Progress on power converter ripple effects and specifications for HL-LHC

M. Fitterer, R. De Maria

Acknowledgments: A. Ballarino, J.-P. Burnet, M. Giovannozzi, S. Fartoukh, H. Thiesen

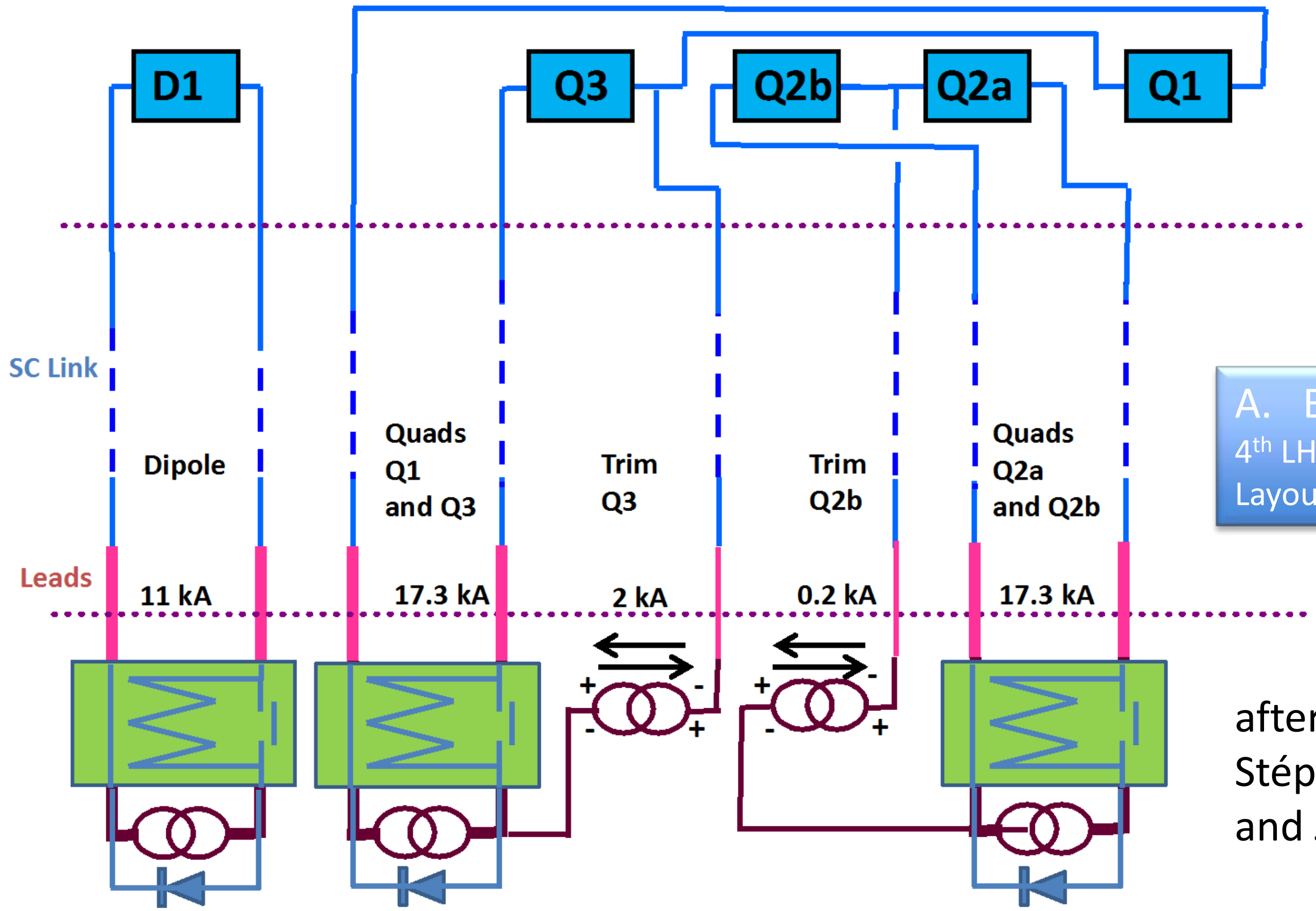
The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404.

Outline

1) Proposed powering scheme
2) Literature and previous studies
3) Model of the field ripple
    a) Specifications power supplies (nominal LHC)
    b) Transfer function voltage to field (nominal LHC)
    c) Eddy currents (HL-LHC)
4) Frequency spectrum
    a) BBQ beam spectrum
    b) Power converter noise through resistive magnet
5) Dynamic aperture studies (SixTrack)
    a) Tune ripple in SixTrack
    b) First DA results

Proposed powering scheme

Proposed powering scheme HL-LHC (Baseline):



A. Ballarino,
4th LHC Parameter and Layout Committee

after discussion with Stéphane, Ezio, Amalia and Jean-Paul

Literature

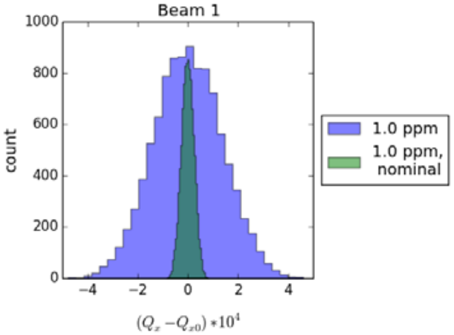
Summary of results of previous studies:

- A ripple on the current/voltage induces a change in tune, beta-beating, orbit, chromaticity ... In general the changes in beta-beating, orbit and chromaticity are negligible, but the induced tune ripple can be non-negligible.
- Experiments at the SPS [1,2] suggest that a tune ripple of 10^{-4} is acceptable while experiences at HERA [3] show that for low frequencies even a tune ripple of 10^{-5} and for high frequencies 10^{-4} can lead to significant particle diffusion.
- Experiment [1,2], theory and tracking studies [4] show that several ripple frequencies are much more harmful than a single one.
- Typical ripple frequencies lie between 5-1200 Hz [1,2,3]

[1] X. Altuna et al., CERN SL/91-43 (AP)
[2] W. Fischer, M. Giovannozzi, F. Schmidt, Phys. Rev. E 55, Nr. 3 (1996)
[2] O. S. Brüning, F. Willeke, Phys. Rev. Lett. 76, Nr. 20 (1995)
[3] O. S. Brüning, Part. Acc. 41, pp. 133-151 (1993)
[4] M. Giovannozzi, W. Scandale, E. Todesco, Phys. Rev. E 57, Nr.3 (1998)

Previous Studies and open questions

Previous studies (see LCU Meeting 26.11.2013):



- First estimate by calculating the tune ripple induced by a uniformly distributed error on the current
- comparison of nominal LHC with the HL-LHC proposed powering scheme and estimate of an eventual gain using an alternative powering scheme (Q1-Q2a and Q2b-Q3)

Open questions:

- Is a tune ripple of 10^{-4} really acceptable?
- Sensitivity to different ripple frequencies/combination of frequencies?
  - 1 DA studies using SixTrack
- What is the transfer function from the voltage ripple to the field ripple seen by the beam?

Model of the field ripple

Model of the field ripple

Magnetic field seen by the beam:

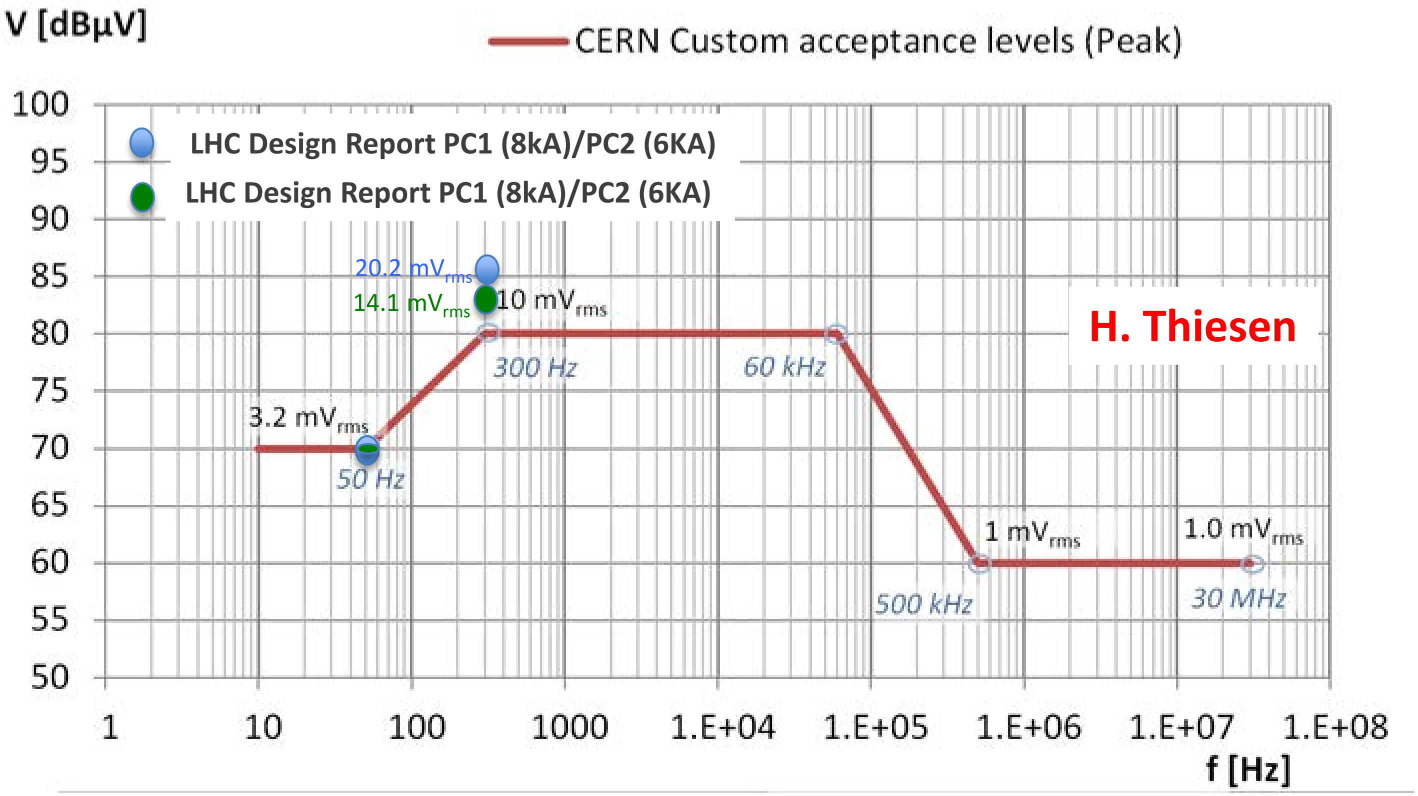
$$B(f) = T_{\mathrm{Vacuum}}(f) \times T_{\mathrm{ItoB}}(f) \times T_{\mathrm{VtoI,load}}(f) \times V_{\mathrm{PC}}(f)$$

with

$V_{\mathrm{PC}}(f)$	Voltage ripple (PC specifications, measured by EPC group)
$T_{\mathrm{VtoI,load}}$	Transfer function of the load (circuit) seen by the PC (measured by EPC group)
T_{ItoB}	Transfer function from the input current of the magnet to the magnetic field (assumed constant)
T_{Vacuum}	Transfer function cold bore, absorber, beam screen etc. (until now only rough guess with simple estimates)

Specifications power supplies

a) Specifications for the output voltage ripple of the LHC low voltage power converter (<20V) (in general the voltage ripple is measured as the current ripple can not be measured precisely enough)

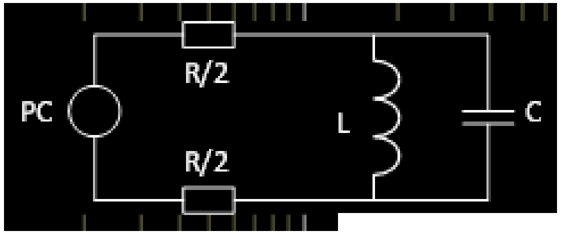


H. Thiesen

harmonics of 50 Hz = main grid, around 9kHz = switching mode power converter

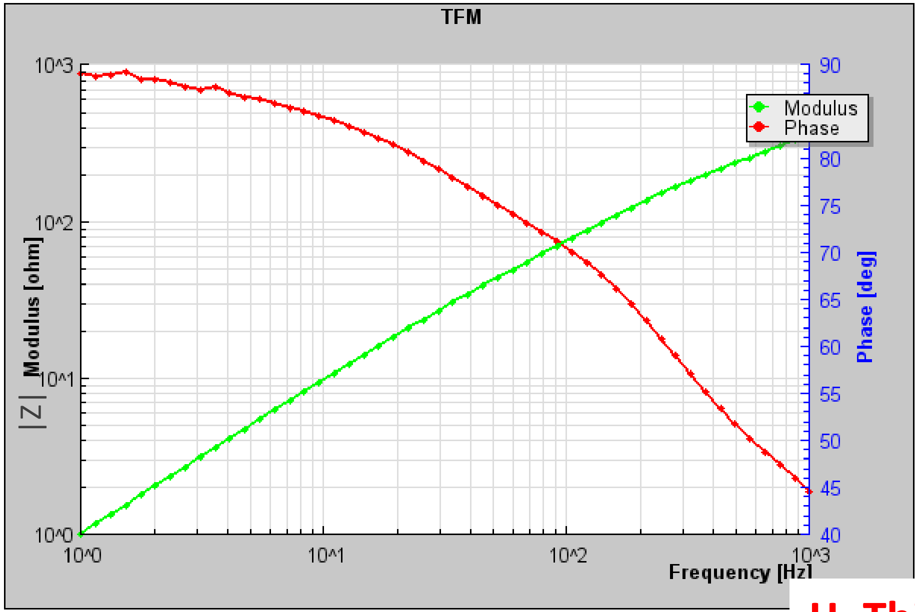
Transfer function magnet to field (1)

2) LHC magnets modeled as RLC circuit
-> the higher the magnet inductance the stronger the damping of the higher frequencies

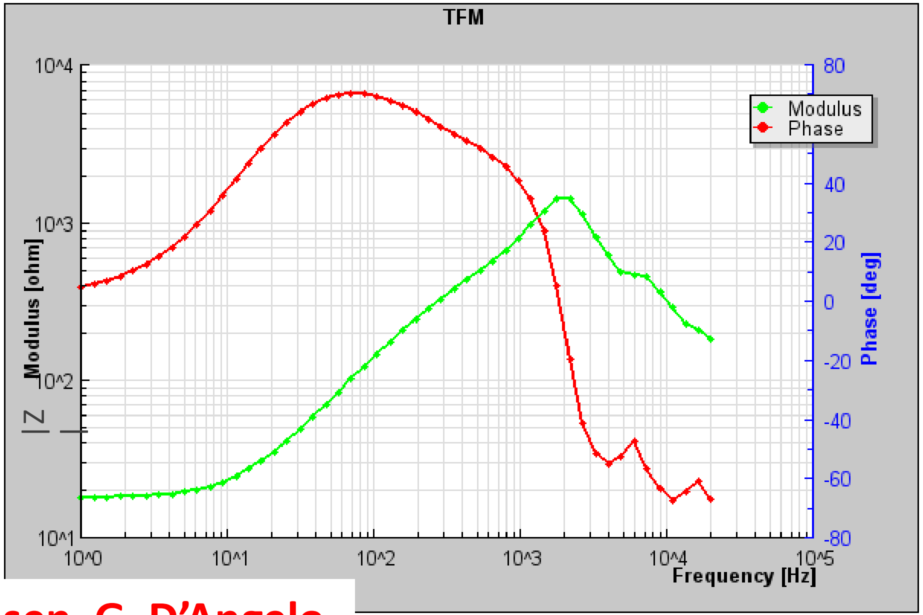


H. Thiesen

LHC measurements 2008 RQX_R1 (H. Thiesen, G. D'Angelo) -> rely on cold measurements



cold

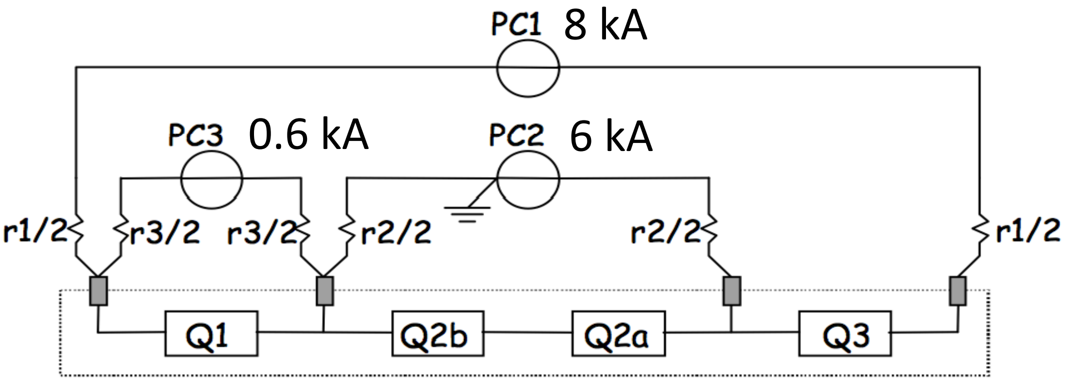


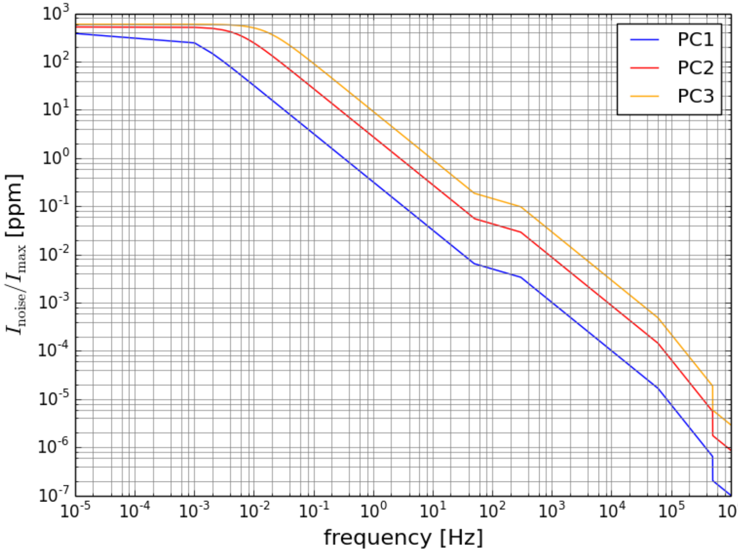
warm

H. Thiesen, G. D'Angelo

Transfer function magnet to field (2)

Example of nominal LHC IT





name	I_{max}	L_{tot}	R_{tot}	τ	I_{noise}/I_{max} [ppm]					
	[kA]	[mH]	[mΩ]	[s]	DC	1 Hz	50 Hz	300 Hz	600 Hz	9 kHz
RQX.L1 (PC1)	7.18	218.0	1.144	190.8	385.0	0.32	0.006	0.0034	0.0017	0.0001
RQX.L1 (PC2)	4.78	38.0	1.262	30.1	524.2	2.77	0.055	0.0292	0.0146	0.0010
RQX.L1 (PC3)	0.6	90.0	8.841	10.2	596.1	9.32	0.186	0.0982	0.0491	0.0033

$$\tau = L_{\text{tot}}/R_{\text{tot}} \qquad I_{\text{noise}} = V_{\text{noise}}/\left|R_{\text{tot}} + i \cdot 2\pi f L_{\text{tot}}\right|$$

Eddy currents BS (1)

c) Eddy currents (Chao, Handbook of Acc. Phys. and Engineering) induced in the BS assuming a round beam pipe of radius b, thickness t and and conductivity σ_c

phase shift

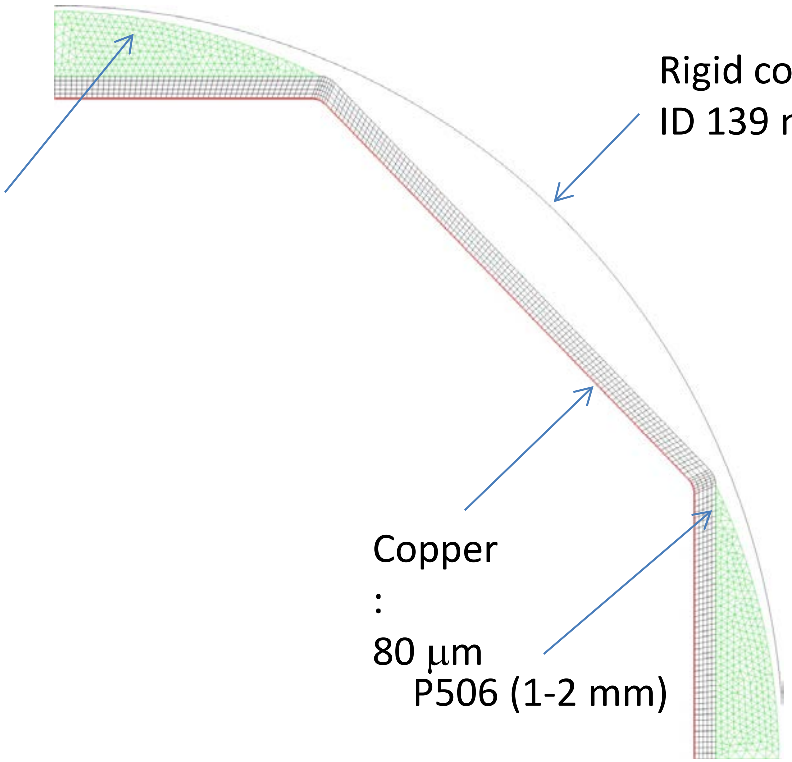
$$K(t) = K_0 \sin(\omega t) \Rightarrow K(t) = \underbrace{\frac{K_0}{\sqrt{1+\omega^2\tau^2/4}}}_{\text{damping term}} \underbrace{\sin\left[\omega t - \tan^{-}1\frac{\omega\tau}{2}\right]}_{\text{oscillatory term}}$$

with $\tau = \mu_0 \sigma_c b t/2$

How good is this approximation (shape of BS, absorber, cold bore …, conductivity)?

Eddy currents BS (2)

Beam screen design HL-LHC IT



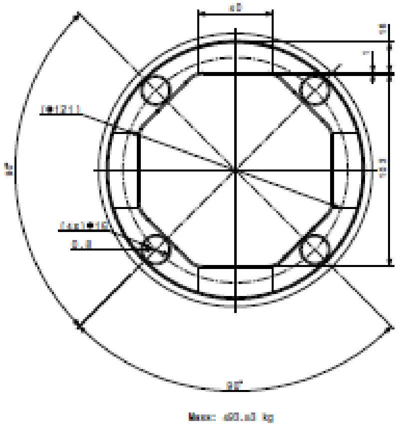
Rigid cold bore :
ID 139 mm

Tungsten
6 or 16
mm

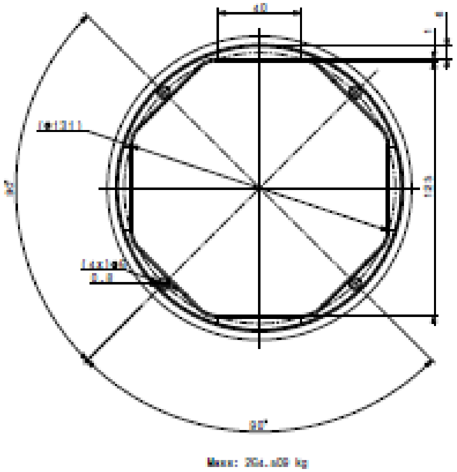
Copper
:
80 µm

P506 (1-2 mm)

Q1



Q2-Q3-D1



R. Kersevan (C. Garion, L. Dassa, R. F. Gomez),
3rd Joint HiLumi HiLumi LHC-LARP Annual Meeting

Eddy currents BS (3)

Electrical resistivity @ 4.5K:

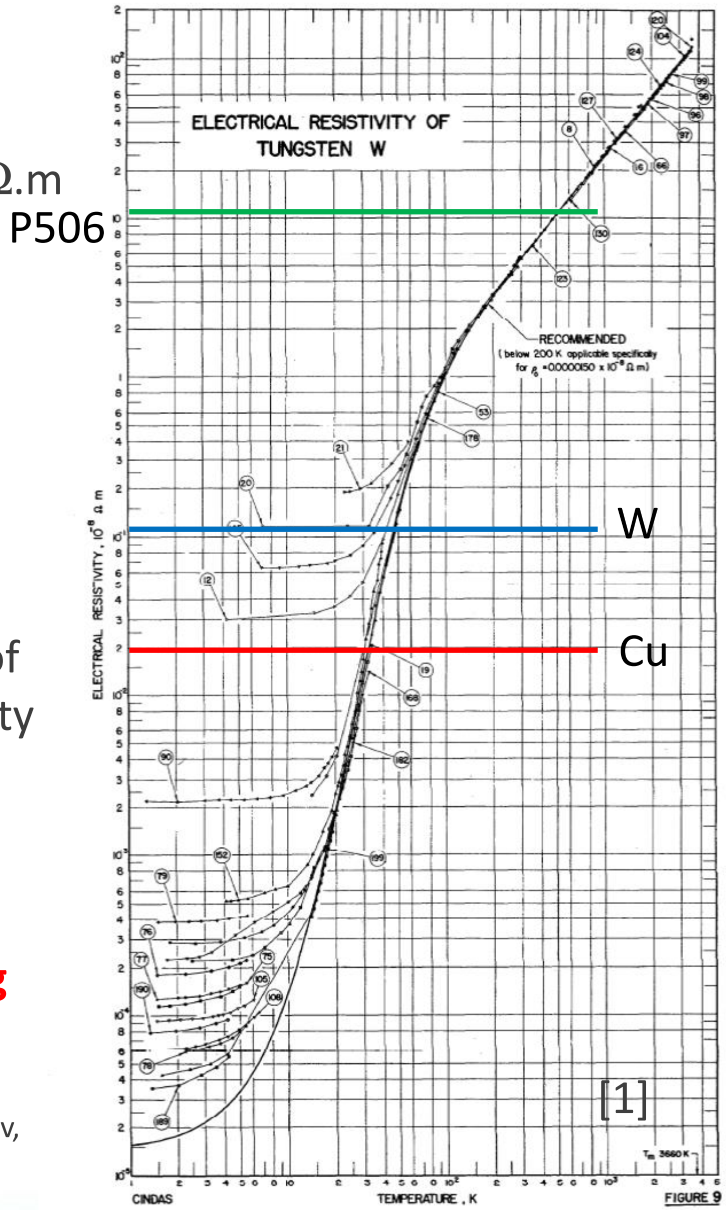
- Copper (measured on beam screen): ~ 1.9.10^{-10} Ω.m
- P506 : 10^{-7} Ω.m
- Tungsten: ~ 10^{-9} Ω.m or below

⇨ behaviour probably dominated by Tungsten

Operational temperature of Beam Screen: 40-60 K

-> Tungsten: 10^{-9} -10^{-10} Ω.m ?

But: BS consists of INERMET (5% Ni,Cu) -> impurity of Tungsten could change considerably its resistivity at low temperatures

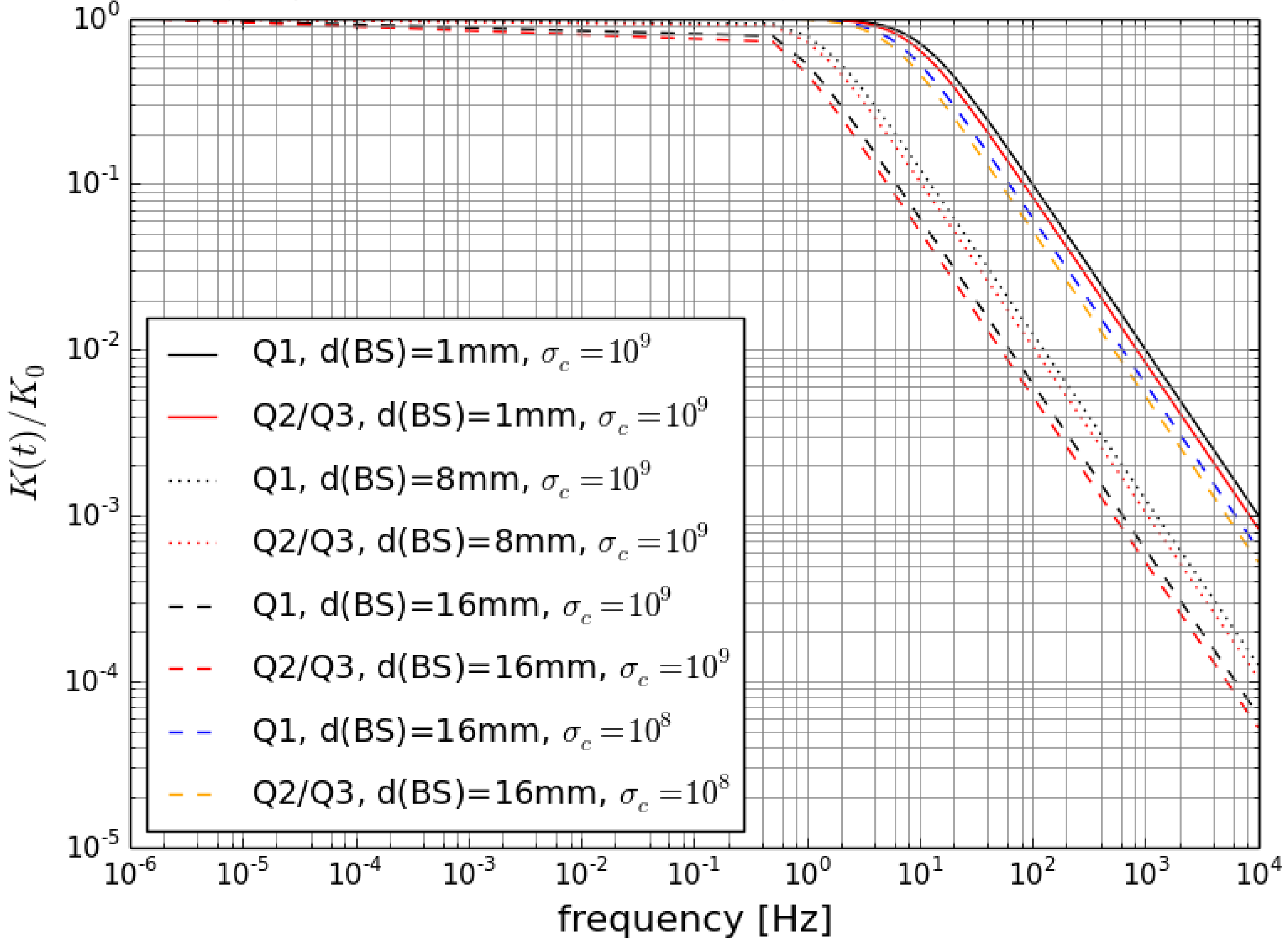


R. Kersevan (C. Garion, L. Dassa, R. F. Gomez),
3rd Joint HiLumi HiLumi LHC-LARP Annual Meeting

[1] N.V. Volkenshtein, L.S. Starostina, V. Ye. Startsev and Ye. P. Romanov, Phys. Met. Metallogr. (USSR) 18, 85 (1964)

Eddy currents BS (4)

Estimate of transfer function of the BS using the simple model of a round beam pipe (only damping term) for the HL-LHC triplet



$$K/K_0 = \frac{1}{\sqrt{1+\omega^2\tau^2/4}}$$

with

$$\tau = \mu_0\sigma_c bt/2$$

and cutoff frequency

$$f_{\text{cutoff}} = 1/(\tau\pi)$$

high conductivity and large thickness are beneficial for (decrease f_{cutoff})

Eddy currents BS (5)

Cutoff frequencies using the simple round beampipe model (HL-LHC IT):

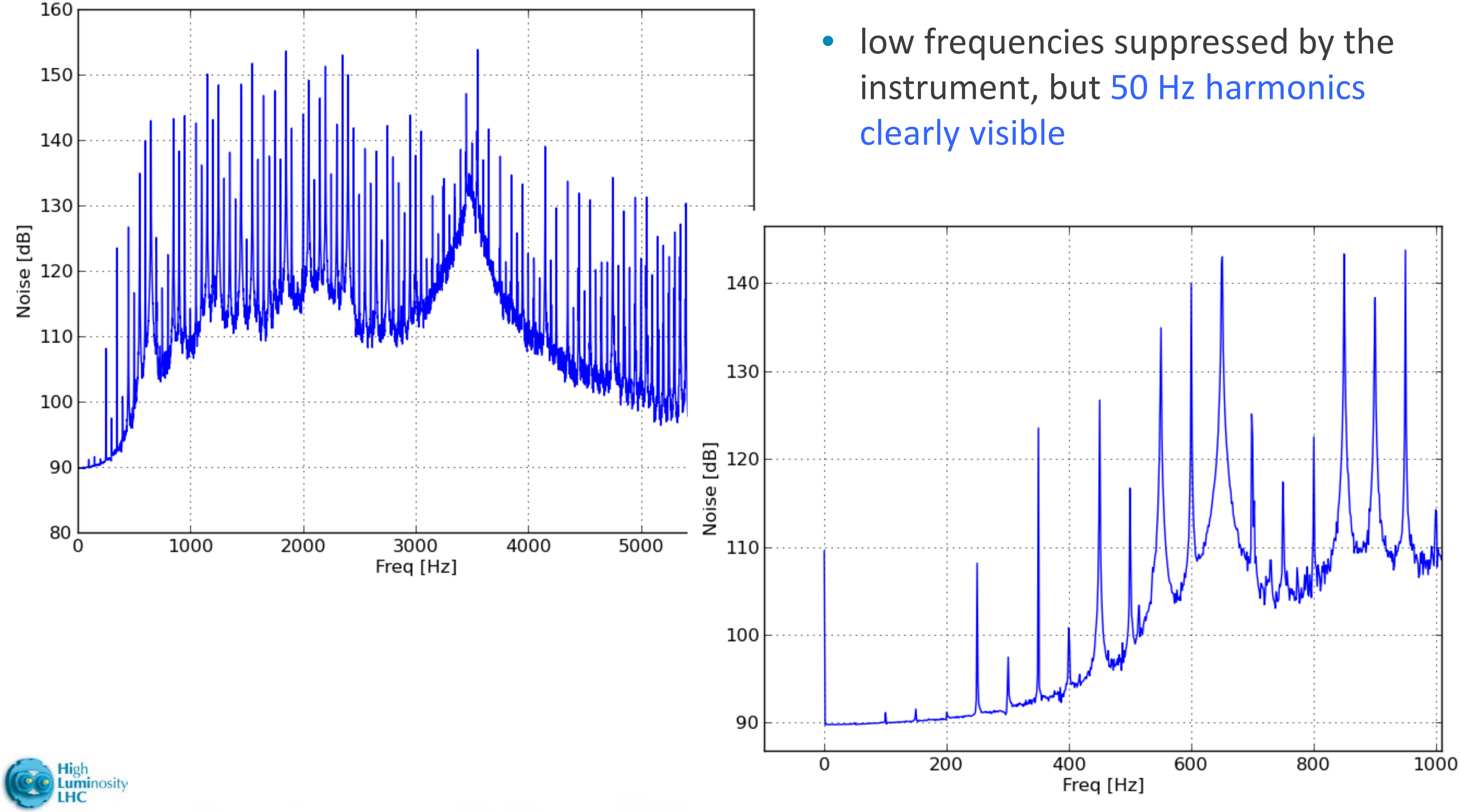
name	d_{BS}	σ_c	$f_{cuttoff}$	K/K_0						
	mm	$[10^9 x(\Omega m)^{-1}]$	[Hz]	DC	1 Hz	50 Hz	100 Hz	300 Hz	600 Hz	9 kHz $[10^{-6}]$
Q1	1	1.0	10.03	1.0	0.99	0.197	0.100	0.033	0.017	1115.0
Q2/Q3	1	1.0	8.37		0.99	0.165	0.084	0.028	0.014	930.4
Q1	8	1.0	1.25		0.78	0.025	0.013	0.004	0.002	139.3
Q2/Q3	8	1.0	1.05		0.72	0.021	0.010	0.003	0.002	116.3
Q1	16	1.0	0.63		0.53	0.013	0.006	0.002	0.001	69.67
Q2/Q3	16	1.0	0.52		0.46	0.010	0.005	0.002	0.001	58.15
Q1	16	0.1	6.27		0.98	0.124	0.063	0.021	0.010	696.7
Q2/Q3	16	0.1	5.23		0.98	0.104	0.052	0.017	0.009	581.5

high conductivity and large thickness are beneficial for (decrease f_{cutoff})

Frequency spectrum (1)

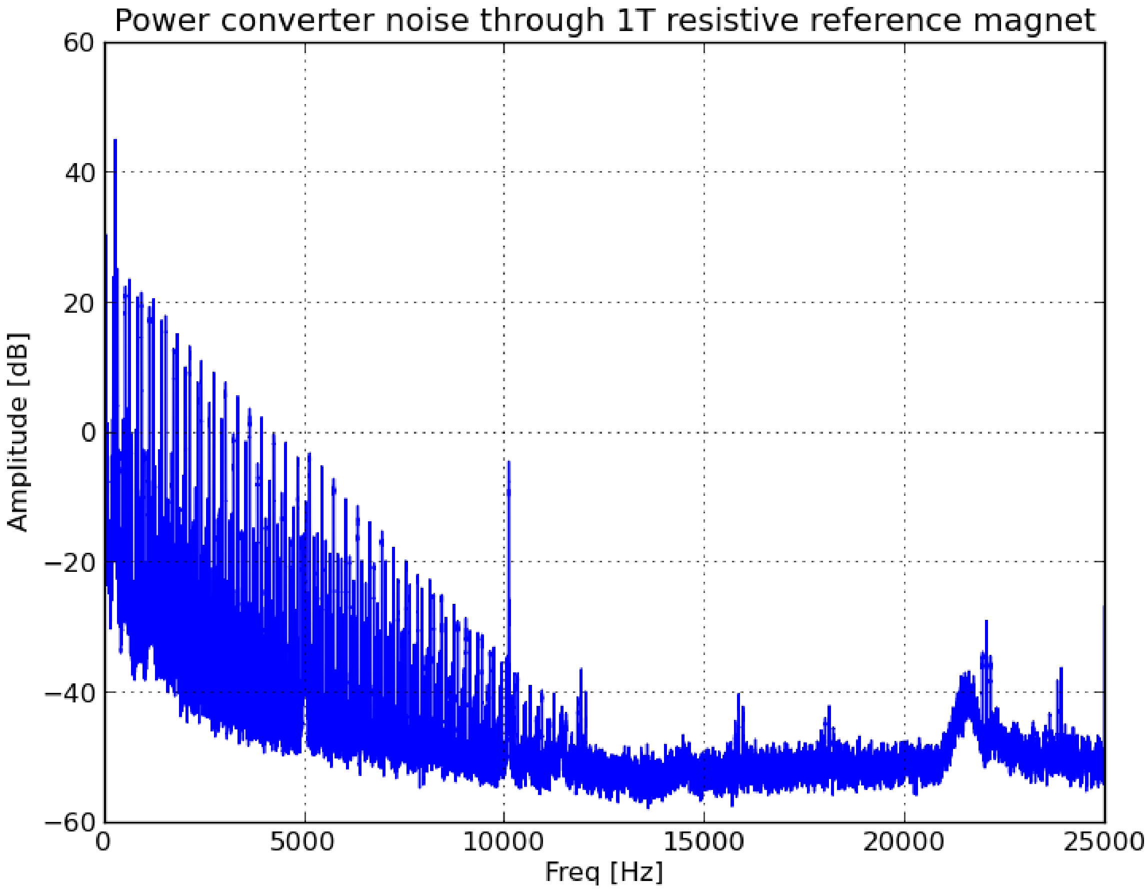
a) BBQ beam spectrum

- low frequencies suppressed by the instrument, but 50 Hz harmonics clearly visible



Frequency spectrum (2)

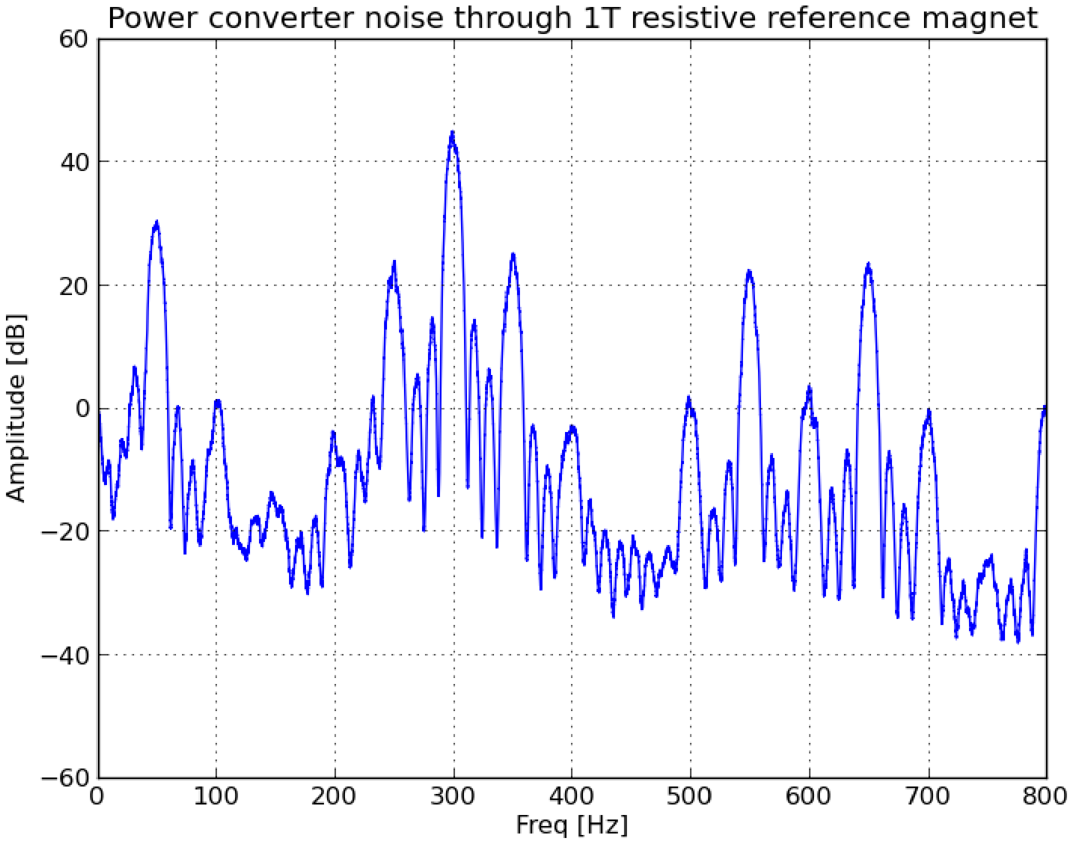
b) Noise of LHC type power converter through 1T resistive reference magnet



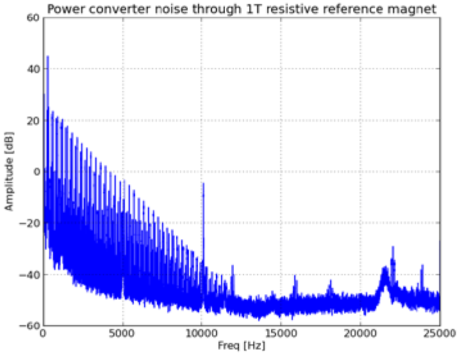
- 50 Hz harmonics
- peak at 10kHz

Frequency spectrum (3)

b) Noise of LHC type power converter through 1T resistive reference magnet (continued)



[0,800Hz] extract of



50 Hz harmonics clearly visible!

DA studies with SixTrack

Tune Ripple in SixTrack (1)

a) Tune ripple implementation in SixTrack

$$k(\mathrm{nturn}) = k_0 \cdot \cos(2\pi(\mathrm{nturn}-1)/f_{\mathrm{ripple}} + \phi_{\mathrm{ripple}})$$

SixTrack Input:

1. Introduce new thin quadrupole as ripple element with kl>1.0e-09 (otherwise SixTrack does not include the element) in mask file

```
dmqx1l5  : multipole, knl:={0, dkx1l5*bv_aux};
dmqx2l5  : multipole, knl:={0, dkx2l5*bv_aux};
…
seqedit,sequence=lhcb1;
  install, element=dmqx1L5,at=-posQ1,from=IP5;
  install, element=dmqx2L5,at=-posQ2,from=IP5;
endedit;
…
dkx1l5=1.0e-09
dkx2l5=1.1e-09
```

Note: one thin quadrupole per ripple frequency, assign different strength to each thin quadrupole (otherwise they are treated as the same element)

Tune Ripple in SixTrack (2)

SixTrack Input (continued):

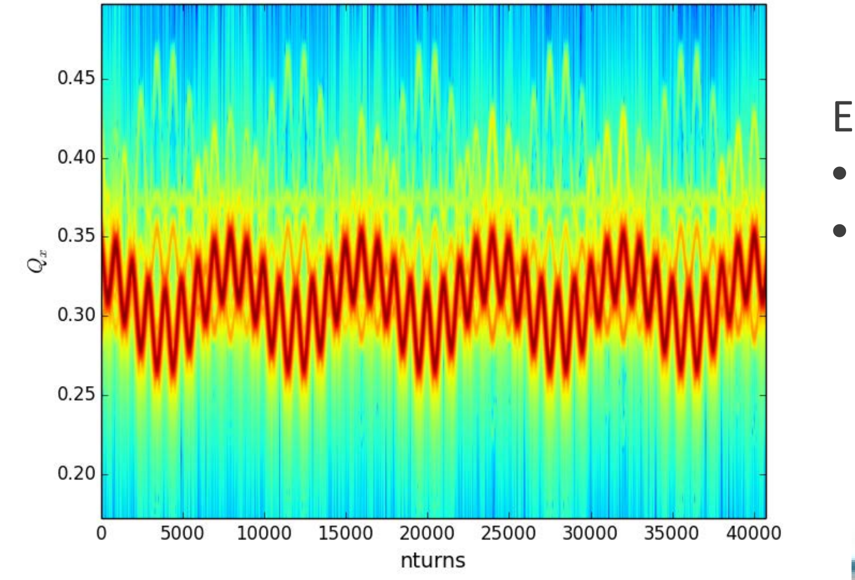
1. Define ripple in fort.3.mother2_col:

phase in rad

```
RIPPLE OF POWER SUPPLIES------------------------
          dmqx1l5  -4.934D-5    8000.0                0
          dmqx2l5  -4.934D-5    1000.0                0
```

k*l (k<0 for hor. foc. quad, overwrites initial strength dkx1l5)

ripple frequency in number of turns e.g. f=50 Hz => $f_{SixTrack}=f_{rev}/50=11245/50$

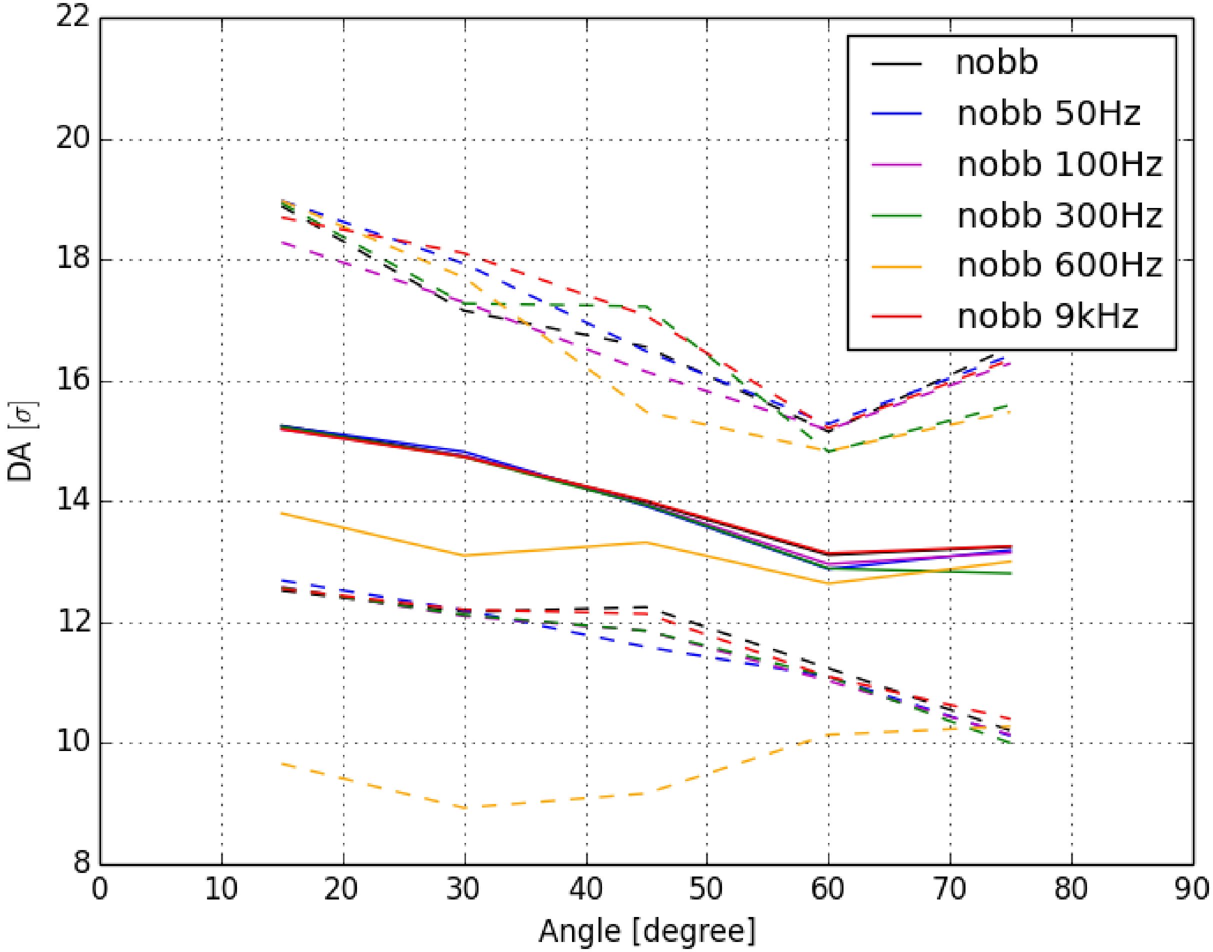


Example of two different ripple frequencies:

- f_1=8000.0, f_2=1000.0
- $dkl_1=dkl_2$=-4.934e-04 (resulting approx. in ΔQ=+/-0.04)

DA results without beam-beam (1)

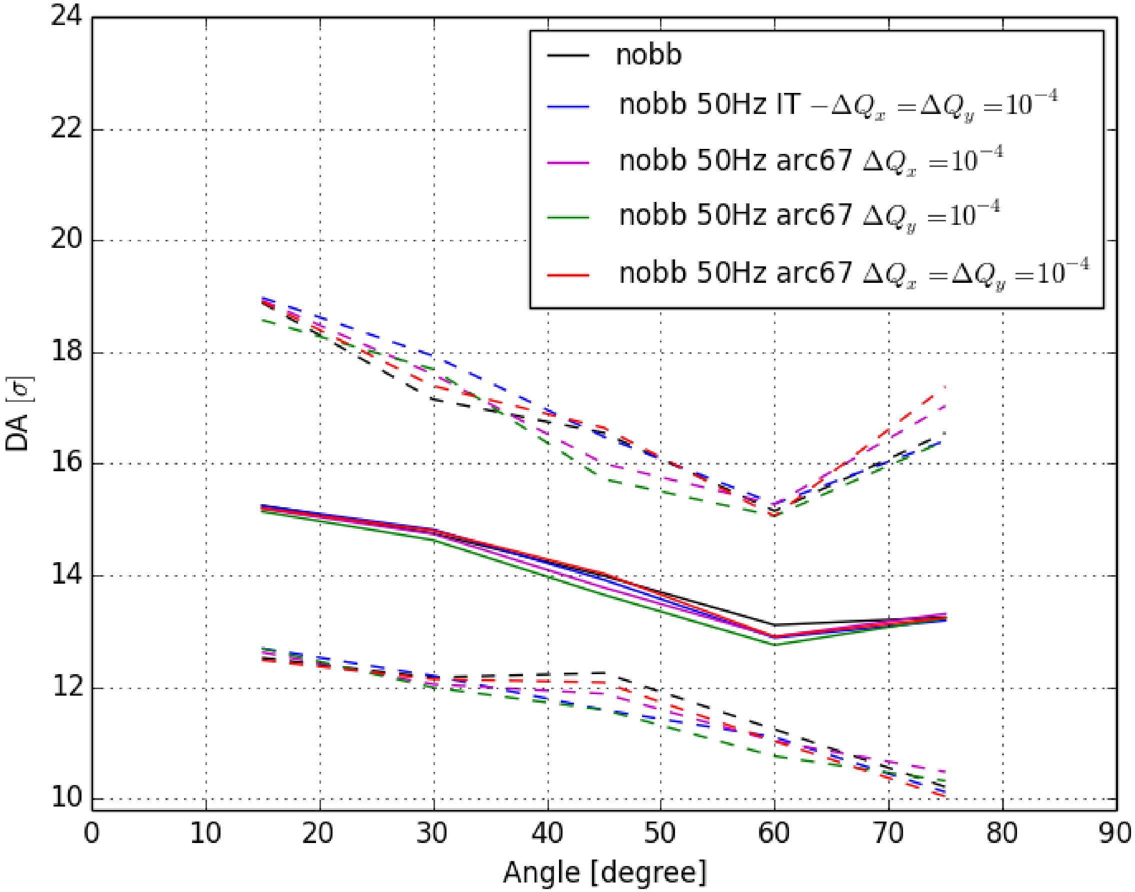
b) Tracking results without beam-beam, optics sLHCV3.1b, seeds=60, nturns=10^6, ripple on main power supply (no trim) of IT (IR1/5) with dk=2.069e-8 (all in phase), single frequency resulting in a max. tune shift of approx. $\Delta Q_x=-1.0\times10^{-4}$ and $\Delta Q_y=+1.0\times10^{-4}$



- Small DA change for 50 Hz, 100 Hz, 300Hz and 9kHz
- Large DA reduction (>2σ) for 600Hz
- note: in reality attenuation of higher frequencies (here we assume same amplitude for all frequencies) due to magnet impedance, eddy currents in BS etc.

DA results without beam-beam (2)

b) Tracking results without beam-beam, optics sLHCV3.1b, seeds=60, nturns=10^6, ripple main quads in arc67 (all in phase), single frequency of f=50Hz with dk chosen to obtain a max. tune shift of (ΔQ_x=-1.0x$10^{-4,}$ ΔQ_y=0) and (ΔQ_x=0,ΔQ_y=+1.0x10^{-4}) and (ΔQ_x=-1.0x10^{-4},ΔQ_y=+1.0x10^{-4})

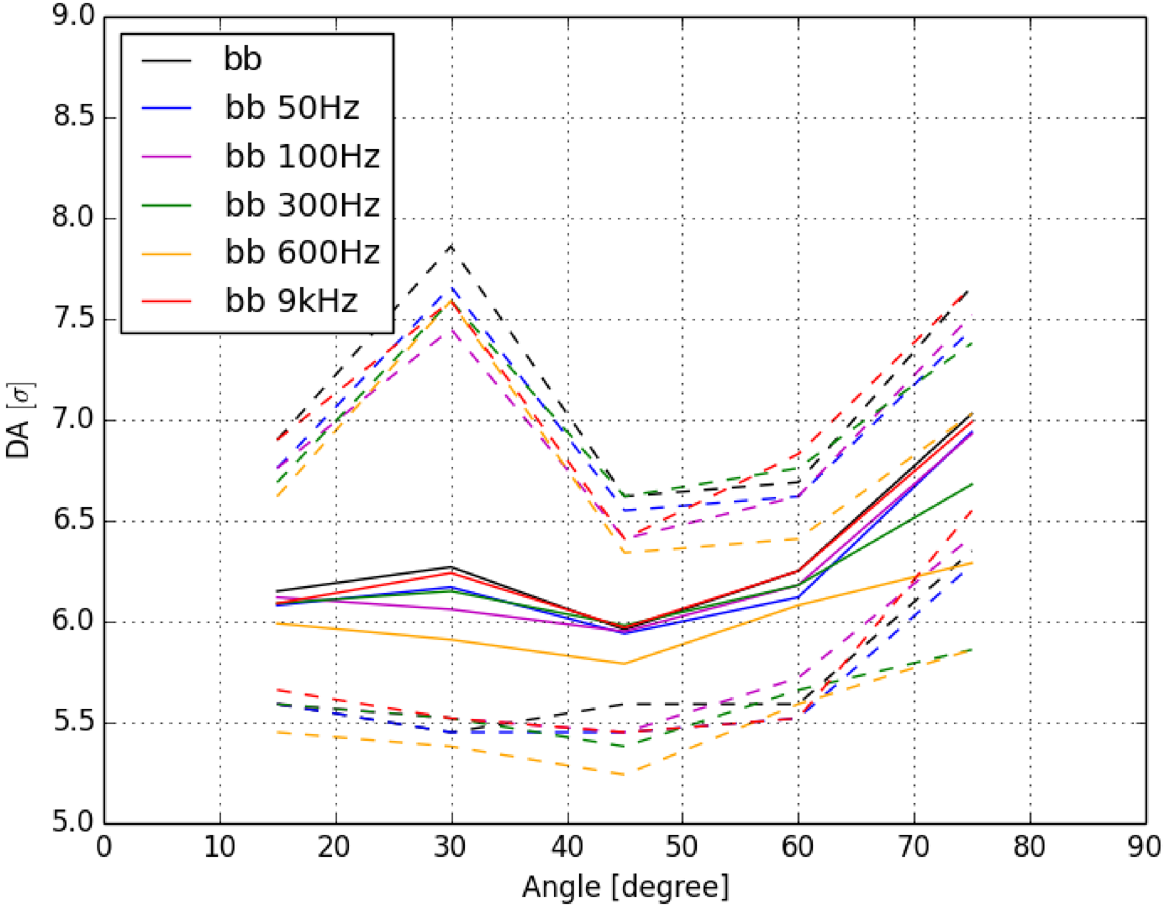


no real difference between:

- localized ripple (IT) compared to distributed ripple (arc)
- hor. and vert. plane

DA results with beam-beam (1)

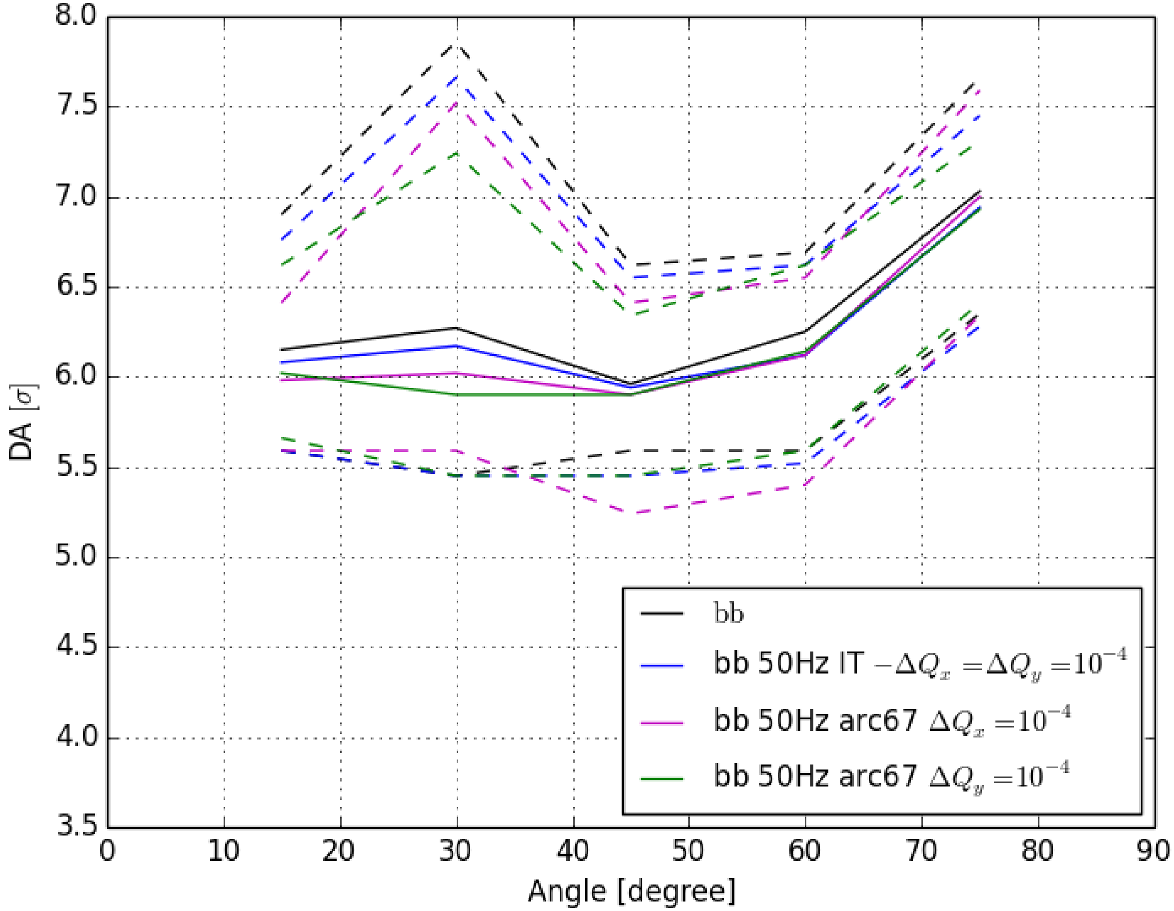
b) Tracking results with beam-beam, optics sLHCV3.1b, seeds=60, nturns=10^6, ripple on main power supply (no trim) of IT (IR1/5) with dk=2.069e-8 (all in phase), single frequency resulting in a max. tune shift of approx. $\Delta Q_x=-1.0\times10^{-4}$ and $\Delta Q_y=+1.0\times10^{-4}$



- Small DA change for 50 Hz, 100 Hz and 9 kHz
- DA reduction (<1σ) for 600 Hz and also 300Hz

DA results with beam-beam (2)

b) Tracking results with beam-beam, optics sLHCV3.1b, seeds=60, nturns=10^6, ripple main quads in arc67 (all in phase), single frequency of f=50Hz with dk chosen to obtain a max. tune shift of (ΔQ_x=-1.0x$10^{-4,}$ ΔQ_y=0) and (ΔQ_x=0,ΔQ_y=+1.0x10^{-4})



- DA of localized ripple (IT) similar to distributed ripple (arc)
- slightly more sensitive to vert. plane?

Summary and conclusions

1) Harmonics of 50 Hz visible in all spectra
2) Reduction of field ripple for higher frequencies due to the magnet impedance and eddy currents in BS, cold bore etc.
3) Tracking studies w/o beam-beam, single ripple frequency (50 Hz, 100 Hz, 300 Hz and 9 kHz) and a max. tune shift of 10^{-4} only show a considerable reduction for 600 Hz w/o beam-beam and also a reduction for 300 Hz with beam-beam

Next steps

1) Refine model of Transfer function

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

explicitly:

   a) magnet impedance/resistance of new IT magnets (T_{VtoI})?
   b) transfer function from current to field (T_{ItoB}), in particular: Is it linear? Does the magnetic field scale with the max. current (trim power supplies)?
   c) more realistic model of the BS, cold bore, absorbers etc. (eventually with the same code used for quench analysis – Opera3d?)

2) Tracking studies:

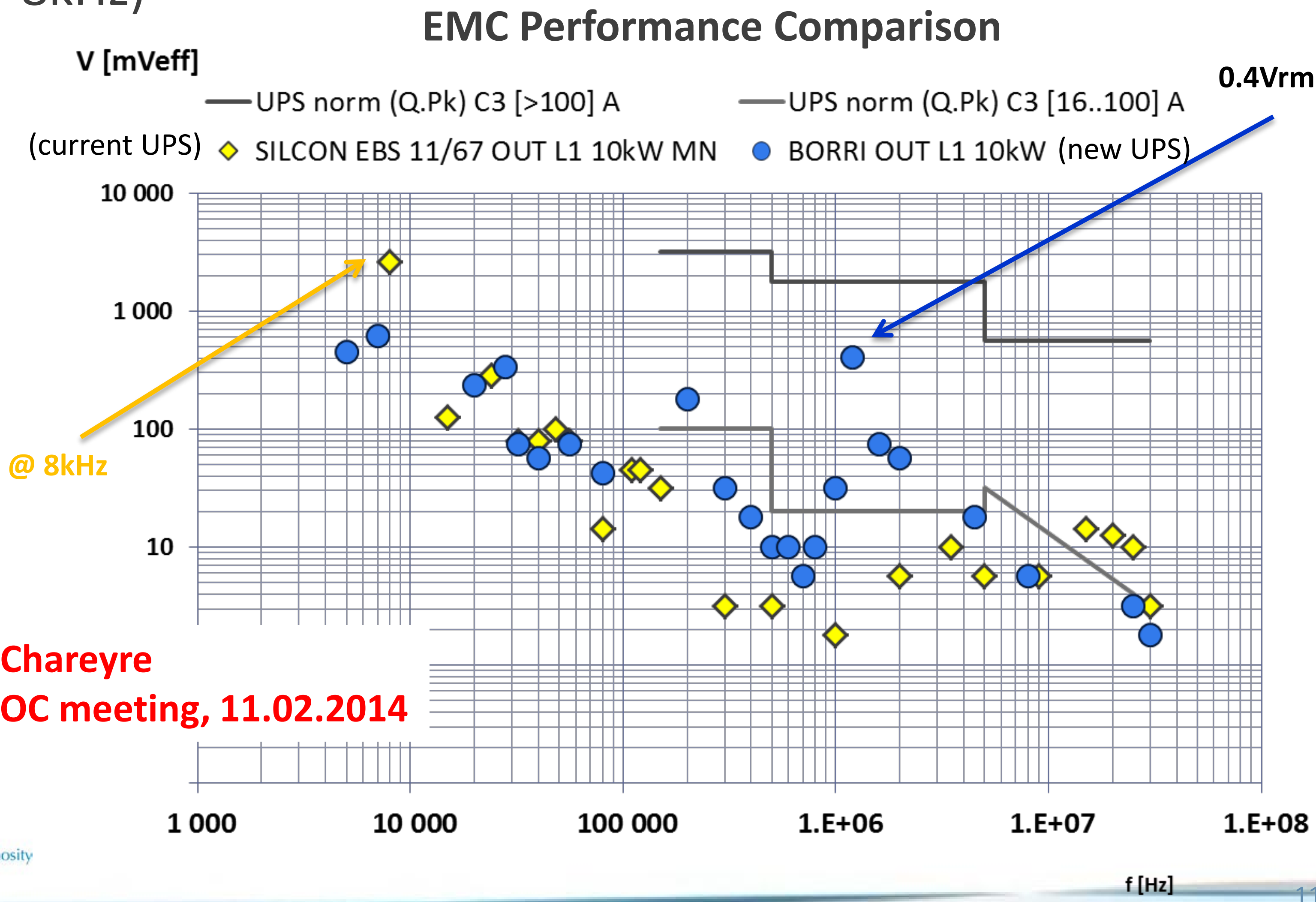
   a) DA for single frequencies for 50 Hz harmonics
   b) DA for several frequencies
   c) Is the standard SixTrack DA analysis the best way of analysis?

High
Luminosity
LHC

The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404.

Noise form UPS system

d) mainly high frequency noise from UPS system (current one at 8kHz)



0.4Vrms @ 1MHz

3Vrms @ 8kHz

V. Chareyre
LBOC meeting, 11.02.2014

SixTrack simulation setup

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_v65) and D1 (D1_errortable_v0), no errors for D2/Q4 and Q5 in IR1/5
sixtrack simulation parameters:
60 seeds, 10^6 turns, 5 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
- scan from 2-20σ in steps of 2σ with 30 points per step

beam-beam:

- HO and LR in IR1/2/5/8, no crab cavities, no additional LR encounters in D1, 5 slices for HO bb
- halo collision in IR2 at 5 sigma
- scan from 2-14σ in steps of 2σ with 30 points per step