ISBN: 978-3-95450-192-2 doi:10.18429/JACoW-IBIC2017-WEPCF06

R&D PROGRESS ON PRECISION CURRENT MONITORING AND CALIBRATION SYSTEMS FOR THE APS UPGRADE UNIPOLAR MAGNET POWER SUPPLIES*

R. Keane#, J. Carwardine, B. Deriy, T. Fors, J. Wang,
Argonne National Laboratory, Lemont, IL

Abstract

The APS Upgrade storage ring multi-bend acromat lattice uses 1000 individually-powered multi-pole magnets operating at current levels to ~260 A. Requirements for power-supply stability, repeatibility and reproducibility are of the order of 10 ppm. MBA SR quad magn et and Q-bend dipole magnet current regulation will require a higher level of accuracy, precision, stability, and independent control than existing APS systems. In order to meet these requirements, the upgrade will include the installation of 1000 new unipolar power supplies. To monitor and ensure the performance of the power supplies, an independent precision current measurement system is under development, based on a commercially available DCCT sensor. An in-situ calibration system is also required that will maintain the ensemble accuracy of the measurement system and magnet-to-magnet relative calibration by providing precise known calibration current to each of the 1000 DCCTs distributed around the 1100-meter ring. R&D on the in-situ cross-calibration scheme is being performed using a network of 6-8 full-spec DCCTs. This paper discusses the proposed approach, and results and lessons from the R&D program.

INTRODUCTION

Figure 1 shows the conceptual design of the external precision current measurement and calibration system. An interface chassis will provide connections for six DCCTs and will house the current-to-voltage converting circuitry and ADC required to produce a digital current reading. Each power supply cabinet will contain one interface chassis; approximately 200 chassis will be needed for the entire system. The raw digital data is sent to the Power Supply Controller (PSC) through an SPI link, and will be available to the system over Ethernet. A calibration circuit will also be housed in the interface chassis to allow in-situ calibrations of each DCCT through built-in calibration windings. Calibration factors will be applied in the PSC FPGA, or in software, to provide calibrated current read-outs. Calibration will be fully automated and performed remotely, at intervals to be determined by data gathered during further performance testing on the preliminary design hardware.

* Work supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Contract No. DE-AC02-06CH11357.
#keane@anl.gov

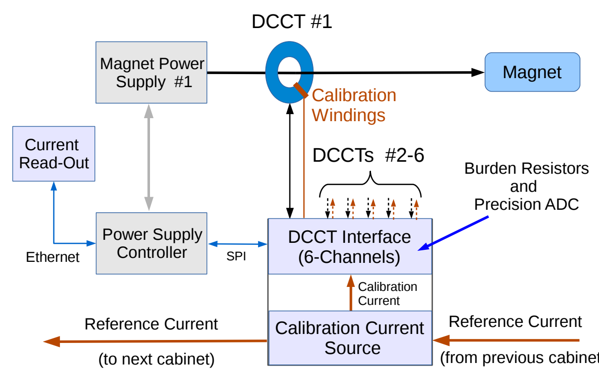

Figure 1: Current measurement and calibration system.

CURRENT MEASUREMENT SYSTEM

DCCT Current Sensor and Burden Resistor

DCCT technology is considered the standard for high-precision current measurement[1], and is capable of very high levels of accuracy, precision and stability. The DCCT is an active, non-interrupting device that produces an output current proportional to the primary DC current. The DCCT under investigation (DaniSence DS200CLSA- 1000) uses a 1:500 ratio, i.e. a 200 A primary current results in a 400 mA secondary output current. This DCCT model has excellent stability and linearity specifications, and includes a built-in calibration winding of 1000 turns. The secondary current is converted to a voltage using a precision burden resistor, and read-out by a precision voltmeter or ADC. Some DCCT models incorporate the burden resistor in the internal circuitry to provide a direct voltage output. Performance of the DCCT system depends strongly on burden resistor performance, so using an external burden resistor allows for better control of the resistor parameters and environmental conditions, particularly thermal conditions. Figure 2 shows the basic components of a DCCT-based current measurement channel.

ISBN: 978-3-95450-192-2 doi:10.18429/JACoW-IBIC2017-WEPCF06

Early R&D for the ADC circuit was conducted separately from the analog components (DCCT and burden resistor). For lab testing of the analog components, a Keysight 3458A DMM along with a multiplex switch was used to digitize the current readings in place of the ADC.

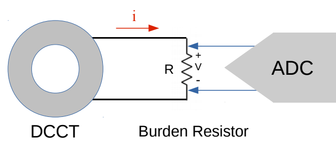

Figure 2: Basic components of a current measurement channel.

CALIBRATION SYSTEM

The current reference is a commercial variable current source that provides a low-noise, stable current from 0 to +/- 110 mA (Krohn-Hite model 523). The voltage output is limited to 110 VDC. Since the calibration winding impedance in the DCCT is on the order of 30 ohms for the unit under investigation, direct (in-series) calibration is limited to a few dozen DCCTs at a time using the instrument directly. A second limitation is the maximum output current of 110 mA. The magnet current specification of 260 A needs a full-scale measurement capability of at least this value, which requires 260 mA into the 1000x calibration winding in the DCCT in order to calibrate at the operating point.

Precision Local Current Source

In order to produce the ~300 mA needed to calibrate over the full range of the measurement system, the 110 mA source needs to be increased by a factor of three. This is achieved using a scheme adopted from NSLS-II [2] and shown in Figure 3. Current is driven through the calibration winding of the DCCT in a local current loop fed from a (non-precision) DC power supply that is regulated using a nulling circuit and additional DCCT, whose calibration winding is fed from the KH523 precision source. A similar circuit was built and tested successfully as a 10 A source during the early stages of R&D.

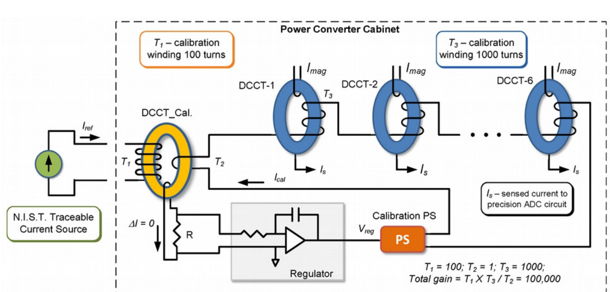

Figure 3: Precision local current source circuit.

Calibration Standards and Traceability

Per manufacturer specifications, the KH523 precision current source must be periodically calibrated using a NIST-traceable precision resistor (Krohn-Hite Model PCR100) and a calibrated NIST-traceable Keysight 3458A DMM. Stability specifications of the KH523 current source, PCR100 resistor, and 3458A DMM are listed in Tables 1-3. The limited time stability of the KH523 requires frequent re-calibration to the transfer sources in order to maintain accuracy over time. This method allows for in-place calibration of the KH525 current source.

Table 1: KH523 Current Source Specifications

Resolution	Stability (24 Hrs)	Max. Output
10 nA	± 2 ppm typ.	110 mA, 110 V

Table 2: PCR100 Calibration Resistor Specifications

Initial Accuracy	Stability (1 Year)	Max. Current
± 0.5 ppm	± 2 ppm typ. ± 6 ppm max.	110 mA

Table 3: Keysight 3458A-004 DVM Specifications

Transfer Accuracy	Accuracy (90 days)	Accuracy (1 Year)
± 0.55 ppm	2.7 ppm	4 ppm

Calibration Reference Current Distribution

A common calibration reference current for all 1000 channels is highly desirable in order to maintain channel-to-channel accuracy. This will require routing the reference current over distances of hundreds of meters. Testing was performed on the KH523 current source to determine its performance over long cable runs. The test set-up consisted of a KH523 sourcing 100 mA through twisted-pair cable to a 100 ohm precision resistor (Krohn-Hite PCR100). The voltage across the resistor was read with a Keysight 3458A DVM. A short, direct run of 4 feet was used as the baseline. Then, the same current was routed through 1600 feet of cable, then though the calibration windings of 4 DCCTs and an additional 100 ohm resistor. Voltage readings were again taken across the PCR100 resistor. The results are shown in Figure 4, and indicate an insignificant effect from the long cable run. The 16 ppm offset in the plotted data is due to the calibration resistor actual value deviation from the nominal 100 ohms.

ISBN: 978-3-95450-192-2 doi:10.18429/JACoW-IBIC2017-WEPCF06

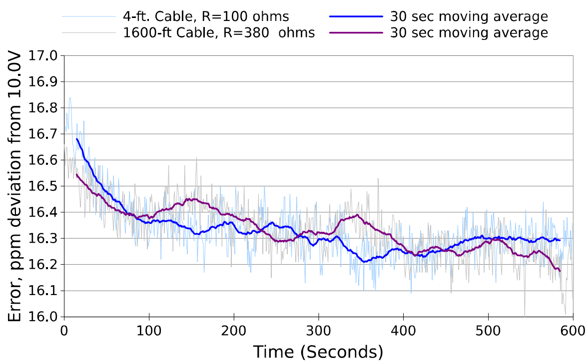

Figure 4: Reference current measurement for short and long current paths.

Full Range Calibration Test

Initially, the magnet current specification was around 190 A, which would have required a full scale range of 200 A. Testing was performed to determine limitations of linear regression calibration over the entire measurement range of 0 to 200 A using the 1000-turn calibration winding in the DCCT. For this test, 200 mA calibration current was achieved by combining the outputs of two KH523 instruments in parallel through a resistor network. After calibration, the DCCTs were used to measure a common primary current from a 200 A power supply, in order to compare the calibrated readings between units (see Figure 5).

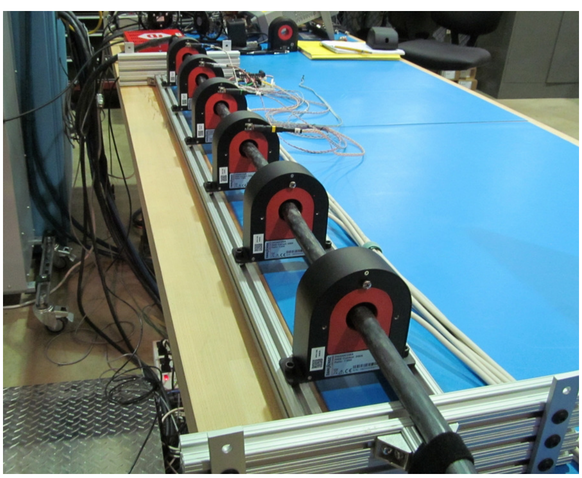
Figure 5: DCCT evaluation with common primary current.

Test results indicated that a single linear calibration over the full range was not adequate; linearity errors were over 10 ppm at the lower end on the scale. A four-zone calibration (50 A per zone), with separate gain-offset pairs for each zone, worked very well for four DCCTs. The results of common primary current measurements for the four DCCTs after the four-zone calibration are plotted in Figure 6, and show agreement within ~3 ppm at all currents. The test also revealed that 2 DCCTs showed unacceptable differences (10-20 ppm) when reading the common primary current after calibration.

These two units were returned to the vendor for evaluation. Consistent agreement between current readings through the primary and calibration windings is a critical requirement, and this issue needs to be examined further.

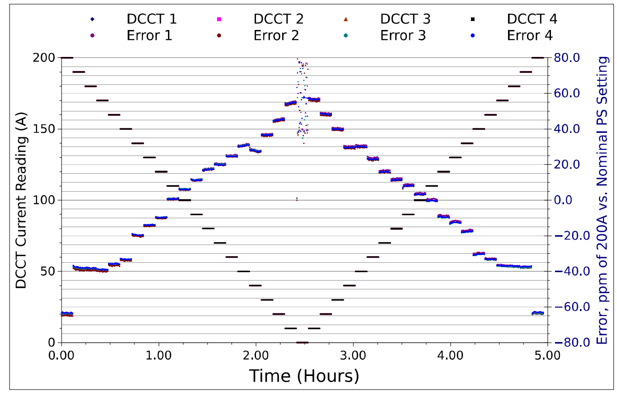

Figure 6: Common primary current from PS measured by four DCCTs after four-zone linear calibration, and the error vs. nominal power supply current setting.

CONCLUSION

Components and processes for a precision current measurement system that will meet better than 10 ppm accuracy and precision have been identified and demonstrated. Sub-5 ppm performance appears possible, but will be challenging and require careful attention to component selection, temperature control, and calibration methods and schedule. The preliminary design is underway for a DCCT interface chassis that will include a custom ADC circuit and temperature-controlled burden resistors, along with a calibration current source and digital interface to the PSC.

Several schemes have been investigated to calibrate all 1000 DCCTs in-situ to a common reference current. R&D results demonstrate that the reference current source under investigation (Krohn-Hite Model 523) can distribute current over the longs lengths necessary. One concern was the lack of agreement between calibration winding and primary current response for two of the six DCCTs examined; this could be an anomaly or a systematic issue. Work to develop a fully automatic, remote calibration system continues.

REFERENCES

[1] M. Cerqueira Bastos, "High Precision Current Measurement for Power Converters", in *Proceedings of the CAS-CERN Accelerator School: Power Converters,* Baden, Switzerland, May 2014.

[2] G. Ganetis, private communication, June 2015.