SLAC-CN--256

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SINGLE PASS COLLIDER MEMO | CN- 256

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TITLE: BEAM-DUMP KICKER MAGNETS

The beam-dump kicker magnets are located in the final focus region and, in conjunction with septum magnets, extract the beams after they have passed the interaction point (IP) and direct them to their respective dumps.

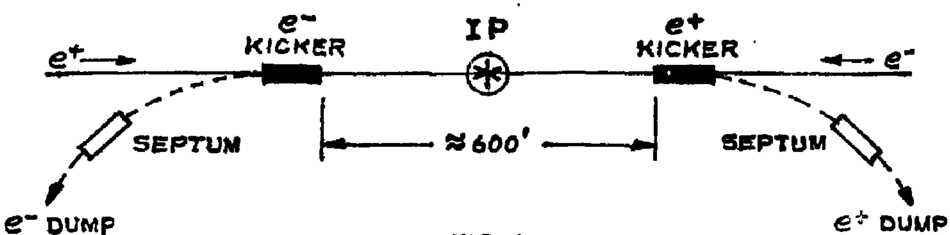


FIG. 1

Two schemes for these kickers have been under consideration.

a. Ferrite transmission line magnets utilizing technology common with damping rings and positron target kickers.

b. Current loop magnets which are possible only for the dump kickers, where the rise time of the magnetic pulse can be comparatively longer; approximately 400 nanoseconds as compared with 50 nanoseconds for the others.

A prototype ferrite kicker has been built and is undergoing tests. Since the current loop requires lower voltage and power plus some additional savings in cost, we decided to build and test a prototype.

This note describes in detail an optimized design for the current loop magnets and their associated pulse circuitry.

Since the transit time between e^+ and e^- kickers is approximately 600 nanoseconds, the magnet current must reach its maximum (kicking) value in somewhat less than this. A rise time of 400 nanoseconds was chosen from two considerations; to be on the safe side time wise and yet large enough to minimize the required voltage, which is proportional to the time derivative of this current. The magnet was split into two sections to further fit the parameters to available circuit components from both a voltage and cost standpoint.

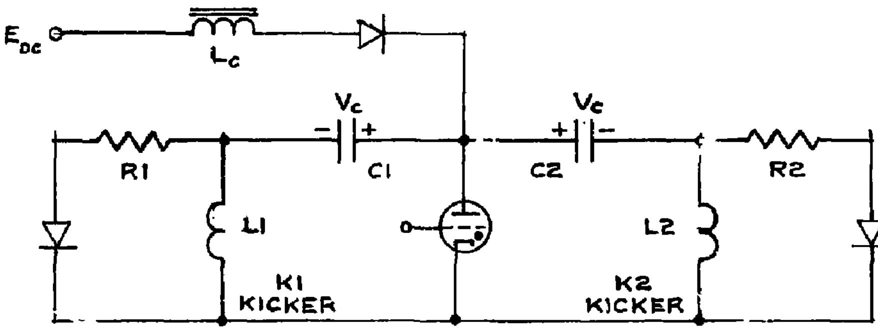


FIG. 2

The circuit used is different from the typical series R-L-C configuration and might be described as a "good news and bad news" type circuit. The "good news" or advantage is that during the current rise from zero to maximum, the storage capacitor discharges thru the magnet and switch with very low resistance in the circuit; i.e., a very high-Q circuit. This results in a smaller storage capacitor and less initial capacitor voltage being required to produce a given peak magnet current. The magnet voltage is negative during this time so that the shunt diode does not conduct.

At the current peak the voltage drops to zero ($di/dt = o$) and then begins to rise in the positive direction. This allows the diode to conduct and for a time current is flowing thru both the diode and thyratron switch. During this period the capacitor is accumulating a negative charge to insure thyratron turn-off.

In order to adjust this negative voltage to the desired value, the circuit must be operated in the "overdamped" mode. This means that the current decay follows an exponential fall off and is many times longer than the risetime. This is the "bad news" and is a distinct disadvantage in some cases, especially if the current is required to reach zero in a particular time after peaking. This is of no consequence, however, in the case of the dump kickers as the storage capacitor begins a slow (4.5 mS) recharge thru the magnet at the beginning of the next cycle. The only requirement is that the capacitor voltage must remain negative long enough to turn the thyratron off.

A comparison of this circuit with the conventional series R-L-C type (using the same peak current, risetime and negative turn-off voltage) reveals that the series R-L-C circuit requires:

1. 47% more initial capacitor voltage
2. 84% more capacitance
3. 400% greater power dissipation

The magnet current is divided into three time frames as shown in Fig. 3; "a" when only the thyratron is conducting, "b" when both thyratron and diode are conducting and "c" when only the diode is conducting.

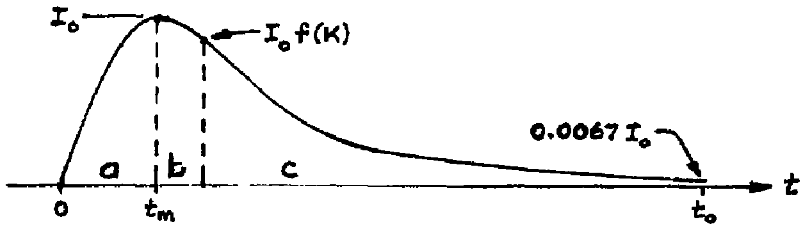


FIG. 3

Letting $\omega_0 = (LC)^{-1/2}$, $\sigma = 1/2RC$, $\omega = (\sigma^2 - \omega_0^2)^{1/2}$ and $\tau = L/R$, the currents in the three segments are as follows:

a. $i(t) = I_0 \sin \omega_0 t.$

b. $i(t) = I_0 \exp(-\sigma t) \left[\cosh \omega t + (\sigma/\omega) \sinh \omega t\right].$

c. $i(t) = I_0 f(K) \exp(-t/\tau).$

Where I_0 is the peak magnet current and f(K) is described later in reference to load resistance calculation on page 8.

MAGNET DESIGN :

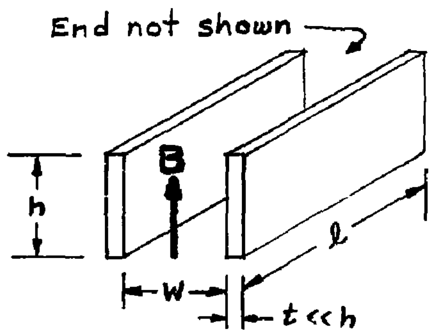
The bending angle θ is <u>1.2 mr at 60 GeV.</u>

$$B_G \ell_m = \frac{\theta P}{3\times10^4} = \frac{1.2\times10^{-3}\times 60\times10^9}{3\times10^4}$$

$$= 2400 \text{ Gauss-meters.}$$

B = <u>600 Gauss</u> for a 4-meter bending length.

The magnet will be split into two sections; each 2 meters long, using 1" × 1/8" copper bars spaced 1" apart.



$t = 1/8"$
$h = 1" = 0.0254$ m.
$W = 1" = 0.0254$ m.
$\ell = 2$ m.

$$K_o = \frac{\tan^{-1}(h/w)}{(h/w)} = 0.7854$$

$$L = 0.8\times K_o\times \ell = 0.8\times 0.7854\times 2 = \underline{1.26\ \mu H}$$

$$I = 125\times B\times \frac{1}{K_o}\times W = 125\times 600\times\frac{1}{0.7854}\times 0.0254$$

$$= \underline{2426 \text{ Amps.}}$$

CIRCUIT DESIGN:

The wiring inductance associated with the magnet, storage capacitance and thyratron tube is estimated to be about 0.3 - 0.35 μH, so that

$$L\,(\text{total}) = 1.26 + 0.34 = \underline{1.6\,\mu H}$$

For $t_m \approx 400$ ns, the time chosen for the magnet current to reach its maximum value of I_o,

$$t_m = \frac{\pi}{2}(LC)^{1/2} \quad \text{and} \quad C = \frac{4\,t_m^2}{\pi^2 L}$$

$$C = \frac{4 \times 400^2 \times 10^{-18}}{\pi^2 \times 1.6 \times 10^{-6}} = 4.05 \times 10^{-8} = \underline{0.04\,\mu F}$$

High Voltage ceramic disc (doorknob) capacitors can be used, ten 0.0039 μF or fifteen 0.0027 μF at 30 to 40 KV.

$$\omega_o = (LC)^{-1/2} = (1.6 \times 10^{-6} \times 0.04 \times 10^{-6})^{-1/2} = 3.95 \times 10^{6}\ r/s.$$

$\dot{\imath}$ (magnet) = $I_o \sin \omega_o t$ during the rise time

$$= 2426 \sin 3.95 \times 10^{6}\, t$$

$$e_L = L\frac{di}{dt} = 1.6\times10^{-6}\,\frac{d}{dt}\left(2426\,\sin 3.95\times10^{6}t\right)$$

$$= 1.6\times10^{-6}\times 2426\times 3.95\times10^{6} = \underline{15.33\ \text{KV}}$$

To determine the approximate power dissipated in the magnet:

d (skin depth) for copper at 20°c $= 6.62(f_{Hz})^{-1/2}$ cm.

A (area) $= d\times P$ (P = perimeter of conductor)

$R = \rho\frac{\ell}{A}$ (ρ for copper $= 1.724\times10^{-6}\ \Omega\text{-cm}$)

Using the frequency associated with the rise time $(0-t_m)$ of the magnet current:

$$f = \frac{1}{4\times400\times10^{-9}} = 625\times10^{3}\ \text{Hz}.$$

$$d\ (\text{skin depth}) = \frac{6.62}{\sqrt{625\times10^{3}}} = 8.37\times10^{-3}\ \text{cm}.$$

$P = 2\tfrac{1}{4}'' = 5.715$ cm.

$A = d\times P = 8.37\times10^{-3}\times5.715 = 4.78\times10^{-2}\ \text{cm}^2.$

$\ell = 2+2 = 4\ \text{m} = 400\ \text{cm}.$

$$R = \rho \frac{l}{A} = 1.724 \times 10^{-6} \times \frac{400}{4.78 \times 10^{-2}} = \underline{0.0144\ \Omega}$$

The magnet current is a sinewave from 0 to t_m and then takes the form of an exponential. This can be approximated by the "critically damped" waveform to determine the RMS current.

$$i\,(\text{magnet}) \approx e I_0 \frac{t}{t_m} e^{-t/t_m} \quad \text{where } e = 2.718$$

$$I_{RMS}\,(\text{magnet}) = \frac{e I_0}{t_m}\left[\frac{1}{T}\int_0^T \left(t e^{-t/t_m}\right)^2 dt\right]^{1/2}$$

$$= 1.36\, I_0 \sqrt{\frac{t_m}{T}} \quad \text{where } T = \frac{1}{(PRR)}$$

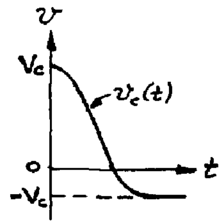
$$I_{RMS} = 1.36 \times 2426 \sqrt{\frac{400 \times 10^{-9}}{5.56 \times 10^{-3}}} = 28 \text{ Amps at } 180 \text{ pps.}$$

$$P\,(\text{magnet}) = 28^2 \times 0.0144 = \underline{11.3 \text{ Watts}}.$$

To determine the value of load resistance required to give a negative voltage ($-V_c$) of approximately 3 KV on the thyratron at the end of current conduction:

$$R = \frac{V_R}{f(K)}\sqrt{\frac{L}{C}} \quad \text{where } V_R = \frac{|-V_c|}{V_c}$$

$$K = \frac{\sigma}{\sqrt{\sigma^2 - \omega_o^2}}, \quad \sigma = \frac{1}{2RC}, \quad \omega_o = \frac{1}{\sqrt{LC}}$$



$$f(K) = K\left[\exp\left(-\frac{K-1}{2}\ln\frac{K+1}{K-1}\right) - \exp\left(-\frac{K+1}{2}\ln\frac{K+1}{K-1}\right)\right]$$

The required initial charge on the storage capacitor is calculated for the lossless case, which is essentially what this circuit is during the rise time.

$$V_c = I_o\sqrt{\frac{L}{C}} = 2426\sqrt{\frac{1.6\times10^{-6}}{0.04\times10^{-6}}} = \underline{15.34 \text{ KV}}$$

which agrees, as it should, with the previously calculated $e_L = L(di/dt) = 15.33$ KV.

$$V_R = \frac{3 \text{ KV}}{15.34 \text{ KV}} \approx 0.2$$

Choosing $\underline{K=3}$ gives a value of $\underline{0.75 \text{ for } f(K)}$. Selecting a value for "K" is a trade-off between the size of the resistor, the peak current thru the resistor/diode and the total time of the magnet current pulse.

$$R = \frac{0.2}{0.75}\sqrt{\frac{1.6 \times 10^{-6}}{0.04 \times 10^{-6}}} = \underline{1.69\ \Omega}$$

$$I_R\,(\text{max.}) = I_o \times f(K) = 2426 \times 0.75 = \underline{1820\ \text{Amps}}.$$

This is the peak current that the diode must conduct, which precludes semiconductor diodes since the turn-on characteristics for devices of this current rating are not satisfactory in this particular case. A delay of 400 nanoseconds in turn-on would allow the storage capacitor to charge to full value in the negative direction, as though no diode and resistor were present.

Hydrogen diodes are the only known devices that can conduct this peak current and turn on in several nanoseconds.

$$P = \frac{\mathcal{E}_o}{T} = (PRR)\,\frac{CV_c^2}{2}\left(1 - V_R^2\right)$$

$$= 180 \times \frac{0.04 \times 10^{-6} \times 15.34^2 \times 10^6}{2}\left(1 - 0.2^2\right)$$

$$= \underline{813\ \text{Watts}}$$

So far, only the current rise time (t_m) ha been specified and used in calculations. The entire pulse length (t_o) will now be determined, where t_o is the time required for the magnitude to decay to 0.67% of I_o

$$t_o = t_m \left[1 + \frac{2V_R}{\pi}\left(\frac{K \ln \frac{K+1}{K-1}}{f(K)}\right) + \frac{10\, f(K)}{\pi V_R} \right]$$

Using the previous values of $V_R = 0.2$, $K = 3$ and $f(K) = 0.75$,

$$t_o = 400 \left[1 + \frac{2 \times 0.2}{\pi}\left(\frac{3 \ln 2}{0.75}\right) + \frac{10 \times 0.75}{\pi \times 0.2} \right]$$

$$= 400\left(1 + 0.35 + 11.9\right) = 400 + 140 + 4760$$

$$= 5300 \text{ nS} = \underline{5.3\ \mu S} \quad \text{for } i_L(t) = 0.0067\, I_o$$

The three terms in the expression for "t_o" represent the three time frames depicted in Fig. 3. The "10" in the third term represents "twice" the number of time constants, hence the 0.67% for 5 time constants. This number of time constants can be changed to any desired value.

As seen in Fig. 2, both circuits are resonantly charged from the same DC power supply.

$$C\ (\text{total}) = 2 \times 0.04\ \mu F = 0.08\ \mu F.$$

$$T\ (\text{time between pulses}) = \frac{1}{(PRR)} = \frac{1}{180} = 5.56\ mS.$$

$$T_c\ (\text{charging time}) = \pi\sqrt{L_c C}$$

For $T_c \approx 4.5\ mS$,

$$L_c = \frac{T_c^2}{\pi^2 C} = \frac{4.5^2 \times 10^{-6}}{\pi^2 \times 0.08 \times 10^{-6}} = 25.7 \approx \underline{25\ H}.$$

$$\text{then } T_c = \pi\sqrt{25 \times 0.08 \times 10^{-6}} = \underline{4.44\ mS}$$

$$E_{DC} = \frac{V_c}{2} = \frac{15.34\ KV}{2} = \underline{7.67\ KV.}$$

$$I_c(\text{Peak}) = E_{DC}\sqrt{\frac{C}{L_c}} = 7.67 \times 10^3\sqrt{\frac{0.08 \times 10^{-6}}{25}} = \underline{434\ mA.}$$

$$I_c(\text{Av.}) = \frac{2}{\pi} \times \frac{T_c}{T} \times I_c(\text{peak}) = \frac{2 \times 4.44 \times 10^{-3} \times 434}{\pi \times 5.56 \times 10^{-3}} = \underline{221\ mA.}$$

$$I_c(\text{RMS}) = I_c(\text{peak})\sqrt{\frac{T_c}{2T}} = 434\sqrt{\frac{4.44 \times 10^{-3}}{2 \times 5.56 \times 10^{-3}}} = \underline{274\ mA.}$$

MAJOR COMPONENTS:

1. Thyratron – English Electric Type CX1574C deuterium-filled ceramic thyratron.
   35 KV, 15 KA peak, 6 Adc.
   Fil. 6.3 V @ 40A, Res. 5V @ 10A.
2. Diode – EG&G Type HR-3 hydrogen-filled ceramic diode.
   25 KV, 2 KA peak, 2 Adc.
   Fil. 6.3 V @ 15A, Res. 6.3 V @ 6 A.
3. Charging Diode – Unitrode Type UDA-15 rectifier stack, 15 KV P.I.V., 0.67 Adc, 30 A surge. (3 required, series connected)
4. Storage Capacitor – High voltage ceramic disc, 0.0027 μF, 30 KV, TDK Type UHV-6 or ERIE Type DH560 N4700 272M-30. (15 required, parallel connected).
5. Load Resistor – Carborundum Type 889SP ceramic power resistor, 12 Ω, 275 W, 10 KV, 12"x1" dia. (7 required, parallel connected).
6. Charging Choke – 25 H, special order to specifications.

SUMMARY

L (magnet)	1.26 μH
L (total)	1.6 μH
C	0.04 μF
t_m (risetime)	400 nS
t_o (total pulse length)	5.3 μS (for $i_L(t) = 0.0067\ I_o$)
I_o (peak magnet I)	2426 A
I_{RMS} (magnet)	28 A
V_c	15.34 KV
$-V_c$	-3 KV
E_{DC}	7.67 KV
R (magnet, high-freq.)	0.0144 Ω
P (magnet)	11.3 W
R (load)	1.69 Ω
I_R (max.)	1820 A (Diode current)
P (load)	813 W
T_c (charging time)	4.44 mS
L_c (charging choke)	25 H
I_c(peak)	434 mA
I_c (average)	221 mA
I_c (RMS)	274 mA
I (thyratron)	4652 A ($2 \times I_o$)

DISCLAIMER