Powering schemes for inner triplet

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Outline

1. Requirements for power converters:
   a) stability and resolution
   b) ripple spectrum
2. Comparison of proposed powering scheme and possible alternatives
3. Ripple tolerances and dynamic aperture studies:
4. Conclusion
5. Further studies

Requirements for power converters

Requirements for power converters

a) Stability and resolution are given in terms of relative current error.

For the HL-LHC the following tolerances can be achieved
(J.-P. Burnet, M. Bastos, Q. King):

resolution: $\Delta I/I_{max} = 0.25\times10^{-6}$, I_{max} = max. current of power supply = 20kA

stability: $\Delta I/I_{max} = 1.0\times10^{-6}$ over 24h

They can be seen as random noise in the <1Hz range

b) Due to the different components of a power converter and the power grid itself, certain frequencies are present in the current spectrum in general referred to as

"power supply ripple frequencies"

The tolerances for the different frequencies are usually given in terms of voltage

Model of the field ripple

Magnetic field seen by the beam:

$$B(f) = T_{\rm Vacuum}(f) \times T_{\rm ItoB}(f) \times T_{\rm VtoI,load}(f) \times V_{\rm PC}(f)$$

with

$V_{\rm PC}(f)$ Voltage ripple (Power converter specifications)

$T_{\rm VtoI,load}(f)$ Transfer function of the load (circuit) seen by the power converter

$T_{\rm ItoB}$ Transfer function from the input current of the magnet to the magnetic field (assumed constant)

$T_{\rm Vacuum}(f)$ Transfer function of the cold bore, absorber, beam screen etc. (input from WP3 needed), $T_{Vacuum} \leq 1$

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Expected voltage spectrum for HL-LHC

expected V_{PC}: from J.-P. Burnet and H. Thiesen

- 50 Hz harmonics (main grid):

  50 Hz: 3.2 mV R.M.S.
  100Hz: 0.8 mV R.M.S.

- 300 Hz harmonics (diode rectifier):

  300 Hz: 10.0 mV R.M.S.
  600 Hz: 2.5 mV R.M.S.

- 20 kHz harmonics (ITPT converters):

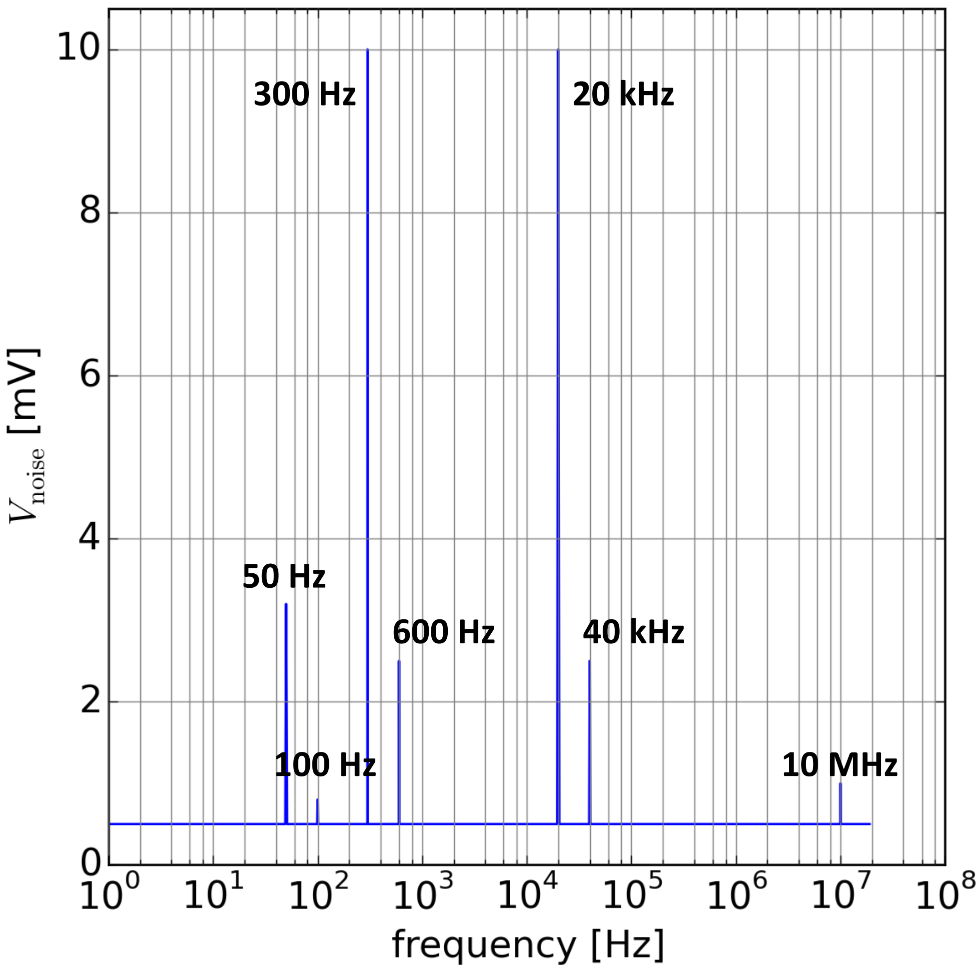
  20 kHz: 10.0 mV R.M.S.
  40 kHz: 2.5 mV R.M.S.

- 10 MHz harmonics:

  10 MHz: 1.0 mV R.M.S. (0.5 mV)

- all other frequencies:

  0.5 mV R.M.S



Expected spectrum of the magnetic field

$T_{Vtol,load}$: LHC magnets modeled as RL circuit

$$I_{\text{noise}}(f) = \frac{V_{\text{noise}}(f)}{|R_{\text{tot}} + 2\pi i f L_{\text{tot}}|}$$

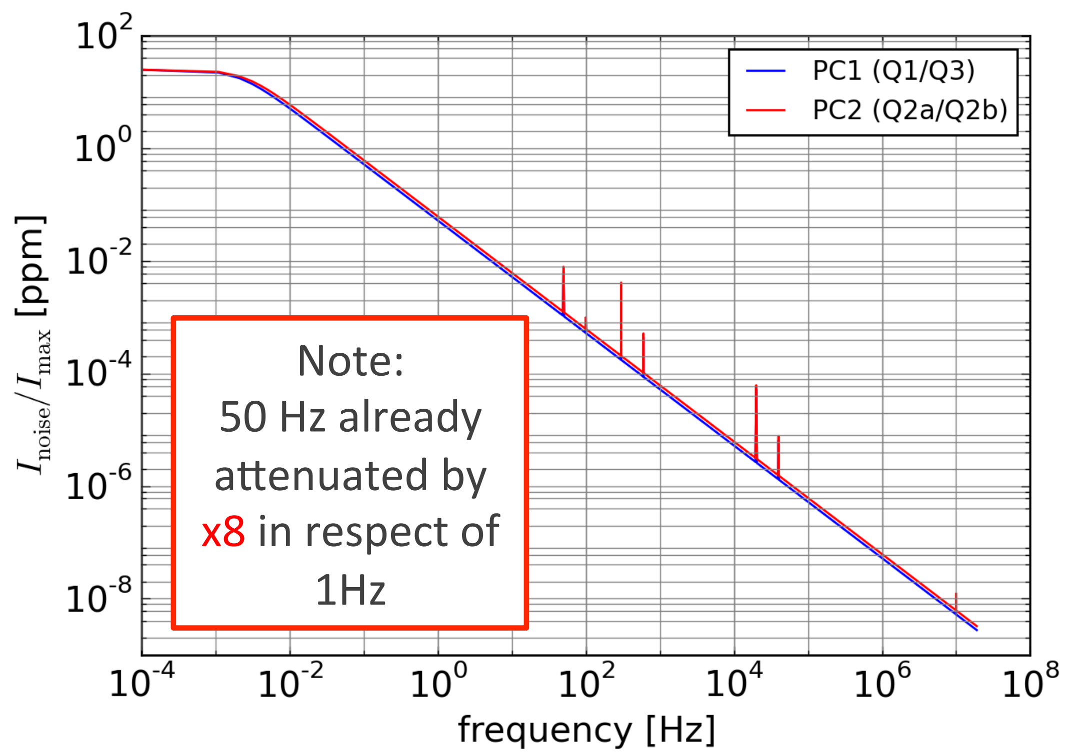
=> the higher the magnet inductance the stronger the attenuation of the higher frequencies (R_{tot} negligible)

Note: powering scheme is not taken into account (single magnet inductance is used for simulations)
= worst case scenario

T_{ItoB}: assume B=const.*I

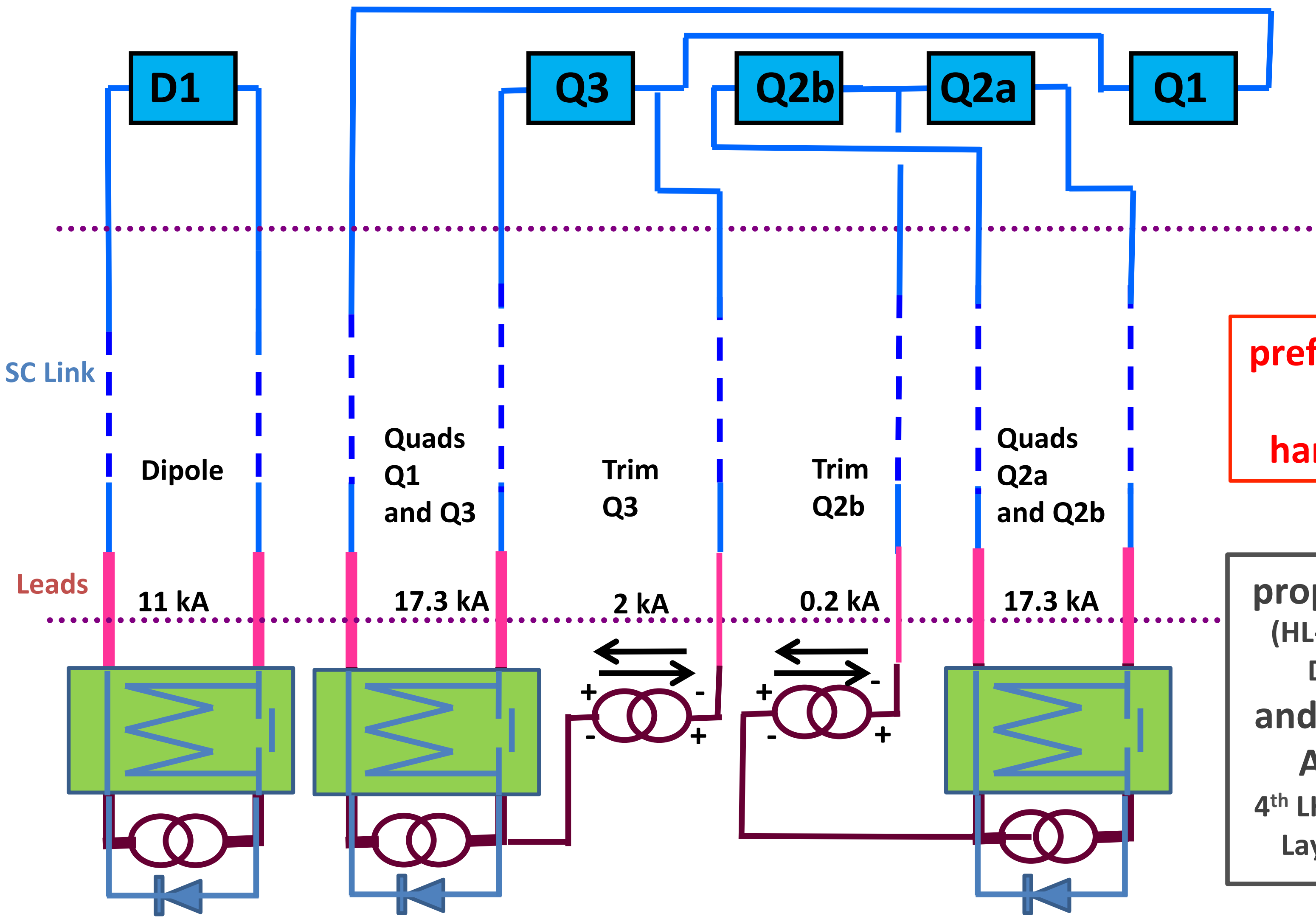
=> $I_{noise}/I_{max}=B_{noise}/B_{max}$

T_{Vacuum}: additional attenuation for frequencies >50 Hz



Proposed powering scheme and possible alternatives

Proposed powering scheme HL-LHC



preferred option from hardware side

proposed by WP3 (HL-LHC perliminary Design report) and presented by A. Ballarino, 4th LHC Parameter and Layout Committee

Comparison of powering schemes

Current ripple of power converter induces a tune shift:

$$\Delta Q = \frac{1}{4\pi} \oint \beta(s) \Delta k(s) ds$$

-> tune shift is the first/most basic figure of merit for beam dynamics:

larger tune spread -> smaller dynamic aperture

First estimate by calculating the tune shift induced by a uniformly distributed error on the current (±1ppm (10^{-6}) = stability over 24 h)

1) comparison of nominal LHC (β*=55 cm, V6.5.coll.str) with the HL-LHC (β*=15 cm, HLLHCV1.0) proposed powering scheme

	rms($(Q_z-Q_{z0})\times10^4$)	ΔQ/ΔQ(nom. LHC)
nom. LHC	0.25	x1.0
HL-LHC (20 kA)	1.57	**x6.3**

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=> tune spread is increased by factor x6.3 in respect to nominal LHC

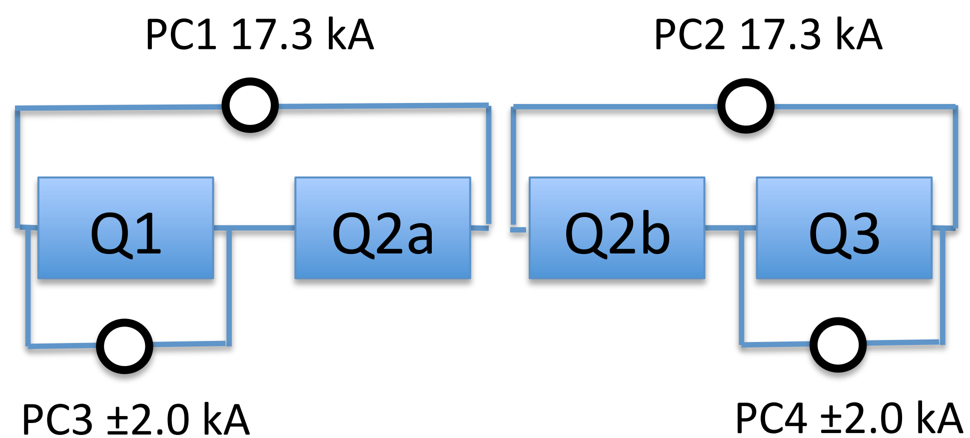
Alternative Powering Schemes HL-LHC

In general: tune spread can be reduced by changing the powering of the IT

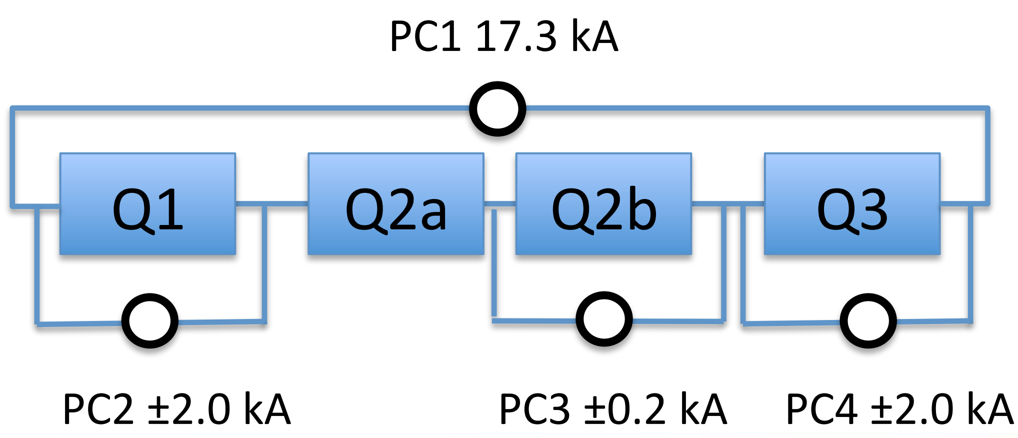
-> exploit compensation between Q1/3 and Q2a/Q2b

Q1-Q2a Q2b-Q3:
largest reduction of tune spread
-> preferred from beam dynamics side

proposed by S. Fartoukh



Q1-Q2-Q3 (all in series):
preferred from hardware side over Q1-Q2a Q2b-Q3



Resolution, accuracy, reproducibility

Estimate of the gain by calculating the tune shift induced by a uniformly distributed error on the current (1ppm (10^{-6}) = stability over 24h)

$$\Delta Q = \frac{1}{4\pi} \oint \beta(s) \Delta k(s) ds$$

2) estimate of an eventual gain using an alternative powering scheme (β^*=15 cm, HLLHCV1.0)

	rms($(Q_z-Q_{z0})\times10^4$)	ΔQ/ΔQ(Baseline)
Baseline	1.57	x1.0
Q1-Q2-Q3	0.78	**x0.5**
Q1-Q2a + Q2b-Q3	0.63	**x0.4**

=> tune spread can be reduced by factor 2-2.5 by changing the powering of the IT

Note: We only look at collision as for injection the effect is about a factor 2.5 less due to the smaller beta-functions in the IT

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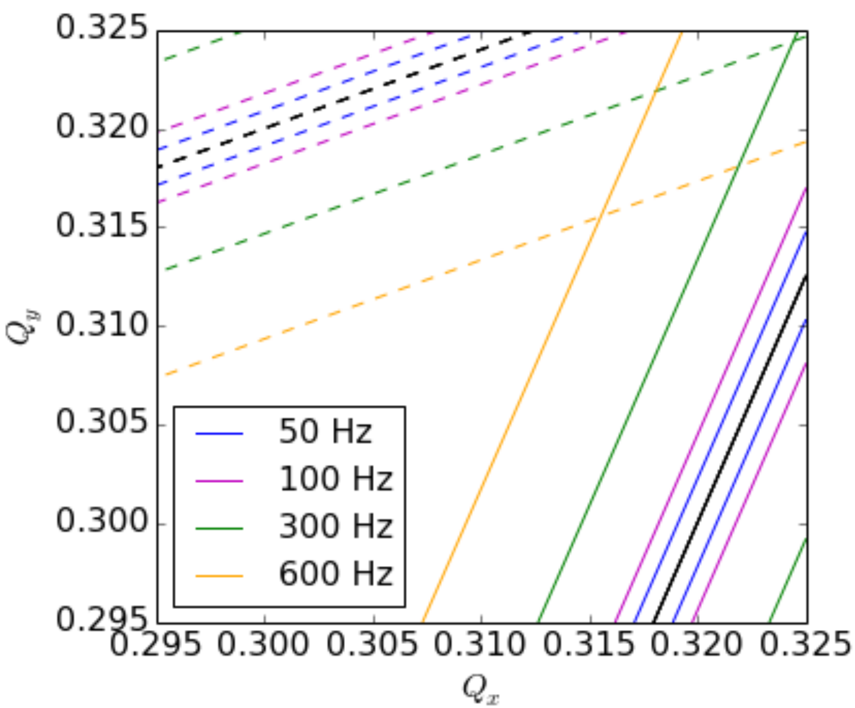
Ripple tolerances and dynamic aperture studies

Theoretical background

In addition to the tune shift the tune modulation (ripple) introduces resonance side bands [5,6]:

$$lQ_x + mQ_y + n\frac{f_{\mathrm{mod}}}{f_{\mathrm{rev}}} = r,\ \text{with } l, m, n, r \text{ integer}$$



7th order resonances

slow modulation (e.g. 50 Hz):
distances between the sidebands are small but amplitudes decrease only slowly with increasing order

fast modulation (e.g. 600 Hz):
distances between the sideband are large and amplitudes decrease rapidly with increasing order

slow+fast modulation: the sidebands of the fast modulation form the seeds for the sidebands of the slow modulation ("seeding resonances")

[5] O. S. Brüning, F. Willeke, Phys. Rev. Lett. 76, No. 20 (1995), [6] O. S. Brüning, Part. Acc. 41, pp. 133-151 (1993)

Dynamic aperture studies

Dynamic aperture studies to asses the influence of the ripple on the long term stability:

1) determination of the dangerous frequencies:
   - 50 Hz, 100 Hz (main grid)
   - 300 Hz, 600 Hz (diode rectifier)
   - high frequency 9kHz (representative for 20 kHz (ITPT converters))

   simulation parameters:
   - same amplitude (δkl) for all quadrupoles taking the polarity and baseline powering scheme into account (no trims - negligible)
   - choose amplitude to obtain $\Delta Q_{x/y} = \pm 10^{-4}$ ($\pm 10^{-3}$, $\pm 10^{-5}$, $\pm 10^{-6}$)

2) frequency spectrum provided by EPC group (slide 6) ("real spec") taking the polarity and baseline powering scheme into account (no trims)
   + 50 Hz harmonics until 1kHz ("real spec 1k")
   + 50 Hz harmonics until 1kHz + 1Hz with $\Delta k/k_{max} = 10^{-6}$ ("real spec 1k 1Hz")
   (first attempt to include current stability of $\Delta I/I_{max} = 10^{-6}$)

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DA studies : simulation setup

Tracking studies with SixTrack using the following parameters (see backup slide):

- optics: sLHCV3.1b, β*=15 cm in IR1/5, β*=10 m in IR2/8
- max number of turns: 10^6
- seeds: 60, angles: 59 (steps of 1.5˚), amplitudes: 2-28 (no bb), 2-14 (bb)
- no phase shift between ripple frequencies
- b2 errors of dipole -> approx. 3% beta-beat

Analysis methods:

1) calculation of minimum, maximum and average DA over the seeds using the particles lost criterion = largest amplitude for which all particles with smaller amplitudes are not lost after the number of turns tracked
2) calculation of the DA as a function of the number of turns ("DA vs turns") (see backup slides) which is more suited for detecting slow long term effects [7]

-> criterion for effect of ripple: DA changes in respect to reference cases without ripple

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[7] M. Giovannozzi, W. Scandale, E. Todesco, Phys. Rev. E 57, No. 3 (1998)

Dynamic aperture studies

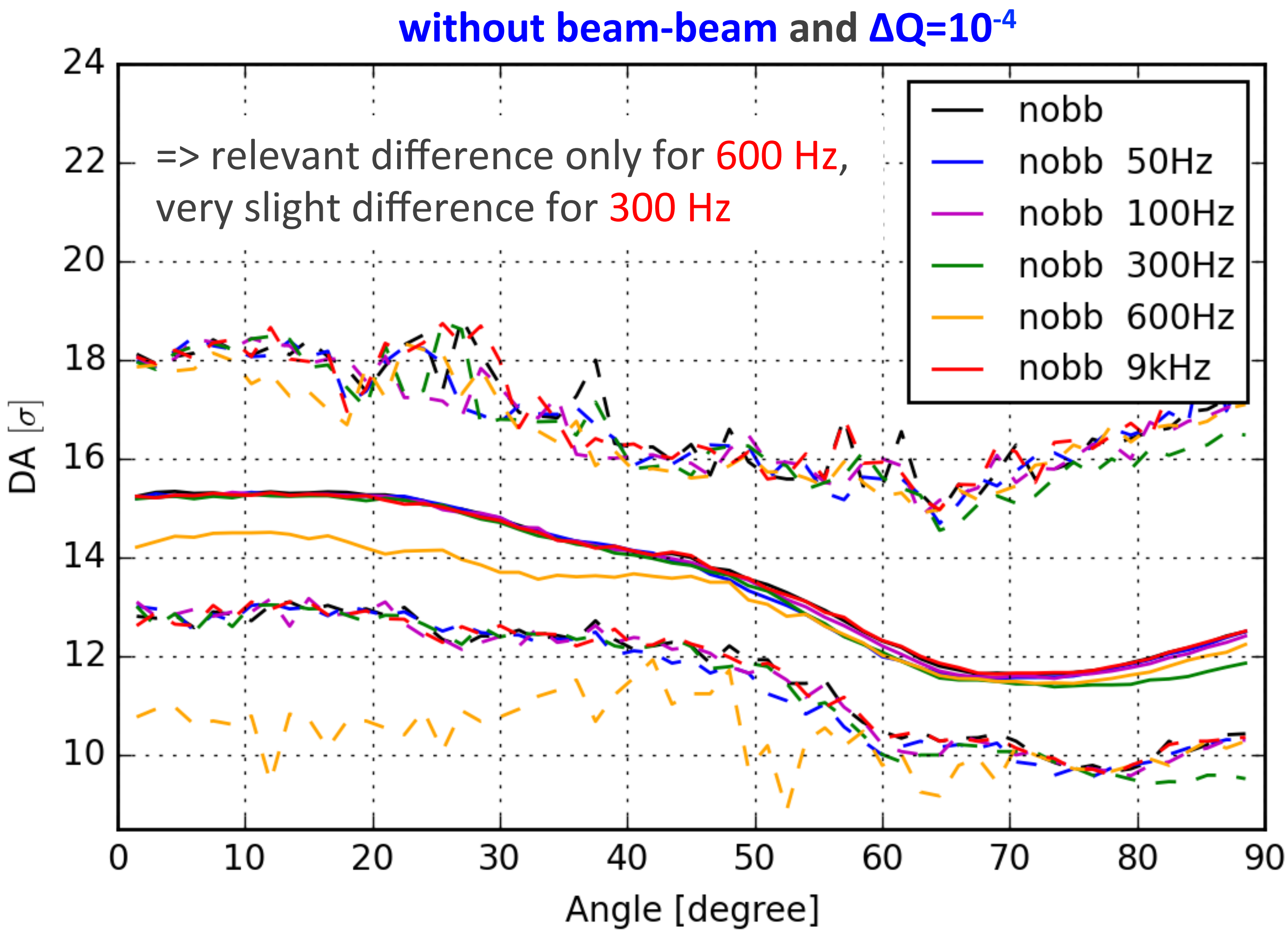
Only selection of studies presented here:

1) w/o beam-beam representing the scenario before and during collisions respectively, w/o crab cavities and w/o octupoles
   note: the smallest DA is usually expected for the case with the largest tune spread
   -> simulations with beam-beam and crab cavities on, if w/o crab cavities has been studied
   -> simulations with octupoles at the moment only without beam-beam for which the largest impact is expected (in terms of tune spread)
3) only results with particles lost criterion are shown and conclusion from da vs turns if differing from result from particle lost criterion

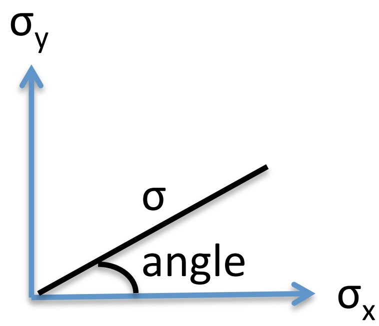
We will go in the following order:

1) Determination of the dangerous frequencies
   a) without beam-beam
   b) with beam-beam w/o crab cavities
2) Real frequency spectrum
   a) without beam-beam
   b) with beam-beam w/o crab cavities
3) Influence of octupoles on DA (only without beam-beam)

Dangerous frequencies - withou bb (1)



no beam-beam:
only simulation
for **$\Delta Q=10^{-4}$**



Dangerous frequencies - withou bb (2)

Summary of tolerances for case without beam-beam (no octupoles) from particles lost criterium and da vs turns analysis - simulation for **$\Delta Q=10^{-4}$**:

frequency	tune shift	limit on δkl
50 Hz	small effect for $\Delta Q=10^{-4}$	$\delta kl \leq 2.1\text{x}10^{-8}$
100 Hz	very small effect for $\Delta Q=10^{-4}$	
300 Hz	visible effect for $\Delta Q=10^{-4}$	$\delta kl < 2.1\text{x}10^{-8}$
600 Hz	large effect for $\Delta Q=10^{-4}$	
9 kHz	very small effect for $\Delta Q=10^{-4}$	$\delta kl \leq 2.1\text{x}10^{-8}$

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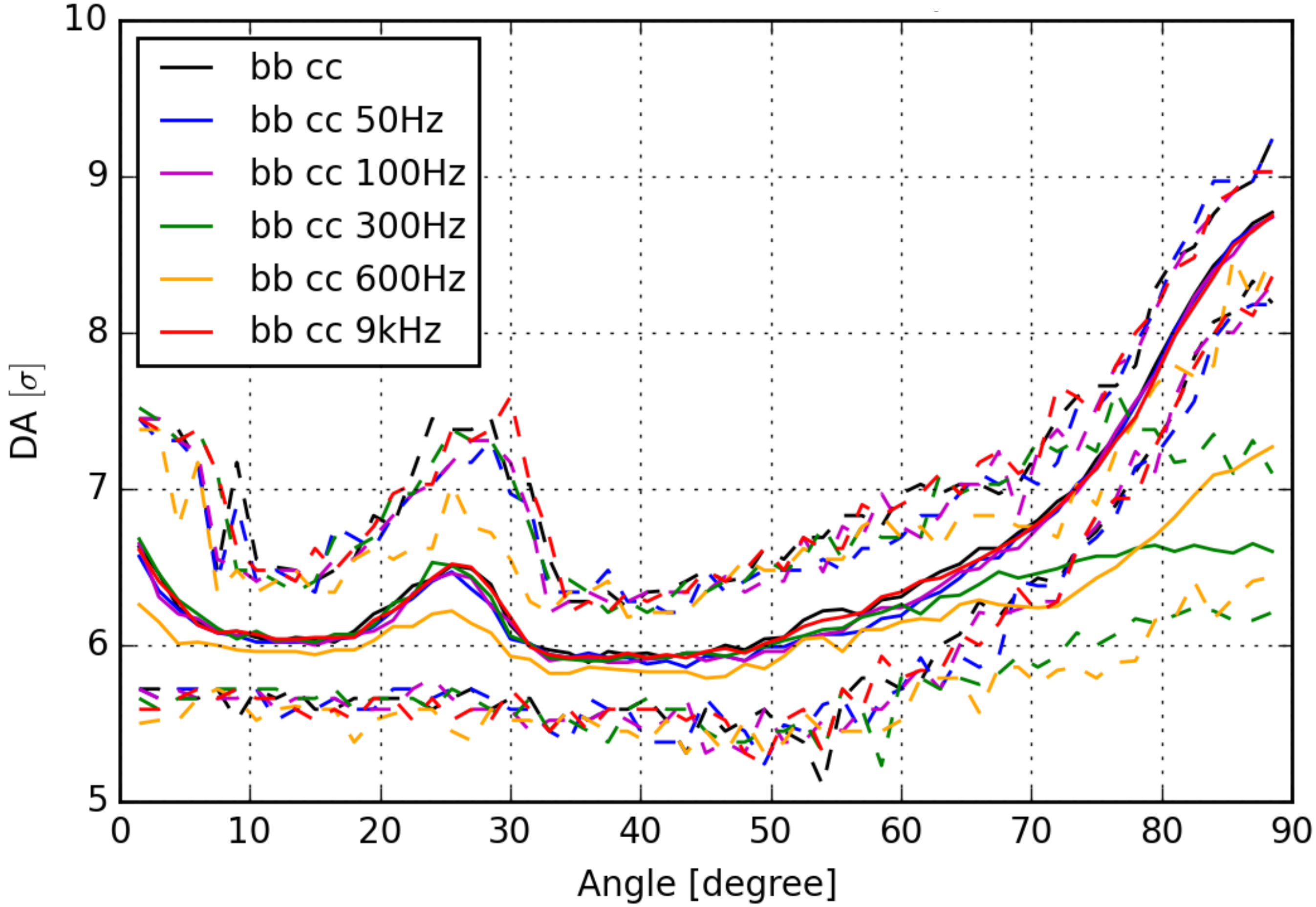
Dangerous frequencies – with bb (1)

with beam-beam and **crab cavities** and **ΔQ=10^{-4}**



with beam-beam - with crab cavities:
simulation for ΔQ=10^{-4}

=> relevant difference for 600 Hz and 300 Hz (same results from da vs turns analysis)

Dangerous frequencies – with bb (2)

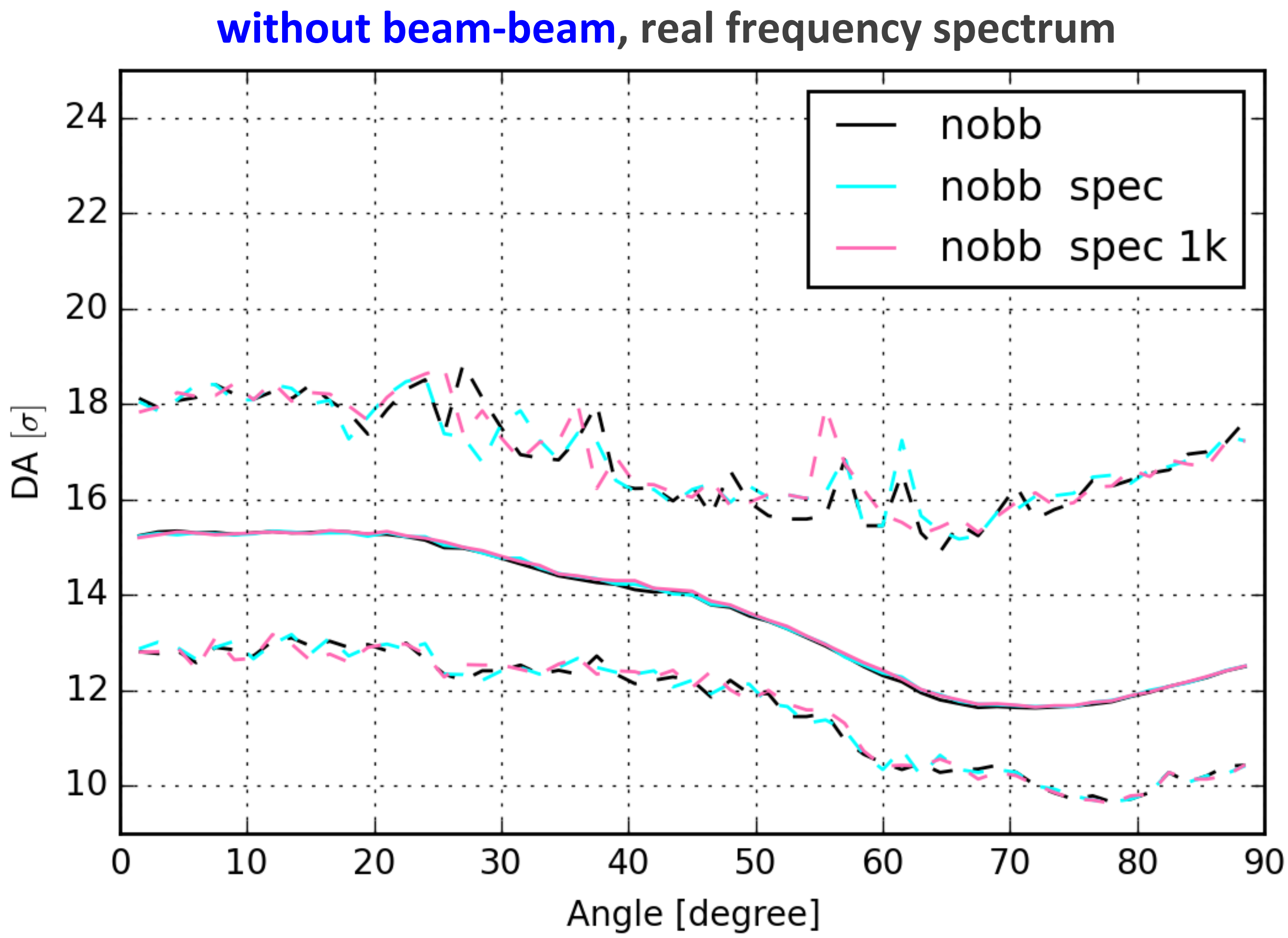
with beam-beam - without crab cavities:

simulation for **$\Delta Q=10^{-6}$-10^{-2}** to determine tolerance on modulation amplitude

frequency	maximum tune shift	limit on δkl
50 Hz	no effect for $\Delta Q=10^{-4}$, visible effect for $\Delta Q=10^{-3}$	$2.1\times10^{-8} < \delta kl < 2.1\times10^{-7}$
100 Hz	no effect for $\Delta Q=10^{-4}$, visible effect for $\Delta Q=10^{-3}$	$2.1\times10^{-8} < \delta kl < 2.1\times10^{-7}$
300 Hz	small effect for $\Delta Q=10^{-5}$, visible effect for $\Delta Q=10^{-4}$	$\delta kl < 2.1\times10^{-9}$
600 Hz	very small effect for $\Delta Q=10^{-5}$, visible effect for $\Delta Q=10^{-4}$	$2.1\times10^{-9} < \delta kl < 2.1\times10^{-8}$
9 kHz	no effect for $\Delta Q=10^{-4}$, visible effect for $\Delta Q=10^{-3}$	$2.1\times10^{-8} < \delta kl < 2.1\times10^{-7}$

=> in the range of highest amplitude (50 Hz) for real frequency spectrum

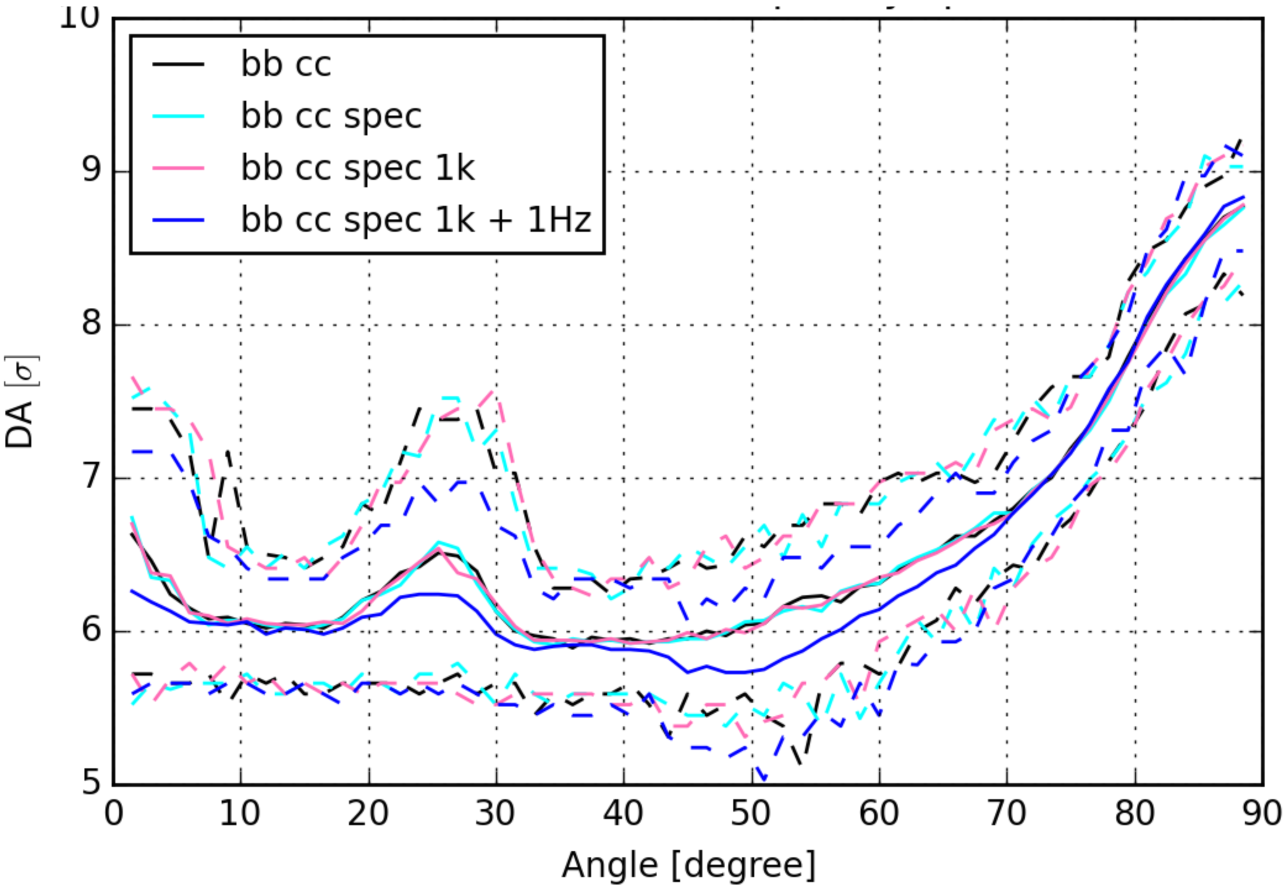
Real frequency spectrum – without bb



no relevant difference

Real frequency spectrum – with bb

with beam-beam and crab cavities, **real frequency spectrum**



no difference for spec and spec 1k but visible difference if the 1Hz modulation is added (continuous slow tune scan)

-> simulation should be compared with bb cc + 1Hz

-> study also white noise (e.g. taking several frequencies)

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Summary: real frequency spectrum

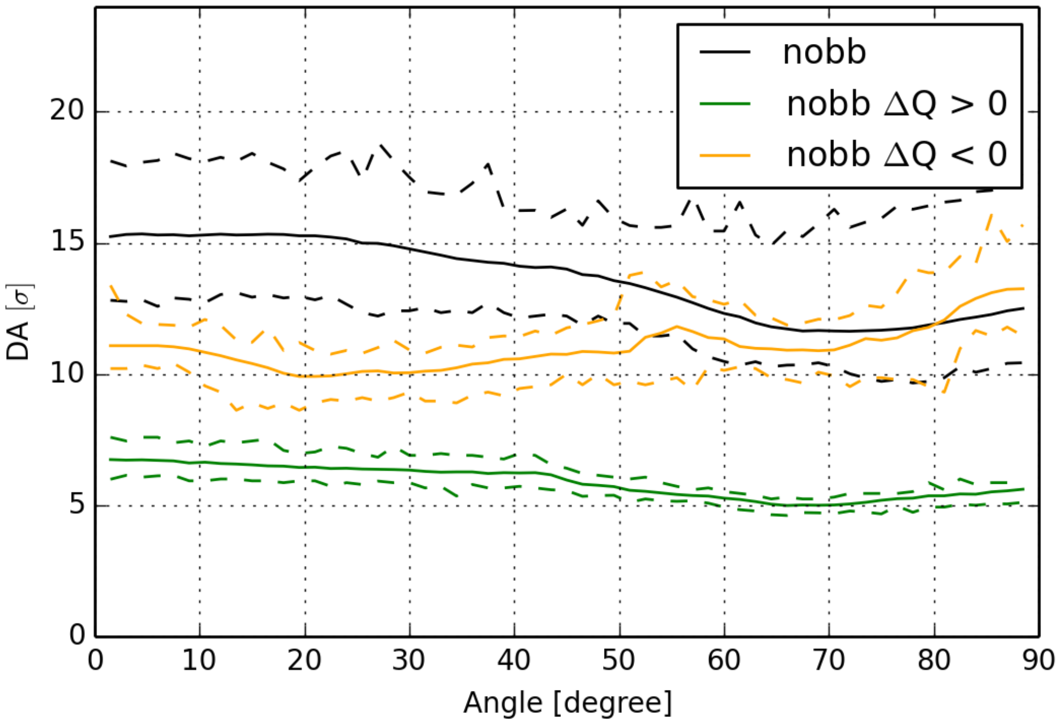
without beam-beam: real frequency spectrum (+1k)
with beam-beam: real frequency spectrum
real frequency spectrum +1k (x10 and x100)
with beam-beam +cc: real frequency spectrum
real frequency spectrum +1k (x10 and x100)

<table>
<tr><th>case</th><th>amplification</th><th>limit on largest δkl</th></tr>
<tr><td>without bb, no octupoles</td><td>no effect for spec 1k, $\Delta Q \approx 10^{-6}$</td><td>$3.2 \times 10^{-10} < \delta kl$</td></tr>
<tr><td>with bb - no crab cavities</td><td rowspan="2">very small effect for spec 1k x10 ($\Delta Q \approx 10^{-5}$), visible effect for spec 1k x100 ($\Delta Q \approx 10^{-4}$)</td><td rowspan="2">$3.2 \times 10^{-10} < \delta kl < 3.2 \times 10^{-8}$</td></tr>
<tr><td>with bb + crab cavities</td></tr>
</table>

Influence of octupoles

Note: largest impact expected in terms of tune spread for case without beam-beam as with beam-beam the tune spread is dominated by the head-on beam-beam tune shift. Beside the largest tune spread the DA could be also increased by resonances driven by octupoles.

without beam-beam and octupoles

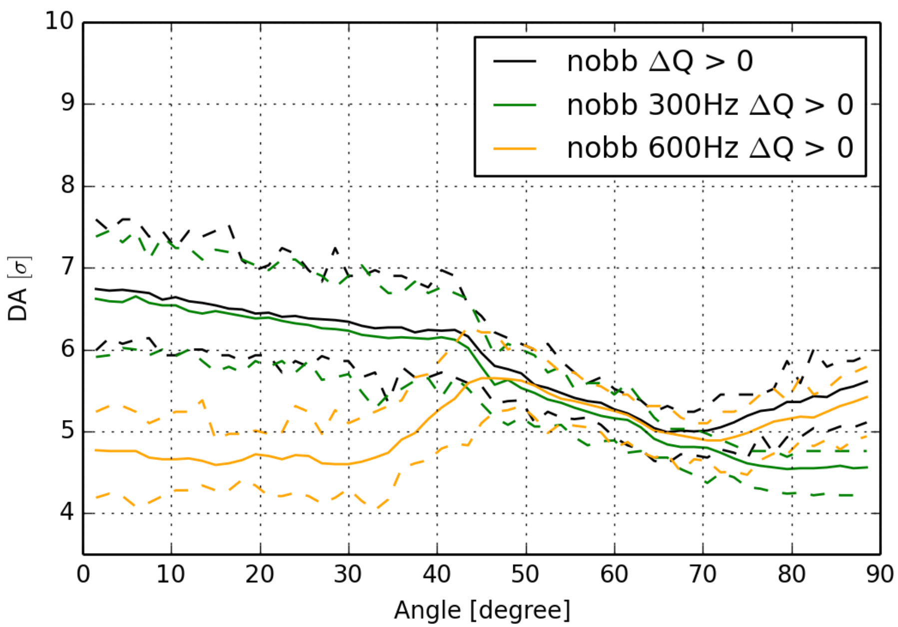


Octupoles at full positive current (ΔQ>0) and negative current (ΔQ<0)

=> large decrease in DA, in particular for ΔQ>0

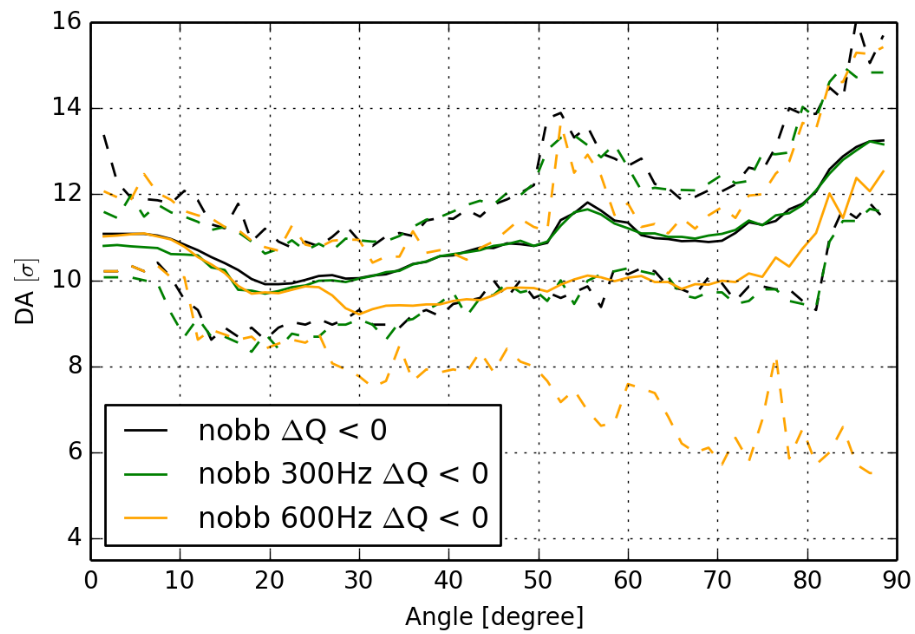
Influence of octupoles

Impact of octupoles at full positive + or negative current on individual frequencies (ripple amplitudes chosen for $\Delta Q=10^{-4}$)



ΔQ>0: relevant difference for 600 Hz and visible difference for 300 Hz

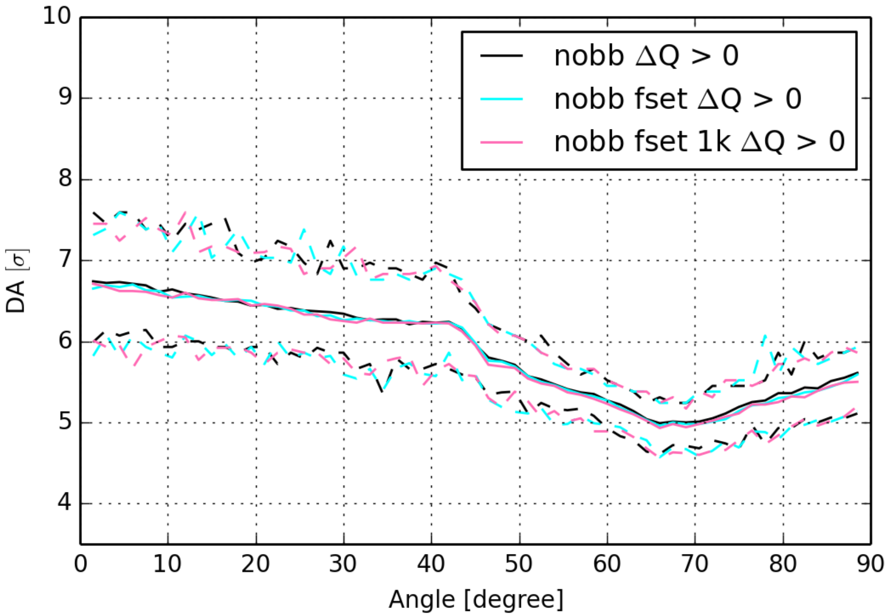
ΔQ<0: relevant difference for 600 Hz and small difference for 300 Hz



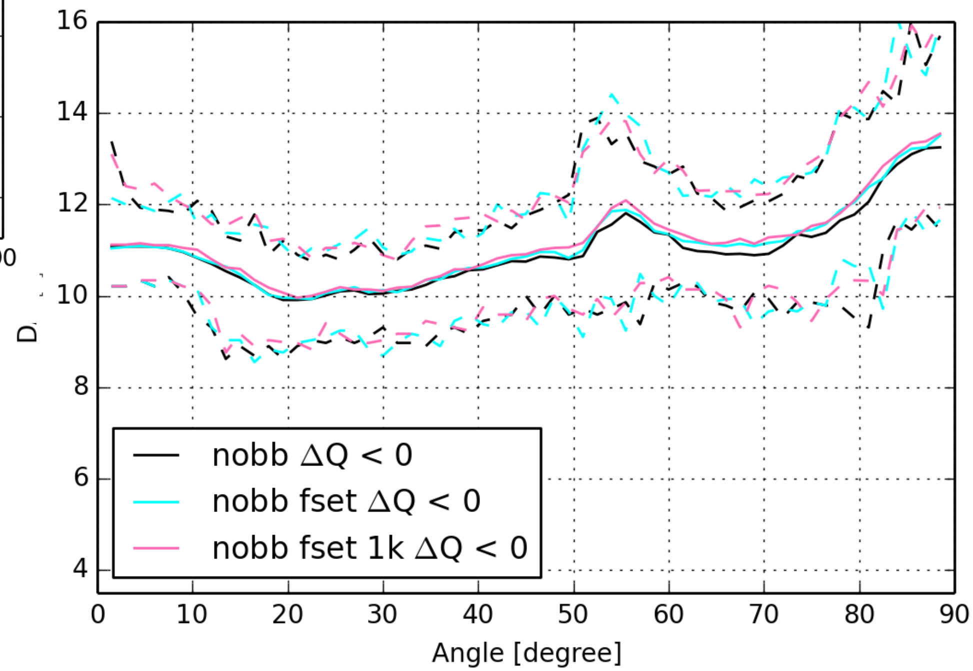
-> 50Hz, 100 Hz and 9kHz to be studied for comparison

Influence of octupoles

real frequency spectrum and real frequency spectrum + 1k



no relevant difference



Conclusion

1. Resolution and stability:

   a uniformly distributed relative **current error of 10^{-6}** results in a **tune spread of approx. 10^{-4}**. The tune spread can be reduced by x2 by powering all triplets in series or Q1-Q2a and Q2b-Q3 in series

2. Model of the field ripple:

   all **frequencies** >1Hz are **strongly attenuated** due to the **magnet inductance** and all frequencies >50 Hz in addition attenuated due to eddy currents induced in the **BS**.

2. Ripple tolerances and dynamic aperture studies:

   a) no effect of the real frequency spectrum on the dynamic aperture for the cases with beam-beam w/o crab cavities and without beam-beam w/o octupoles.
   A very small effect is seen if the spectrum is amplified by x10 and a visible effect if amplified by x100 (case with beam-beam w/o crab cavities, without beam-beam not studied).

Conclusion

2. Ripple tolerances and dynamic aperture studies:

   a) sensitivity to 300 Hz and 600 Hz in all cases.
   Tolerances for individual frequencies in terms of tune shift (with beam-beam, no crab-cavities):

   - 300 Hz: $\Delta Q < 10^{-5}$ (same order of magnitude as largest amplitude for real frequency spectrum)
   - 600 Hz: $10^{-5} < \Delta Q < 10^{-4}$
   - 50 Hz, 100 Hz and 9 kHz: $10^{-4} < \Delta Q < 10^{-3}$

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Further studies

1) Tolerances for different frequencies also for without beam-beam and with beam-beam and crab cavities
2) DA studies with octupoles without beam-beam for 50 Hz, 100 Hz, and 9 kHz and with beam-beam w/o crab cavities for all scenarios
3) Effect of slow modulation and white noise (<1Hz)
4) Tune scans to investigate the dependence of the simulation on the chosen WP
5) Similar analysis for alternative powering schemes
6) Similar analysis also for the matching section quadrupoles

Thank you for your attention!

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Spectrum of the magnetic field

Parameters used for HL-LHC (T_{VtoI}, load, T_{ItoB}):

- $R_{PC1,PC2}$ = 1.144 mΩ (same as for PC1 of nominal LHC)
- $length_{Q1,Q3}$ = 8.0 m, $length_{Q2}$ = 6.8 m
  $L_{Q1,Q2,Q3}$ = 10.8 mH/m
  L_{tot}=$L_{Q1/Q2/Q3}$= single magnet inductance
- $I_{max,PC1,PC2}$ = 17.5 kA
- $k_{max,Q1,Q2,Q3}$ = 0.5996 x 10^{-2} 1/m^2

T_{Vacuum}: Spectrum of the magnetic field seen by the beam

T_{Vacuum}: Transfer function of the magnetic field produced by the magnet to the magnetic field seen by the beam.

-> eddy currents in cold bore, absorber and beam screen

simple model for eddy current effects (Chao, Handbook of Acc. Phys. and Engineering):

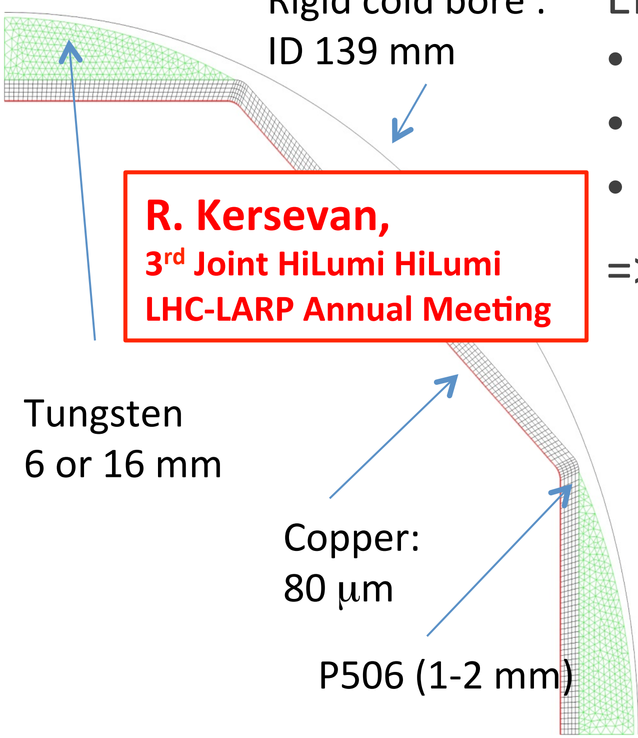
$$K(t) = K_0 \sin(\omega t) \Rightarrow K(t) = \underbrace{\frac{K_0}{\sqrt{1+\omega^2\tau^2/4}}}_{\text{damping term}} \underbrace{\sin\left[\omega t - \tan^{-1}\frac{\omega\tau}{2}\right]}_{\text{oscillatory term}} \quad \text{with} \quad \tau = \mu_0\sigma_c b t/2$$

phase shift: $\tan^{-1}\frac{\omega\tau}{2}$

assuming a round beam pipe of radius b, thickness t and and conductivity σ_c

T_{Vacuum}: Spectrum of the magnetic field seen by the beam

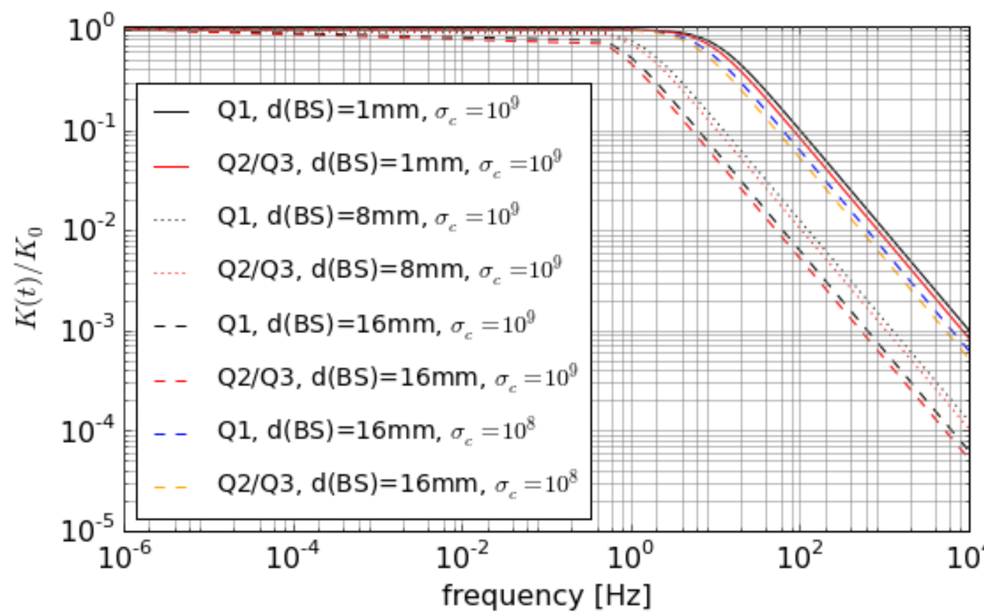
Beam screen design HL-LHC IT:



Electrical resistivity (13th HL-LHC TC):

- Copper @ 4.2K: 1.9×10^{-10} Ωm
- P506 : 10^{-7} Ωm
- Tungsten (INERMET) @ 50K: ~ 3×10^{-8} Ωm

=> behaviour probably dominated by Tungsten



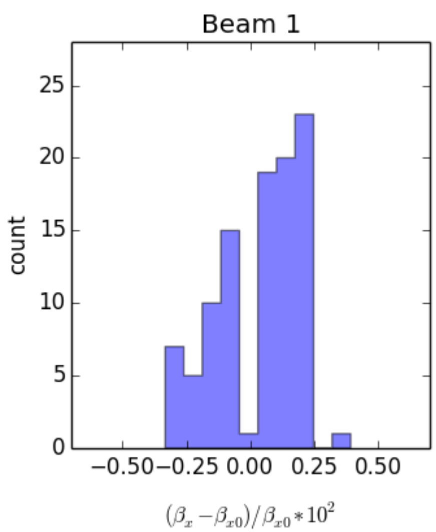
=> frequencies >50 Hz are further attenuated

Expected beta-beat and orbit deviation

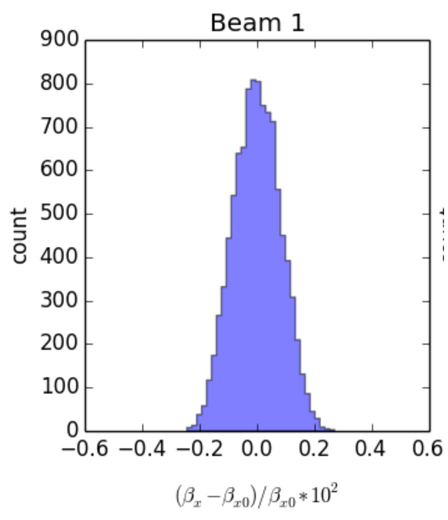
Beta-beat and orbit deviation at the IP (β^*=15 cm, HLLHCV1.0) for 1 ppm (10^{-6}) - baseline:

=> around 0.5% maximum beta-beat (complete ring), around 0.2% at the IP

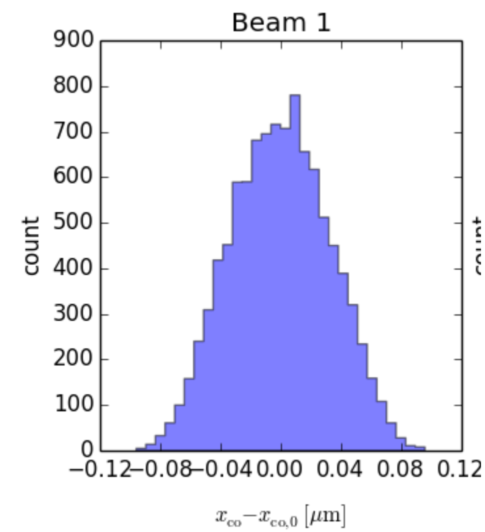
=> around 0.12 µm maximum orbit deviation (for ε_N=2.5 µm, σ_{IP}=7.1 µm => 1.7% orbit deviation)



max. over 100 seeds (complete ring)



IP5, 10000 seeds



IP5, 10000 seeds

=> 1 ppm uniformly distributed error on the current results in approx. 10^{-4} tune spread, 1% beta-beat and 2% orbit deviation at the IP

Experiments in the past

Experiments were done at the SPS [1,2,3] and HERA [4]:

- in case of the SPS a tune ripple of 10^{-4} is acceptable while experiences at HERA show that for low frequencies even a tune ripple of 10^{-5} and for high frequencies 10^{-4} can lead to significant particle diffusion.
- several ripple frequencies are much more harmful than a single one [1,2]

[1] X. Altuna et al., CERN SL/91-43 (AP)

[2] W. Fischer, M. Giovannozzi, F. Schmidt, Phys. Rev. E 55, Nr. 3 (1996)

[3] P. Burla, D. Cornuet, K. Fischer, P. Leclere, F. Schmidt, CERN SL/94-11 (1996)

[4] O. S. Brüning, F. Willeke, Phys. Rev. Lett. 76, Nr. 20 (1995)

SixTrack simulation parameters

lattice: sLHCV3.1b
optics: β*=15 cm in IR1/5, β*=10 m in IR2/8
x-scheme: separation: ±0.75 mm (IR1/5), ±2.0 mm (IR2/8), x-angle: : ±295 µm (IR1/5) , ±240 µm IR2, ±305 µm IR8
tune: Q_x/Q_y=62.31/60.32
beam parameters: E_{beam} = 7 TeV, bunch spacing: 25 ns, $\varepsilon_{N,x/y}$=2.5 µm (mask), $\varepsilon_{N,x/y}$=3.75 µm (sixtrack), σ_E=1.1e-4 (madx), Δp/p=2.7e-04 (sixtrack), N_b=2.2e+11
error tables: LHC measured errors (collision_errors-emfqcs-*.tfs), no a_1/b_1 from all magnets, no b_{2s} from quadrupoles, target error tables for IT (IT_errortable_v66), D1 (D1_errortable_v1), D2 (D2_errortable_v4), and Q4 (Q4_errortable_v1) and Q5 (Q5_errortable_v0) in IR1/5
sixtrack simulation parameters:
60 seeds, 10^6 turns, 59 angels
corrections:

- MB field errors
- IT/D1 field errors
- coupling
- orbit (rematch co at IP and arc for dispersion correction)
- spurious dispersion
- tune and linear chromaticity

corrections not included:

- no correction of residual Q'' by octupoles

no beam-beam:

- no beam-beam, no collision
- without octupoles and with octupoles (strength set to kof=±0.29*6/0.017^3*0.3/NRJ)
- scan from 2-28σ in steps of 2σ with 30 points per step

beam-beam:

- HO and LR in IR1/2/5/8, one additional LR encounters in D1, 5 slices for HO bb
- without crab cavities and with crab cavities at 100% (fraction_crab=1)
- halo collision in IR2 at 5 sigma
- scan from 2-14σ in steps of 2σ with 30 points per step