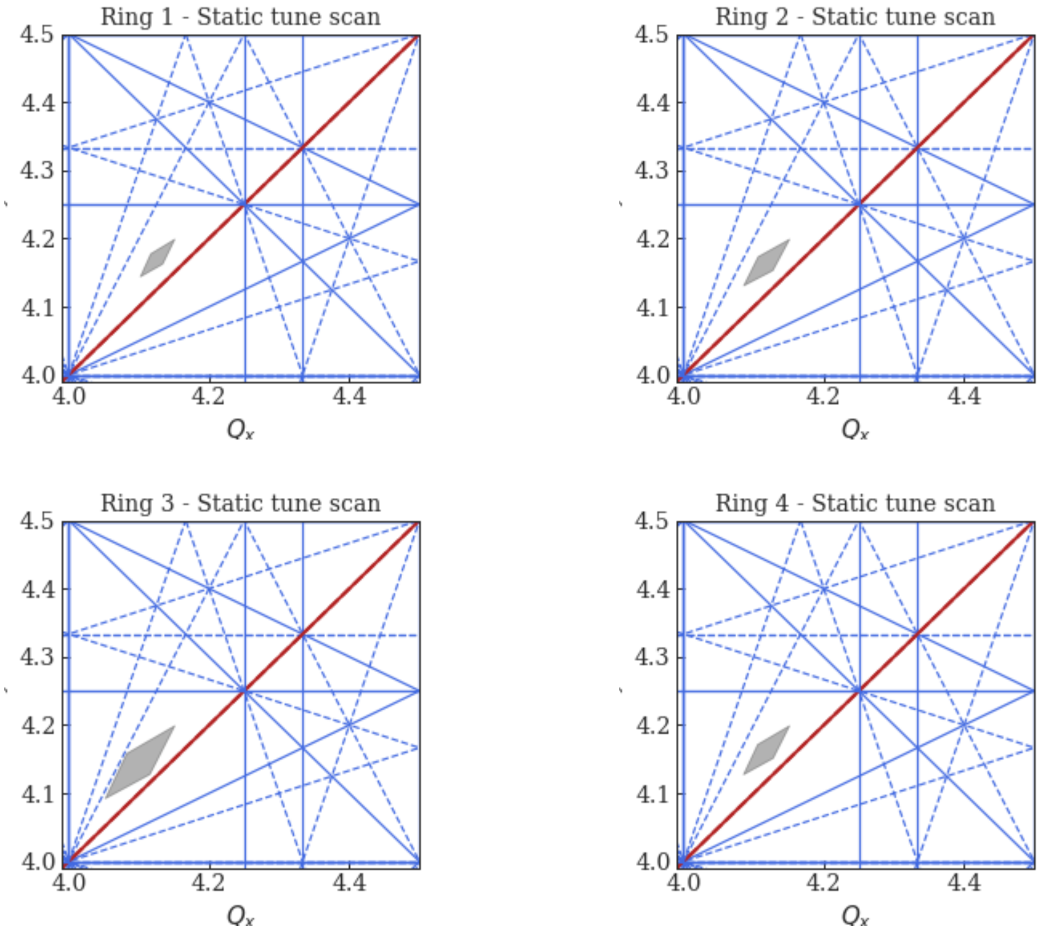
Initial parameters (static)

Initial parameters	Ring 1	Ring 2	Ring 3	Ring 4
Bunch Intensity [10^{10} protons]	100	120	130	130
Horizontal emittance [um.rad]	9.226	7.889	5.915	8.718
Vertical emittance [um.rad]	7.980	7.849	5.596	7.974
Bunch length [ns]	594	602	577	600
Momentum spread [10^{-3}]	1.28	1.33	1.2	1.33
Space charge tune spread ΔQ_x	0.049	0.065	0.098	0.065
Space charge tune spread ΔQ_y	0.055	0.068	0.11	0.071

- Double harmonic used to elongate the bunch and reduce the peak line density
- The transverse damper was on except for ring 2, where the damper destroyed the beam for certain tunes (shown later).

Space charge tune spread calculated with: /eos/project/l/liu/Toolbox/Tune_diagram.py

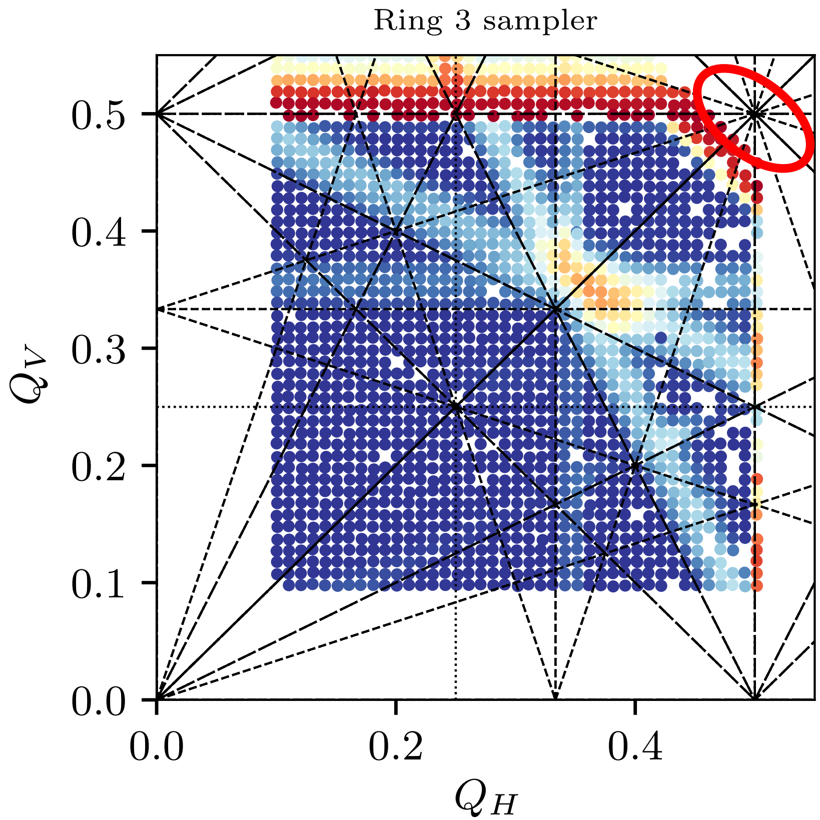
Initial tune spread (static)



Space charge tune spread calculated with: /eos/project/l/liu/Toolbox/Tune_diagram.py

Static tune scans

The tune was varied with a step of **0.01**
→ **1886** different working points per ring (**very** time consuming)



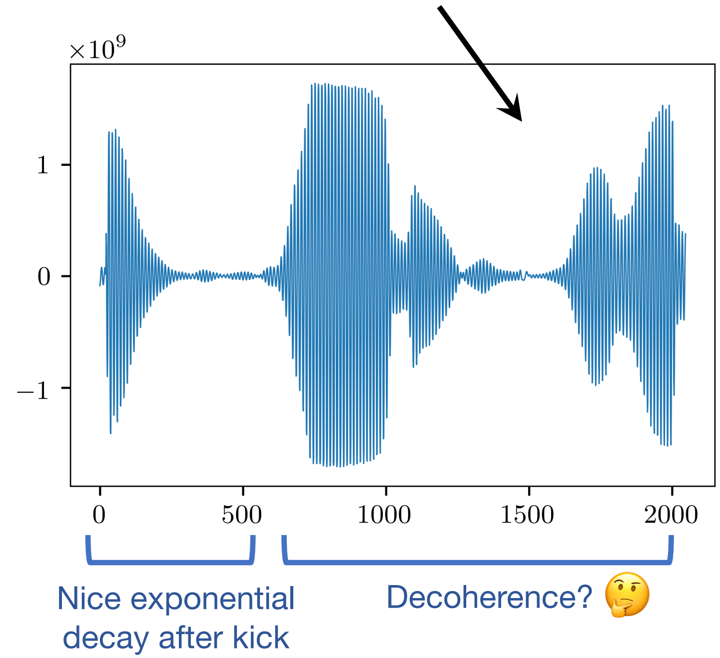
Some tune trim errors in this area (knob calculates negative currents)

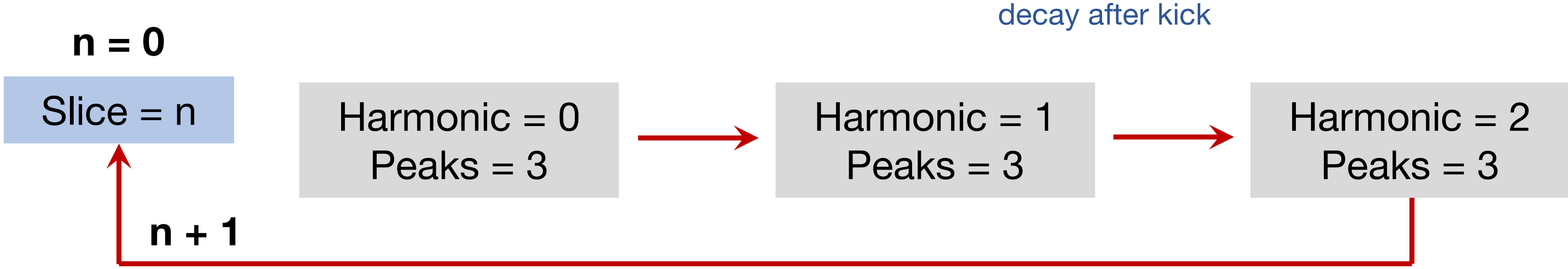
Data analysis

- By saving the raw data from the BBQ (BaseBand tune measurement), i.e. the amplitude of the particles after the kick given by the BBQ system, we can extract the tune in the machine by analyzing its frequency components.

- For this the PyNAFF module was used, a Python module that implements the Numerical Analysis of Fundamental Frequencies method. The PyNAFF module gives back the frequency peaks found for a specific harmonic.

- For the tune scans presented here 1024 turns of amplitude data were recorded and analyzed in two slices of 512.





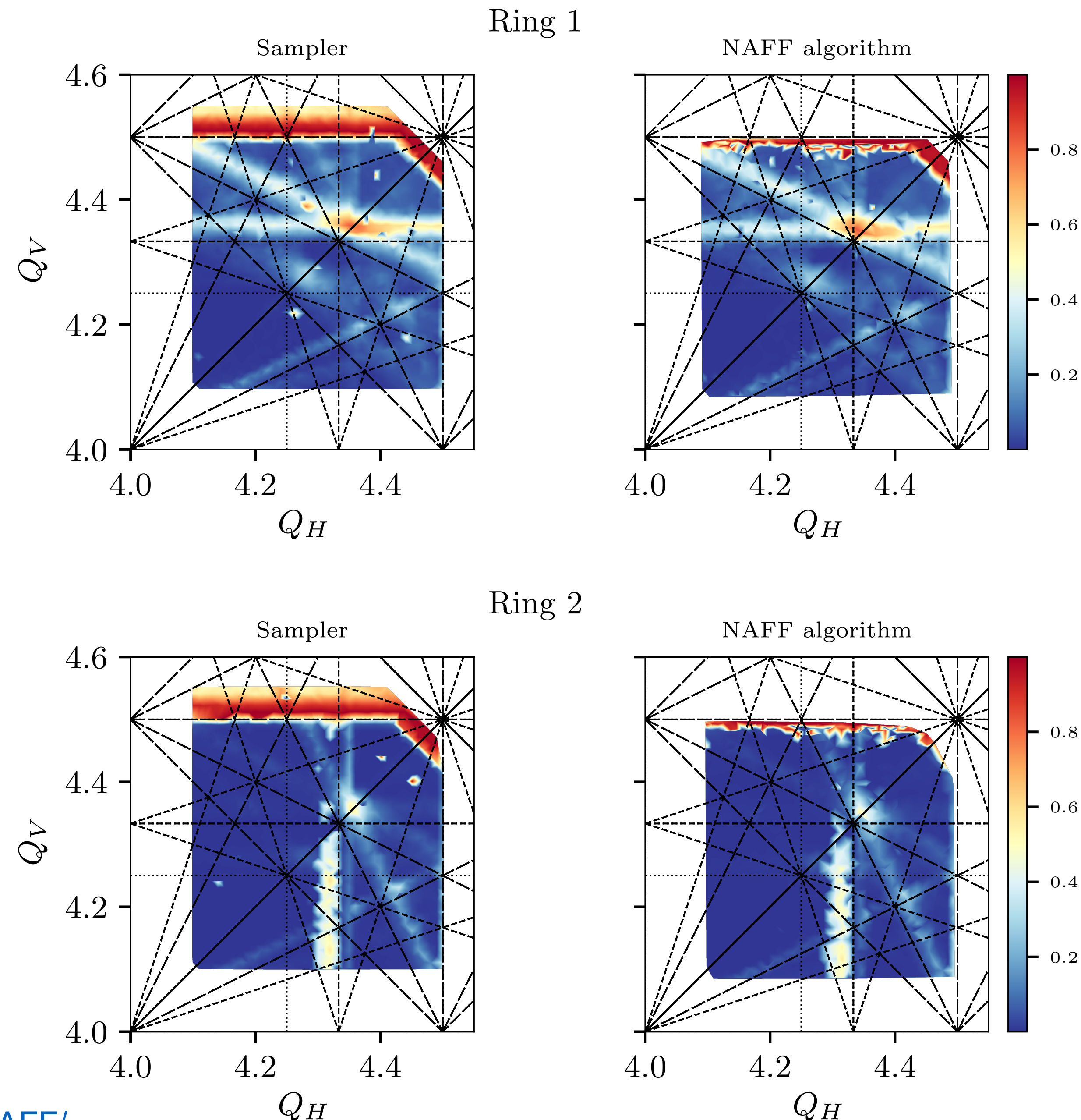
Resonances

$2Q_y = 9$

$Q_x + 2Q_y = 13$

$3Q_y = 13$

$Q_x - 2Q_y = -4$



$2Q_y = 9$

$2Q_x + Q_y = 13$

$3Q_x = 13$

$Q_x - 2Q_y = -4$

https://pypi.org/project/PyNAFF/

Resonances

$2Q_y = 9$

$Q_x + 2Q_y = 13$

$3Q_y = 13$

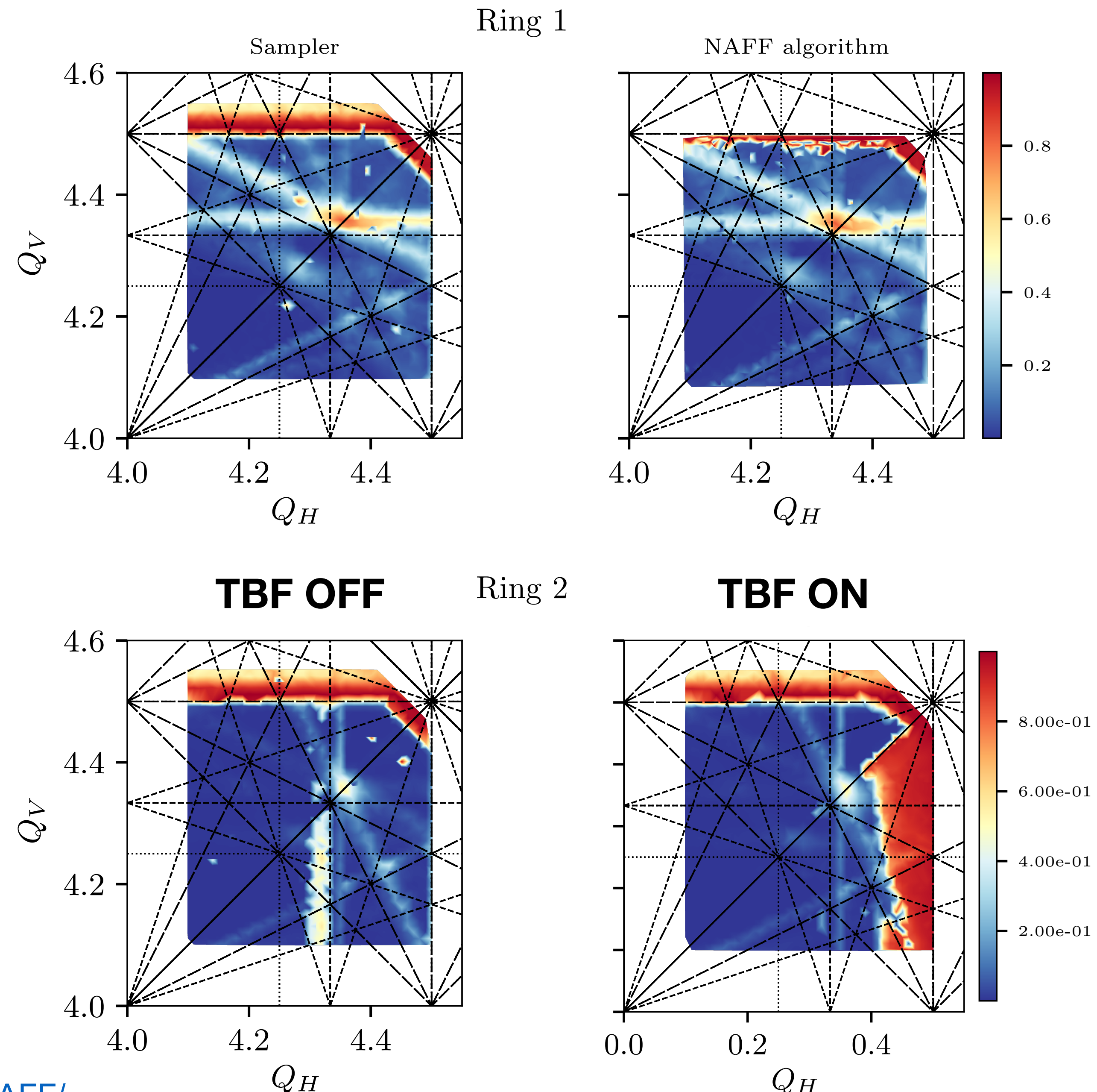
$Q_x - 2Q_y = -4$

$2Q_y = 9$

$2Q_x + Q_y = 13$

$3Q_x = 13$

$Q_x - 2Q_y = -4$



https://pypi.org/project/PyNAFF/

Resonances

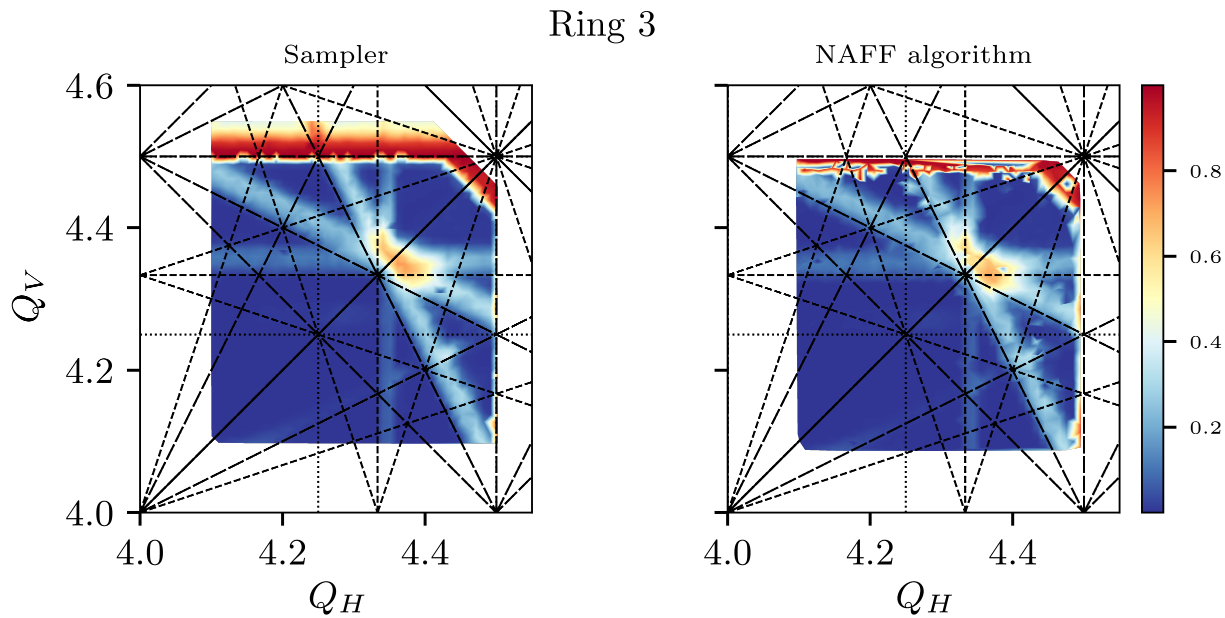
$2Q_y = 9$

$Q_x + 2Q_y = 13$

$2Q_x + Q_y = 13$

$3Q_y = 13$

$3Q_x = 13$

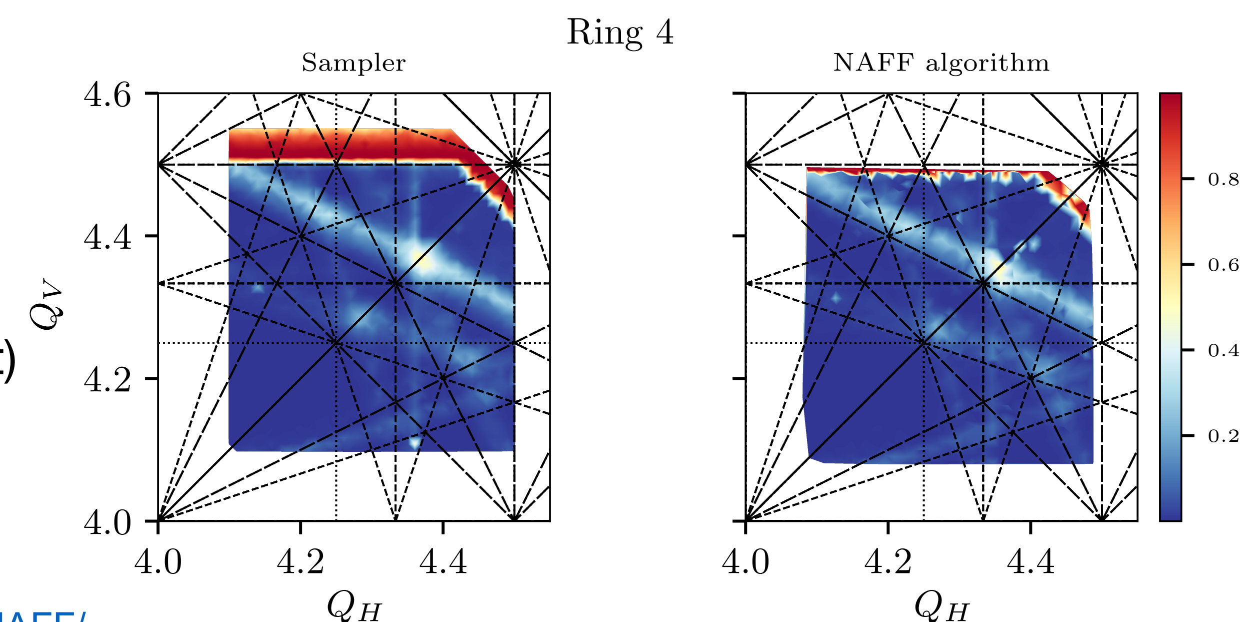


$2Q_y = 9$

$Q_x + 2Q_y = 13$

$3Q_x = 13$ (very faint)

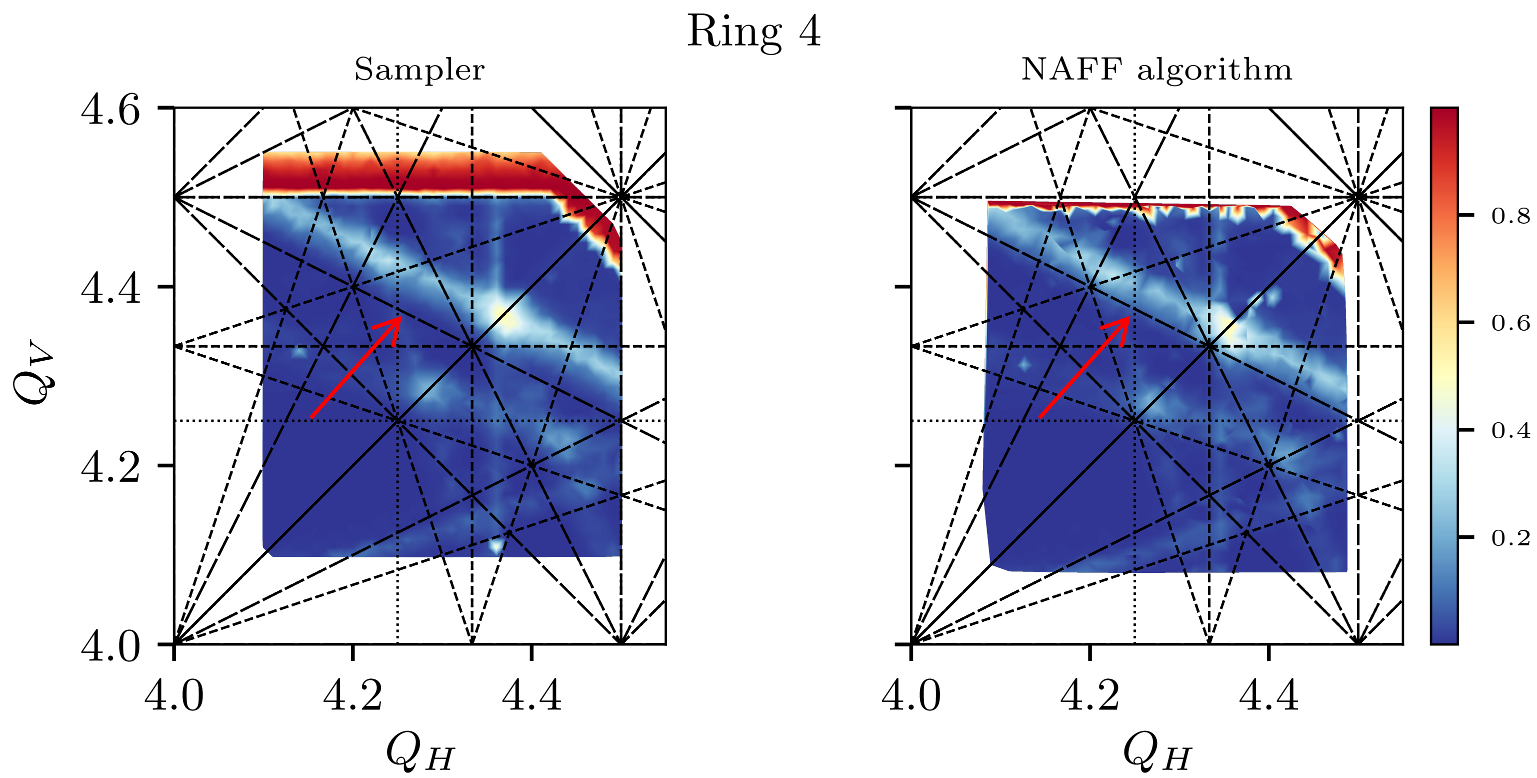
$(Q_x - 2Q_y = -4?)$



https://pypi.org/project/PyNAFF/

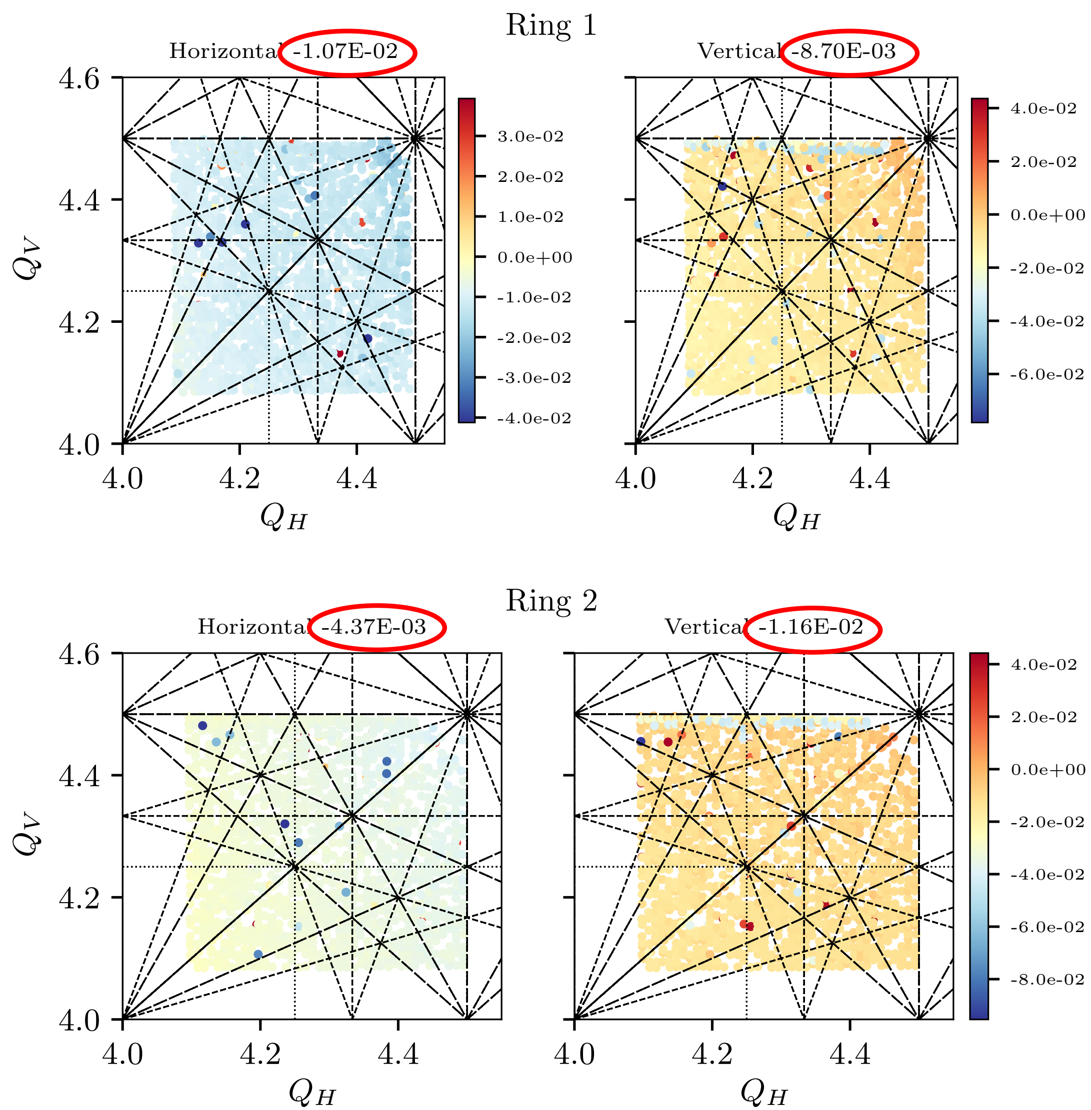
Sampler vs BBQ

The tune that is given as input (sampler) is reflected in the machine differently (BBQ)

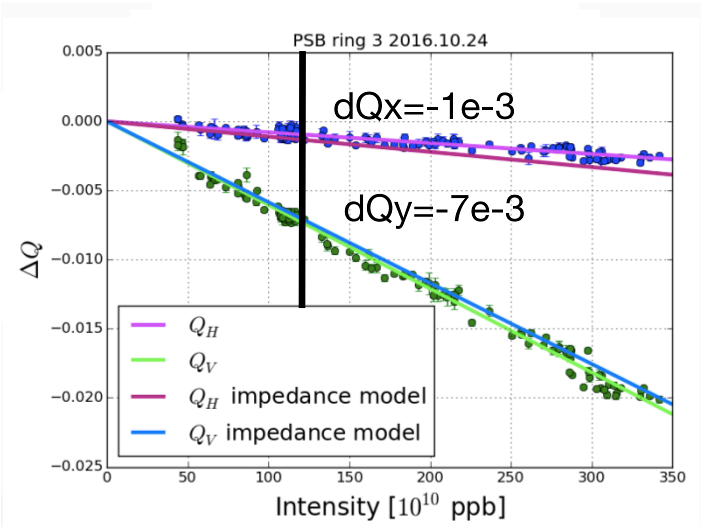


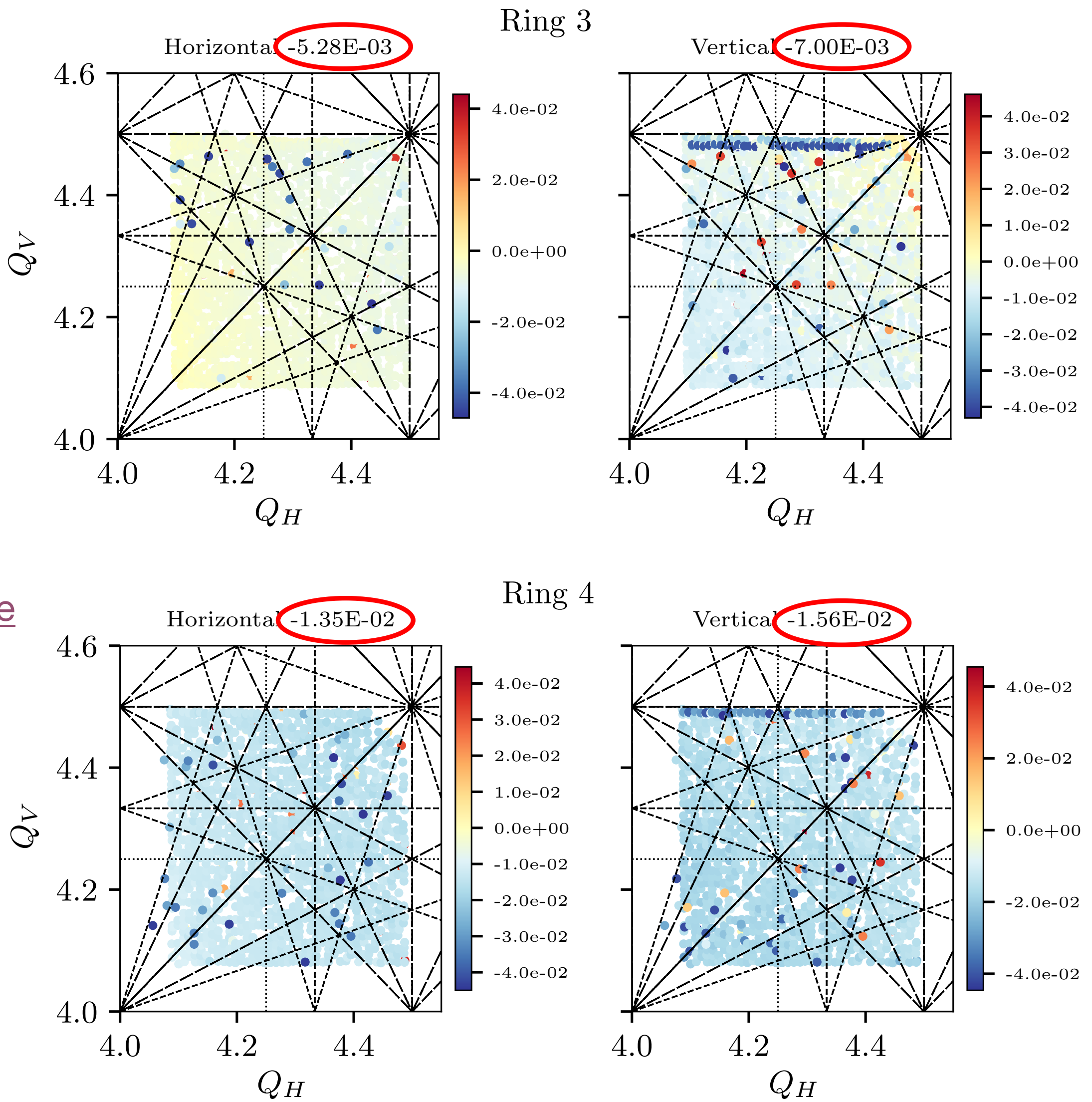
Sampler vs BBQ

Difference between the tune given by the sampler and the BBQ



Sampler vs BBQ





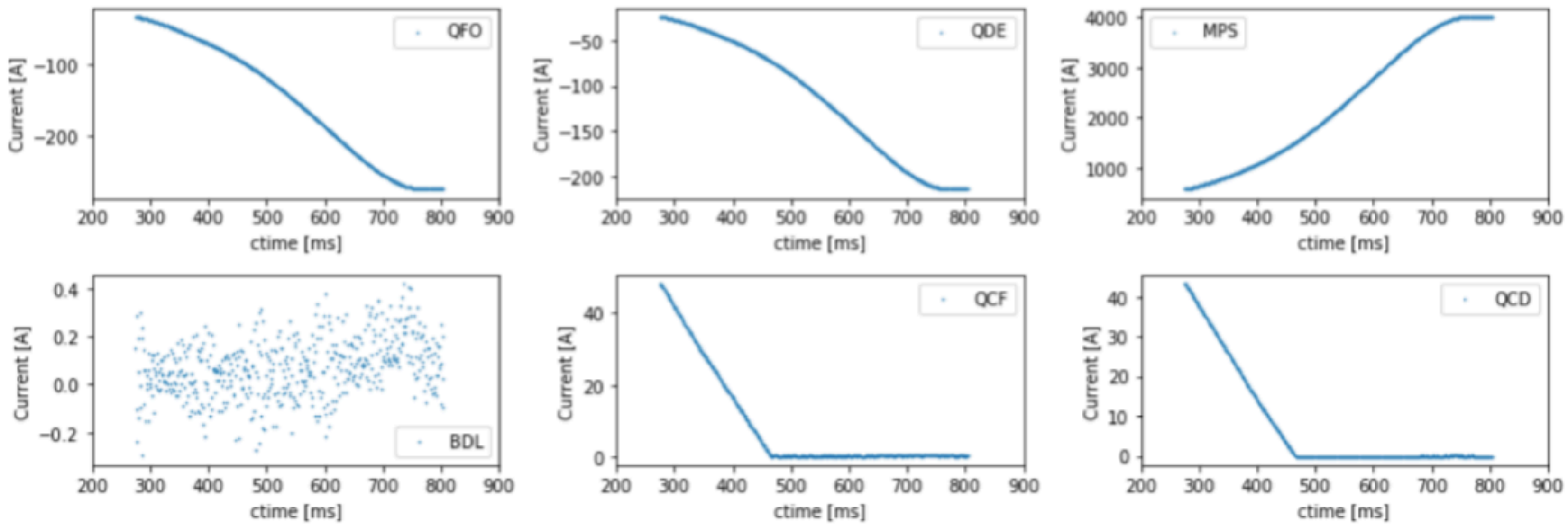
Presented here by T. Rijoff, published here

Could this be compatible with a coherent tune shift from impedance? To verify the energy and chromaticity used

Sampler vs BBQ

Sensitivity matrix connecting the change in strength of the quadrupoles to the change in tune done in MAD-X by ABP, to be mapped and tested with the recorded quadrupolar current for different working points:

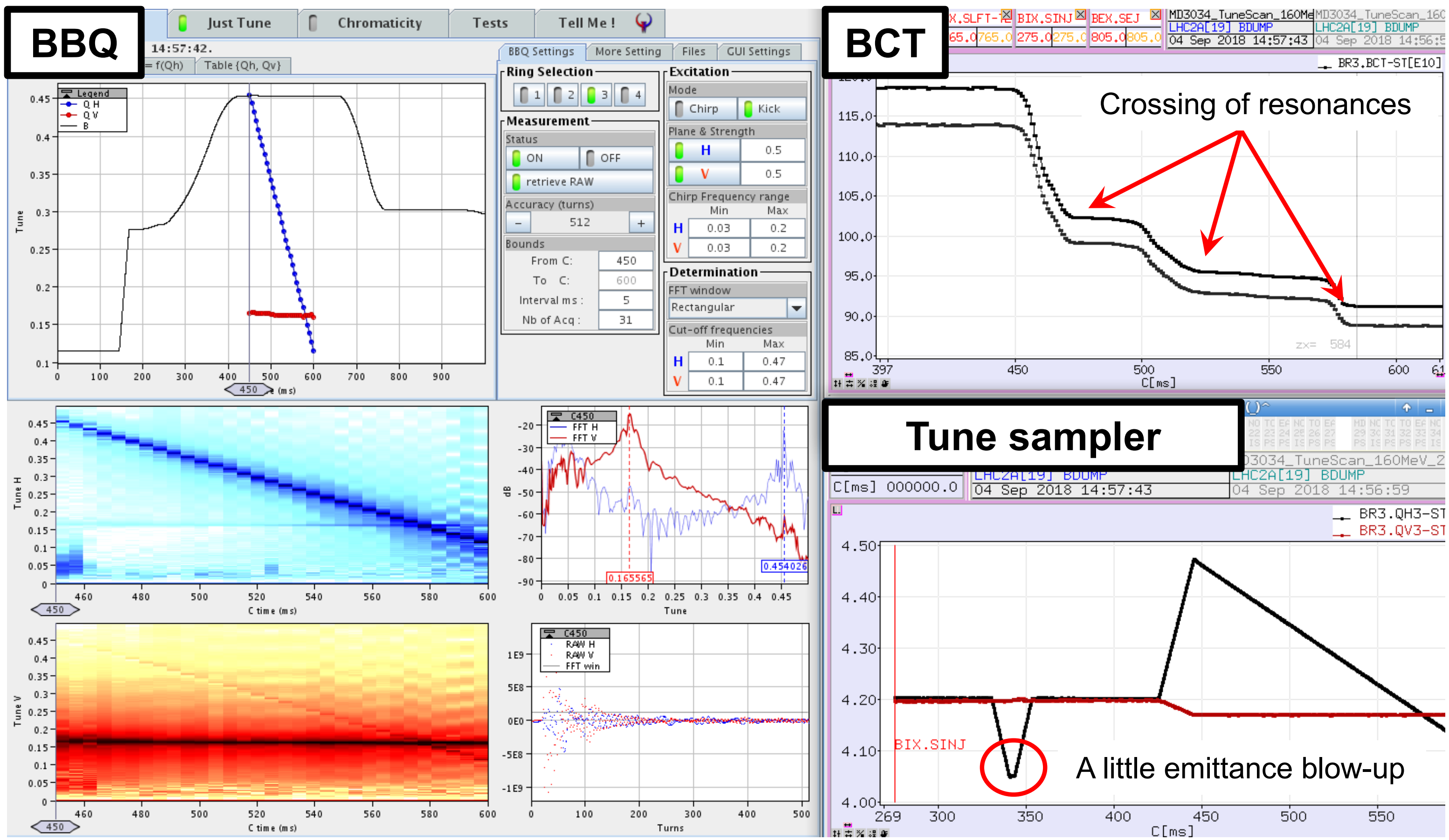
https://gitlab.cern.ch/PSB/tune_knob



Dynamic tune scans

Dynamic tune scans

In a **dynamic tune scan** one tune is maintained constant while the other varies in time, scanning all the possible tune values.



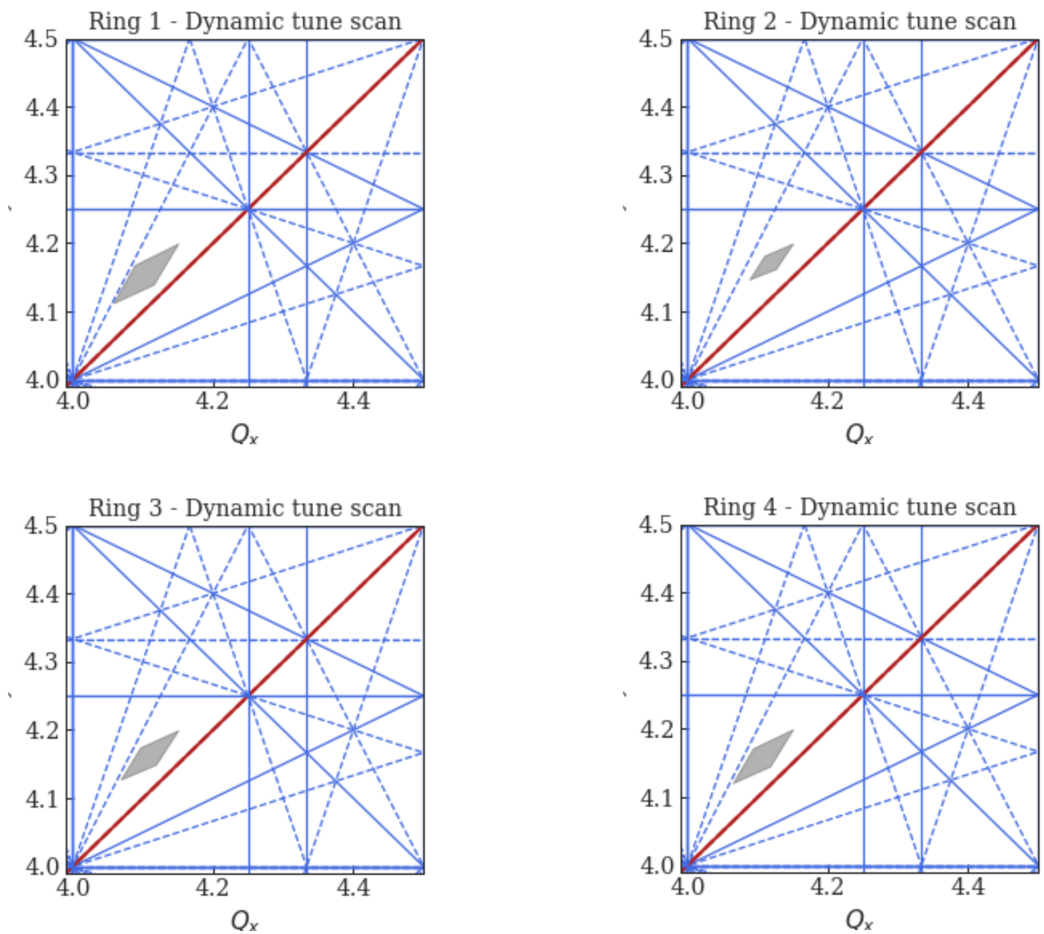
Initial parameters (dynamic)

Initial parameters	Ring 1	Ring 2	Ring 3	Ring 4
Bunch Intensity [10^{10} protons]	157	116	131	134
Horizontal emittance [um.rad]	6.414	7.044	6.069	5.965
Vertical emittance [um.rad]	7.980	10.599	8.663	7.843
Bunch length [ns]	634	610	610	619
Momentum spread [10^{-3}]	1.43	1.36	1.39	1.39
Space charge tune spread ΔQ_x	0.092	0.062	0.081	0.085
Space charge tune spread ΔQ_y	0.087	0.053	0.072	0.078

- Double harmonic used to elongate the bunch and reduce the peak line density
- The transverse damper was on.

Space charge tune spread calculated with: /eos/project/l/liu/Toolbox/Tune_diagram.py

Initial tune spread (dynamic)



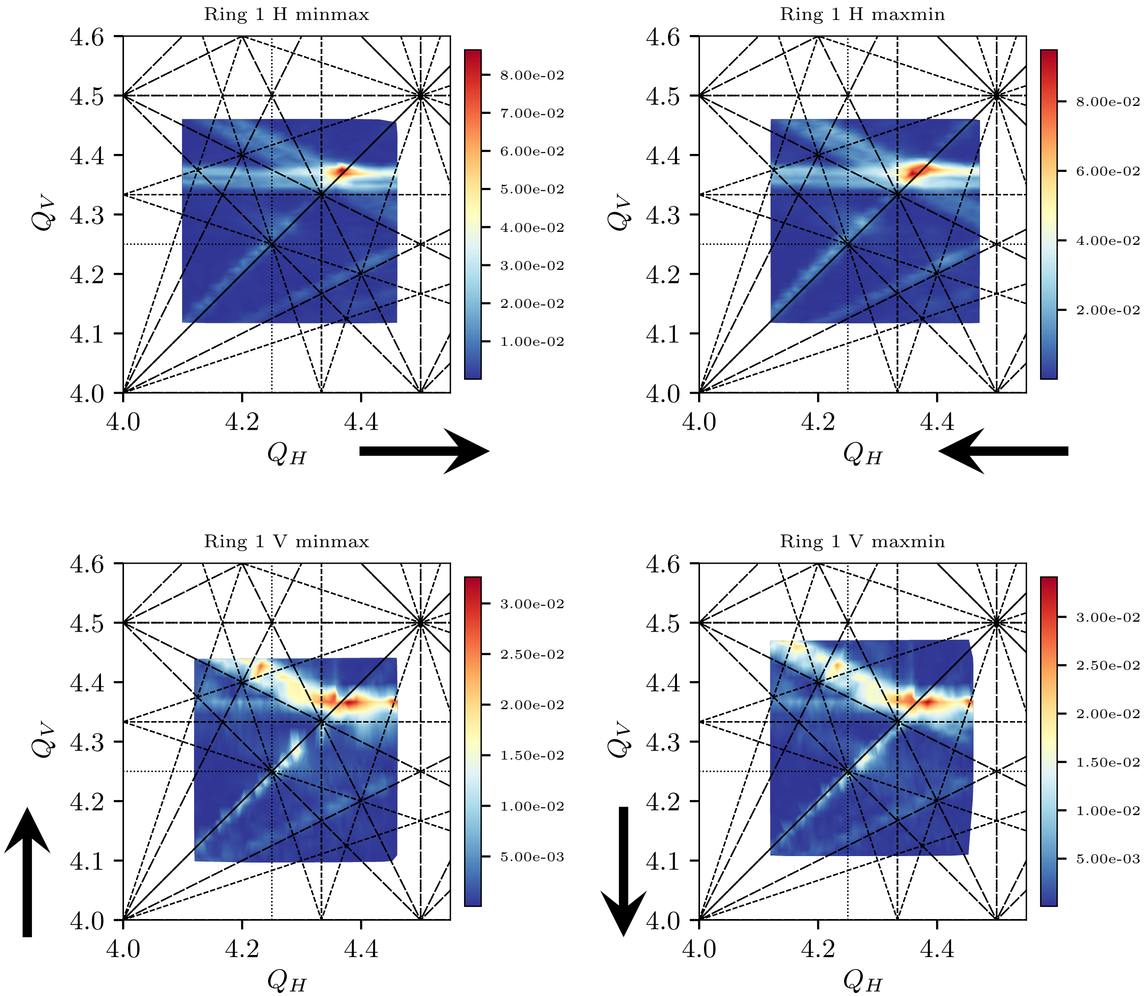
Space charge tune spread calculated with: /eos/project/l/liu/Toolbox/Tune_diagram.py

Dynamic tune scans – Ring 1

$2Q_y = 9$: not shown

- ✓ $Q_x + 2Q_y = 13$
- ✓ $3Q_y = 13$
- ✓ $Q_x - 2Q_y = -4$

+ coupling line $Q_y = Q_x$ from dynamic scan

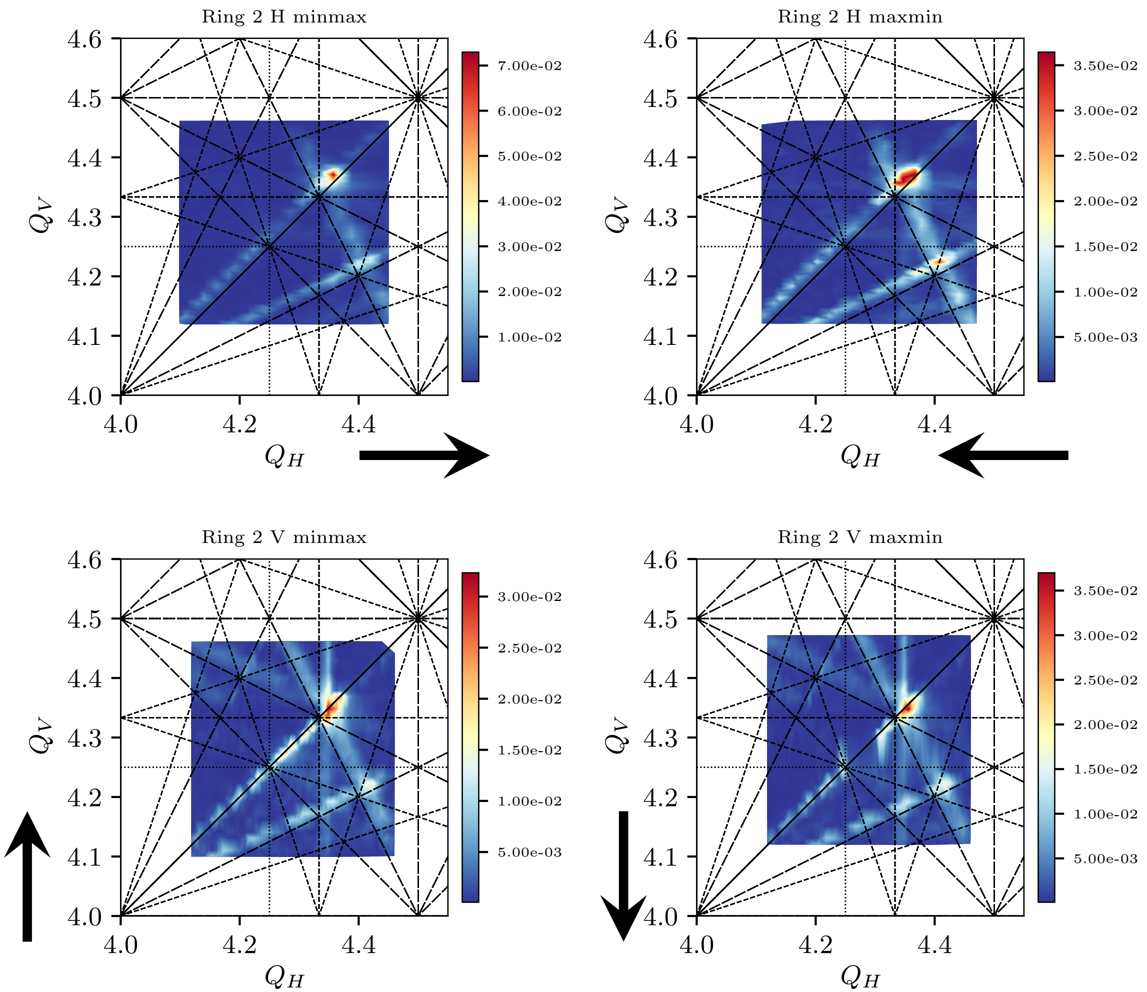


Dynamic tune scans – Ring 2

$2Q_y = 9$: not shown

- ✓ $2Q_x + Q_y = 13$
- ✓ $3Q_x = 13$
- ✓ $Q_x - 2Q_y = -4$

+ coupling line $Q_y = Q_x$ from dynamic scan

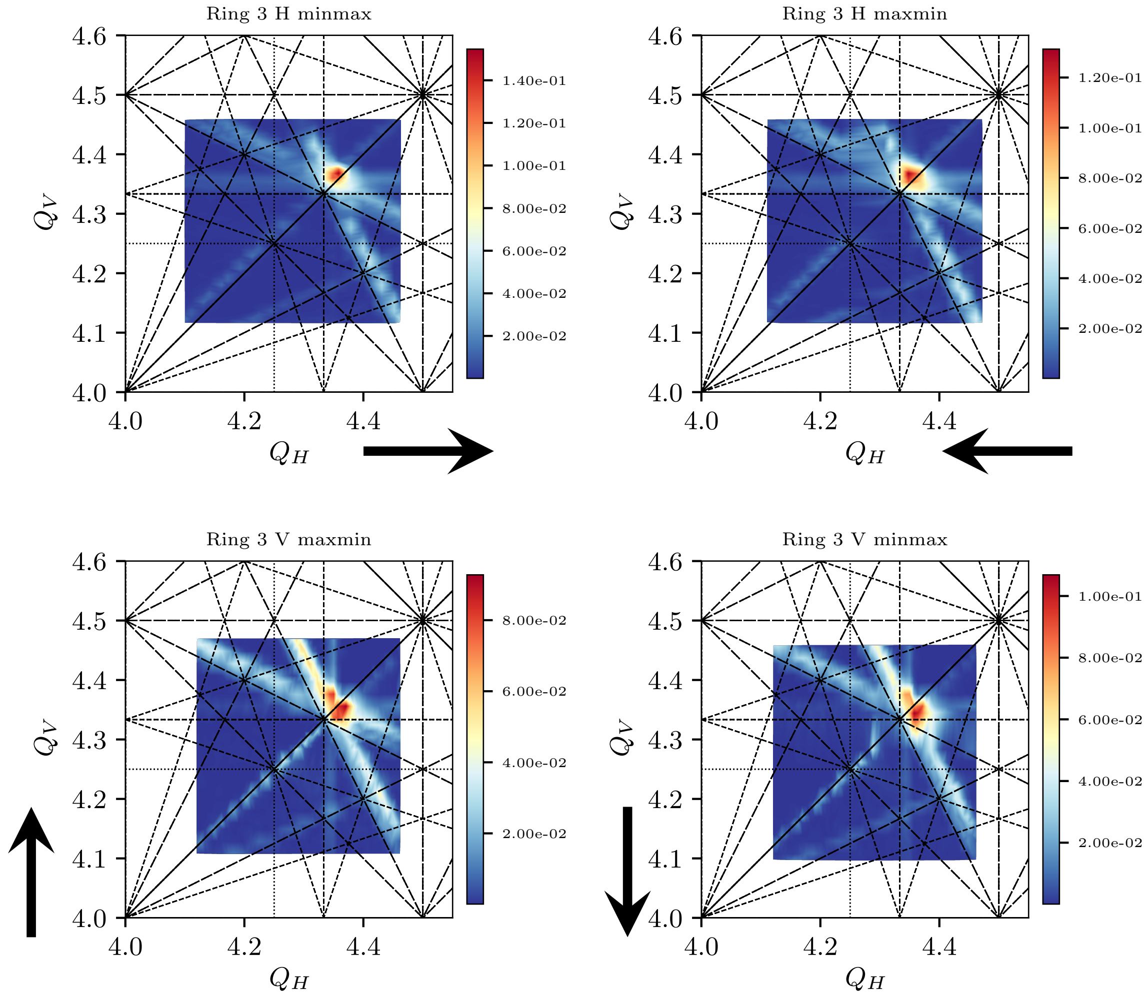


Dynamic tune scans – Ring 3

$2Q_y = 9$: not shown

✓ $Q_x + 2Q_y = 13$
✓ $2Q_x + Q_y = 13$
✓ $3Q_y = 13$ (faint)
✓ $3Q_x = 13$ (faint)

+ coupling line $Q_y = Q_x$ from dynamic scan



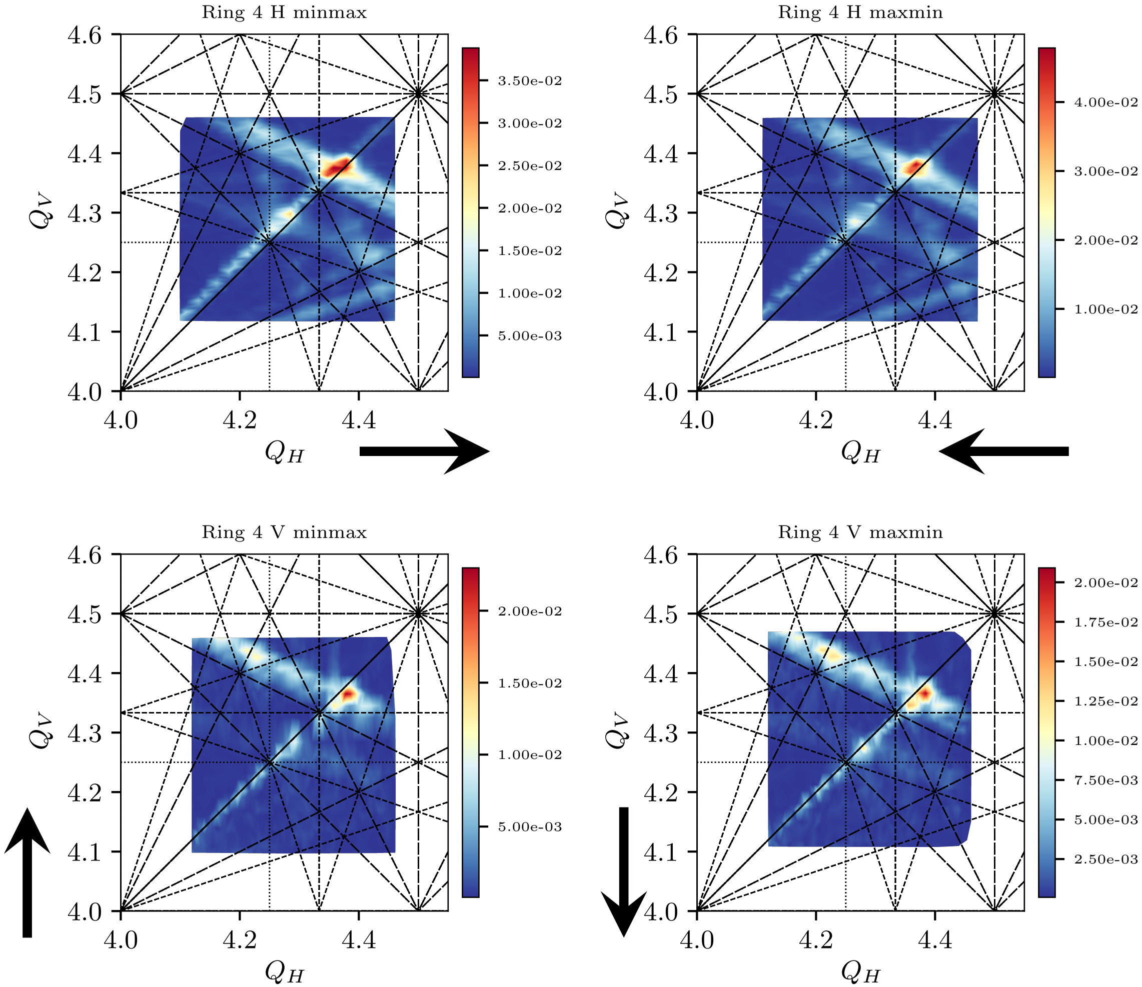
Dynamic tune scans – Ring 4

$2Q_y = 9$: not shown

✓ $Q_x + 2Q_y = 13$

- $3Q_x = 13$ (not visible)
- $Q_x - 2Q_y = -4$

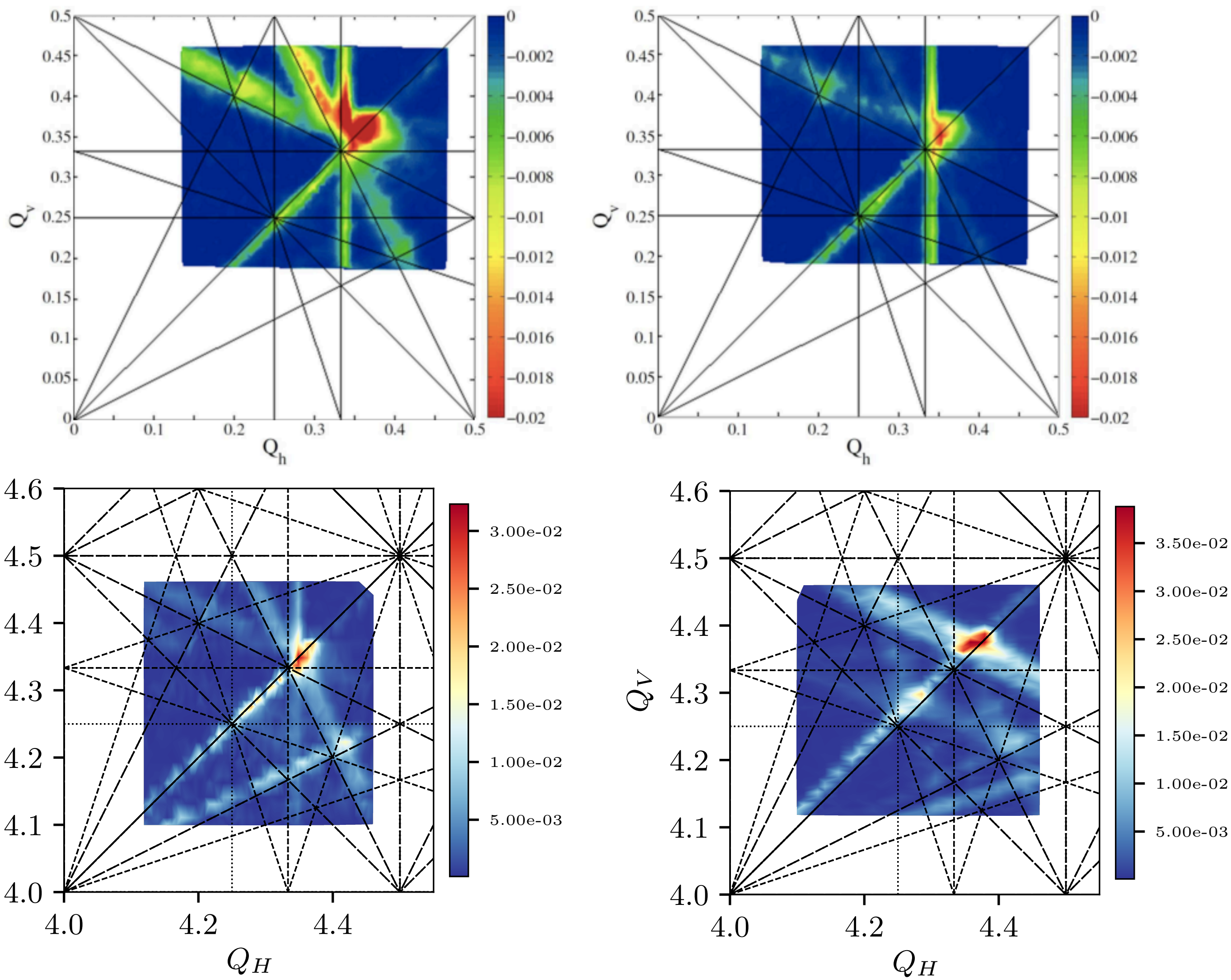
+ coupling line $Q_y = Q_x$ from dynamic scan



Ring 2 / Ring 4

2014

2018



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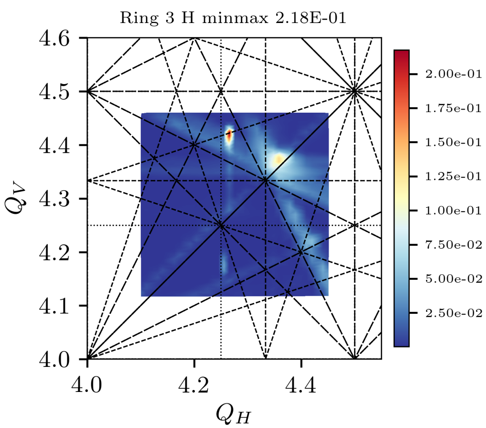
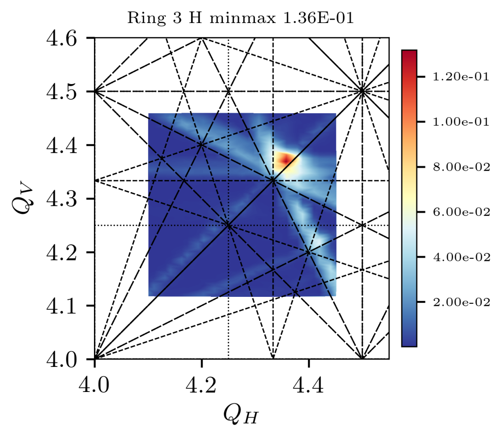
V. Forte

- Ring 2: resonances remained the same.
- Ring 4: the 3Qx = 13 resonance has disappeared.

Other loss maps

Dynamic tune scans provide a quick way of observing different effects

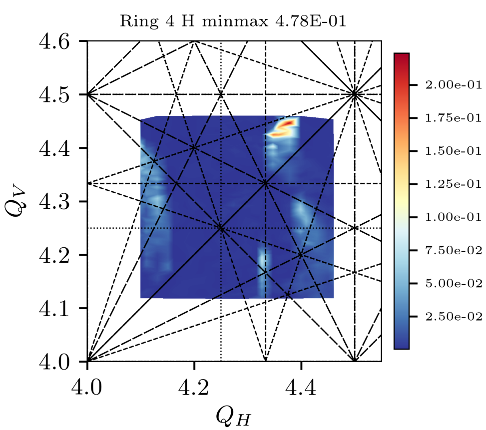


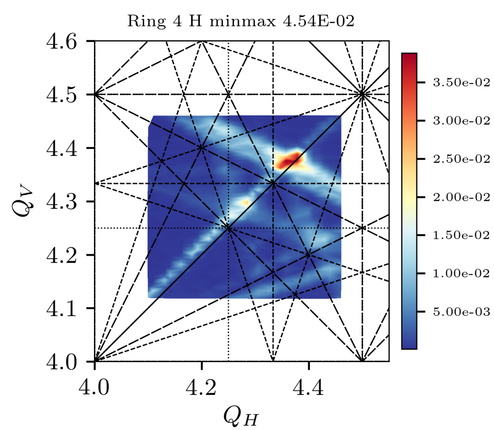


Intensity related instability (currently being studied in ring 3 by E. Koukovini-Platia et al)

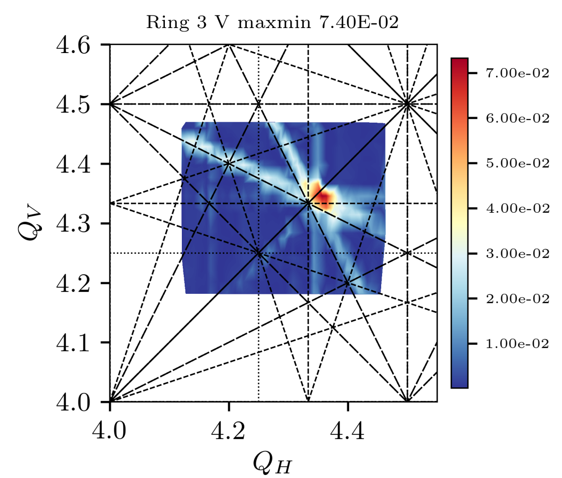
TBF OFF

TBF ON





Test on a BCMS beam (along the cycle…!)

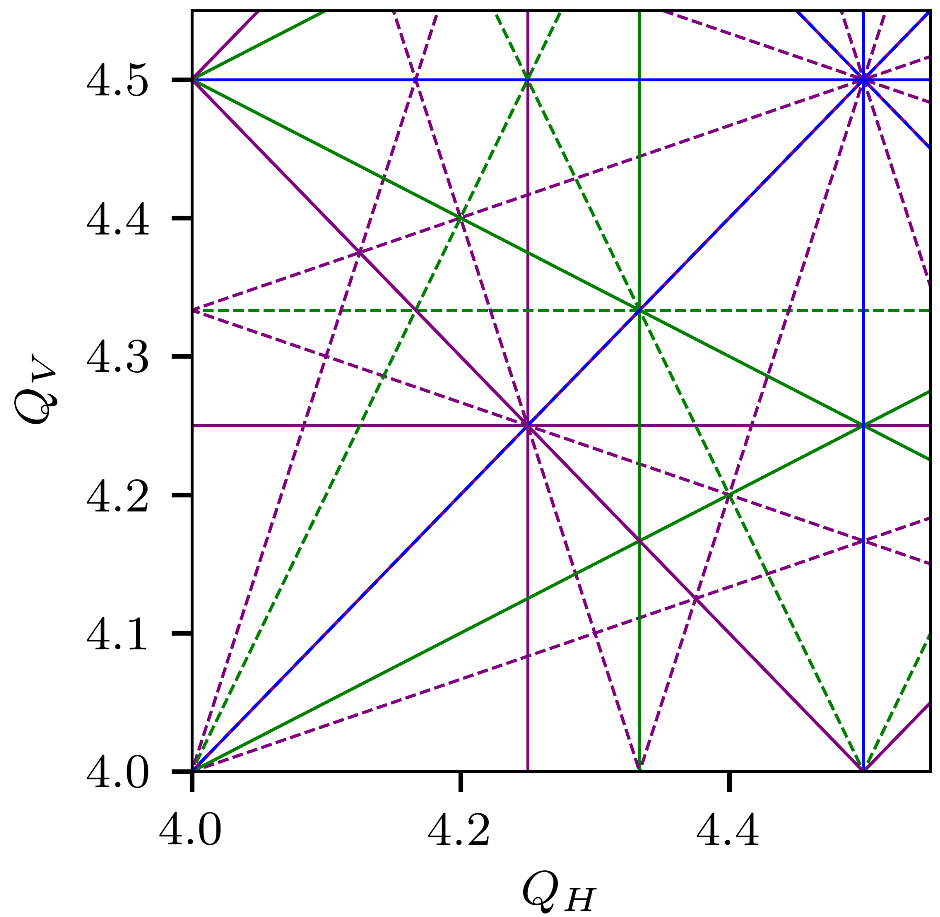


Resonance compensation

Resonance compensation

The available correctors at the PSB are the types:

- QNO, QSK: for normal and skew quadrupolar correction (2nd order).
- XNO, XSK: for normal and skew sextupolar correction (3rd order).
- ONO, OSK: for normal and skew octupolar correction (4th order). Not used, no connected to all rings.



To compensate a particular resonance two multipoles of the correct type are needed, with the optimal phase advance between them.

By compensating a resonance, another one can be excited

OP shutdown lectures 2014: Resonance compensation in the PS Booster (E. Benedetto)

Resonance compensation

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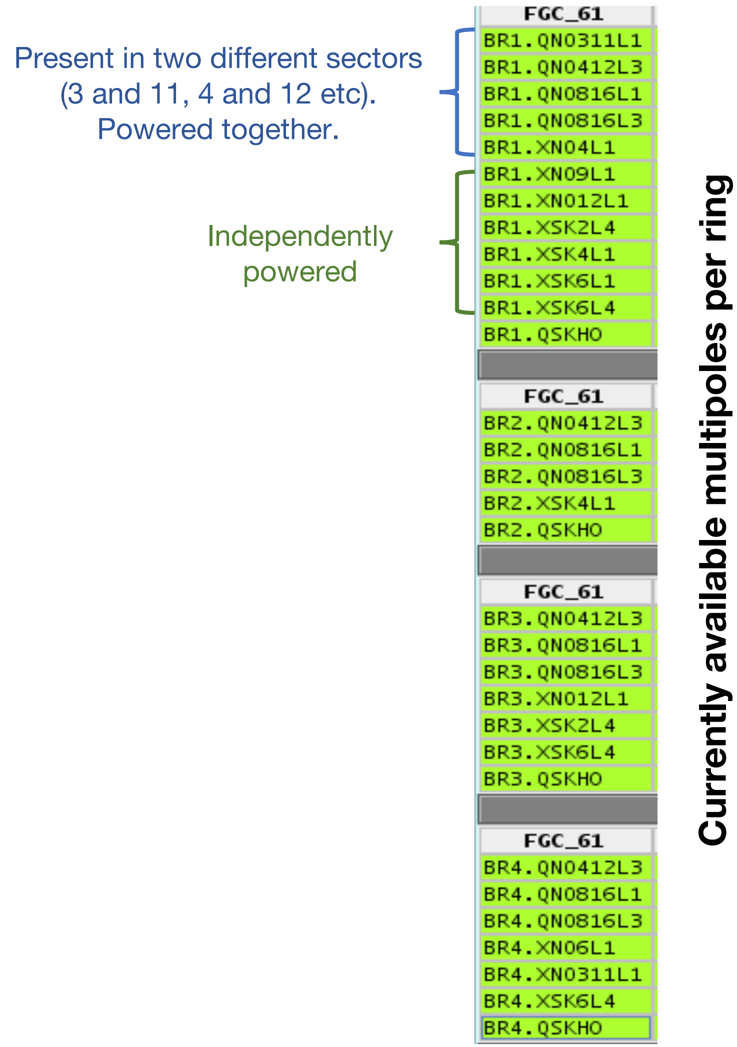


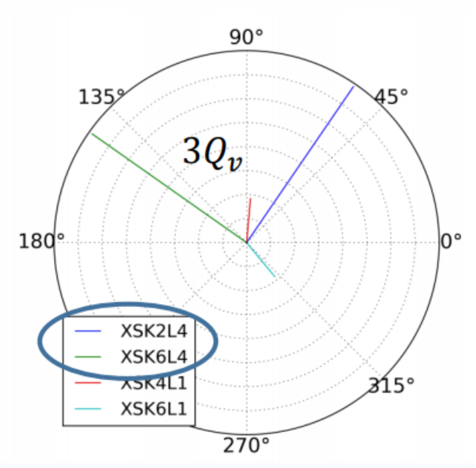
OP shutdown lectures 2014: Resonance compensation in the PS Booster (E. Benedetto)

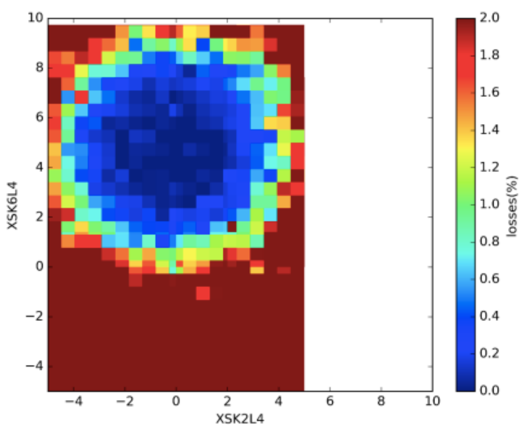
Resonance compensation

The multipole current values for resonance compensation were calculated by **F. Asvesta** and **H. Rafique** (thank you!!)

- They calculated the Resonance Driving Terms for the available magnets in PTC to identify how each individual magnet acts on the resonance. They selected orthogonal sets that would allow to create any vector.

- They then scanned the multipoles' currents at the desired resonance, selecting the current values with less losses.



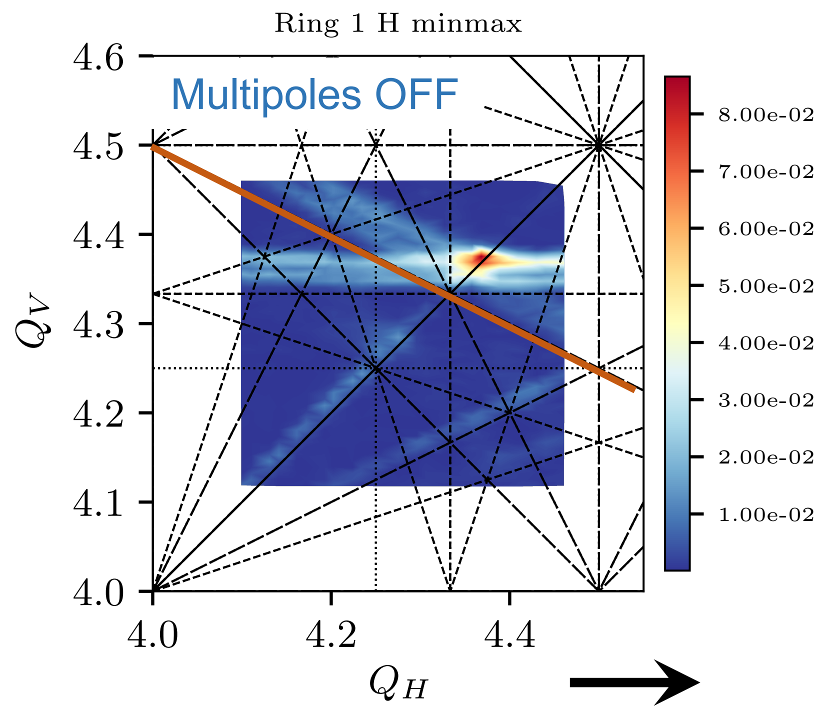


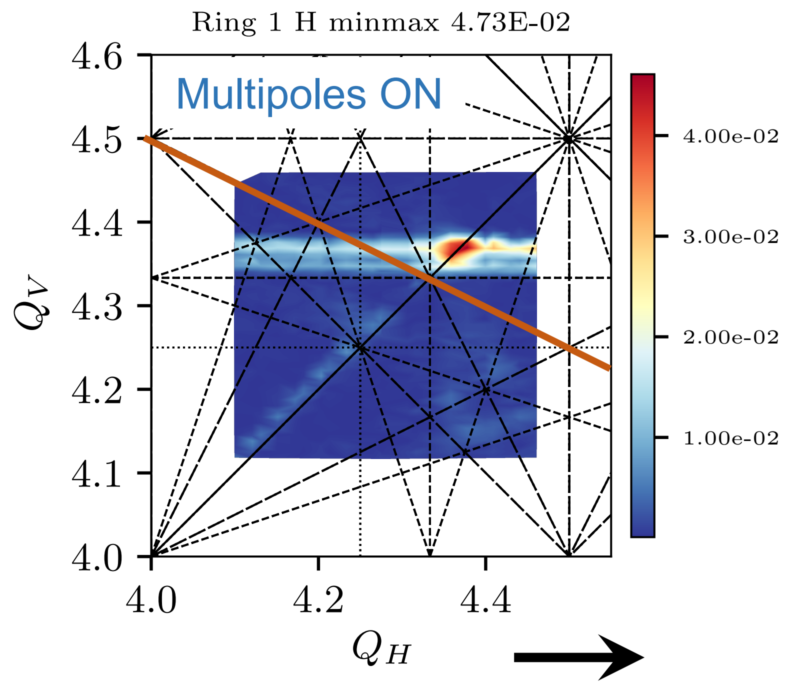
More information given here

Compensation – Ring 1

Compensation of Qx + 2Qy = 13 with normal sextupoles

BR1.XNO9L1 = -9.99 A
BR1.XNO4L1 = -6.07 A

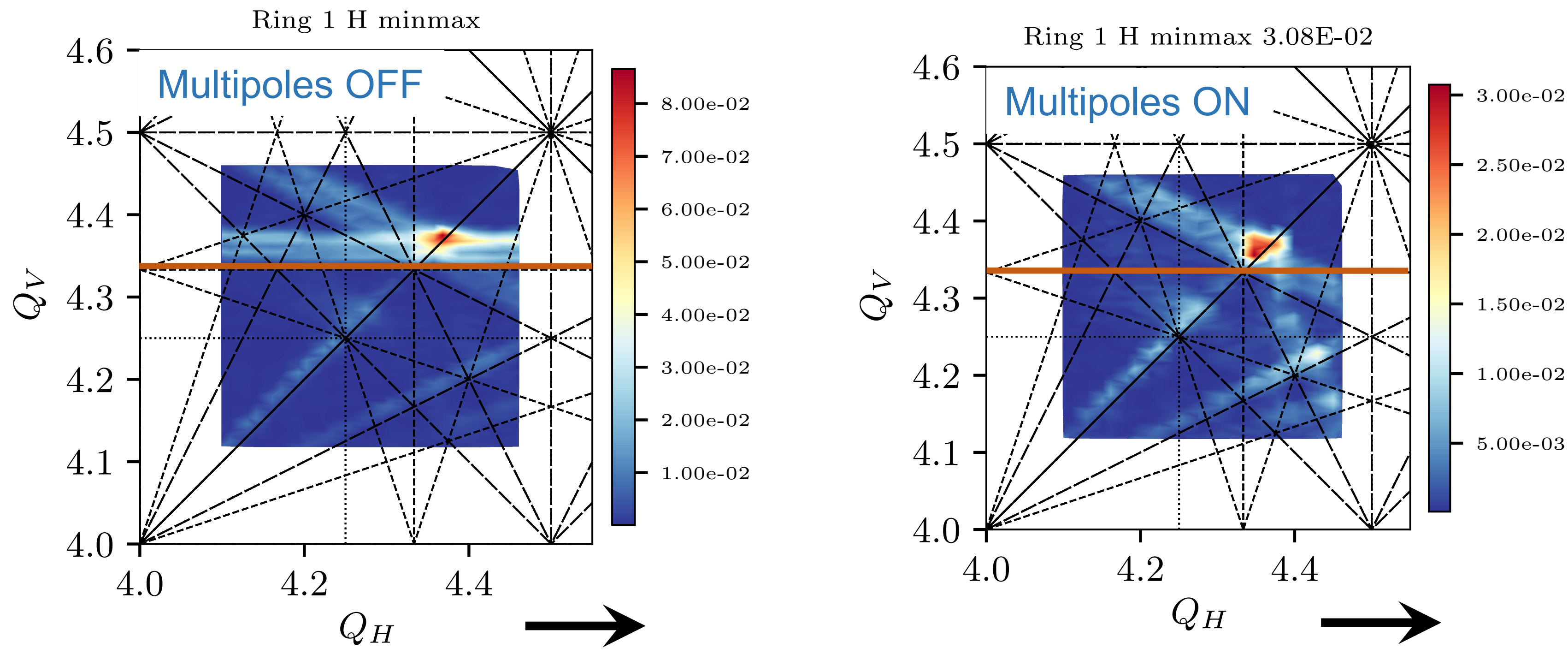




Compensation – Ring 1

Compensation of 3Qy = 13 with skew sextupoles

BR1.XSK6L4 = 2.77 A
BR1.XSK2L4 = -8.33 A

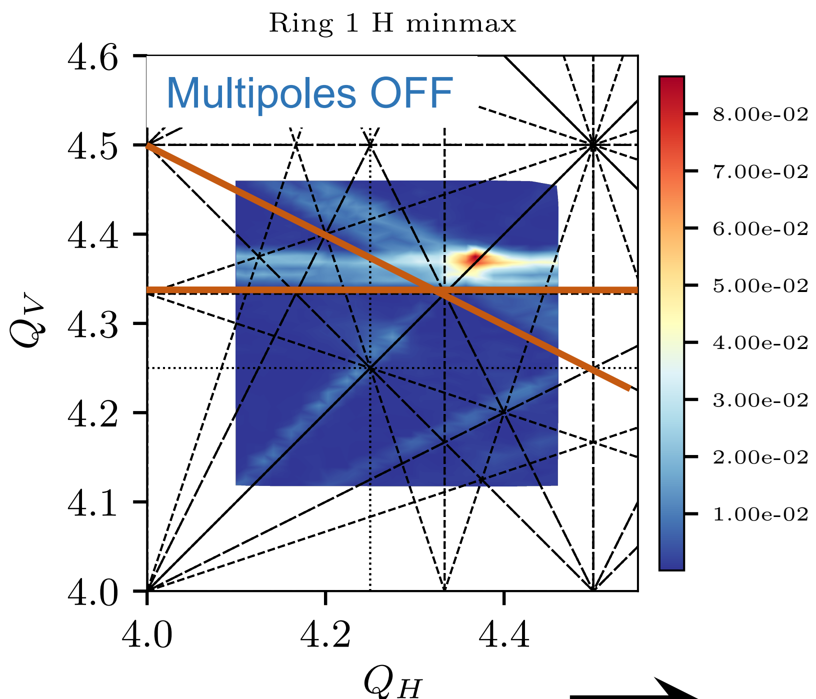


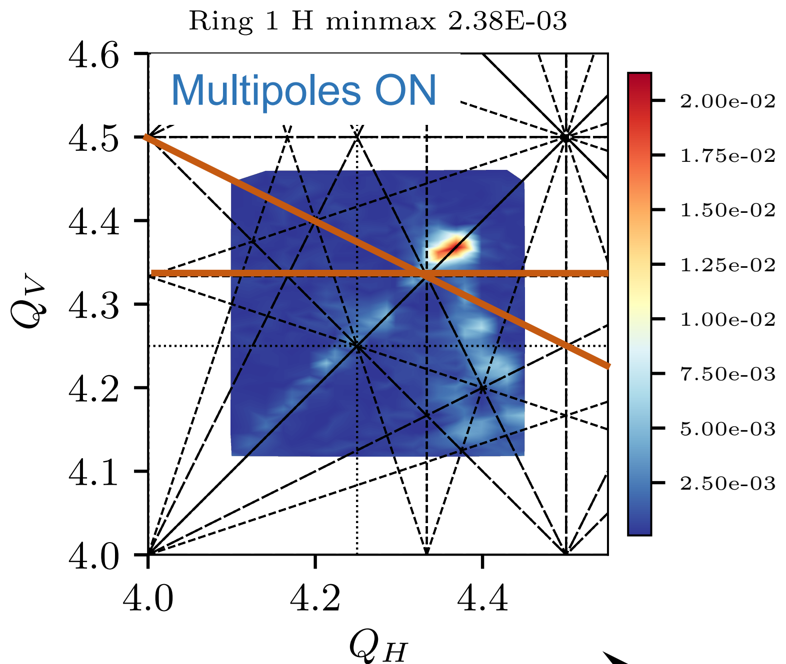
Compensation – Ring 1

Compensation of 3Qy = 13 and Qx + 2Qy = 13

BR1.XSK6L4 = 2.77 A
BR1.XSK2L4 = -8.33 A

BR4.XNO9L1 = -9.99 A
BR4.XNO4L1 = -6.07 A

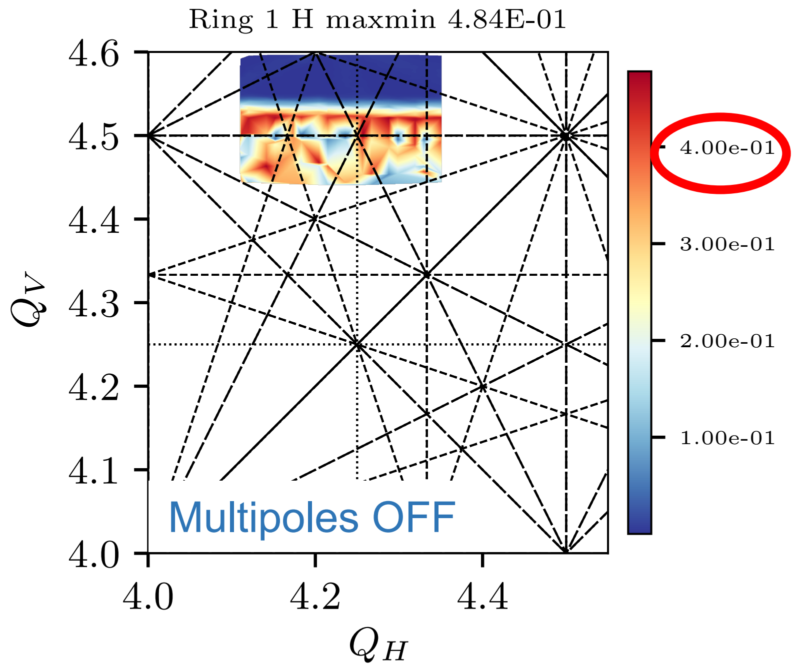


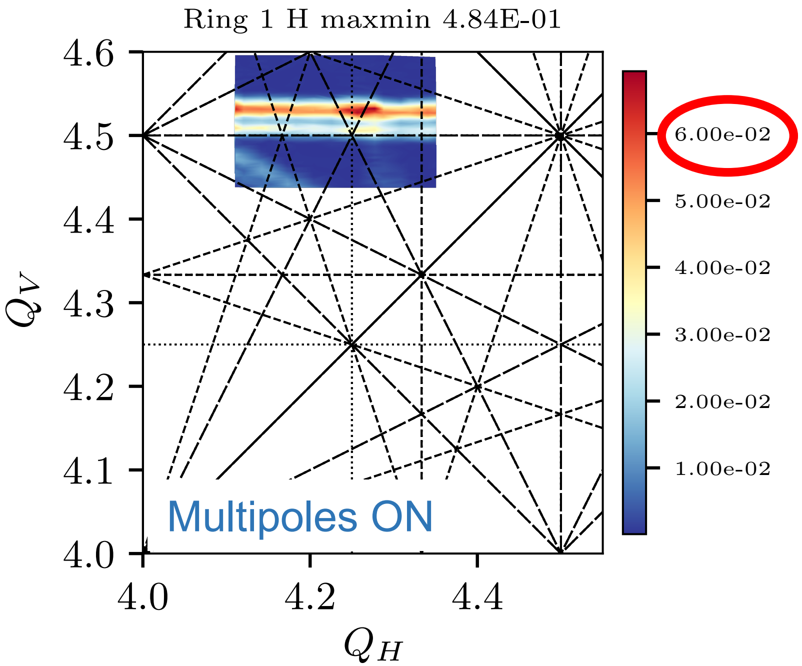


Compensation – Ring 1

Compensation of 2Qy = 9 (half integer) with normal quadrupoles

BR1.QNO816L3 = -4.33 A
BR1.QNO412L3 = 1.55 A

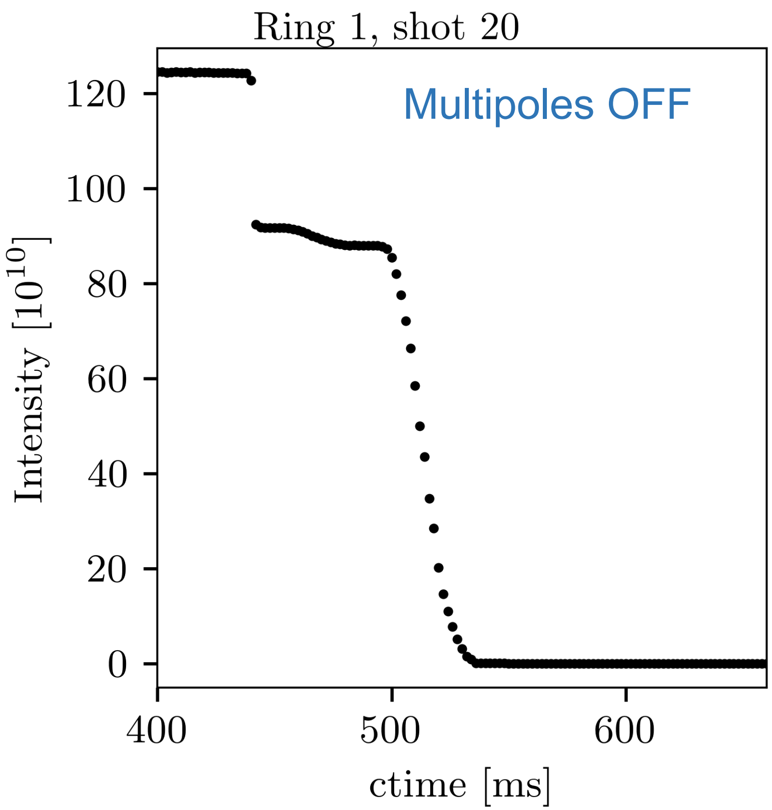


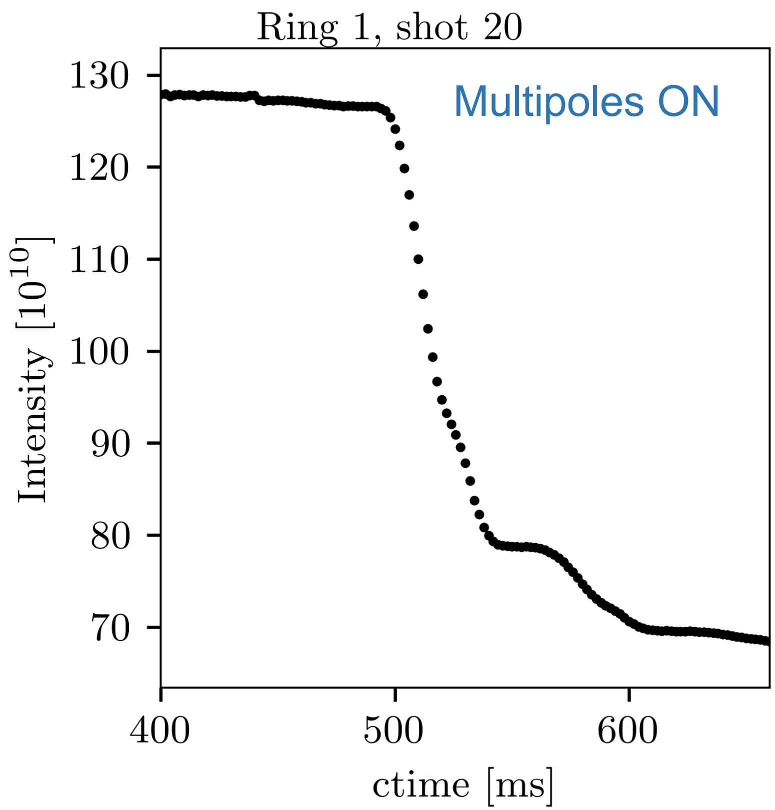


Could have put a little compensation to cross the half integer resonance…

Compensation – Ring 1

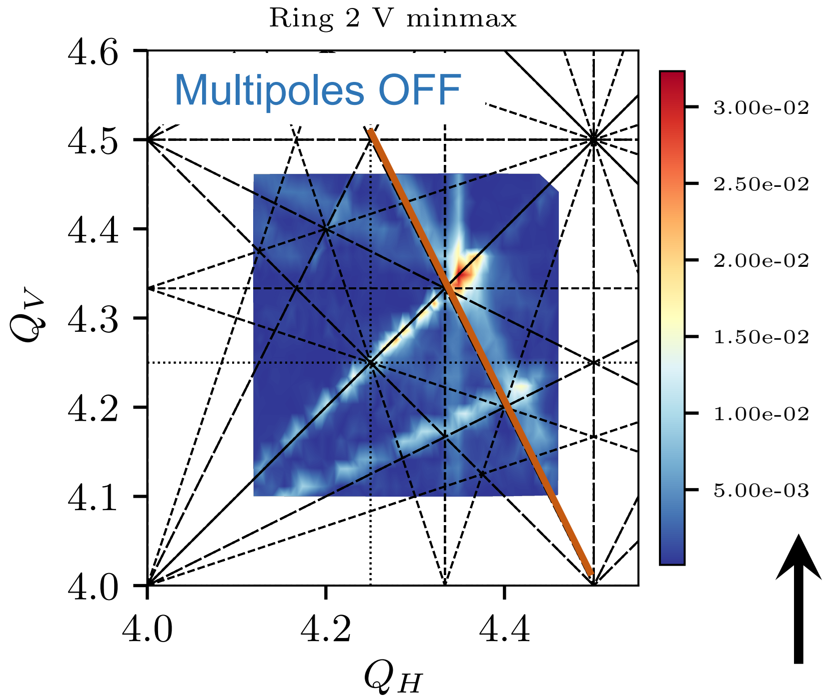
Compensation of 2Qy = 9 (half integer) with <u>normal</u> quadrupoles quadrupoles

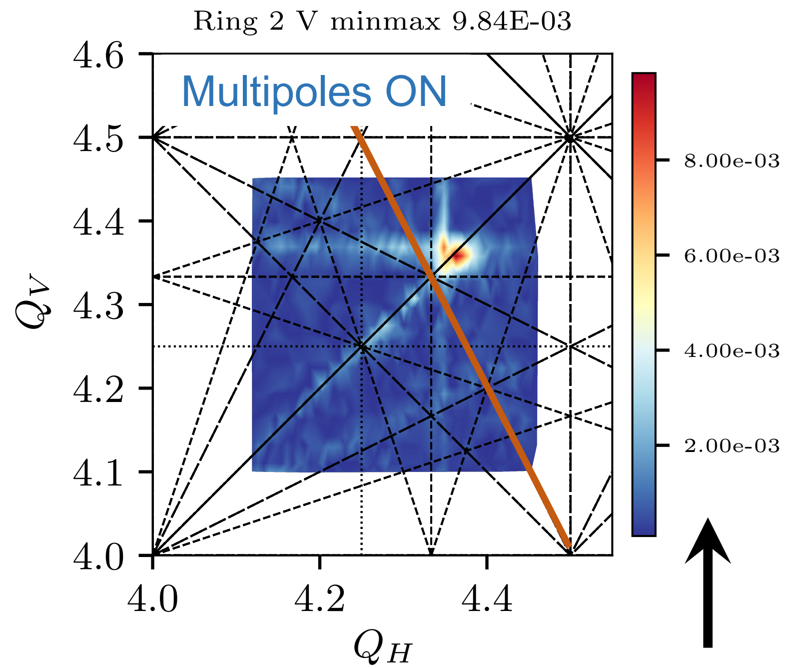




Compensation of 2Qx + Qy = 13 with skew sextupoles

BR2.XSK6L4 = -1.42 A
BR2.XSK2L4 = 4.28 A

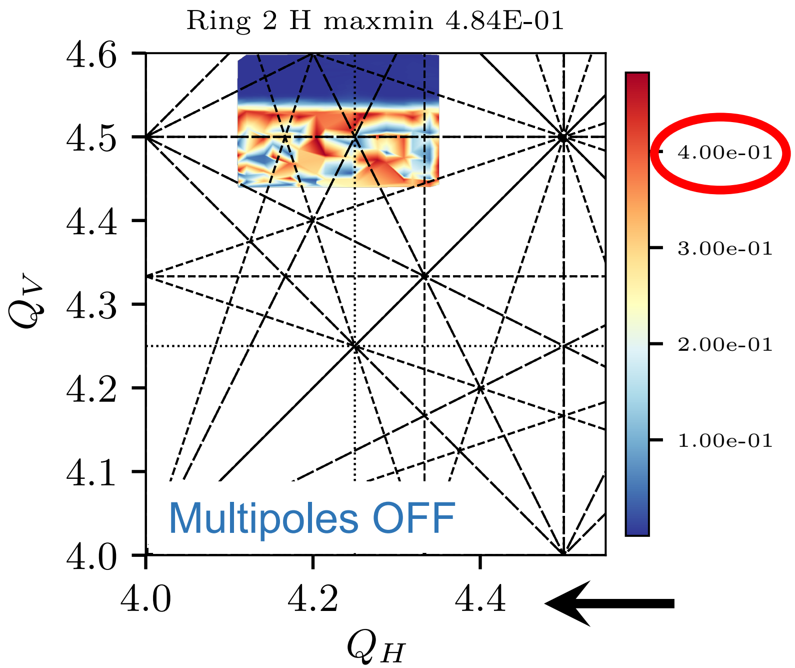


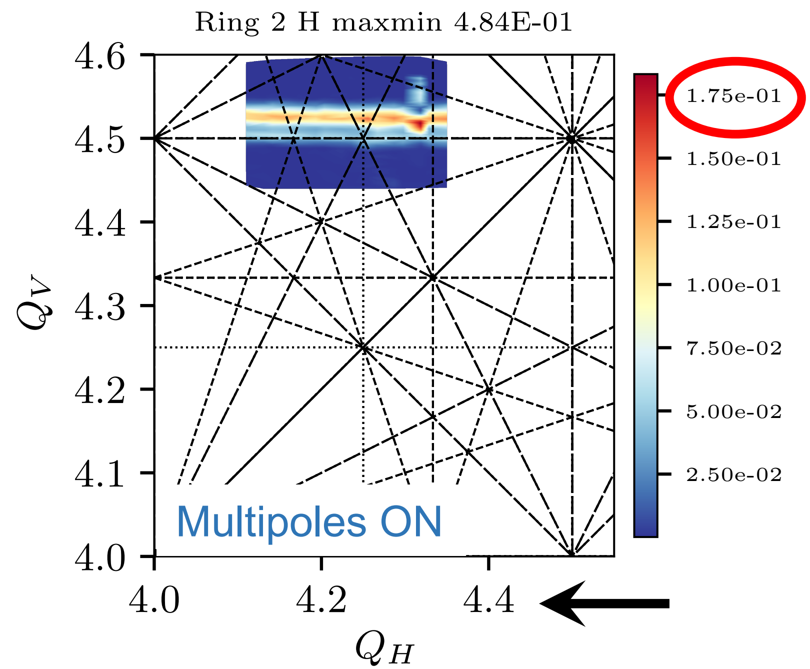


Compensation – Ring 2

Compensation of 2Qy = 9 (half integer) with normal quadrupoles

BR2.QNO816L3 = -5 A
BR2.QNO412L3 = 1.44 A

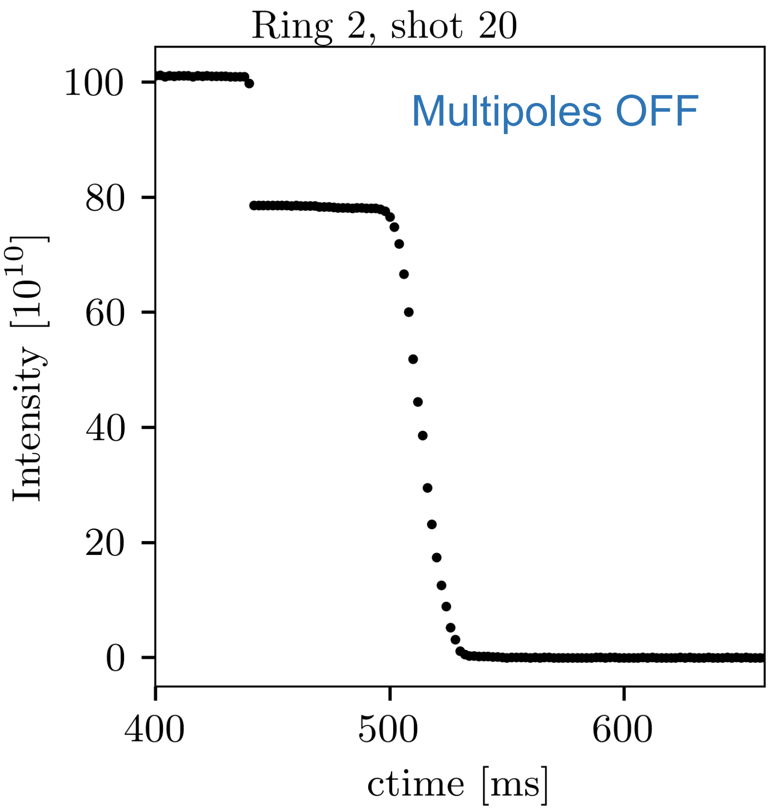


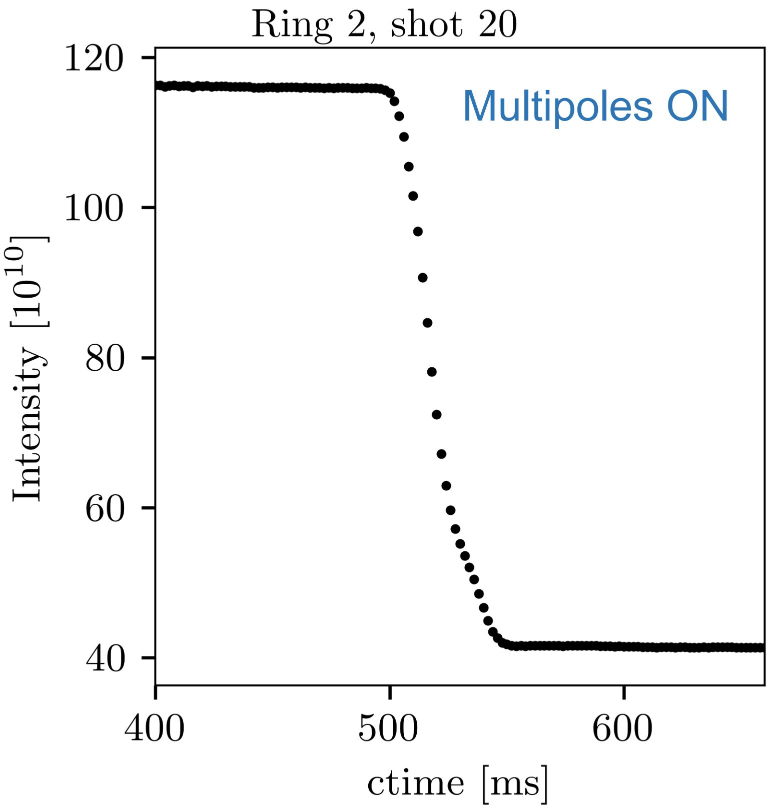


Could have put a little compensation to cross the half integer resonance…

Compensation – Ring 2

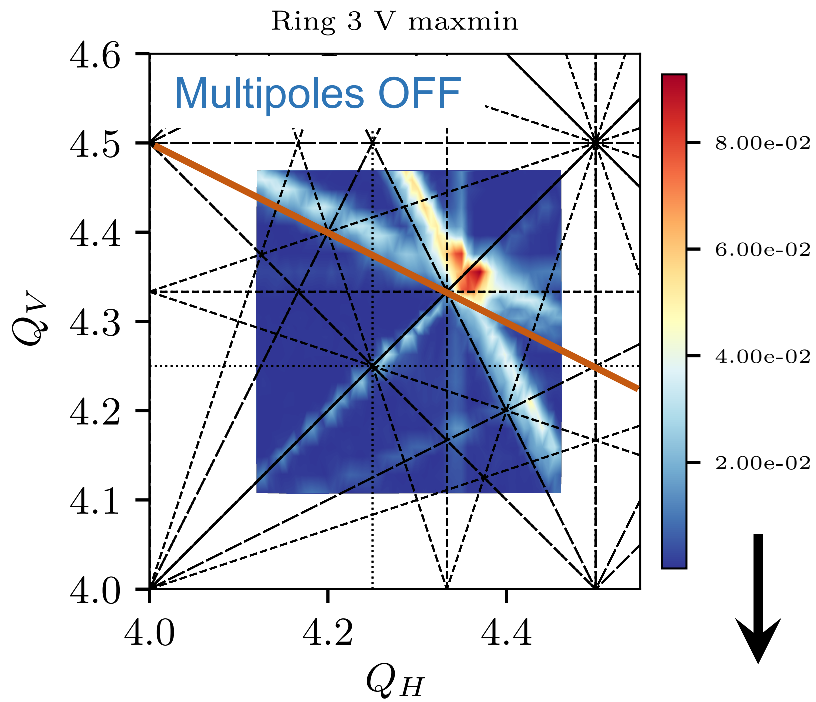
Compensation of 2Qy = 9 (half integer) with normal quadrupoles quadrupoles

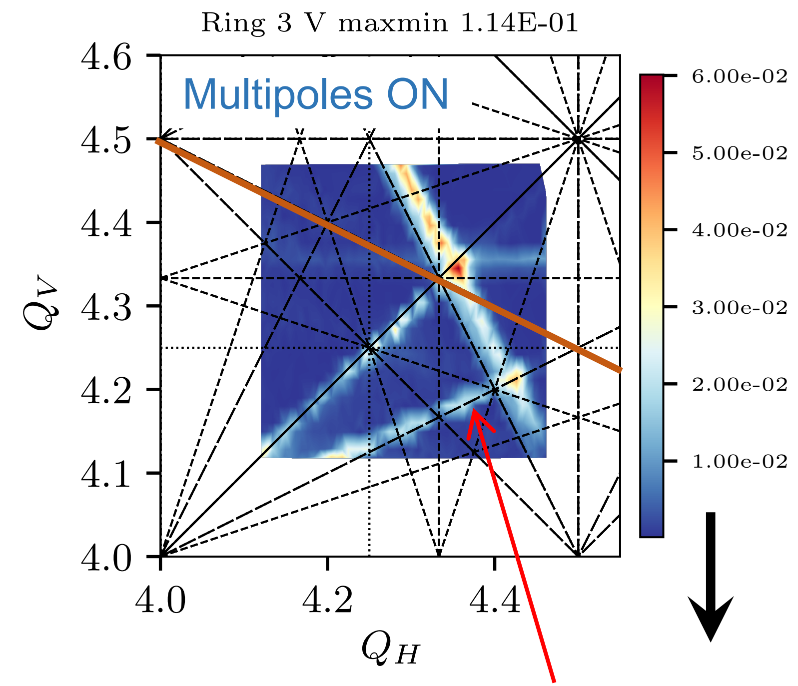




Compensation of Qx + 2Qy = 13 with normal sextupoles

BR3.XNO4L1 = 3.15 A
BR3.XNO9L1 = -24.73 A



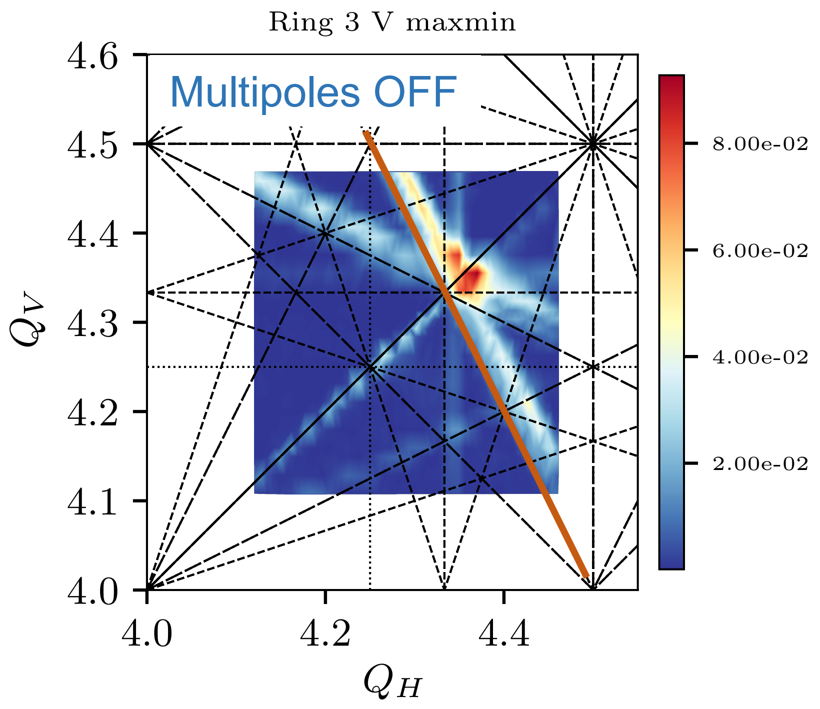


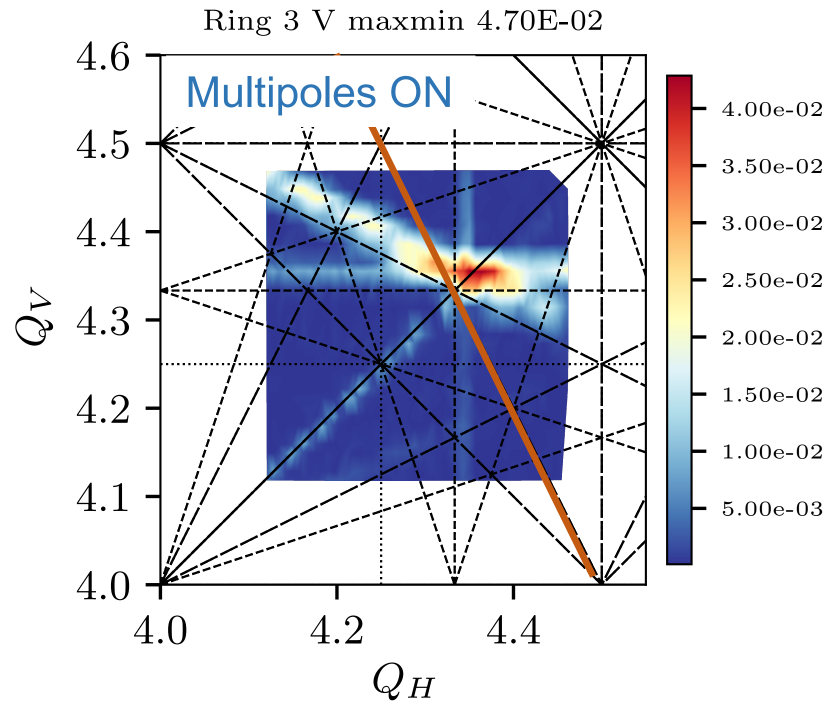
Excitation of Qx - 2Qy = -4

Compensation – Ring 3

Compensation of 2Qx + Qy = 13 with skew sextupoles

BR3.XSK2L4 = -9.99 A
BR3.XSK6L4 = 6.66 A

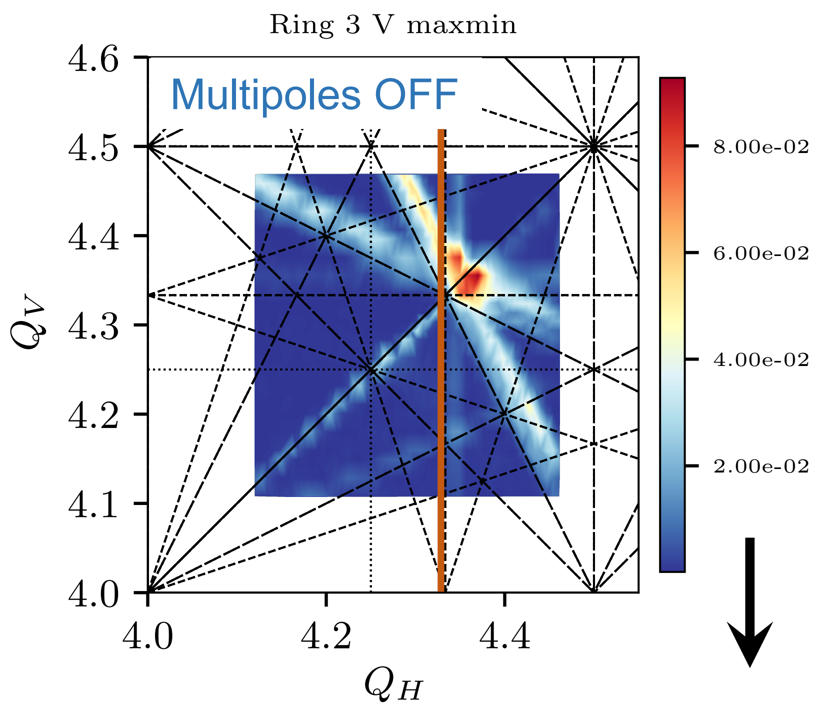


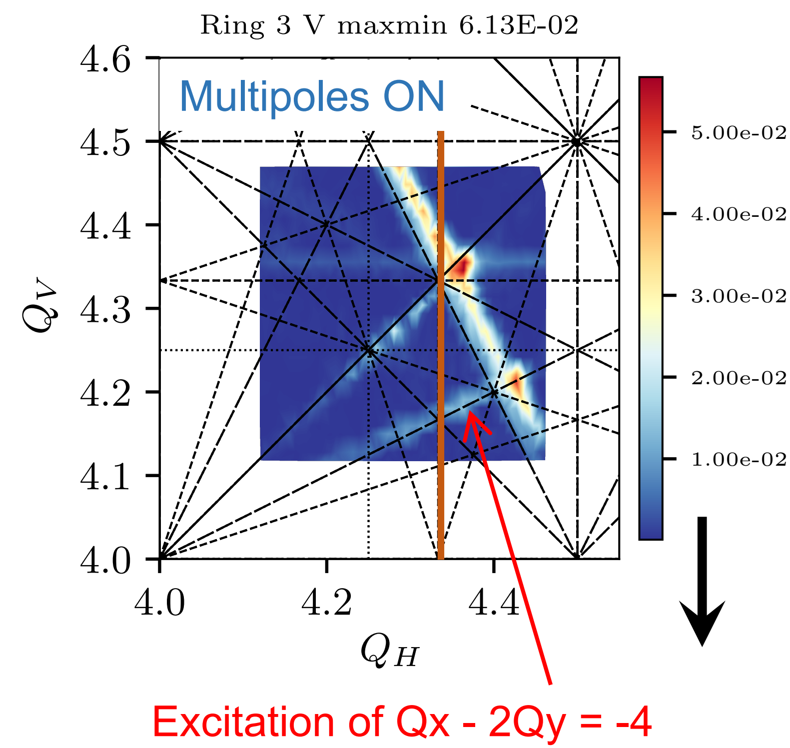


Compensation – Ring 3

Compensation of 2Qx = 13 with normal sextupoles

BR3.XNO9L1 = -17.14 A
BR3.XNO4L1 = 4.28 A

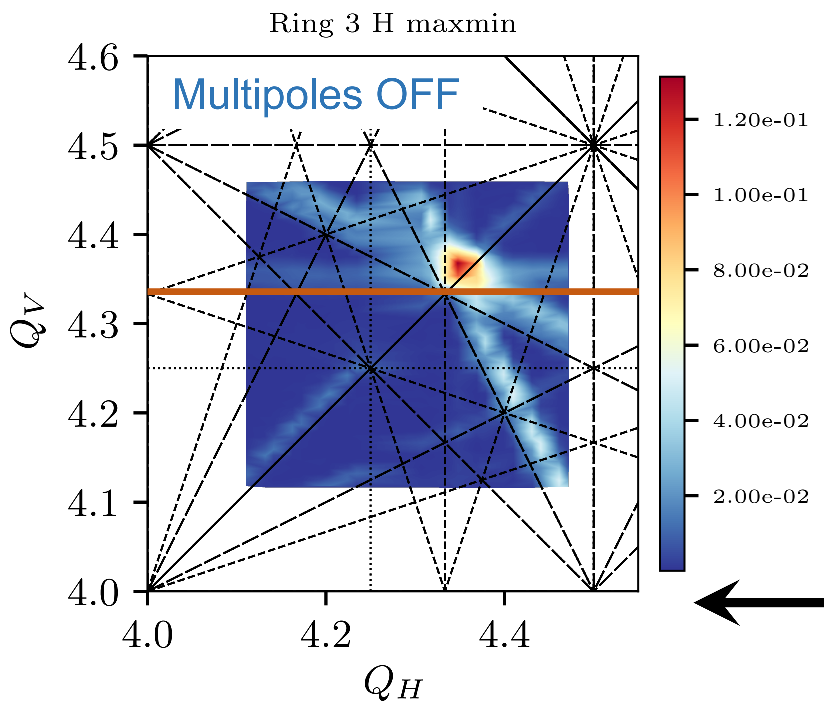


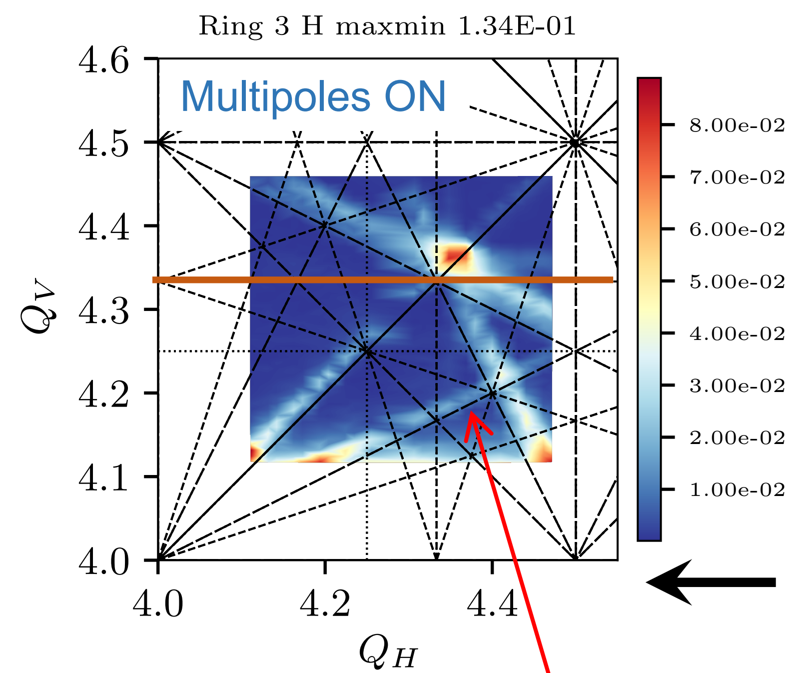


Compensation – Ring 3

Compensation of 3Qy = 13 with **skew** sextupoles

BR3.XSK2L4 = -0.26 A
BR3.XSK6L4 = 4.47 A

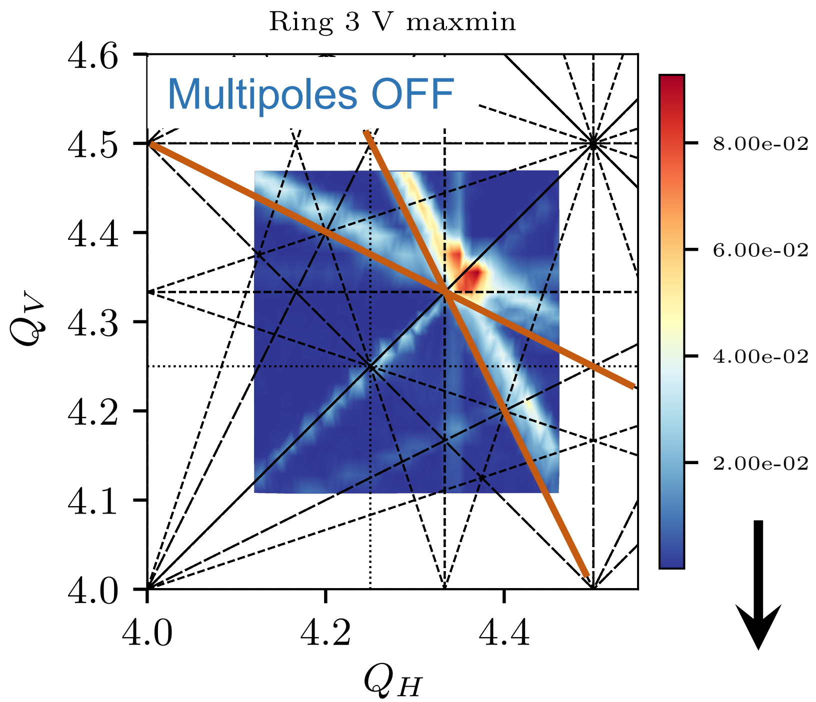


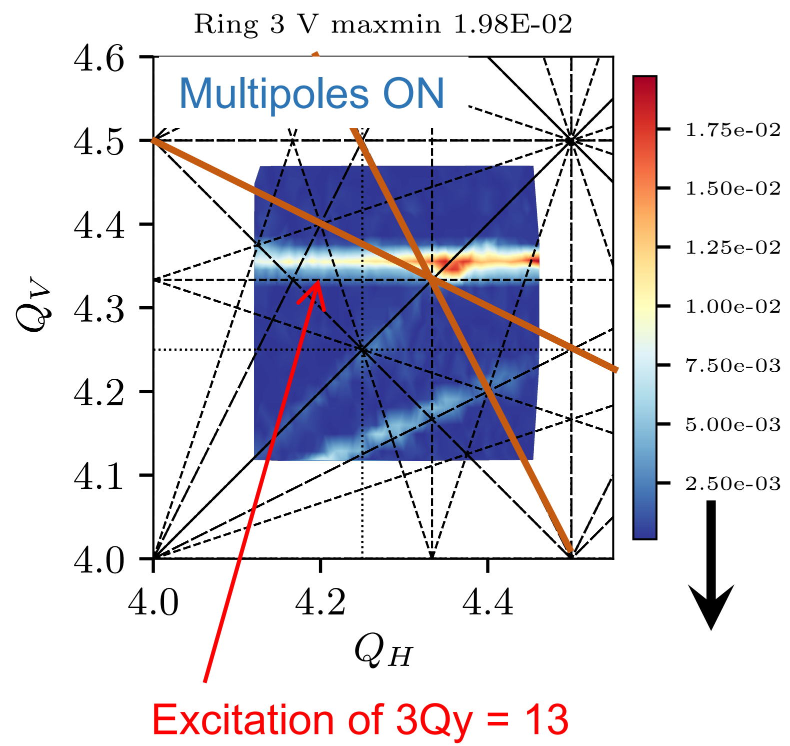


Compensation – Ring 3

Compensation of Qx + 2Qy = 13 and 2Qx + Qy = 13

BR3.XSK2L4 = -9.99 A   BR3.XNO9L1 = -24.73 A
BR3.XSK6L4 = 6.66 A   BR3.XNO4L1 = 3.15 A



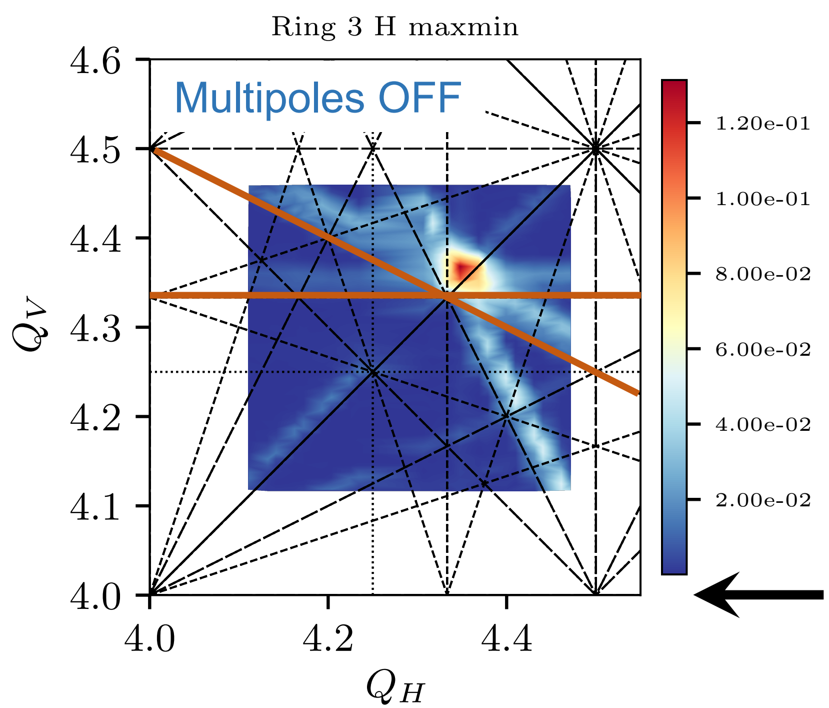


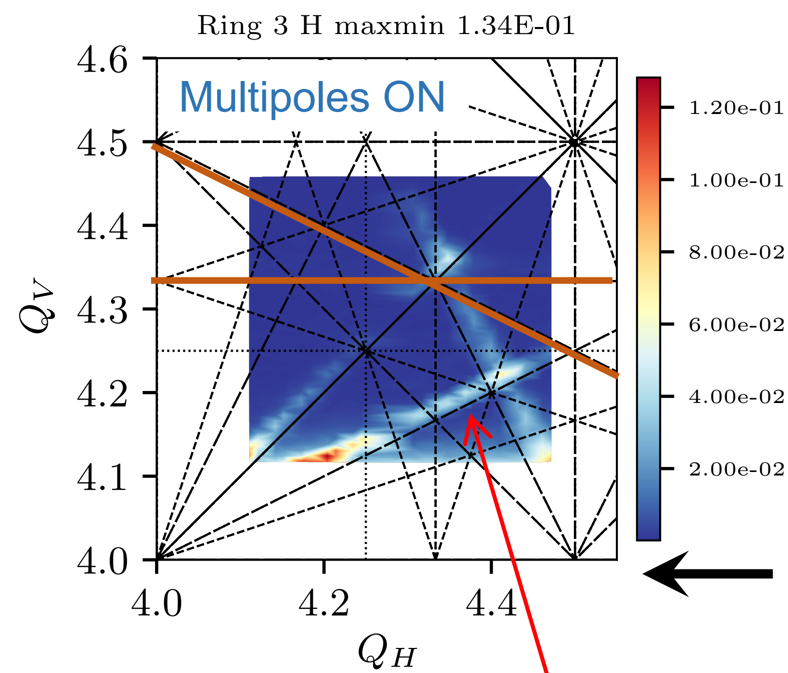
Compensation of 3Qy = 13 and Qx + 2Qy = 13

BR3.XSK2L4 = -0.26 A
BR3.XSK6L4 = 4.47 A

BR3.XNO4L1 = 3.15 A
BR3.XNO9L1 = -24.73 A

👍



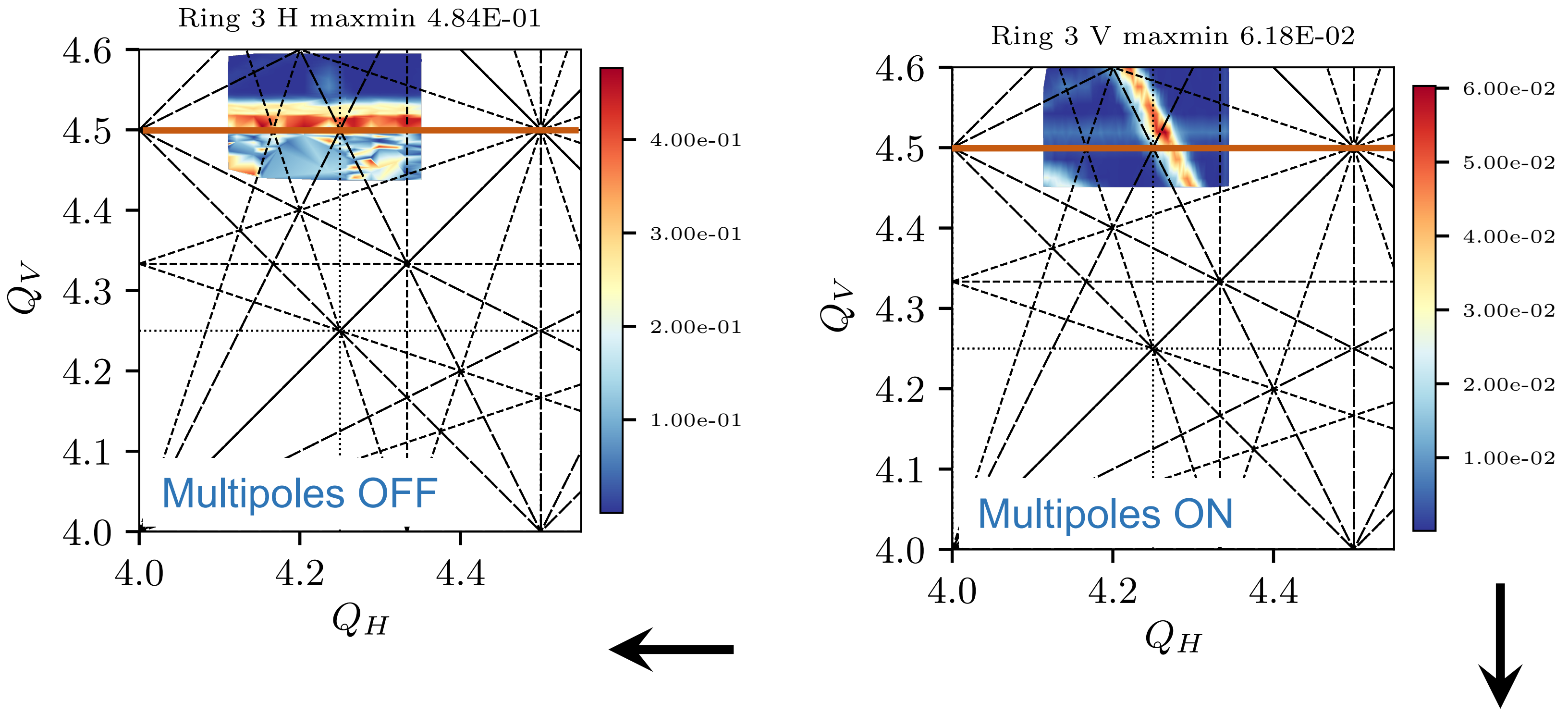


Excitation of Qx - 2Qy = -4

Compensation – Ring 3

Compensation of 2Qy = 9 (half integer) with normal quadrupoles

BR3.QNO816L3 = -3.65 A
BR3.QNO412L3 = 1.42A

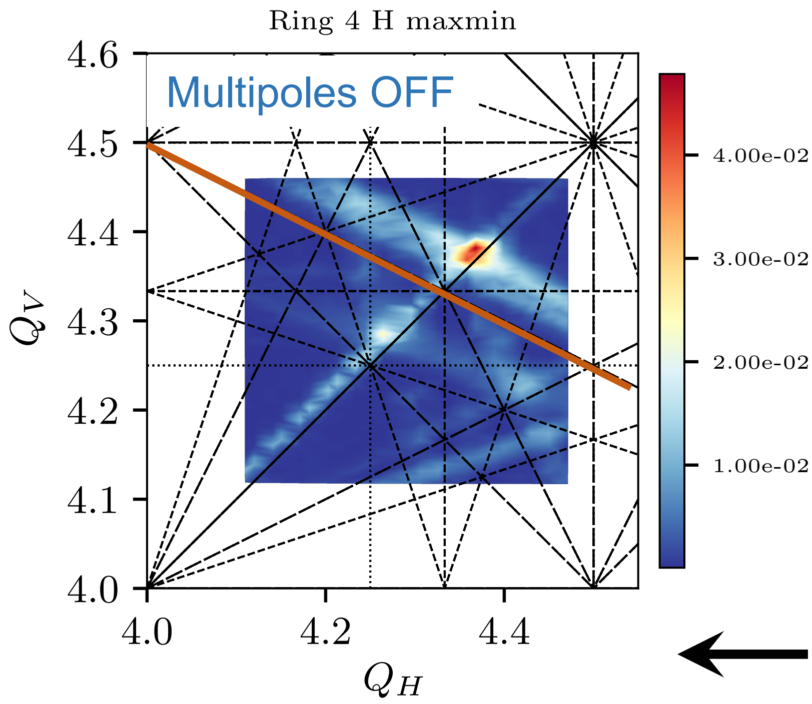


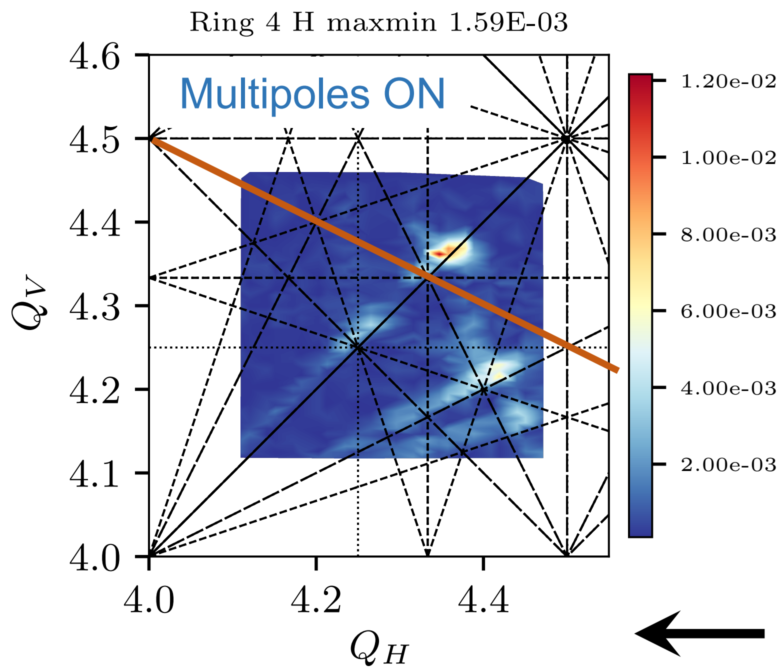
Could have put a little compensation to cross the half integer resonance…

Compensation – Ring 4

Compensation of Qx + 2Qy = 13 with normal sextupoles

BR4.XNO9L1 = -8.68 A
BR4.XNO4L1 = 7.63 A

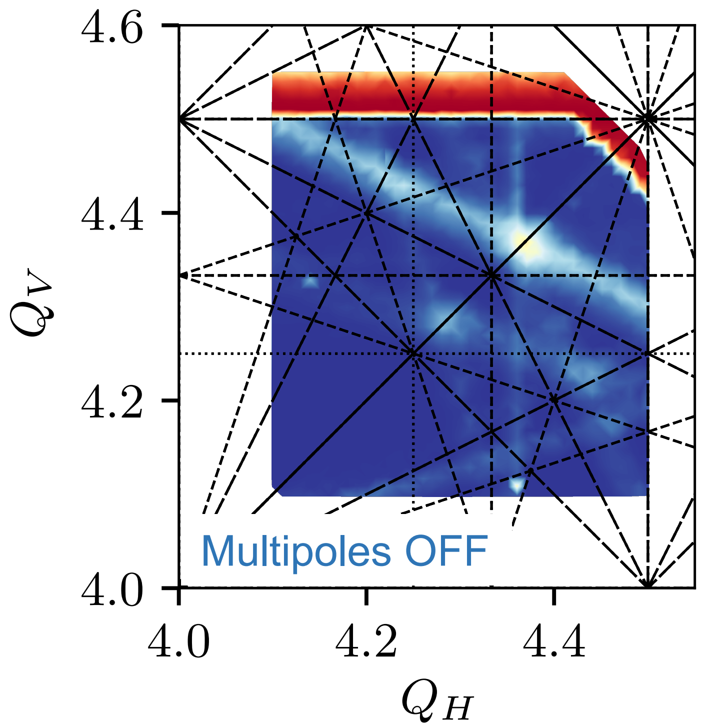


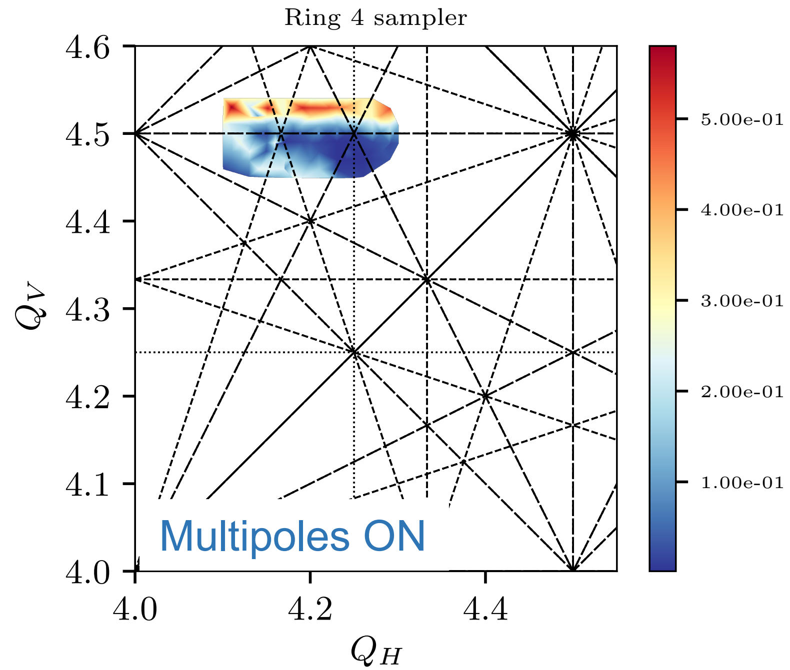


Compensation – Ring 4

Compensation of 2Qy = 9 (half integer) with normal quadrupoles

BR4.QNO816L3 = -3.83 A
BR4.QNO412L3 = 2.94 A





Gave up on the dynamic scans and did a short static tune scan

Summary & outlook

- ✓ Tools developed to carry out static and dynamic tune scans: https://gitlab.cern.ch/PSB/tune_scans
- ✓ Resonances identified for all rings for both types of scan.
- ✓ Additional compensation of resonances proposed for 160 MeV (could be used upon the restart of the machine).

- Investigate the difference in tune between the sampler (input tune) and the BBQ (real tune). Test knobs using the recorded currents and see if it could be a coherent tune shift from impedance.

Still one week of beam left…any suggestions? 😁

Some references

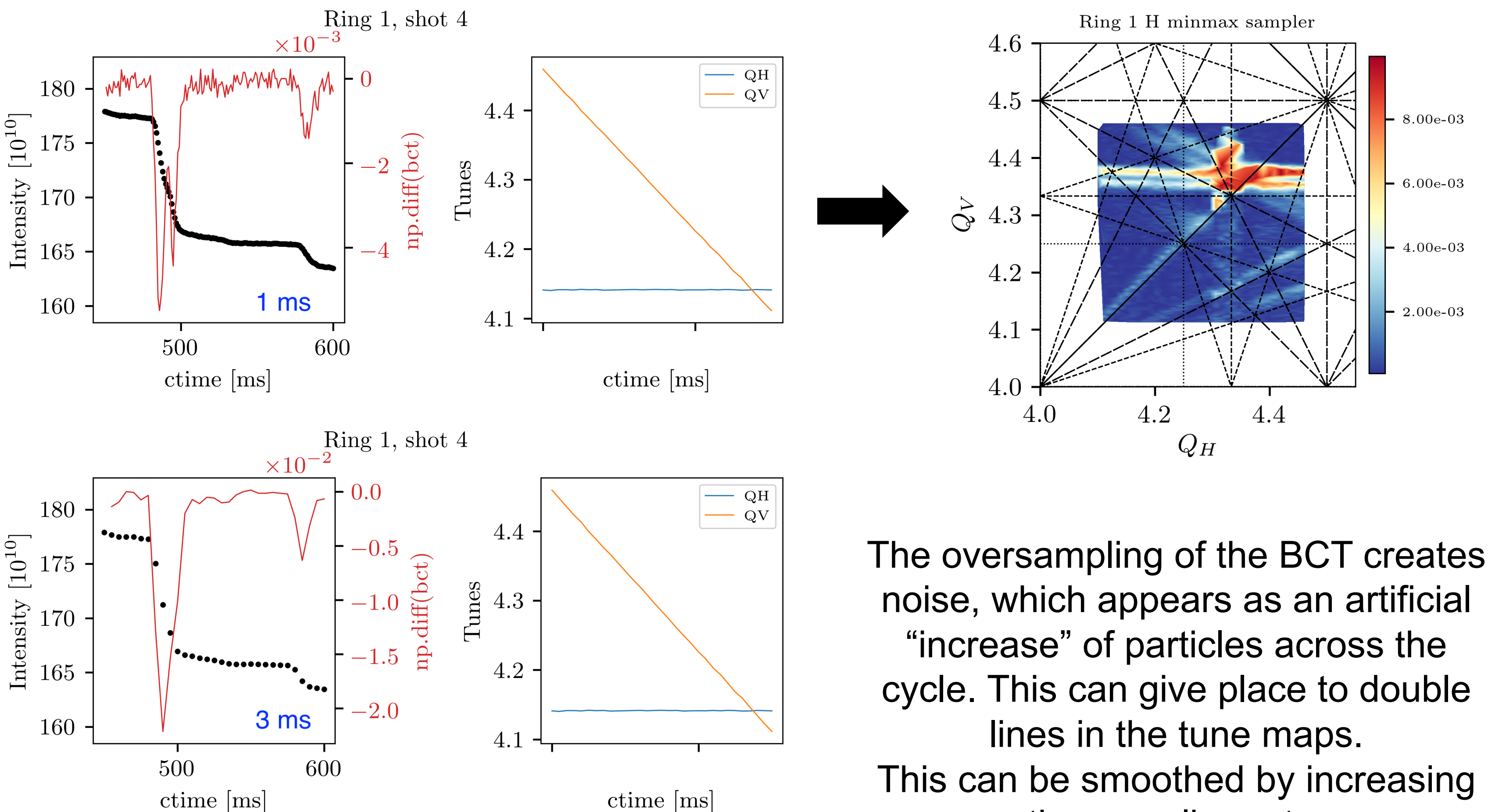
Previous presentations

- LIU-PSB Beam Dynamics WG #9
- LIU-PSB Beam Dynamics WG #13

Some studies

- OP shutdown lectures 2014: Resonance compensation in the PS Booster (E. Benedetto)
- Space charge studies in the PSB MD report, V. Forte (CERN-ACC-NOTE-2014-0056)
- Performance of the CERN PSB at 160 MeV with H^- charge exchange injection, V. Forte (CERN-THESIS-2016-063)
- Investigations on CERN PSB beam dynamics with strong direct space charge effects using the PTC-orbit code, V. Forte et al. (IPAC'13 WEPEA052)
- Measurement and Compensation of Betatron Resonances at the CERN PS Booster Synchrotron (P. Urschütz)

Dynamic scans - analysis



The oversampling of the BCT creates noise, which appears as an artificial “increase” of particles across the cycle. This can give place to double lines in the tune maps.
This can be smoothed by increasing the sampling rate.