DEVELOPMENT OF A RASTER ELECTRONICS SYSTEM FOR EXPANDING THE APT PROTON BEAM *

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Abstract

A 1700 MeV, 100 mA proton linear accelerator is being designed for Accelerator Production of Tritium (APT). A beam expansion system is required to uniformly irradiate a 19 x 190 cm tritium production target. This paper describes a beam expansion system consisting of eight ferrite dipole magnets to raster the beam in the x- and y-planes and also describes the salient features of the design of the electronics that are unique to the expander. Eight Insulated Gate Bipolar Transistor (IGBT)-based modulators drive the raster magnets with triangular current waveforms that are synchronized using phase-locked loops (PLLs) and voltage controlled crystal oscillators (VCXOs). Fault detection circuitry shuts down the beam before the target can be damaged by a failure of the raster system. Test data are presented for the prototype system.

1 BACKGROUND

In the proposed raster-type beam expander, there will be four horizontal and four vertical raster magnets. They will be modulated so that the target is "painted" by the 1 x 2 cm proton beam in a pattern somewhat like the ones shown in Fig. 1. The pattern is achieved by modulating the vertical- and horizontal-axis magnets with triangular current waveforms at slightly different frequencies in the 500 to 600 Hz range [1]. The entire target is then irradiated in a period of approximately 20 ms.

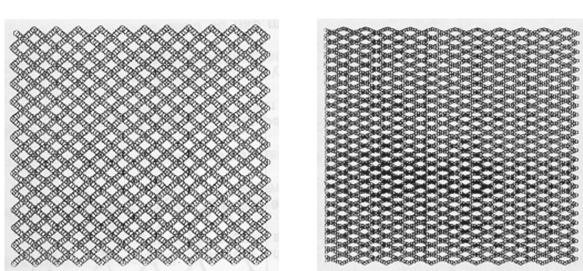

Figure 1: Sample patterns that are available by changing the ratio of the x- and y-plane rastering frequencies.

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An obvious requirement of using a rastered approach to beam expansion is that the beam must not be allowed to dwell on one spot of the target for very long (on the order of 0.5 ms) or else damage to the target could result. The prevention of common mode and single point failures has been a major design driver. The eight magnet systems are purposely designed to operate synchronously and independently, so that a failure of one system will not affect the operation of any other system, and therefore the beam will always be moved across the target (see Section 2.2). Fig. 2 shows the raster magnets as they fit into the high energy beam transport (HEBT) portion of the APT Linac.

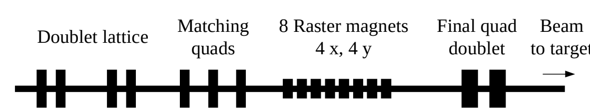

Figure 2: Raster magnets in HEBT

2 SYSTEM DESCRIPTION

The block diagram of the Raster Magnet System is shown in Fig. 3. The logical blocks of the system are the 1) Master Clock, 2) PLL/IGBT Gate Driver, 3) IGBT Modulator, 4) Raster Magnet and 5) Fault Detection Circuitry.

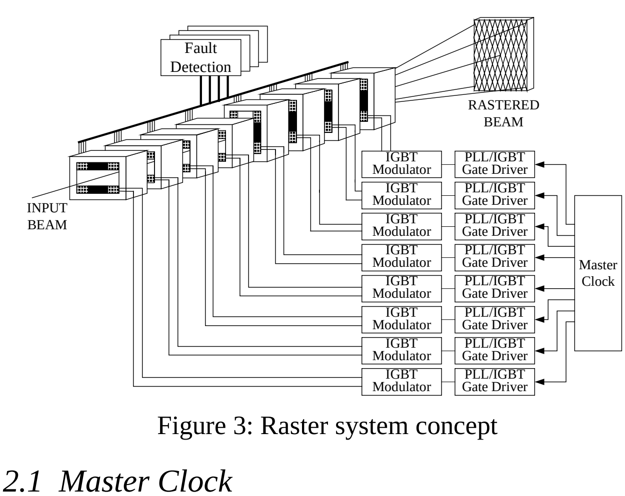

Figure 3: Raster system concept

2.1 *Master Clock*

The Master Clock produces two different frequencies, one for the four x-plane magnets and a second for the four y-plane magnets. The choice of frequencies is carefully made to avoid beat patterns. Important design issues of the Master Clock are related to accurately splitting out a 1.024-MHz crystal-controlled master oscillator to two different “divide by N” circuits to drive the horizontal and vertical planes with a minimum amount of skew between the channels. The Master Clock includes on-card fault check circuitry that monitors the clocks to notify the user of a fault. The clock fault outputs are sent to four independent divisions in the Beam Enable circuitry to turn off the Linac beam before a raster system failure causes damage to the target.

2.2 PLL/IGBT Gate Driver

Each magnet gets its timing signal from the Master Clock described above. Each of the magnets has a PLL/IGBT Gate Driver that will, using a phase-locked loop, synchronize itself to the Master Clock, or else if the Master Clock fails, is able to produce its own clock so that the beam continues to be rastered onto the target. This design approach is used to preclude a common mode failure that might cause damage to the target blanket.

For this application a sequential type of phase detector, rather than an analog multiplier type, is used in each PLL to generate error signals for the VCXOs in each IGBT gate driver. The sequential phase detector results in modulator-to modulator phase errors less than about 50 ns at the rastering frequencies. The phase detector then outputs the error signal to a VCXO that varies the frequency accordingly. If the Master Clock signal fails, the VCXOs of each modulator will maintain a clock signal, although the modulators will no longer be synchronized. However, the drift is slow, allowing ample time for the fault detection circuitry to detect the problem and take action.

The PLL/IGBT Gate Driver, as the name implies, generates properly timed signals at sufficient power to directly drive the gates of the IGBTs of the modulator. Correct timing also requires that the signals sent to the IGBTs include some deadtime to ensure that two IGBTs in series are never turned on at the same time, thus avoiding shoot-through failures.

2.3 IGBT Modulator

The IGBT modulator consists of an ac/dc converter, a capacitor bank, and an IGBT H-bridge (Fig. 4). Each modulator will be powered by uninterruptible power to prevent a common mode failure due to the loss of ac input voltage. The ac/dc converter will charge up and maintain a constant voltage on the capacitor bank. Charge is drawn into and out of the capacitor bank by the H-bridge. The value of the dc output voltage of the power supply is dictated by system level requirements in that the dc voltage represents the rate of change of the current in the raster magnet inductance (V = L*dI/dt).

The dc voltage values are different for the x-axis magnets and y-axis magnets because the required peak deflections (i.e. peak B-field) differ. Final beam expansion and sizing is actually controlled by two quadrupole magnets located downstream of the raster magnets in the HEBT beamline as shown in Fig. 2. The dc capacitor bank exchanges reactive power with the magnet on a 1000 Hz timescale (twice per cycle). The IGBT H-Bridge circuit drives the raster magnets with a voltage square wave, resulting in a triangular current waveform. The timing of the IGBT gate circuit is controlled by the PLL/IGBT Gate Driver already mentioned.

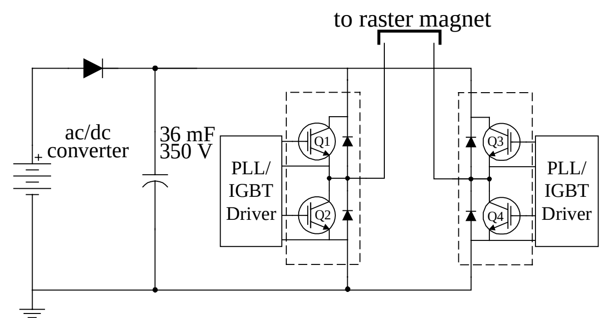

Figure 4: IGBT Modulator

The choice of IGBTs as the switches for the H-bridge was made on the basis of the operating frequency of 500 Hz and the low losses that these devices exhibit, in contrast to the choice of MOSFET switches in the system described in [2]. Freewheeling diodes are included across each switch to return the stored energy in the inductive load to the capacitor bank each half cycle, which is whenever the voltage applied to the load changes polarity. Because of this exchange of stored energy or reactive power between the capacitors and the magnet, the applied dc real power to maintain charge on the 36 mF capacitor bank is only 4% of the peak reactive power in the load, making this a very efficient system.

2.4 Fault Detection Circuit

The beam can not be allowed to stop sweeping across the target. The Fault Detection Circuit is the watchdog circuitry consisting of magnetic field and current sensors and the associated processing circuits that will check to be sure no serious failure modes exist in the Raster System. If a failure is detected, the Fault Detection Circuit removes the beam enable from the Linac, thus shutting down the beam until repairs can be made.

There are two B-dot pickup coils wound in each magnet that will have a voltage induced in them when there is a change in the magnetic field (dB/dt). Since the field is a triangular waveform, this induced voltage is essentially a square wave that can be used to detect a fault in either the magnet or the magnet drive. There are also two Rogowski current loops per magnet that will be used to measure the derivative of the triangular current. Each of these four sensors removes the beam enable signal from one of the four divisions of the Fault Detection Circuitry if it detects a fault. The beam is shut off if two or more of the four beam enable signals are missing.

2.5 Raster Magnet

The raster magnets are ferrite, 30-cm long with an 8-cm square aperture. A magnet cross-section is shown in Fig. 5. A prototype magnet has been built and tested which uses Ceramic Magnetics CMD5005 Hi-mu, low loss ferrite rather than the air core of [2]. This is a nickel-zinc material with a permeability of 4500 * μ_0 H/m at 1500 Gauss. The inductance with two 20-turn coils is 1.1 mH which produces peak fields of 640 Gauss at 100 A. From a radiation hardness standpoint, there is experience with ferrite cores as kicker magnets at Brookhaven National Laboratory that show that the ferrite material will outlast the coils.

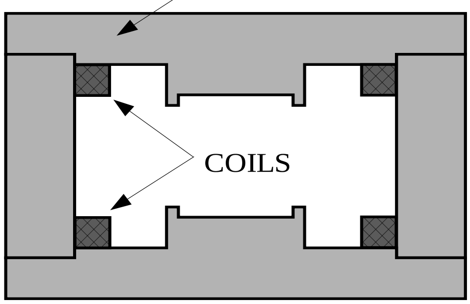

Figure 5: Raster magnet cross section

3 TEST RESULTS

A raster modulator and magnet have been successfully tested at LANL. A photo of the modulator and the resulting triangular current is shown in Fig. 6. The modulator is designed to operate at voltages up to 300 V and 1000 Hz. For this magnet with an inductance of approximately 1.1 mH, when the voltage is set to 243 V, peak operating current is +/- 100 A (59 A rms).

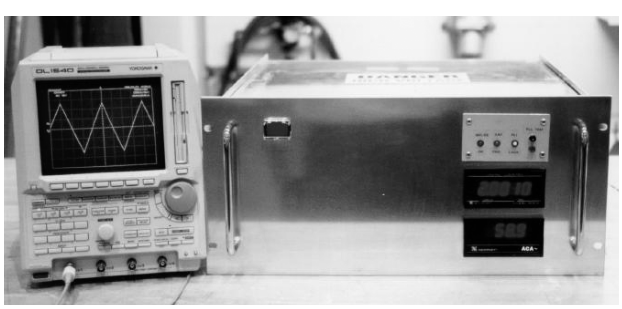

Figure 6: Modulator and test waveform
(+/-100 A, 500 Hz)

The output power capability of the power supply is based on the predicted losses in the load, which is the sum of the losses in the IGBT H-bridge, the cable, and losses in the magnet which include the magnet cable resistance and the magnet eddy current losses. At 243 V and 100 A peak current, the output power is essentially reactive and equal to 14,030 VARs. The measured input power (real) is only 925 Watts. With approximately 1000 joules stored in the 36 mF capacitor bank, the magnet field drops to the 1/e point in about 2 seconds if the dc charging circuit is turned off. Fig. 7 shows the raster waveforms as measured on an oscilloscope.

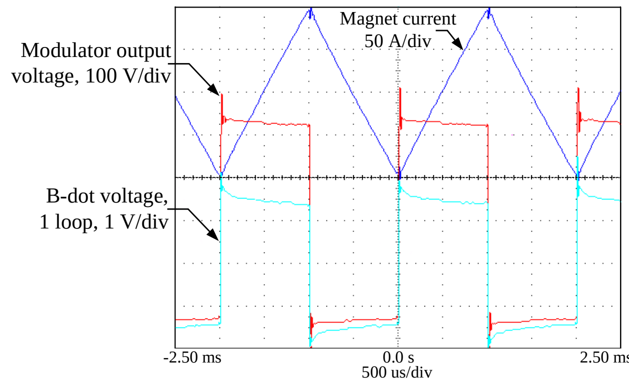

Figure 7: Measured waveforms of modulator

The spikes visible in the modulator voltage are caused by the stray inductances being switched by the IGBTs in the modulator. The peaking that is seen on the B-dot waveform, on the otherhand, has two distinguishable features:

- An overall L/R droop due to the resistance of the circuit, and
- A short overshoot of about 10% at the beginning, with a time constant of about 100 microsec. This is due to eddy currents in the coil that essentially shield part of the volume of the ferrite magnet. The voltage overshoot is thereby caused because the initial inductance is only 90% of its dc value.

4 CONCLUSIONS

A raster magnet system that is capable of safely and reliably expanding a proton beam onto the APT target has been developed and tested. Test data taken on a prototype indicate that the required ac power is about 4% of the peak reactive power in the raster magnet. The full-scale design is robust due to the application of redundancy as well as the use of independent fault detection circuitry that monitors the operation of the raster system. Based on the positive results of the prototype test, a complete system of eight magnets, modulators and fault detect circuits is currently being fabricated for full system evaluation and testing.

5 REFERENCES

[1] C.R. Rose and R.E. Shafer, "A 200-A, 500-Hz, Triangular Current Wave Modulator and Magnet Used for Particle Beam Rastering," Proc. 1997 Particle Accel. Conf., #7P089 (Vancouver, 5/97).

[2] C. Yan, et al., "Target Raster System at CEBAF," Nucl. Inst. and Meth., Vol. A365, pp 46-48 (1995).