RASTER SCANNING MAGNETS FOR RELATIVISTIC HEAVY IONS*

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Summary

A raster scanning system has been developed for biomedical applications to spread heavy-ion beams with a maximum magnetic rigidity of 8.0 T-m to deliver uniform doses into large target areas, up to 40 cm by 40 cm, at a distance of 6 meters. The scanning system consists of two dipole magnets: the fast magnet with a gap of 5.7 cm height and 10.2 cm width, raster speed of 40 Hz, and maximum field of 0.27 T; and the slow magnet with a gap of 15.2 cm height and 8.9 cm width, scan speed of 0.5 Hz, and 0.34 T field. Both magnets are "picture frame" type to achieve uniform field across the aperture width. The yoke of the fast magnet is composed of 1.5 mm thick laminations to decrease field perturbations and power loss due to eddy currents. A bifilar type of winding method is used to increase the coil section in the fast magnet, and thus its electrical time constant, which provides for a linear magnetic ramp field.

Introduction

Heavy-ion beams are used at the Bevalac facility for experimental patient therapy. Extracted beams are generally small in diameter compared to the desired target area, and thus various methods have been developed to spread the beams uniformly over the target [1].

A raster scanning system has been developed for use at the Bevalac. The scanning system is shown schematically in figure 1. The system scans a small diameter beam across the target in rasters. Two magnets provide the scanning. The first magnet (furthest from target) scans the beam quickly in one plane, while the second scans more slowly in the orthogonal direction. If beam energy, intensity, and scanning rate are held constant, a uniform dose is delivered to the target.

The system is designed to sweep a 2.5 cm diameter, 8.0 T-m beam (e.g. ^{20}Ne of an energy per nucleon of 580 MeV) into a 40 cm x 40 cm area at the target. The fast magnet scans at 40 Hz, and the slow magnet at 0.5 Hz.

Magnet Design

Table 1 shows the design parameters of the two scanning magnets. A "picture frame" type design was chosen for both magnets to achieve uniform field across the aperture width. The fast magnet is centered on a point 6.0 m from the target. The required scan width of ±20 cm leads to a bend angle of 33.3 mrad. A magnet length of 1.0 m was chosen in order to reduce the field required, which has the effect of reducing the field and current ramp rates, which lower the power supply requirements and decrease the eddy current effects.

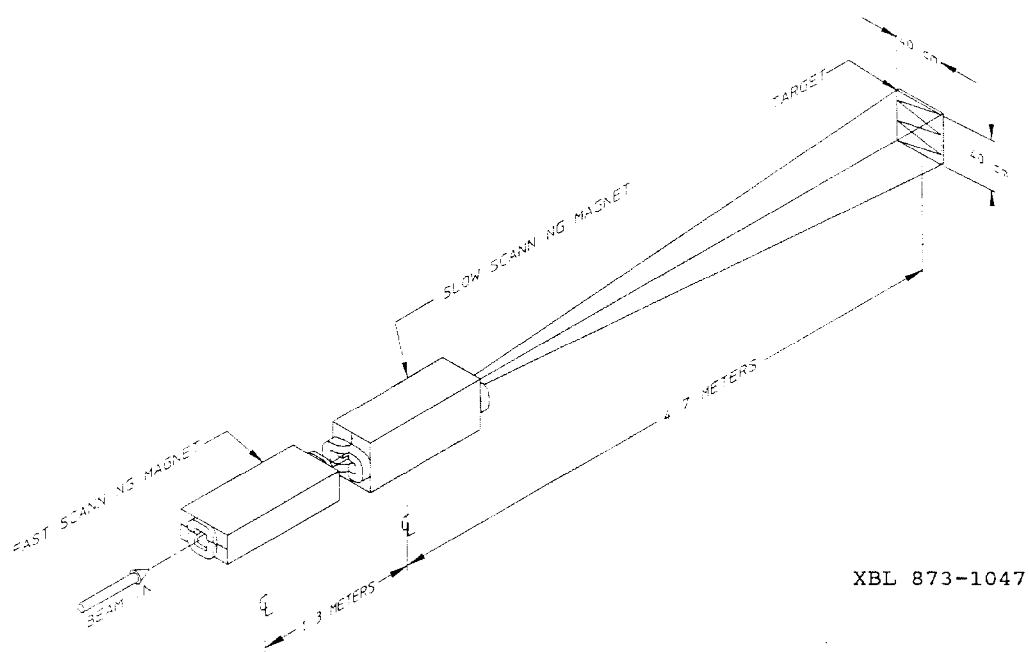

Figure 1
Raster Scanning System

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Table 1
Raster Scanning Magnets Design Parameters

	Fast Magnet	Slow Magnet
Frequency	40 Hz	0.5 Hz
Bend angle	33.3 mrad	42.5 mrad
Field gap	5.7 cm	15.2 cm
Field width	10.2 cm	8.9 cm
Effective length	1.00 m	1.00 m
Conductor size	0.647 cm sq	0.647 cm sq
Winding method	bifilar	singular
Number of turns	32	160
Maximum field	± 2.7 kG	± 3.4 kG
Field ramp rate	24 T/s	2.8 T/s
Maximum current	426 A	269 A
Current ramp rate	34,100 A/s	2,152 A/s
Max. current density	624 A/cm^2	787 A/cm^2
Avg. coil eddy current	84.2 A	4.9 A
Coil resistance	22.9 mΩ	220 mΩ
Inductance	3.43 mH	26.6 mH
Time constant	0.15 s	0.12 s
Lamination thickness	1.5 mm	23.9 mm
D.C. voltage	9.7 V	59.2 V
Reactive voltage	595 V	57.2
Eddy current voltage	1.0 V	1.1 V
Average coil Power	1.42 kW	5.31 kW
# of cooling ckts/coil	1	5
Total water flow	0.2 gal/min	1.0 gal/min
Water temperature rise	30°C	30°C
Coolant pressure drop	40 lbf/in^2	40 lbf/in^2

The slow magnet is located 4.7 m from the target, and also requires a scan range of ±20 cm at the target, leading to a maximum bend angle of 42.5 mrad. A magnet length of 1.0 m is again chosen for the same reasoning. Since the beam has already been deflected in the fast magnet before entering the slow magnet, the required gap is a comparatively large 15.2 cm high x 8.9 cm wide. A 160 turn coil is chosen to reduce the current required.

The coils are standard saddle-type coils made with hollow copper conductor. The conductor chosen for both magnets is 0.647 cm (.255 in) square, hollow copper. The hole diameter is 0.315 cm (.124 in).

For the fast magnet, larger conductor cross sections are not acceptable, since the eddy current in the conductor increases with the square of the conductor width and linearly with the thickness. The current density is lowered by winding the coil in a bifilar manner.

For the slow magnet, the current required due to the large field gap dictates the large number of turns in the coil, and the coil size is minimized by use of the same conductor.

Power Supply

The relationship between field, current and voltage are shown schematically in figure 2. V_r is the voltage due to the inductive load, V_e is the voltage required to overcome the eddy current load in the conductor and core, and V_{dc} is the voltage due to resistive loading at full current. The power supply for the raster scanning system is described in another paper [2].

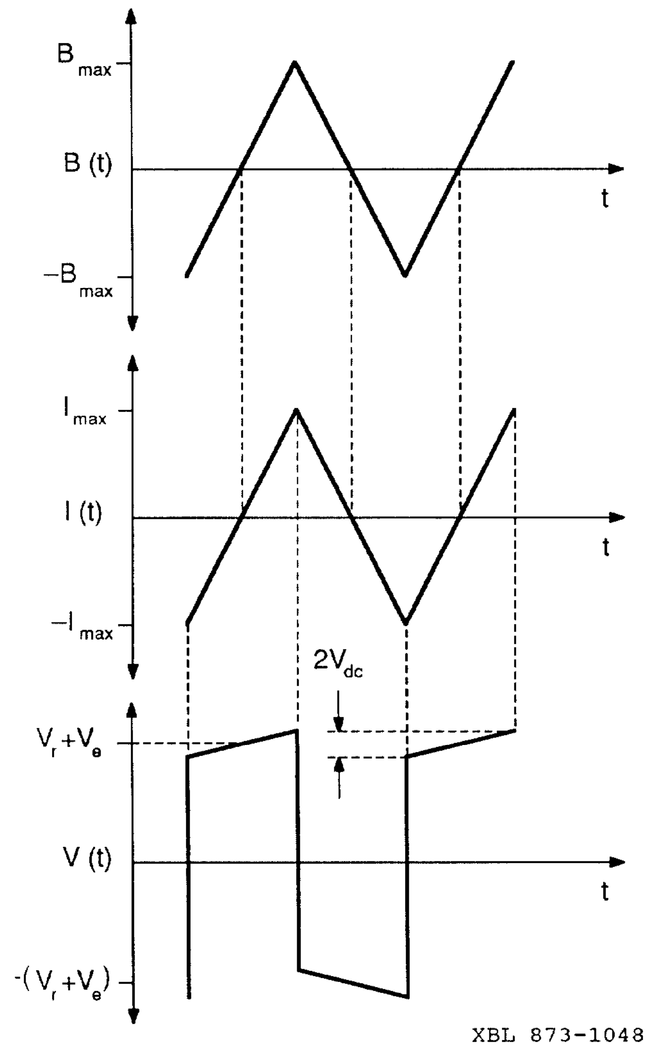

Figure 2
Field, Current and Voltage relationship

Thermal Loading and cooling

The time averaged power dissipated in the coil is one third the peak power, plus the constant eddy current load. The eddy current load is constant because the magnitude of the current ramp rate (dI/dt), and thus the magnitude of the field ramp rate (dB/dt), are constant. For the fast magnet, the average power dissipated is 1.38 kW due to the normal resistive load, and 0.04 kW due to the eddy current load. For the slow magnet these values are 5.3 kW for the standard load and .005 kW for the eddy current load.

The coils are cooled with low conductivity water. The fast magnet has one water circuit per coil, which corresponds to 16 conductor turns per circuit, and the slow magnet has 5 circuits per coil, also corresponding to 16 turns per circuit. The pressure drop is 40 lbf/in^2 . The water flow rates for the coils are 0.2 gal/min for the fast magnet and 1.0 gal/min for the slow magnet.

Both magnet cores are fabricated using laminations to reduce eddy currents in the core. The slow magnet is made of 23.9 mm thick laminations, and the fast magnet of 1.5 mm. The slow magnet laminations are sufficiently thick to serve the purpose of end compression plates. For the fast magnet, however, 25.4 mm plates are added at the ends. Stainless steel is used so that the plates have a high resistivity and a low permiability, thus decreasing the eddy current load. The eddy current heat load is high enough, however, to warrant cooling of the end plates. This is accomplished by machining passages in the end plate and brazing in a cooling tube. The plates are cooled by the same water supply as the coils.

Assembly

The magnet yoke was assembled by compressing the core laminations in a compression fixture which was integral to the finished yoke. The compression bars were manufactured to be longer than the magnet. The bars were pinned to one magnet end plate and allowed to float over the second during compression. Three hydraulic jacks hosed in parallel were used to apply the compression force. While the core was under compression, holes were drilled into the second end plate, and the compression bars were pinned to the core. After the removal of the preload, the excess length of the compression bars was removed. Iron impregnated epoxy was added to the space between the compression bars and the core to provide torsional rigidity. This procedure removes the need for welding, which can result in warpage of the core.

The completed fast scanning magnet is shown in figure 3.

Support

A rotating fixture is being built for the magnet system, in order to provide for the option of fast scanning in many planes. The rotating fixture has a range of 90° from the horizontal. This allows the magnet system to be adjusted for maximum efficiency in scanning irregular target areas.

Acknowledgments

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References

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[2] 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," Elsewhere in these proceedings.

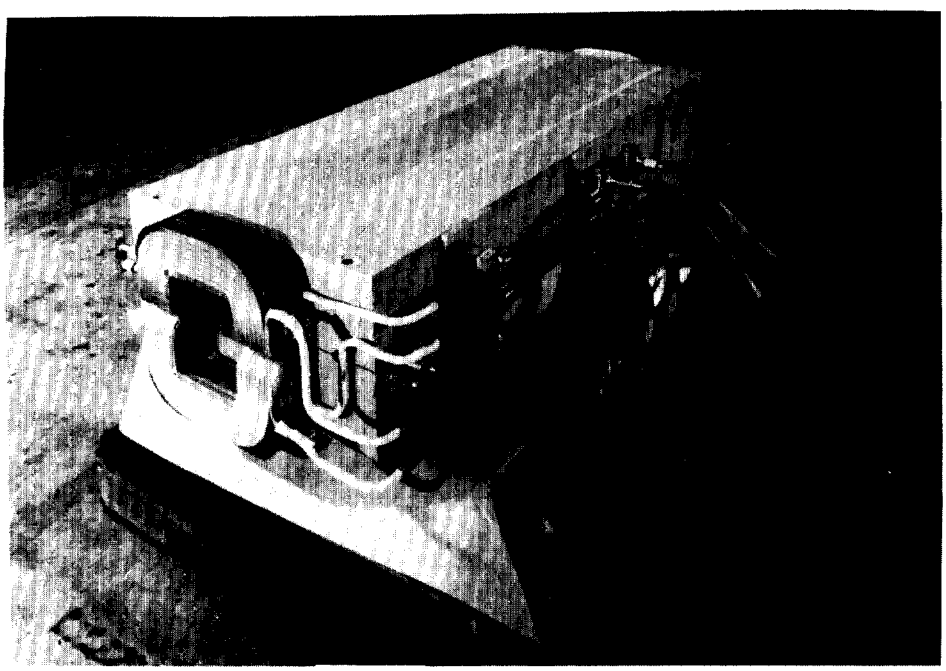

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Figure 3
Fast Scanning Magnet