CERN PS/FES/TN-165 May 1970

ON THE DESIGN OF "DELAY LINE" MAGNETS

P.G. Innocenti, B. Kuiper, A. Messina, H. Riege

Abstract

Fast pulsed deflection magnets called kicker magnets are the heart of modern fast extraction systems at high energy particle accelerators. The construction of a fast ejection system for the Serpukhov proton synchrotron required theoretical investigations and experimental testing work on low voltage magnet models. The behaviour of different types of delay line kicker magnets was studied. The most important problems are, how pulse response, e.g. rise-time, amplitude and flat top ripple of the magnetic field, and reflections depend on the numerous constructional parameters. The final solution adopted for the Serpukhov ejection kicker is a compromise between a multi-section delay line magnet and a lumped inductance magnet. The hybrid construction of the chosen two section delay line kicker magnet combines a favourable rise-time to a short reflection which may be placed between subsequent bunches. Based on the results of low voltage measurements and computations a high voltage prototype magnet was manufactured and successfully tested.

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CERN

1. INTRODUCTION

Fast pulsed deflection magnets have become very important at high energy particle accelerators during the last few years. The specific characteristics of these magnets, usually called kicker magnets (KM), are fast rise- and fall-time of the magnetic field and a flat top with small ripple and a homogeneous field distribution. The KM is normally incorporated in a delay line circuit consisting of a delay line type pulse generator, matched transmission cables and terminating resistors$^{1)}$ (Fig. 1 a).

The most important application of kicker magnets, up to now, was seen in fast extraction systems of high-energy particle accelerators, where charged particles are ejected in times of the order of one revolution period. Kicker magnets are also used as fast inflectors for injection of particles into accelerators and storage rings, or for particle collision experiments in proton and electron storage rings.

Here we will deal with KM's for fast ejection systems and especially with the KM of the Serpukhov 70 GeV accelerator fast ejection system, the layout of which is given elsewhere$^{2)}$.

The main difficulties in the construction of a KM for fast ejection arise with the high pulse voltage necessary to feed the magnet. This is especially true for the most obvious constructional solution of a KM, namely a full aperture, stationary magnet which is engaging on the particle beam during the whole acceleration process$^{3)}$. The fact that at high kinetic energy the particle beam diameter contracts to a small fraction of its initial value after injection, enables to relax the voltage requirements by application of "small aperture" KM's, which engage on the circulating beam only during ejection. Then, either the contracted beam is adiabatically switched from its equilibrium position into the small aperture of a stationary KM outside the accelerator aperture or the KM is moved into a central working position, when the beam has contracted. As a compromise between full and small aperture KM's recently other solutions (flap or moving pole magnets) have been proposed$^{4)}$.

Claims for a perfectly developed beam sharing technique (multishot, multichannel operation$^{5)}$ of modern fast extraction equipment steadily increased the requirements for a good pulse response (rise, fall, flat-top) of the KM in order to keep a high ejection efficiency.

Besides electromagnetical and high voltage performance there are, however, a number of further aspects, which, sometimes, can be decisive for the choice of a certain KM construction. Here we have to remember that a KM has to work in a vacuum tank (space limitations) under the influence of high radiation doses. Also maintenance and serviceability are important factors in the design of the construction.

2. PRINCIPAL PROPERTIES AND PARAMETERS OF A KM

A KM has to provide a certain kick K defined as the field integral $\int$Bdl along the particle orbit in order to deflect the particle beam from the accelerator equilibrium orbit. The KM is electromagnetically representing an inductance, the value of which is given by the aperture dimensions height h, width w and total length l. Generally the aperture dimensions and the magnetic length are given by the beam diameter and the available space between the main accelerator magnet units. In order to reduce the voltage V necessary to fill the inductance in the desired time t_r with a current i, one can split the whole KM into n separate modules. Then the gap inductance of one module follows approximately as

$$L_K \simeq \mu_o \frac{wl}{nh} \qquad (1)$$

The current is corresponding to the desired kick strength K is given by

$$i = \frac{Kh}{l\mu_o} \qquad (2)$$

The current should rise up to its full amplitude in a time t_r less than the bunch distance of the accelerator. We can define a time constant

$$\tau_o = L_K/R_o \qquad (3)$$

given by the gap inductance and the impedance R_o of the delay line circuit.

The real field rise-time t_r of the KM will always be greater than τ_o,

$$t_r = x \cdot \tau_o, \tag{4}$$

by a degrading factor $x > 1$. The pulse voltage V has to be chosen such that with the impedance R_o the desired current of Equ. (2) is obtained :

$$V = \frac{L_K \;\; i}{\tau_o} = \frac{x \; Kw}{t_r \; n} \tag{5}$$

Equs. 1) through 4) are only rough approximations because losses in the ferrites of the KM (for $\mu_r \neq \infty$) and end effects of the different modules are neglected.

Furthermore, at low impedance levels the voltage pulse rise-time is increased by stray inductances of the pulse generator and by the transmission cable characteristics. Also the deteriorating effects of stray inductances of the KM circuit are more expressed for smaller impedance and, therefore, the factor x is increasing with decreasing R_o. By splitting the KM inductance gradually into more modules in order to reduce the pulse voltage V, one therefore does not gain proportionally, since the increase of x has to be compensated again by more voltage. If, on the other hand, the KM is operated at a high voltage level, one has to keep greater distances in the magnet construction leading to higher stray inductances and hence greater x-values.

For a KM pulsed in a delay line circuit (Fig. 1 a) one will generally observe a time variation of the magnetic kick K similar to that shown in Fig. 1 b. In a fast ejection system which has to provide the multiple extraction of any arbitrary number of the circulating bunches a clipping gap can be used (Fig. 1 a) which cuts the tail of the voltage pulse coming from the pulse generator in order to obtain a short fall time. Reflections are returning to the KM , if they hit the clipping gap in a short circuited condition, and as a consequence, they may partly deflect one or more bunches of the remaining beam. By a proper choice of the transmission cable length between pulse generator and KM the reflection can be sometimes placed between two subsequent bunches.

For the Serpukhov ejection system it seemed possible to build a stationary full aperture KM. The main parameters are given in table 1. The flat top kick amplitude has to be reached within less than 165 ns, e.g. the bunch distance of the Serpukhov proton synchrotron. A maximum charging voltage of 80 kV is adopted for the delay line pulse generators and as a consequence an impedance level around 5Ω comes out, if the KM is divided into 10 separate modules. It was assumed that a degrading factor of $x \simeq 1.4$ can be obtained with the KM. Theoretical investigations together with testing of low and high voltage KM models were carried out in order to find out the best type of magnet and to define the minimum requirements for the whole delay line pulser circuit. The computations partly dealt with idealized magnet circuits to explore the general behaviour of a KM type and to study the separate influence of different parameters, partly ,the real conditions and the actual magnet parameters (measured or estimated on low and high voltage models)were taken into account. The x-values, which, in the case of idealized magnets, are nearly equal to 1, may increase to about 1.5 at such low impedance levels as 5Ω.

3. DELAY LINE KM WITH MANY L-C SECTIONS

One way to build fast kickers is to simulate, by construction, an artificial delay line consisting of several L-C-sections, where the inductances L represented by ferrite loaded line sections deliver the deflecting field and, together with the capacitors C, determine impedance and rise-time of the magnet. At higher impedance levels it seems also possible to build a distributed delay line KM6).

The equivalent electrical circuit of a lumped delay line type magnet is approximately represented by Fig. 2a. Numerical computations showed, how rise-time, fall-time and flat top ripple of the kick depend on the number of sections, on stray and coupling inductances in the magnet, on voltage pulse rise-time (fall-time) and small mismatching effects. By calculating the influence of the most important parameters on the KM behaviour, a prediction of the factor x (equ. 3) obtainable with a certain magnet configuration can be given provided the stray inductances can be properly estimated or measured on magnet models. Fig. 3 shows a plot of computed kick rise-time and ripple as function of the number N of L-C-sections. Whilst also for a rather small number of sections the kick rise-time is practically equal to the delay-time of an ideal homogeneous delay line, the ripple Δ K is increasing considerably with decreasing N. On the other hand the response for a magnet with a few sections may be improved by properly adjusting the capacitor values of each section. A real disadvantage at small values of N is the substantial reflection of a certain part of the incident voltage pulse back towards the pulse generator. The length of the reflected voltage pulse is mainly determined by the delay time of the first L-C-section. For greater section numbers ($N > 5$) the kick excited by the full voltage pulse reflection is negligible.

The construction of a low impedance delay line KM creates a space problem for distributing the capacitors. The capacitances may be formed by metal plates between the ferrite frames (as in the CERN OSF KM$^{7)}$). However, at low impedance levels the transversal plate dimensions become rather large. Big transversal capacitor dimensions are leading to high stray inductances and delay line effects within the capacitor itself. The space for placing more capacitors in the longitudinal dimension is restricted by the minimum distances between capacitor plates, which have to be maintained in order to avoid flash-over. On the other hand ceramic capacitors can replace the vacuum plate capacitors. For this solution special configurations of the capacitors are necessary to avoid surface flash-over.

In our laboratory a full size delay line KM model (Fig. 2b) with 11 sections and 5 Ω impedance was built with ceramic capacitors and tested at low voltage. Coupling coefficients and stray inductances were measured. Measurements of kick and computations using the real parameters were in good agreement and the rise-time of the magnet was satisfactory. An x-value around 1.35 was obtained. The model was however not yet ripe for high voltage tests, since the problems of surface flash-over on the ceramic capacitors could not be solved in the available time.

4. LUMPED KICKER MAGNET

The case of a one section "delay line" KM, called lumped magnet, combines simplicity of construction with a good electromagnetic performance as long as reflections can be accepted, e.g. for a fast ejection system, which has to extract the whole particle beam at each acceleration cycle. Fig. 4 a shows a lumped KM module construction and Fig. 4 b gives the basic circuit. An advantage of the lumped KM is the fact that the capacitor C can be placed outside the vacuum tank, which is hardly possible for the real delay line KM. The whole magnet length is available for ferrite frames. No voltage appears on the magnet during the flat top of the current, since it is connected to earth potential.

The rise-time and ripple of the lumped KM-circuit can be varied, by changing the value of the capacitor C. In Fig. 5 the dependence of kick rise-time and overshoot on the ratio $RC/\tau_o = \beta$ is computed for the basic circuit (Fig. 4 b) without stray inductances. The ripple is considerably reduced, if β is chosen much less than one, say about 0.4. This means a reduction of capacity of $60^o/o$ compared with a multisection delay line magnet. In Fig. 5 also the kick amplitude and length excited by the fully reflected part of the voltage pulse are plotted as functions of β .

The reflections can be completely eliminated by a matching circuit (Fig. 4c) connected to the input of the lumped KM. But then the rise-time for the kick goes up by more than $50^o/o$.

Recently it was proposed8) to reduce the reflections by connecting a saturable inductance in series with the short-circuit clipping gap (Fig. 1a). This inductance should be saturated during the fall-time of the storage line and desaturated when the first reflection is returning from the KM. Practically, there is only a reduction of the peak amplitude of the reflection kick, but almost no decrease of the kick amplitude at the times where bunches are passing the KM. Furthermore such an inductance deteriorates the performance of the clipping gap.

Measurements and computations on a low voltage lumped KM agreed very well. Also a high voltage full aperture lumped KM prototype was successfully tested for two million pulses of 1 μs length at 80 kV charging voltage in a vacuum tank. During the test no breakdown occurred on the magnet.

5. THE TWO-SECTION (JANUS) KICKER MAGNET

The two extreme cases (i) the multisection delay line magnet offering a good electromagnetic performance but difficult construction problems and (ii) the lumped magnet with a simple construction, but giving rise to undesired reflections led to a compromise between the two types. As a solution a two section "delay line" magnet, called "Janus KM" (after the Roman god with the two faces), is proposed. The basic circuit is shown in Fig. 6a. Two configurations are considered. In the "single C" solution (Fig. 6b) the open C-shape magnet is divided by a metallic plate into two parts representing the two main inductances L_1 and L_2. The plate is connected with the capacitance C_1 and one of the end plates with C_2 and the endresistor RE. The capacitors may be placed outside the vacuum tank. In the "double C" construction shown in Fig. 6c each side of the double C-shape ferrite frame represents one of the main inductances. The beam at the centre may take advantage of the faster field rise-time in L_1, if $L_1 > L_2$. The end plate at the backside is connected with C_1 and one half of the front plate with C_2 and the endresistor RE, the other half being the input plate. Both solutions combine simplicity of construction with a considerable reduction of the voltage pulse reflection in comparison with the reflection of a lumped KM.

The rise-time of the "single C" Janus-KM, related to a certain ripple, is comparable with the rise-time for the delay line KM. Kick rise-time and ripple of the two section "single C" Janus magnet can be influenced by varying the values of C_1 and C_2. Fig. 7 a and b show the situation for two circuits with $L_1 = L_2$ and with $L_1 = 1.5\ L_2$ excited by a unit step input pulse. Length and amplitude of the kick from the voltage pulse reflection are mainly determined by $\beta_1 = R_0 C_1 / \tau_0$ (that is, by the capacitor C_1), which must have a value of about 0.5 in order to obtain a decently small reflection. If $L_1 = 1.5\ L_2$, the capacitor C_1 has only a negligible influence on the rise-time of the kick. A small increase of L_1 (starting from $L_1 = L_2$) improves the rise-time without changing the ripple, but lengthens the reflection.

The "double C" solution has the peculiarity that the field during the rise-time is varying in radial direction and a coupling exists between the two halves which is 2 to 3 times as strong as in the "single C" magnet.

Hence the situation is less clear. The magnetic field distribution in the aperture was determined with resistive paper models and introduced into the circuit equations for the Janus KM. So it was possible to obtain also an impression of the performance of the "double C" version. If L_1 is chosen slightly bigger than L_2 (e.g. $L_1 = 1.5\ L_2$), the rise-time on the center line in the "double C" case was found about 5-10°/o less than for the "single C" construction (related to a comparable value of kick ripple). However, the reflections of the "double C" magnet are longer and higher in amplitude. This behaviour is obvious since on account of the asymmetrical field distribution during current variation, the current J_1 through L_1 contributes with a higher weight factor than the current J_2 through L_2, and the oscillations of J_1 are more expressed than the oscillations of the sum $J_1 + J_2$. By arranging an even number of KM modules in opposite sense with an alternating sequence, the linear magnetic field gradients in each module can be compensated. The overall sextupole-effect in the beam region was found to be negligible (less than 2°/o of the nominal amplitude) at the moment when the kick in the centre is crossing the 100°/o level.

6. COMPARISON AND CHOICE BETWEEN DELAY LINE, LUMPED AND JANUS KM IN THE VIEW OF THE SERPUKHOV FAST EJECTION SYSTEM

Table 2 summarizes the main features, advantages and disadvantages of the different kicker magnet types. Comparing the unit step response of the idealized magnet configurations (Fig. 8) there is no clear preference to be given to any type with respect to rise-time. Only the lumped KM has a slightly better rise-time (~5°/o), however the length of the overshoot in time is greater for this type. The Janus KM has an overshoot length approximately equal to the rise-time. Then, if the kick is rising just between two subsequent bunches, the following bunch comes near to the next crossing of the 100°/o level. Thus deflection errors are minimized. Reflections can be neglected in the multisection delay line magnet, whilst in the lumped KM they are considerably big in amplitude as well as in length (length of reflection is about 50°/o longer than the rise-time). The reflections of the Janus KM are reduced so much that one may be able to place them just between two subsequent particle bunches by choosing correctly the transmission cable length between KM and pulse generator (see Fig. 1a).

Fig. 9 shows photographs of the typical kick response measured on low voltage KM models of the delay line, lumped and Janus type. The delay line KM has an almost linear rise-time followed by a short overshoot, whilst the lumped and the Janus KM are characterized by an exponential rise of the field.

The real delay line magnet though quite satisfactory with respect to electromagnetic performance, was abandoned for the Serpukhov ejection system, since constructional problems connected with the ceramic capacitors would have required advanced engineering developments. Though the lumped KM offers the advantage of a very simple construction and of having the magnet at earth potential, since the capacitors can be easily placed outside the vacuum tank, it was considered to be not acceptable on account of its long reflections which would have led to a remarkable loss in ejection efficiency. Both Janus KM versions combine the advantages of the lumped KM (simple construction, magnet at earth, voltage only during rise-time) with a considerable reduction of the reflections.

The "single C" two section magnet was envisaged as a final solution for the Serpukhov fast ejection system. A decision had to be taken at a time, when the behaviour of the "singla C" magnet was understood better. The tests on a low voltage model were advanced and in good agreement with the theoretical predictions. The "double C" solution theoretically seemed to be promising too, however, accurate measurements on a low voltage model seemed to be more difficult, since the transversal field distribution comes in as an important factor. The final optimization (by varying L_1, C_1 and C_2) of the KM would have been more complicated than for the "single C" magnet. In addition the "single C" version has the advantage that no voltage appears on its cold side plate. Therefore one can easily mount a pick-up coil for kick measurement.

For the "single C" type the best response is expected with $L_1 = 1.5\ L_2$. In this case the reflection length and the rise-time can be separately adjusted by the capacitances C_1 and C_2 and the stray inductance L_1 in series with C_1 plays a negligible role with respect to the kick rise-time (Fig. 7 b). In Fig. 10 the kick rise-time and overshoot measured on a low voltage "single C" Janus KM are plotted in dependence on the variables β_1 and β_2. The results agree rather well with the curves computed for the same magnet model taking now into account the measured or estimated stray inductances and the applied input voltage pulse rise-time. Comparing the curves in Fig. 10 a and 7 b one gets an idea of the deterioration of the x-factor by stray effects with respect to the response of an ideal magnet circuit.

The good agreement between all measurements and computations gave us confidence to design and manufacture a high voltage Janus KM module of the "single C" type (Fig. 11 a, b). The ceramic capacitors C_1, C_2 and the electrolytic terminating resistor RE are housed in an oil-filled box underneath the KM vacuum tank. In this configuration the stray inductances are slightly increased compared with the tested low voltage "single C" Janus KM model the rise-time and ripple of which are given in Fig. 10.

The prototype was already successfully pulsed 2 x 10^6 times with 5 µsec long pulses from a storage line with 5 Ω impedance charged to the design voltage of 80 kV. The kick response shown in Fig. 12 is not yet the optimum obtainable, since the rise- and fall-time of the voltage pulse can be still improved in the final system. Also the optimization of the response by varying C_1 and C_2 has not been carried out up to now. Nevertheless the kick rise-time is less than 160 µsec and the reflections are hoped to be placed between subsequent bunches.

7. CONCLUSIONS

The main criteria to be considered, if a certain type of KM has to be chosen for the application in a fast ejection system, are electromagnetic performance e.g. field rise-time, flat top and reflections, high voltage level and simplicity of construction. At higher impedance levels, say above 10 Ω, the multi-section delay line KM is superior. The lumped KM is preferable, when reflections can be neglected, for example, if only full beam extraction is foreseen. For the Serpukhov fast extraction system the best compromise seemed to be a two section delay line KM, which has a reasonable rise-time and a reflection short enough to be placed between two subsequent bunches.

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Table 1 APPROXIMATE PARAMETERS FOR THE SERPUKHOV FAST EJECTION KM

Parameter	symbol	unit	value
Magnetic length in ss 16	l	m	3
Gap width	w	m	0.14
Gap height	h	m	0.10
Radial beam jump at septum of septum magnet 24 for 75 GeV	ΔS	m	0.025
Angular deflection	$\Delta\alpha$	mrad	1.1
Total kick necessary for Δ S=0.025	K	Tm	0.28
Bunch distance	t_r	nsec	165
Total kick proposed for the estimation of the following parameters	K	Tm	0.36
Magnetic field	B	T	0.12
Intrinsic KM delay time	τ_o	nsec	120
Number of magnet modules	n	-	10
Degrading factor	x	-	1.4
Pulse voltage	V	kV	40
Charging voltage of pulse generator	V_L	kV	80
Pulse current	i	kA	9
Total stored energy	W	kJ	22
Characteristic impedance	Z	Ω	4.45
Inductance per module	L_K	μH	0.54
Capacitance per unit			
delay line KM	C_K	nF	27
lumped KM	C_K	nF	≈13
Janus KM	C_K	nF	≈20
Pulse duration	T_p	μsec	0.15-5.0

Table 2 : COMPARISON BETWEEN DELAY LINE, LUMPED AND JANUS KICKER MAGNET

	Delay line KM	Janus KM	Lumped KM
A. Pulse response of idealized magnets			
a) Unit step response :			
Rise-time τ_k (o/1oo) for 6 $^{o}/_{o}$ kick ripple	1.01 τ_o with N = 9 sections	1.02 τ_o with $L_1=1.5L_2$, $\beta_1=0.5$, $\beta_2=0.25$	0.97 τ_o with $\beta = 0.44$
b) Response for finite input pulse rise-time $\tau_i=0.25\,\tau_o$ for the same magnet parameters as above			
Rise-time τ_k (o/1oo)	1.17 τ_o	1.16 τ_o	1.11 τ_o
Kick ripple Δk ($^{o}/_{o}$)	4.6	5.7	6.0
c) Reflections			
Max. amplitude (in $^{o}/_{o}$) of flat top kick)	negligible	26 $^{o}/_{o}$ L_1, β_1, β_2 as above	40 $^{o}/_{o}$ β as above
Length of reflection	negligible	1.22 τ_o	1.55 τ_o
B. High voltage performance			
a) Max. voltage across magnet	Slightly more than pulse voltage	Line charging voltage during rise-time	Line charging voltage during rise-time
b) Voltage on the magnet during flat top	Pulse voltage	No voltage (magnet at earth potential)	No voltage (magnet at earth potential)
c) Construction	Complex. Capacitors inside vacuum tank, therefore space and connection problems. Double feedthrough.	Simple. Capacitors outside of vacuum tank. Complex double feedthrough necessary.	Very simple. Capacitors outside of vacuum tank. Single feedthrough.