Amendment to HL-LHC circuits specifications

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137th HiLumi WP2 Meeting – 11/12/2018

Requests and References

- **Requests** from WP6b:
  - Verify **new PC specifications**.
  - Can the HL-LHC **120A PCs** be classified as **class 4** (**instead** of **3**), as the LHC ones?
  - Can the HL-LHC **RQSX** circuits be powered by a **600A** PC?
    - **instead** of **200A** -> i.e. 3 times more "noisy"
  - Can the HL-LHC **RTB8** circuit be powered by a **600A** PC?
    - **instead** of **300A** -> i.e. 2 times more "noisy"
  - Do we need to create a **new class "1-2"** for HL-LHC 2kA?
  - Can we **replace "remote" by "on request"** PC **calibrations**?

- Additional **questions** within WP2:
  - What is the **maximum separation collapse speed** we can achieve?

- **References**:
  - **WP2** original document CERN-ACC-2017-0101
  - New specifications by **EPC**: EDMS #2048827
  - **Amendment** on Overleaf (read-only) link

New specifications (w.r.t. old ones)

Optimistic value could be <u>0.12</u>
!!! preliminary – Dec2018 !!!

New class

PC class:	0^a	1^a	1-2	2	3	4
Setting resolution [ppm]	0.5	0.5	0.5	1	1	1
Initial uncertainty after cal. [2×r.m.s. ppm]	2	2	2	~~5~~ (3)	~~10~~ (7)	~~20~~ (10)
Linearity [|.| max ppm]	2	2	2	5	~~10~~ (8)	~~10~~ (9)
Stability during a fill (12 h) [~~|.| max~~ (2×r.m.s.) ppm]	1	2	7	~~5~~ (15.5)	~~5~~ (34)	~~20~~ (40)
Short term stability (20 min) [2×r.m.s. ppm]	0.2	0.4	0.3	~~1~~ (1.2)	2	5
Noise (0.1-500 Hz) [2×r.m.s. ppm]	3	5	4	~~10~~ (7)	15	~~25~~ (19)
Fill-to-fill repeatability [2×r.m.s. ppm]	~~0.5~~ (0.7)	~~1~~ (1.6)	7	~~2~~ (14.5)	~~5~~ (32)	~~10~~ (38)
Long term fill-to-fill stability [~~|.| max~~ (2×r.m.s.) ppm]	~~10~~ (9.5)	~~10~~ (9.5)	11.5	~~20~~ (26.5)	~~50~~ (56)	~~100~~ (64)

- Take into account **better estimate of ambient temperature** variation at the location where PC are typically installed
- All values (but "Noise") are for ***f* < 0.1 Hz**.
  - At higher frequency the PC works in voltage-regulation.
  - **Assumption**: the effective (e.g. dumped by inductance etc.) **B field jitter** due to <u>voltage ripple at any frequency</u> is **<< current jitter at low *f***.
    - …still one should be **careful** to **resonances**...
- Introduced a new possible **PC class (1-2)**
  - Is a class 2 PC with a different ADC module.
  - **Significant additional cost** (about 200 kCHF more in total) if we "buy" it!

Main parameters for each (main) circuit

Circuit name	I_{rated} [A]	PC class	Short term stability [ppm 2×r.m.s.]	Stability during a fill (12 h) [ppm 2×r.m.s.]	Long term fill-to-fill stability [ppm 2×r.m.s.]
RB[a]	13000	1	0.4	2	~~10~~ (9.5)
RQ(D/F)[a]	13000	1	0.4	2	~~10~~ (9.5)
RQX	18000	0	0.2	1	~~10~~ (9.5)
RTQX1	2000	2	~~1~~ (1.2)	~~5~~ (15.5)	~~20~~ (26.5)
RTQXA1[b]	~~120~~ (60)	4	5	~~20~~ (40)	~~100~~ (64)
RTQX3	2000	2	~~1~~ (1.2)	~~5~~ (15.5)	~~20~~ (26.5)
RCBX	2000	2	~~1~~ (1.2)	~~5~~ (15.5)	~~20~~ (26.5)
RQSX[d]	~~200~~ (600)	3	2	~~5~~ (34)	~~50~~ (56)
RC(S/O)X	120	~~3~~ (4)	~~2~~ (5)	~~5~~ (40)	~~50~~ (64)
RC(D/T)X	120	~~3~~ (4)	~~2~~ (5)	~~5~~ (40)	~~50~~ (64)
RD(1/2)	13000	0	0.2	1	~~10~~ (9.5)
RCBRD	600	3	2	~~5~~ (34)	~~50~~ (56)
RQ(4/5)[a]	6000	2	~~1~~ (1.2)	~~5~~ (15.5)	~~20~~ (26.5)
RCBY[a]	120	4	5	~~20~~ (40)	~~100~~ (64)
RQ6[a]	6000	2	~~1~~ (1.2)	~~5~~ (15.5)	~~20~~ (26.5)
RCBC[a]	120	4	5	~~20~~ (40)	~~100~~ (64)
RTB8[c]	~~300~~ (600)	3	2	~~5~~ (34)	~~50~~ (56)

[a] Existing circuit assumed not to be upgraded.

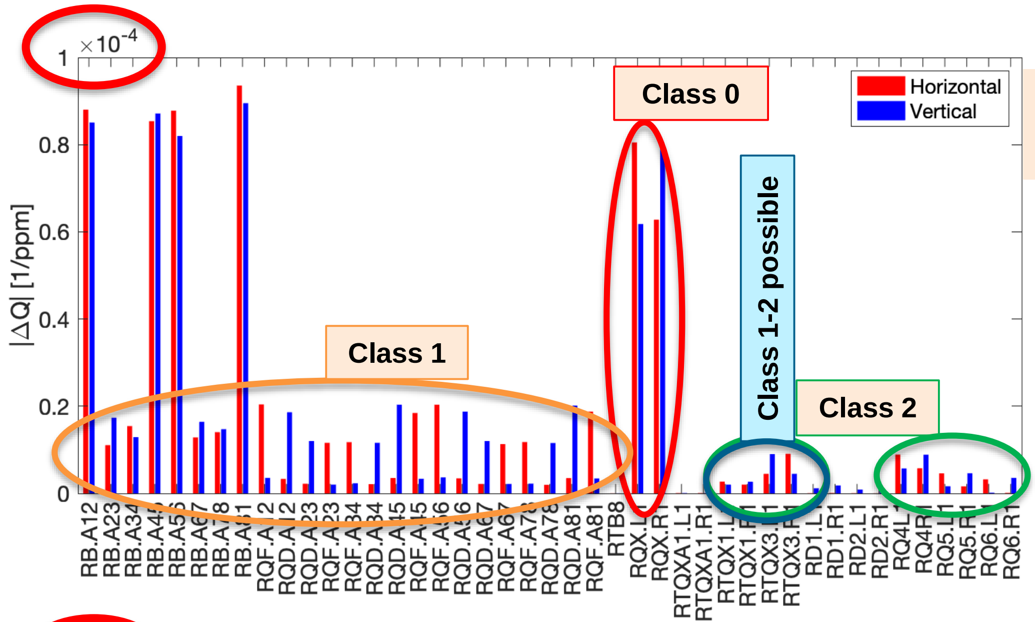
[b] The rated current for this circuit has not been defined yet. The proposed value is compatible with the use of the trim as $I_{max} = 35$ A in operation.

[c] A standard 600 A PC of class 3 is assumed even though $I_{max} = 250$ A in operation.

[d] A standard 600 A PC of class 3 is assumed even though $I_{max} = 200$ A in operation.

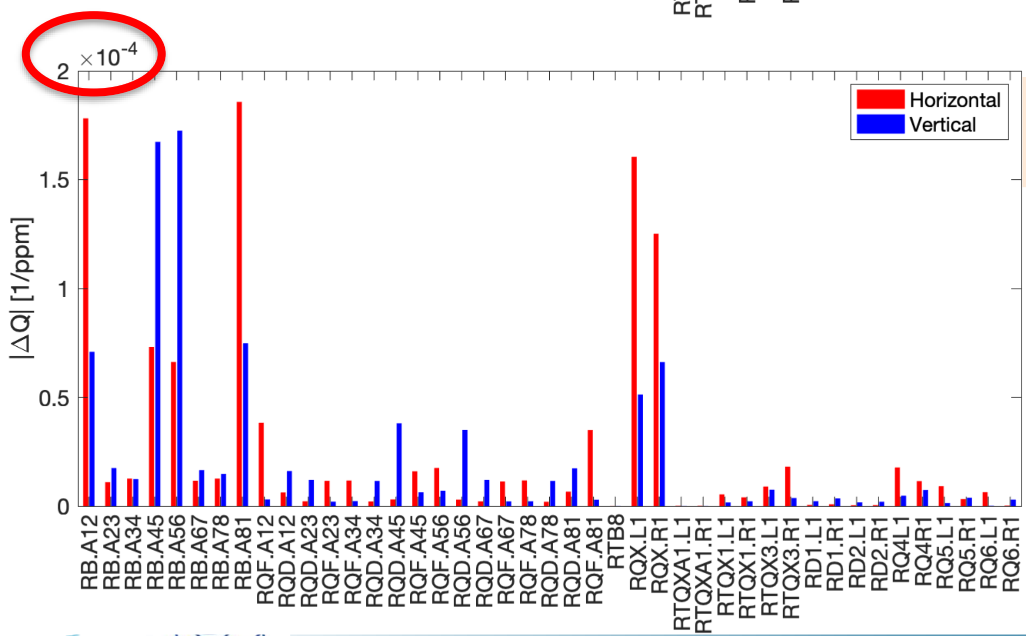
Before given as ~~I~~ I_{max}

Optics sensitivity: impact on tune



HL-LHC 1.3 baseline optics
Beta* = 15cm

- “ATS” arcs as important as triplet in IR1/5
- Already presented in previous WP2 meetings (99th) and CERN-ACC-2017-0101



HL-LHC 1.3 flat optics
Beta* = 7.5-18cm

- Checking if flat optics (not baseline) are more demanding.
- Clearly asymmetric due to asymmetric betas
  - (IR5 H = IR1 V and vice versa)

Expected tune stability

- Old specifications vs. new specifications (15cm beta*):

Class 1-2 on new 2kA PCs

	Tune jitter [10^{-5} r.m.s.]					
	20min.		**12h fill**		**Long term**	
	Old	**New**	**Old**	**New**	**Old**	**New**
x	4.1 (2.8^+)	4.2 (2.9^+ 4.1^*)	23.9	26.6 (24.4^*)	138	116 (114^*)
y	4.1 (2.8^+)	4.1 (2.9^+ 4.0^*)	23.4	26.3 (24.2^*)	135	113 (112^*)
Target	< 1		n.a.		n.a.	

$^+$ Assuming to upgrade arc dipoles in sectors 8–1, 1–2, 4–5, 5–6 to class 0.

* Assuming to us… QX3 and RCBX circuits.

Class 0 on ATS arc dipoles

- New specifications. Round (15 cm) vs Flat (7.5-18cm)

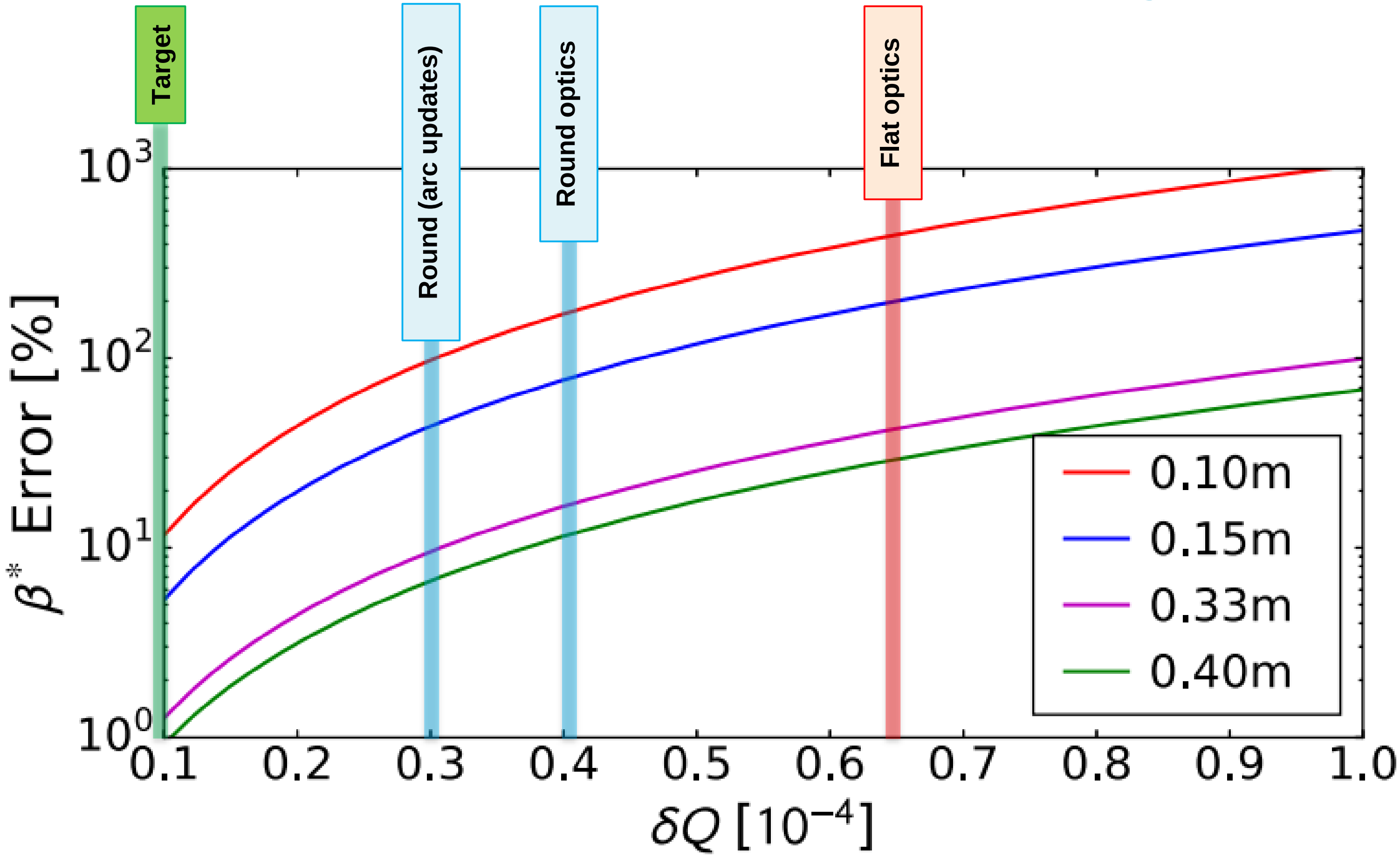
	Tune jitter [10^{-5} r.m.s.]					
	20min.		**12h fill**		**Long term**	
	15 cm	**7.5 cm**	**15 cm**	**7.5 cm**	**15 cm**	**7.5 cm**
x	4.2 (2.9^+)	6.4 (4.3^+)	26.6	40.7	116	177
y	4.1 (2.9^+)	6.3 (4.2^+)	26.3	39.9	113	172
Target	< 1		n.a.		n.a.	

$^+$ Assuming to… 8–1, 1–2, 4–5, 5–6 to class 0.

”Far” from target…

Order 10^{-3} over one year

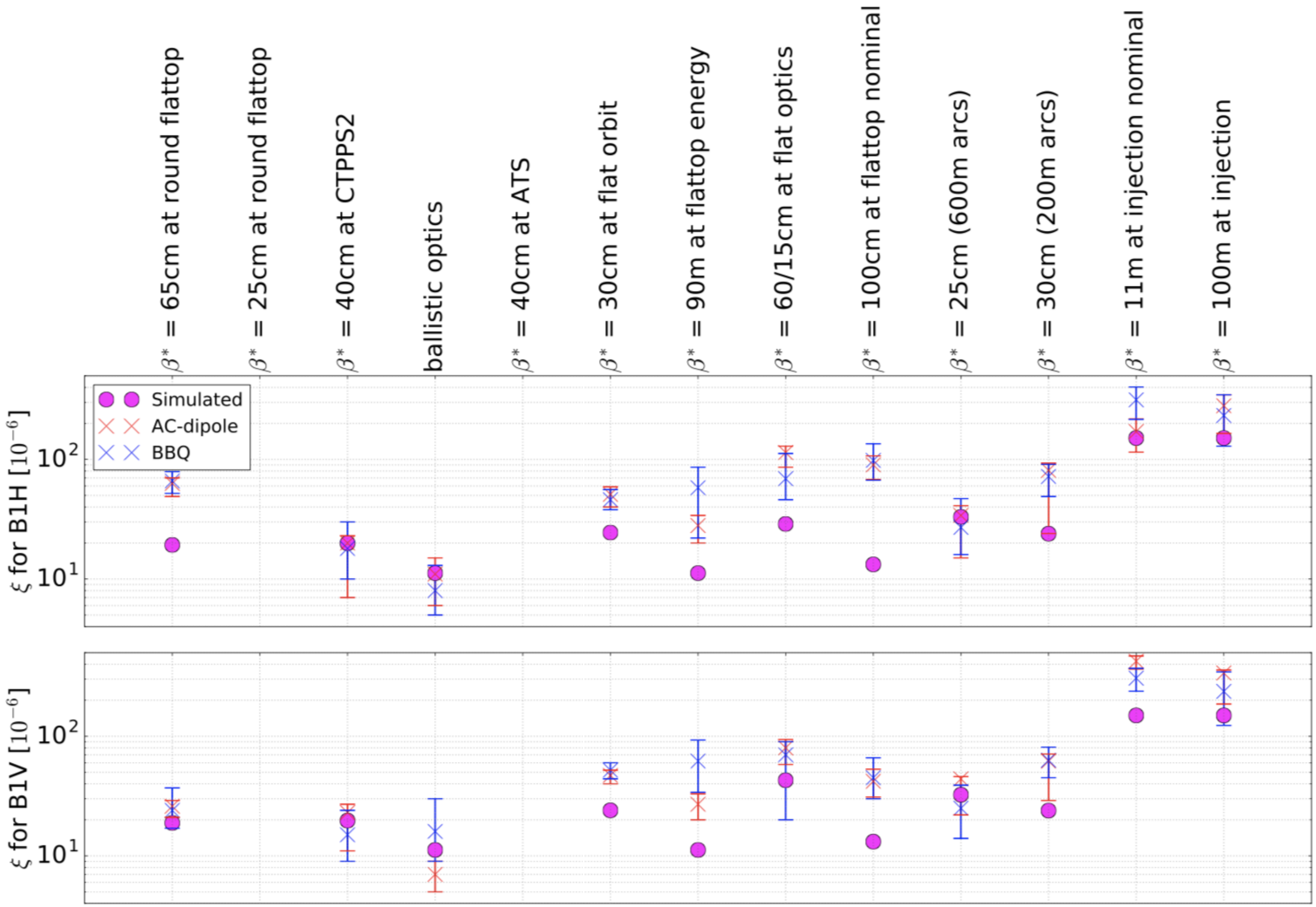
Reminder: beta* vs tune stability



- **The smaller beta* the more difficult** to measure/correct the optics
  - => danger for luminosity reach/imbalance.
  - Smaller beta* only toward the end of the fill with beta* levelling.

From PhysRevAccelBeams.20.011005

LHC experience: how far are we from PC noise limit?

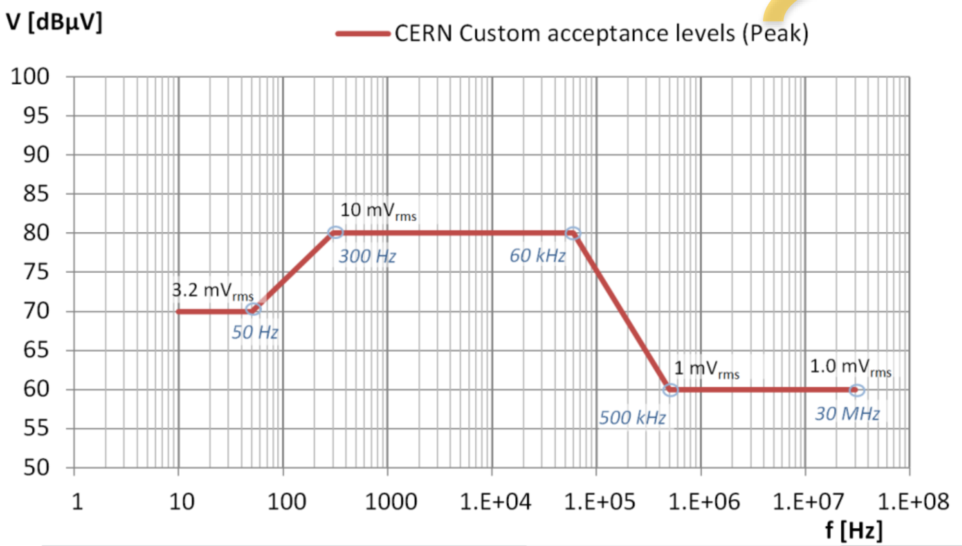


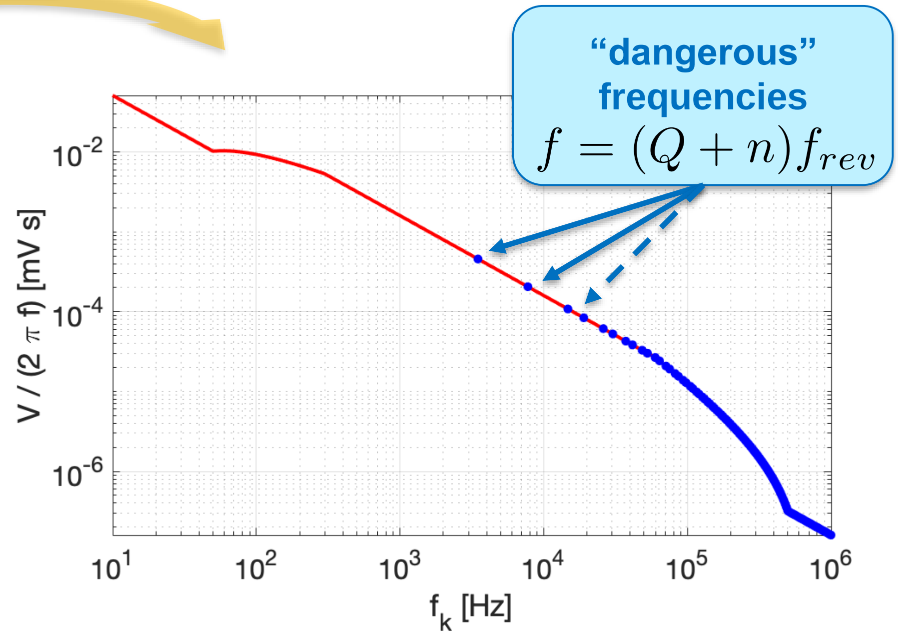
- Simulations seems to be consistent with observed tune jitter.

Observation: voltage ripple

$$\frac{\mathrm{d}B(f)}{B_{nom}} = \begin{cases} \frac{\mathrm{d}I(f)}{I_{nom}} & \text{for } f \le f_0 \\ T_{Vacuum}(f) \times T_{VtoB}(f) & \text{for } f > f_0 \end{cases}$$

$$\text{with: } T_{VtoB}(f) = T''_{VtoB}(f) \times \frac{\mathrm{d}V(f)}{2\pi f L_{DC} I_{nom}}$$





- This only give **acceptance levels**, it should be populated only by a few lines
- **No information between 0.1 and 10 Hz**
  - **We always assume that there are no lines there, but is it true?**

Voltage ripple -> current (from Gabarit)

Assuming acceptance level equal to **3.2 mV down to 0.1 Hz**
+ Simplified model

$$\frac{\mathrm{d}I(f)}{I_{rated}} \leq \frac{\mathrm{d}V(f)}{\sqrt{(2\pi f L_{DC})^2 + R_{DC}^2} I_{rated}}$$

Circuit name	I_{rated} [A]	L [mH]	R [mΩ]	$\Delta I/I_{rated}$ @0.1Hz @3.2mV [ppm rms]	$\Delta I/I_{rated}$ @10Hz @3.2mV [ppm rms]
RB[a]	13000	15708	1	<0.1	«0.1
RQ(D/F)[a]	13000	263	1	1.5	<0.1
RQX	18000	255	0.3	1.1	<0.1
RTQX1	2000	69	1.4	37	0.4
RTQXA1[b]	~~120~~ (60)	34.5	n.a.	4213	42
RTQX3	2000	69	1.4	37	0.4
RCBX	2000	29	1.5	101	1
RQSX[d]	~~200~~ (600)	1247	10	20.4	0.2
RC(S/O)X	120	118	13	354	3.6
RC(D/T)X	120	52	13	755	8
RD(1/2)	13000	25	0.2	16	0.2
RCBRD	600	600	1	18	0.2
RQ(4/5)[a]	6000	74	0.6	18	0.2
RCBY[a]	120	5270	n.a.	10	0.1
RQ6[a]	6000	21	0.5	52	0.5
RCBC[a]	120	2840	n.a.	20	0.2
RTB8[c]	~~300~~ (600)	127	12.9	158	1.6

Would be unacceptable values!

Realistic?

Extreme! PC should normally still be in current regulation… **(not specified anywhere(?))**

Voltage ripple -> current (from PC "Noise")

Assuming "Noise" value is measured with **L = 1mH** (or less)
+ Simplified model

$$\frac{\mathrm{d}I(f)}{I_{rated}} \leq Noise \times \frac{1[mH]}{L[mH]}$$

Careful:
at **high *f* L** might actually **decrease**…

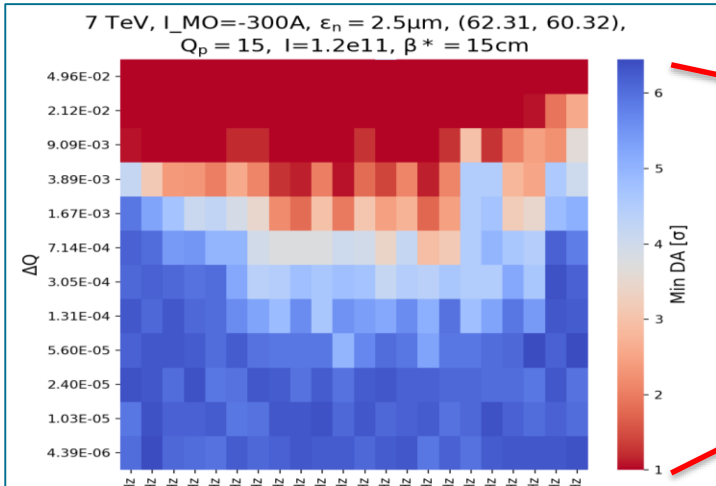
PC class:	0[a]	1[a]	1-2	2	3	4
Noise (0.1-500 Hz) [2×r.m.s. ppm]	3	5	4	~~10~~ (7)	15	~~25~~ (19)

Circuit name	I_{rated} [A]	L [mH]	PC class	Short term stability	Noise	Scaled Noise
RB[a]	13000	15708	1	0.4	5	<0.1
RQ(D/F)[a]	13000	263	1	0.4	5	<0.1
RQX	18000	255	0	0.2	3	<0.1
RTQX1	2000	69	2	1.2	7	0.1
RTQXA1[b]	60	34.5	4	5	19	0.6
RTQX3	2000	69	2	1.2	7	0.1
RCBX	2000	29	2	1.2	7	0.2
RQSX[d]	600	1247	3	2	15	<0.1
RC(S/O)X	120	118	4	5	19	0.2
RC(D/T)X	120	52	4	5	19	0.4
RD(1/2)	13000	25	0	0.2	3	0.1
RCBRD	600	600	3	2	15	<0.1
RQ(4/5)[a]	6000	74	2	1.2	7	0.1
RCBY[a]	120	5270	4	5	19	<0.1
RQ6[a]	6000	21	2	1.2	7	0.3
RCBC[a]	120	2840	4	5	19	<0.1
RTB8[c]	600	127	3	2	15	0.1

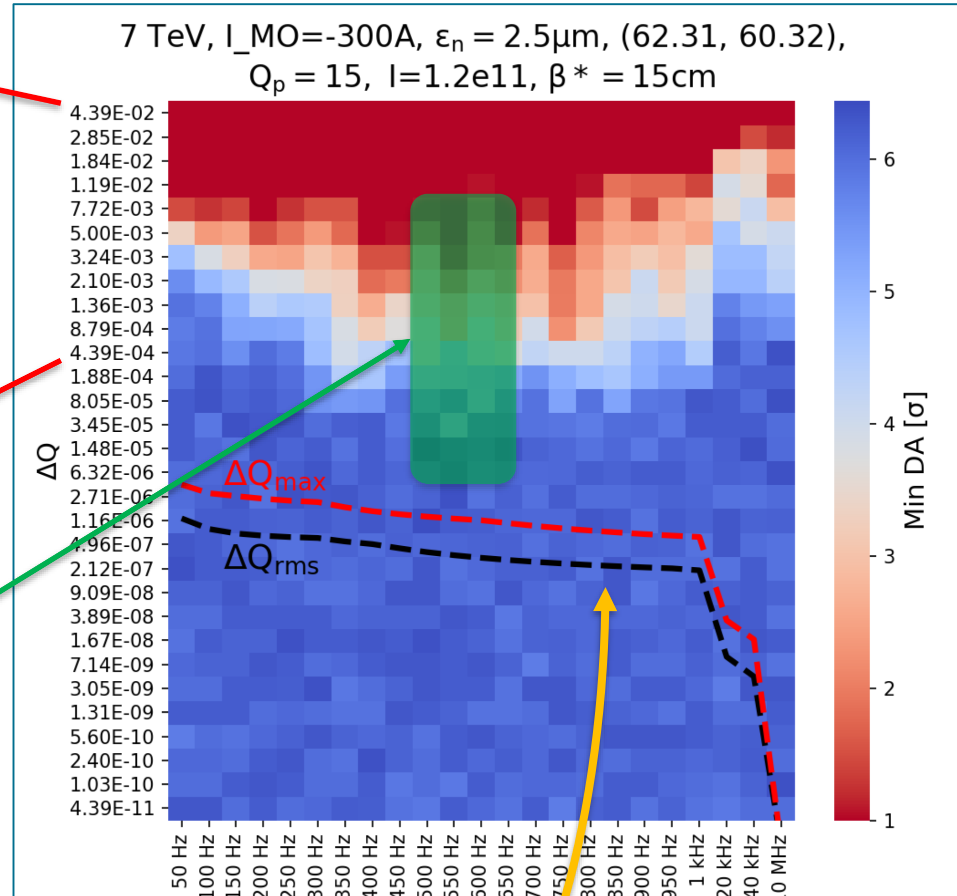
More reasonable values… but but but…

Dynamic Aperture studies

Preliminary
by S. Kostoglou

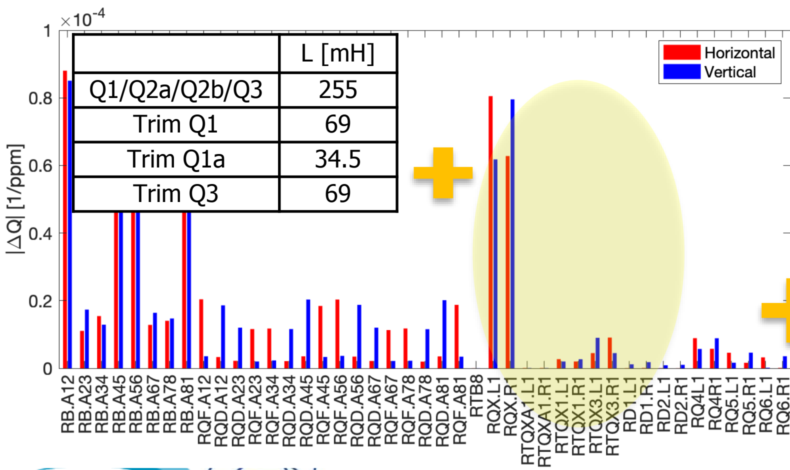


With CC (no major difference)



Without CC

Similar study in **LHC**, gives similar reduction of DA @600Hz for **ΔQ=2e-4**.



	L [mH]
Q1/Q2a/Q2b/Q3	255
Trim Q1	69
Trim Q1a	34.5
Trim Q3	69

$$\frac{\mathrm{d}I(f)}{I_{rated}} \leq \frac{\mathrm{d}V(f)}{(2\pi f L_{DC}) I_{rated}}$$

Seems like **we are safe!**

Careful: at **high *f* L** might actually **decrease**…

Also: Expected Orbit Stability

- Old specifications vs. new specifications (15cm beta*):

	$\Delta(x^*\|y^*)$ [10^{-2} σ_{beam} **r.m.s.**]					
	20min.		**12h fill**		**Long term**	
	Old	**New**	**Old**	**New**	**Old**	**New**
IP1 H	0.3 (0.2^+)	0.3 (0.3^+ 0.3^*)	1.3	2.6 (2.1^*)	8.8	8.2 (7.7^*)
IP1 V	0.2 (0.2^+)	0.2 (0.2^+ 0.2^*)	1.1	2.3 (1.8^*)	6.2	4.7 (4.0^*)
IP5 H	0.3 (0.3^+)	0.3 (0.3^+ 0.3^*)	1.8	2.7 (2.2^*)	11.2	8.9 (8.4^*)
IP5 V	0.2 (0.2^+)	0.2 (0.2^+ 0.2^*)	1.2	2.3 (1.8^*)	6.4	4.8 (4.1^*)

$^+$ Assuming to upgrade arc dipoles in sectors 8–1, 1–2, 4–5, 5–6 to class 0.

* Assuming to use class 1-2 PC for RTQX1, RTQX3 and RCBX circuits.

- New specifications. Round (15 cm) vs Flat (7.5-18cm)

	$\Delta(x^*\|y^*)$ [10^{-2} σ_{beam} **r.m.s.**]					
	20min.		**12h fill**		**Long term**	
	15 cm	**7.5 cm**	**15 cm**	**7.5 cm**	**15 cm**	**7.5 cm**
IP1 H	0.3 (0.3^+)	0.3 (0.3^+)	2.6	3.0	8.2	9.2
IP1 V	0.2 (0.2^+)	0.3 (0.3^+)	2.3	2.7	4.7	5.1
IP5 H	0.3 (0.3^+)	0.4 (0.4^+)	2.7	3.3	8.9	10.5
IP5 V	0.2 (0.2^+)	0.3 (0.3^+)	2.3	2.6	4.8	5.1

$^+$ Assuming ...

Negligible <<1% lumi loss | **Order 3%σ during fill** | **Order 10%σ over one year**

Other topic: orbit separation collapse

Other topic: orbit separation collapse

- +- 0.75 mm **separation knob** requires **very little strength** compared to total available.
- **Ramp/acceleration rate were chosen from orbit feedback considerations**

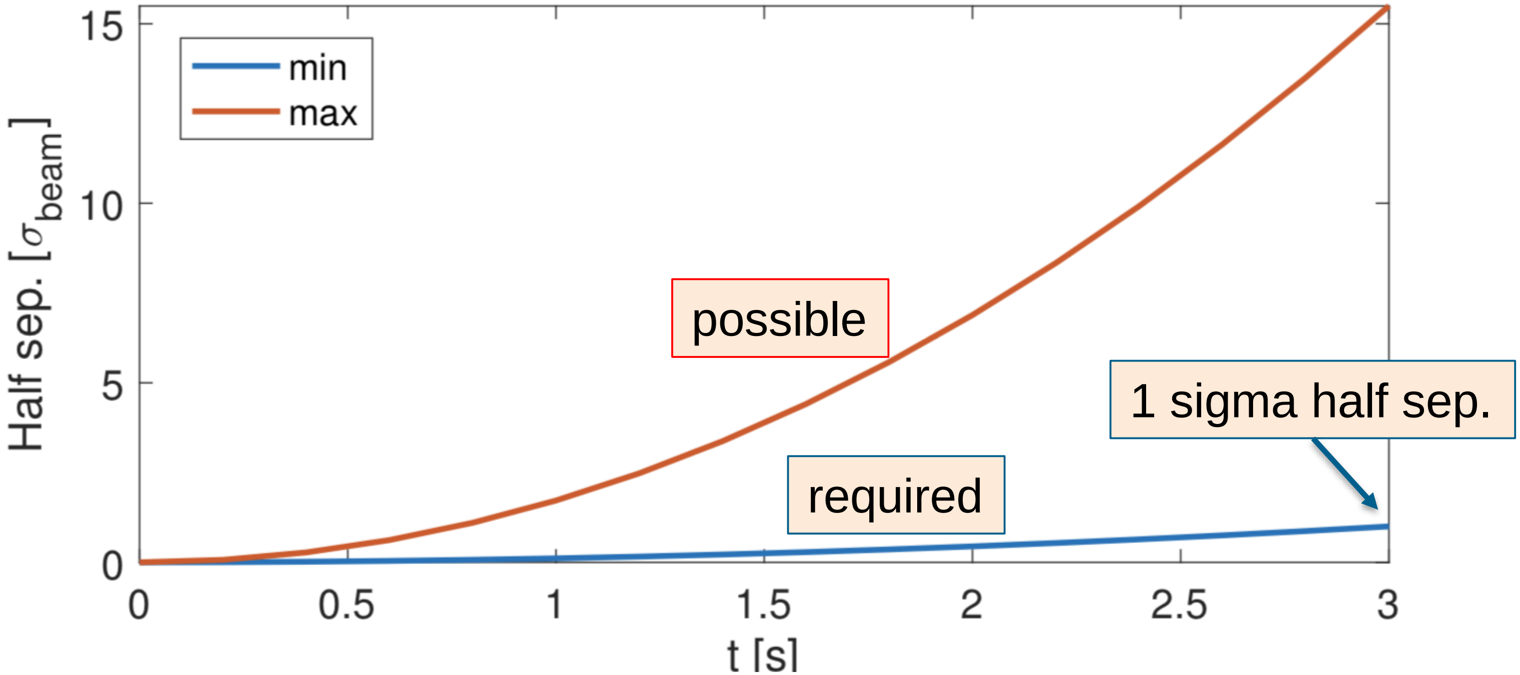
Circuit name	Half-separation [Tm]	$\int B_{nom}\mathbf{d}l$ [Tm]	I_{nom} [A]	Ramp rate [A/s]	Acceleration [A/s^2]
RCBX1	0.08	2.5	1600	15	5
RCBX2	0.08	2.5	1600	15	5
RCBX3	0.20	4.5	1600	15	5
RCBRD4	0.10	5	430	2	1
RCBY4	0.02	2.79	88	0.67	0.25

<<

From orbit feedback considerations

Other topics: orbit separation collapse

- **Requirement: from 2 to 0 beam sigma in less than 3 seconds**
- **Here assuming round beta* = 70cm**



Circuit name	Ramp rate [A/s]		Acceleration [A/s^2]	
	Required	Max	Required	Max
RCBX1	0.70	10.8	0.23	3.6
RCBX2	0.70	10.8	0.23	3.6
RCBX3	0.97	15	0.32	5
RCBRD4	0.12	1.81	0.04	0.60
RCBY4	0.01	0.13	<0.01	0.04

(My) Conclusions

- **New** PC specs **not too different from old** ones.
  - No major impact on tune jitter/orbit in using:
    - **class 4** PCs for **120A** circuits
    - **RQSX** powered by a **600A** PC
    - **RTB8** powered by a **600A** PC
  - **No sizable improvement from adopting class 1-2**
    - Proposed to “skip” this class and save money.
- Over **one year: 10^{-3} tune jitter**; **10%σ beam orbit jitter**
  - **No** need of a **remote calibration** system for **class 0** PCs
- Specs. in **0.1 – a few Hz** range are a bit **dodgy**
  - **Should maybe improve definitions/constraints.**
  - From “Noise” guess everything seems fine
  - **“High” frequency regime seems to be fine.**
    - **To be kept under control** with new findings…
- **Orbit separation collapse** can be executed much **faster than required**
  - (at least from a circuit/PC point of view)

-- Thanks for your time and comments --