MULTIKILOGAUSS FAST KICKERS

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Introduction

The Main Ring and Doubler need high-field fast kickers, especially for the beam-abort system.[1] Figure 1(a) is one example of a 5 kG kicker for the Doubler. For the abort geometry II of the Doubler, a total kick of about 44 kG-m is required. For geometry I, the necessary kick is about 7 kG-m.

Purpose

One purpose of this note is to show how the energy in the kicker system depends on various parameters. We find there are some interesting relationships. Another reason for writing this is to assert that as energy goes, so goes the cost. This is in disagreement with Ref. 2 whose authors emphasize power. I believe we can readily construct either of the systems visualized in Ref. 1 or even much higher energy systems and that such systems always cost the same--for concreteness, say $4/joule. It is not the purpose here to determine a real $ number, although that should be done promptly, but rather to call attention to the existence and significance of the $/J coupling.

Costs

Costs I believe to be directly related to energy are i) capital investment in items of the system, ii) R&D time and effort, iii) installation,

iv) maintenance, and v) spares. Under R&D effort I include such problems as

a) Sparking of conductors, magnetic circuit parts, connections, terminating resistors and the like.

b) Time dependence and homogeneity of field over aperture, including ringing and overshoot.

c) Simple and rugged construction, especially of tunnel items.

d) Guarantee of enough lifetime for items like gaps and capacitors that wear out after so many shots.

The circuit envisaged is a charging supply, a pulse line for energy storage, a switch (triggered gap or thyratron/ignitron), matched impedance cables, terminating resistors and lumped-element kicker magnets in a series circuit. See Fig. 3.

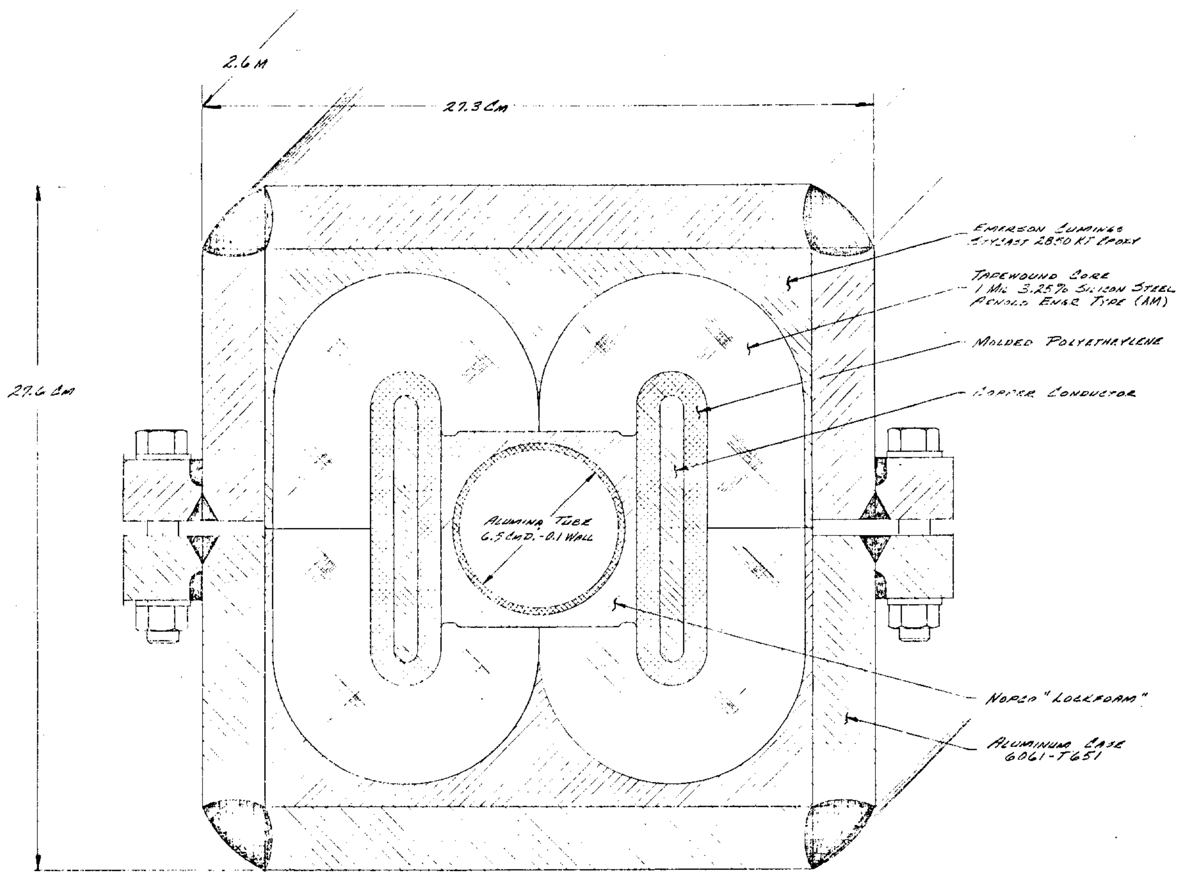


Fig. 1(a). 5 kG kicker magnet module. ½ scale.

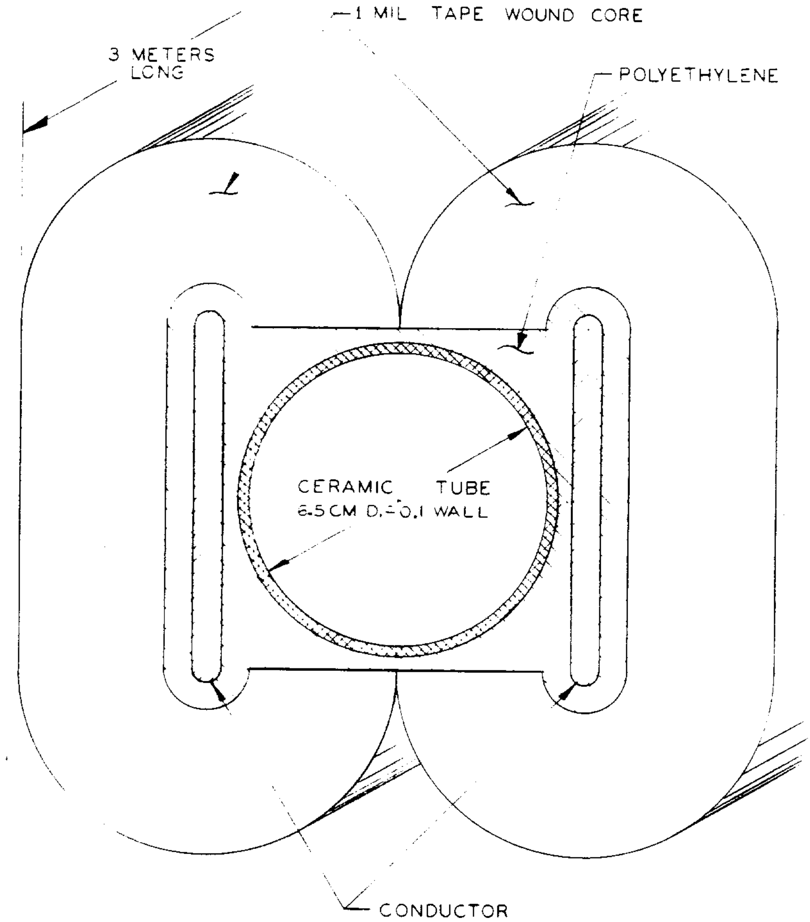


Fig. 1(b). 2 kG kicker magnet module.

The magnetic field as a function of time will look like Fig. 2(a) on the next page for a fast rise system or Fig. 2(b) for a slower system. In either case, the current rises on an L/R time constant, so, e.g., in three time constants, the current (and hence B) will have risen from 0 to 95%.

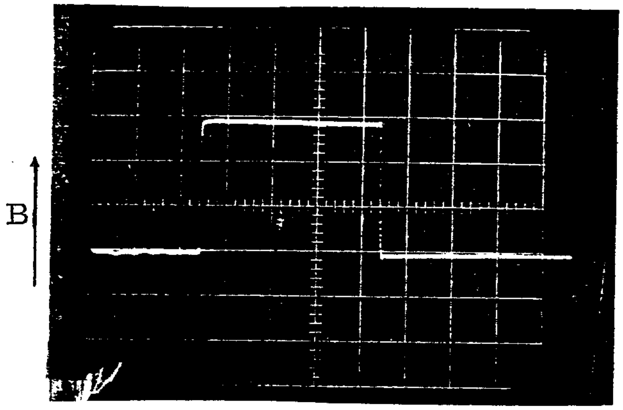
Units

Use mks units and let

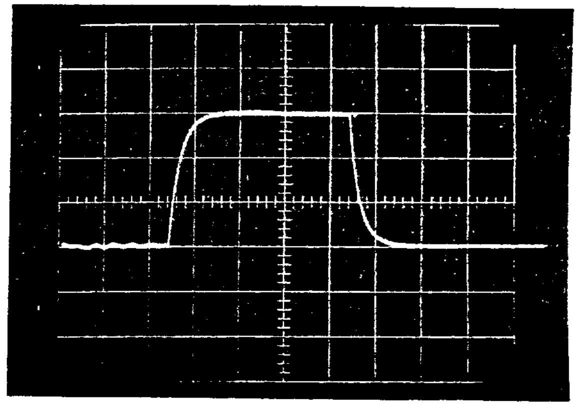
B = magnetic field

ℓ = length along orbit

Z_o = pulse line characteristic impedance



time →
Fig. 2(a)



time →
Fig. 2(b)

L = kicker magnet inductance

t = pulse length ≈ 21 μs

d = magnetic air gap ≈ 5-8 cm for Doubler

I = kicker current at equilibrium (flattop)

V = pulse line voltage into a matched load

U_p = pulse line stored energy

U_k = kicker stored energy

τ = time for current to rise from zero to [1 - (1/e)] of the flat-top current

For the idealized lumped-element kicker we are discussing, the current waveform is an exponential rise with a risetime

$$\tau = \frac{L}{2Z_o}. \qquad (1)$$

The factor 2 arises because the resistance feeding the magnet inductance L is the sum of the pulse line impedance Z_o and the equal-valued terminating resistor R. The Main Ring fast-extraction kicker at E48/D0 is an excellent example of this type of system.

We know the required current is related to the field and the gap as

$$I = \frac{Bd}{\mu_o} \qquad \text{(Ignore MMF due to iron or ferrite by assuming } \mu \to \infty) \qquad (2)$$

and we know the inductance of the kicker is related to the length as

$$L = \mu_o \ell \qquad \text{(Fig. 1 is a 377 } \Omega\text{-"square" parallel-plate transmission line)} \qquad (3)$$

From (2) and (3), the kick equals the flux divided by the gap,

$$B\ell = \frac{\mu_o I}{d} \frac{L}{\mu_o} = \frac{LI}{d} = \frac{\text{Flux}}{\text{Gap}} .$$

For now, we want to treat the kick $B\ell$ as a given quantity, so we write it in brackets $(B\ell)$.

Pulse Line Energy

Next we want to find the energy stored and delivered by the pulse line. With our previous definitions, the energy equals the current $\times$ voltage $\times$ time.

$$U_p = IVt. \qquad (4)$$

From (1), (2), (3) and Ohm's Law,

$$V = IZ_o.$$

We find

$$I = \frac{(B\ell)d}{\mu_o \ell}$$

$$V = IZ_o = \frac{(B\ell)d}{\mu_o \ell} \cdot \frac{L}{2\tau} = \frac{(B\ell)d}{2\tau}. \qquad (5)$$

Thus,

$$U_p = I\,V\,t = \frac{(B\ell)d}{\mu_o \ell} \cdot \frac{(B\ell)d}{2\tau} \cdot t$$

$$\boxed{U_p = \frac{(B\ell)^2 d^2}{2\mu_o \ell} \, \frac{t}{\tau}.} \qquad (6)$$

Now look at the energy stored in the kicker,

$$U_k = \frac{1}{2} B \cdot H \cdot \text{Volume} = \frac{1}{2} \frac{B^2}{\mu_o} \cdot \text{Volume} = \frac{1}{2} \frac{B^2}{\mu_o} \ell d^2$$

$$\boxed{U_k = \frac{(B\ell)^2 d^2}{2\mu_o \ell}.} \qquad (7)$$

Comparing (6) and (7),

$$\boxed{\frac{U_p}{U_k} = \frac{t}{\tau}.} \qquad (8)$$

<u>t, τ, ℓ and Power</u>

We see the pulse line energy is required to be greater than the kicker stored energy by the factor

$$\frac{t}{\tau} = \frac{\text{Pulse Length}}{\text{Pulse Risetime}}.$$

We also see that both the pulse line energy and the kicker energy go down directly as ℓ is lengthened.

The power is interesting; it is in the gigawatt range and can be summarized briefly:

$$\text{Peak Power} = I\,V$$

$$\text{Peak Power} \times t = \text{Pulse Line Stored Energy}$$

$$\text{Peak Power} \times \tau = \text{Kicker Stored Energy.}$$

Voltage

What about voltage? If it's too high, we are troubled with sparks. We can see it's better not to demand too small a value of τ.

From Eq. (5),

$$V = \frac{(B\ell)d}{2\tau}. \tag{9}$$

We can cut V in half by using push-pull drivers. For example, look at Fig. 1 and imagine we pulse the left-hand conductor + and the right-hand conductor -. The voltage contributing to sparking is cut in half; the price we pay is that now we have two pulse lines (a + and a -), two sets of cables, two terminating resistors, and two charging supplies.

If we have gone to push-pull, made τ as large as possible, and still have too high a voltage, the total kicker length can be supplied in several shorter pieces each ℓ' in length.

Then

$$\ell' = 2\,\frac{2\tau V_{max}}{Bd} \tag{10}$$

and we must use a number of pieces equal to ℓ/ℓ'.

For the Fig. 1 kicker module of 5 kG and 2.6 m, if we take $\tau = 0.5$ μs which permits a 0 to 95% risetime in the dead space (1.6 μs) of one missing Booster batch,

$$V = \frac{(B\ell')d}{2\tau} = \frac{(0.5\times 2.6)\frac{8}{100}}{2\times 0.5\times 10^{-6}}$$

$$V = 104 \text{ kV if single-ended}$$

$$= 52 \text{ kV if push-pull}$$

Note: 5 kG may be too high to be economical, but I picked it as an existence proof for kickers > 2 kG. We may prefer a Fig. 1(b) or something in between.

What About Transmission-Line Kickers?

Transmission-line kickers have the complication of capacitors in the kicker module and sustained voltage across the kicker (the voltage persists for t instead of τ; for us, that's about 40× longer and may lead to sparking problems).

However, transmission-line kickers do have the advantage that they permit a terminated system and hence minimum reflections. Lumped-constant kickers do involve an open-circuit reflection that we may discuss as follows:

The circuit is

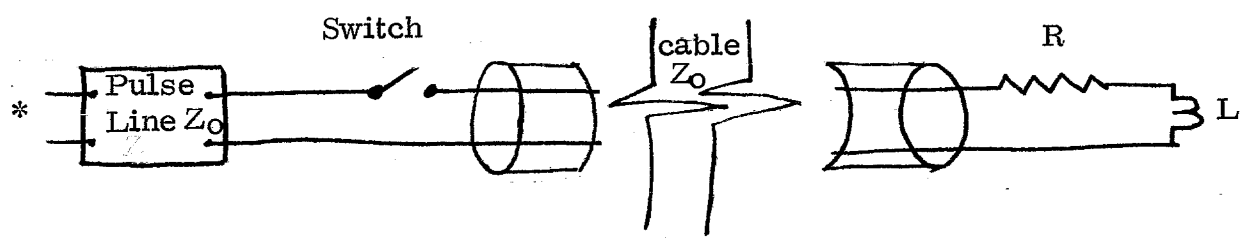


Fig. 3

So the magnet risetime

$$\tau = \frac{L}{2R} \equiv \frac{L}{2Z_o}, \qquad (1)$$

and there is a τ-length reflection (open-circuit type) sent back along the cable, through the switch backwards through the pulse line, but it will not

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*Reference 2 suggests a tail-biter here, an idea evolved in early radar.

return to the kicker until 21+ μs later. Thus the reflection doesn't bother our abort kicker but may be troublesome in an inflection kicker, perhaps thereby suggesting that one may prefer impedance-matched kickers for injection.

Finding Z_o

What value should Z_o be? Z_o appears after selecting τ and ℓ'. Because

$$\tau = \frac{L}{2Z_o} \quad (1)$$

and from (3),

$$L = \mu_o \ell'.$$

For the Fig. 1 kicker,

$$Z_o = \frac{L}{2\tau} = \frac{\mu_o \ell'}{2\tau} = \frac{4\pi \times 10^{-7} \times 2.6}{2 \times 0.5 \times 10^{-6}}$$

$$= 1.04\pi \text{ ohms.}$$

If we use push-pull, each side stores half the energy and runs at half the impedance.

Further Significance of t and τ

Reexamine Fig. 2(b). Note that energy flows into the kicker during the risetime τ . This process fills the kicker. After τ and for all of t, energy continues to flow into the system but is then flowing out just as fast and being converted into heat in R. As far as cost is concerned, it seems exorbitant that the pulse line must be sized to store t/τ as much energy as the kicker actually needs to fill it. Energy flows in and then on out. A reason people accept this state of affairs is that it was one of the earliest ways discovered to produce a flat-topped pulse. We generate pulses blithely at TTL levels with no concern for the wasted energy, but kilojoule pulses deserve more consideration.

How might a kicker system be made energetically more conservative? One way would be to use a barium ferrite or samarium cobalt permanent magnet, magnetizing it up to the proper level during τ, and degaussing it after t. Another scheme would be to set up a current in a superconducting magnet during τ, and dump the magnet after t. With present technology, neither of the above appears cost-effective.

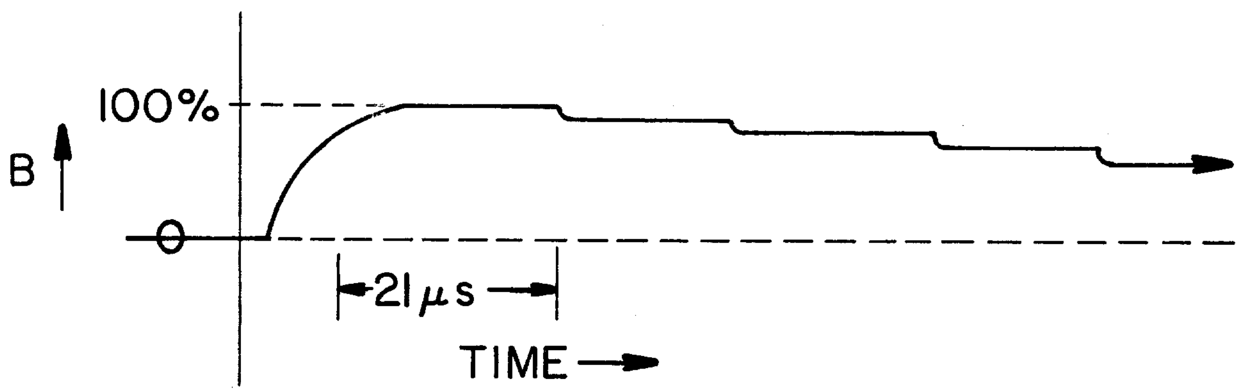
Another way that might actually be competitive would be to use two separate power supplies for t and τ. A capacitor C_1 could generate a $\frac{1}{4}$ sine wave during τ, and a low-voltage pulse line, PL_2, could support the magnet IR drop during t. We would eliminate any terminating resistor R, but we would need a high-current switch or diode actuated at the beginning of flattop. This scheme is similar to crowbarred magnet coils as used for MHD and fusion work. I do not know at what energy level the two power supply scheme begins to pay off in kickers. Of course, the charging of both C_1 and PL_2 must track machine energy, but a tracking feature would be expected for any abort system.

There is one energy-conserving scheme suitable for abort, not injection, that is not too difficult yet gains us a factor of two. That is to leave out the terminating resistor R of Fig. 3 and install a clipping diode at * (the doide prevents voltage reversal on the pulse line capacitors--

otherwise the capacitor life would be shortened). We choose a pulse line (and connecting cables) of twice the previous impedance, to secure the same τ as before, and a number of good things happen:

1) There is no longer any resistor in the tunnel (easier maintenance).
2) The cables are not subject to a sustained voltage of duration t, but only pulses τ (better reliability).
3) The pulse line energy is only half as much as before (lower cost).

The disadvantage is that the current decay doesn't mirror the rise but has instead the form of a descending staircase with 21 μs treads and exponentially decreasing risers. Typically the current might take a millisecond to decay. The pulse line energy (since there is no terminating R) is



dissipated principally in the various conductors of the system. This fact in itself is no drawback because the conductors for other reasons have much greater heat capacity than a terminating resistor R would have had.

Treating Disposable Parameters

Consider again Eq. (6), the central result. We want to minimize system energy and hence cost. The magnet gap d will be made as small as possible. We take the kick ($B\ell$) as given by whatever abort geometry is chosen. We know that t must equal at least 21 μs. That leaves as the disposable parameters τ and ℓ. Both τ and ℓ should be made as long (seconds and meters respectively) as possible to hold down energy and hence cost, and they help equally. Finally, if we treat R as disposable, and dispose of it, we gain a factor of two.

References

[1] F. Turkot, Energy Doubler Beam Abort System, UPC No. 20, December 7, 1978, Revised January 7, 1979.

[2] E. B. Forsyth and M. Fruitman, Particle Accelerators **1**, 27 (1970).