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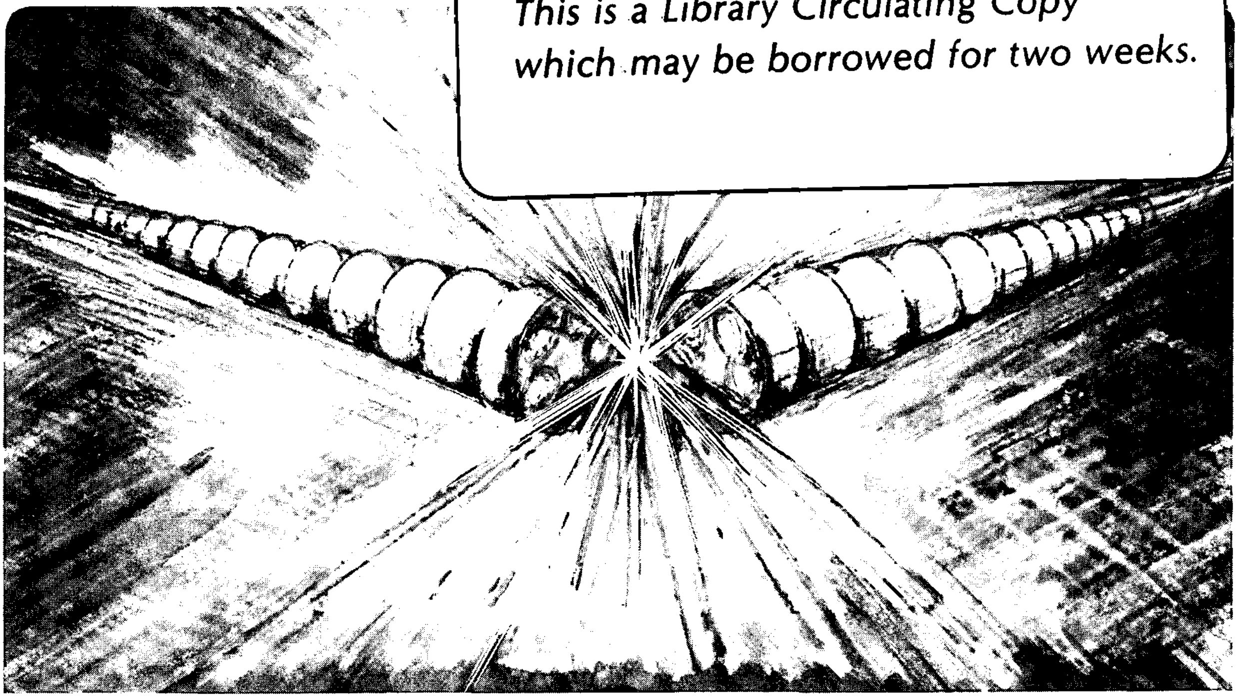
G. Stover, J. Halliwell, M. Nyman, and R. Dwinell

March 1989



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G. Stover, J. Halliwell, M.Nyman, and R. Dwinell

Accelerator and Fusion Research Division
Lawrence Berkeley Laboratory
1 Cyclotron Road
Berkeley, CA 94720

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OPERATIONAL RESULTS FOR THE RASTER SCANNING POWER SUPPLY SYSTEM CONSTRUCTED AT THE BEVALAC BIOMEDICAL FACILITY*

G. Stover, J. Halliwell, M. Nyman, and R. Dwinell
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

Abstract

A raster scanning power supply for controlling an 8.0 Tesla-meter relativistic heavy-ion beam at the Biomedical Facility has been recently completed and is undergoing electrical testing before on-line operation in 1989. The scanner system will provide tightly controlled beam uniformity and off-axis treatment profiles with large aspect ratios and unusual dimensions. This article will discuss original specifications, agreement with measured results and special device performance (i.e. GTOs, FET actuator assembly, etc.).

Introduction

The construction of a new raster scanning power supply system has been completed and the full power qualification of the electronic system is in the final testing phase. The scanner, which is an integral component of a "next generation" of beam delivery system being developed at the Bevalac Biomedical Facility, was designed to deflect a tightly focused light ion beam in a raster scanning fashion in order to project a rectangularly shaped dose distribution into a treatment volume. The projection can have any desired aspect ratio with scan dimensions ranging from 5.0 cm to 40 cm. The beam spot size (a Gaussian distribution with a 1.0 cm s) and sweep spacing have chosen to provide a dose uniformity of ±2.5% across the selected scan geometry. The primary ions will be Ne^{+10} and Si^{+14} with a nominal energy per nucleon of 585 MeV. The beam pulse will be delivered to the treatment volume over a period of one second with an average intensity of 10^{+9} particles/pulse. This article will analyze the measured results obtained from the system testing program and compare them with the intended design specifications.

Review of system concepts.

As discussed in our previous papers[1,2] two separate power supply systems control separate orthogonally oriented dipole magnets, mounted in-line, 6 meters upstream from the target isocenter. The horizontal "fast" power supply sweeps the beam in a left to right fashion at 1200 cm/sec or a frequency of 30 Hz over a ±20 cm sweep field. The vertical "slow" supply will steer the beam from top to bottom at 40 cm/sec or one sweep per second over the maximum vertical distance of 40 cm.

As shown in Fig. 1 the fast scan system is powered by a single unipolar SCR-controlled power supply which applies a bipolar forcing voltage to the magnet via a synchronized bridge network of Gate Turn-On Thyristor (GTO) switches[3]. The magnet field is precisely controlled by a current-regulated shunt-series feedback topology during both the charging and discharging cycles. The power controlling element (426 amps @ 220 volts peak) is a MOSFET transistor actuator assembly (16 heat sinks with 25 devices per heat sink) which is mounted in the return leg of the GTO bridge network. During the discharge cycle the excess stored energy of the magnetic field is dissipated in the diode resistor (energy dump) network. High power back-to-back zener diodes connected across the magnet protects the actuator and GTOs from excessive inductive voltage spikes during switching cycles.

As seen in Fig. 2 the "slow" scan magnet is driven (270 amps peak) by a standard push-pull combination of two 16.0 kW actuator assemblies (eight heat sinks per assembly) which are controlled by a shunt-series current feedback arrangement. Power to the system is supplied by two opposite-polarity power supplies.

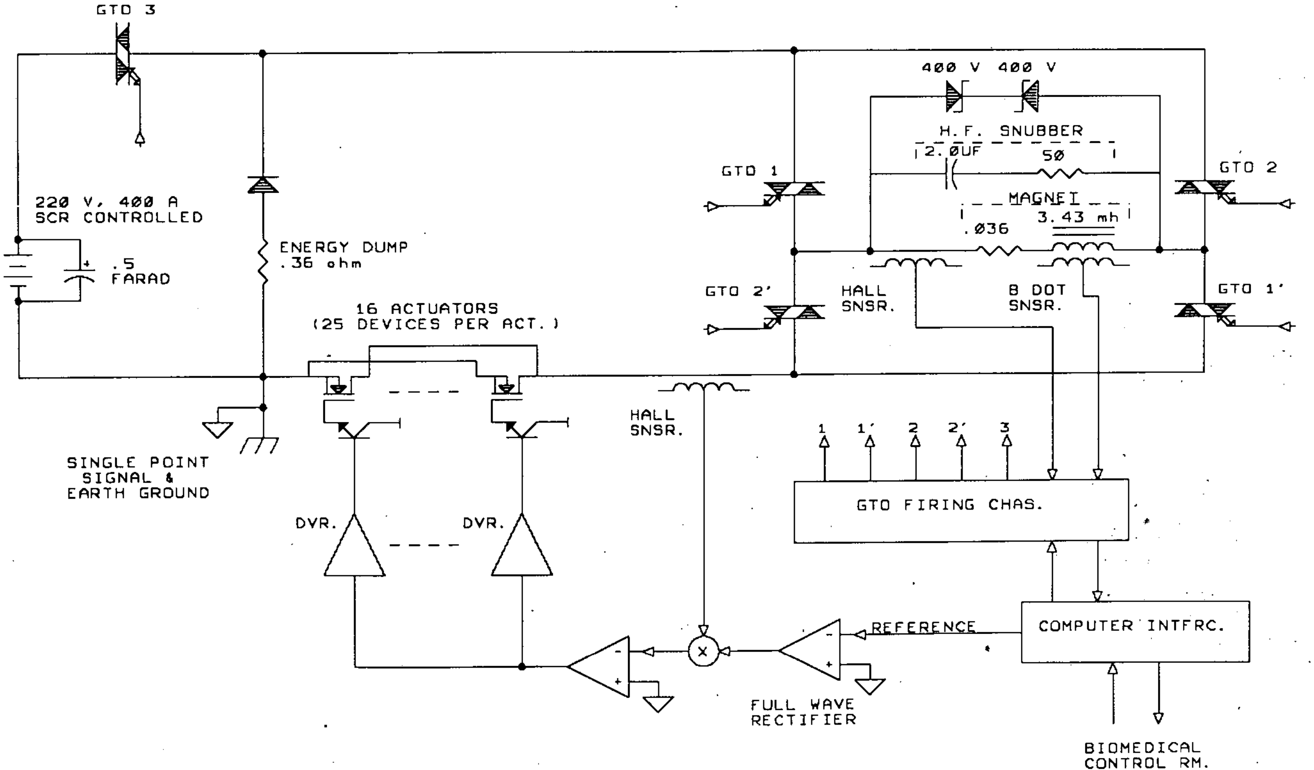

Fig. 1
"Fast" scan system

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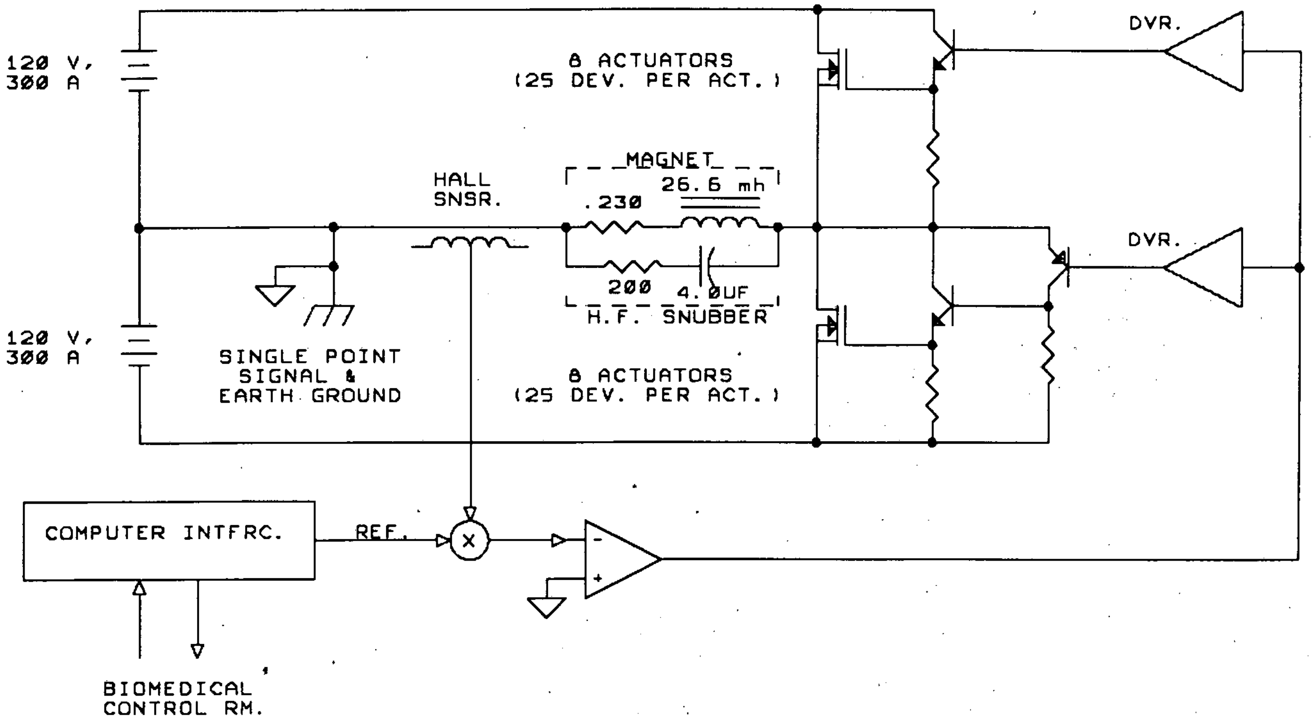

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Fig. 2
"Slow" scan system

Grounding and noise considerations

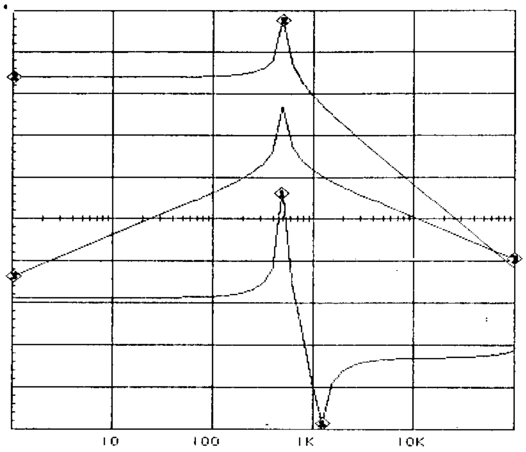
The magnitude of the power that is controlled by these systems has demanded that painstaking attention be given to cable routing, shielding, and subsystem grounding. To prevent extraneous ground loops the magnet, actuators, and most of the electronic chassis of both systems are connected to a single point earth ground. All the standard methods of noise suppression and decoupling were employed to suppress cross talk and undesirable feedback effects. Still, at the beginning of the testing program, several man-weeks of time were needed to track down and eliminate excessive noise and oscillation.

Critical specifications

Given a constant beam flux, the dose delivered at any point in the scan is inversely proportional to the scan speed. In order to achieve a dose uniformity of ±2.5% across the selected geometry the regulation of the magnet current should be controlled to approximately ±0.25%. A simple sensitivity analysis demonstrated that to maintain the specified current uniformity through the transition regions (at zero magnet current) the DC closed loop gain of both supplies had to be at least 60 db with a bandwidth of 10.0 kHz for the fast scan system and 1.0 kHz for the slow.

Initial estimations indicated that a stable closure of the feedback loop at the specified bandwidth for either system would be limited by the frequency response of the combined actuator assembly and its respective magnet load. This supposition was confirmed by (single actuator) prototype tests and IS-SPICE[4] circuit simulations. The SPICE small signal AC transfer function for the fast actuator and load has been chosen for discussion by virtue of its stringent bandwidth requirements and is shown in Fig. 3.The scaled (8/384) actuator model consists of a parallel array of eight MOSFET transistors (SPICE model, level 3) driven by an emitter follower and loaded by a scaled magnet load of 715 μH and 1.73 ohm.

The high frequency roll-off at 40 db/dec (CH 2 I_{drain} vs freq.) would suggest that the forward gain of the actuator is strongly influenced by two dominant low frequency poles. These would most likely be the magnet load reactance and the combined effects of the Miller gate to drain capacitance (C_{gd}) and the source impedance of the transistor driving the FET devices. The high frequency peaking at 12.6 kHz for this particular gain indicates that the root locus of the dominant poles is tending towards the unstable region of the right half plane.



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CH 1  VDBGATE vs FREQ    CURSOR    LEFT           RIGHT           DIFFERENCE
 YSCALE 10DBV/DIV
 YZERO  -22.0 DBV         VER      -15.9 DBV      -70.5 DBV       -54.7 DBV
 XSCALE 10.00 HZ
                          HOR      4.87KHZ        12.6KHZ         7.72KHZ

CH 2  IDBDRAIN vs FREQ   CURSOR    LEFT           RIGHT           DIFFERENCE
 YSCALE 20DBA/DIV
 YZERO  -104 DBA          VER      -35.9 DBA      -8.51 DBA       27.4 DBA
 XSCALE 10.00 HZ
                          HOR      10.00 HZ       5.01KHZ         5.00KHZ

CH 3  VDBDRAIN vs FREQ   CURSOR    LEFT           RIGHT           DIFFERENCE
 YSCALE 20DBV/DIV
 YZERO  12.0 DBV          VER      -15.5 DBV      -7.29 DBV       8.20 DBV
 XSCALE 10.00 HZ
                          HOR      10.00 HZ       1.00MEGHZ       1.00MEGHZ
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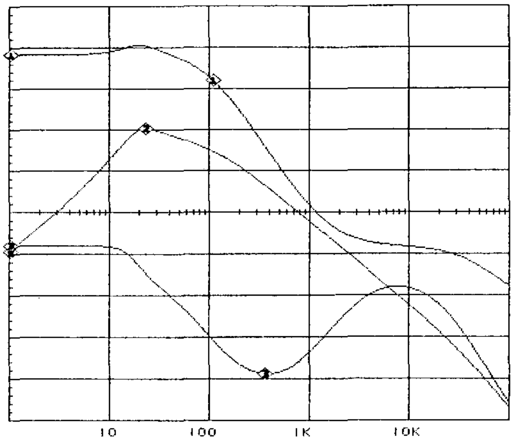
Fig. 3
Small signal AC transfer function of the fast scan actuator with a simple magnet load

A resistor capacitor (R-C) snubber circuit (see Fig. 1) was connected across the magnet to protect the transistors from high frequency inductive voltage swings and was adjusted to effectively stabilize the actuator transfer function. As shown in Fig. 4 the peaking is markedly reduced. The deviation from the normal 40 db/dec roll-off at approximately 100 kHz is due to the addition of the parasitic drain to source capacitance (44.0 nF) of the actuator mechanical assembly and of the capacity (22 nF) of the connecting cables to the magnet.

The measured frequency response of the installed actuator was in good agreement with the SPICE model but showed much smaller high frequency peaking even with the snubber circuit removed. With the actuator transistors operating in the linear region the fast scan system control loop was closed at approximately 8.0 kHz.

For the specific case of the fast scan system the magnet current direction is reversed as it passes through the zero magnetic field point. During this time (<150 μs) the actuator transistors may temporarily be forced to conduct in the ohmic rather than the normal saturated region. In this mode the Gate to drain (C_{gd}) and the gate to source (C_{gs}) capacities can be 5 to 10 times larger than in the saturated mode. This problem can have very adverse affects on the system control loop stability. This problem was greatly minimized by keeping the driver source impedance small and removing the parasitic suppression resistors in the gate leads of the FET transistors

Because MOSFETs have a very high gate input impedance, they have a natural tendency to oscillate in the megahertz region. The original suppressor circuit was composed of a 100 ohm resistor and two Ferroxcube[5] shielding beads mounted in series with the gate lead of each device. Though this effectively suppressed the parasitic oscillations it increased the effective driver source impedance and thereby reduced the actuator bandpass frequency to less than 2.0 kHz. It was empirically discovered that five ferrite beads mounted on a straight conductor provided enough energy loss at the natural oscillation frequencies to make the gate resistor unnecessary.



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CH 1  IDBDRAIN vs FREQ   CURSOR   LEFT          RIGHT         DIFFERENCE
 YSCALE 5DBA/DIV
 YZERO  -55.0 DBA         VER     -35.9 DBA     -39.0 DBA     -3.11 DBA
 XSCALE 100.0 HZ
                          HOR     100.0 HZ      10.9KHZ       10.8KHZ

CH 2  VDBDRAIN vs FREQ   CURSOR   LEFT          RIGHT         DIFFERENCE
 YSCALE 10DBV/DIV
 YZERO  14.0 DBV          VER     4.43 DBV      29.7 DBV      34.1 DBV
 XSCALE 100.0 HZ
                          HOR     100.0 HZ      2.27KHZ       2.37KHZ

CH 3  PI(V2) vs FREQ     CURSOR   LEFT          DIFFERENCE    RIGHT
 YSCALE 20DEG/DIV
 YZERO  16.0 DEG          VER     -12.5MDEG                   -61.7 DEG
 XSCALE 100.0 HZ
                          HOR     100.0 HZ                    36.5KHZ
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Fig. 4
Small signal transfer function of actuator and load and with snubber and parasitic capacitance included

GTO switch performance

As a precaution against uncontrolled turn-on of the GTO devices during periods of high transient voltages and currents a manufacturer recommended snubber circuit was connected across each device. Further testing revealed that for this particular switching application these circuits tended to interfere with the zero-current switching point and subsequently were removed.

During the final testing phase of the project two GTOs were separately damaged during accidental over-current conditions. Our post investigation of both faults seems to indicate that the specified surge current (6000 amps for a nonrepetitve one-cycle surge) of the devices had not been exceeded. With this limited experience we have concluded that these devices are not very tolerant of over-current conditions and the specification may not be very accurate. In addition the manufacturer-supplied gate firing control units (GU-62A) have a maximum triggering rate of 1.0 kHz beyond which the internal flyback power transistor is immediately shorted.

Results

Commissioning tests have been underway since the beginning of February. The first full system tests with beam through the magnet were conducted on March 1st of this year. At the time of this test the slow system was completely operational but the GTO firing circuits had not been fully tested and were strapped out of the fast circuit. As a result of this modification the fast system could only be operated in only one quadrant. To reduce the excess power dissipation of the actuator, which is normally absorbed by the energy dump resistor when the GTOs are operational, the scan frequency was reduced from 30 to 20 Hz. The oscilloscope photograph in Fig. 5 shows the transductor magnet current for both systems. The upper trace illustrates the zig-zag pattern of the fast system scanning with the x axis ranging from 0 to 175 amps. The lower waveform shows the concurrent sweep of slow system starting at -175 amps and sweeping to +175 amps over a period of 800 ms and then returning to a 0 current level. Since that time the firing circuit tests have been completed, and full four quadrant operation with beam through the magnet was demonstrated on March 15th 1989.

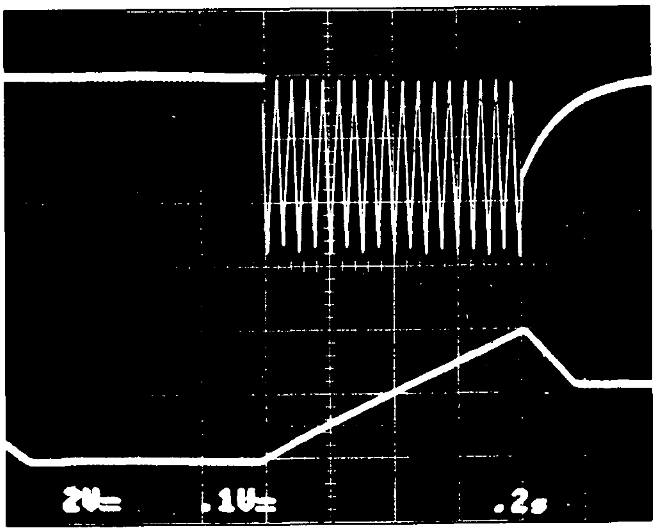

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Fig. 5
Fast and slow system magnet current waveforms

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[1] G. Stover, M. Nyman, J. Halliwell, I. Lutz, and R. Dwinell. "A Raster Scanning Power Supply System For Controlling relativistic Heavy Ion Beams at the Bevalac Biomedical Facility". Proceedings of 1987 IEEE Particle Accelerator Conference, Washington, D.C., March 1987, Publishing Services, IEEE, New York, pp. 1410-1412 (1987).

[2] J. E. Milburn, J. T. Tanabe, T. R. Renner, and W. T. Chu, "Raster Scanning Magnets for Relativistic Heavy Ions", Ibid pp. 2000-2002 (1987).

[3] Manufactured by Toshiba semiconductor of Japan.

[4] Trademark of Intusoft, 2515 South Western Ave., suite 203, San Pedro, Ca. 90732.

[5] Trademark of Ferroxcube corp.