CONCEPT FOR POWERING THE DIPOLE MAGNET IN A RECIRCULATING INDUCTION ACCELERATOR FOR HEAVY ION FUSION†

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In a Recirculating Heavy Ion Fusion Induction Accelerator the largest energy consumption occurs in the bending-magnet fields. Because these fields are pulsed, they cannot be generated by superconducting magnets. The bending magnets will consist of iron core dipoles with multiturn copper conductors. The energy stored in the magnetic field is many tens of megajoules and over 90% of this energy must be recovered and reused to make this type of accelerator practical. To make this approach competitive, a cost-effective and reliable energy recovery system must be designed. Two similar concepts are proposed which show promise for high efficiency and reasonable cost. A small scale prototype of the pulser and dipole magnet were built and tested. The two systems and very preliminary test results of one will be described.

1 INTRODUCTION

A recirculating induction accelerator is simply a linear one which is foreshortened and bent into a circular ring[1]. The recirculator imparts energy to the heavy ions by sending them through the same acceleration cells many times, whereas the linear accelerator imparts energy by serially adding many cells. Our preliminary design of a recirculating induction accelerator consists of several rings, each adding energy to the heavy ions. The last ring or High-Energy Ring (HER) takes the beam energy from 1 GeV to 10 GeV prior to extraction.

In a recirculating induction accelerator, bending or dipole magnets are required to guide the heavy ions around their circular path. The stored energy in the magnetic field for the High Energy Ring (HER) alone amounts to many tens of megajoules for each cycle of the recirculation process. At any repetition rate such an energy loss would be totally unacceptable. It is imperative, therefore, to recover the energy required for the bending fields with a minimum loss and to reuse it in the next cycle. It is also very important that the energy recovery process be simple and cost-effective due to the large investment. Two similar systems are under investigation; one is based on the least expensive capacitor technology (electrolytics) and the other based on more conventional bipolar type of capacitor. The system based on electrolytic capacitors will require an energy recovery system which maintains the proper polarity

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on the capacitors, while the bipolar system will require a switching system which maintains the proper current flow through the dipole magnet despite the polarity reversal in the capacitors.

2 SYSTEM DESCRIPTION

Every recirculating ring in the HIF driver requires bending fields, which are adjusted according to the energy gain of the ion beam. Ideally, the ramping field should be a linear function of time; that is, $B = k_1 t + k_0$, where k's are constants. The simplest way to generate a quasi-linear magnetic field is to use the rising portion of a sinusoidal current waveform. Other waveform generators will be investigated, but for this first design only the sinusoidal case will be considered.

The largest fraction of the energy required for the bending fields occur in the High-Energy Ring (HER). The HER requires a ramping magnetic field to one tesla in about one millisecond. To maintain a ramp which deviates from linearity by less than $\pm 5\%$, the 1-T field occurs at an angle of 60 degrees of the sinusoidal waveform.

Figure 1 shows one half-cycle of the current waveform which will be generated by the circuit in Figure 2 to produce the ramping magnetic field. SCR1 and SCR2 are triggered simultaneously into the magnet. The bipolar capacitors and the dipole magnet form a high-Q, ringing circuit. The current will be one half-cycle of a sinusoid and these SCRs will open as the current tries to reverse. The voltage waveform will be one half-cycle of a cosine, thus recharging the capacitors to the inverse polarity. Because of the system losses, the capacitor voltage will be slightly lower than the original charging voltage; recharging occurs between cycles. SCR3 and SCR4 are

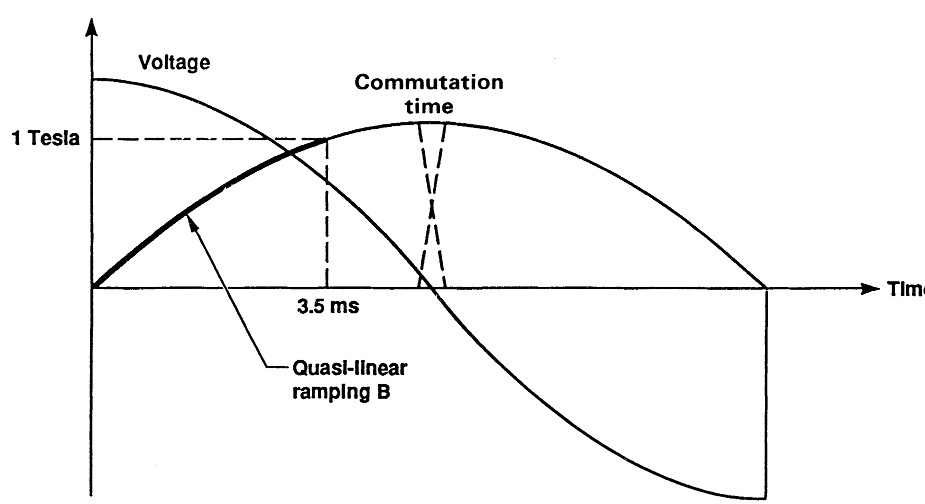

FIGURE 1 Voltage and Current Waveforms that Generate a Quasi-Linear Magnetic Field.

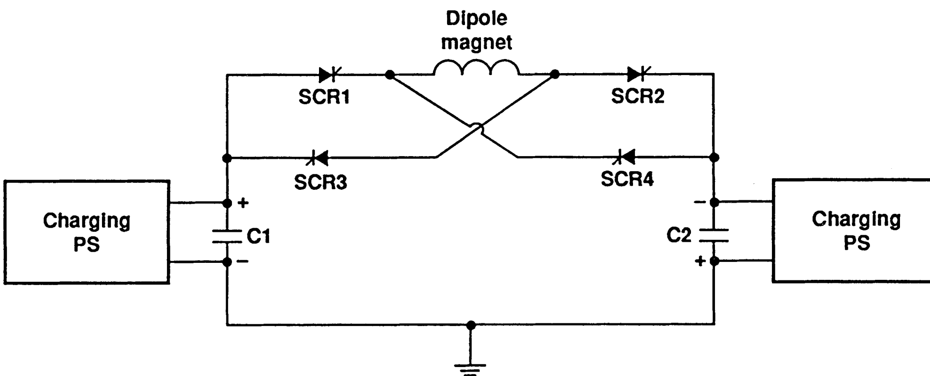

FIGURE 2 Self Commutating Bipolar Capacitor Bank and Silicon Controlled Rectifier System.

triggered next, generating a magnetic field of the same polarity as the first. The operating cycle continues at the repetition rate required by the HIF system.

The simplified circuit shown in Figure 3 is very similar to the one just described, with one major exception. SCR1 and SCR2 are fired simultaneously, but at the peak of the current waveform (zero-voltage crossing) they are commutated off by a separate circuit. This transfers the current from the SCRs to the diodes D1 and D2 with no interruption to the current flowing in the magnet. Diverting the current from the SCRs to the diodes recharges the electrolytic capacitors to the same polarity and voltage (minus the losses). This type of circuit is being considered simply because the cost of energy storage in electrolytics is considerably less than for other types of capacitors.

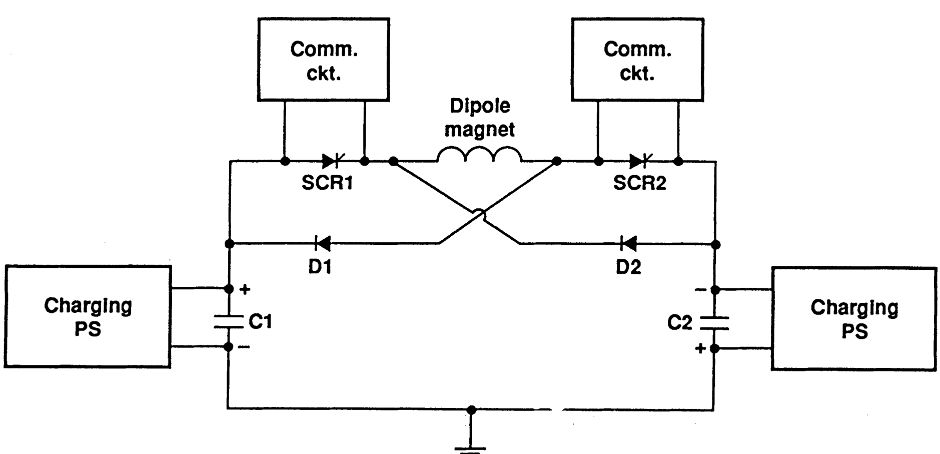

FIGURE 3 Forced Commutation Electrolytic Capacitor Bank and Silicon Controlled Rectifier-diode System.

3 THE DIPOLE MAGNET

The key component in the HIF bending system is the dipole magnet. The efficiency and cost optimization process must, therefore, include the pulser, the magnet, the cooling system and operating costs. Preliminary studies in the HIF system have led us to the design of a dipole magnet with the approximate dimensions shown in Figure 4. Dipole magnets of this type have been used extensively in high-energy accelerators for many years; their properties and design are well understood[2]. Because these magnets have to produce a ramping field, they cannot be of the superconducting variety. Optimization of dipole magnets for HIF drivers is critical in achieving high overall efficiency. The losses in a dipole magnet come from the iron core and the current-carrying conductor. Most laminated magnets are made from sheet steel (1–2 mm thick) cut to shape by a punch-and-die operation. These types of magnets are acceptable for high-energy accelerators but may be too lossy for HIF drivers. A number of other magnetic materials are available which offer much lower hysteresis and eddy-current losses. The conductor losses, which consist of the resistive and eddy-current losses, can likewise be reduced by proper choice of conductor cross section and number of parallel windings to achieve the optimum current density. The present design for the HER calls for 1280 magnets for each of four beam lines. The total stored energy in the gap volume is $E_s = (B^2/2\,\mu_0) \times$ volume:

$$E_s = (\tfrac{1}{2})(4 \times 1280)\mu_0^{-1}(0.14)^2 \quad \text{or} \quad E_s = 40\text{ MJ},$$

where $2R = 0.14$ m and $\mu_0 = 4\pi \times 10^{-7}$. The length of the magnets varies but 1 m is an average value for this exercise. For one tesla at the gap, the ampere-turns required are

$$ni = 2RB^2\mu_0 = (111)10^3 \text{ A-turns}.$$

The inductance of one dipole magnet is:

$$L = \mu_0 n^2(A/2R) = 1.25\ 10^{-6} n^2 H$$

Before deciding on the number of turns for the dipole magnet, it is important to consider the cost and reliability of the pulser to drive it. There is a considerable

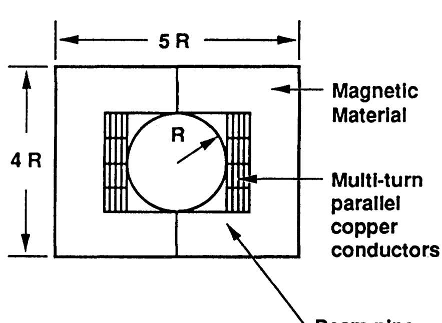

FIGURE 4 Approximate cross section of Dipole Magnet for Recirculating Heavy Ion Fusion Induction Accelerator.

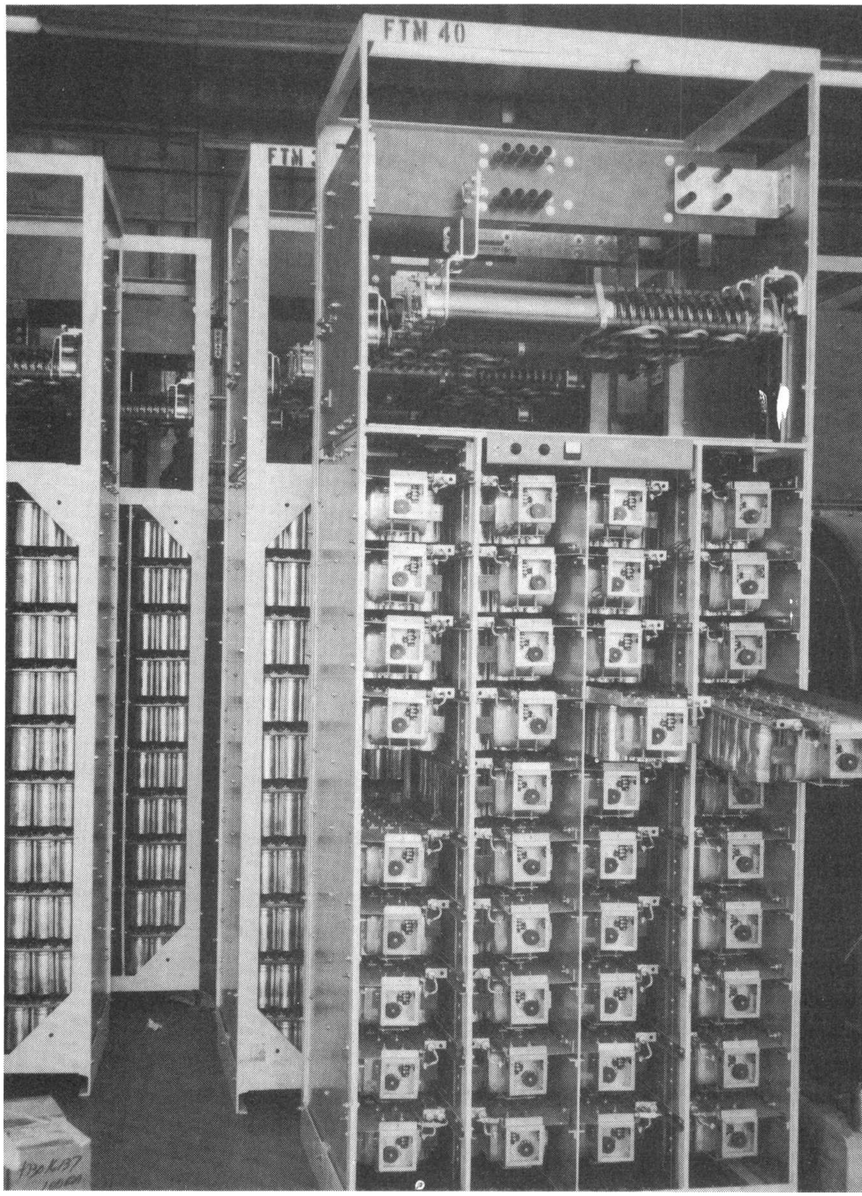

FIGURE 5 Six-MJ Electrolytic Capacitor Bank for Magnetic Fusion.

difference in cost and reliability between a high-voltage system that uses thyratrons and a low-voltage system with SCR. It is proposed that the voltage levels be kept at a few kilovolts so that solid-state devices and electrolytic capacitors can be applied directly. The rise time for the magnetic field to 1 T is 1 ms; this corresponds to a frequency of 166 Hz. To limit the charging voltage to ± 450 V, which is a standard for electrolytics, the maximum number of turns is n = 6, the inductance $L = 45\ \mu$H and the current $i = 18.5$ kA. Since 1 T is reached at a conduction angle of 60 degrees, the actual peak current is 21 kA. Conventional SCRs can conservatively carry 1500 A, so twelve devices in parallel are chosen. The type of capacitor that will ultimately be used in this application will be established after circuit optimization in terms of cost and efficiency. If electrolytics are used, the commutation circuit shown in Figure 3 must be made to operate efficiently. Electrolytic capacitors are not usually considered applicable to pulsed systems. However, since the early 1970s they have been used to generate millisecond pulses in magnetic fusion. The maximum current extractable from an electrolytic capacitor is limited by the internal series inductance and resistance; this limit for most capacitors is in the hundreds of amperes. For the dipole pulser application, the maximum current per capacitor will be chosen so that the maximum energy loss due to the internal series resistance is less than 1% of the total stored energy. Studies conducted in the construction of a 6 MJ capacitor bank (Figure 5) for the magnetic fusion program indicated that the internal inductance was in the range of 200 to 300 nH and the internal resistance was in the range of 15–25 mΩ[3].

For the system in Figure 3, the total capacitance $C = 1/\omega^2 L$, or 20000 μF. Since the capacitors are in series, the individual capacitance is twice this value. The total energy storage $E_c = 8100$ J; to limit the i^2R losses to one percent of this, the current must be limited to less than one kiloampere per capacitor. The circuit would be similar to that of Figure 5.

A number of studies have been conducted on efficiencies of pulsed dipole magnets. Warm dipole magnets at Fermilab and other laboratories with parameters more stringent than the HIF requirements have achieved efficiencies of over 80%. It appears that with some development in magnetic material and conductor windings, over 90% efficiency should be achievable.

To gain confidence that the 90% efficiency assumed in our studies was not an unreachable goal, we built a one-quarter scale prototype magnet and pulser. Figure 6 shows the double C magnet cores forming an H type of dipole magnet with winding

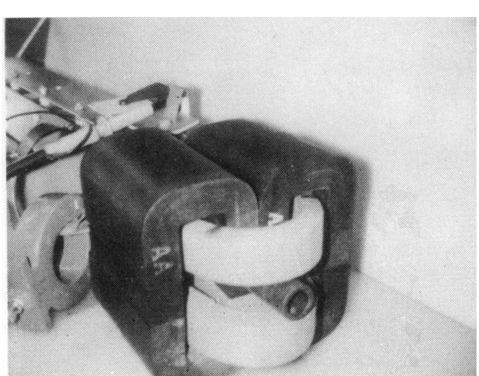

FIGURE 6 Pre-prototype 1/4-Scale H-type Dipole Magnet with SCR-Driven Bipolar Capacitor Bank.

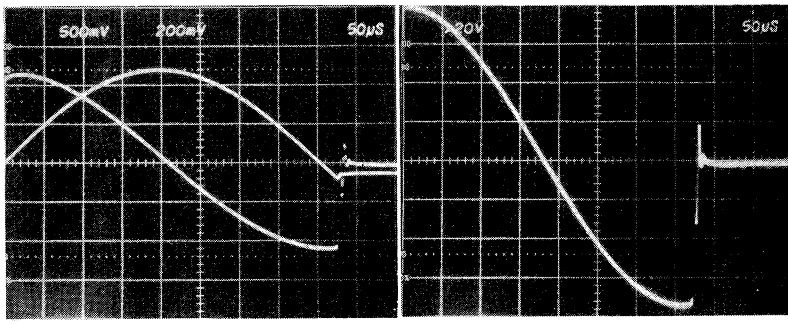

FIGURE 7 Current and Voltage Waveforms for H-type Dipole Magnet.

and simulated beam pipe at the center. The magnetic material was of the standard 60 Hz transformer variety. The windings consisted of four parallel copper straps 30 turns each. The capacitor was a 40 μF bipolar type switched by a standard SCR. The resulting current and voltage wave forms are shown in Figure 7. The magnet inductance $L = 180\ \mu$H and the ringing half period $T = 375\ \mu$s. Even at this higher frequency of ringing of about 1 kHz, the combined eddy current, resistive, core and switching losses were about 8%. The ratio of the remnant voltage to the charging voltage is 0.95, and since the energy is the square of the voltage, the recovery was 90%. The calculated losses agree closely with the measured values. At these low levels, the core losses were about 1%, the i^2R losses were 5% and the switching losses accounted for the remaining 4%. This simple small-scale test is a far cry from the eventual dipole magnet, but it does show that with some effort a 95% efficient and cost-effective magnet should be achievable.

4 CONCLUSION

One of the critical elements of a recirculating HIF driver is the bending or dipole magnet. It appears that small improvements in existing magnet and pulser technology should yield over a 90% efficient system. Two options are currently under consideration, one somewhat more economical than the other. Much more detailed studies will have to be carried out to decide on the optimum solution. Preliminary studies and tests are encouraging.

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