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A PULSED BEAM SHUTTER FOR RADIO-FREQUENCY SEPARATED BEAMS AT THE ZGS*

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Summary

A pulsed beam shutter magnet is required to deflect a beam of separated high energy particles into a beam stop after a desired number of particles have reached the 12-ft bubble chamber at the ZGS. The magnet has a core, wound from 2 mil grain-oriented steel, an aperture 15 cm x 15 cm, and a $\int Bdl = 1\,kGm$. The pulse has a risetime of $\leq 3\ \mu s$ and a flattop of 40 µs. The above is achieved by discharging a high voltage capacitor bank into the magnet inductance, followed by a power-crowbar. The design of the magnet and the switching circuits is described and formulas for calculating the pulse shapes are given. Graphs of calculated flattops to 500 µs are shown.

Introduction

At the Zero Gradient Synchrotron (ZGS) a beam transport system is in use with the 12-ft bubble chamber (BC) which separates particles of high energy beams by means of radio frequency.[1] For good resolution it is desirable to have 5 to 7 particle tracks per picture. Typically, this number of particles is reached within 9 µs for protons and within 35 µs for kaons. Additional particles of the $\leq 50\ \mu s$ beam spill are prevented from reaching the BC by the pulsed field of a 1 kGm bending magnet which deflects the beam into a beam stop. A risetime of $\leq 3\ \mu s$ is required for the field of this beam shutter magnet, and the field must be maintained within ±5% for at least 40 µs.

Circuit Operation

In the circuit of Fig. 1 pulse energy is provided by capacitors C_1. They determine the current risetime in conjunction with the circuit inductance. A magnet pulse is initiated at time t_0 by applying a high voltage

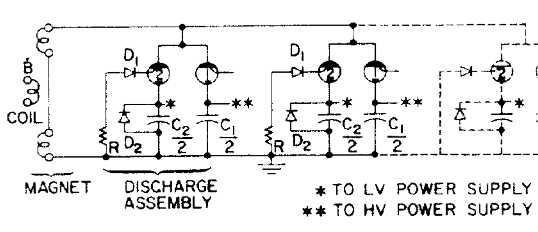

Fig. 1. Simplified pulsed magnet system.

pulse to the ignitor of ignitrons 1. These ignitrons conduct within 1 µs connecting the high voltage (HV) capacitors C_1 across the magnet. Between t_0 and t_1 a sinusoidal current will flow as shown in Fig. 2.

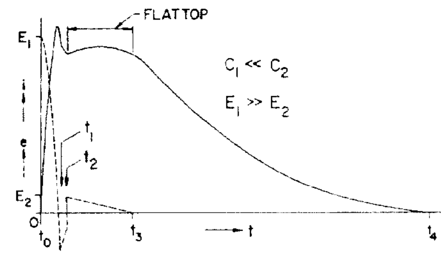

Fig. 2. Typical discharge pulse.

When the voltage on capacitors C_1 reverses, it will drive current through the ignitors of ignitrons 2 via HV diodes D_1 and current limiting resistors R shown in Fig. 1. At time t_1, the negative voltage on capacitors C_1 is large enough to strike an arc in ignitrons 2, and the current commutates from the HV to the low voltage (LV) capacitors. At time t_2, ignitrons 1 have turned off and with $C_2 >> C_1$, the change of current is decreased. At time t_3, capacitors C_2 have discharged to a negative potential of a few volts and LV diodes D_2 are conducting. This terminates the flattop region of the current pulse. Between t_3 and t_4 the magnet current decays to zero with the L/R time constant of the circuit. Capacitors C_1 and C_2 are recharged between pulses from their respective power supplies. To pulse the magnet once every ZGS pulse, two discharge assemblies as shown in Fig. 1 are required. For double or triple pulsing, additional discharge assemblies are operated in parallel.

Design Features

Magnet

Figure 3 illustrates the magnet design. For $\int Bdl = 1$ kGm, the 42 cm long magnet requires 2.38 kG in its 15 cm x 15 cm aperture. The flux density in the core is approximately 14 kG. To reduce the voltage on C_1, a single-turn coil is used. The two one-turn coils wound around opposite sides of the core as shown in Fig. 3, are connected in series. They act

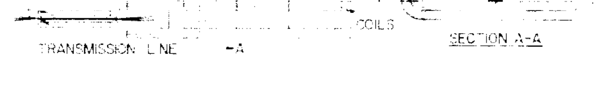

Fig. 3. Pulsed beam shutter magnet.

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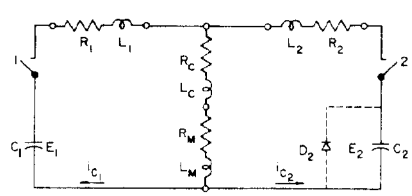
like a one-turn coil that surrounds the air volume inside the magnet, but do not obstruct the magnet aperture. The core is made up from six sections of tape wound, 2 mil grain-oriented steel. The sections are insulated from each other by a sheet of mylar. The peak stored energy is 215 J and a peak current of 33.3 kA is required to obtain a nominal flattop current of 28.3 kA. The magnet inductance is ~ 530 nH.

Discharge Assembly

Each of the two assemblies of Fig. 1 consists of two size D ignitrons, a 3 μF, 15 kV extended foil capacitor, a LV capacitor assembly, and the rectifiers shown. Common to both assemblies are a LV and a HV power supply. The total inductance of one discharge assembly is approximately 140 nH. This includes the contributions of the capacitors, the coaxially mounted ignitrons, and the parallel-strip transmission line. With two assemblies connected in parallel to the magnet, we have a total circuit inductance of 600 nH. All discharge current carrying circuit components are rigidly mounted to counteract the magnetic forces. Depending on the desired duration of the flattop, C_2 may consist of paper capacitors as used in SCR commutation applications, or of stacked foil electrolytic capacitors. With paper capacitors, rectifier D_2 is not required.

Circuit Analysis

Figure 4 is an equivalent circuit of the magnet system. Inductance L_1 associated with the connections to C_1 and ignitron 1, and inductance L_2 associated with the connections to C_2 and ignitron 2 are made as small as practicable. These inductances determine the time it takes to commutate the current from C_1 to C_2.



R_1, L_1 : HV circuit interconnections

R_2, L_2 : LV circuit interconnections

R_C, L_C : Transmission Lines

R_M, L_M : Magnet

Fig. 4. Equivalent circuit of magnet system.

Between times t_0 and t_1 the magnet current is

$$i(t) = i_{C_1}(t) = \frac{E_1}{\omega L'} \sin \omega t \; \epsilon^{-\alpha' t} , \tag{1}$$

and the magnet voltage

$$e(t) = e_{C_1}(t) = E_1 \sin(\omega t + \theta)\, \epsilon^{-\alpha' t} , \tag{2}$$

where

$$\omega = \sqrt{\frac{1}{L'C_1} - \left(\frac{R'}{2L}\right)^2}$$

$$\theta = \text{arc tg } \frac{\omega}{\alpha'} , \quad \alpha' = \frac{R'}{2L'}$$

$$L' = L_1 + L_C + L_M , \quad R' = R_1 + R_C + R_M$$

$$E_1 = \text{Voltage on } C_1 \text{ at } t_0 .$$

For a peak current of 33.3 kA through L' = 600 nH, the 6 μF capacitor C_1 must be charged to E_1 = 10.5 kV.

Between times t_2 and t_3 the current can be written

$$I(s) = \frac{I_0 L + E_2/s}{R + sL + 1/sC_2} , \tag{3}$$

where

s = Laplace variable

I_0 = Magnet current at time t_2

E_2 = Voltage on C_2 at time t_2

$L = L_2 + L_C + L_M$, $R = R_2 + R_C + R_M$.

With $(R/L)^2 < 4/LC_2$ the circuit is oscillatory, and the time response of (3) is

$$i(t) = \left[I_0 \cos\beta t + \left(\frac{V_0}{\beta L} - I_0 \frac{\alpha}{\beta} \right) \sin\beta t \right] \epsilon^{-\alpha t} \tag{4}$$

where

$$\alpha = \frac{R}{2L} , \quad \beta = \sqrt{\left(\frac{R}{2L}\right)^2 - \frac{1}{LC_2}} ,$$

with $(R/L)^2 = 4/LC_2$ the circuit is critically damped and the time response becomes

$$i(t) = \left[I_0 + \left(\frac{E_2}{L} - \alpha I_0 \right) t \right] \epsilon^{-\alpha t} . \tag{5}$$

Finally, with $(R/L)^2 > 4/LC_2$, the circuit is overdamped having a time response of

$$i(t) = \left[I_0 \left(\frac{-\alpha + \beta}{2\beta} \right) + \frac{E_2}{2L\beta} \right] \epsilon^{(-\alpha+\beta)t}$$

$$- \left[I_0 \left(\frac{-\alpha - \beta}{2\beta} \right) + \frac{V_0}{2L\beta} \right] \epsilon^{(-\alpha-\beta)t} . \tag{6}$$

From t_3 to t_4 capacitor C_2 is bypassed by D_2 and the current decays exponentially. The circuit resistance without the ignitron is ~2.9 mΩ. Because the voltage drop across the ignitron is nearly constant, the damping factor exp $(-\frac{R}{L} t)$ increases as the current decreases. The current decay was calculated in steps of Δt = 1 μs using the expression

$$I_{t+\Delta t} = I_t \exp - \left(\frac{\dfrac{18\ \mathrm{V}}{I_t} + 2.9 \times 10^{-3}\ \Omega}{0.6 \times 10^{-6}\ \mathrm{H}} \right) \Delta t \qquad (7)$$

Figures 5 through 8 show calculated current pulses. At time t_2 the resistive voltage drop is ~ 100 V. A voltage E_2 larger than 100 V will cause the current to overshoot. One makes use of this fact to hold the current within ±5%, using a capacitance much smaller than would be required if no overshoot were permitted. In Fig. 5 magnet current i and capacitor voltage e_{C_2} are shown as a function of time for a 7500 μF crowbar bank charged to initial voltage values E_2 ranging from 100 V to 250 V.

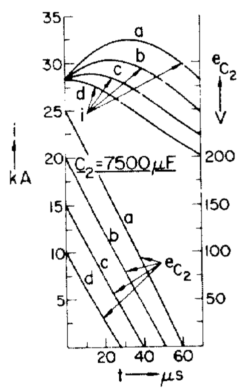


Fig. 5. Crowbar pulses for C_2 = 7500 μF and various values of E_2.

If the value of C_2 is doubled to 0.015 F, the response is as shown in Fig. 6. A small gap in the trace of the current pulses indicates where the flattop ends and the L/R decay begins.

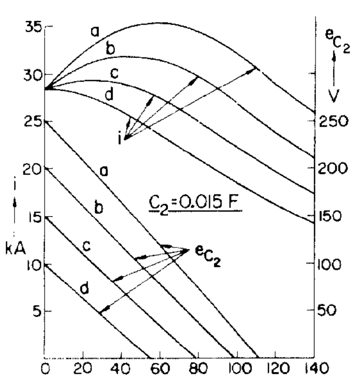


Fig. 6. Crowbar pulses for C_2 = 0.015 F and various values of E_2.

In Fig. 7 the current i and voltage e_{C_2} are shown as a function of time for a fixed value of E_2 = 150 V, and crowbar capacitance values C_2 ranging from 0.0 F to 0.15 F. For this application a 7500 μF capacitor bank, made from 125 μF, 200 V metalized paper units and charged to E_2 = 150 V, was selected. Since these capacitors can be charged to a negative voltage, rectifiers D_2 are not used.

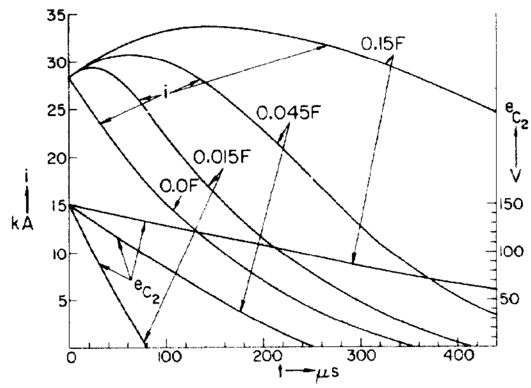


Fig. 7. Crowbar pulses for various values of C_2 and E_2 = 150 V.

The corresponding current pulse is shown in Fig. 8.

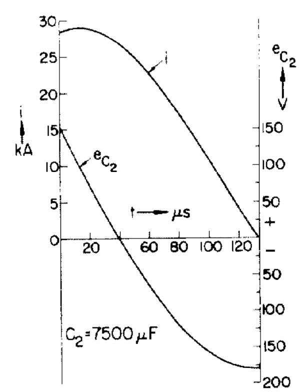


Fig. 8. Crowbar pulse of beam shutter magnet.

At the ZGS we have two more pulsed magnet circuits which utilize power crowbars. These have slower risetimes and flattops several ms long.[2, 3]

References

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