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FAST KICKERS†

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Fast kickers are high speed magnets in which the deflecting force reaches a peak value in less than a few hundred nanoseconds. They were first used as inflectors and have been intensively developed over the last decade as part of the fast extraction system of strong focusing proton synchrotrons. A simple analysis of magnets and pulsing circuits is given, followed by descriptions of the major high power components in modern kickers. In conclusion there is a summary of the characteristics of kickers in service and under development.

1. INTRODUCTION

The development of high speed deflector magnets has been greatly spurred by the requirements of fast extraction from strong focusing proton synchrotons. In this application the magnet is universally known as a 'fast kicker'. The first magnetic kicker was built by O'Neill and served as an inflector magnet for an electron storage ring. He recognized that the magnet could also be used to achieve highly efficient fast extraction from strong focusing machines.(1) When this suggestion was made, in 1959, the alternating-gradient synchrotrons at CERN and Brookhaven were near completion. It had been intended to use a similar fast extraction method to that used on current weak focusing accelerators, i.e., a Piccioni loss target as first step. However, due to the large momentum compaction factor of strong focusing machines, this method promised poor efficiency, perhaps 30%. By pulsing a magnet in which the field rose between the passage of one circulating bunch and the next a coherent betatron oscillation was set up which delivered the beam to the high field aperture of a septum magnet with virtually no loss. This is the basic mechanism of all fast extraction schemes used on strong focusing machines.(2) Besides the applications as inflectors and in extraction systems, kickers have also been used as beam choppers.(3)

The circuits which pulse fast kicker magnets are direct descendants of the line type modulators developed during World War II for radar. However, the restrictions set by the accelerator itself and the inductive nature of the load have led to many ingenious variations of the basic circuit.

2. BASIC CIRCUITS

Consider a rectangular volume of space, width w, height h, and length l meters. These dimensions are bounded by a material of infinite permeability. If this volume is filled with flux such that in the time period t the flux density is increased by B tesla, then define the power W as:

$$W = \frac{B^2\, whl}{\mu_0\, t}\ \text{watts}, \tag{1}$$

where μ_0 is the permeability of free space in mks units. W may be the peak, mean or other power, depending on how the stored energy varies with time. Equation (1) may be rewritten as:

$$W_s = \frac{(Bl)^2 A}{\mu_0\, lt} = \frac{(B\rho\theta)^2 A}{\mu_0\, lt}, \tag{2}$$

where $A = w \times h =$ magnet aperture,
$B\rho =$ magnetic rigidity of a charged particle,
$\theta =$ deflection angle of particle in magnet of length l.

The factors of this equation are set by the accelerator design in which the magnet is to be used, that is, W_s is the power supplied defined in terms of synchrotron parameters. For a given energy and deflection angle the power is minimized by reducing A and increasing l and t. This general statement is applicable to any magnet of the accelerator, from the main ring magnets to the fast kicker. In the case of the fast kicker, l is the length of straight section available for the magnet and t is the time between particle bunches. It is clear that power to energize fast kickers is minimized if the initial choice is a low harmonic number for the rf accelerating system. W_s can be regarded as a performance criterion that the kicker designer must strive to meet.

Figure 1a shows a ramp current waveform in the magnet and the voltage necessary to produce this current in a purely inductive magnet. It is not

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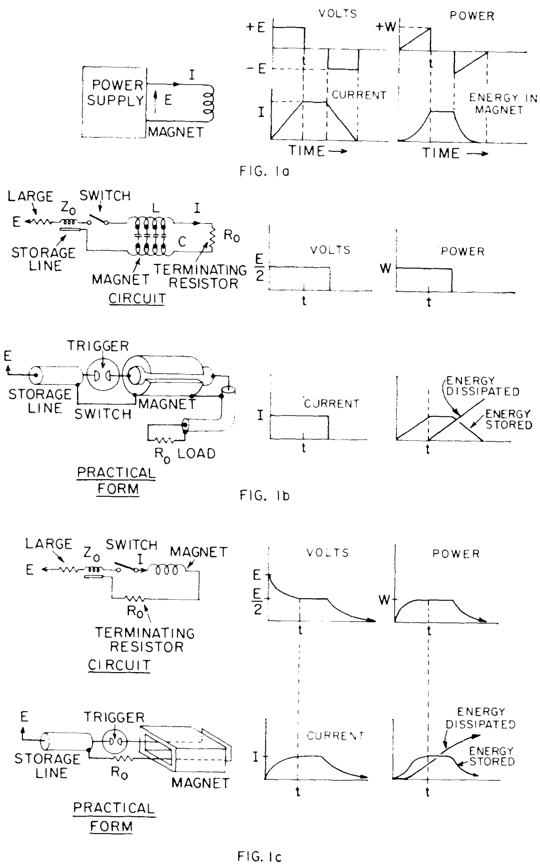

FIG. 1. Three kinds of magnet pulsers and associated waveforms.

a. An 'ideal' supply. The current waveform is similar to that of synchrotron main magnets but is rarely achieved in practical kicker circuits.

b. This circuit is the classical line modulator; the magnet is loaded with capacitance so it behaves like a transmission line of the correct impedance.

c. This is a modulator with a mismatched load. Propagation of the wavefront through the magnet is almost instantaneous but the current rises exponentially as a function of time.

difficult to show that

$$W_s = \frac{(B\rho\theta)^2 A}{\mu_0 lt} = EI, \tag{3}$$

where $E = L\dfrac{di}{dt} = \dfrac{LI}{t}$ volts (a constant),

$$I = \frac{Bh}{\mu_0} \text{ ampere turns,}$$

and $L = \mu_0 \dfrac{wl}{h}$ henrys/turn squared.

In this case W_s is the peak power.

The waveforms shown in Fig. 1a are identical to those associated with the main magnet power supply of a synchroton. The same type of supply cannot be used to energize fast kicker magnets because of the very fast rise time requirement. There are two ramifications of this:

(1) Very high peak powers are needed.
(2) Propagation time in the circuit networks is of the same order of magnitude as the rise time.

The O'Neill inflector and many subsequent fast kickers were built using a line type radar modulator as pulser and the magnet was 'disguised' as a transmission line of the correct impedance by connecting capacitors at several points along the length of the magnet. The circuit is shown in Fig. 1b; the switch is a triggered breakdown device. In this type of kicker the current wavefront propagates along the magnet, filling the magnet with flux of density B in time t given by:

$$t = \sqrt{LC},$$

where L = total magnet inductance,
C = total added capacitance.

The characteristic impedance is

$$Z_0 = \sqrt{L/C}.$$

Using these relationships we find the power to store field, W_m, and the power to store electric charge, W_e, in the magnet during the flux rise time are:

$$W_m = \frac{EI}{4},\ W_e = \frac{EI}{4},\ W_{fk} = W_m + W_e = \frac{EI}{2} \tag{4}$$

where $I = \dfrac{E}{2Z_0}$.

It can also be shown that $W_{fk} \geqslant W_s$, where W_s is defined in equation (2). In an ideal design of this circuit $W_s = EI/2$, but in general W_s is the smaller.

The total rise time of the deflecting force is the current rise time (which is affected mainly by stray circuit inductance, i.e., mismatches), plus the propagation time, or filling time, of the magnet. The force is constant until the waveform travels to the end of the storage line and back, at which time the force decreases in approximately the same time as it took to rise. In practice the tail is always a little longer because the waveform becomes distorted during the trip along the line. If the system is carefully designed no spurious reflections occur. The pros and cons of this circuit may be summarized:

Advantages
(1) Matched system: no reflections.
(2) Maximum voltage on magnet is half line charging volts.
(3) Rise and fall times are approximately the same.

Disadvantages
(1) The capacitors increase mechanical complexity and reduce length available for ferrite.
(2) Half line charging voltage is across magnet during current flat-top.

The mechanical complexity of the transmission line magnet has led to the use of simple magnets which are not loaded with capacitance and thus form a mismatched discharge circuit. In this case the current waveform is exponential in form. The circuit is shown in Fig. 1c. The tail is also exponential in character but with a time constant about 1.4 times longer than the rise time constant. It can be shown that:

$$W_{fk} = W_m + W_r = \frac{EI}{2} \tag{5}$$

where W_m = power to store field in magnet,
W_r = power dissipated in termination.

As before, $W_{fk} \geqslant W_s$, and $t \approx 2.2\, L/2R_0$, $I = E/2Z_0$ The expression for t is the time to rise from 10% to 90% of full current. In practice, 90% will lie outside the tolerable current deviation during extraction but the waveform can be improved in shape by the addition of a capacitor across the load. The capacitor is a special case of the shaping networks discussed in the next section. In this case the current waveform is critically damped or underdamped in form. For a given pulser there is little difference in the time for the deflecting force to reach full value between this circuit and the transmission line magnet.[4] A lumped magnet is used in the present AGS fast kicker.[5] The power from Eq. (5) is the peak power and is twice the power actually used to store flux in the magnet; the difference is accounted for as energy dissipated in the terminating resistor during the rise time. The wavefront propagation in the magnet is at the speed of light, thus the deflecting force is proportional to the instantaneous current. The fall time is approximately 1.4 times the rise time and may have to be improved by the networks discussed in the next section if the kicker is used for partial extraction. The characteristics may be summarized:

Advantages
(1) No voltage across magnet during current flat-top.
(2) Simple mechanical construction.
(3) Full length of magnet is available for ferrite.
(4) No abrupt rise of current in the switch.

Disadvantages
(1) Maximum voltage on magnet is line charging volts.
(2) Reflections may have to be absorbed by additional circuit elements.
(3) Rise and fall waveform may have to be shaped by additional networks.

The two pulsers discussed by no means exhaust all the possibilities. Kickers have been designed with no terminating resistor and with two storage lines[6] (the Blumlein circuit), to name two variations.

3. STRATAGEMS

Stratagems refer to the ingenious manipulations made by kicker designers to build a system that will do the job specified by Eq. (2) and stay within component ratings. A study of Eq. (2) will show that area, time and length may be manipulated. However, it is worth noting that the designers of the National Accelerator Laboratory booster have reduced the deflection angle for extraction by kicking vertically.

Area

The peak power of a kicker is proportional to the area of the magnet aperture. As soon as the kicker method of fast extraction was proposed it was appreciated that advantage could be taken of the adiabatic damping of betatron oscillation in a strong focusing accelerator. The kicker magnet, then, is made with an aperture large enough to contain the beam at extraction energy but not at injection. At injection the magnet is withdrawn mechanically to leave a clear aperture; naturally a 'C' magnet must be used in this application so the poles can slide over the circulating beam without disturbing it. This type of magnet is called a ramming or mobile kicker. The disadvantages are:

(1) The mechanical complexity of the ramming system.
(2) The relatively long period after partial extraction as the magnet is withdrawn. During

this time the use of the beam for targeting or slow extraction may be inhibited.

This type of magnet was used on the first fast extraction scheme installed at CERN.[7]

In principle a closed orbit deformation of the accelerator can be used to move the beam into the kicker magnet instead of vice versa, but when the orbits of the over-all extraction system are considered this method may be unattractive.

At Brookhaven it was felt that the mechanical complexity of ramming outweighed the saving in peak power and the first kicker was made with an aperture large enough to permit injection.[5]

Proposals have been made for magnets with salient poles or eddy currents shields which have an aperture large enough to permit injection but only a small area in the center in which the flux is generated. Usually the problem is to get an acceptably homogeneous field.

Time

The intention is to improve the rise and fall time, or at least improve the shape of the field buildup waveform, without any great penalty so far as peak power is concerned. These methods generally take the form of networks connected across the load and across either end of the storage line, as shown in Fig. 2a. Any combination of networks may be used and the networks may contain linear and nonlinear elements and switches. A method proposed for the CERN booster is the use of nonlinear transmission lines in which smaller currents travel slower than large currents.[8] Hence a ramp function current waveform is steepened by transmission through this network. This is analogous to the formation of tidal bores as water flows into a shoaling estuary. The shallow water travels slower than the deep water and a steep front of water is formed. This technique is used to speed up the current wavefront before it is launched into a transmission line magnet. The problem with the addition of networks is that they are usually mismatched and cause undesirable reflections which perturb the current waveform after the rising period is over. Another drawback is that the operating point of nonlinear devices must be fixed; this limits the adjustment range of a kicker. A circuit which is popular is shown in Fig. 2b. The network at the end of the storage line is a switch and terminating resistor of the correct matching value. S_2 is closed before reflections from the load reach it, therefore they are absorbed. Premature closing of S_2 will shorten the discharge pulse; this is known as a tail-biter and provides a technique for smoothly varying the length of the discharge pulse. This circuit is used in the current CERN kicker, providing the facility to extract any desired number of bunches.[9]

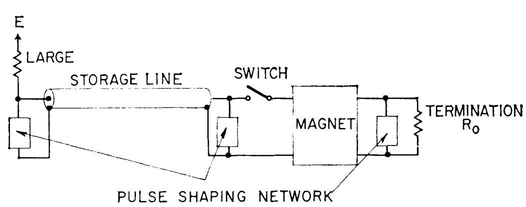

FIG. 2a

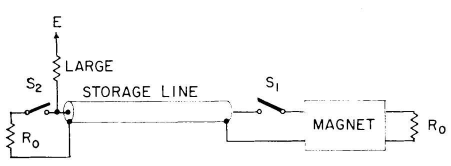

FIG. 2b

FIG. 2. Some additional networks used to improve the waveform in practical kickers.

a. Circuit elements and switches may be used in any combination in the places shown. Networks may be located on the load or line side of the switch.

b. A practical example is the 'tail biter' formed by the termination and switch S_2. This produces a pulse of variable length in the magnet, depending on the relative timing of S_1 and S_2.

The required rise time may be lengthened by injecting into the accelerator in such a way that empty buckets exist. The kicker rise is coincident with this longer gap.

Length

If the length of straight section in an accelerator is too small for the required bending angle two kickers can be placed effectively in series by locating them at straight sections which are spaced an integral number of half betatron oscillations apart. The timing of the kickers must be arranged so that they both deflect the same bunch, but this is not difficult. Another maneuver is to place two 'C' type magnets together, gap to gap, and form a full aperture magnet from two sections which are in parallel.[10]

It might be mentioned here that an arbitrary choice of magnet length cannot be made if the conditions on aperture, deflecting force, maximum switch hold-off voltage, and rise time are met simultaneously. Suppose the length of straight section available for kicker magnets is S meters, then rewrite Eq. (2):

$$W_s = \frac{(B\rho\theta)^2 A}{\mu_0 St}. \tag{6}$$

If n magnets of length l each are placed in the straight section, then:

$$\frac{W_s}{n} = \frac{(Bl)^2 A}{\mu_0 lt}. \tag{7}$$

We have from Eqs. (4) and (5) that $W_{fk} = EI/2$. Let the power dictated by synchrotron parameters, W_s, be related to W_{fk} by:

$$W_{fk} = \frac{kW_s}{n}, \tag{8}$$

where k is a safety factor. B is given by:

$$B = \frac{(B\rho\theta)}{S} \text{ tesla} \tag{9}$$

and

$$I = \frac{Bh}{\mu_0} \text{ amperes.} \tag{10}$$

From Eq. (8):

$$W_{fk} = \frac{kW_s}{n} = \frac{EI}{2}.$$

Substituting for I and B:

$$\frac{kW_s}{n} = \frac{E}{2} \cdot \frac{h}{\mu_0} \cdot \frac{(B\rho\theta)}{S} \tag{11}$$

or

$$En = \frac{2kW_s \mu_0 S}{(B\rho\theta) h}. \tag{12}$$

E and n are chosen such that E is the maximum permissible circuit voltage and n is the smallest integer possible. The most efficient use of the straight section is when the minimum number of individual magnets are installed due to the space that must be allowed for feedthroughs, etc.

4. NUMERICAL EXAMPLE

Typical values for a hypothetical full aperture kicker will be found using the parameters of the Serpukhov proton synchrotron. Assume $\theta = 1$ milliradian, $S = 4$ meters, $B\rho = 2.5 \times 10^2$ tesla meters, $h = 0.12$ meter, $w = 0.17$ meter, $A = 2 \times 10^{-2}$ m^2. The bunch-to-bunch time is 150 nsec.

From Eq. (6):

$$W_s = 1.7 \times 10^9 \text{ watts.}$$

Choose $k = 1.5$, which allows for typical values of stray inductance and jitter.

From Eq. (9):

$$B = 0.063 \text{ tesla.}$$

From Eq. (10):

$$I = 6000 \text{ amperes for a single turn magnet.}$$

From Eq. (12):

$$En = 8.3 \times 10^5.$$

Thus for eight magnet sections $E = 103$ kV per pulser. This is a practical hold-off voltage for available spark gaps or deuterium thyratrons. For each pulser we find $Z_0 = 1.03 \times 10^5/2 \times 6 \times 10^3 = 8.6$ ohm. The magnet length is 0.5 meter and has an inductance of $L \approx 1.0 \times 10^{-6}$ henrys. If a transmission line magnet is used, then the total capacitance of the magnet is $C \approx 13 \times 10^{-9}$ farad. These values must be regarded as the first set of solutions, each subsequent set being refined as detailed calculations are made which allow for tolerable ripple on current waveform, the impedance of available cables, etc. The effect of stray inductance can be illustrated numerically by assuming the total circuit stray is 200×10^{-9} henrys. Then the associated rise time is 23 nsec. This is important considering the maximum permissible rise time in the magnet is only 150 nsec or so. The design difficulty is to keep strays low and still allow sufficient spacing to prevent arcing at 103 kV on the storage line. Note that the stray capacitive rise time using 200×10^{-12} farad is only 1.7 nsec. In practical kickers where Z_0 usually lies between 2 and 20Ω the stray inductance is much more important than the stray capacitance.

5. COMPONENTS

The major components of a kicker consist of the storage line, the switch, the magnet, and the termination. The final design of any system is ultimately limited by the voltage and current capability or the stray inductance of one of these components. Only one of these components was commercially available when the first kickers were made; high voltage coaxial cable which was used as the initial section of the storage line. Nowadays one can buy lumped constant pulse forming networks (PFN's), thyratron switches and high power resistors with characteristics suitable for some kicker applications. The state of the art of thyratron switches has, in particular, been influenced in design by fast kicker requirements.

Switches

Spark gaps were used on the original O'Neill kicker[1] and still represent the only choice as a switch in some kicker applications. Pressurized spark gaps have the advantage of small size and thus inherently low stray inductance. No commercial gap is available which will provide the lifetime necessary in kickers. This is because commercial gaps are usually designed as energy diverters ('crowbars' is the common term) to protect other components in the event of a fault in high power equipment. In this service a lifetime of 10^4 shots is adequate. The development and use of spark gaps in kickers requires a fair-sized group who specialize in this art. The arguments for using spark gaps can be summarized:

Advantages

(1) Best for very fast rise time applications.
(2) Design can be closely tailored to match rest of system.
(3) Charging voltage polarity can be reversed.

Disadvantages

(1) Requires a specialist group for development and maintenance.
(2) Somewhat limited life.
(3) Limited range of voltage adjustment.
(4) High voltage trigger required.

The spark gaps used on the present CERN fast extraction system[9,11] come close to state of the art capability in this area. They operate over a range of 30 to 70 kV with peak currents of 3500 A. Overall jitter is less than 12 nsec and current rise time for a 10Ω resistive load is 20 nsec. The reported lifetime is 10^7 shots, which is very good indeed for this type of device.

Hydrogen thyratrons were first installed in the AGS kicker using the type 7890† rated at 40 kV and 2500 A peak.[12] However, it operated satisfactorily at 6000 A peak. The peak current rating of commercial thyratrons is based on high repetition rate radar service; the limiting peak current in synchrotron applications of about one pulse per second is considerably higher but not accurately known. The 7890's were used for four and a half years at the AGS with only precautionary replacement each year. The advent of deuterium thyratrons permitted replacement by the CX 1168‡ which has so far operated in the same circuit for about 7×10^6 shots. The lower inductance of deuterium tubes permitted the magnet aperture to be increased. By adding internal gradient grids the hold-off voltage of these tubes has been progressively increased to 80 kV at 5000 A peak (CX 1175‡), 120 kV at 2500 A peak CX 1171‡), and 180 kV at 2500 A peak (CX 1199‡). It is proposed to use the CX 1168 to switch the inflector of the CERN Intersecting Storage Rings (ISR), and a study[13] indicated jitter of ±2 nsec at 1800 A peak. The current rise time was 30 nsec with a 14Ω resistive load.

The highest voltage deuterium thyratron has not yet found application in fast kickers as the additional gradient grids produce a concomitant increase in stray inductance. The characteristics of this type of switch may be summarized:

Advantages

(1) Long lifetime without maintenance.
(2) Commercial availability.
(3) Low trigger voltage required.
(4) Wide range of operating voltage.
(5) Somewhat higher voltage and current ratings then spark gaps.

Disadvantages

(1) Larger stray inductance than a spark gap.
(2) Charging voltage polarity cannot be reversed.

Storage Lines

Coaxial cables are usually used as the first section of storage lines since the distributed characteristic guarantees a rise time that agrees fairly well with theory. For pulse lengths longer than a few hundred nanoseconds, cables get very bulky and it is more practical to use a lumped constant delay line. Several types of cable used or developed for fast kickers are shown in Table I. Lumped constant storage lines can be made with impedances as low as 2Ω. They are obtainable on special order from many manufacturers. The capacitors used are generally extended foil, paper dielectric in oil. A group at Berkeley has developed a network using ceramic capacitors.[14] The pulse forming networks of the present CERN kicker are shown in Fig. 3.

Many ways are used to recharge storage networks. In view of the low duty factor, series

† Manufactured by General Electric, I.T.T., Tung-Sol, etc. Equivalent types made by E.G.G. and English Electric Valve Co.

‡ Manufactured by English Electric Valve Co.

TABLE I

Type	Manufacturer	Maximum volts	Current (A)	Z_0 (Ω)	Comments
100 P2/2	British Insulated Callenders Cables	100 kV	275 rms	14	Used on present AGS fast kicker for last 4 years
100 P3	British Insulated Callenders Cables	100 kV	720 rms	14	
YR 10914	Belden Corp. Chicago, Ill.	120 kV	8000 peak	14	Under test for post-conversion AGS fast kicker. Ratings for 10% duty factor.
	Les Cables de Lyon	100 kV	3000 peak	20	Solid conductor, low loss. Pressurized with SF_6.

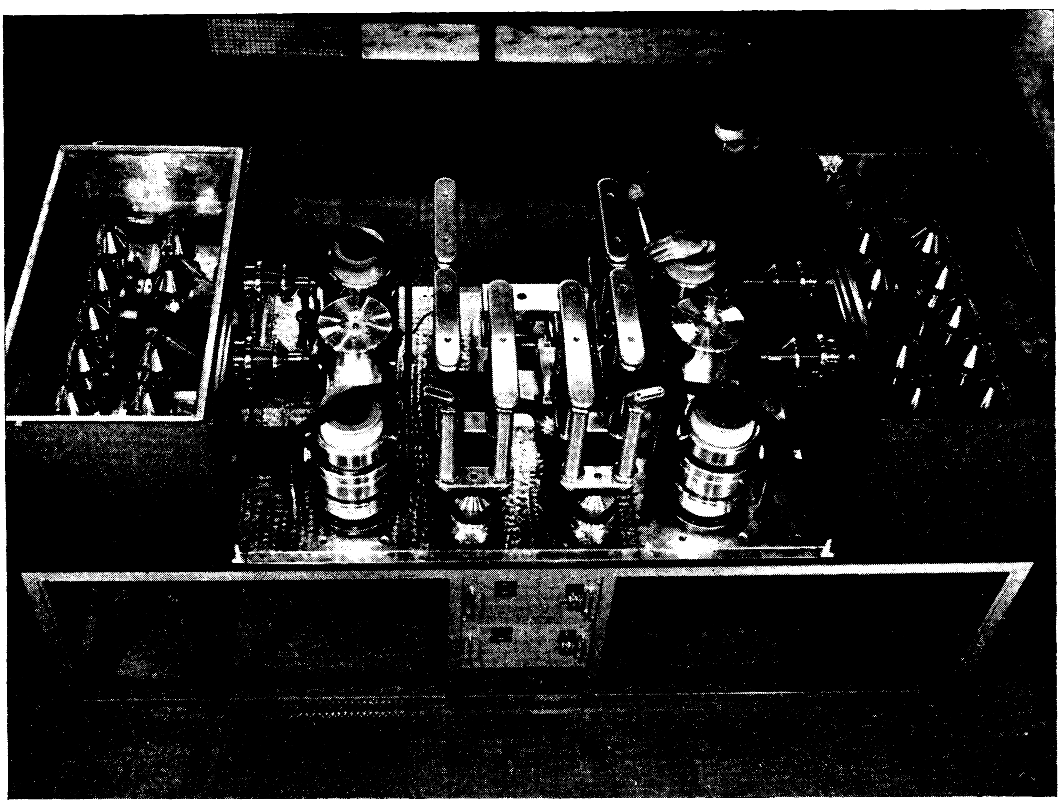

FIG. 3. Pulser of the present CERN PS kicker. Two storage networks can be seen at either end. Switching spark gaps and high voltage components are inboard of the networks. (Credit: CERN PHOTO)

resistance charging from a conventionally regulated high voltage power supply is often attractive. The accuracy of pulse-to-pulse recharge voltage is of the order of a part in five hundred for most kickers. This method loses its appeal when short recharge times are necessary, say 100 msec or so. The quick charge may be required for multishot operation in one accelerator cycle or to avoid the onset of corona in very high voltage kickers. In these cases the charging supply is gated on by means of SCR's or ignitrons in the primary circuit. These control devices may also be used to regulate the dc level.

Proposals have been made to charge the line through a step-up pulse transformer from a low voltage energy storage source.[15] The conventional resonant charging system commonly used in radar modulators is not appropriate for kicker service due to the slow, and possibly variable, repetition rates.

Magnets

The operational characteristics of lumped and transmission line magnets have already been discussed. Either type may be built as a 'C' magnet or a picture frame, depending on whether it is rammed or not. 'C' magnets are usually made in a coaxial form with a radial slot. Slotted discs of ferrite are used which, in the case of transmission line magnets, are interleaved with the loading capacitors. Ceramic, oil and vacuum are the most common dielectric between the plates of the capacitors. Ramming magnets are equipped with flexible parallel strip transmission lines to make the connections at either end of the magnet (see Fig. 4). For kickers with a system impedance of 20Ω or less it is impractical to match these lines and they add to the total inductive strays. The lumped magnets of the present AGS kicker are made from rectangular bricks of ferrite. Lumped magnets are usually single turn, but multiturn magnets may be used advantageously in special situations such as low power, fast rise time kickers. The ferrite in both types of magnet is usually a high resistivity nickel-zinc type with frequency response between 1 and 10 MHz, depending on the kicker rise time. The

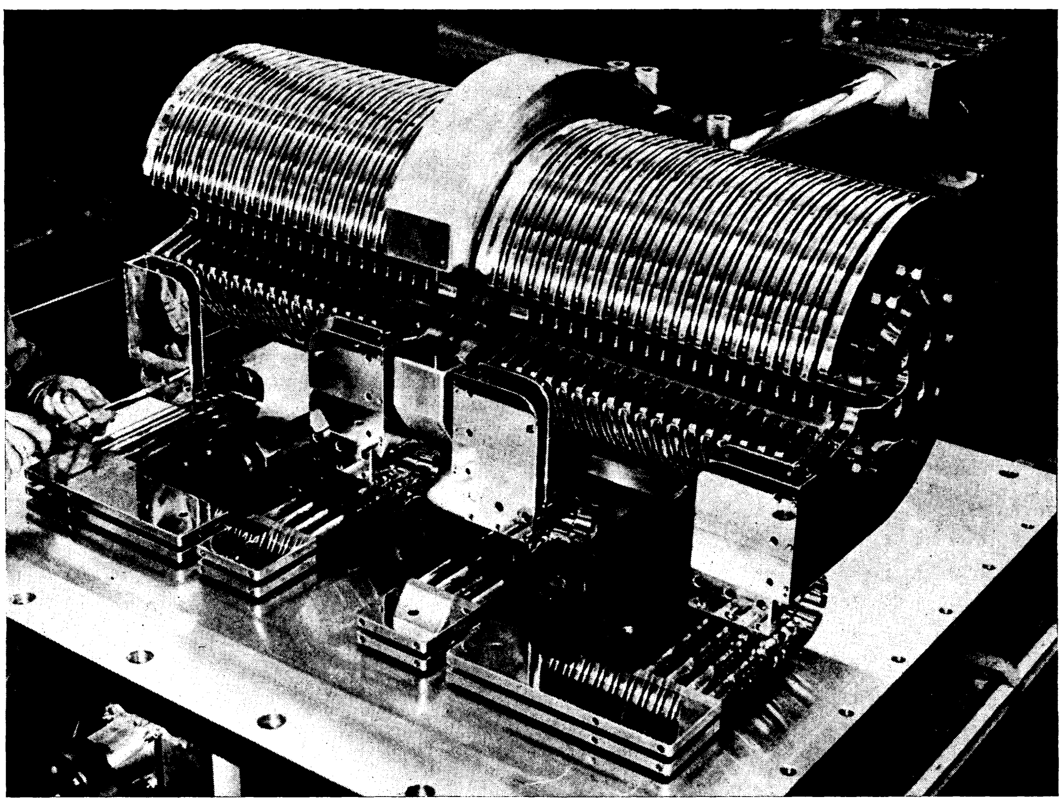

FIG. 4. Magnet used at present on the CERN PS. Four pairs of parallel strip line connections can be seen lower front. The arm which rams the magnet into position after injection is at the back. (Credit: CERN PHOTO)

maximum flux density in the ferrite is limited to about 0.3 tesla. In low power kickers it is possible to increase the aperture so that a nonmetallic vacuum pipe can be located inside the magnet which obviates feedthroughs and the associated stray inductance.

Terminations

The availability of suitable cables for storage and transmission lines usually fixes the specific characteristic impedance of a kicker system. For higher powered systems cables may be connected in parallel. Several methods of making matched terminating resistors are commonly employed. The requirements for a termination are:

(1) Minimum series inductance.
(2) Good ohmic stability when dissipating very high peak power.
(3) Good ohmic stability as a function of temperature and age.

As an example, the post-conversion AGS kicker, now under development, will pulse a 14Ω termination with over 100 kV, corresponding to a peak power of just over one gigawatt but considering duty factor the average power will be approximately 3 kW. This termination can easily be constructed of multiple units in parallel, providing the unit is built to withstand the severe peak power, which frequently becomes a matter of withstanding voltage gradient. To this end the AGS termination uses an oil immersed, parallel coaxial configuration of carbon compound resistors. Each resistor is rated at 150 W in still air and industry experience indicates a factor of 3 to 4 increase in power is attained in oil. This termination is shown in Fig. 5. The CERN ISR inflector uses a series combination of carbon compound resistor discs in a coaxial chamber and an oil circulator with temperature regulation to heat or cool the coil and control the temperature coefficient of the resistors.[16]

Another technique is the electrolytic resistor as used in the CERN multishot kicker. Such resistors are essentially electrolytic plating tanks where the electrolyte is the resistive element and the plates are the end connections. Since the electrolyte resistivity is temperature sensitive it requires cooling and thermostatic control to maintain a fixed resistance. Such devices can also be built in coaxial structures to minimize inductive effects. Since the resistive element is also the heat transfer medium, high average power can be dissipated.

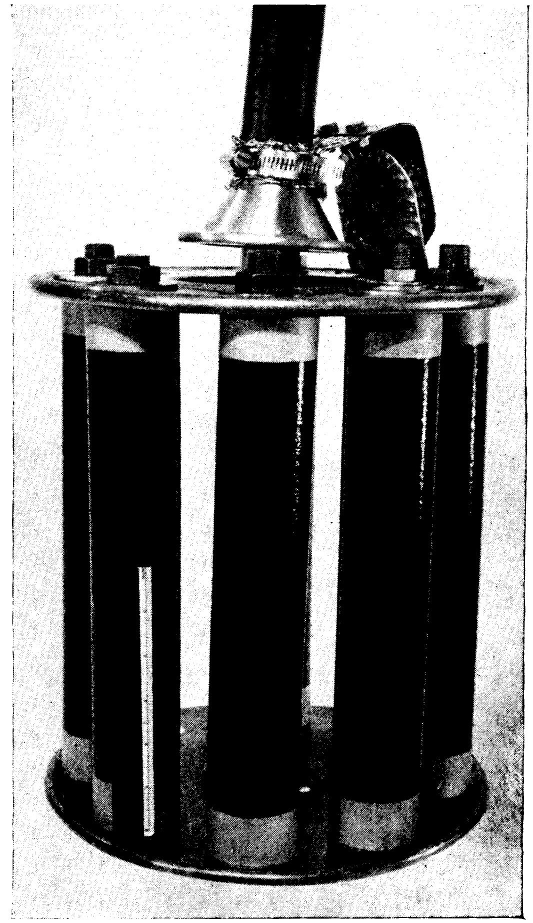

FIG. 5. Terminating resistor under development for the post-conversion AGS kicker. A current viewing resistor can be seen upper right. The threaded rod and nuts are epoxy glass. The complete assembly is immersed in oil. The ruler is 6 in. (15 cm) long.

6. INSULATION

In any high voltage equipment considerable effort must be made to solve voltage insulation problems. But in kickers conditions are exacerbated by the requirement of short current paths in unmatched portions of the circuit. Since spacing cannot be increased indefinitely to prevent high voltage corona and breakdown, it becomes necessary to use mediums of higher dielectric strength than air. Such mediums are vacuum, transformer oil, and sulfur hexafluoride (SF_6). Vacuum can, of course, most easily be used for the magnet which is already in the accelerator vacuum chamber. Air, oil, and SF_6 can be, and are, used as

TABLE II

Installation	Max. proton energy (GeV)	Magnet type	Individual magnet aperture $w \times h \times l$ (cm^3)	No. of magnet sections n	Total deflecting force (T-m)	E, Maximum charging volts (kV)	Z_0 per magnet (Ω)	Bunch separation (nsec)	W_s (MW)	Switches	Comments
Present CERN PS kicker	25	Transmission line. Mobile	2.2 × 2 × 28	2	0.14	70	10	100	110	6 × spark gap	Selectable number of bunches. Capable of multishot operation. Recharge in 150–200 msec depending on energy.
Present AGS kicker	30	Lumped magnet. Full aperture.	15 × 6.7 × 38	4	0.08	40	7	200	170	2 × deuterium thyratrons	Capable of full beam extraction or multiple single bunch extraction 100 msec apart
Post-conversion AGS kicker	30	Lumped magnet. Full aperture.	15.3 × 7 × 38	4	0.2	100	14[a]	200	1240	4 × deuterium thyratrons	Under development. A Blumlein circuit is being tested
CERN Booster extraction kicker	0.8	Transmission line. Full aperture.	11.5 × 7 × 48	4	0.04	33	25[a]	50[b]	106	1 × deuterium thyratrons plus spark gap	Part of a complex system including 4 horizontal kickers, 3 vertical kickers and an inflector
CERN ISR inflector kicker	25	Transmission line. Moved after stacking	4.5 × 2 × 137	2	0.23	40	14	310[b]	46	2 × deuterium thyratrons	Under development. See Ref. 16
NAL Booster extraction kicker	8	Unloaded transmission line. Full aperture.	6.9 × 6.9 × 100	4	0.03	70	50	45[b]	19	4 × deuterium thyratrons	No extra capacitance needed to operate magnet in transmission line mode at this impedance. Vacuum chamber inside aperture
Serpukhov/CERN extraction kicker	70	Transmission line. Full aperture.	14 × 10 × 30	10	0.36	80	5	150	3300	30 × spark gaps	Under development. Will feature variable bunch selection and multishot operation. See Ref. 17.
CERN PS extraction kicker	25	Transmission line. Full aperture.	15 × 5.5 × 23	12	0.17	80	15	100	750	36 × deuterium thyratrons	Under development.

[a] The circuit produces E, not $E/2$, across termination.

[b] Deflection force rise time.

insulation around most other high voltage components in the system. Each has its particular benefits and problems and only the major ones are touched upon here.

Air is the easiest medium to use if the voltage gradients are low enough, and it has been used successfully in many instances. However, as the kicker requirements increase, there appears to be little choice but to use other insulators. A practical limit to the charging voltage level in air is about 50 kV—perhaps a little more for high impedance kickers. Still, it should be kept in mind that approximately a 50% increase in dielectric strength can be attained by pressurizing air to two atmospheres absolute. It is quite possible that this relatively simple method is not used as frequently as it might be. The CERN multishot kicker spark gap(11) is designed to operate up to 4.5 atmospheres to take advantage of this effect.

SF_6 can be considered to have a dielectric strength of two to three times that of air in typical electrode configurations. As SF_6 is pressurized it increases in dielectric strength faster than air. It has, however, the rather distressing possibility of forming hydrofluoric acid and hydrogen sulfide if water is present when an arc occurs(14) and this can cause considerable damage.

Transformer oil has been the most widely accepted high voltage insulating medium in industry, but there seems to be some reluctance to use it in accelerator installations. This is probably due to its recognized flammability. However, safe methods of coping with the flammability problem are well known and some are, in the USA, approved by the National Electrical Code and the National Fire Protection Association which publishes the National Fire Codes. These codes state, for instance, that oil-filled transformers may be installed in buildings not conforming to the codes' transformer vault provisions if such buildings do not endanger other buildings and if such buildings are used 'only in supplying electrical service' and are accessible only to qualified personnel. Other precautions that are generally taken when oil is used are the use of secondary containers to capture the oil in case of a tank rupture and the use of automatic carbon dioxide fire extinguishing systems. Clean transformer oil has a dielectric strength of at least 17 kV for 0.1 in. (6.7 kV per mm); it is dense enough to act as a very suitable coolant for heat sources such as terminations and thyratrons, and it can easily be repurified by a filter and circulating pump.

Other dielectric mediums not yet used in kicker systems but which might be considered are the fluorochemical liquids. These compounds are completely inert and nonflammable, have a dielectric strength comparable to oil, are good coolants, and will evaporate without residue from vacuum systems. Their drawback is cost, which, at over $100 per gallon, is probably reason enough for their lack of general use. Chlorinated oils are generally available and nonflammable but are not often used because they are corrosive to many common materials.

7. KICKERS IN SERVICE AND UNDER DEVELOPMENT

The fast kickers in service at present at the CERN PS and Brookhaven AGS are basically the ones installed in 1962 and 1963, respectively. At CERN, modifications have been made over the years to increase operational flexibility by providing fully variable pulse width, multishot operation in one accelerator cycle, and magnet polarity selection. At the AGS minor improvements have been made in aperture and deflecting force; this installation is shown in Fig. 6. This confirms the suspicion that a decade is needed to change a major component of an operating synchrotron if it works: if it does not, only five years are needed! A new kicker is under development at the AGS with a larger deflecting force; this will be needed due to the increase in beam emittance when the high beam intensity conversion program is complete. Groups at CERN and the Efremov Research Institute of Electrophysical Equipment in Leningrad are designing kickers which will serve three fast extraction channels at the 70-GeV Serpukhov accelerator.(17)

Challenging problems in this field are presented by the extraction system of the CERN 0.8-GeV booster, extraction from the PS, and inflection into the ISR. Several interesting innovations have been proposed by the designers of the extraction system from the 8-GeV booster to the 200-GeV synchrotron at the National Accelerator Laboratory in Batavia, Illinois.

The characteristics of these kickers are summarized in Table II. It is left as an exercise for the reader to compare the safety factor, k, for these designs by comparing W_s with the product $nEI/2$ or nEI in the case of the exceptions noted.

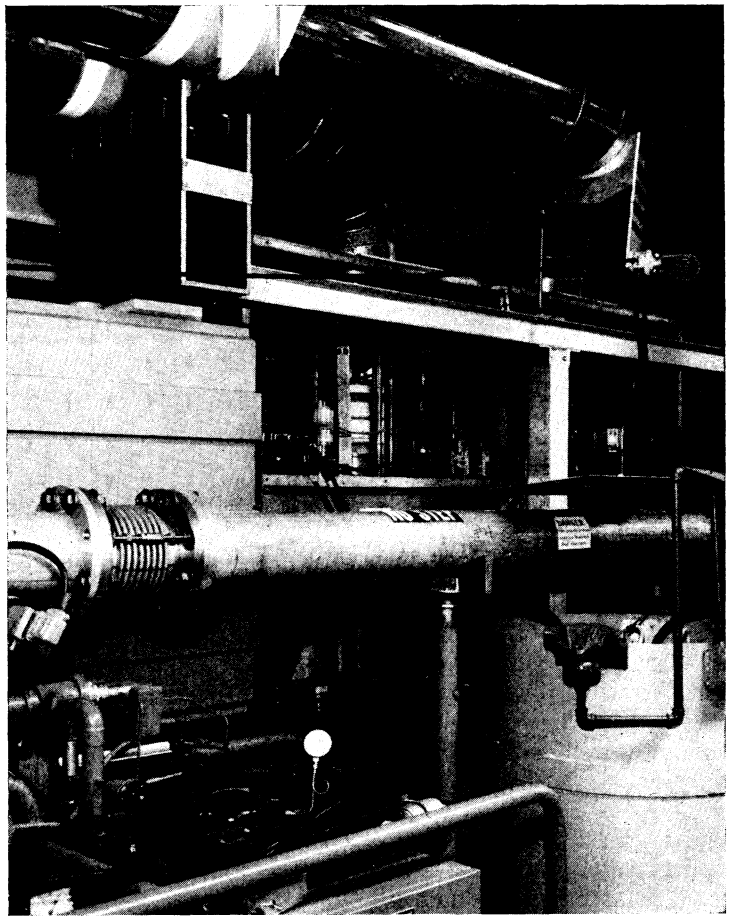

FIG. 6. The present kicker installed in the AGS. The storage cables are contained in the ducting seen at the top. The switch tubes are mounted on the vacuum box holding the ferrite magnets. The back of a main magnet is on the left-hand side.

REFERENCES

1. G. K. O'Neill, 'Storage Rings for Electrons and Protons,' *Proc. Int. Conf. High Energy Accelerators and Instrumentation, CERN* 1959, p. 125.
2. K. H. Reich, 'Beam Extraction Techniques for Synchrotrons,' Section III of *Progress in Nuclear Techniques and Instrumentation*, Vol. II, F. J. M. Farley, Ed. (North Holland, Amsterdam, *1959*), p. 163.
3. R. J. Averill and T. L. Collins, 'Post Accelerator Beam Pulse Length Chopper,' *IEEE Trans. Nucl. Sci.*, **NS–16,** No. 3, 150 (1969).
4. E. B. Forsyth, 'Comparison of Lumped and Distributed Inflector Magnets,' Brookhaven National Laboratory, Accelerator Dept. Report EBF-2, BNL 6880 (1963).
5. E. B. Forsyth and C. Lasky, 'The Fast Beam Extraction System of the Alternating-Gradient Synchrotron,' Brookhaven National Laboratory Report BNL 910 (T-373), Clearinghouse for Federal Scientific and Technical Information, Springfield, Virginia, U.S.A.
6. G. N. Glasoe and J. V. Lebacqz, Eds., *Pulse Generators*, Vol. 5 of the Radiation Laboratory Series (McGraw-Hill, New York, 1948), p. 465.
7. R. Bertolotto *et al.*, 'The Fast Ejection System of the CERN 25 GeV Proton Synchrotron,' *Proc. Int. Conf. High Energy Accelerators, Dubna, 1963* (Atomizdat, Moscow, 1964), p. 669.
8. A. Brückner, 'A Non-Linear Step Pulse Steepening Delay Line,' CERN Report 68–25.
9. R. Bossart *et al.*, 'Multishot and Multichannel Fast Ejection,' *IEEE Trans. Nucl. Sci.*, **NS–16,** No. 3, 286 (1969).
10. H. Fischer, 'Some Reflections on Full Aperture Kickers,' CERN Report 63–24.
11. L. Caris and E. M. Williams, 'The Spark Gap Switches of the New Fast Beam Extraction System at the CERN Proton Synchrotron,' CERN Report 69–13.
12. E. B. Forsyth, 'A Hydrogen Thyratron Magnet Pulser,' *Proc. 8th Symposium on Hydrogen Thyratrons and Modulators, Fort Monmouth, N.J., 1964*, p. 301.
13. H. O'Hanlon and J. P. Zanasco, 'A High Voltage Thyratron Switch for the Fast Inflector of the ISR,'

Proc. 10th Modulator Symposium, New York, 1968, p. 337.
14. J. W. Davis, W. L. Gagnon and R. H. Smith, 'Experimental Studies of the Omnitron Electrical Components,' *IEEE Trans. Nucl. Sci.*, **NS–14,** No. 3, 250 (1967).
15. A. Brückner and J. F. Labeye, 'A Resonant Charging Pulsed High Voltage Power Supply,' CERN Report SI/Int. MAE/68–6.
16. H. Kuhn, W. C. Middelkoop and H. O'Hanlon, 'The Design of the ISR Inflector,' *IEEE Trans. Nucl. Sci.*, **NS–16,** No. 3, 738 (1969).
17. B. Kuiper, B. Langeseth, and K. P. Myznikov, 'The Fast Ejection System in Particular Channel A, of the Serpukhov Accelerator,' CERN Report CERN/PS/FES/int. 69–8.

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