Run 3 requirements: Octupole, chromaticity, gain and bandwidth

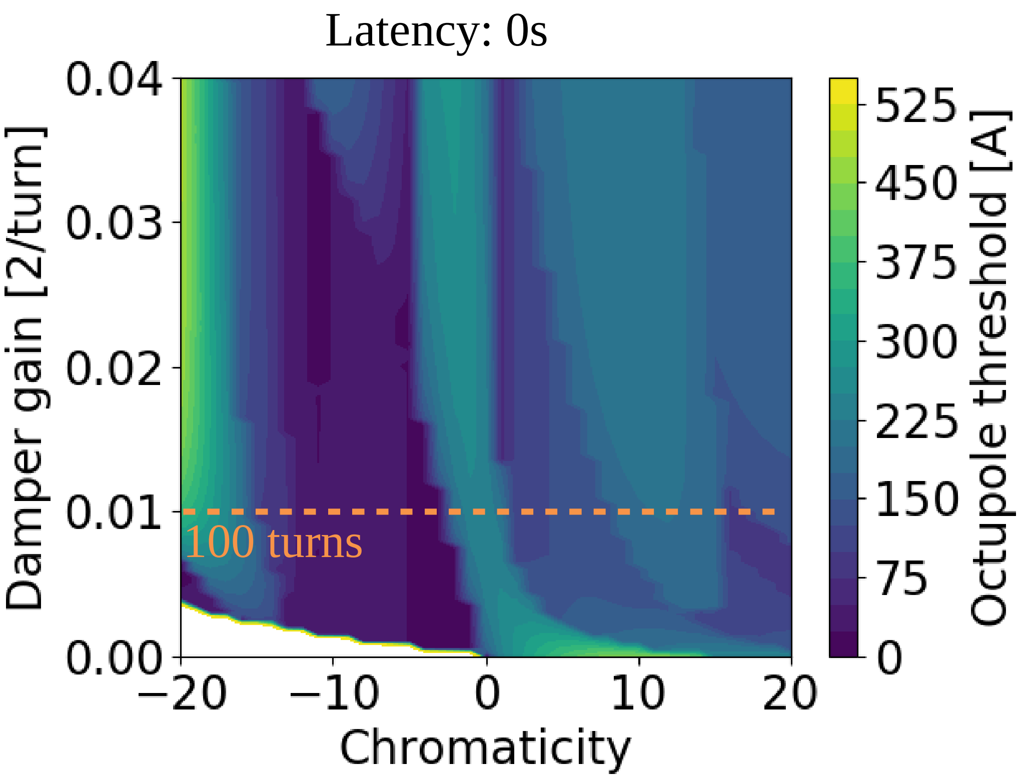
X. Buffat, S.V. Furuseth and N. Mounet

- Octupole threshold including latent instabilities
- Mitigation of the coupled bunch instability
- Conclusion

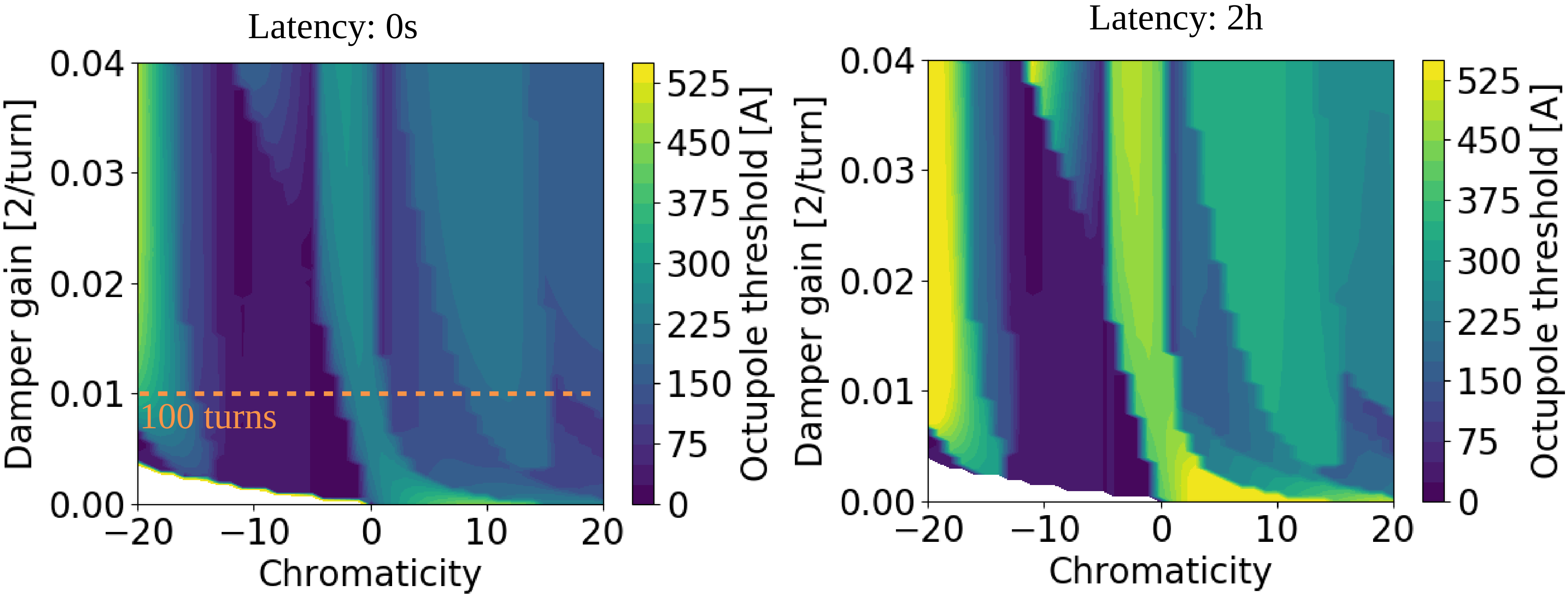
Run 3 study case

Parameter	Value
Bunch intensity [10^{11} p]	1.8
Energy [TeV]	7
Transverse emit. [μm]	2.1
Bunch length [ns]	1.2
RF voltage [MV]	12
ADT damping time [turns]	100
Chromaticity	[10,15]
Impedance model	N. Mounet @ LCR3 21.09.2018 and 27.03.2020
Machine noise [σ]	$4\cdot10^{-5}$
ADT BPM noise @100 turns [σ]	$2.2\cdot10^{-5}$
Teleindex	1.0

Octupole threshold including the latency

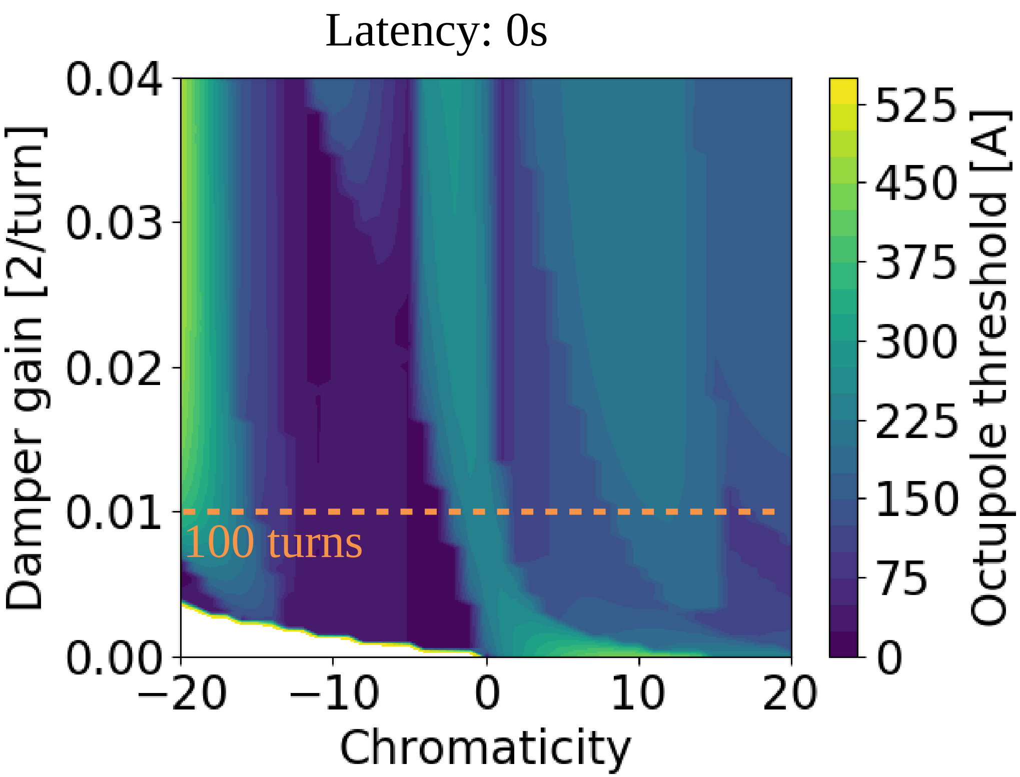


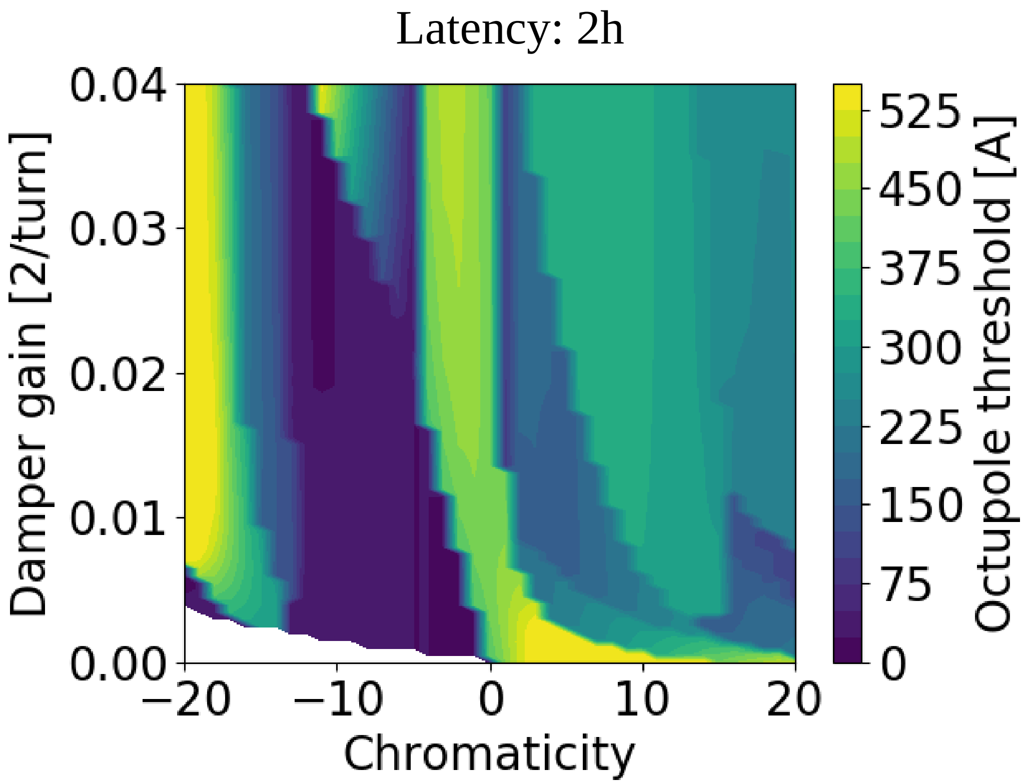
Octupole threshold including the latency



- The octupole requirements to maintain a 2h latency are overall between 1.1 to 2 times larger than the ‘0-latency’ threshold

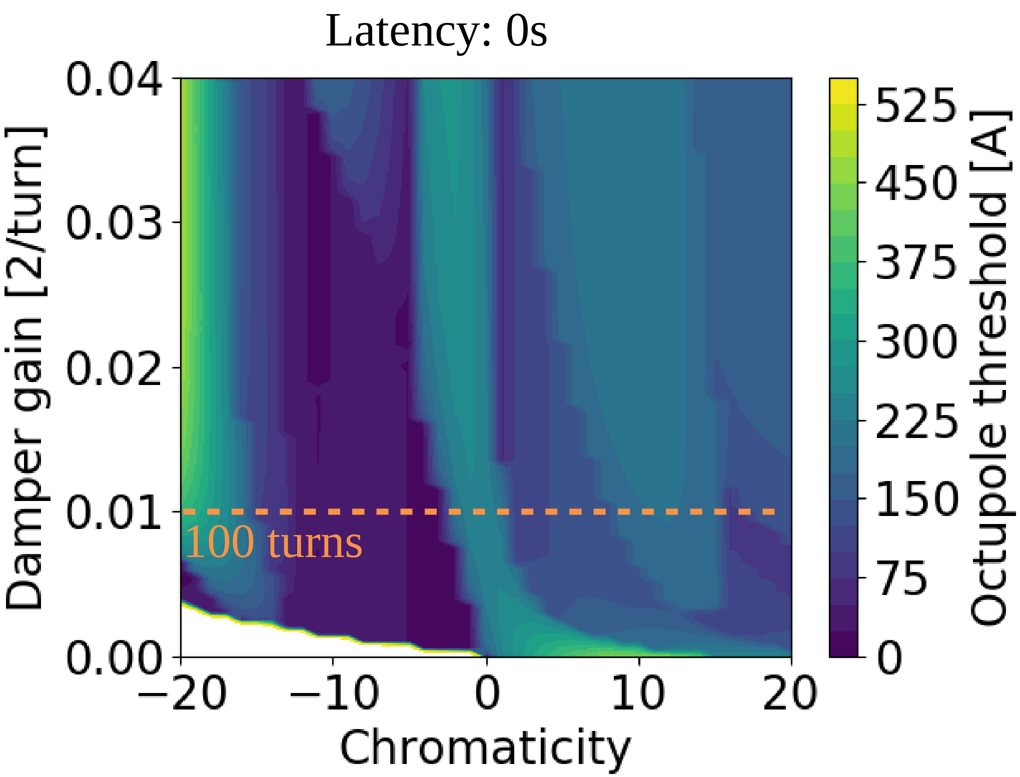
Octupole threshold including the latency

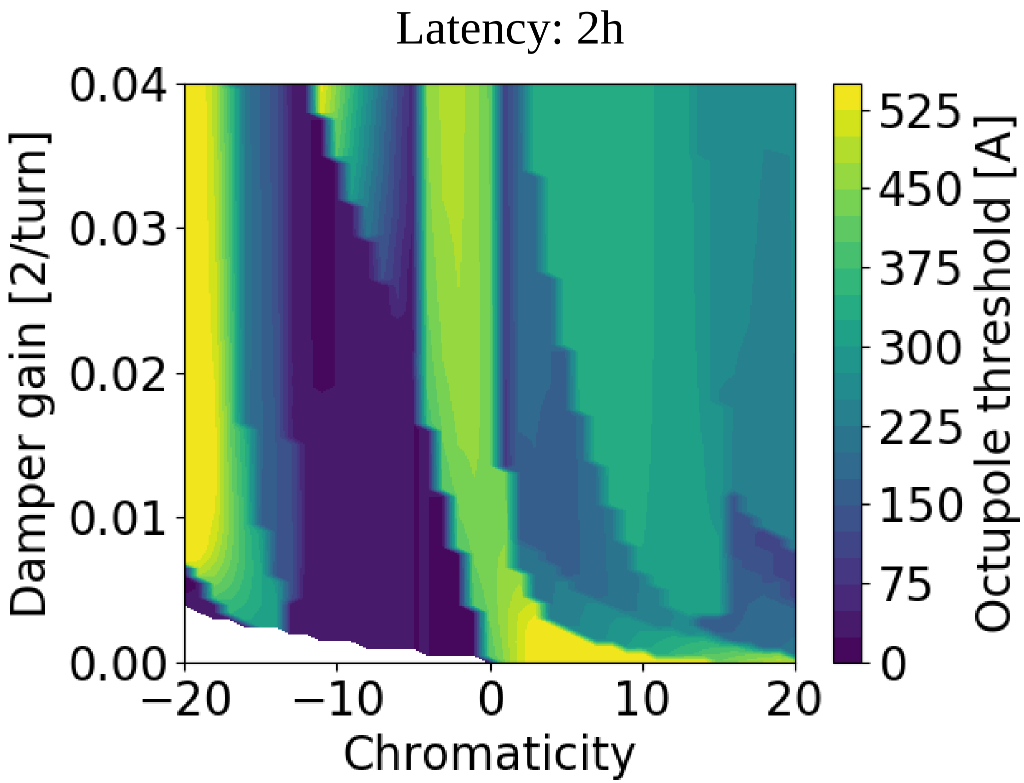




- The octupole requirements to maintain a 2h latency are overall between 1.1 to 2 times larger than the ‘0-latency’ threshold
- The stable area with negative chromaticity still appears as an ideal spot

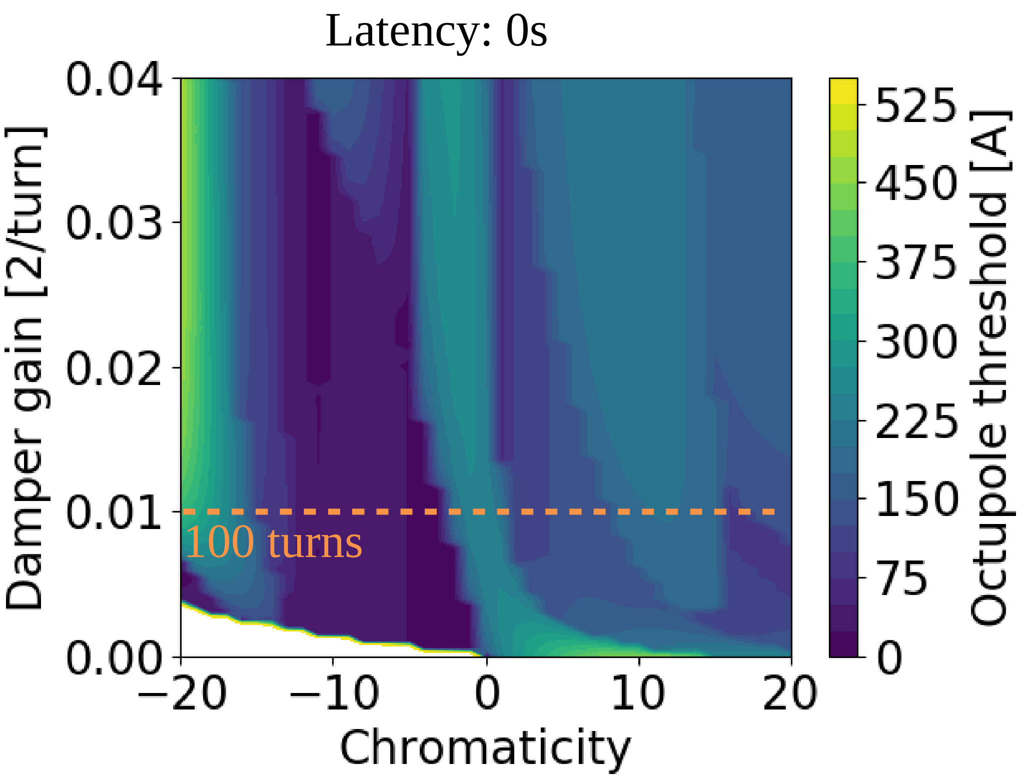
Octupole threshold including the latency

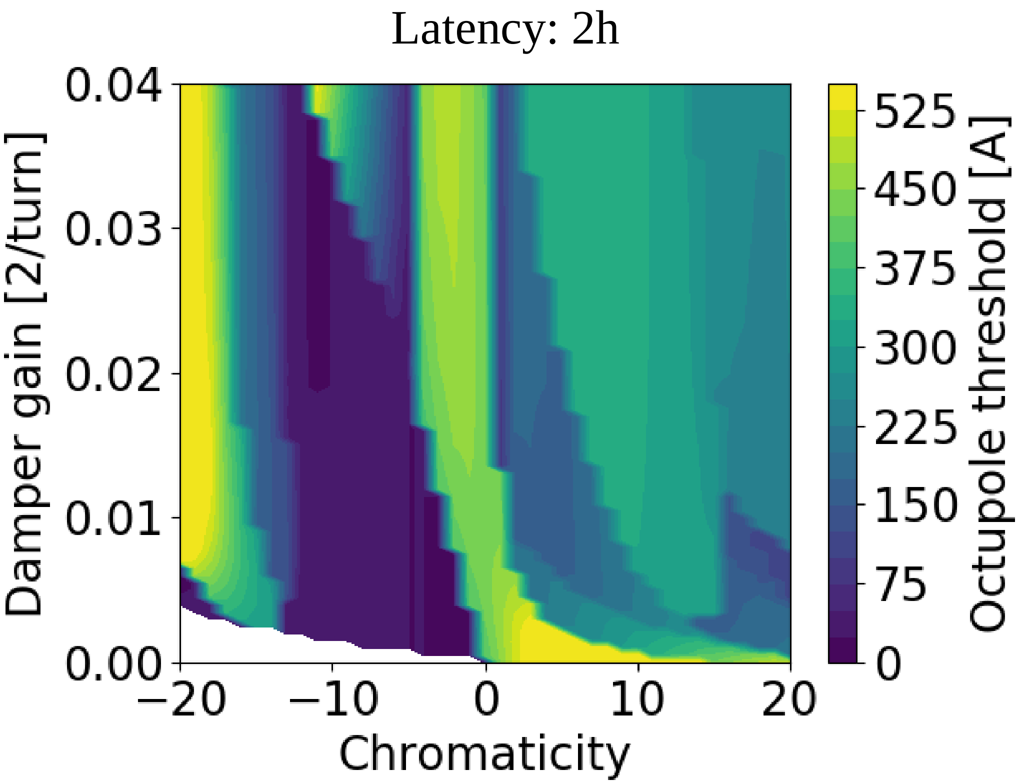




- The octupole requirements to maintain a 2h latency are overall between 1.1 to 2 times larger than the '0-latency' threshold
- The stable area with negative chromaticity still appears as an ideal spot
- The second most ideal area is with a mild damper gain and a chromaticity about 5 units (confirmed experimentally during the latency MD in 2018)

Octupole threshold including the latency





- The octupole requirements to maintain a 2h latency are overall between 1.1 to 2 times larger than the ‘0-latency’ threshold
- The stable area with negative chromaticity still appears as an ideal spot
- The second most ideal area is with a mild damper gain and a chromaticity about 5 units (confirmed experimentally during the latency MD in 2018)

→ We should aim at exploiting this working point. That requires mastering the control of chromaticity

Estimation of the octupole threshold

- Up to now the octupole requirent was defined as twice the estimate obtained by comparing the tune shifts from DELPHI and the stability diagram
- Here we compute the octupole current required to obtain a given latency, using Sondre's formula*:

$$\frac{\tau}{\tau_{rev}} = \frac{\Im(\Delta Q_{SD} - \Delta Q)^5}{2.5\Im(\Delta Q_{SD})a^2|\Delta Q|^2} \frac{\Re(\alpha)^4 S}{J_{\text{eff}}\sigma^2\eta^2}$$

* S.V. Furuseth and X. Buffat, Loss of transverse Landau damping by noise and wakefield driven diffusion, accepted for publication in PRAB

Estimation of the octupole threshold

- Up to now the octupole requirent was defined as twice the estimate obtained by comparing the tune shifts from DELPHI and the stability diagram
- Here we compute the octupole current required to obtain a given latency, using Sondre's formula*:

Tune shift (BimBim)

$$\frac{\tau}{\tau_{rev}} = \frac{\Im(\Delta Q_{SD} - \Delta Q)^5}{2.5\Im(\Delta Q_{SD})a^2|\Delta Q|^2}\frac{\Re(\alpha)^4 S}{J_{\text{eff}}\sigma^2\eta^2}$$

Mode's sensitivity to dipole noise (BimBim)

* S.V. Furuseth and X. Buffat, Loss of transverse Landau damping by noise and wakefield driven diffusion, accepted for publication in PRAB

Estimation of the octupole threshold

- Up to now the octupole requirent was defined as twice the estimate obtained by comparing the tune shifts from DELPHI and the stability diagram
- Here we compute the octupole current required to obtain a given latency, using Sondre's formula*:

Tune shift (BimBim)

$$\frac{\tau}{\tau_{rev}} = \frac{\Im(\Delta Q_{SD} - \Delta Q)^5}{2.5\Im(\Delta Q_{SD})a^2|\Delta Q|^2} \frac{\Re(\alpha)^4 S}{J_{\text{eff}}\sigma^2\eta^2}$$

Mode's sensitivity to dipole noise (BimBim)

Direct detuning coefficient

Effective action of the particles resonant with the mode

* S.V. Furuseth and X. Buffat, Loss of transverse Landau damping by noise and wakefield driven diffusion, accepted for publication in PRAB

Estimation of the octupole threshold

- Up to now the octupole requirent was defined as twice the estimate obtained by comparing the tune shifts from DELPHI and the stability diagram
- Here we compute the octupole current required to obtain a given latency, using Sondre's formula*:

$$\frac{\tau}{\tau_{rev}} = \frac{\Im(\Delta Q_{SD} - \Delta Q)^5}{2.5\Im(\Delta Q_{SD})a^2|\Delta Q|^2} \frac{\Re(\alpha)^4 S}{J_{\text{eff}}\sigma^2\eta^2}$$

Tune shift (BimBim)

Relative noise amplitude

Direct detuning coefficient

Effective action of the particles resonant with the mode

Mode's sensitivity to dipole noise (BimBim)

* S.V. Furuseth and X. Buffat, Loss of transverse Landau damping by noise and wakefield driven diffusion, accepted for publication in PRAB

Estimation of the octupole threshold

- Up to now the octupole requirent was defined as twice the estimate obtained by comparing the tune shifts from DELPHI and the stability diagram
- Here we compute the octupole current required to obtain a given latency, using Sondre's formula*:

$$\frac{\tau}{\tau_{rev}} = \frac{\Im(\Delta Q_{SD} - \Delta Q)^5}{2.5\Im(\Delta Q_{SD})a^2|\Delta Q|^2} \frac{\Re(\alpha)^4 S}{J_{\text{eff}}\sigma^2\eta^2}$$

Tune shift (BimBim)

Parameter related to the Taylor expansion into the stability diagram α ≈ 1

Self-consistency correction factor 1.0≤S≤1.25

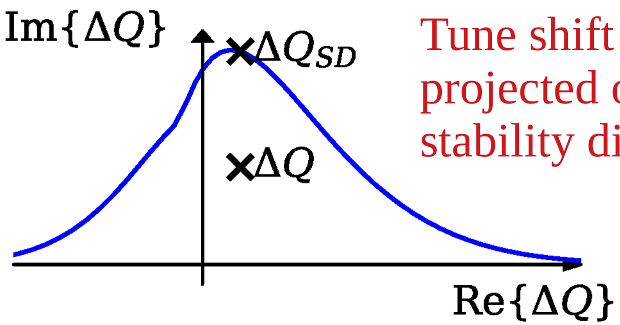
Relative noise amplitude

Tune shift projected on the stability diagram

Direct detuning coefficient

Effective action of the particles resonant with the mode

Mode's sensitivity to dipole noise (BimBim)



* S.V. Furuseth and X. Buffat, Loss of transverse Landau damping by noise and wakefield driven diffusion, accepted for publication in PRAB

Estimation of the octupole threshold

- Up to now the octupole requirent was defined as twice the estimate obtained by comparing the tune shifts from DELPHI and the stability diagram
- Here we compute the octupole current required to obtain a given latency, using Sondre's formula*:

$$\frac{\tau}{\tau_{rev}} = \frac{\Im(\Delta Q_{SD} - \Delta Q)^5}{2.5\Im(\Delta Q_{SD})a^2|\Delta Q|^2} \frac{\Re(\alpha)^4 S}{J_{\text{eff}}\sigma^2\eta^2}$$

Tune shift (BimBim)

Parameter related to the Taylor expansion into the stability diagram α ≈ 1

Self-consistency correction factor 1.0≤S≤1.25

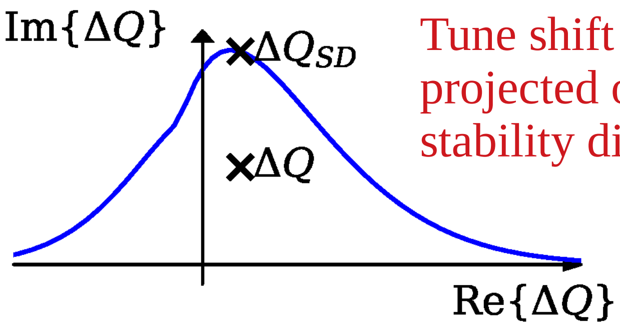
Relative noise amplitude

Tune shift projected on the stability diagram

Direct detuning coefficient

Effective action of the particles resonant with the mode

Mode's sensitivity to dipole noise (BimBim)



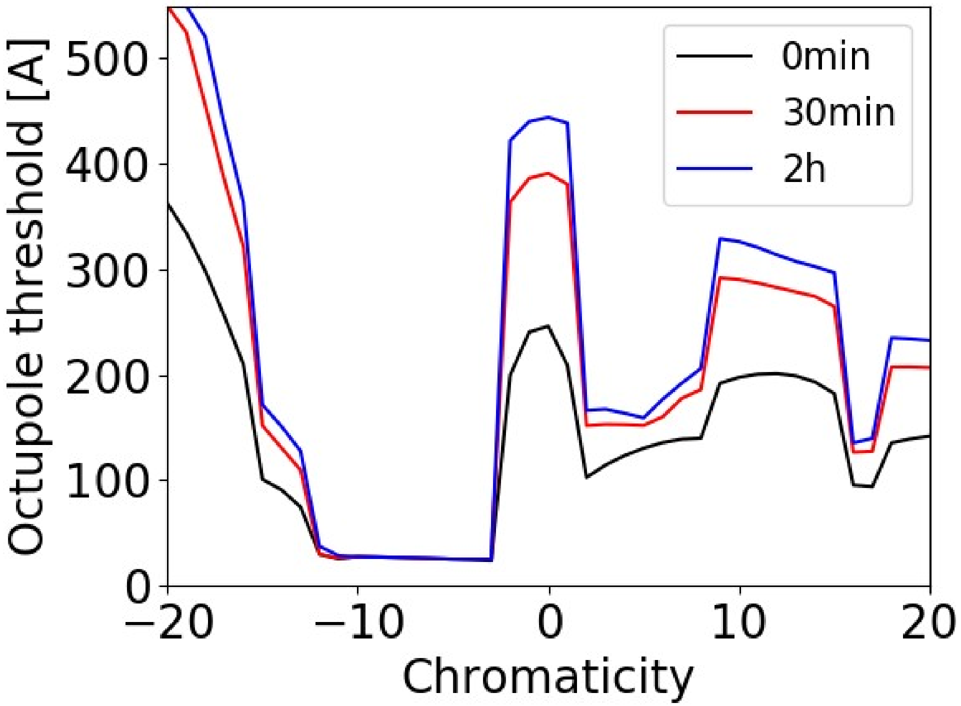
- The formula is based on strong approximations. Benchmarking against more accurate numerical calculations revealed that the latency predicted with the formula is usually about twice too high

→ A target latency of 2h seems like a reasonable target for safe operation

* S.V. Furuseth and X. Buffat, Loss of transverse Landau damping by noise and wakefield driven diffusion, accepted for publication in PRAB

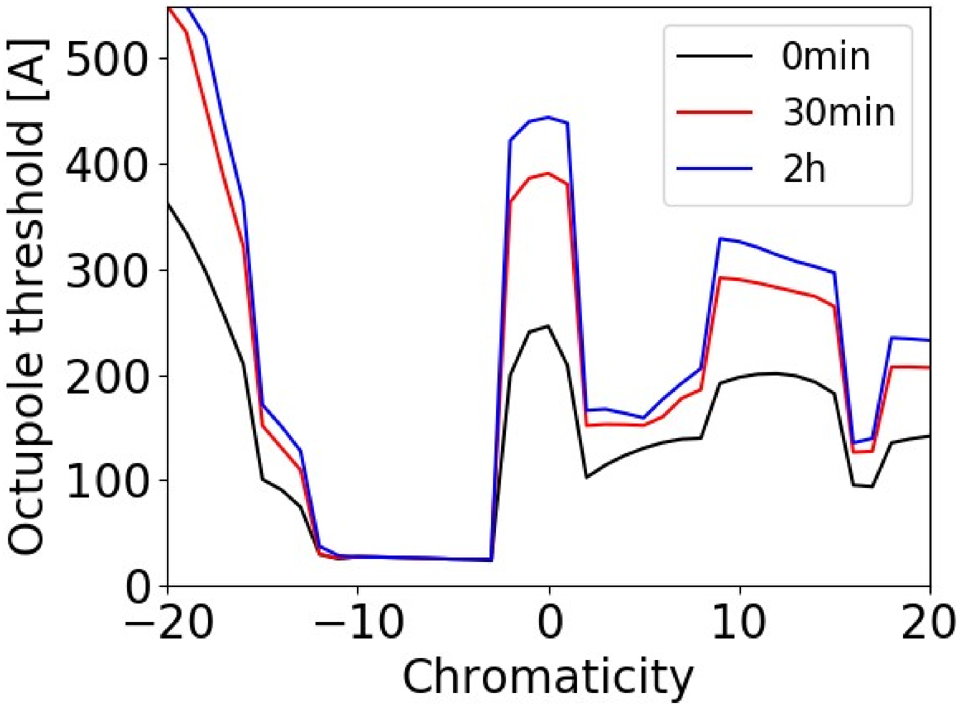
Octupole threshold including the latency

chromaticity scan at 100 turns damping



- At our ususal working point (Q'~15), the required octupole current is 50% larger than the 0-latency threshold

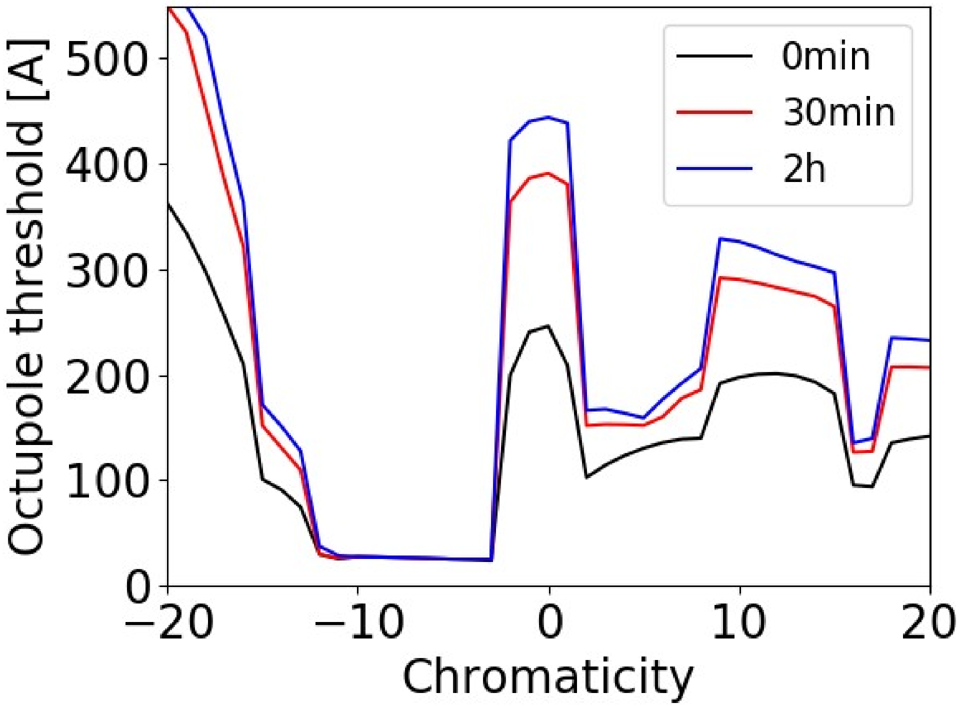
Octupole threshold including the latency
chromaticity scan at 100 turns damping

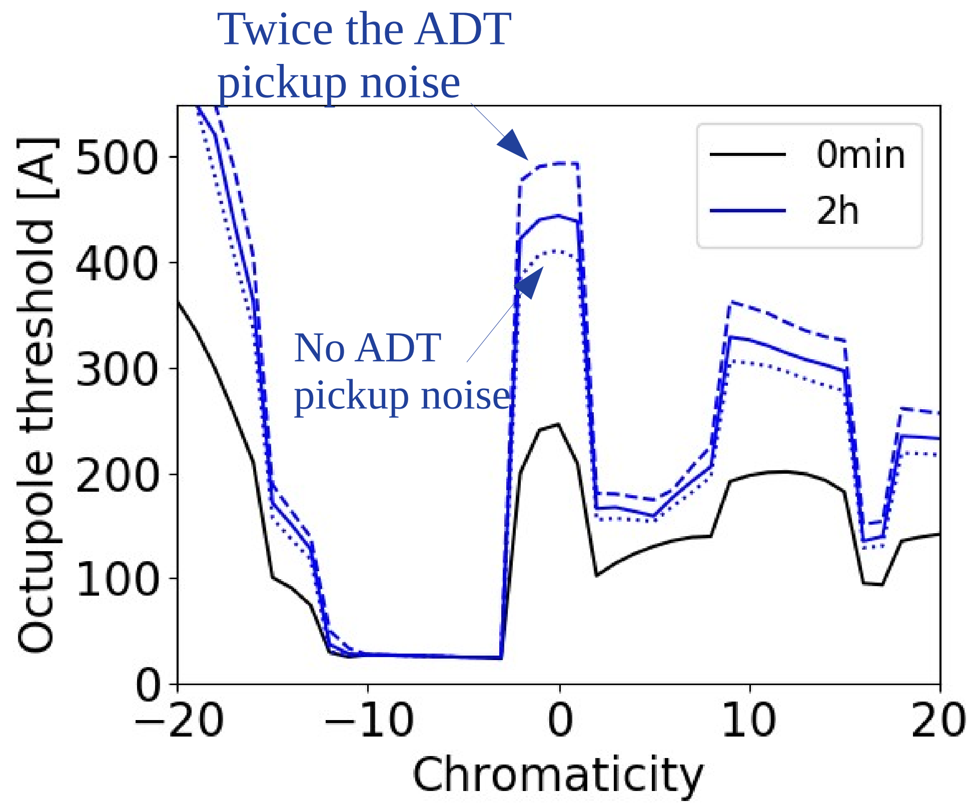


- At our ususal working point (Q'~15), the required octupole current is 50% larger than the 0-latency threshold
- Close to Q'~0, the factor reaches 100%

→This may explain (at least part of) the discrepancy observed experimentally in this range of chromaticities

Octupole threshold including the latency
chromaticity scan at 100 turns damping





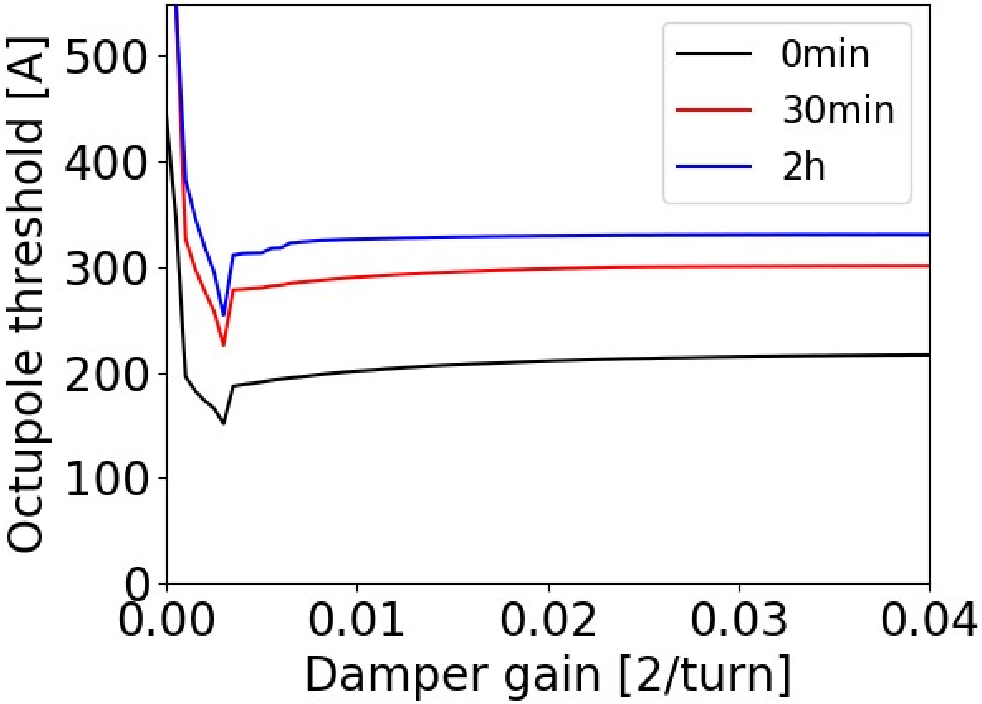
- At our ususal working point (Q'~15), the required octupole current is 50% larger than the 0-latency threshold
- Close to Q'~0, the factor reaches 100%

  → This may explain (at least part of) the discrepancy observed experimentally in this range of chromaticities

- The role of the damper pickup noise is rather marginal

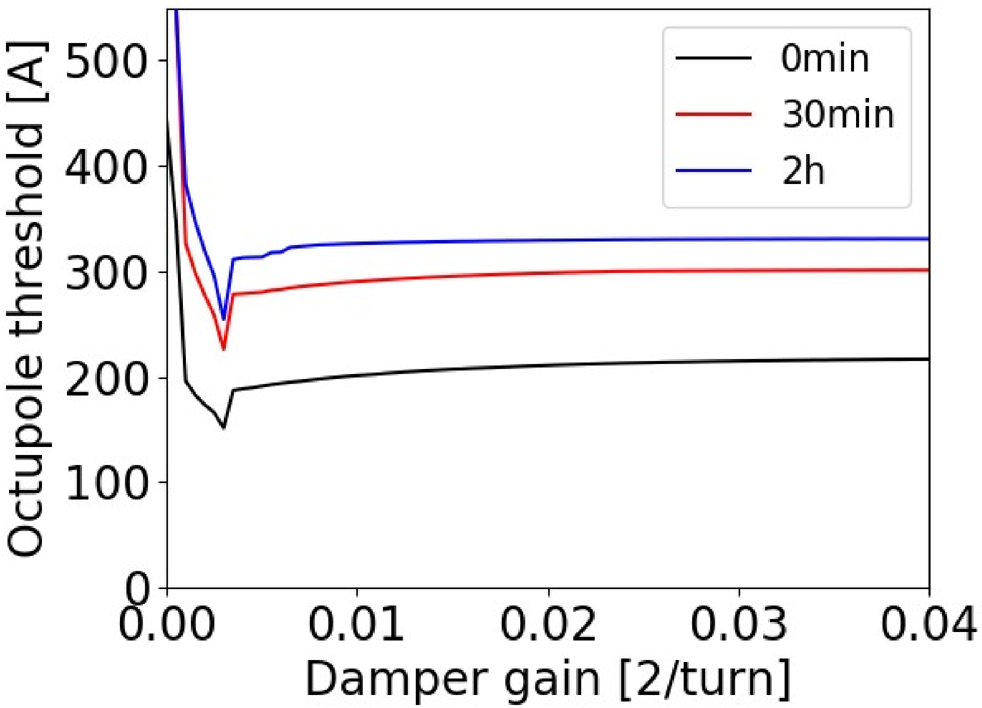
Octupole threshold including the latency

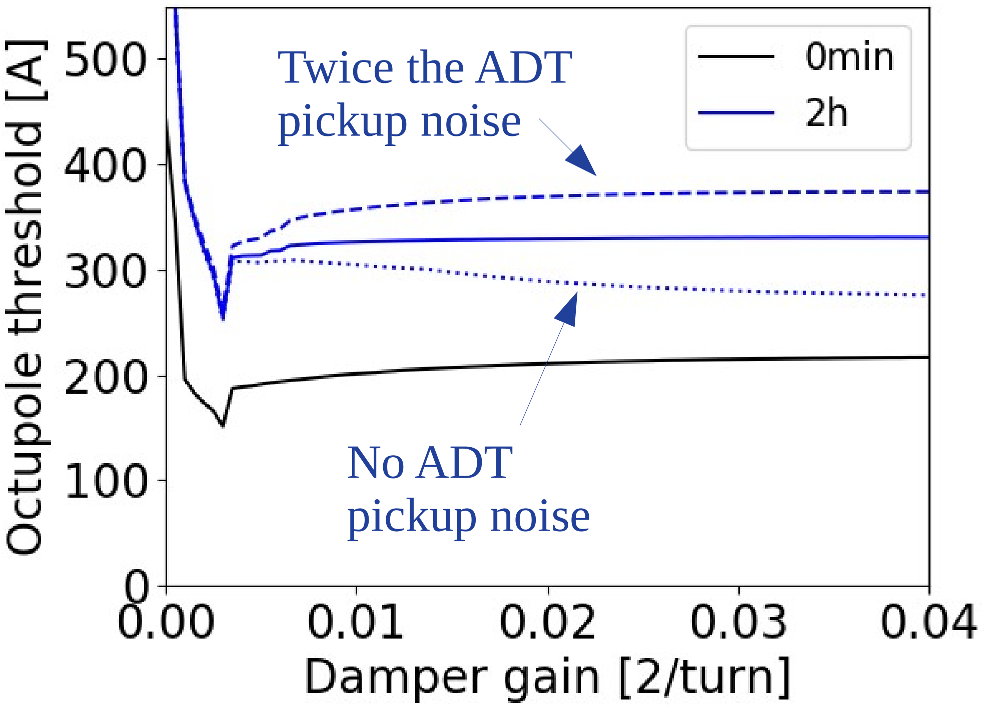
Gain scan with 10≤Q'≤20



- At high gains (i.e. damping times faster than 1000 turns), the octupole threshold is almost independent of the gain
  - The increase in pickup noise at high gain compensates the beneficial impact of the damper

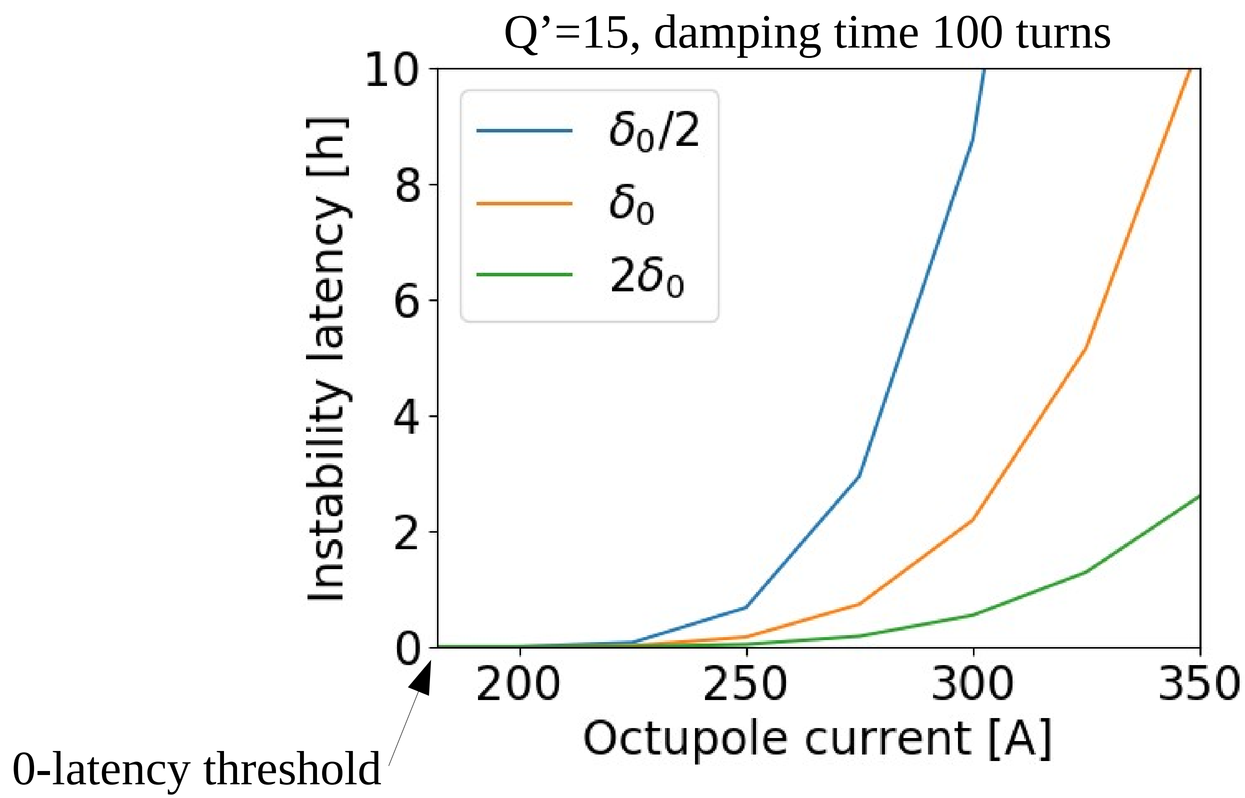
Octupole threshold including the latency
Gain scan with 10≤Q'≤20





- At high gains (i.e. damping times faster than 1000 turns), the octupole threshold is almost independent of the gain
  - The increase in pickup noise at high gain compensates the beneficial impact of the damper
- The role of the damper pickup noise remains rather marginal

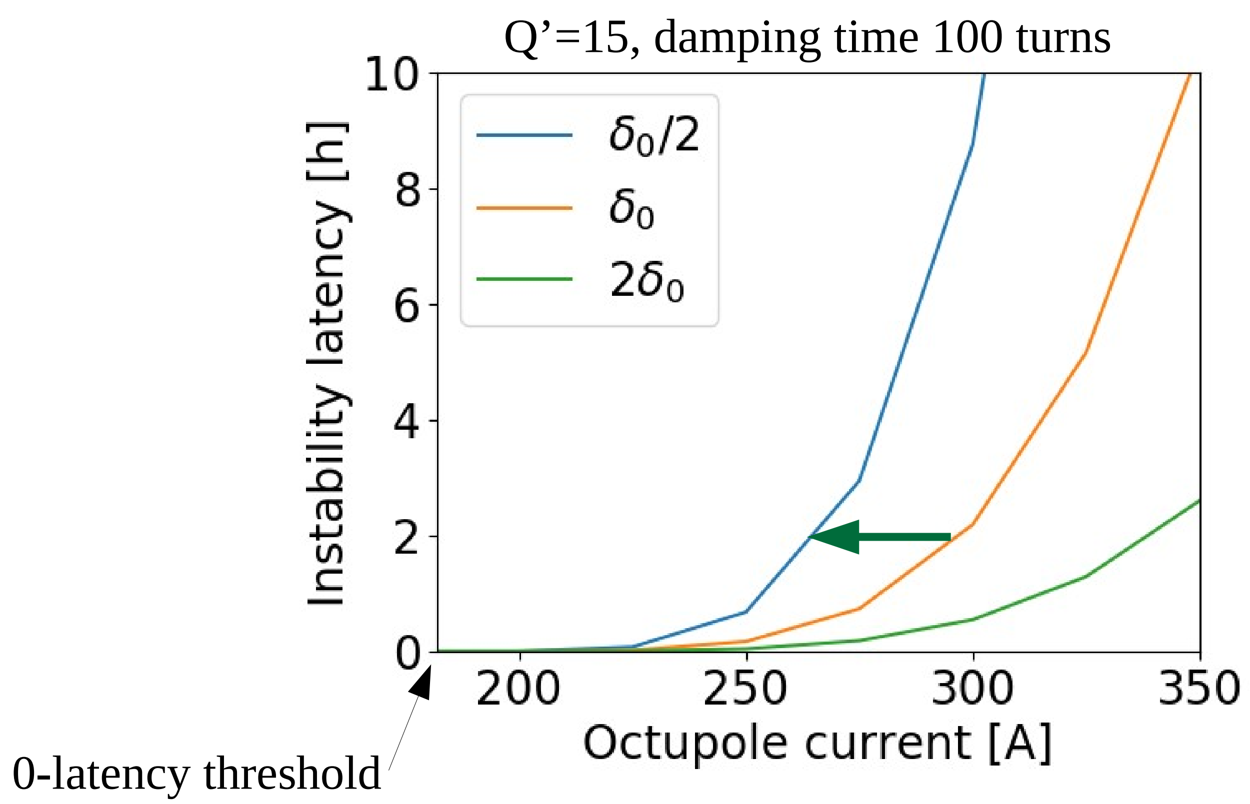
Instability latency



- Close to the threshold, the latency is a rather flat function of the octupole current

  → A reduction of the noise amplitude does not result in a proportional improvement in octupole threshold

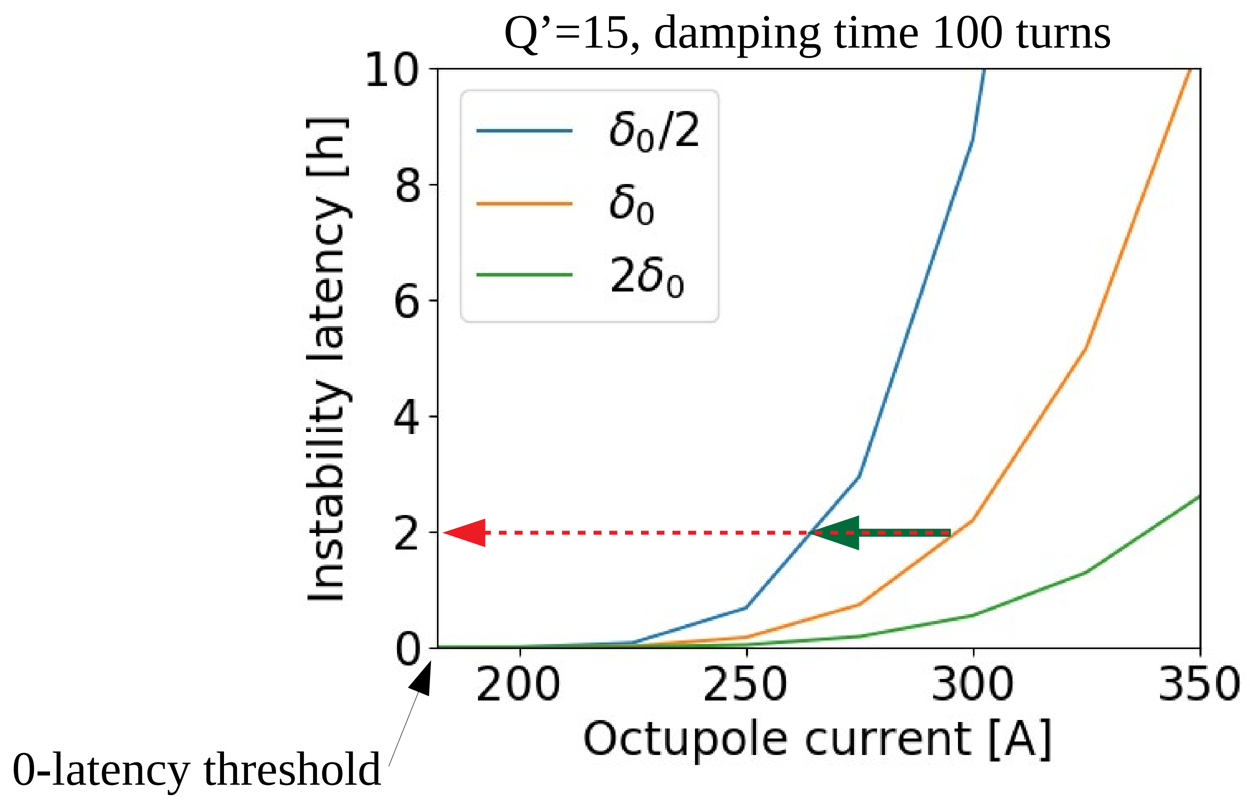
Instability latency



- Close to the threshold, the latency is a rather flat function of the octupole current

→ A reduction of the noise amplitude does not result in a proportional improvement in octupole threshold

Instability latency

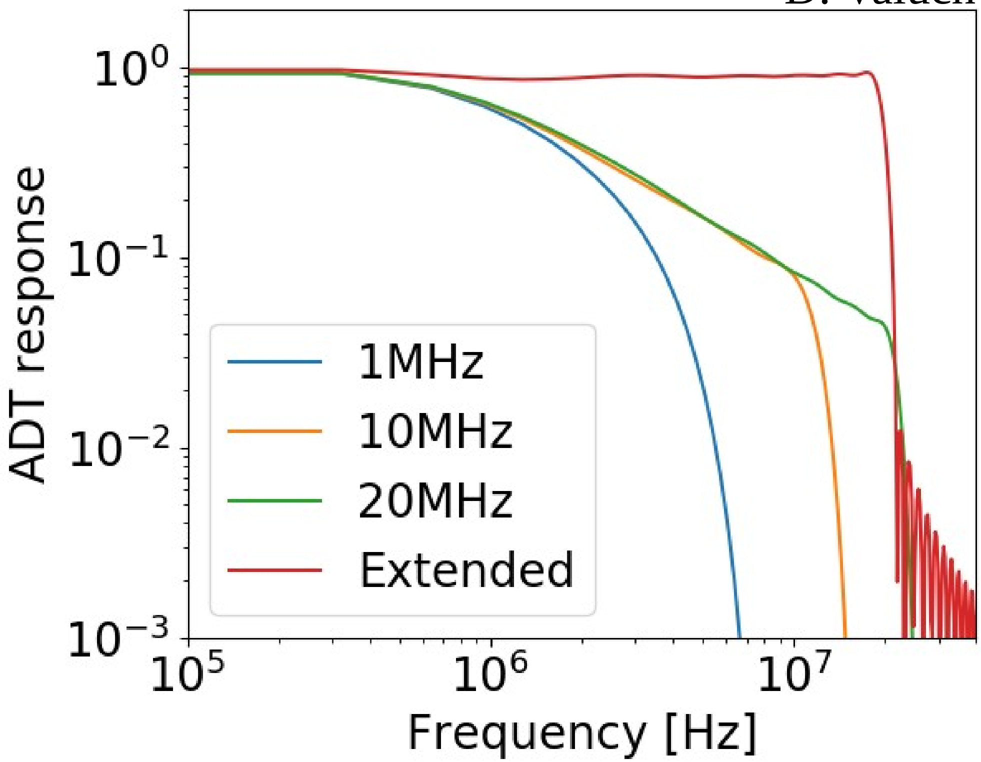


- Close to the threshold, the latency is a rather flat function of the octupole current

  → A reduction of the noise amplitude does not result in a proportional improvement in octupole threshold

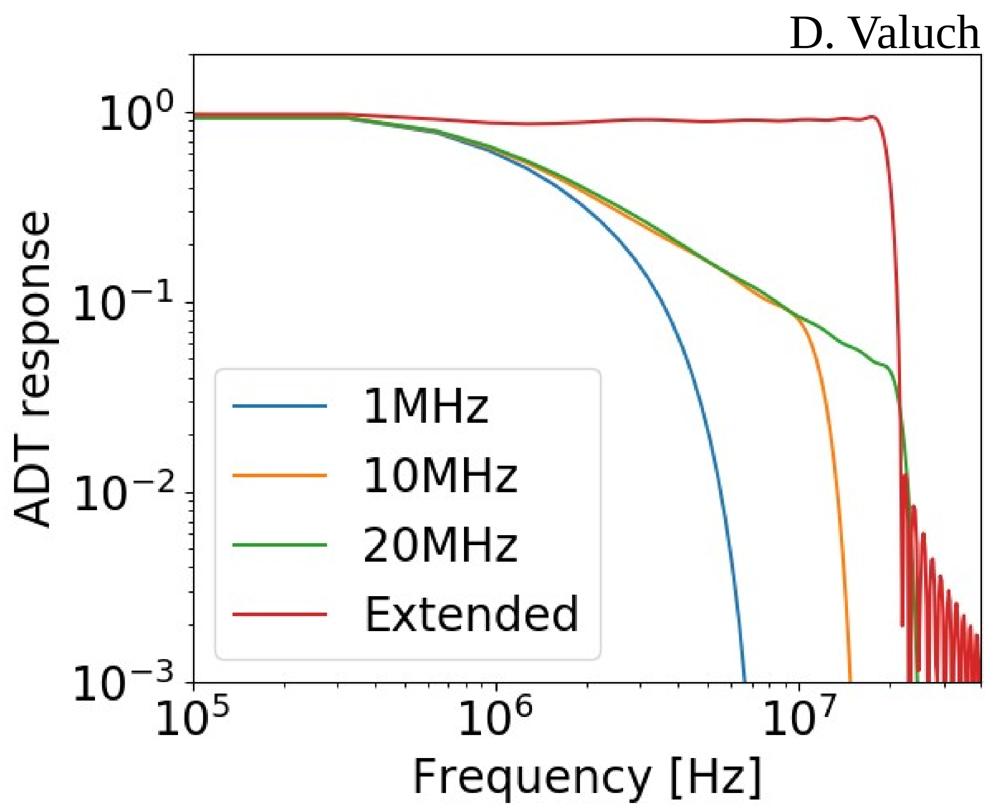
ADT bandwidth

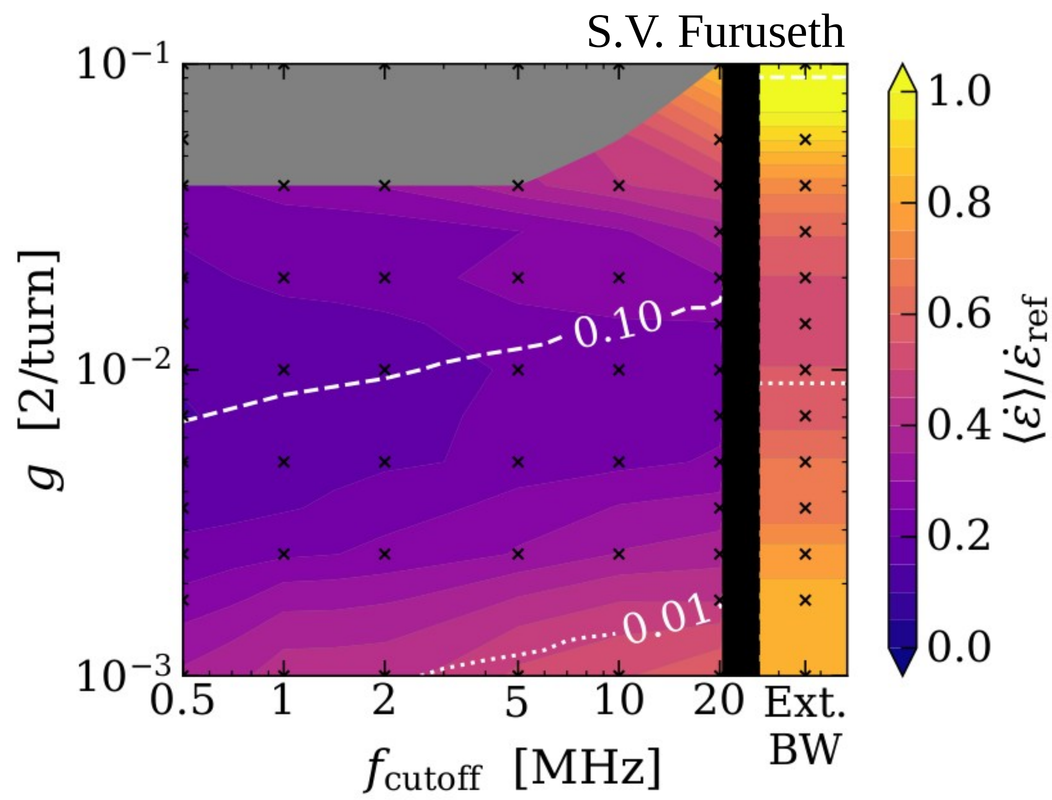
D. Valuch



- D. Valuch provided the ADT response with various filters:
  - The ‘Extended’ bandwidth featuring a flat response for all coupled bunch modes (i.e. up to 20MHz)
  - The ‘standard’ filters with bandwidth from 20MHz to 0.5 MHz

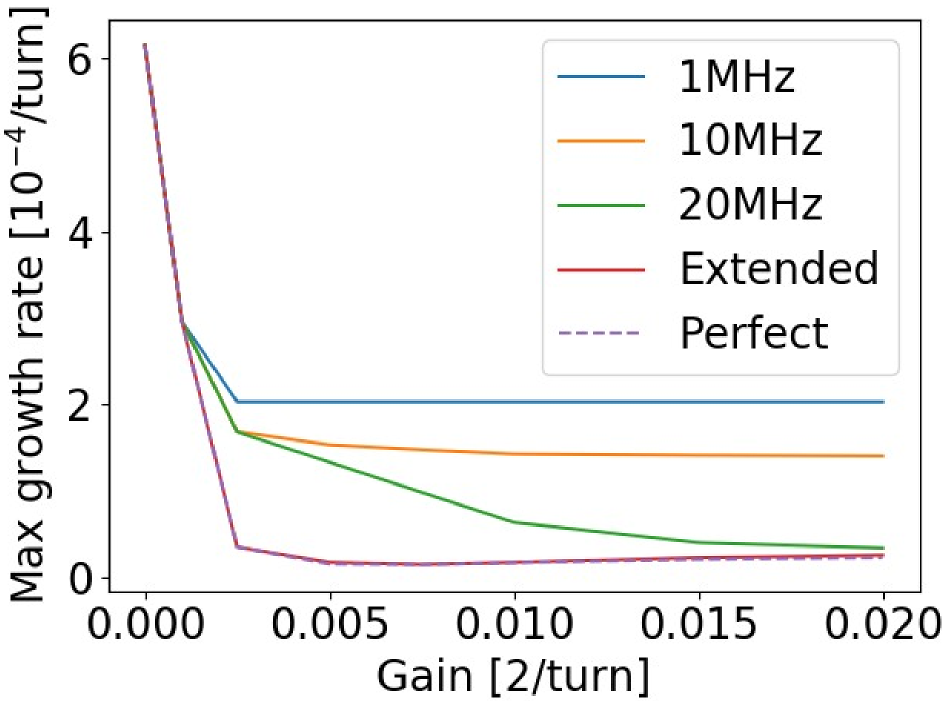
ADT bandwidth



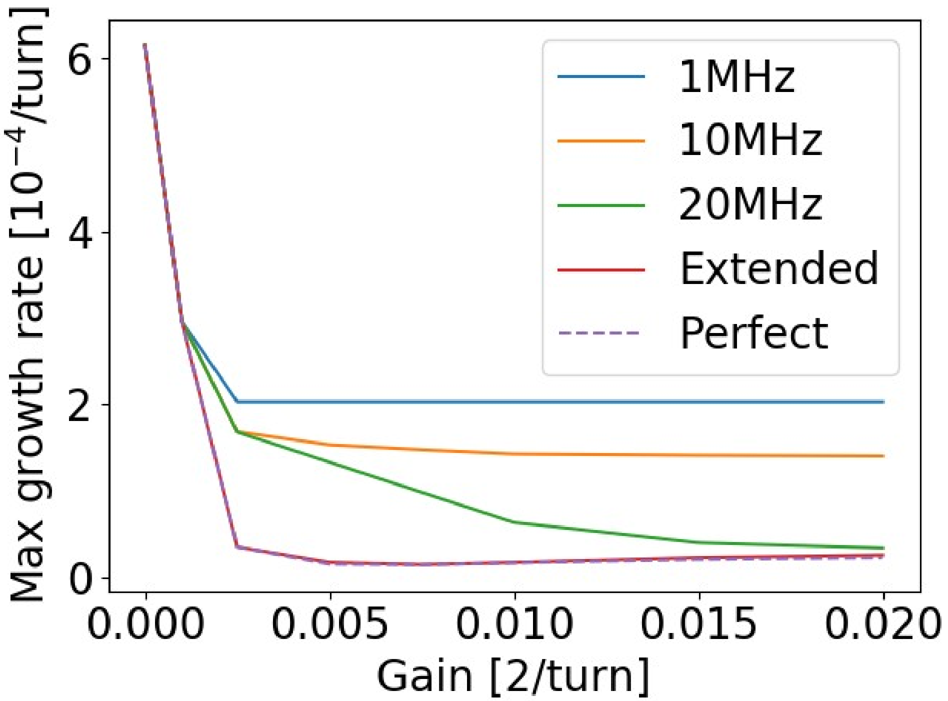


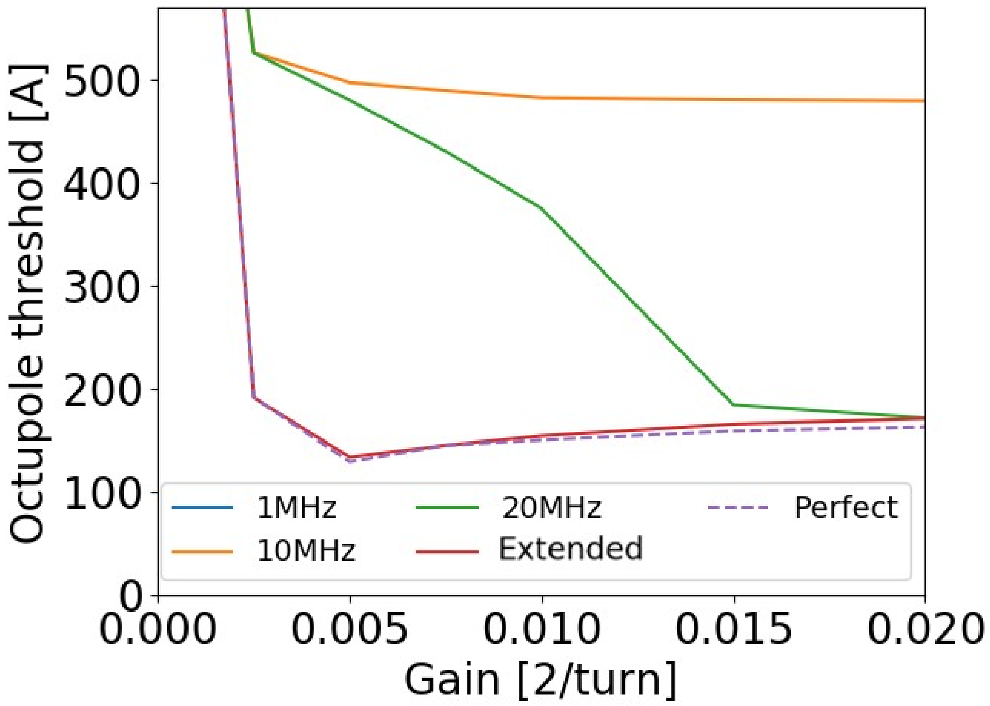
- D. Valuch provided the ADT response with various filters:
  - The ‘Extended’ bandwidth featuring a flat response for all coupled bunch modes (i.e. up to 20MHz)
  - The ‘standard’ filters with bandwidth from 20MHz to 0.5 MHz
- Low bandwidth can be interesting to limit the impact of the emittance growth driven by the ADT pickup noise on colliding beams

Gain requirement

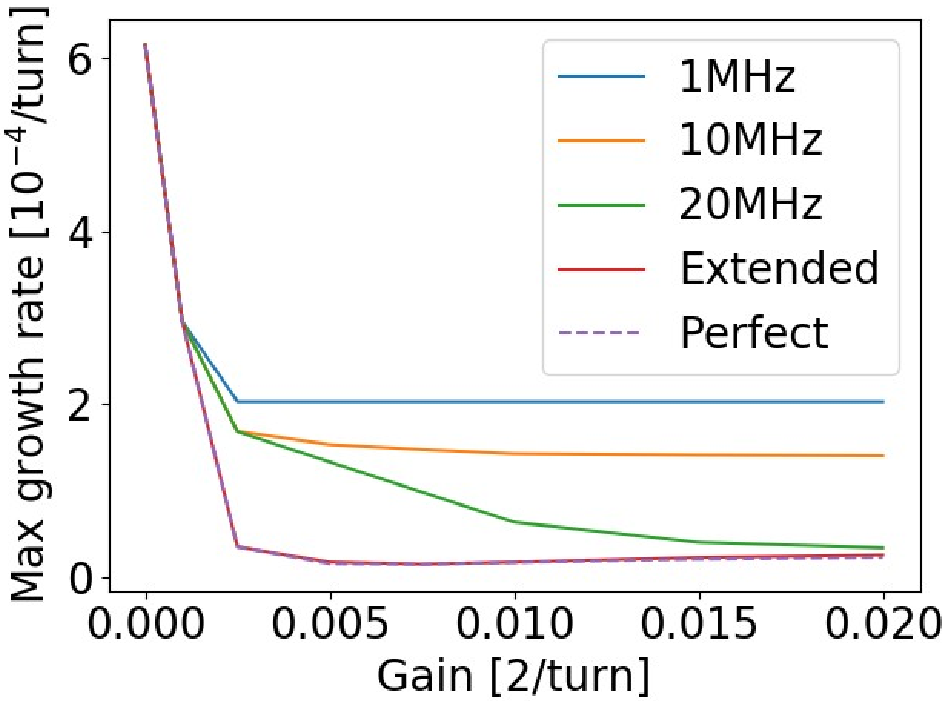


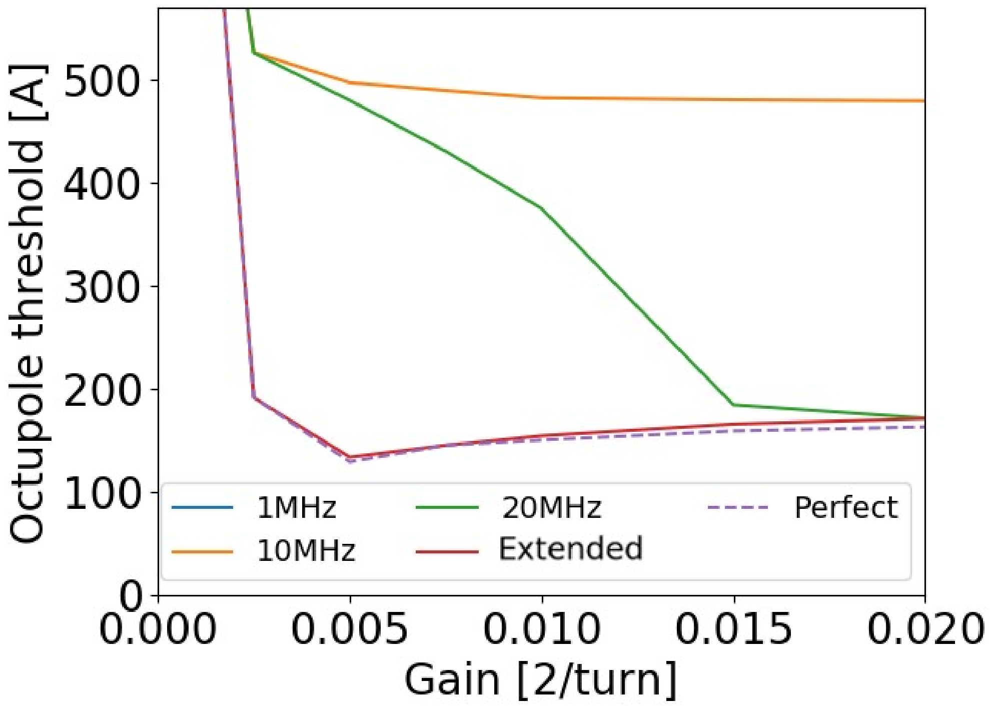
Gain requirement





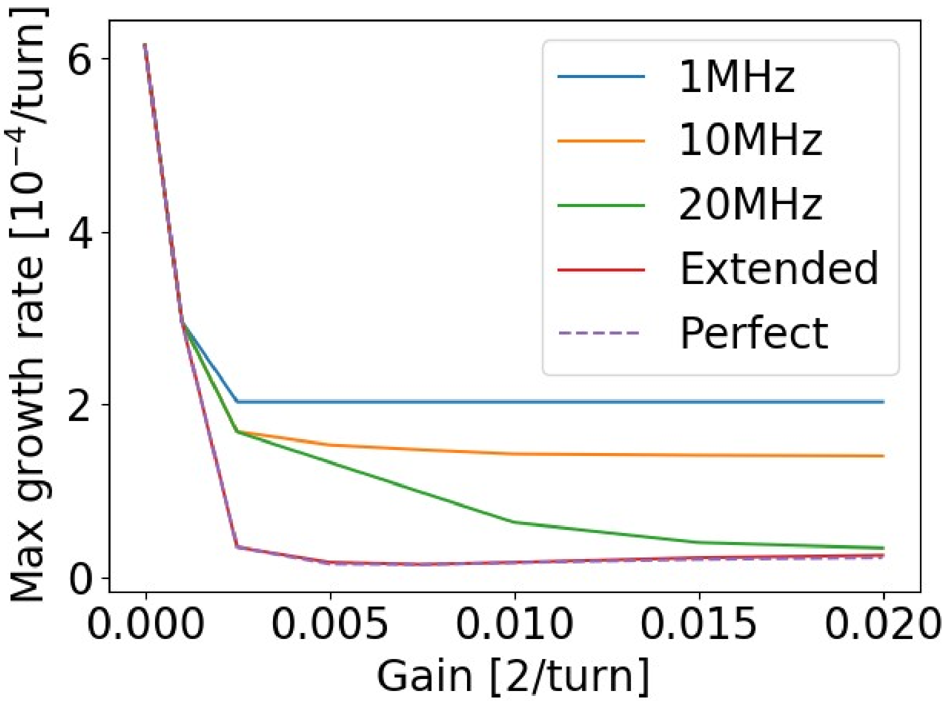
Gain requirement

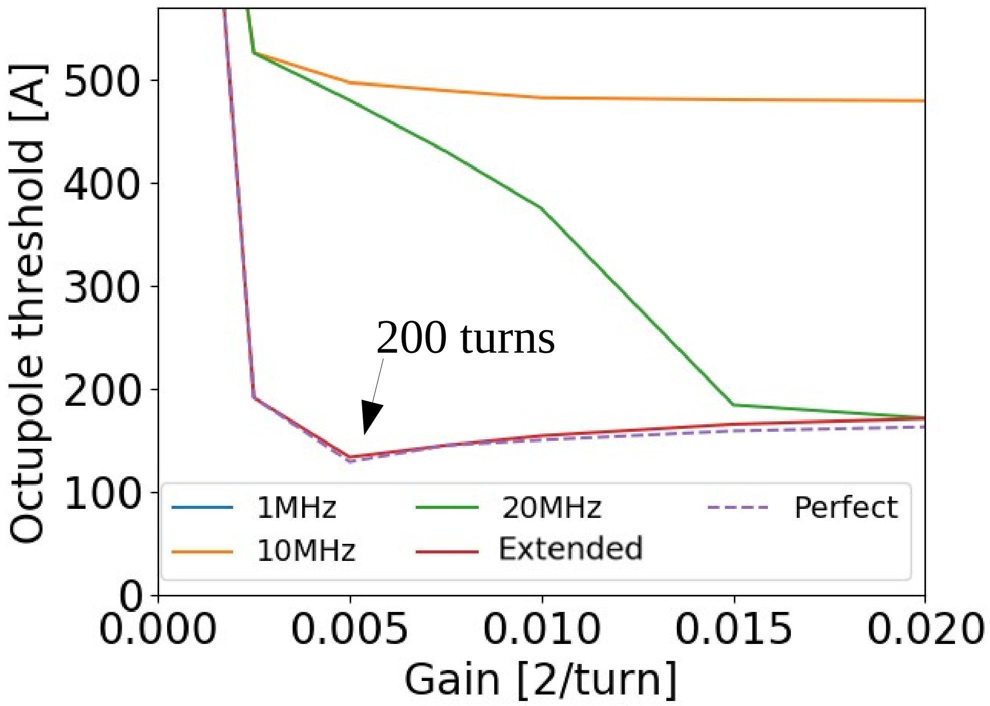




- The ‘extended’ bandwidth and the perfect damper yield quasi-identical results

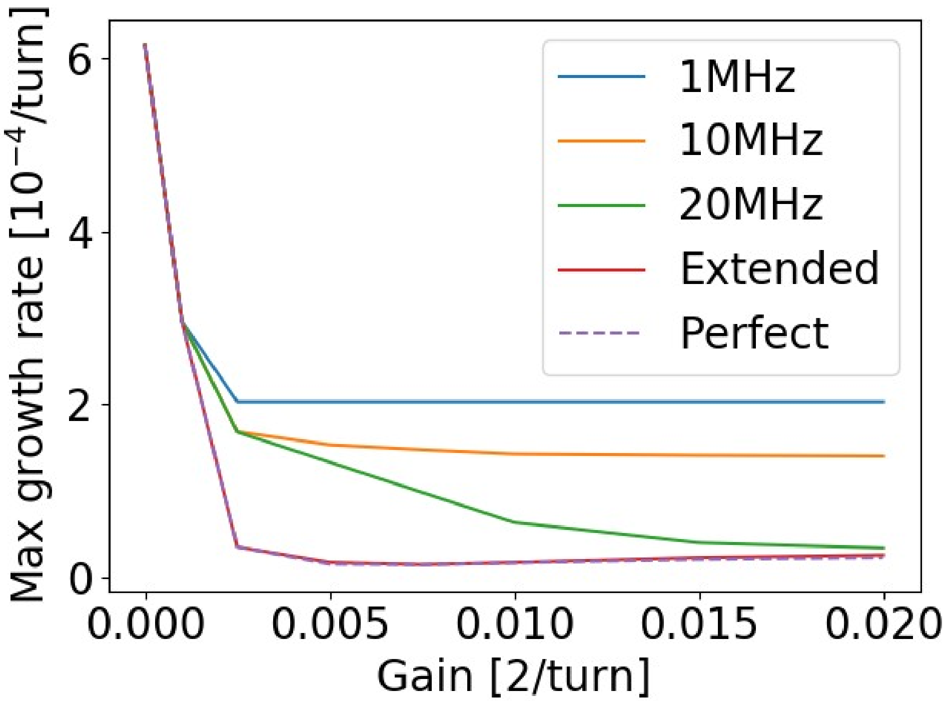
Gain requirement

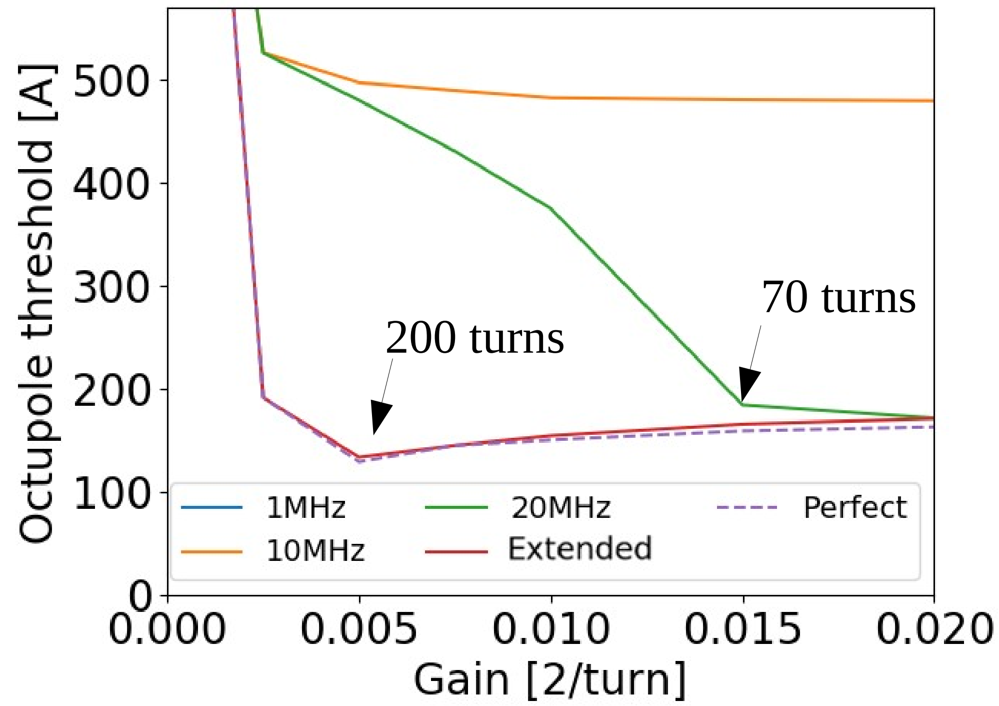




- The ‘extended’ bandwidth and the perfect damper yield quasi-identical results
  - The gain required to fully suppress the coupled bunch instability is about 200 turns

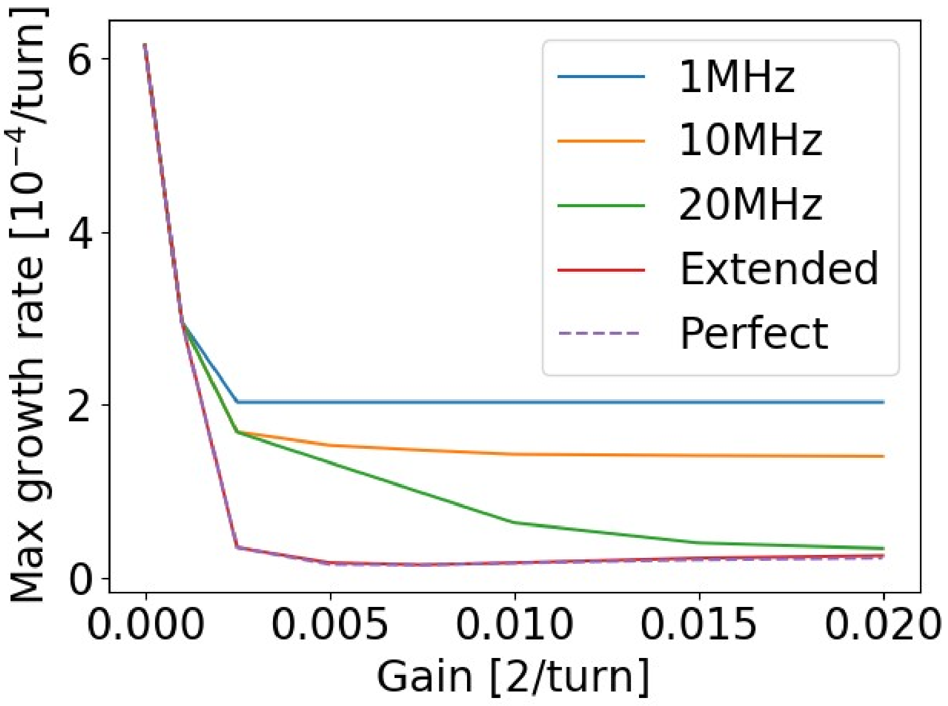
Gain requirement

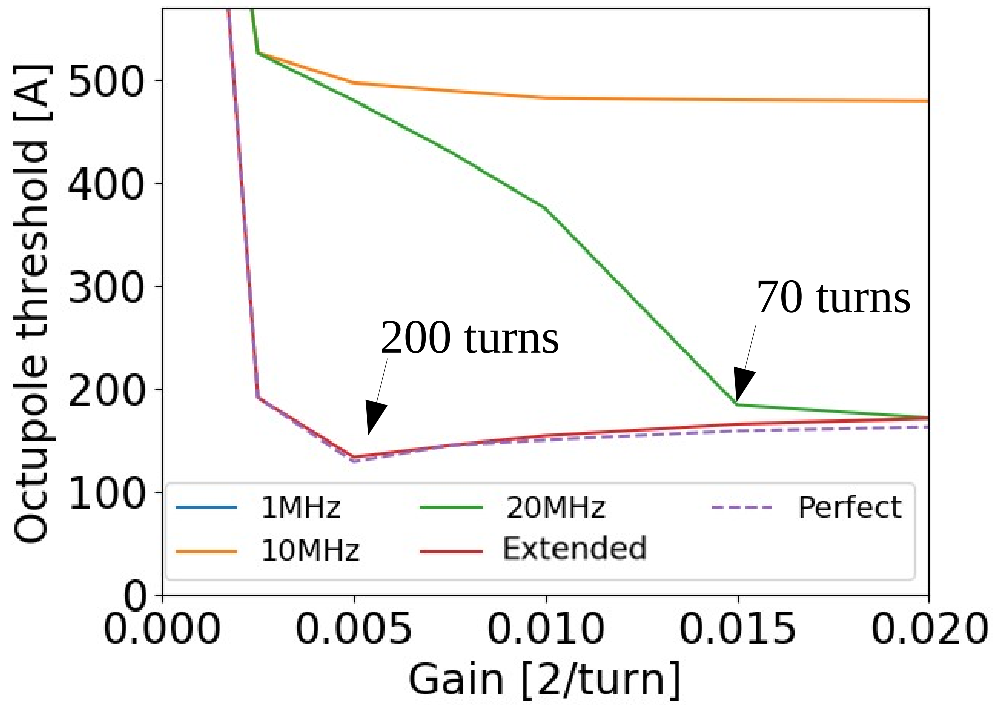




- The ‘extended’ bandwidth and the perfect damper yield quasi-identical results
  - The gain required to fully suppress the coupled bunch instability is about 200 turns
- With the 20MHz bandwidth, at least 70 turns is needed

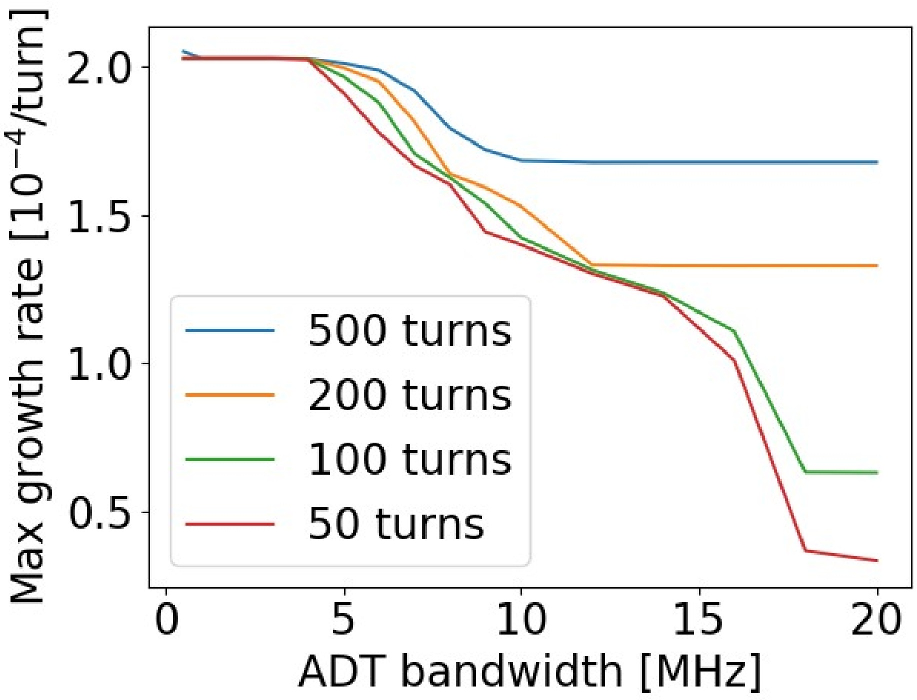
Gain requirement

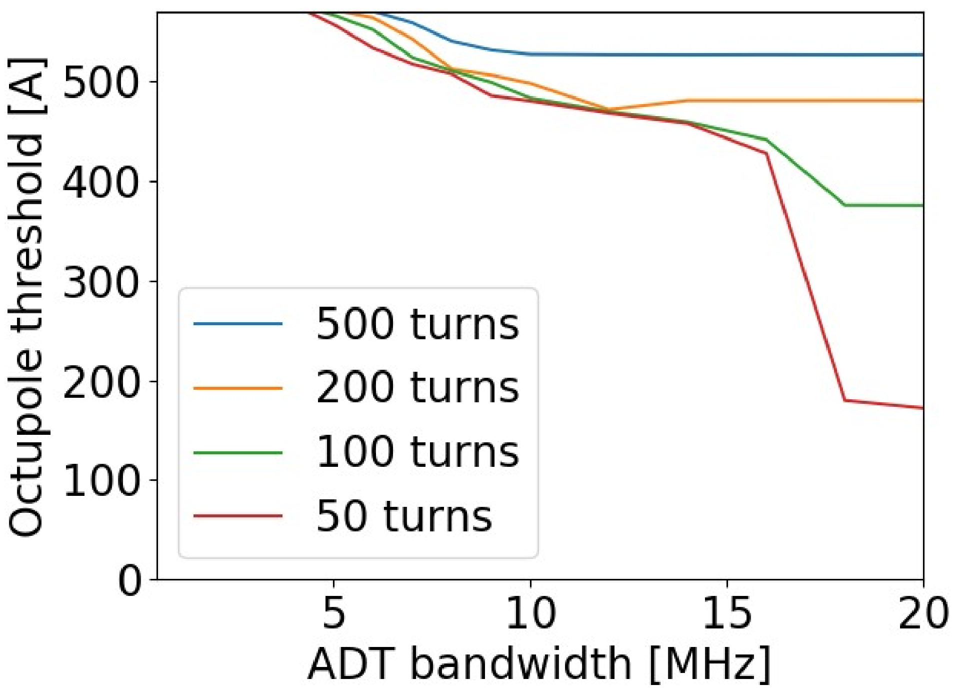




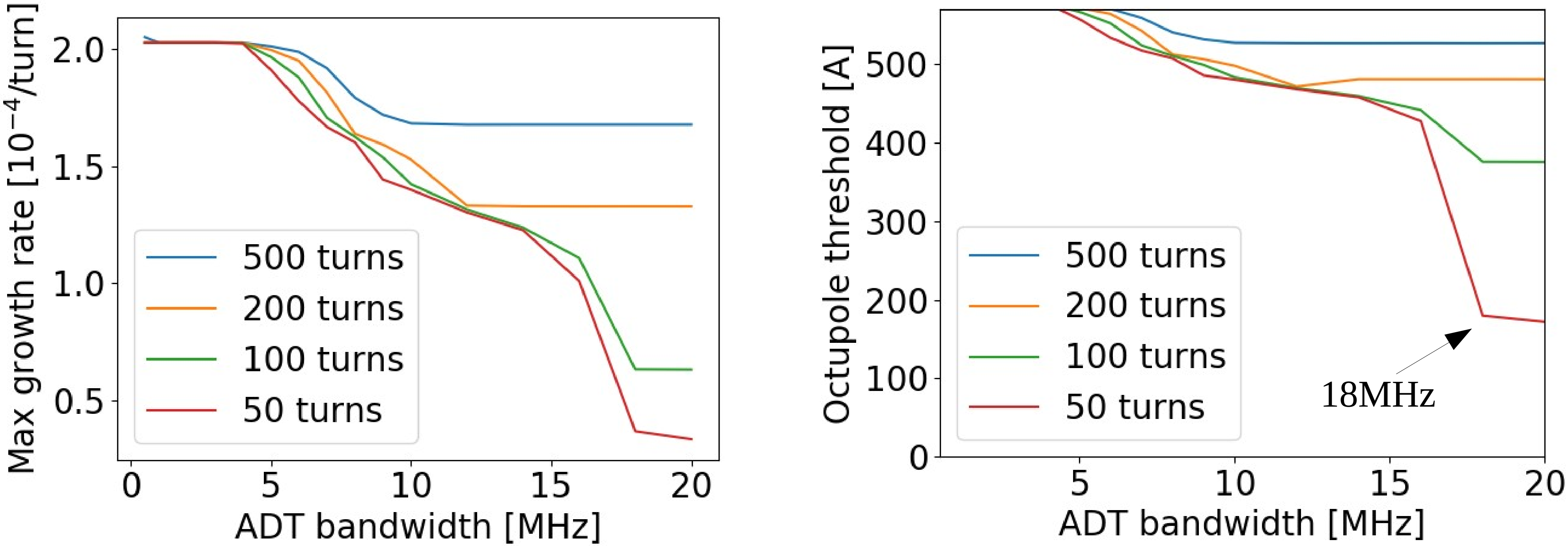
- The ‘extended’ bandwidth and the perfect damper yield quasi-identical results
  - The gain required to fully suppress the coupled bunch instability is about 200 turns
- With the 20MHz bandwidth, at least 70 turns is needed
- Due to the large imaginary and real tune shift of the coupled bunch instabilities, the need for octupole increases strongly if it is not properly suppressed

Bandwidth requirement



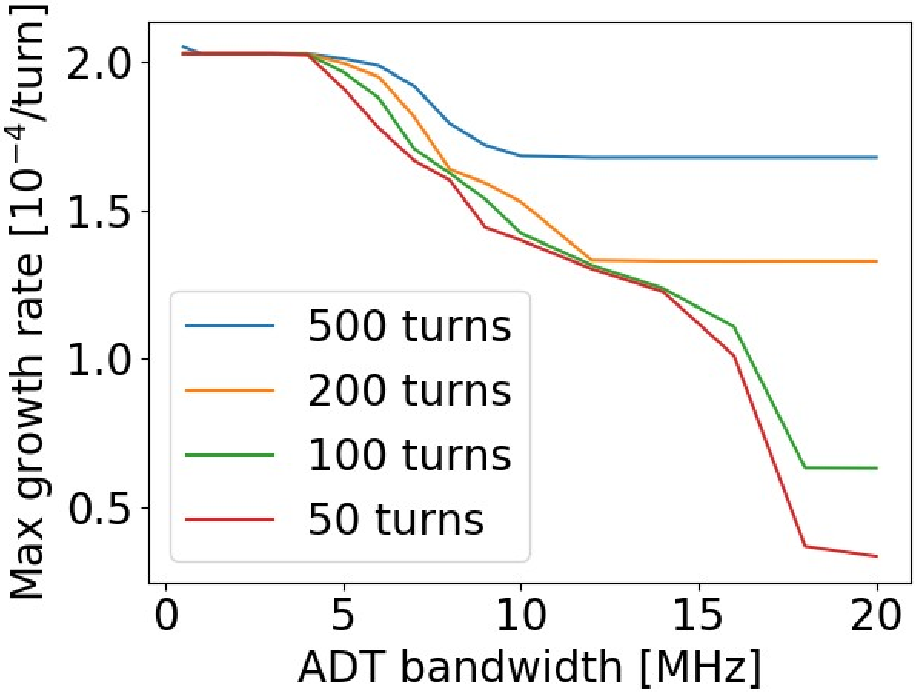


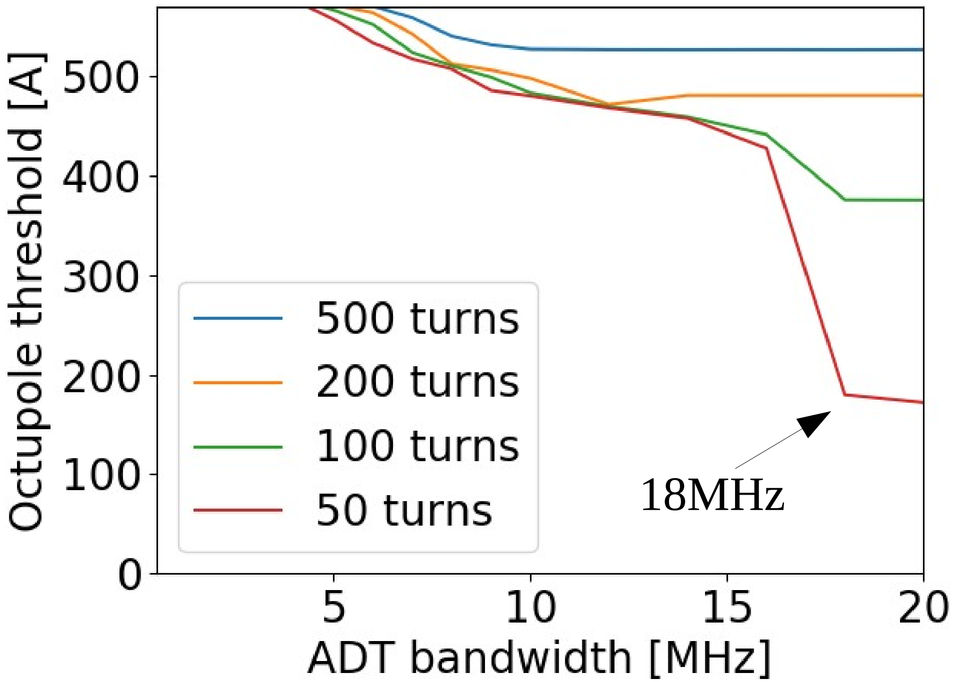
Bandwidth requirement



- A full suppression can be achieved with damping time below 50 turns and bandwidth about 18MHz

Bandwidth requirement

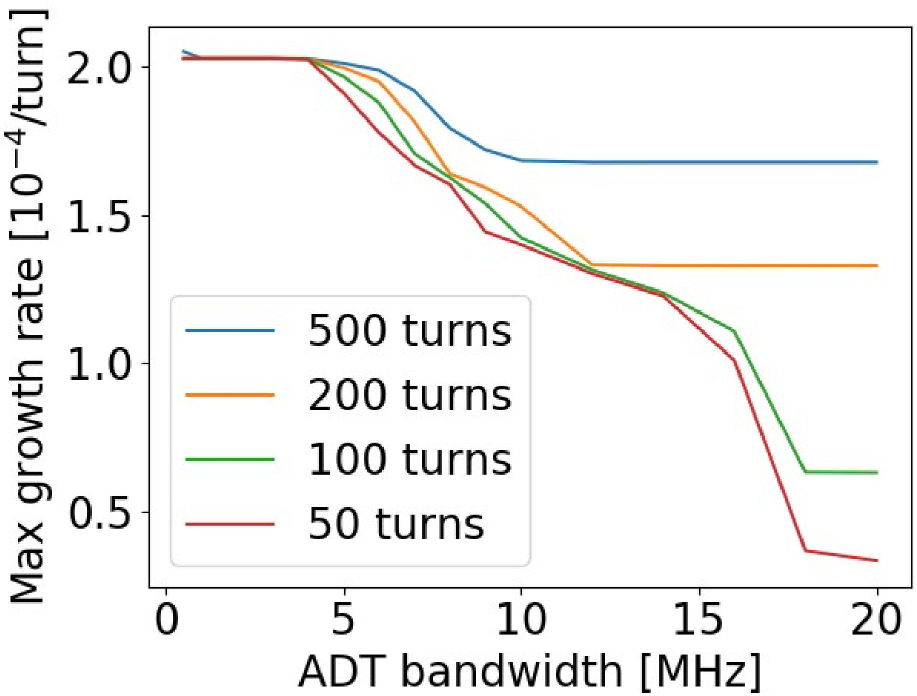


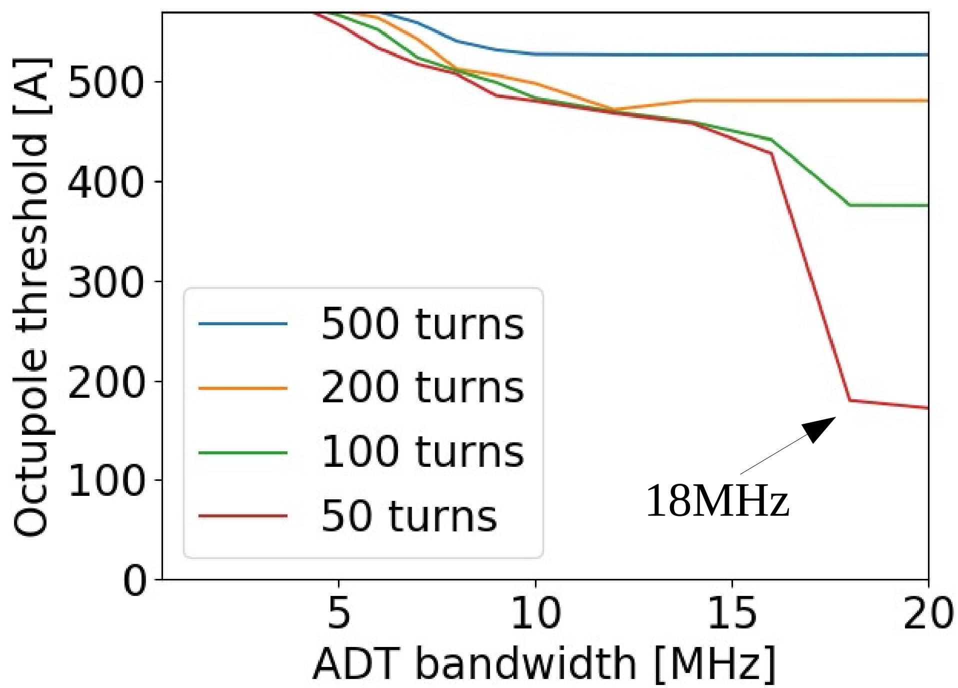


- A full suppression can be achieved with damping time below 50 turns and bandwidth about 18MHz

  → The current strategy with ‘Extended’ bandwidth during the cycle and ‘standard’ 20MHz during collision seems adequate also for Run 3

Bandwidth requirement





- A full suppression can be achieved with damping time below 50 turns and bandwidth about 18MHz

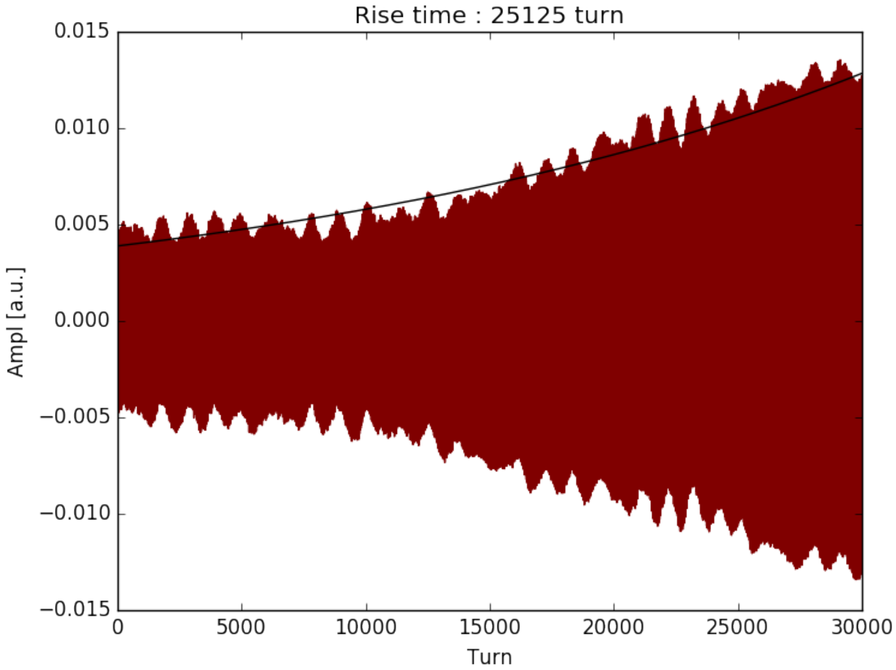
  → The current strategy with ‘Extended’ bandwidth during the cycle and ‘standard’ 20MHz during collision seems adequate also for Run 3

- Operating with a lower bandwidth in collision requires a detailed study of the coupled-bunch coupled-beam (CB^2) instability

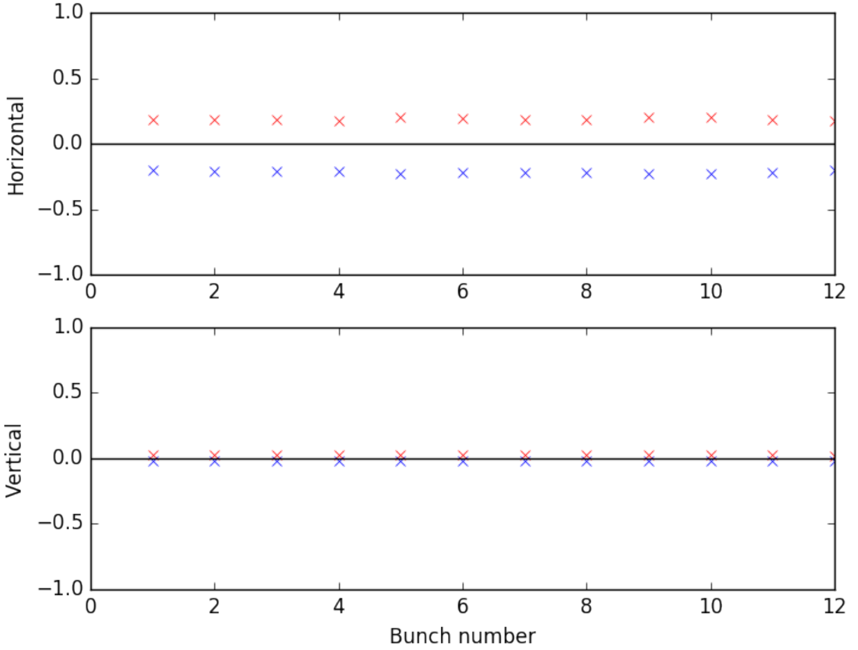
The CB² instability

X.Buffat, et al., Expectations and observations during ADJUST
@ 1/2-day internal review of LHC performance limitations (linked to transverse collective effects) during run II (2015-2016)

- During an ‘end of MD MD’ in 2016, the beams were dumped on an instability featuring perfect correlation in the motion of all bunches in both beams during a separation scan with the ADT off



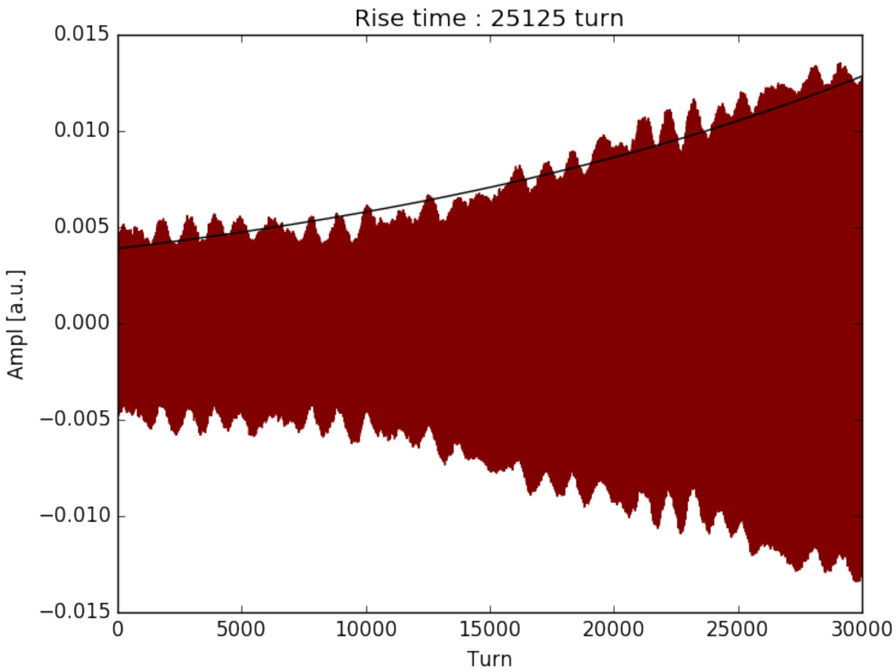
SVD of bunch by bunch turn by position from the ObsBox (Post Mortem)



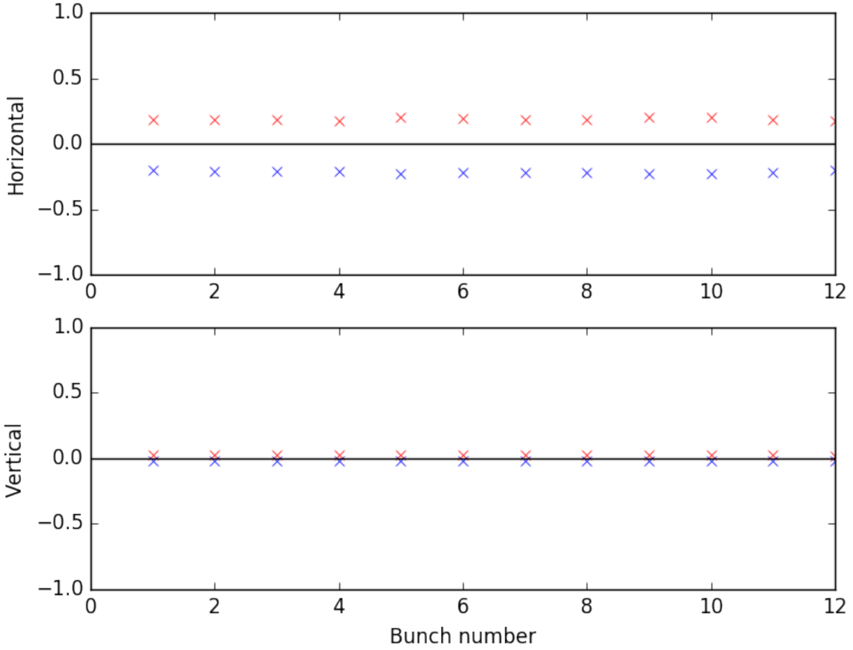
The CB^2 instability

X.Buffat, et al., Expectations and observations during ADJUST
@ 1/2-day internal review of LHC performance limitations (linked to transverse collective effects) during run II (2015-2016)

- During an ‘end of MD MD’ in 2016, the beams were dumped on an instability featuring perfect correlation in the motion of all bunches in both beams during a separation scan with the ADT off

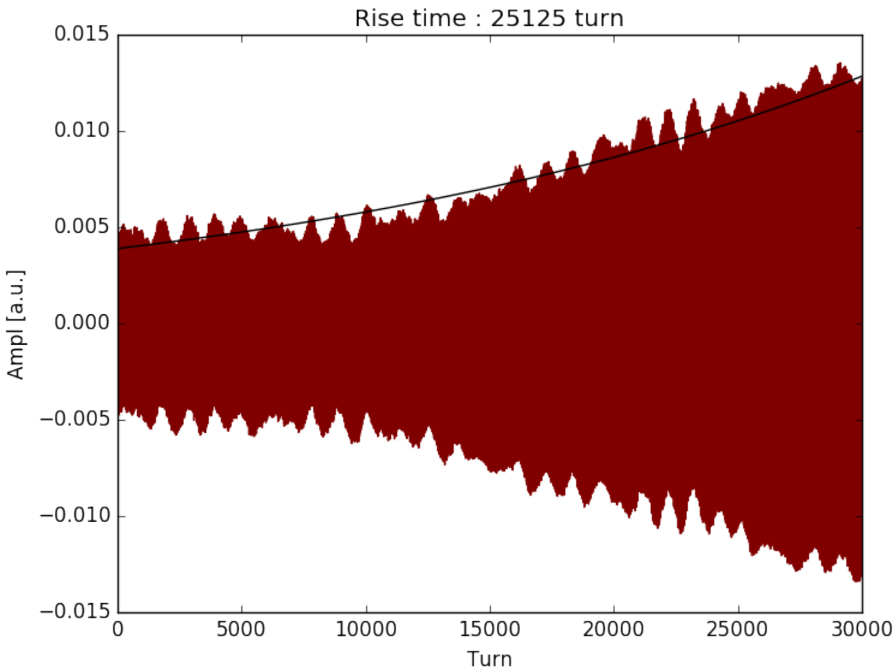


SVD of bunch by bunch turn by position from the ObsBox (Post Mortem)

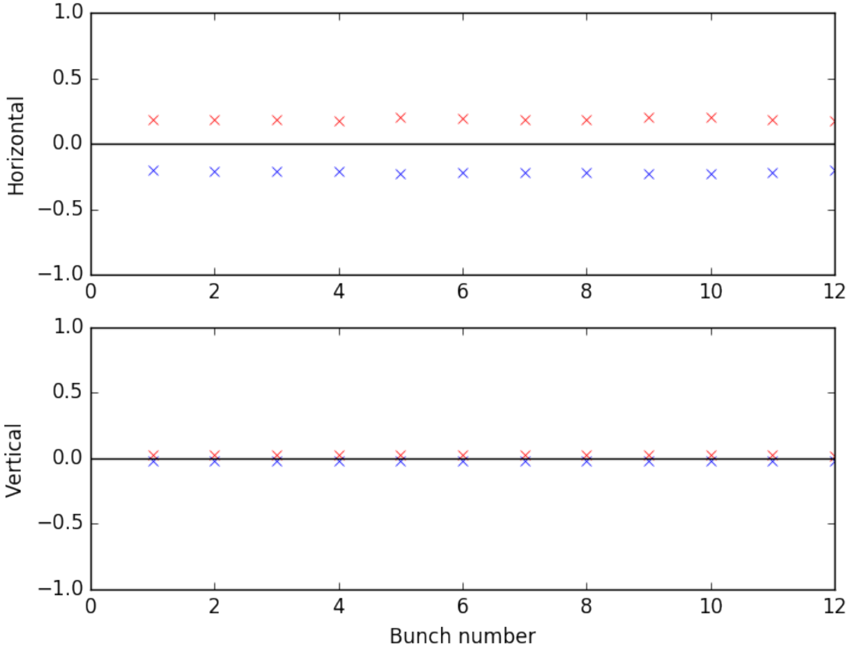


- Similarly to the single beam coupled bunch instability, the CB^2 will not be damped by the ADT with a too low bandwidth

- During an ‘end of MD MD’ in 2016, the beams were dumped on an instability featuring perfect correlation in the motion of all bunches in both beams during a separation scan with the ADT off



SVD of bunch by bunch turn by position from the ObsBox (Post Mortem)



- Similarly to the single beam coupled bunch instability, the CB^2 will not be damped by the ADT with a too low bandwidth
- Similarly to the single bunch π-mode, it is likely not stabilised by Landau damping

Conclusion

- Depending on the chromaticity, the octupole current that allows for a latency of 2h varies between 1.1 and 2 times the stability threshold without noise
  - For the usual working point (100 turns damping, Q' ≈ 10-15), the factor is about 1.5
  - For damping times lower than 1000 turns and Q' ≈ 10-15, the octupole threshold for single bunches is almost independent of the gain
  - Operating with a Q' ≈ 5 seem optimal from the point of view of octupole requirement and should be further investigated

Conclusion

- Depending on the chromaticity, the octupole current that allows for a latency of 2h varies between 1.1 and 2 times the stability threshold without noise
  - For the usual working point (100 turns damping, Q’ ≈ 10-15), the factor is about 1.5
  - For damping times lower than 1000 turns and Q’ ≈ 10-15, the octupole threshold for single bunches is almost independent of the gain
  - Operating with a Q’ ≈ 5 seem optimal from the point of view of octupole requirement and should be further investigated
- Reductions of the damper bandwidth in collision below 20MHz could be beneficial in terms of mitigation of the emittance growth driven by the ADT pickup noise, nevertheless the stability of the CB^2 instability seems problematic → to be investigated

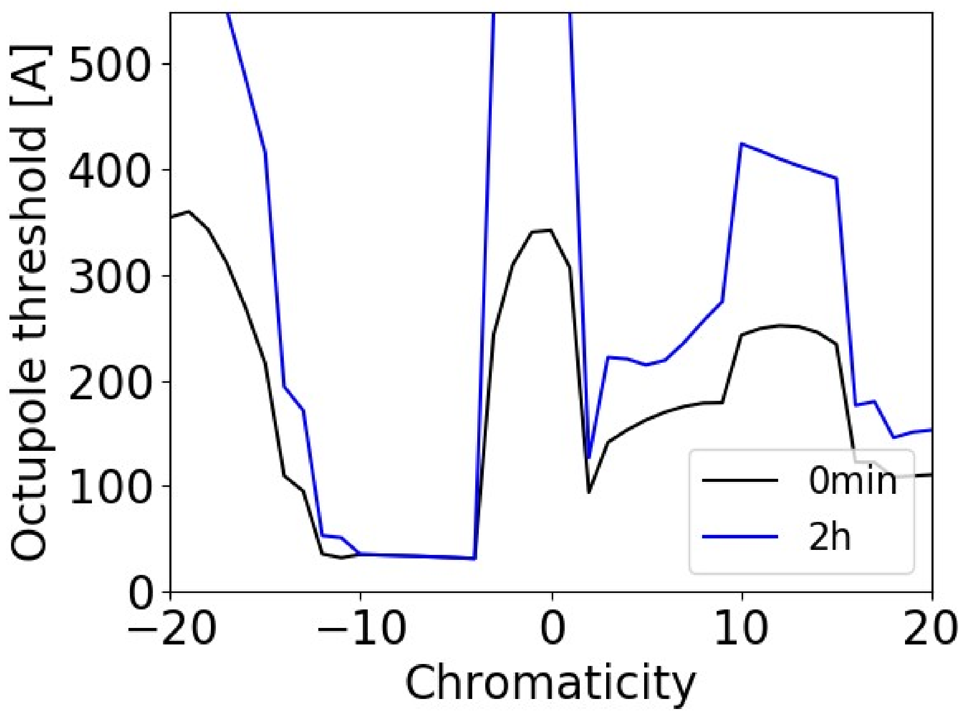
Conclusion

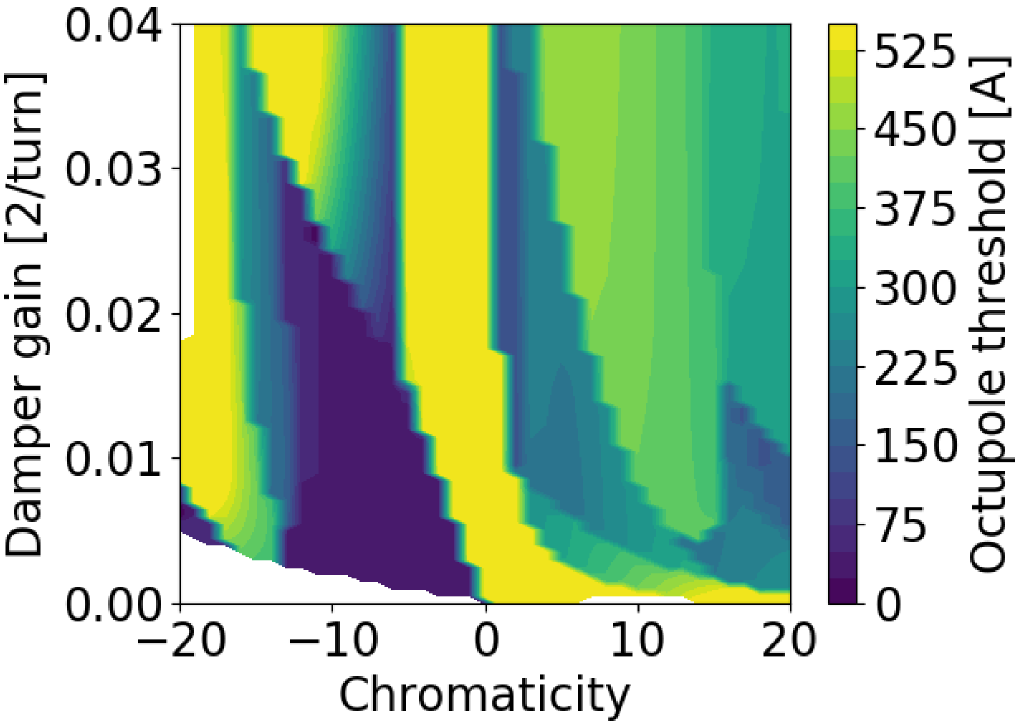
- Depending on the chromaticity, the octupole current that allows for a latency of 2h varies between 1.1 and 2 times the stability threshold without noise
  - For the usual working point (100 turns damping, Q' ≈ 10-15), the factor is about 1.5
  - For damping times lower than 1000 turns and Q' ≈ 10-15, the octupole threshold for single bunches is almost independent of the gain
  - Operating with a Q' ≈ 5 seem optimal from the point of view of octupole requirement and should be further investigated
- Reductions of the damper bandwidth in collision below 20MHz could be beneficial in terms of mitigation of the emittance growth driven by the ADT pickup noise, nevertheless the stability of the CB^2 instability seems problematic → to be investigated
- Proposal for Run 3:
  - Define the recommendations in terms of 2h-threshold including the uncertainty on the impedance model, rather than the 'factor 2'
  - Maintain the strategy to operate the cycle with 'Enhanced' bandwidth and enable the 20MHz bandwidth once in collision.

Conclusion

- Depending on the chromaticity, the octupole current that allows for a latency of 2h varies between 1.1 and 2 times the stability threshold without noise
  - For the usual working point (100 turns damping, Q' ≈ 10-15), the factor is about 1.5
  - For damping times lower than 1000 turns and Q' ≈ 10-15, the octupole threshold for single bunches is almost independent of the gain
  - Operating with a Q' ≈ 5 seem optimal from the point of view of octupole requirement and should be further investigated
- Reductions of the damper bandwidth in collision below 20MHz could be beneficial in terms of mitigation of the emittance growth driven by the ADT pickup noise, nevertheless the stability of the CB^2 instability seems problematic → to be investigated
- Proposal for Run 3:
  - Define the recommendations in terms of 2h-threshold including the uncertainty on the impedance model, rather than the 'factor 2'
  - Maintain the strategy to operate the cycle with 'Enhanced' bandwidth and enable the 20MHz bandwidth once in collision.
- Next step : Implementation of the computation of η, ΔQ_{SD} and the latency in the IRIS framework (i.e. in DELPHI) and benchmark against BimBim

HL-LHC intensity in Run 3





Mitigation of the coupled bunch instability