

A RASTER SCANNING POWER SUPPLY SYSTEM FOR CONTROLLING RELATIVISTIC HEAVY ION BEAMS AT THE BEVALAC BIOMEDICAL FACILITY*

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Abstract

A power supply system is currently being designed and constructed to sweep an 8.0 Tesla-meter relativistic heavy ion beam in a raster scanning mode for radiotherapy use. Two colinear dipole magnets with orthogonally oriented magnetic fields are driven by the system to produce a rectangular field (40 x 40 cm max.) with a uniform dose ($\pm 2.5\%$) to a target volume 6 meters away. The "fast" horizontal scanning magnet is driven by a single power supply which in conjunction with a triac bridge network and a current regulated linear actuator will produce a 1200 cm/sec max. sweep rate. The "slow" (40 cm/sec) vertical scanning magnet will be controlled by dual current regulated linear actuators in a push-pull configuration. The scanner system can provide off-axis treatment profiles with large aspect ratios and unusual dimensions.

Introduction

The charged heavy ion particle beam extracted from the Bevatron and transported to the treatment room is usually small in diameter compared to the target volume. Over the developmental history at this research facility a number of different beam spreading methods have been devised to cover the entire target volume. Initially the double scattering¹ method was employed with the anticipated low efficiencies. This was followed by the wobbler method² which produced ring-shaped fluxes by using a rotating magnetic field. It allowed for the removal of absorbing materials which increased the residual particle range and produced far fewer collisional fragments. It also generated larger radiation fields than those attainable with scattering materials of reasonable thickness. Unfortunately this method produced a circular radiation field which had to be collimated for each patient. This drawback was overcome by a scanning method which sweeps a pencil sized beam across the desired treatment field in rasters. If the level of the extracted beam from the accelerator and the scan speed are held constant a uniform radiation field results. The entire field is scanned over many times in a given treatment in order to dilute any mismatching of the rasters, which introduce dose nonuniformities. This paper will discuss the salient features of the raster scanning power supply system required to control the heavy ion beam in the desired fashion.

Design Philosophy

Requirements and Specifications

The new beam scanning system being developed at the Biomedical facility involves deflecting a tightly focused light ion beam in a raster scanning fashion in order to project a rectangularly shaped dose distribution into the 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 σ), spacing, and interleaving will be constructed to provide a dose uniformity of $\pm 2.5\%$ across the selected scan geometry.

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The primary ions will be Ne^{+10} and Si^{+14} with a nominal energy per nucleon of 585.0 MeV. The beam will be delivered to the treatment volume over a period of one second with an average intensity of 10^{+9} particles/pulse. Because this system will be used in the treatment of patients, reliability and the ease of maintenance are paramount in the design and planning phases.

System Concepts

To accomplish these tasks two separate power supply systems will drive individual dipole magnets which have orthogonally oriented magnetic fields, and are mounted in series, 6 meters upstream from the isocenter. They are low-inductance, water-cooled magnets that were designed³ to optimally satisfy a simple optical arrangement (beam centered on target with zero magnetic field), achieve the desired scan rate, and provide the proper impedance match for the most economical power supply driving voltages. The horizontal "fast" power supply will sweep the beam in a left to right fashion at 1200cm/sec or at a frequency of 30 cps 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. Additionally, the vertical supply will have the capability to idle at any chosen vertical offset point until the beam is delivered to the target at which time the scanning will commence. Both systems will have tightly (0.25% or better) controlled current feedback loops which when working in tandem will project a very uniform and rectangular dose to the treatment area.

The field can be reduced within the specified limits to any rectangular size. In the y axis this is accomplished by adjusting the vertical sweep speed to cover a shorter distance in the same one second time interval. Due to the design of the "fast" power system the horizontal sweep speed is fixed for all excursion widths. If the beam flux is assumed to be constant, the dose delivered at any point is inversely proportional to the scan speed. As the horizontal peak to peak deflection is decreased the scan frequency and dose rate are increased. In order maintain a constant total dose to the treatment volume for narrower scans the beam intensity will be correspondingly decreased.

"Fast" Scan Power System

For reasons of economy the fast scan system is powered by a single unipolar power supply which drives the horizontal magnet with a bipolar forcing voltage. As seen in fig. 1 this is accomplished by connecting the magnet to its power source through a properly timed bridge network of Gate Turn-on Thyristor (GTO) switches. The firing sequence is described as follows.

To begin the horizontal scan deflection, GTO's 1, 4, and 5 (substitute 2, 3 and 5 for starting in the opposite direction) are simultaneously turned on to apply a constant forcing voltage of approximately 175 volts to the inductive load. The exponential rise of the magnet current is linearized by the current-controlled transistor actuator connected in

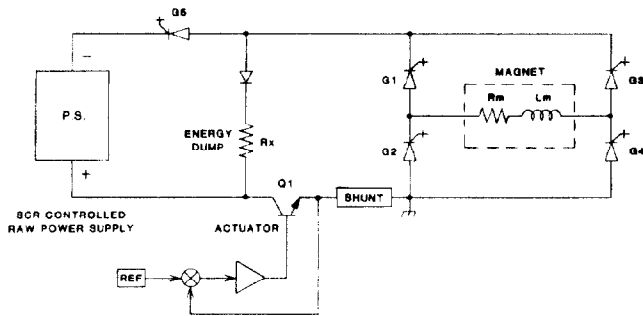


Fig. 1 "Fast" scan system

the return leg of the circuit. As seen in fig. 2 when the peak deflection current ($I_{max} = 426.0$ Amperes) has been reached GTO 5 is switched off effectively isolating the power supply from the load. This also causes the magnet voltage to reverse polarity and forces its current to decay towards zero in a linear fashion as dictated by the actuator and the diode resistor network R_1 and D_1 . The resistor R_1 provides a substantial amount of power dissipation during the discharge cycle thereby reducing the power requirements of the more expensive transistor actuators. When the magnet current reaches zero, GTO's 1 and 4 are turned off and 2, 3, and 5 are turned on applying a forcing voltage of the opposite polarity to the magnet load which repeats the above cycle for the opposite scan direction.

At the point of voltage reversal when the beam will begin to sweep in the opposite direction the system may exceed its regulation specification and subsequently cause some beam divergence. During this time of maximum excursion and possible instability the beam will be blocked by a metallic collimator circumscribing the target area.

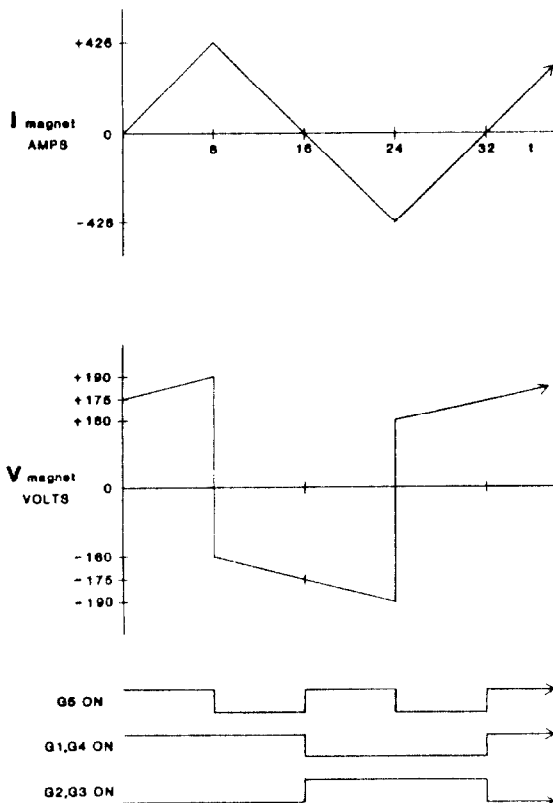


Fig. 2 "Fast" scan waveforms

The use of GTO's which is now a fully mature technology greatly simplifies the design of the switching network. These thyristor devices are now available with voltage ratings as high as 4.5 kV. By eliminating the need for bulky and expensive LC networks required to commutate equivalent SCR's, these devices allow reductions in size, weight, and manufacturing cost. However, their more complex gate waveforms increase drive-circuit complexity which fortunately has now become very modularized. The devices for this system have been prototyped and tested under various load conditions with no observable switching delays or missing pulses.

Advances in current sensing have also reduced circuit cost and complexity. A relatively new (in the last 10 years) Hall effect current sensor⁴ can provide a bipolar output from d.c. to 100 kHz for peak currents up to a 800 amperes, with very low drift ($0.5 \times 10^{-4}/^{\circ}\text{C}$ of I_{max}), excellent linearity (0.1% of I_{max}) and an accuracy better than 0.5% of I_{max} at one fifth the cost of constructing a standard four core transducer at this facility.

The actuator required to regulate the proposed system will require 16 water-cooled heat sink assemblies connected in parallel with 25 transistors per sink for a total of 400 devices. Each heat sink can conservatively dissipate 2.0 kW of d.c. power for a total of 32 kW for the entire system. A future upgrade which will allow for modulation of the horizontal sweep which will require an additional 16 kW of heat sink capacity. The complexity of this actuator and the requirement for high reliability dictates the use of very rugged transistors in combination with standard device protection circuits.

An N-channel enhancement mode power MOSFET was specifically selected in this application for its excellent high voltage capabilities and freedom from the Safe Operating Area (SOA) limitations associated with standard bipolar devices. Unfortunately in linear applications such as ours the wide variations in gate thresholds required the installation of source resistors to improve current sharing among the devices. This did reduce the derated power capability by approximately 5% but still offered a significant advantage over bipolar devices. In combination with its excellent frequency response we have continued to use this device. The General Electric transistor was chosen for the aforementioned capabilities and specifically for a newly enhanced UIS (Unclamped Inductive Switching) parameter⁵ which is similar to the E_s/b (Energy second breakdown) test used for bipolar devices. This is the measured ability of a power MOSFET's internal parasitic transistor to sustain repetitive operation in the reverse secondary breakdown mode during inductive switching cycles. Our actuator, operating in series with an inductive load could be subjected to these kinds of conditions subsequent to the failure of a protection device. The testing of several lots of similar FET's from other manufacturers revealed the G.E. device to be vastly superior in this specific parameter. Since the time of the initial investigations in the spring of 1986 a number of other manufactures have initiated programs to make similar parameter improvements in their own devices.

"Slow" scan power system:

Though the inductance (26.6 millihenries) of the vertical scanning magnet is six times greater than the horizontal (3.43 millihenries) magnet, the ramping rate (40 cm/sec vs 1200cm/sec) is thirty time slower requiring a much lower forcing voltage and a greatly reduced power requirement. At these power levels a

more cost effective, less complex bipolar design was selected. As shown in figs. 3 and 4 the magnet load is driven by a push-pull combination of two 16.0 kW actuator assemblies (eight heat sinks per assembly) connected in a current feedback arrangement and powered by dual opposite-polarity power supplies. The current sensor and actuators are identical to those used in the "fast" scan system.

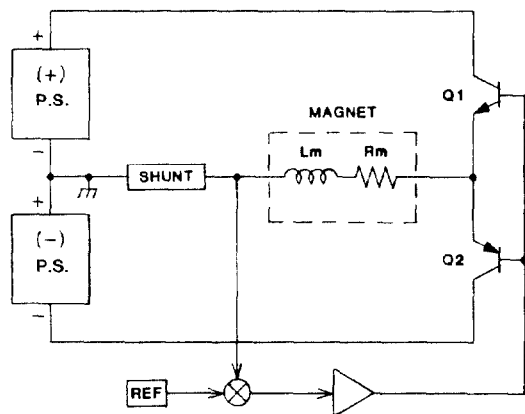


Fig. 3 "Slow" scan system

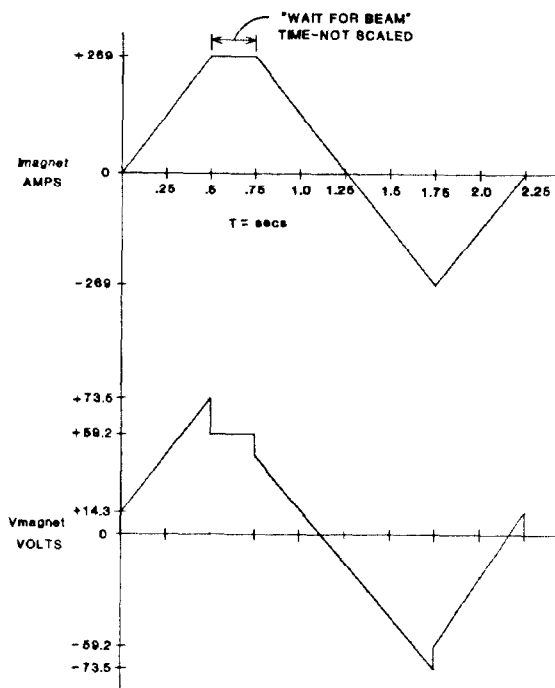


Fig. 4 "Slow" scan waveforms

Scan Controller:

The scan controller generates reference signals for the "fast" and slow" power supplies. The process starts with the computer activating the supplies and downloading the rectangular boundary limits, the beam start position, and its initial sweep direction. As mentioned previously the limits are set at least 3.5 cm outside the collimator boundaries to assure a flat field within the treatment volume. The computer also determines the scan height which is normally just the difference between the top and bottom limits. However, in a situation in which the lower part of the field needs filling in, due to a premature beam

interruption, the upper limit can be lowered without changing the scan height in order to maintain a constant horizontal scan frequency. When the beam reaches the bottom of the scan before the end of the spill it will be clamped off.

Accelerator timing and the status of the beam, control the start of scanning sequence. One second before the beam arrives, the vertical deflection is driven to the upper limit. Upon beam arrival the horizontal magnet begins sweeping. When the beam passes through the preselected start position and is traveling in the correct direction, the vertical magnet begins its downward sweep. Its rate is set to reach the bottom before the end of the beam spill.

The controller also monitors power supply, accelerator, and computer faults. It checks and confirms the actual beam position while storing pertinent information about the previous scan. The controller also displays the boundaries and scan position in real time on a variable persistence scope in the Biomed Control Room.

Project Status

The construction and the final phases of the design of both systems was begun in early November of 1986, and the commencement of the systems testing will take place by late summer 1987 with complete commissioning for patient trials by January 1988.

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