



BNL-100932-2013-CP

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magnet power supply system***

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*Presented at the North American Particle Accelerator Conference (NA-PAC 13)
Pasadena, CA
September 29 – October 4, 2013*

**Collider-Accelerator Department
Brookhaven National Laboratory**

**U.S. Department of Energy
DOE Office of Science**

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OVERVIEW OF THE RHIC E-LENS SUPERCONDUCTING MAGNET POWER SUPPLY SYSTEM *

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Abstract

A new superconducting solenoid magnet was installed in the yellow ring of RHIC before Run 13 as part of the e-lens project. The second solenoid superconducting magnet will be installed in RHIC after Run 13 is over. There are 6 power supplies required for the solenoid, fringe and anti-fringe coils for both magnets. Commercial off the shelf unipolar power supplies are used to power the solenoid, fringe and anti-fringe coils. There are 24 corrector power supplies required for both magnets. Custom built 50A bipolar power supplies are used to power the correctors. Quench protection and quench detection have also been installed in this power supply system. In addition, 4 new phase shift power supplies have been installed in RHIC which are needed for the new e-lens system. These phase shift power supplies have been installed across the yellow focusing and defocusing arcs as well as the blue focusing and defocusing arcs from sector 8 to sector 10. Power Supply technology, control system, connections, the quench detection/protection system, and status will be presented.

E-LENS POWER SUPPLIES

Power Supplies Description

There are thirty power supplies (p.s.'s) used in the e-lens p.s. system. Fifteen p.s.'s for each magnet. These are all current regulated power supplies with a DC Current Transformer (DCCT) current sensing element.

The two Solenoid p.s.'s are rated at 20Volts and 750Amps dc. The ac input to both Solenoid p.s.'s is 480Vac. The two Fringe and two Anti-Fringe p.s.'s are rated at 15Volts and 534Amps dc. The ac input to the Fringe and Anti-Fringe p.s.'s is 480Vac. The Solenoid and Helical p.s.'s are commercially available voltage regulated switchmode p.s.'s which are used within the BNL designed current regulator. The required p.s. current reproducibility is 0.01% of maximum current.

The twenty four bipolar trim p.s.'s are 20Volts and 50Amps dc. The ac input to the bipolar trim p.s.'s is 208VAc. These are the same bipolar p.s.'s that are used for the RHIC corrector magnets. The required p.s. current reproducibility for the trim p.s.'s is 0.1% of maximum current.

During normal operation these p.s.'s ramp up slowly to a dc level and stay there.

The Solenoid, Fringe and Anti-Fringe p.s.'s are all

connected to their own quench protection assemblies (QPA's). These QPA's contain an energy extraction resistor across an IGBT switch as well as a diode across the output of the p.s. The IGBT and energy extraction resistor are connected to the positive output terminal of the p.s. and the magnet. The diode is connected across the dc terminals of the p.s. When a fault occurs in the p.s. or the QPA, or if the magnet quenches, the diode conducts across the p.s. and the IGBT opens so the energy extraction resistor is now in series with the load. The current from the load goes through the diode and through the energy extraction resistor. The supply also trips to the STANDBY-FAULT state. A DCCT was installed in the QPA for the regulation of the e-lens p.s. The trim p.s.'s don't have a separate QPA; they have a crowbar with an energy extraction resistor built into them.

There is a quench detector (qd) for the e-lens p.s. system which monitors the voltage across the magnets and the current of the magnets. The qd trips the p.s. to STANDBY-FAULT if a quench is detected. Whenever the p.s. trips to the STANDBY-FAULT state, the energy extraction resistor becomes part of the circuit.

e-Lens P.S. Magnet Loads

There are 17 superconducting magnets in one cryostat. The main Solenoid is connected to one p.s. The two Fringe magnets are connected in series to one p.s. The two Anti-Fringe magnets are connected in series to one p.s. The 12 trim magnets are connected to 12 individual p.s.'s. The Solenoid magnet has an inductance of 14H. Each Fringe magnet has an inductance of 515mH. Each Anti-Fringe magnet has an inductance of 38.4mH. The two long (vertical and horizontal) trim magnets are 5.34mH each. The 5 short vertical and 5 short horizontal trim magnets are 19.2mH each. The dc resistance of the corrector cables to the magnets is between 74mohms and 120mohms depending on the cable size used.

Quench Detection for e-Lens

The yellow solenoid magnet is made up of 11 double layers (coils). In order to protect the magnet during a quench the coil difference is taken between 5 coils and 6 coils. If this coil difference ever exceeds 125mV the qd will tell the QPA to open the series IGBT, then the energy extraction resistor is connected in series with the load. The p.s. contactor opens after the IGBT in the QPA opens. The blue solenoid magnet is made up of 10 double layers. The coil difference is taken between 6 coils and 4 coils because of the available voltage taps.

* Work supported by Brookhaven Science Associates, LLC under Contract No. DE-AC02-98CH10886 with the U.S. Department of Energy

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There are 2 Fringe coils in each magnet and 2 Anti-Fringe coils in each magnet. Each Fringe coil has dc terminals that come out of the magnet. The Two Fringe coils are connected in series outside of the magnet to one p.s. The coil difference is taken between these two Fringe coils. The qd coil difference trip setting is 125mV. Each Anti-Fringe coil has dc terminals that come out of the magnet. The two Anti-Fringe coils are connected in series outside of the magnet to one p.s. The coil difference is taken between these two Anti-Fringe coils. The qd coil difference trip setting is 125mV.

The gas cooled leads for the Solenoid, Fringe and Anti-Fringe coils are set to trip at 250mV.

The super conducting leads for the Solenoid, Fringe and Anti-Fringe coils are set to trip at 25mV.

The corrector coils do not have qd on the coils, gas cooled leads or superconducting leads. The p.s.'s have an overvoltage interlock which fires a crowbar SCR and connects an energy extraction resistor in series with the magnet coil when the voltage crosses a threshold. The overvoltage trip has been adjusted to make sure that we stay below the Miits rating the corrector coils and superconducting leads when the corrector coil or superconducting leads quench.

Quench Protection for e-Lens

This is the Miits calculation for the solenoid magnet coil.

- The solenoid maximum voltage can see to is 600V across the magnet or +/-300V to ground.
- The maximum current for the magnet is 500A.
- The energy extraction resistor = $600V / 500A = 1.2\text{ohms}$.
- The inductance of the magnet = 14H.
- The time constant $\tau = 11.67\text{seconds}$.
- Miits rating of the solenoid = $I^2(\tau/2)*10^{-6}=1.46\text{Miits}$
- The Miits rating of the magnet must be at least 1.46Miits.

The original design of the solenoid magnet showed it could only absorb 0.5Miits. Diodes were added across each solenoid coil in order to raise the magnet's Miits rating from 0.5Miits to 1.5 Miits. These diodes are able to handle 1.5Miits.

The solenoid superconducting leads also had to have their Miits rating raised from 0.5Miits to 1.5 Miits. Stabilizing copper was added to the leads to increase the Miits rating.

The energy extraction resistor for the solenoid magnet was built to absorb 1.75MJ ($E=1/2LI^2$) with a temperature rise of 100C. A stainless steel resistor was used and it was assumed that all of the energy was dumped into the stainless steel. Using $q = m \times C \times \Delta T$ one can solve for m = mass of stainless steel resistor. C= specific heat of material, q=energy dumped into material and ΔT is the desired temperature rise. Once the mass is known the resistor can be constructed.

For the Fringe magnet, the maximum voltage to ground is +/-150V and the maximum current is 500A. For 2 coils in series the Miits rating needs to be at least 0.215 Miits.

The Fringe coils are designed for 0.48Miits so no extra protection was required for the Fringe coils.

The energy extraction resistor for the Fringe magnet was built to absorb 128.75KJ ($E=1/2LI^2$) with a temperature rise of 100C. A stainless steel resistor was used.

For Anti-Fringe magnet, the maximum voltage to ground is +/-50V and the maximum current is 400A. For 2 coils in series the Miits rating needs to be at least 0.0215 Miits. The Fringe coils are designed for 0.48Miits so no extra protection was required for the Fringe coils.

The energy extraction resistor for the Anti-Fringe magnet was built to absorb 6.3KJ ($E=1/2LI^2$) with a temperature rise of 100C. A stainless steel resistor was used.

For the corrector the voltage threshold the SCR crowbar circuit is set to fire at 8V (and the current is limited to 45A) which tells us the magnet must absorb at 1847 Miits. The corrector coils, and superconducting leads, Miits rating is 2296 so we are well below the rating.

NEW PHASE SHIFT POWER SUPPLIES

Power Supply Configuration

Four new phase shift ps's (to shift the phase of the beam for e-lens) were installed in RHIC during RHIC runs 12 and 13.

Two new phase shift p.s.'s were installed in RHIC during Run 12. One was installed in the blue ring on the quad defocusing bus from sector 8 to sector 9 across the quad arc magnets. The other p.s. was installed in the yellow ring on the quad defocusing bus from sector 8 to sector 9 across the quad arc magnets.

In Run 13 two more phase shift ps's were installed in RHIC. One was installed in the blue ring on the quad focusing bus from sector 8 to sector 9 across the quad arc magnets. The other p.s. was installed in the yellow ring on the quad focusing bus from sector 8 to sector 9 across the quad arc magnets. All four phase shift p.s.'s were operational for run 13. Each p.s. is connected to 12 quad magnets in each arc. The total inductance each p.s. sees is about 18mH.

All four of the phase shift p.s.'s are located in one service building.

Power Supplies Description

The phase shift p.s.'s are commercially available voltage regulated switchmode p.s.'s which are used within the BNL designed current regulator. These p.s.'s are rated at 16Volts and 185Amps dc. The ac input to these p.s.'s is 208Volts ac and 12Amps rms.

The phase shift p.s.'s each have a QPA which operates in a similar way to the e-lens power supplies QPA's, however, a crowbar SCR was used to short out the p.s. instead of a diode.

Quench Detection Modification for phase shift p.s.'s

The qd's for the phase shift p.s.'s reside in two service buildings (1008B and 1010A) and one alcove (9B).

The voltage of the arc quad magnets was already being measured in the alcove 9B qd from the original design of RHIC. The calculation of the arc quad magnets voltage, using the di/dt method, is also done in the same qd. The voltage calculation had to be modified to include the current contribution of the phase shift p.s.'s. This was achieved by sending the p.s. current readback signal from the p.s.'s in the service building (through the tunnel) to the alcove over fiber optics.

The qd voltage tap measurement of the gas cooled lead and super conducting lead was already being done in 2 service buildings (1008B and 1010A) from the original design of RHIC. These voltage taps had to be modified to include the contribution of the phase shift ps current. This was done by sending the p.s. current setpoint over the Real Time Data Link (RTDL) from the p.s. Waveform Generators (WFG's) located in 1010A to the qd's located in 1008B and 1010A.

CONTROL SYSTEM

e-lens and Phase Shift P.S. Control System

Both the e-lens and phase shift p.s.'s use the same 3u chassis control bucket. In this control bucket resides the setpoint card, the current regulator card, the buffer card, the DC overcurrent (DCOC) card, the digital isolation card and the control card. The setpoint card receives a 0-10V analog signal from a fiber optic interface card which resides in another bucket. This analog setpoint is sent over the 3u control chassis backplane to the BNL designed current regulator card. This current regulator card has a removable PC board for adjusting time constants to stabilize the p.s. current loop. The buffer card sends four analog signals back to the Multiplexed Analog to Digital Converter (MADC). These four signals are p.s. current setpoint, output current, output voltage and p.s. current error. The phase shift p.s.'s and the e-lens Fringe and Anti-Fringe p.s.'s use a 0-10V output DCCT head. The e-lens Solenoid p.s. uses a current output DCCT head. This current output is sent to a BNL designed DCCT card which converts the current to a voltage. The DCOC card receives the shunt input from the commercial p.s. shunt and uses this shunt on the DCOC card. The digital isolation card receives commands from a Node card which is external to the p.s. and sends p.s. statuses back to this Node card. The Node card communicates over a MODBUS Plus network to a MODICON Programmable Logic Controller (PLC).

OPERATIONAL EXPERIENCE & STATUS

Phase Shift P.S. Problems During Runs 12 & 13

During Run 12 some problems were encountered with the first two phase shift p.s.'s. We learned from these

problems in order to improve the reliability of these p.s.'s for Run 13. The problems during Run 12 included:

- Running a copper BNC cable for the p.s. current readback to the qd through the tunnel. The current readback would move with beam. This was corrected by running a fiber through the tunnel.
- Workmanship problems with the wiring harness which caused a ground fault and other problems. Workmanship was improved to correct this problem and inspections were done.
- The p.s. isolation voltage rating was below the rating required for p.s.'s in the ring. This did not cause any problems but still was corrected. New p.s.'s were purchased with the correct voltage isolation rating.
- Open channels on the qd card picking up a signal from an adjacent channel, which had a p.s. current readback on it, would cause the qd to trip out. These open channels were shorted out.
- A hard reset was required for the yellow qd's to accept changes made for the yellow phase shift p.s.'s.

e-lens P.S. Testing

The e-lens p.s.'s have not been used by operations for the RHIC runs yet but the yellow e-lens p.s.'s have been tested during RHIC run 13 and at the end of RHIC run 13.

The solenoid ps. was operated up to 392A maximum. The Fringe p.s. was operated up to 470A maximum and the Anti-Fringe p.s. was operated up to 330A.

One problem encountered with the e-lens p.s.'s was the placement of the DCCT head in the QPA. The DCCT head was placed too close to the energy extraction dc cable. When a quench would occur, and the energy extraction system would kick in, the DCCT head would see a spike on the current during the decay. The DCCT head was moved to correct this problem.

When the p.s.'s are off we have seen that the coil voltage taps pick up a signal when adjacent warm magnets are ramped. Injecting or dumping beam might also affect these coil taps. This has caused the qd to trip. This is currently being investigated.

The correctors were not been tested on the magnet as of yet but they have been tested on short circuits.

ACKNOWLEDGEMENTS

The authors would like to thank the technician's in the Collider Electrical p.s. group who worked very hard on these p.s.'s. They are Mitch DeLavernge, Joe Drozd, Don Gosline, Gregg Heppner, Brian Karpin, Rich Kurz, Tom Nolan, Fred Orsatti, Frank Scheifele, Jeff Wilke, and Ron Zapasek. This work was supported by Brookhaven Science Associates, LLC under Contract No. DE-AC02-98CH10886 with the U.S. Department of Energy.

REFERENCES

- [1] The RHIC Configuration Manual
- [2] J. Muratore et al., "Test Results for the Electron Lens Superconducting Magnets at RHIC", MT23 Conference, Boston, July 2013.

- [3] D. Bruno et al., “Overview of the AGS Cold Snake Power Supplies and the New RHIC Sextupole Power Supplies”, PAC07, Albuquerque, MOPAS090, June 2007, p. 637 (2007); <http://www.JACoW.org>.