

HL-LHC current measurement and acquisition: METRON-CERN review

Present

Miguel Cerqueira Bastos (**mcb**, CERN),
 Carlo Baccigalupi (**cb**, CERN),
 Michele Martino (**mm**, CERN),
 Greg Hudson (**gh**, CERN),
 Nikolai Beev (**nb**, CERN),
 John Pickering (**jp**, METRON Designs)

Programme

Wednesday 25/04/2018

9h: startup meeting, schedule – **mcb, jp, gh, mm, nb, cb**

9h30-12h00 HL-LHC current measurement – **mcb, gh, jp, nb**

- Presentation of HL-LHC requirements and current measurement strategy
- Presentation of present performance of class 1 DCCTs
- Discussion on resistor ratio devices: thin film parallel device, powertron option, network resistor option
- Discussion on other current sense methods: Second stage DCCT, burden resistor
- Discussion on reference units for DCCT testing

13h30-17h00 HL-LHC current measurement – **mcb, gh, jp, nb**

- General discussions
- Test of discrete thin film ratio device

Thursday 26/04/2018

9h: startup meeting

9h30-12h00 HL-LHC ADCs – **mcb, cb, nb, jp**

- Presentation of HL-LHC requirements and current measurement strategy
- Presentation of the work done on the upgrade of the DS22 and performance evaluation
- Discussion on the work done on idle tone suppression
- Discussions on further work for improving the performance of the DS22

13h30-17h00 HL-LHC current ADCs – **mm, cb, nb, jp**

- Presentation of the status of the work on the new class 0 ADC for HL-LHC
- Discussions on the new class 0 ADC for HL-LHC and practical circuit aspects

Friday 27/04/2018

9h: startup meeting

9h30-12h00 General discussions – **mcb, cb, nb, jp, gh**

- Circuit implementation for the new ADC design
- Test of thin film ratio device

13h30-14h30 Wrap up – **mcb, jp, gh, mm, nb, cb**

Summary/Conclusions

HL-LHC current measurement:

1. Powertron resistor ratio device:
 - a. An order has been prepared according to Powertron's proposal for 1 + 10 resistors and will be sent soon
 - b. It is not clear which implementation Powertron is planning to follow. In particular Powertron has yet to fully reply to METRON's questions on the validity of proposal B. METRON thinks option B has an interesting potential due to the fact that paralleling two resistors can achieve lower resistance using smaller individual areas, allowing the number of squares in the high value resistor to be smaller and the trace wider. Powertron have however replied positively to the question of knowing if a smaller lead distance is possible, clarifying that 2.54mm is possible using other type of contacts.

Actions:

John Pickering will contact Kevin Smith from Powertron the first week of May to try to obtain a reply to the questions concerning proposal B. He will also try to understand which implementation they plan to use.

- c. The resistors are planned to be delivered in June. They will be tested individually by Greg using the MIL bridge with a range extender. Two will be sent to METRON for evaluation.

Actions:

Greg Hudson will check if the range extender before the end of May to ensure ratios of 100 are possible.
Greg Hudson shall send two units to METRON for evaluation.

2. Thin film parallel 0805 ratio device:

- a. Tests were carried out with METRON's parallel thin film ratio device at 1A, 2A, 5A, 7A, 10A using a current calibrator. Measurements showed a relatively stable zero with little impact from Thermal emfs but a significant thermal settling at 10A (> 20ppm) with consequent non linearity when measuring at different currents. John estimates the TC to be near zero so the observed non linearity seems to be PC caused and could be related to the thermal balance between series and parallel paths. Measurement with a thermal camera revealed a significant impact of the main connector on the temperature of the parallel path but not on the series path. METRON believes this can be improved but it seems difficult to reach the level of improvement required for HL-LHC class zero (12h stability of 0.6ppm, linearity of ± 0.8 ppm). Nevertheless John will look into improving the copper design on the board and Nikolai will look for a 25ppm/C version of the 0805 thin film resistors.
- b. In addition to lower-TC resistors and better copper layout, Nikolai suggested to consider using Al-core PCB or PCB with embedded bulk copper, to improve the thermal coupling and to reduce copper resistance errors. Another thing to consider is heat leakage through the current wires. In the prototype those are simple Cu wires, but we can probably do better with more resistive wiring, optimization of the connection position, etc.
- c. Nikolai also suggested to replace the 100ppm/K 1 ohm resistors by 25 ppm/K. An example are the Bourns CRT series ref. CRT0805-CY-1R00ELF

3. Network resistors

- a. METRON considers that the network resistor option for building a ratio device would be worth re-evaluating using a 10R version of the VSOR networks, which was not available at the time of the 0.5A calibration which used 33R. METRON proposed to mount the 10R devices on a bare board for evaluation.

Actions:

John Pickering will evaluate 10R VSOR networks

4. Burden resistor for 5A measurement:

- a. The possibility of paralleling several resistors for direct measurement of the 5A was discussed. CERN has seen variations on VCS332Z resistors at the 10ppm level for periods of weeks and suspects humidity, although the origin is not yet confirmed. So a hermetically sealed packaged would be preferred. One of the possibilities discussed was if VHP202Z type on a hermetically sealed package could be used. These resistors are well known from other applications. Some concerns are the spread on the specified TC, but for a wide temperature range, METRON believes that for our range of temperatures, TC should be close to 0.2ppm/C. The smallest value is 5R which would mean at least 25 resistors for a 0.2 Ohm resistor and a dissipation of 0.2W per resistor (5W total). Cost would be high at 500 EUR per assembly. VHP202Z is normally available in 2 lead packages and although the value is high at 5R, lead TC could still have an impact at the ppm level (1ppm/C for 1mR lead). So it was agreed that the option of having a 4 lead resistor shall be explored but this would probably increase the price. Another possibility would be the VHP4Z. These are available to much lower values and are hermetically sealed. A number could be paralleled, although cost could be an issue.
- b. The problem of 5A measurement against 10A was discussed (*). It is suspected that at 18kA it might be difficult to manufacture a DCCT with calibration winding using the present 13kA dimensions. In that case we might have to go to 10A secondary current which would not be desirable.

Actions:

Greg Hudson will contact PM to understand what would be the dimensions of a 18kA DCCT with calibration windings and 5A compensation current. This has an important impact on the project since it can impact the power converter design and volume.

Greg Hudson will ask for a price for 10 and 100 units of 1R VHP4Z to Vishay.

5. 10R low current side measurement

- a. This is the resistor used on the secondary side of the ratio device. It shall measure a current in the order of 100mA. One of the possibilities discussed was if VHP202Z type on a hermetically sealed package could be used. These resistors are well known from other applications. Some concerns are the spread on the specified TC, but for a wide temperature range, METRON believes that for our range of temperatures, TC should be close to 0.2ppm/C. They also have only 2 lead packages and although the value is high at 10R, lead TC could still have an impact at the ppm level (0.5ppm/C for 1mR lead). So it was agreed that the option of having a 4 lead resistor shall be explored.

Actions:

John Pickering will contact Kevin Smith from Powertron to see what they have to offer for this application.

John Pickering will contact Hero Faierstein from Vishay to see what he recommends and if a 4 lead VHP202Z or an equivalent design is possible. He will also inquiry about the interest of the design with a hanging chip on the back of a dummy chip which could be interesting to minimize stress on the chip.

6. Second stage DCCT

- a. Considering what was mentioned in (*) this option can become much more attractive in case a 10A measurement is required. METRON has been working on a simulation of a DCCT with no AC winding and with a different detection method and presented some of the results. The idea for a second stage DCCT solution would be to use multi-turn on the primary to work at ~100At with a 1000:1 ratio. A 10R resistor as discussed in (4) could then be used to measure the secondary current. CERN's experience with commercial DCCTs at 1000:1 ratio at hundreds of Amp currents is that the current output is not just the turn ratio: an offset drift in the order of a few ppm is often observed both at warmup but mainly after a current step. The origin of this drift needs to be investigated: if it comes from the electronics it could probably be improved. If it comes from the head, then this would pose some new questions on the feasibility of a second stage DCCT for class 0 measurements.

Actions: **Miguel Cerqueira Bastos** will share data on the testing of current output DCCTs and will carry out new measurements to evaluate the origin of the offset drift

7. Reference devices for DCCT testing

- a. Class 0 DCCTs will be evaluated before installation in the power converters. The evaluation relies on the availability of a reference device with better performance than the unit under test. The current output performance of the present reference units, a 20kA MIL range extender and a 24kA Danfysik DCCT was evaluated in [1]. Matching between the two units and linearity were measured to be sub ppm but drift with temperature and time were non negligible and required proper warm up and the electronic chassis to be installed in a temperature controlled environment in order to reach sub ppm performance. Noise was described to be at the 0.1ppm level but bandwidth of measurement was not defined. It would be desirable to carry out a new measurement campaign to understand the real performance of these devices.
- b. To measure the current output of reference devices such as the 20kA MIL range extender and the 24kA Danfysik DCCTs, the CERN Current Calibrator (CDC) is used. The noise of one CDC unit was characterized recently and showed to be at the same level as a high current DCCT. The same can be expected from drift. If the CDC is to be used to measure short term and 12h stability either by direct injection on the calibration winding or by back to back with a reference DCCT, it would be essential to improve its performance. CERN thinks that by modifying some aspects of the design, in particular thermal, EMC and PCB design, as well as replacing some amplifiers by auto zero, low drift ones, some gains can be achieved.

- c. METRON pointed out that a new improved version of METRON's PBC can be built by selecting the LTZ for noise, given that there is some spread within the LTZ devices, and by upgrading some of the Opamps in the PBC circuit.

Actions: Miguel Cerqueira Bastos and Greg Hudson will commission the repaired MIL and Danfysik units and carry out a test campaign to evaluate them.

Miguel Cerqueira Bastos and Carlo Baccigalupi will carry out a review of the CDC design and suggest improvements.

Analogue to Digital Conversion and acquisition:

1. Update of the DS22 design
 - a. The work on the update of the DS22 design has yielded an improvement of about a factor of 6 in low frequency noise, placing it well within the short stability and full stability requirements for HL-LHC. The most significant improvement was obtained by the replacement of IC10, followed by small gains after replacement of the input buffer and adjustment of the chopper stabilization. Several other small improvements were identified such as replacing thick film resistors by thin film and all capacitors by NPO and adding a bit more filtering on the -5Vref.
 - b. Although the LF noise improvement means the DS22 is well within the specification for 12h stability when it concerns to noise, this might not be the case if we consider temperature dependency. In that respect, the stability of the DS22 temperature regulation loop is essential and could probably be improved. In particular, it would be interesting to review the temperature sensor performance as well as the position of the several precision components in the temperature regulated area of the PCB and inside the aluminum block where the Peltier element is installed.
 - c. Results were presented for measurements carried out on the performance of 4 DS22 units and showed to be within requirements for linearity and low frequency noise. The interpretation of the temperature coefficient for offset and gain was a little more difficult since it is clear that there is a significant loss of efficiency from the temperature control above a certain temperature which was even suggested that could be saturated. It should be understood what happens exactly at this point and the temperature dependency must be evaluated below this point in order to understand what the TC is when the temperature regulation is working correctly.

Actions:

Carlo Baccigalupi shall calculate the TC using only data below the critical temperature. He shall also carry out a measurement of the behavior of the Peltier at the point where efficiency is lost.

- d. Concerning the evaluation of the performance of the DS22 and other high performance ADCs, it was agreed that we are limited by the performance of the LTZ1000 since most devices that could be used to evaluate the DS22 are also based on the same reference. METRON uses several PBC units in parallel to create a better reference against which to measure individual units. This is an easy method and CERN has enough units to do the same. METRON also mentioned a newly found "Chinese" reference zener that could be used to build a super reference. Noise is lower than the LTZ100 but long term drift is not well known yet. In addition, the possibility of a new improved reference showing up in the market soon was also discussed and some positive signs were mentioned. In any case CERN will try to establish a collaboration with a metrology laboratory with the aim of evaluating both the DS22 as well as the new ADC design against a Josephson voltage standard.
- e. Idle tones were also evaluated and it was shown that the suppression provided by the present dither is not satisfactory. Suppression levels vary with the amplitude and the frequency of the dither and although for the

first case an optimum is easily found, that's not the case in the latter since idle tone attenuation dependency on dither amplitude seems to vary for different input DC levels. CERN has tried an alternative dither strategy by injecting white noise (PRBS generated with an FPGA). This has produced very good results almost completely eliminating all idle tones but increasing noise floor above 100Hz. Band-passing the noise limits the increase to a narrow band that can be filtered digitally.

2. Status of new ADC design

- a. CERN short listed two ADCs as candidates for the new commercial chip based ADC for HL-LHC: SAR ADCs by Linear (LTC23xx) and the AD7177-2 from Analog Devices. The AD7177 was the clear winner of the comparison and will be used on the design of a new ADC for HL-LHC power converters. The new ADC will conditioning circuit will use auto zero amplifiers and arrays to ensure minimum drift and temperature dependency. Arrays will also be used for the LTZ1000 conditioning circuit. METRON discussed the details of the LTZ1000 conditioning circuit used on the PBC and suggested some approaches based on the same network ratio technology also used on the PBCs.
- b. METRON suggested some strategies that could be used on the new ADC to improve performance: we can try improving the INL of AD7177-2 by providing a tuneable coupling from the input signal to VREF. 5-point self-calibration would probably solve the INL problem too. The input range can be made smaller, t.e. 10-15% over FS (in the initial sketch it's >30%). The LTZ1000 reference can be left out of the temperature-stabilized block, to reduce the amount of heat that the Peltier element has to handle

References

[1] Gunnar Fernqvist, Hans-Erik Jorgensen, and Alfredo Saab, *Design and Verification of a 24 kA Calibration Head for a DCCT Test Facility*, IEEE TRANSACTIONS ON INSTRUMENTATION AND MEASUREMENT, VOL. 48, NO. 2, APRIL 1999