HL-LHC power converter requirements

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HL-LHC Power converters

- Performance mostly defined by: precision components, voltage source, load and the current regulation loop
  - **Precision components, ADCs and DCCTs: LF performance**
  - **Voltage source and load: ripple**
  - **Current regulation loop, implemented in the FGC: LF performance**

HL-LHC ADCs

- Three FGC plattforms will co-exist in HL-LHC:
- FGC2:

  SD-350 Sigma-Delta Analogue Board – INT ADC used up to class 2
  CERN DS22 ADC – EXT ADC used up to class 1

- FGC Lite:

  FGCLite Analogue board – INT ADC used up to class 4
  FGCLite Analogue board with TC comp – INT ADC used up to class 2

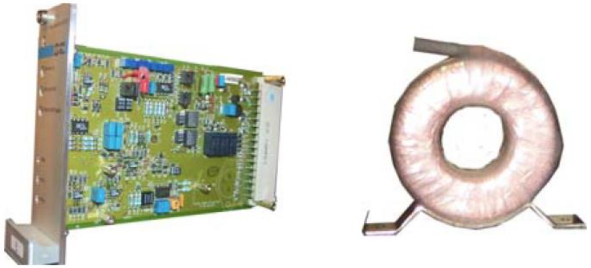
- FGC3.2 (new, to be developed):

  ANA-104 – Dual-Purpose Analogue Board – INT ADC used up to class 3
  DS24 or AD7177 based new ADC – EXT used in class 0 and 2

HL-LHC DCCTs

- D0 – still to be developed: class 0
- D1, D2 – same performance: classes 1, 2

- D3: class 3



- D4: class 4

HL-LHC power converters

PC class	PC type	Configuration ADC	DCCT type
0	(UR) – 18kA IT, 13kA D1 & D2	FGC3.2 + EXT ADC + AIRCON RACK	D0
1	(UA) – 13kA MDQ	FGC2.1 + EXT ADC + AIRCON RACK	D1
2	(UR) – 2kA HL-LHC	FGC3.2 + EXT ADC	D2
2	(UA) – 4-7kA Kempower	FGC2.1+ INTERNAL ADC + TC COMP	D2
2	(RR) – 4-7kA R2E	FGCLITE + INTERNAL ADC + TC COMP	D2
3	(UA) – 600A Transtecknik	FGC2.1 + INTERNAL ADC + TC COMP	D3
3	(UR) – 600A HL-LHC	FGC3.2 + INTERNAL ADC	D3
3	(RR) – 600A R2E	FGCLITE + INTERNAL ADC + TC COMP	D3
4	(UR, RR) – 120A HL-LHC, R2E	FGCLITE + INTERNAL ADC + TC COMP	D4
4	(UA) – 120A LHC	FGC2.1 + INTERNAL ADC + TC COMP	D4
4	(Tunnel) – 60A R2E	FGCLITE + INTERNAL ADC	D4
4	(UR) – 60A HL-LHC (Q1a trim)	FGC3.2 + INTERNAL ADC	D4

Performance parameter definitions

HL–LHC definition	BW/Condition	Units / Distribution function/calculation method	Notes
Setting resolution Smallest step in current that can be induced and discerned.	n.a.	ppm	
Initial uncertainty after calibration Variation of the delivered current with respect to an accepted current reference immediately after calibration.	1 mHz–100 mHz; Constant temperature	Expressed in: (2 x rms) ppm Considers that the error is normally distributed	This quantity can be used to estimate the relative error between different circuits.
Linearity Maximum deviation, in absolute value, of the delivered current from the current reference along the setting range from $-I_{rated}$ to 0A and from 0A $+I_{rated}$ (or from I_{min} to $+I_{rated}$ for unipolar PCs), corrected for gain and offset.	Constant temperature	Expressed in: (max abs) ppm The Linearity error of "n" converters is considered to be uniformly distributed. The value given by this parameter can be interpreted as the maximum (in absolute value) of the uniform distribution. The linearity error is measured from $-I_{rated}$ to 0A and from 0A $+I_{rated}$ (or from Imin to $+I_{rated}$ for unipolar PCs). Corrected for positive gain, negative gain and offset	The gain and offset correction mean the deviation is zero at $-I_{rated}$, 0A, $+I_{rated}$.
Stability during a fill (12 h) Variation of the delivered current (for a constant reference) during a period of 12h, measured up to a frequency of 10mHz.	20 µHz–10 mHz Constant temperature	Expressed in: (max abs) ppm The stability of "n" converters is considered to be uniformly distributed. The value given by this parameter can be interpreted as the maximum (in absolute value) of the uniform distribution.	The stability during a 12h period is impacted both by drift (due to mechanical stress and environmental effects) and by flicker noise (1/f). Since 1/f and drift can have similar magnitude over the considered time scale, it was decided for the sake of simplicity, to define the 12h stability as a slow and monotonic variation of the delivered current during a fill. It can be either positive or negative for different PCs.
Short term stability (20 min) Variation of the delivered current (for a constant reference) during a period of 20 minutes, measured up to a frequency of 0.1Hz.	1 mHz –100 mHz; Constant temperature	Expressed in: (2 x rms) ppm The value given by this parameter is based on the rms value of the low frequency noise (normally distributed) measured during 20 minutes. Considering there are "n" converters, the noise to which this rms value refers is the worst case noise amongst "n" converters measured.	This parameter is considered to be dominated by flicker noise (1/f).

Performance parameter definitions

Noise (0.1-500 Hz) Variation of the delivered current (for a constant reference) for a bandwidth from 0.1 Hz to 500 Hz.	100 mHz –500 Hz; Constant temperature	Expressed in: (2 x rms) ppm The value given by this parameter is based on the rms value of the noise (normally distributed) measured with a bandwidth of 500Hz. Considering there are “n” converters, the noise to which this rms value refers is the worst case noise amongst “n” converters measured.	This parameter is considered to be a combination of voltage source noise translated into current according to the load transfer function and white noise originating from the current loop.
Voltage spectrum tones Spectrum line amplitudes at 50 Hz, 150 Hz, 300 Hz, fsw, 2 × fsw, where fsw is the switching frequency (normally of the order of a few kHz) of the power converter.	50 Hz, 150 Hz, 300 Hz, 600 Hz, fsw, 2x fsw Constant temperature		These are the most likely tones where to expect voltage ripple, but other tones might appear. In general all tone amplitudes shall be below what specified in the “CERN output ripple limits profile” reported in Figure 2.
Fill-to-fill repeatability Fill to fill variation of the average of the delivered current (for a constant reference), measured over 10 consecutive fills.	measured over 10 consecutive fills Constant temperature	Expressed in: (2 x rms) ppm The value given by this parameter is based on the rms value of the distribution (assumed normal) of the averages of 10 fills. Considering there are “n” converters, the distribution to which this rms value refers is the worst case amongst “n” converters measured.	
Long term fill-to-fill stability Variation of the delivered current for the same reference current after one year from the last calibration.	1 year time span Constant temperature	Expressed in: (max abs) ppm The stability of “n” converters is considered to be uniformly distributed. The value given by this parameter can be interpreted as the maximum (in absolute value) of the uniform distribution.	This implies many cycles of the PC. This parameter is dominated, during the first months/years, by ageing of the precision components, which translates as a drift. It is therefore described as a slow and monotonic variation of the delivered current along the year. The direction of the drift varies from PC to PC. Often, drift due to ageing effects (mechanical stress relief) decreases with time and in that case only the flicker noise (1/f) and environmental effects remain.
Temperature coefficient (ppm/C) Dependency of the output current of the power converter with ambient temperature.	n.a.	Expressed in: (max abs) ppm The TC of “n” converters is considered to be uniformly distributed. The value given by this parameter can be interpreted as the maximum (in absolute value) of the uniform distribution.	The expected temperature variations for each class are provided separately. For the specific case of the HL-LHC locations, this is provided for the different accuracy classes and is used to calculate the uncertainty for three of the parameters above, which are effected by temperature: stability (12h), fill to fill repeatability and long term stability.

ADCs and DCCTs

DCCT class	D0	D1	D2	D3	D4
cal uncertainty rms	1.0	1.0	1.0	5.0	8.0
Linearity max*	1.0	1.0	1.0	4.0	5.0
Stability 12h max*	0.5	0.6	0.6	3.0	6.0
ST stability rms	0.1	0.2	0.2	1.0	4.0
noise rms	2.0	3.0	3.0	9.0	15.0
repeat rms	0.3	0.6	0.6	1.5	3.0
LT stability max*	4.0	4.0	4.0	20.0	30.0
TC max*	0.8	1.0	1.0	3.0	3.0

	FGC3.2-EXT	FGC2.1-EXT	FGC2.1-INT	FGCLITE-INT-TC	FGC3.2-INT	FGCLITE-INT
cal uncertainty rms	1.0	1.0	2.0	2.0	2.0	2.0
Linearity max*	1.0	1.0	4.0	4.0	4.0	4.0
Stability 12h max*	0.2	0.4	3.5	3.5	5.0	3.5
ST stability rms	0.1	0.2	1.0	1.0	1.0	1.0
noise rms	1.0	2.0	4.0	4.0	6.0	4.0
repeat rms	0.1	0.2	2.0	2.0	2.5	2.0
LT stability max*	4.0	4.0	15.0	15.0	20.0	15.0
TC max*	0.2	0.2	1.5	1.5	2.5	3.5

HL-LHC power converter requirements

	Class 0		
	FGC3.2-EXT-AC-D0		
	total PC	**dcct**	**adc**
Resolution [ppm]	0.5		0.2
Initial uncertainty after cal [2xrms ppm] normal	2.0	1.0	1.0
Linearity [ppm] [max abs ppm] uniform	2.0	1.0	1.0
Stability during a fill (12h) [max abs ppm] uniform	0.7	0.5	0.2
Short term stability (20min) [2xrms ppm] normal	0.2	0.1	0.1
Noise (<500Hz) [2xrms ppm] normal	3.0	2.0	1.0
Fill to fill repeatability [2xrms ppm] normal	0.4	0.3	0.1
Long term fill to fill stability [max abs ppm] uniform	8.0	4.0	4.0
Temperature coefficient [max abs ppm/C] uniform	1.0	0.8	0.2
12h Delta T for HL-LHC [max C] constant	0.5	0.5	0.5
1 y Delta T for HL-LHC [max C] constant	0.5	0.5	0.5

HL-LHC PC requirements

	PC REQUIREMENTS SUMMARY - ACCURACY CLASSES				
	0	**1**	**2**	**3**	**4**
Resolution [ppm]	0.5	0.5	1.0	1.0	1.0
Initial uncertainty after cal [2xrms ppm] normal	2.0	2.0	3.0	7.0	10.0
Linearity [ppm] [max abs ppm] uniform	2.0	2.0	5.0	8.0	9.0
Stability during a fill (12h) [max abs ppm] uniform	0.7	1.3	5.1	10.0	11.9
Short term stability (20min) [2xrms ppm] normal	0.2	0.4	1.2	2.0	5.0
Noise (<500Hz) [2xrms ppm] normal	3.0	5.0	7.0	15.0	19.0
Fill to fill repeatability [2xrms ppm] normal	0.4	0.8	2.6	4.0	5.0
Long term fill to fill stability [max abs ppm] uniform	8.0	8.0	19.0	40.0	45.0
Temperature coefficient [max abs ppm/C] uniform	1.0	1.2	2.5	5.5	6.5
12h Delta T for HL-LHC [max C] constant	0.5	1.0	5.0	5.0	5.0
1 y Delta T for HL-LHC [max C] constant	0.5	1.0	5.0	5.0	5.0

Expected performance in HL-LHC

	0	**1**	**2**	**3**	**4**
Stability during a fill (12h) [2xrms ppm]	1.0	2.0	15.6	33.8	40.0
Fill to fill repeatability [2xrms ppm]	0.7	1.6	14.7	32.0	37.9
long term fill to fill stability [2xrms ppm]	9.3	9.3	26.3	56.1	64.1

Voltage ripple

- Voltage ripple needs a separate discussion following recent studies on the impact of voltage ripple on the beam:

$$B(f) = \begin{cases} T_{vacuum}(f) \times T_{Ito\,B}(f) \times I(f) & f < f_0 \\ T_{vacuum}(f) \times T_{Ito\,B}(f) \times T_{Vto\,I,\text{load}}(f) \times V(f) & f > f_0 \end{cases}$$

$T_{\text{VtoI,load}}(f)$

is dependent on the full circuit (including beam screen, magnet and cables) – dominated by R and L though

$T_{\text{ItoB}}(f)$

depends on magnet and beam screen only; for the magnet alone it was measured for the new Inner Triplet magnets, using a short model available for tests in SM18 and the main conclusion is that the magnetic field produced by the magnet shows a low-pass response with respect to the circuit current.

$T_{\text{Vacuum}}(f)$

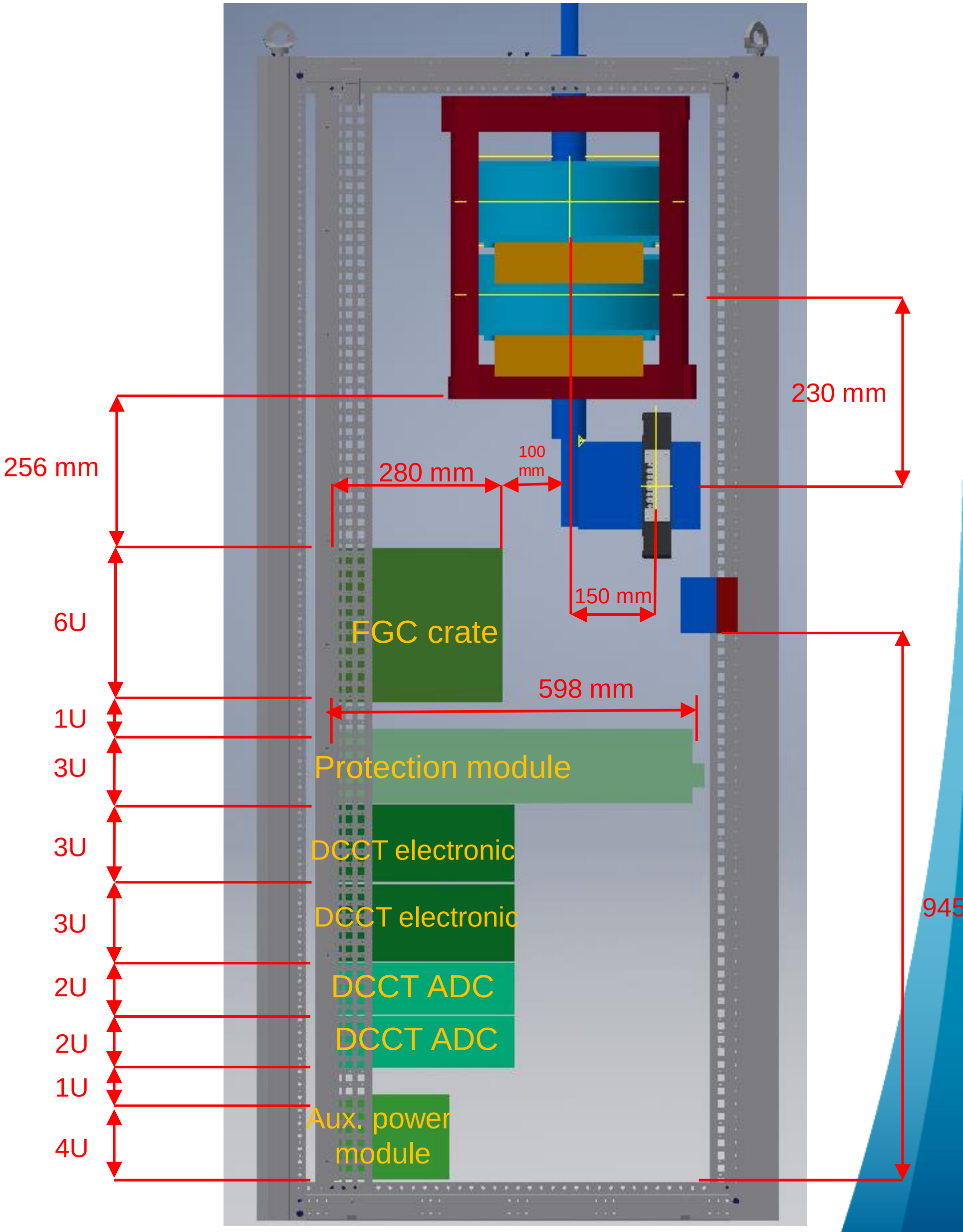
depends only on the beam screen; it was estimated in a recent study. An approximation based on a single pole response was proposed for the LHC case (being validated…). For the HL-LHC Inner Triplet, D1, D2 magnets, a -3dB cutoff frequency of < 80Hz is estimated. Recent mechanical measurements on BS short model during quenches seem to have validated the model used for simulation ☺

QUESTIONS TO DISCUSS

- **Class 1-2 issue for 2kA in HL-LHC**
  - Direct impact on rack integration
  - DCCTs for class 1-2 require more space
  - DCCTs for class 1-2 more costly
  - ADC will be the same: FGC3.2 EXT

If 2kA can be class 2:

- Easier rack integration
- Savings in the order of 150kCHF



Other QUESTIONS TO DISCUSS

- **120A class 3 or 4: 120A are presently class 4, if they need to be upgraded to class 3 they would be different from the LHC ones, which would mean a new DCCT for this class**
- **Calibration system: Remote calibrations require a dedicated calibration system in-situ. The present system used in the Dipoles would need an update because it is obsolete, which means a non-negligible development effort, followed by production and installation. We estimate, from LHC performance that an in situ calibration system is not required to guarantee long term stability of class 0. In the dipoles the motivation is tracking between sectors, which is not the case for the IT circuits.**

HiLumi
HL-LHC PROJECT