

THE NEW 20 kA 80 V POWER SUPPLY FOR THE 520 MeV H⁻ CYCLOTRON AT TRIUMF

S.Carrozza, L.Bondesan, A.Morato, M.Pretelli, G.Taddia, OCEM Power Electronics, Bologna, Italy
 Y.Bylinski, A.Leung, D.Louie, F.Mammarella, R.Nussbaumer, C.Valencia, TRIUMF, Vancouver, Canada,
 JP.Burnet, M.Cerqueira-Bastos, G.Hudson, Q.King, G.Le Godec, O.Michels, CERN, Geneva, Switzerland

Abstract

The new 20 kA, 80 V power supply for the main magnet of the 520 MeV H- Cyclotron at TRIUMF was awarded to OCEM. It has replaced the original system (commissioned in 1976) based on a series pass regulator.

The final acceptance tests have demonstrated the compliance with the project specifications, especially for the high current stability required for the Cyclotron operation. The current stability is ± 5 ppm, including current ripple, for a period of more than 8 hours of continuous operation. In addition, the magnetic field can be further stabilized using feedback of a flux loop signal.

OCEM designed the power supply to use the third generation of Function Generator/Controller (FGC3) control electronics from CERN. This was chosen to obtain the high current stability required by TRIUMF. This collaboration was facilitated through a Knowledge Transfer agreement between CERN and OCEM. The power supply commissioning has been performed as a collaboration between OCEM, TRIUMF and CERN.

This paper describes the topology of the power supply, the control electronics, the high-precision current measurement system and the associated software as well as the commissioning results carried out with the magnet.

TECHNICAL SPECS AND TOPOLOGY

The new 20 kA, 80 V power supply for the main-magnet coil of the 520 MeV H- Cyclotron at TRIUMF (referred to as the “power supply” in this paper) features (i) a 12-pulse input stage made by two three-phase transformers phase-shifted by 30 degrees, (ii) a modular power conversion stage and (iii) a freewheeling diode dissipating the energy stored in the magnet [1]. Table 1 lists the main technical features and measured performance parameters.

Figure 1 shows the structure of a single power module, which consists of three IGBTs (Mitsubishi CM600DX) in parallel switching at 10 kHz. Figure 2 presents the overall schematic of the power supply. The modular structure with

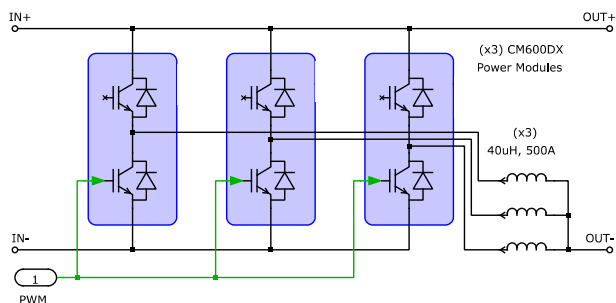


Figure 1: Electrical diagram of a single power module.

sixteen power modules allows an interleaved approach giving an overall switching frequency of 160 kHz.

Table 1: Main Features of the 20 kA, 80V Power Supply

Parameter	Value
AC Input	3-phase, 3-wire, 800±40 VAC
Topology	Modular Buck converter
Cooling	Air and water cooling
Equivalent switching frequency	160 kHz
Current ripple	± 2 ppm of 20 kA
Short-term (5m) stability	$\leq \pm 2$ ppm of 20 kA
Long-term (8h) stability	$\leq \pm 5$ ppm of 20 kA
Power factor	$\geq 97\%$
Input current THD	5.1% at 18.13 kA
Max efficiency	92.3%
Footprint	20.7 x 8.4 feet
Magnet load	120 mH, 3.9 mΩ

CONTROL ELECTRONICS

The control and acquisition electronics were described in some detail in [1]. They are an evolution of the controls originally developed for power converters in the CERN Large Hadron Collider [2,3]. At TRIUMF, the absolute accuracy requirement is much less demanding than in the LHC, but the stability requirements are similar.

The controls electronics includes a third generation CERN Function Generator/Controller (FGC3) [4] which uses a TMS320C6727 DSP to run the CERN converter control libraries [5,6]. In addition, the controls electronics includes a CERN-designed board with a TMS320C28346 DSP that is responsible for the voltage regulation, output filter damping and IGBT PWM generation. Other cards manage the MCB, the pre-charge circuit, analogue and digital interlocks and the conditioning of analogue signals.

The FGC3’s DSP supports digital regulation of the circuit current, as measured by twin TOPACC-HC (LHC type) 20 kA DCCTs from PM Special Measuring Systems. Achieving the current ripple and 5-minute stability specifications requires low noise on the current measurement and an appropriate choice of filtering and regulation parameters in the software. For the 8-hour stability specification, the temperature coefficient and environmental conditions for the analogue measurement chain are critical.

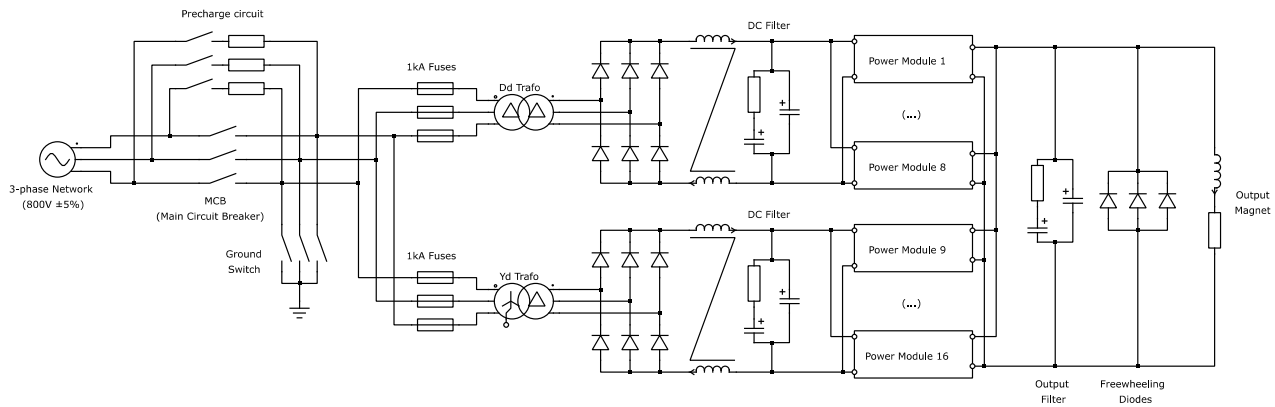


Figure 2: Electrical diagram of power supply.

Current Measurement

The TOPACC-HC DCCTs were selected for their low noise and low temperature coefficient (~ 1 ppm/ $^{\circ}\text{C}$), however, the temperature coefficient of the FGC3's ADCs and associated signal conditioning chains is not as good (~ 2 ppm/ $^{\circ}\text{C}$). To meet the long-term stability specification, the DCCT electronics and FGC3 are housed in a temperature-controlled rack ($< \pm 1^{\circ}\text{C}$). The FGC3 has four LTC2378-20 ADCs, sampled at 500 ksp/s. The FPGA in the FGC3 accumulates sets of 50 samples and provides the results to the software, which runs at 10 kHz.

Digital Filtering

During the commissioning, it was found that at 18 kA, the 10 ksp/s current measurements have 17 mA p-p at 60 Hz and 51 mA p-p at 120 Hz (note that 20 mA is 1 ppm). If regulated directly, this is sufficient to jeopardize the current ripple specification. To combat this noise, a single sliding-average FIR filter was activated in the software at 10 kHz, with a length of 167 taps. This provides notches at 59.88 Hz and multiples of this frequency. It completely eliminates the 60 Hz noise and reduces the 120 Hz to an insignificant 0.13 mA p-p, but at a cost of 8.4 ms of latency.

Integration with EPICS at TRIUMF

A Knowledge Transfer project was started at CERN in 2016 to develop the necessary software to allow FGC3-based controls to be easily exploited at other labs. This has resulted in two software components (so far) becoming available for other labs: an FGC Ethernet gateway [7] and an expert web interface called PowerSpy. The gateway can run on any Linux PC with two network interfaces; one for the FGC_Ether fieldbus (FGC protocol over raw Ethernet packets) and the other for the controls LAN (IP protocols). An FGC Ethernet gateway can control up to 64 FGC3s via standard unmanaged Ethernet switches.

The FGC Ethernet gateway implements a simple ASCII protocol through TCP ports that allows applications to set and get values in the FGC3. The controls group at TRIUMF were able to configure the existing EPICS streamDevice component to work with this protocol, without requiring any new software to be written.

COMMISSIONING ACTIVITIES

After installation, numerous tests were carried out to guarantee that the power supply achieved the same performance observed at OCEM before shipping. In particular, tests were made of the (i) insulation resistance, (ii) digital and analogue interlocks, (iii) electromechanical components, (iv) PWM drive signals, and (v) voltage and current transducers. After these tests, the power supply was considered safe for powering to start, beginning with voltage loop tuning and followed by current loop tuning, first at low current and then at nominal current. Extensive use was made of thermal imaging and thermal strips to detect any overheating. Finally, thermal reliability tests were conducted at 18.13 kA for more than eight hours.

Voltage and Current Regulation

The digital voltage regulator was configured to have a bandwidth of 500 Hz and a damping factor of 0.8. The latency of the regulator was measured to be ~ 150 μs .

Once the voltage regulator was configured, a Transfer Function Analysis (TFA) program was used with the FGC to measure the transfer function of the power supply and magnet. The tool measured the current response to a series of cosine excitations on the voltage reference, from 15 mHz to 90 Hz. The result is shown in Figure 3.

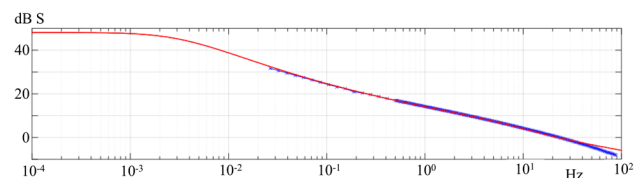


Figure 3: Measured admittance (blue crosses) and fitted model (red line).

What is striking is how far the transfer function is from a nominal first order response. From 0.1 Hz to 10 Hz the attenuation increases by only 22 dB instead of the nominal 40 dB. The FGC software includes a current regulator synthesis algorithm that can handle this type of response, but only if the measurement latency is less than about 40% of the regulation period, which is 10 ms. The 167-tap (60 Hz)

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2018). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.

FIR filter latency of 8.4 ms is too great, but an extrapolation stage can be activated after the FIR filter. This eliminates the measurement latency at the cost of a modest increase in noise. This approach is used successfully in the LHC and it works very well with the TRIUMF power supply. With a constant reference of 18.5 kA, the regulation error over 20 seconds was measured to be 82 mA p-p (± 2 ppm), 11.4 mA rms (0.6 ppm).

Flux Loop Feedback

The original power supply used analogue regulation of a current measurement made using a huge water-cooled 20 kA shunt resistor. Unsurprisingly, the short-term current stability was not adequate, so in 1984 a flux loop signal was integrated into the analogue regulator as a ΔI_{ref} [8].

The specification for the new power supply required the option to exploit this flux loop signal, in case it was found to be needed for the short-term stability. TRIUMF developed a signal conditioning card that fits in the FGC control electronics crate and routes the filtered flux loop signal to the unused fourth ADC channel in the FGC3.

In the software, the measured flux loop value can be scaled to become ΔI_{ref} using an adjustable gain parameter. When this gain is set to 5 A/V, it results in a reduction in the variation of the flux loop signal from around ± 50 mV to ± 4 mV. Figure 4 shows the flux loop voltage before and after the activation of the flux loop feedback.

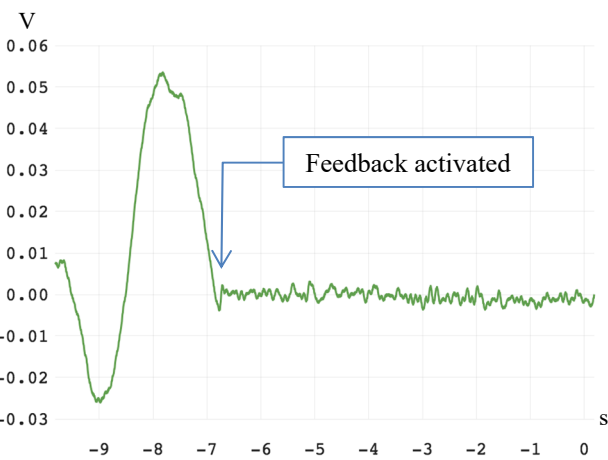


Figure 4: Flux loop voltage before and after activation of feedback.

With a gain of 5 A/V, the ± 4 mV fluctuation in the flux loop signal translates into a ± 20 mA or ± 1 ppm modulation of the current reference.

While it is clear that the software can significantly reduce the variation of the flux loop voltage, it is not clear at the time of writing whether this improves the performance of the cyclotron. This will be the subject of further tests in the coming weeks.

Efficiency & Total Harmonic Distortion (THD)

The input 3-phase line was monitored with a Fluke 435 power analyser in order to evaluate the overall efficiency and THD of the voltage and current. The results are shown in Figure 5 for different output current values.

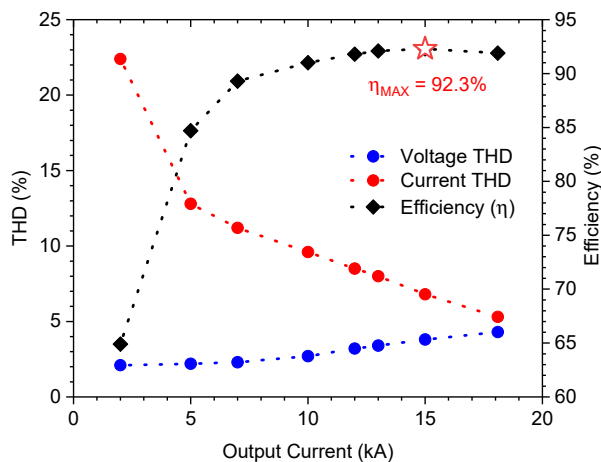


Figure 5: Efficiency and THDs as a function of current.

Magnetic Field Stability

While the FGC can report that the rms current regulation error is 0.6 ppm, it is not possible to know if the current is really that stable without an independent, trusted current measurement. An alternative validation method at TRIUMF is to measure the magnetic field using the NMR probe installed inside the magnet [9]. This has a resolution of 0.01 G, which is 1.8 ppm of the nominal field. Figure 6 shows (a) the measurement settling over about two days followed by (b) steady-state for two days and (c) steps in the field corresponding to current steps of 100 mA. From this we can see that the short-term stability is better than ± 2 ppm and the two-day stability is better than ± 4 ppm. With the flux loop signal it was possible to see the effect of steps in current of 10 mA (0.5 ppm), but this was below the resolution of the NMR.

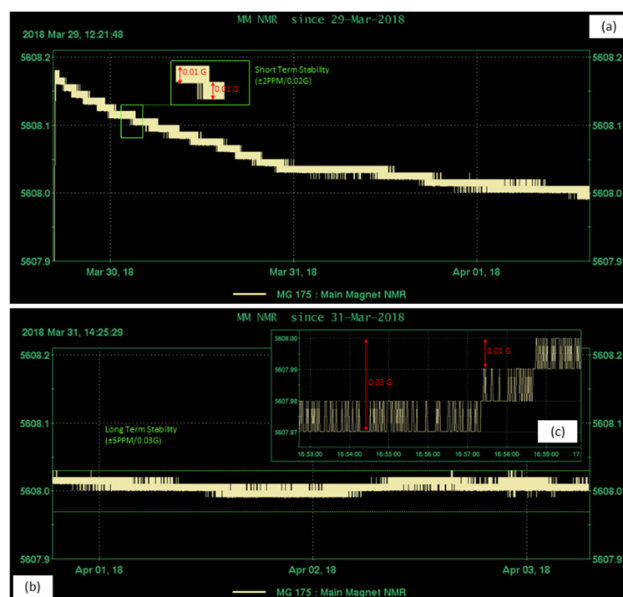


Figure 6: NMR probe acquisition of magnetic field. (a) Initial settling time; (b) steady state after two days; (c) increase of field by means of two distinct 100mA steps.

CONCLUSION

The power supply has been successfully verified as (i) fulfilling the electrical specifications, (ii) sustaining endurance thermal tests, (iii) meeting the ripple and (according to the NMR measurements) the short and long-term stability requirements and (iv) integrating successfully within the EPICS controls framework.

Further tests are foreseen to investigate if the regulation of the flux loop measurement improves the beam performance.

ACKNOWLEDGEMENT

We would like to express our gratitude to all colleagues involved in this challenging work. We would like to mention F.Burini, R.Donato, M.Farioli, O.Gamberini, R.LoV-erso, A.Musile Tanzi, L.Rinaldi (OCEM); J.Alfonso, J.Herttuainen, K.Leboida, M.Magrans De Abril, R.Murillo Garcia, D.Zielinski (CERN).

REFERENCES

- [1] S.Carrozza, F.Burini, E.Ferrari, M.Pretelli, G.Taddia, Q.King, G.Le Godec, G.Hudson, M.Bastos, D.Louie, Y.Bylinski, R.Nussbaumer, "A New Concept of High Current Power Supply for the Main Cyclotron Magnet at TRIUMF" in *Proc. 21st International Conference on Cyclotrons and their Applications (CYC'16)*, Zürich, Switzerland, September 2016, paper TUP10, pp. 186-189.
- [2] F. Bordry, H. Thiesen, "RST Digital Algorithm for controlling the LHC magnet current", *LHC Project Report 258*, CERN, Geneva, Switzerland, 1998.
- [3] Q. King et al, "The All-Digital approach to LHC power converter current control" in *Proc. 8th Int. Conf. on Accelerator and Large Experimental Physics Control Systems (ICALEPCS'01)*, San Jose, USA, November 2001, paper THBT004, pp. 453-455.
- [4] D.Calcoen, Q.King, P.F.Semanaz, "Evolution of the CERN Power Converter Function Generator/Controller for Operation in Fast Cycling accelerators" in *Proc. 13th International Conference on Accelerator and Large Experimental Physics Control Systems (ICALEPCS'11)*, Grenoble, France, October 2011, paper WEPMN026, pp. 939-942.
- [5] Q. King et al., "Function generation and regulation libraries and their application to the control of the new main power converter (POPS) at the CERN CPS" in *Proc. 13th International Conference on Accelerator and Large Experimental Physics Control Systems (ICALEPCS'11)*, Grenoble, France, October 2011 paper WEPMN008, pp. 886-889.
- [6] Q. King et al., "CCLIBS: The CERN Power Converter Control Libraries" in *Proc. 15th Int. Conf. on Accelerator and Large Experimental Physics Control Systems (ICALEPCS'15)*, Melbourne, Australia, Oct. 2015, paper WEPGF106, pp. 950-953.
- [7] S. Page et al., "Migration from WorldFIP to a low-cost Ethernet fieldbus for power converter control at CERN" in *Proc. 14th Int. Conf. on Accelerator and Large Experimental Physics Control Systems (ICALEPCS'13)*, San Francisco, CS, USA, Oct. 2013, paper TUPPC096, pp. 805-808.
- [8] K. Reiniger, H. Baumann, D. Dohan, D. Pearce, "Stability improvements in the TRIUMF cyclotron magnetic field to ± 0.7 ppm" in *Journal de Physique Colloques*, 1984, 45 (C1), pp.C1-225-C1-228. <10.1051/jphyscol:1984145>. <jpa-00223701>
- [9] R. Burge, G. Dennison and D.A. Dohan, "PRECISION NMR MEASUREMENT OF THE TRIUMF CYCLOTRON MAGNETIC FIELD" in *Proc. of the Tenth International Conference on Cyclotrons and their Applications*, East Lansing, MI, USA, pp. 82-84