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# A PULSED, CURRENT REGULATED MAGNET POWER SUPPLY FOR SMALL MAGNETS*

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*Abstract*

The University of Maryland Electron Ring (UMER) has two pulsed quadrupoles in the injection section that must be current regulated to the same precision as the other DC quadrupoles in the ring, as well as accurately synchronized to the ring operating cycle. To meet this need a practical pulsed current, regulated power supply has been designed and built using a commercial power operational amplifier for output, standard operational amplifiers for feedback control and monitoring, and matched resistor pairs to produce the desired transfer function of 10 Volts to 6 Amperes. For other applications the circuit can be modified to produce a range of transfer functions by varying the appropriate resistor pair ratios. Output pulse width and timing are generated by a standardized TTL pulse from the control system that gates the output of the amplifier. Installed safety circuitry detects the absence of a proper control pulse, an open circuit or shorted output, and measures and returns to the control system the operating amplitude of the current pulse. In this paper we present the design, implementation, and operational results of the prototyped pulsed current source.

## INTRODUCTION

A detailed description of UMER can be found in reference [1]. It was built as an instrument to study the physics of charged particle beams with extreme space charge; that is, beams with incoherent tune shifts that are more than several integer values and coherent tune shifts of more than 0.5. The original motivation was research in support of the heavy ion fusion concept which would have operated in these space charge extremes. Because the UMER design goal was for a simple inexpensive machine with a beam kinetic energy of 10 keV, the magnets were designed using windings of precision, flexible mylar based printed circuits mounted in nonmagnetic aluminum alloy housings.

As the resulting magnetic fields are rather low, the lattice is densely packed with 72 quadrupoles and 36 dipoles in an 1152 cm circumference, or about 10.5 cm center-to-center spacing. Injection is a special problem as the beam pipe had to be enlarged from a 5 cm diameter to 8 cm over ~ 62 cm to facilitate the beam offsets at injection. This larger diameter meant the two injection quadrupoles are larger, requiring more current to match the gradients in the rest of the ring - ~4.5 A. The PC windings overheat at these currents and so are pulsed. Originally powered by discharging capacitor banks using IGBTs, the resulting current droop over the 10,000 turn storage, remedied with a recently installed RF cavity, is unacceptable. Thus, use of precision power operational amplifiers was indicated, and in the absence of affordable commercial units the design presented here was undertaken.

## BASIC DESIGN REQUIREMENTS

Normally operated at 60 Hz, the most extreme case for quadrupole heating, the ring can operate as low as 10 Hz. At 10,000 turns and a 0.2 μsec revolution period, injection quadrupoles have to be driven for at least 2.0 msec. There is an additional need to let the eddy currents, induced in the stainless steel beam pipe during turn-on, to decay sufficiently before beam is injected into the machine adding an additional 250 μsec for a total of 2.25 msec on-time out of the 60 Hz period of 16.7 msec. While the injection quadrupoles normally operate from 4 to 5 A, an operating range of 3 to 6 A is assumed to allow for a range of settings that may be needed to match injection into ring optics. The requirement at the maximum heating case, set by the 13.5% duty cycle and pulsed current amplitude of 6 A, is that no runaway heating occurs in either the quadrupoles or the final stage power operational amplifier.

Two other major amplifier requirements are: (1) that the precision of the current signal be 2 mA out of 6000 mA and (2) the output of the amplifier be short circuit protected. The first is consistent with the required current regulation precision in the regular DC ring quadrupoles, which sets the resolution of the digital-to-analog conversion (DAC) at 12 bits or 1.5 mA per bit. This also includes read back confirmation of the desired operating current level by the control system, adding the necessity for a strobed analog-to-digital converter (ADC) of the same precision. The second requirement is standard in current regulated power supplies but has to be specifically accommodated in a custom design such as this one.

Control timing is via a single pulse generated by a computer controlled pulse generator in the ring central control system which signals the timing and duration in the operating cycle of the two quadrupoles. As noted above the maximum number of turns allowed is 10,000 but the ring can be set to operate at any number of turns less than this by shortening the control pulse.

In addition to the current foldback protection, there needs to be a number of internal monitoring and control functions including timing of the ADC sample pulse, missing control pulse detection, and detection of analog set current signal and analog output current mismatch.

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## AMPLIFIER DESIGN

A search for a commercial power operational amplifier with the recommendations in the invaluable book by Horowitz [2], led to the choice of the OPA541 power operational amplifier [3]. It is capable of peak current outputs of 10 amps and dual supply voltages of ± 40 volts. The basic current regulation operational amplifier derives from a circuit suggested in the Texas Instruments Handbook of Operational Applications [4]. The resulting circuit has a design transfer function of 0-6 A out for 0-10 V in, using a small input precision operational amplifier as part of the feedback network with the OPA541. The block diagram for the amplifier module is shown in Fig. 1.

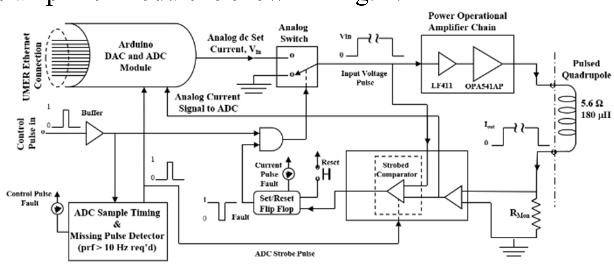

Figure 1: Block diagram of entire amplifier module.

To set the current the control system sends a digital voltage signal to the DAC module which provides a DC set voltage, $V_{in}$. A precision analog switch, controlled by the UMER timing system generated input control pulse, switches the input of the operational amplifier chain from ground to $V_{in}$ for the coil pulse width. Read back of the set current to the control system is via a special sense amplifier across $R_{Mon}$ that produces a voltage pulse equal to $V_{in}$ if the system is operating correctly.

The timing diagram is shown in Fig. 2. The ring central control system generates the 60 Hz repetition pulse rate from line voltage using two BNC 575 delay generators. This sets the sequence of pules and pre-pulses required for UMERs control system and the operation of all other systems (such as oscilloscopes, etc). A 200 µsec delay will be imposed on the 20 µsec sampling window for the ADC, which gives sufficient time for the coil pulse to level out while also allowing the sampling to occur before any noise inducing injection.

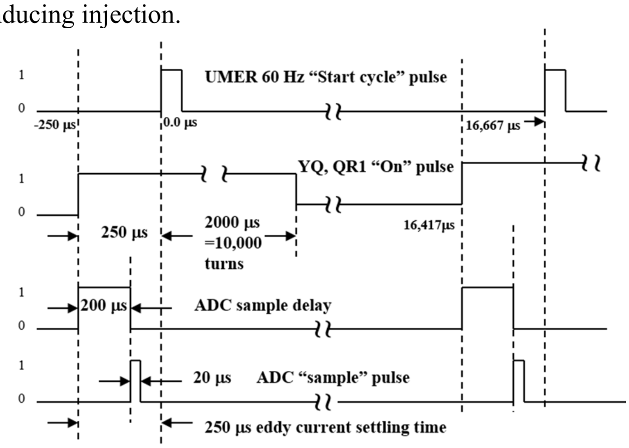

Figure 2: Timing diagram for the pulsed quadrupole amplier.

The constructed prototype of the amplifier design shown in Fig. 3 consists of two stacked circuit boards, with the timing and multistage amplifying circuitry on the lower board, and the safety circuitry on the upper board as to allow visual aid of the fault detection lights. The OPA541 which produces the bulk of the thermal dissipation in the amplifier is separated from the two boards and tightened to a Wakefield-Vett 403k heatsink. A copy of the injection quadruple magnet is housed in a square bakelite mount with its inner diameter surrounded by a thin layer of G-10 to keep the geometry of the magnet constant during heating. Terminal strips were used to connect the power supplies, the quadrupole magnet, as well as the reset switch on the safety circuit. The final product will be made on a PCB and mounted inside a NIM crate near the injection section.

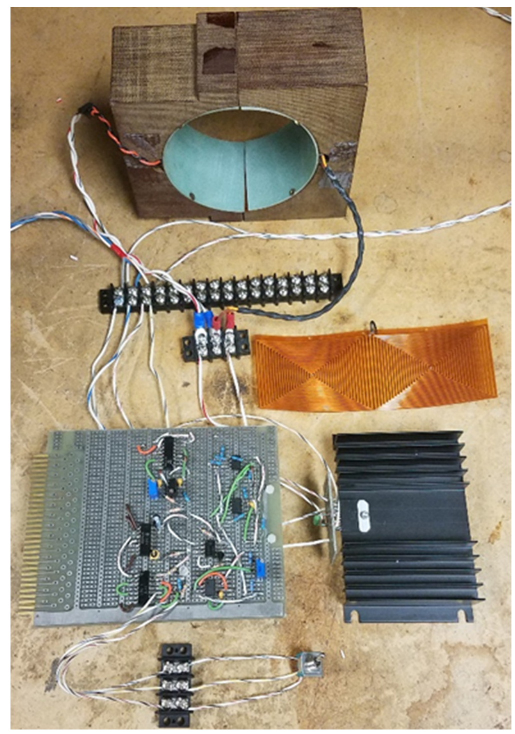
Figure 3: Picture of full circuit prototype. (Clockwise from top) injection quadrupole, mylar coated magnet coil, OPA541, reset switch, amplifier and safety circuity.

## OPERATION PERFORMANCE

The prototype was tested under the maximum injection conditions, as thermal stability and output regulation must be held throughout any operating condition. The most imperative property to test is the independence of the amplifier's output to the load resistance, meaning constant current can be applied with a varying load. As the quadrupole coils are driven they will produce large amounts of ohmic energy, and this increase in temperature will increase the resistivity of the copper traces which would result in a decreased magnetic strength unless proper current regulation is applied.

Current regulation tests were conducted by incrementing $V_{in}$ and recording the respective current amplitude across the load, as shown in Fig. 4. Starting with the injection

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quadrupole magnet and then increasing the load to the injection quadrupole magnet in series with a precision 1.0Ω resistor. The results show a clear and linear transfer function with a varying load, demonstrating the current regulation properties of this amplifier design.

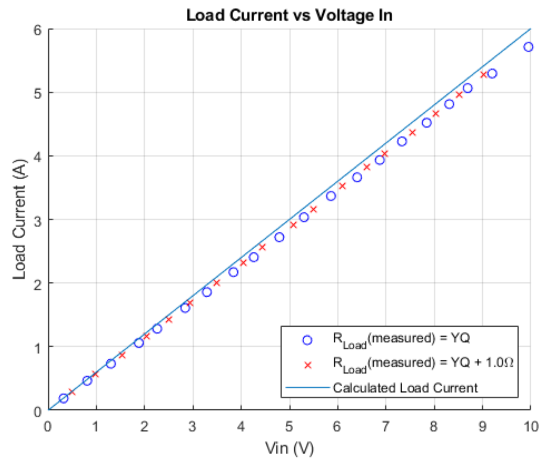


Figure 4: Measured and Calculated Load Current.

Set to the normal operating current pulse of 4.5 Amperes the error is less than 4% from the desired value, and with current sensor read backs this can properly be negated with minute offsets to $V_{in}$. This error is most likely due to slight mismatches in the resistor pairs even though 1% resistors were used.

A flat output pulse is needed throughout the injection timing as any drop in output could significantly affect beam injection. The amplifying circuit was tested under the maximum operating condition with a pulse width of 2250 μsec at 60 Hz and an output of 6 Amperes. Normally voltage spikes occur with a pulsed inductive load as the voltage rises with the derivative of the current, these spikes can cause unwanted attributes and even damage to other electronics. To negate this, feedback capacitors in the amplifying stage were carefully chosen to roll off the voltage spikes while minimizing the effect on the rise and fall times of the pulse. The voltage output in Fig. 5 shows a constant DC voltage starting after the 200 μsec delay and continuing until the gate pulse is turned off 2050 μsec later.

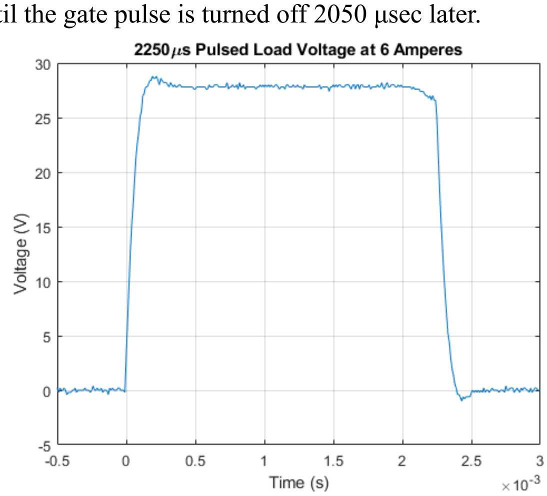


Figure 5: Pulsed load output voltage.

The final part of testing was the thermal stability and capability of the quadrupole coils, and more importantly the OPA541. As before, maximum heating conditions are tested at a 6 Ampere pulse for 2.25 msec at 60 Hz. The temperature measurements were taken on the surface of the G-10 at one of the quadrupole's poles, as well as the surface of the OPA541 amplifier.

Figure 6 shows that the coil temperature does not run away and stabilizes after around two hours of run time, which was expected as the other various magnets installed in the ring take a similar amount of time to reach stability. The quadrupole initially had a resistance of 4.58Ω, and after the three hour test finished with a resistance of 5.04Ω. As previously shown, the transfer function has been proven to hold for up to a 1Ω increase in load resistance, above the tested equilibrium resistance of the quadrupole. The OPA541 operating temperature leveled out within 1 hour of heating and reached a maximum of 129.7 °F, well below the maximum safe operating temperature of 185 °F [3].

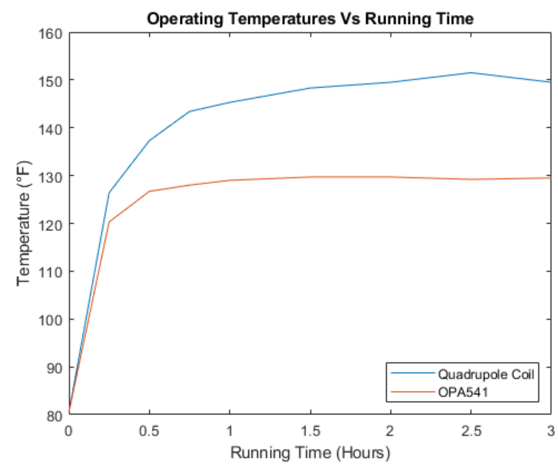


Figure 6: Operating temperatures of injection quadrupole coil and OPA541.

## CONCLUSION

A fully operating prototype amplifier has been built and tested. It has been demonstrated that the amplifier accurately performs with the desired transfer function independent of load resistance, and that it can also power a UMER pulsed quadrupole under the maximum heating conditions safely. The next step is the design of a standard etched PCB and housing in a NIM module where three units are planned to be made.

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