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ABSTRACT

The specified performance of the full aperture kicker for the Serpukhov 70 GeV proton accelerator required substantial extrapolations of existing techniques, hence a new assessment of the relative merits of a number of contructtional types. The dependence of pulse response, i.e. rise-time, flat top and reflections on various constructional parameters has been studied theoretically and verified on high and low voltage models. The two-section magnet adopted is a hybrid, combining some constructional advantages of the lumped inductance magnet with reflections that are adequately reduced to be compatible with multiple partial ejection. Construction and performance of the successfully operated full voltage prototype are described.

1. INTRODUCTION

Fast pulsed deflection magnets, called "kicker magnets" (KM) are the heart of modern ejection and inflection systems in high-energy particle accelerators. Particular features of these magnets are a homogeneous magnetic field with a fast rise- and fall-time and a flat top with small ripple. For this purpose the KM is usually incorporated in a line type pulse generator circuit[1,2] for example as shown in Fig. 1a. The pulse shape gives a constant particle deflection during one or part of a revolution of the particles in the accelerator and may permit us to synchronize the rise and fall of the field between the passage of two particle bunches of the RF structured beam. This strongly reduces beam losses, which become a problem due to the radioactivity that lost particles induce in the accelerator hardware. The foregoing requirements and the growing need for highly flexible and efficient beam sharing techniques, such as multiple shot and multiple channel operation of modern fast ejection equipment[3,4], have steadily increased the requirements for the pulse response (i.e. rise-time, fall-time, flat top). Accordingly, the kicker magnet for the fast ejection system of the Serpukhov 70 GeV proton accelerator is meant to have all the features given in the papers by Bossart et al.[3,4]. A general description of the system is given in the paper by Kuiper et al.[5]. Due to higher proton energy, full aperture and restricted space, the paremeters of this magnet are beyond the range of presently available experience and required some extrapolations of the existing techniques, hence re-assessment of the merits of various possible circuits and magnet constructions.

The main problem is typical for all pulsed magnets. The power, required to fill a given aperture volume within a given time with a certain magnetic energy, may be supplied on a high voltage level or on a high current level (meaning low impedances) or both. These two are conflicting, but to a certain extent interchangeable so that the difficulty may be shifted in one direction or in the other. Designing a kicker magnet then means striking a compromise between what we may call "high voltage performance" and "pulse performance", within a framework of other constraints such as (i) space limitations, material and components choice, compatible with (ii) vacuum technology, (iii) resistance to ionizing radiation, (iv) commercial availability, (v) engineering complications and reliability, and (vi) accessibility for maintenance and quick replacement of components. This paper will mainly treat problems of pulse performance. Since the problems of high voltage and those of points (i) to (vi) above are different from case to case and may be open to interpretation, they cannot be discussed in a balanced way within the scope of this paper and are, therefore, only mentioned in context with other considerations. This should not mislead one to think that these factors are of second order. In certain cases they may even become dominant. In the choice of the Serpukhov kicker magnet they carried about half the weight.

One way of relaxing the requirements for a KM is to reduce the stored energy by reducing the field volume. Instead of the most obvious solution of a KM, where the "full aperture" coincides with the accelerator aperture[6], one may go to a KM whose "small aperture"[9] is just enough to engage the circulating particle beam, which only fills the accelerator aperture at injection but contracts to a fraction of that size at times relevant for ejection. The beam may then either be brought into the aperture of the stationary KM outside the accelerator aperture by a local adiabatic closed orbit deformation, or the whole KM may be moved towards the central beam by a mechanical device. Hybrid constructions, called "flap magnet" and "moving pole magnet" [7] have also been proposed. Their stored energy is comparable with a small aperture and only parts of the magnet are moving. In addition to the specified performance, points (i) to (vi) heavily influence a choice between these types. For Serpukhov it proved possible to make a full aperture magnet. We shall now further discuss the choice between different possible executions of this type.

2. SOME PROPERTIES AND PARAMETERS

The specified angular deflection and the particle energy require a certain field integral ("kick") $K = \int B \, d\ell$ along the particle orbit in the KM. If a high permeability magnetic circuit (ferrite) is used, the inductance of the single excitation loop KM is given by its aperture height h, width w and total length ℓ, which are generally defined by the beam diameter and the available length between the accelerator main magnet units. Voltage reduction may be obtained by dividing the whole KM into n separate modules. The gap inductance L_K of one module is then

$$L_K \simeq \mu_0 \frac{w\ell}{nh} \tag{1}$$

and the current J for the desired kick strength K

$$J = \frac{Kh}{\ell\mu_0} . \tag{2}$$

We may now define a time constant

$$\tau_0 = L_K/R_0 , \tag{3}$$

given by the gap inductance and the characteristic impedance R_0 of the delay line circuit. The total rise-time t_r of the kick

$$t_r = x\tau_0 \tag{4}$$

is always greater than τ_0 by a degrading factor $x > 1$, which accounts globally for all such non-ideal effects as non-zero rise-time of the excitation pulse, parasitic inductances and imperfect matching of the circuit. The pulse voltage $V = JR_0$, to produce the current J on the impedance R_0 may be expressed as

$$V = \frac{xKw}{t_r n} . \tag{5}$$

Equations (1) to (5) are only rough approximations, because losses in the ferrite ($\mu_0 \neq \infty$) and leakage fluxes at the ends are neglected.

Equation (5) gives the pulse voltage V in terms of primary quantities, i.e. the kick K (from angular deflection and particle energy), aperture width w (from beam size) and rise-time t_r, the latter being frequently defined by the requirement that the kick rises between the passage of two particle bunches.

In order to obtain acceptable voltage levels one may then choose n and hence the circuit impednace R_0. However, when going to lower 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 have more influence for smaller impedance and, therefore, the factor x is generally increasing with decreasing R_0. Therefore, when dividing the KM into more modules one gains less than in proportion to n, since the increase of x has to be compensated again by more voltage. For a given total magnet length ℓ one also loses effective bending length due to more connections. This again requires some more voltage to keep the kick constant. If, on the other hand, the KM is operated at higher voltage levels, one has to keep greater distances in the magnet construction leading also to higher stray inductances.

For a KM pulsed in a delay line circuit such as Fig. 1a, one will generally observe a time variation of the magnetic kick as in Fig. 1b. For partial extraction, a clipping gap is used (Fig. 1a), which cuts the tail of the voltage pulse in order to obtain a shorter fall time. Reflections from the KM hitting the clipping gap in a short-circuited condition will return to the KM and may partly deflect one or more bunches of the remaining beam. By a proper choice of transmission cable length between pulse generator and KM the reflection may sometimes be placed between two subsequent bunches.

From these considerations it follows that one cannot *a priori* calculate a set of final parameters. Rather, one will make an intelligent guess at the degrading factor x and calculate by Eqs. (1) to (5) a preliminary set of parameters that look realizable. It is then inevitably necessary to make full-scale models with dimensions as dictated by the adopted voltage levels and mechancial engineering. These permit, on the one hand to check the assumed values of x and on the other hand to estimate or measure stray inductances, and from these to predict x-values for other related configurations. For the Serpukhov full aperture KM a degrading factor $x \simeq 1.4$ was assumed. Computer and low and high voltage model studies were then carried out to find the most appropriate type of magnet and to define the minimum requirements of the whole delay line circuit. One part of the computations dealt with idealized magnet circuits, in order to explore and compare the general behaviour of the different types and to study the influence of a number of parameters separately. Another part dealt with real conditions and magnet parameters as measured or estimated from the models. Computations and measurements confirmed for the investigated types that x-values are around 1.4 to 1.5 for impedance levels around 5 Ω. The main parameters thus obtained for the Serpukhov KM are given in Table 1.

3. THE "DELAY LINE" KM

One way to build fast KM's is to simulate an artificial delay line consisting of several L-C sections. The inductances L, represented by ferrite loaded line sections, deliver the deflecting field and determine impedance and rise-time of the magnet together with the capacitors C. At higher impedance levels it is also possible to build delay line KM's with distributed parameters[8].

The approximate equivalent electrical circuit of a lumped parameter delay line magnet is given in 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 on small mismatches. By calculating the influence of the most important parameters on the KM behaviour, a prediction may be made of the degrading factor x for certain magnet configurations, provided stray inductances can be properly estimated or measured on magnet models. Figure 3 shows the computed rise-time and ripple as a function of the number N of L-C sections. Whilst even for small numbers of sections the kick rise-time is practically equal to the delay time of an ideal homogenous delay line, the ripple ΔK increases considerably with decreasing N. On the other hand, the response of a magnet with few sections may be improved by the proper choice of the capacitances of each section. A disadvantage at small N is the substantial reflection of rise and fall of an 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 meets a space problem for the capacitors. At high enough impedance the capacitors may be formed by metal plates and vacuum dielectric[9]. At low impedance levels, however, the transversal plate dimensions become larger, which leads to higher stray inductances and delay line effects within the capacitors. The space for capacitors is longitudinally restricted by the voltage gradient to avoid flash-over. Ceramic capacitors may be used instead but they must have a special configuration to avoid surface flash-over.

A full-size delay line KM model with 11 sections and 5 Ω impedance was built (Fig. 2b) with ceramic capacitors and has been studied 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 subjected to high voltage tests, since it was estimated that the problems of surface flash-over on the ceramic capacitors could then not be solved in the available time.

4. THE "LUMPED INDUCTANCE" KM

A one section KM, called lumped inductance magnet has a simple construction with a good pulse response, but it gives a strong and long reflection. This may be acceptable for total beam extraction. Figure 4a shows a possible construction and Fig. 4b gives a basic circuit. An advantage of this version is the fact that the capacitors C can be placed outside the vacuum tank, which is hardly possible for the many capacitors of a delay line KM. The whole module length is available for ferrite frames. No voltage appears on the magnet during the flat top of the current since one terminal may be earthed.

The rise-time and ripple of the lumped inductance KM can be varied with the capacitance C. In Fig. 5 the dependence of kick rise-time and overshoot on the ratio $RC/\tau_0 = \beta$ is computed for the basic circuit (Fig. 4b) without stray inductances. The ripple is considerably reduced, if β is chosen to be about 0.4. This means a capacity reduction of 60% with respect to a delay line magnet. In Fig. 5, amplitude and duration of the kick excited by the fully reflected part of the voltage pulse are also plotted as a function of β.

The reflection can be completely eliminated by a matching circuit connected to the input of the lumped inductance KM (Fig. 4c), but this increases the rise-time by more than 50%.

It was recently proposed[10] to reduce the reflections by connecting a saturable inductance in series with the clipping gap (Fig. 1). 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 when bunches are passing the KM. Also, the scheme breaks down when the reflection coincides with the fall-time of the pulse and the presence of an inductance deteriorates the normal performance of the clipping gap.

Measurements on a low voltage model agreed with computations. A high voltage prototype of a full aperture lumped inductance KM has successfully been tested in a vacuum tank by two million pulses of 1 µsec length at 80 kV line charging voltage.

5. THE "JANUS" KM

A two-section magnet, called "Janus" KM after the Roman god with two faces, is a compromise, combining some constructional and high voltage advantages of the lumped inductance magnet with reflections that, in height and duration, are sufficiently reduced to be compatible with multiple partial ejection. The basic circuit is shown in Fig. 6a.

Two configurations are considered. In the "single C" version (Fig. 6b) the C-shaped ferrite yoke is divided by a metallic plate into two parts, each length representing one of 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 the capacitance C_2 and the terminating resistor RE. The other end plate and the side plate closing the aperture are earthed. The capacitors may be placed outside the vacuum tank. In the "double C" version (Fig. 6c) each side of the two C-shaped ferrite frames 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 back side is connected with C_1 and one half of the front plate with C_2 and RE, the other half being earthed. For a given ripple the rise-time of the "single C" Janus KM is comparable with the rise-time for the delay line magnet. Kick rise-time and ripple of the "single C" Janus KM can be influenced by C_1 and C_2. Figures 7a and 7b show the pulse response for two circuits with $L_1 = L_2$ and $L_1 = 1.5\ L_2$ excited by a unit step input pulse. Duration and amplitude of the kick from the voltage pulse reflection are mainly determined by $\beta_1 = R_0C_1/\tau_0$ (i.e. by C_1), which must have a value of about 0.5 for a decently small deflection. 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.

In the "double C" version the field varies radially during the rise-time and the coupling between the two halves is two to three times as strong as in the "single C" magnet. The contribution of each side to the magnetic field distribution was determined with resistive paper models and used to weight the currents as derived from the circuit equations for the Janus KM.

If L_1 is around 1.5 L_2 the rise-time on the centre line, for a given kick ripple, is 5-10% less than for the "single C" construction. However, the reflections of the "double C" magnet are longer and higher in amplitude. This behaviour is explained by the asymmetrical field distribution during current variations, since the current J_1 through L_1 contributes with a higher weight and the oscillations for J_1 are stronger than the oscillations of the sum

$J_1 + J_2$, which gives the kick in the "single C" magnet. By arranging an even number of KM modules alternating in opposite sense the field gradients may be cancelled and the over-all sextupole effect in the central region may be less than 2% of the nominal amplitude at the moment when the kick there is crossing the 100% level.

6. COMPARISON AND CHOICE

Table 2 summarizes the main features, advantages and disadvantages of the three KM types. Comparing the unit step response Figs. 8a, b, c) of the idealized magnets there is no clear preference to be given to any type from the point of view of rise-time. Small theoretical differences will then be negligible compared to results from constructional differences. The lumped inductance KM has a 5% better rise-time but the duration of the overshoot is greater for this type. The Janus KM has an overshoot duration approximately equal to the rise-time. This permits placing the second extracted bunch close to the second crossing of the 100% level, thus minimizing deflection errors. Reflections may be neglected in the delay line magnet, whilst in the lumped inductance KM they are substantial in amplitude and their duration is about 50% longer than the rise-time. The reflections of the Janus KM are reduced in amplitude and duration, so that they may be placed between two subsequent particle bunches by appropriate choice of the length of the transmission cables between pulse generator and KM (Fig. 1a). This would leave the non-ejected particles in the accelerator virtually untouched. Figure 9 shows typical oscillograms of the kick response measured on low voltage KM models of the delay line, lumped inductance 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 a more exponential rise of the field with a longer overshoot. One clearly identifies the second crossing of the 100% level for the Janus KM, which is absent in the lumped inductance KM.

The delay line magnet, though satisfactory in pulse response, was abandoned for the Serpukhov ejection system since voltage flash-over problems of the ceramic capacitors were then estimated to take more than the available time. The lumped inductance KM has the advantage of a simple construction with a magnet at earth potential and allows the capacitors to be placed outside the vacuum tank. It was, however, discarded for its long reflection, causing beam losses that are undesirable in a system that emphasizes efficient multiple shot and multiple channel operation. Both Janus KM versions combine the advantages of the lumped inductance KM (simple construction, magnet at earth - hence voltage only during rise-time) with a considerable reduction of the reflections.

The "single C" Janus KM has been chosen for the Serpukhov fast ejection system. A decision had to be taken at a time when the behaviour of the "single C" magnet was better understood. Low voltage model studies were in an advanced stage and in good agreement with theoretical predictions. Also the "double C" version is in principle promising, but accurate low voltage model measurements and optimization by varying L_1, C_1 and C_2 are more tedious and difficult to interpret due to transversal field variations. No voltage appears on the cold side plate of the "single C" version, thus facilitating the installation of pulse-viewing pick-up loops.

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 C_1 and C_2 and the stray inductance ℓ_1 in series with C_1 has a negligible influence on the kick rise-time (Fig. 7b). 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 satisfactorily with the curves computed for the same magnet model, taking account of the measured or estimated stray inductances and the voltage pulse rise-time. Comparing the curves in Fig. 10a and 7b one gets an idea of the deterioration of the x-factor by "parasitic" effects with respect to the response of an ideal magnet circuit.

The agreement of measurements and computations gave us confidence to design and manufacture a high voltage prototype of a Janus KM module of the "single C" type (Figs. 11a and 11b). The ceramic capacitors C_1, C_2 and the electrolytic terminating resistor RE are housed in an oil-filled box under the KM vacuum tank. In this configuration the stray inductances are slightly increased compared with those of the low voltage "single C" Janus KM module, the performance of which is given in Fig. 10. The prototype has been successfully operated for more than 2×10^6 pulses of 5 μsec duration from a delay line pulse generator of 5 Ω impedance charged to the design voltage of 80 kV. The kick response shown in Fig. 12 is not yet the optimum since the rise- and fall-time of the voltage pulse may be improved and no optimization of the response by varying C_1 and C_2 has yet been carried out. Nevertheless, the kick rise-time is less than 160 μsec and the reflections may be placed between subsequent bunches.

7. CONCLUSIONS

The criteria to be considered when a KM has to be chosen for a fast ejection system are on the one hand the pulse response, i.e. field rise-time, flat top variations and reflections, and on the other hand high voltage performance. All these must be viewed in the frame-work of a number of other constraints labelled (i) to (vi) in Section 1. These constraints carry substantial weight in the decision and may occasionally be decisive. *A priori* calculations of parameters appear grossly insufficient, since one of the main parameters, the field rise-time, may come out substantially larger than the ideal one by a degrading factor x, which can only be assessed by full-scale model-work. It is impossible to give decisive preference to one of the investigated magnet constructions since the choice is too dependent on the specific accelerator parameters, the application envisaged and on the other prevailing constraints. Some over-all tendencies may, however, be discerned. The delay line KM still shows the best pulse response, but becomes difficult to make for the lowest impedances. The lumped inductance KM is still the simplest configuration, hence the most promising for the lowest impedances, if the reflections may be accepted. The Janus KM may be a convenient solution for a low impedance magnet, where the application for partial ejection imposes restrictions on the reflections. A Janus "single C" configuration has been adopted for the Serpukhov Fast Ejection System.

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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 magnet 24	Δr	m	0.025
Angular deflection	$\Delta\alpha$	mrad	1.1
Total kick necessary for Δr = 0.025 m at 75 GeV	K	Tm	0.28
Kick rise-time (Bunch distance = 165 nsec)	t_r	nsec	165
Total kick proposed for the estimation of the following parameters	K	Tm	0.30
Magnetic field	B	T	0.10
KM time constant	τ_0	nsec	118
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	J	kA	8
Total stored energy	W	kJ	19
Characteristic impedance	Z	Ω	5
Inductance per module	L_K	μH	0.53
Capacitance per unit			
delay line KM	C_K	nF	24
lumped KM	C_K	nF	≈ 10
Janus KM	C_K	nF	≈ 18
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
Pulse response of idealized magnets			
a) Unit step response:			
Rise-time $\tau_k^{(0/100)}$ for 6% kick ripple	$1.01\ \tau_0$ with N = 9 sections.	$1.02\ \tau_0$ with $L_1 = 1.5L_2$, $\beta_1 = 0.5$, $\beta_2 = 0.25$.	$0.97\ \tau_0$ with $\beta = 0.44$
b) Response for non-zero input pulse rise-time $\tau_i = 0.25\ \tau_0$ and for the same magnet parameters as above:			
Rise-time $\tau_k^{(0/100)}$	$1.17\ \tau_0$	$1.16\ \tau_0$	$1.11\ \tau_0$
Kick ripple ΔK (%)	4.6	5.7	6.0
c) Reflections:			
Max. amplitude (in %) of flat top kick	Negligible.	26% L_1, β_1, β_2 as above.	40% β as above.
Duration of reflection	Negligible.	$1.22\ \tau_0$	$1.55\ \tau_0$
High voltage performance			
a) Max. voltage across magnet due to unit step pulse.	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 vacuum tank. Double feed-through.	Very simple. Capacitors outside vacuum tank. Single feedthrough.

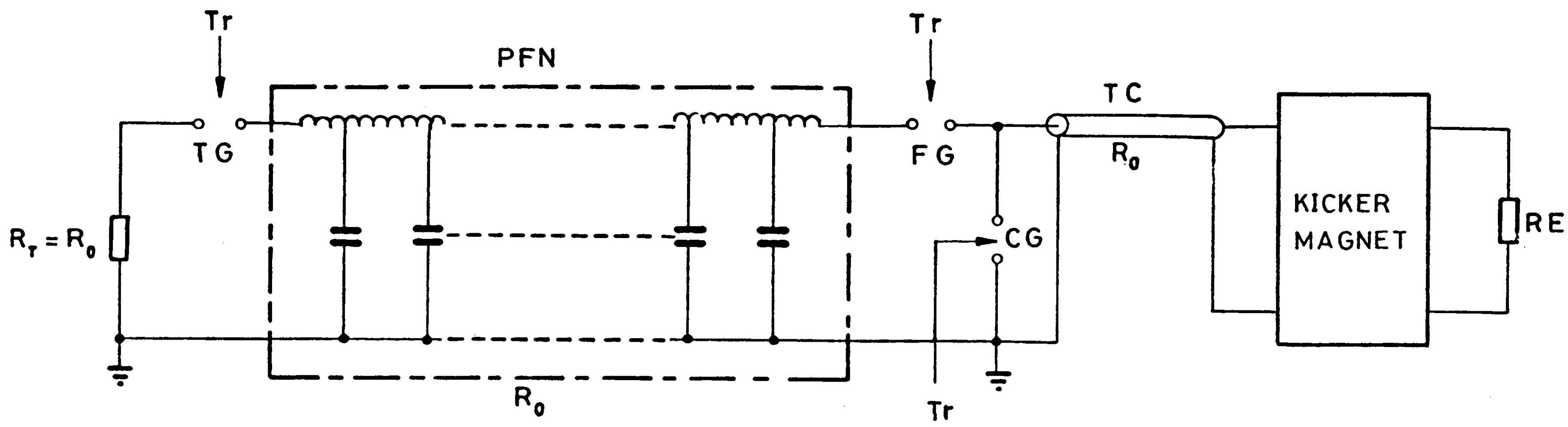


Fig. 1a

Delay line circuit for pulsing a fast ejection KM. PFN = pulse forming network with impedance R_0, FG = front spark gap switch, TG = tail spark gap switch, CG = clipping spark gap, Tr = triggers, R_T = tail resistor, RE = terminating resistor, TC = transmission cables with impedance R_0.

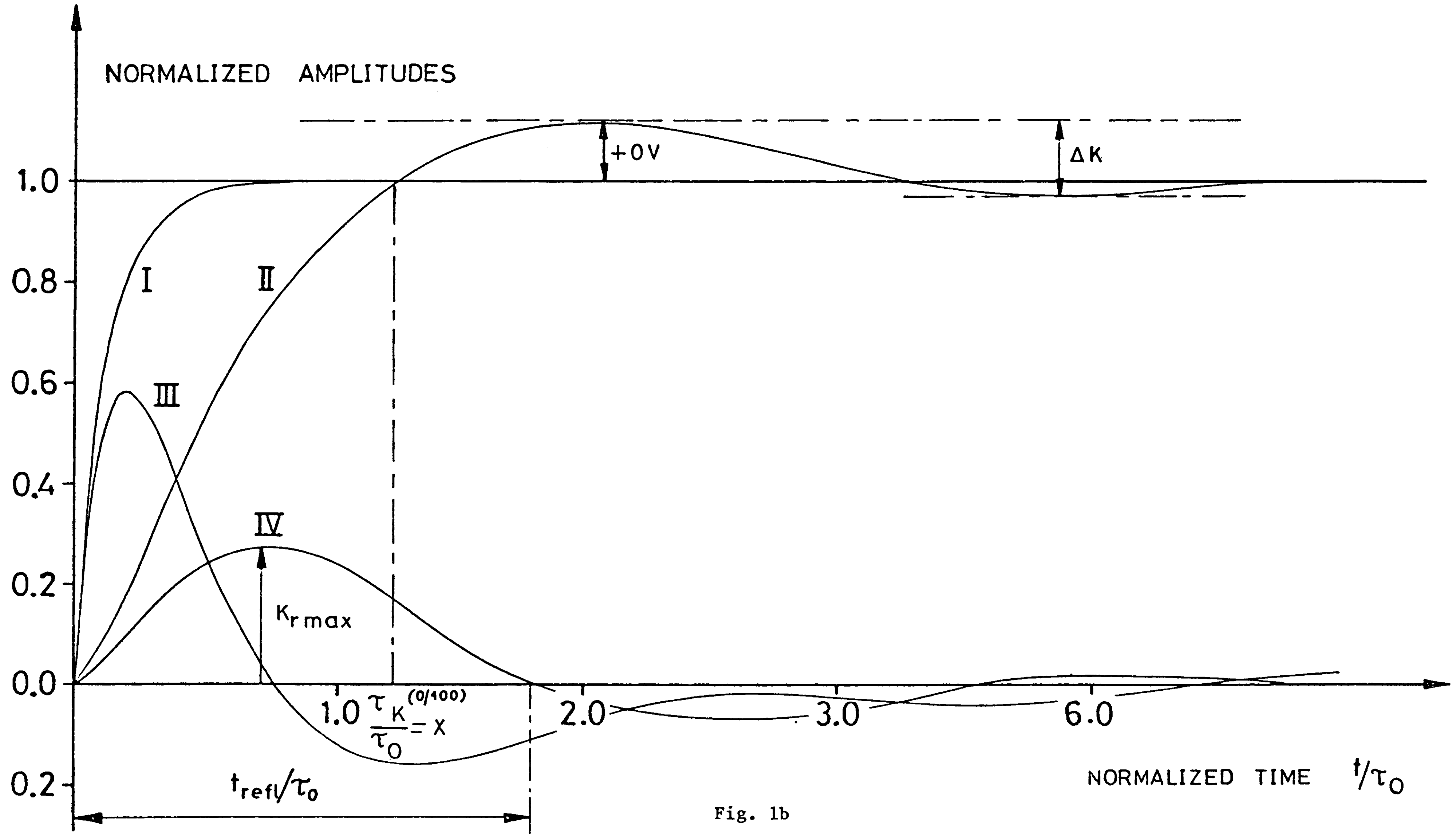


Fig. 1b

Typical response of a KM: I = Incident voltage pulse, II = Kick, +ov = positive overshoot of kick, Δk = kick ripple, III = Voltage pulse reflection, IV = Kick excited by reflected voltage pulse, K_{rmax} = max. amplitude, t_{refl} = length of reflection. $\tau_0 = L_k/R_0$. The rise-time t_r is defined as $\tau_K^{(0/100)}$ from 0 to 100% of the flat top value.

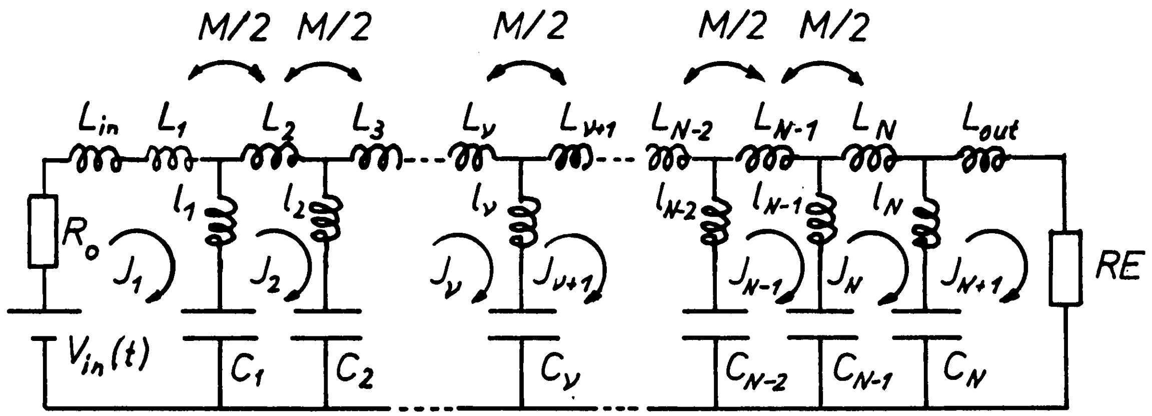


Fig. 2a

Equivalent circuit for an N-section delay line KM

L_ν = main gap inductances producing the kick together with M
M/2 = coupling coefficients
l_ν = transversal stray inductances
L_{in} = additional input inductance
L_{out} = additional output inductance
C_ν = cell capacitors
R_0 = impedance of pulse generator
RE = end resistor
N = number of L-C sections
J_ν = mesh currents
V_{in} = source voltage = 2 × arriving pulse voltage

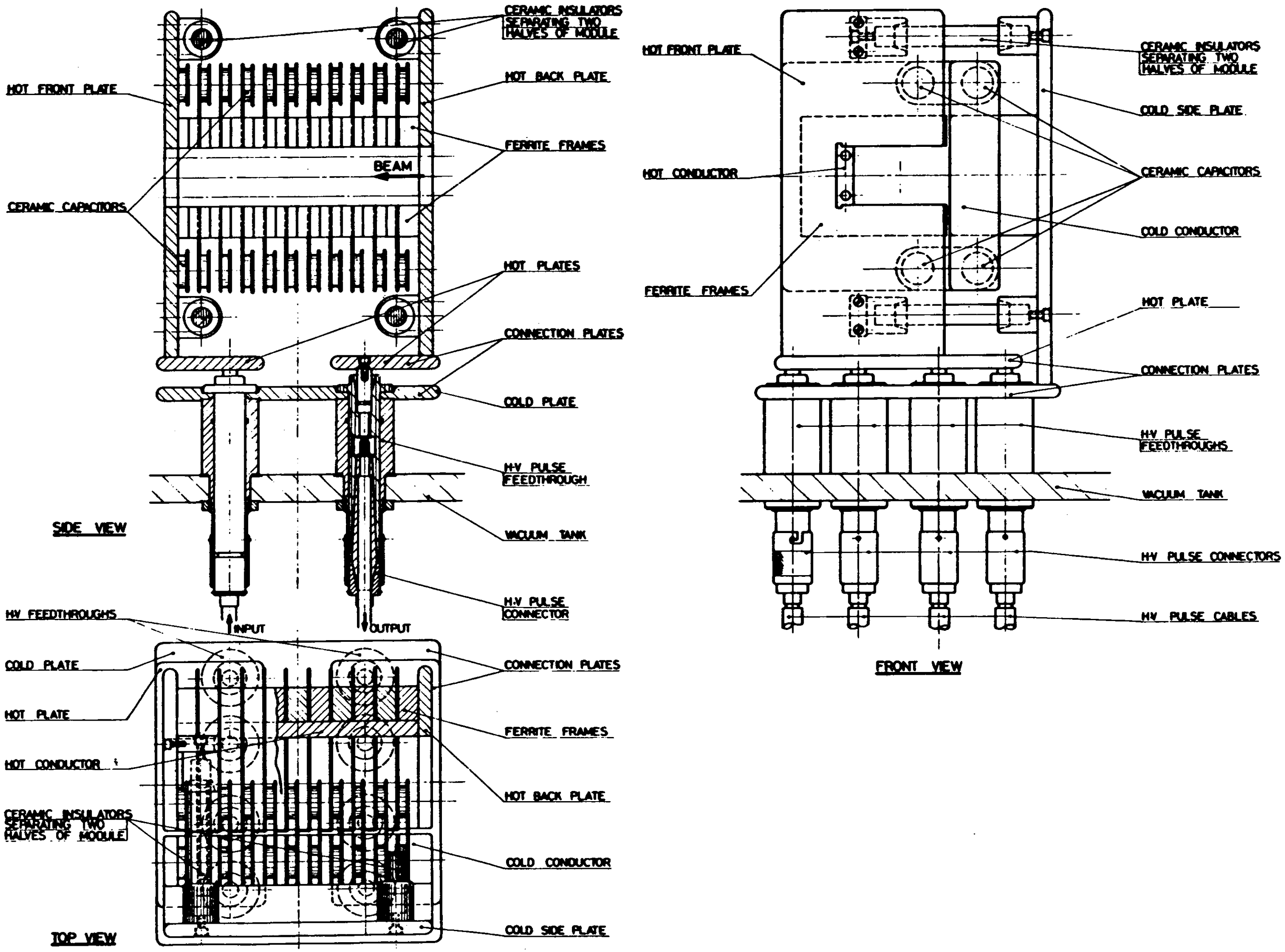


Fig. 2b

Construction of a delay line KM

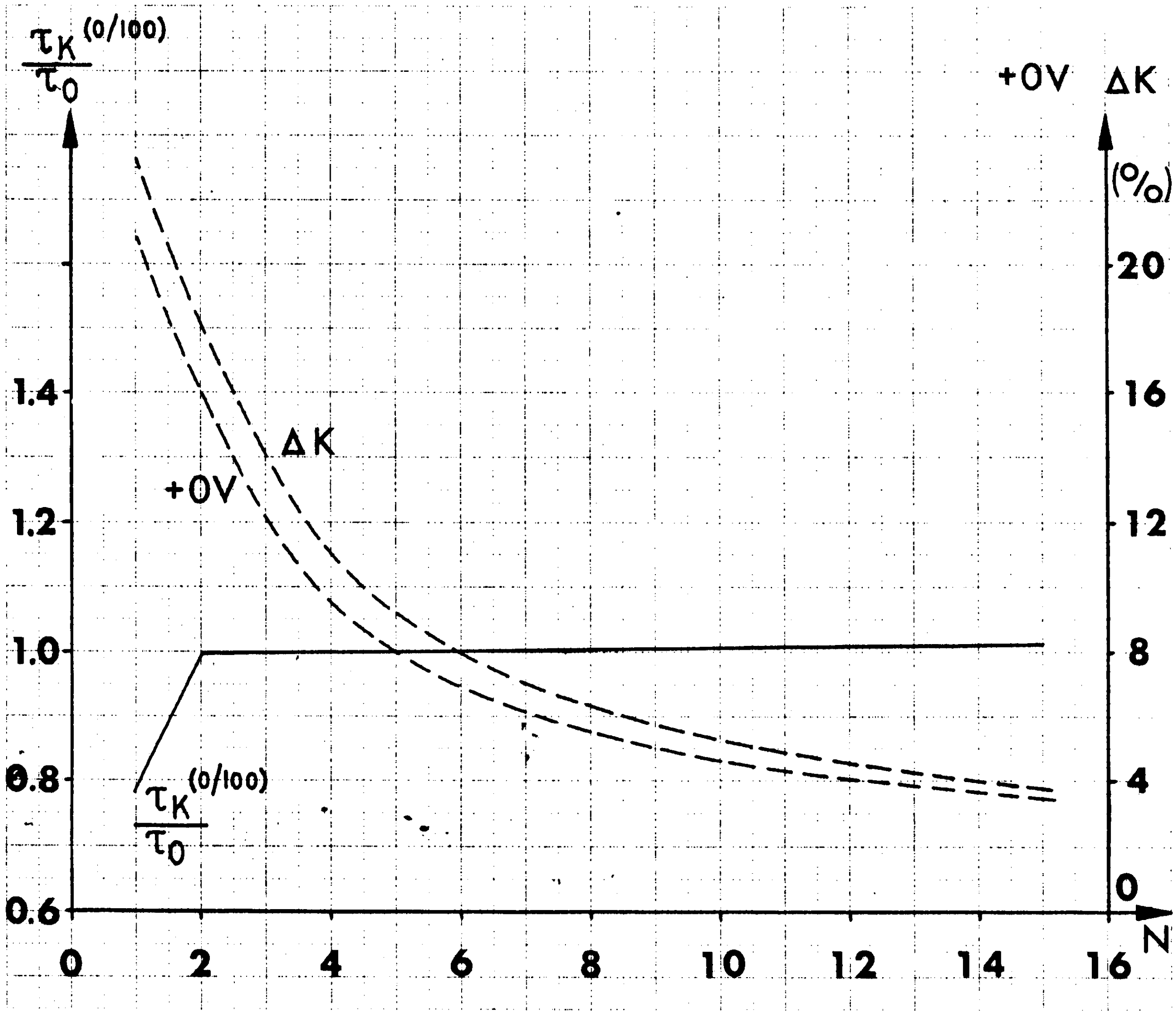


Fig. 3

Kick rise-time $\tau_K^{(0/100)}$ from 0 to 100% of the flat top value, kick ripple ΔK and overshoot +ov versus number of sections N of an ideal delay line KM circuit excited by a unit step voltage pulse. The stray inductances are equal to 0 ($\ell_\nu = L_{in} = L_{out} = 0$). $\tau_K^{(0/100)}$ is normalized to $\tau_0 = L_K/R_0$, the time constant of the KM. The end resistor RE is matched with the impedances of pulse generator R_0 and magnet $Z = \sqrt{L_\nu C_\nu}$.

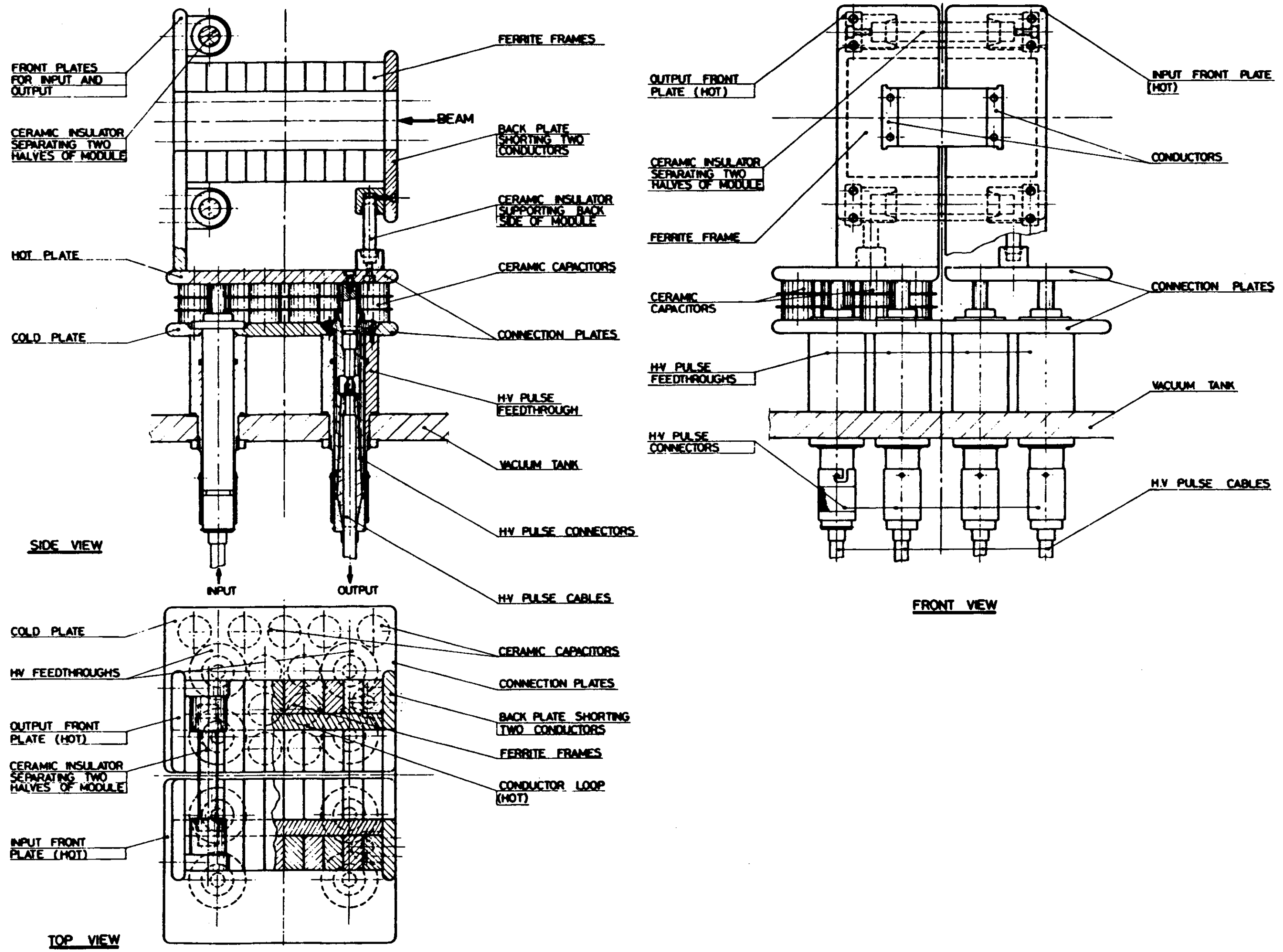


Fig. 4a

Construction of a lumped KM

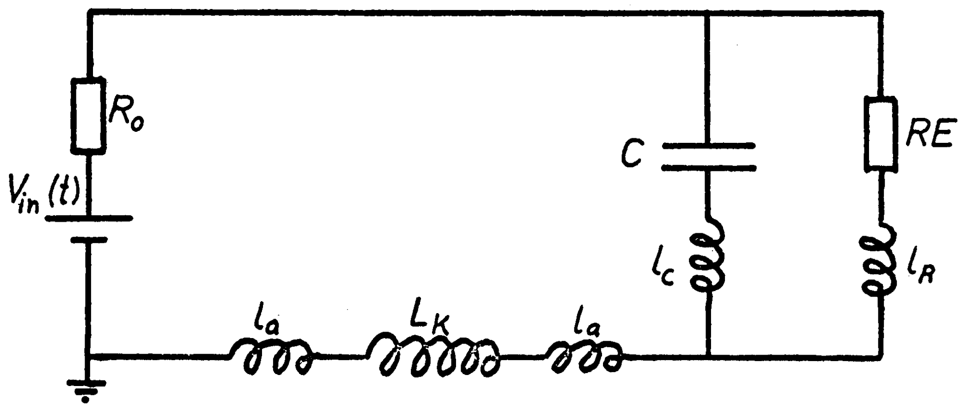


Fig. 4b

Equivalent circuit of a lumped KM

L_K	= main gap inductance
ℓ_a, ℓ_c, ℓ_R	= stray inductances
C	= capacitor
R_0	= impedance of pulse generator and cables
RE	= terminating resistor

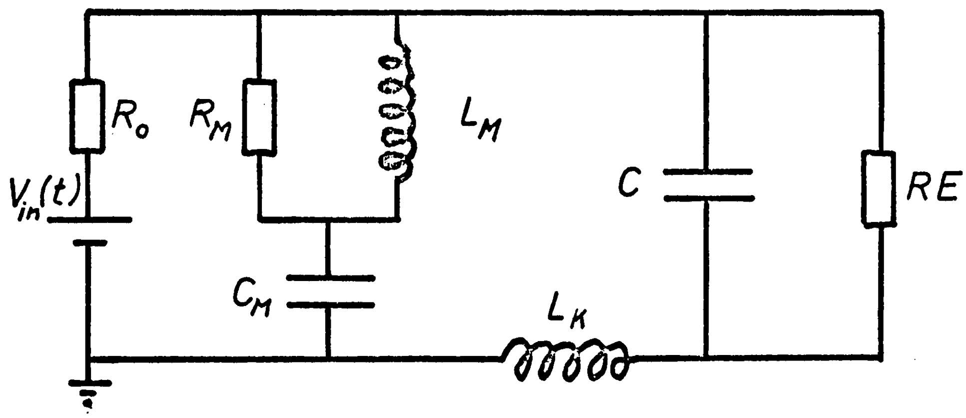


Fig. 4c

Simplified equivalent circuit of a matched lumped KM.
Matching conditions : $L_M = L_K$;
$R_M = R_0 = RE$; $C_M = C = \frac{1}{2} L_K/R_0$

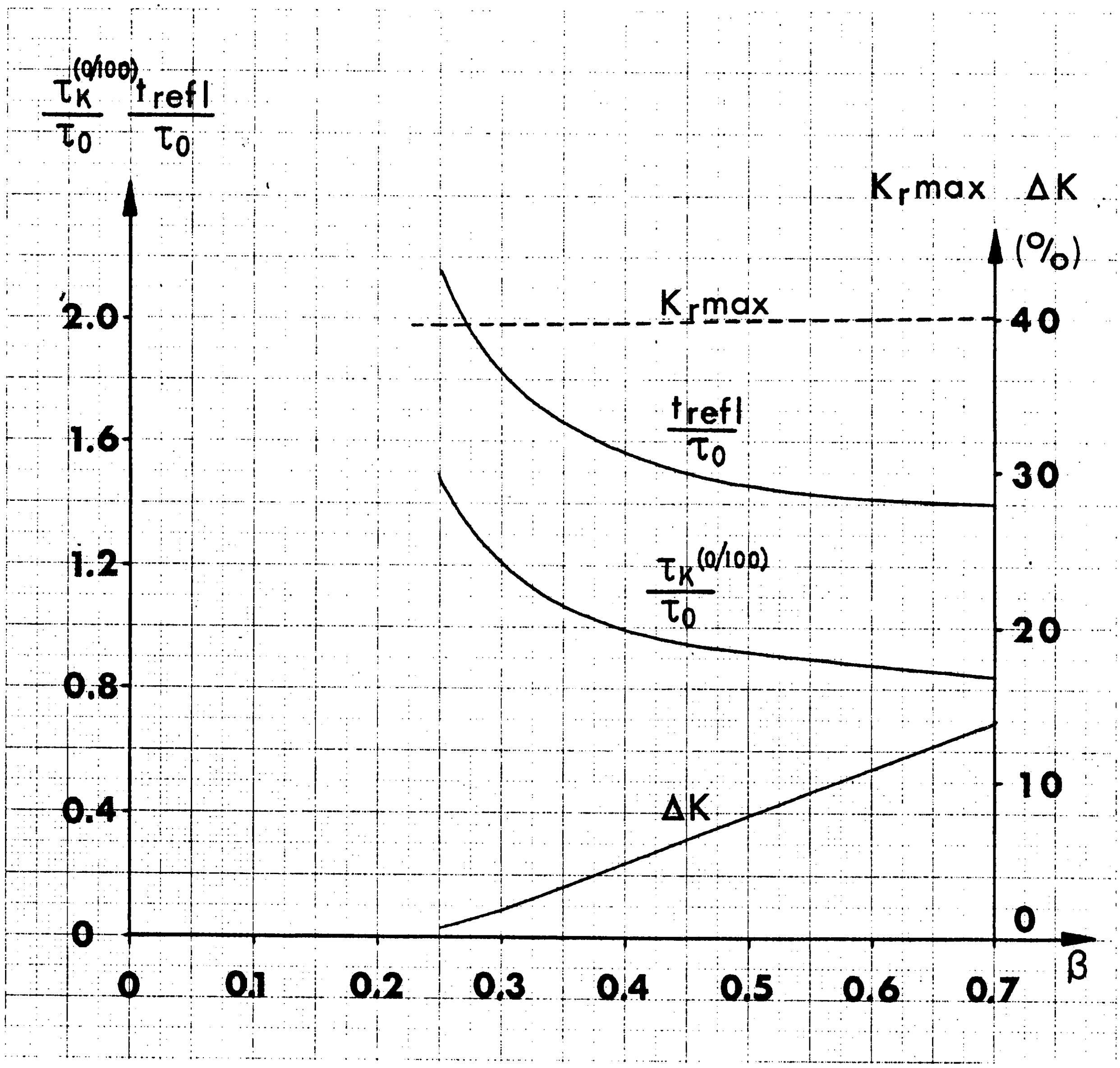


Fig. 5

Kick rise-time $\tau_K^{(0/100)}$, kick ripple ΔK, maximum reflected kick amplitude K_{rmax}, and length t_{refl} of reflected kick as functions of $\beta = R_0^2C/L_K$, valid for an idealized lumped KM without stray inductances excited by a unit step input pulse. $\tau_K^{(0/100)}$ and t_{refl} are normalized with respect to $\tau_0 = L_K/R_0$.

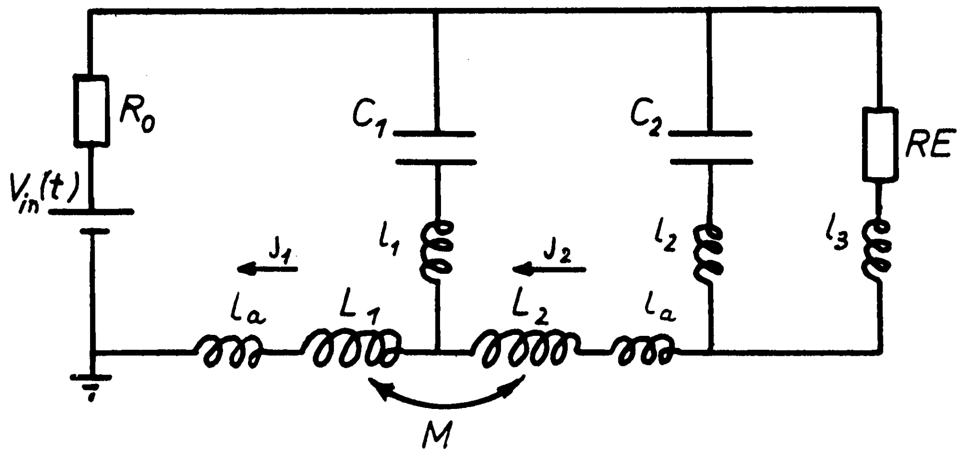


Fig. 6a

Equivalent circuit for the two-section KM (Janus KM).

L_1, L_2 = main gap inductances giving the kick
$L_1 + L_2$ = total KM gap inductance L_K
ℓ_a = additional input and output inductances
$\ell_{1,2,3}$ = transversal stray inductances
M = coupling inductance
$C_{1,2}$ = cell capacitors
R_0 = impedance of pulse generator
τ_0 = L_K/R_0 = time constant of the KM
RE = end resistor
$J_{1,2}$ = currents through L_1, L_2.

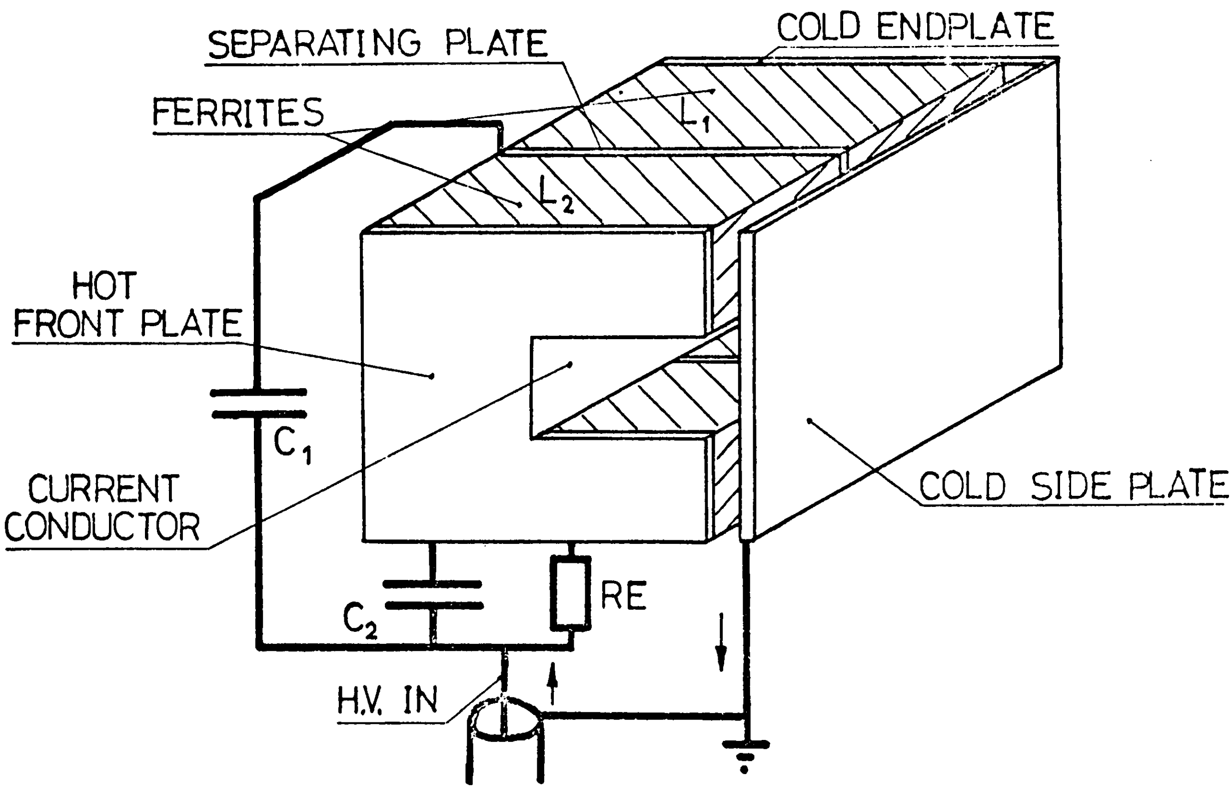


Fig. 6b Configuration of the "single C" Janus KM version

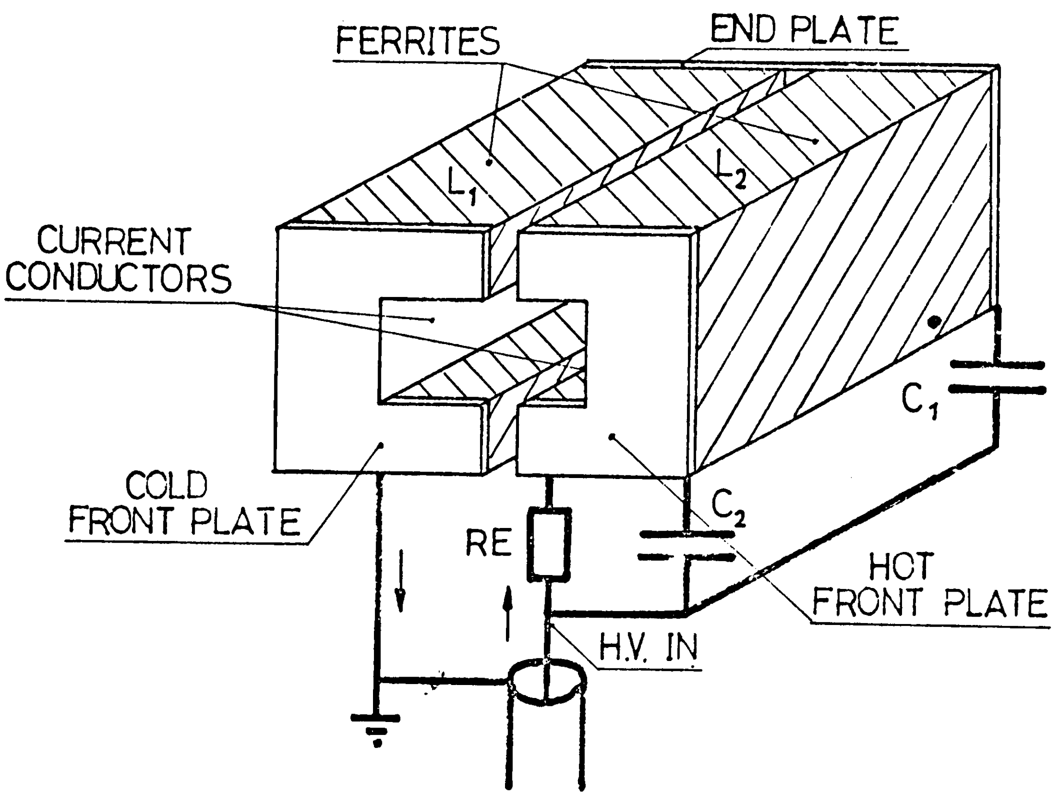


Fig. 6c Configuration of the "double C" Janus KM version

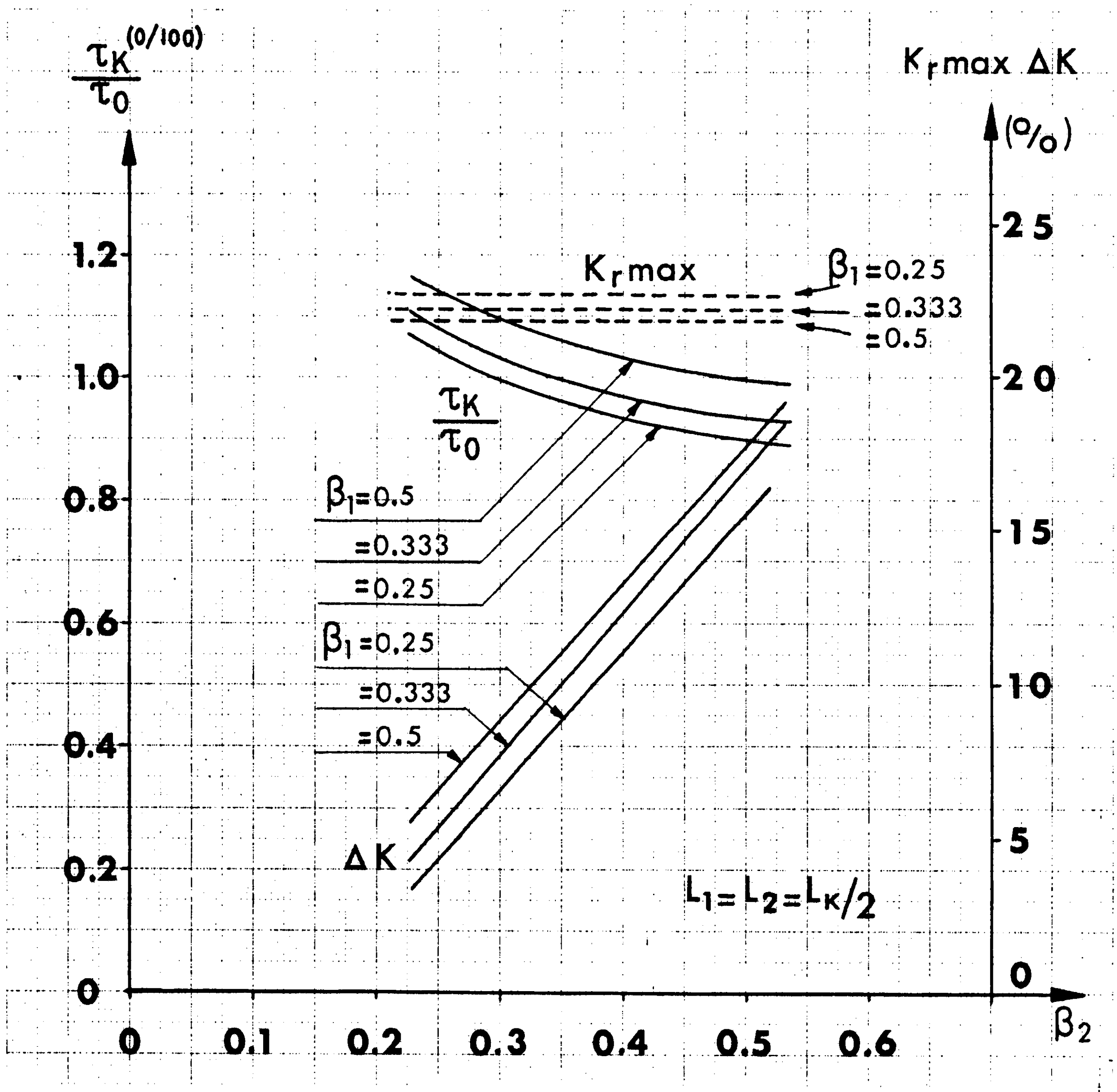


Fig. 7a

Rise-time $\tau_K^{(0/100)}$, kick ripple ΔK and maximum kick amplitude K_{rmax} of the reflected pulse for a Janus KM with $L_1 = L_2$ as function of $\beta_2 = R_0^2 C_2/L_K$ with $\beta_1 = R_0^2 C_1/L_K$ as parameter. The idealized circuit (without stray inductance) is excited by a unit step input pulse. $RE = R_0$. The essential part of the reflection in this case is much shorter than the value t_{refl} defined in Fig. 1b.

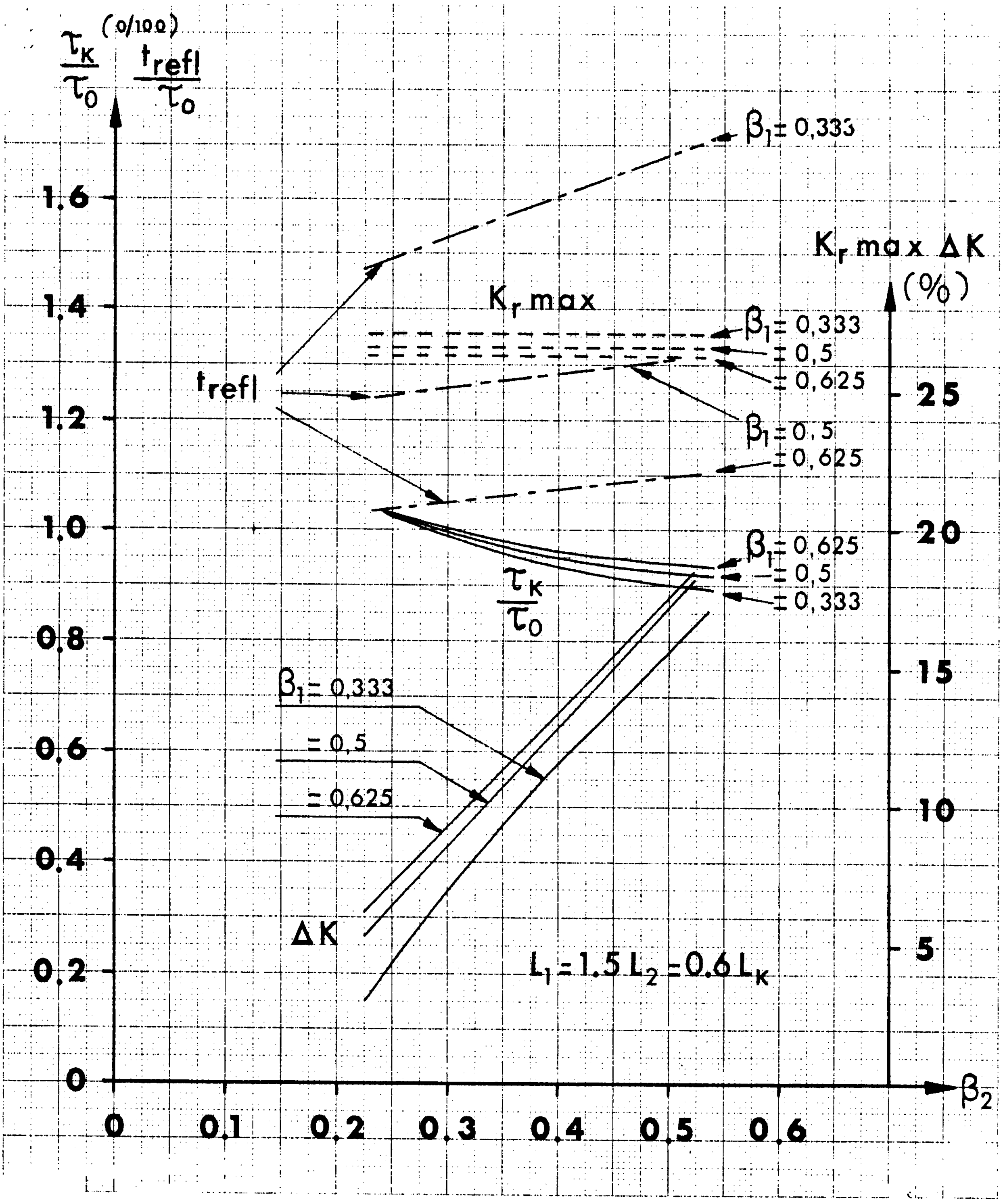


Fig. 7b

Rise-time $\tau_K^{(0/100)}$, kick ripple ΔK, maximum kick amplitude K_{rmax} and length t_{refl} of the reflected pulse for a Janus KM with $L_1 = 1.5\ L_2$ as a function of $\beta_2 = R_0^2 C_2/L_K$ with $\beta_1 = R_0^2 C_1/L_K$ as parameter. Idealized circuit excited by a unit step pulse. $RE = R_0$.

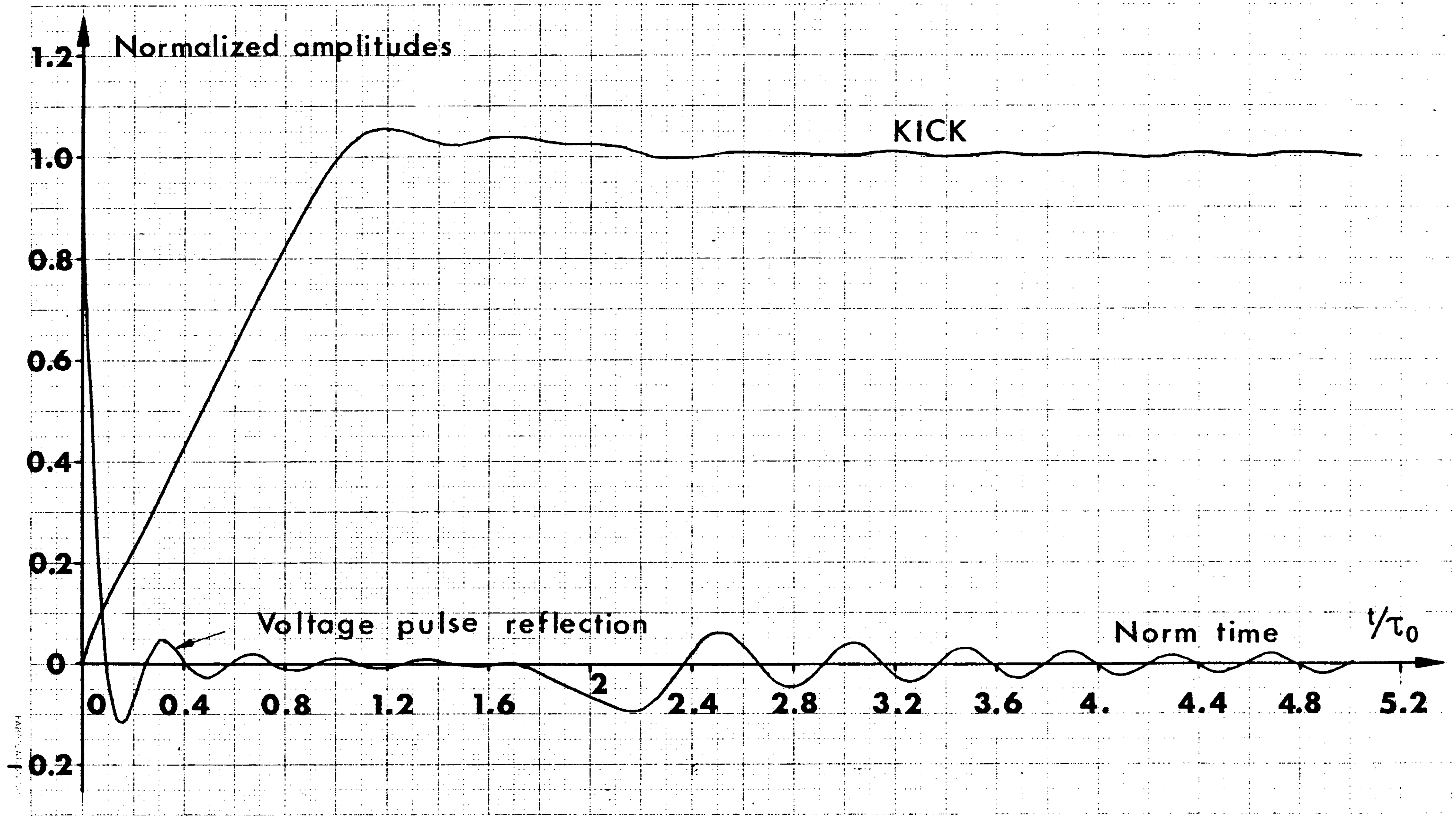


Fig. 8a

Kick and voltage reflection of an idealized delay line KM with nine sections as function of time t normalized to $\tau_0 = L_K/R_0$. $RE = Z = R_0$.

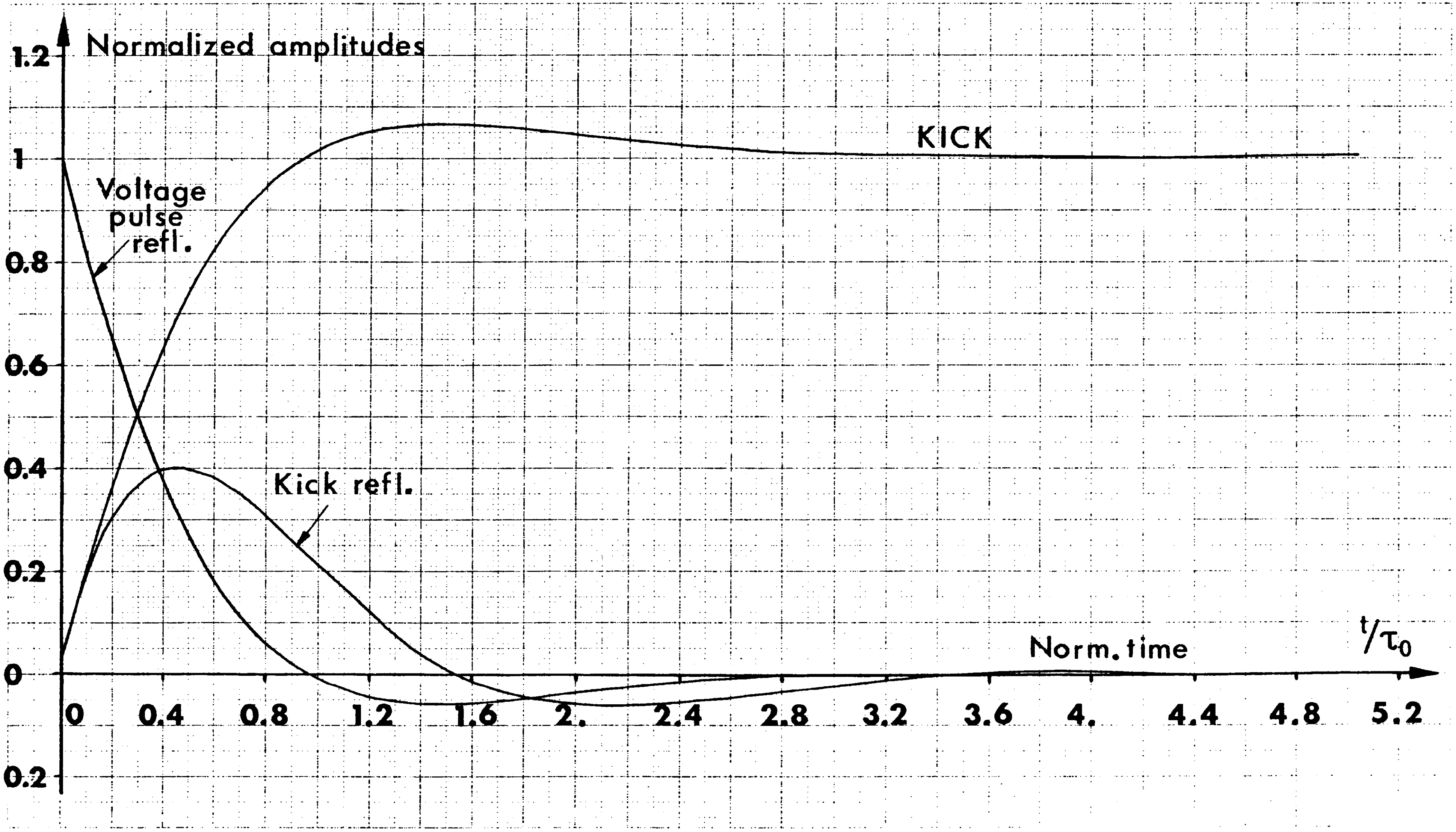


Fig. 8b

Kick and reflection in voltage and kick of an idealized lumped KM with $\beta = 0.44$ as a function of normalized time t/τ_0. $RE = R_0$.

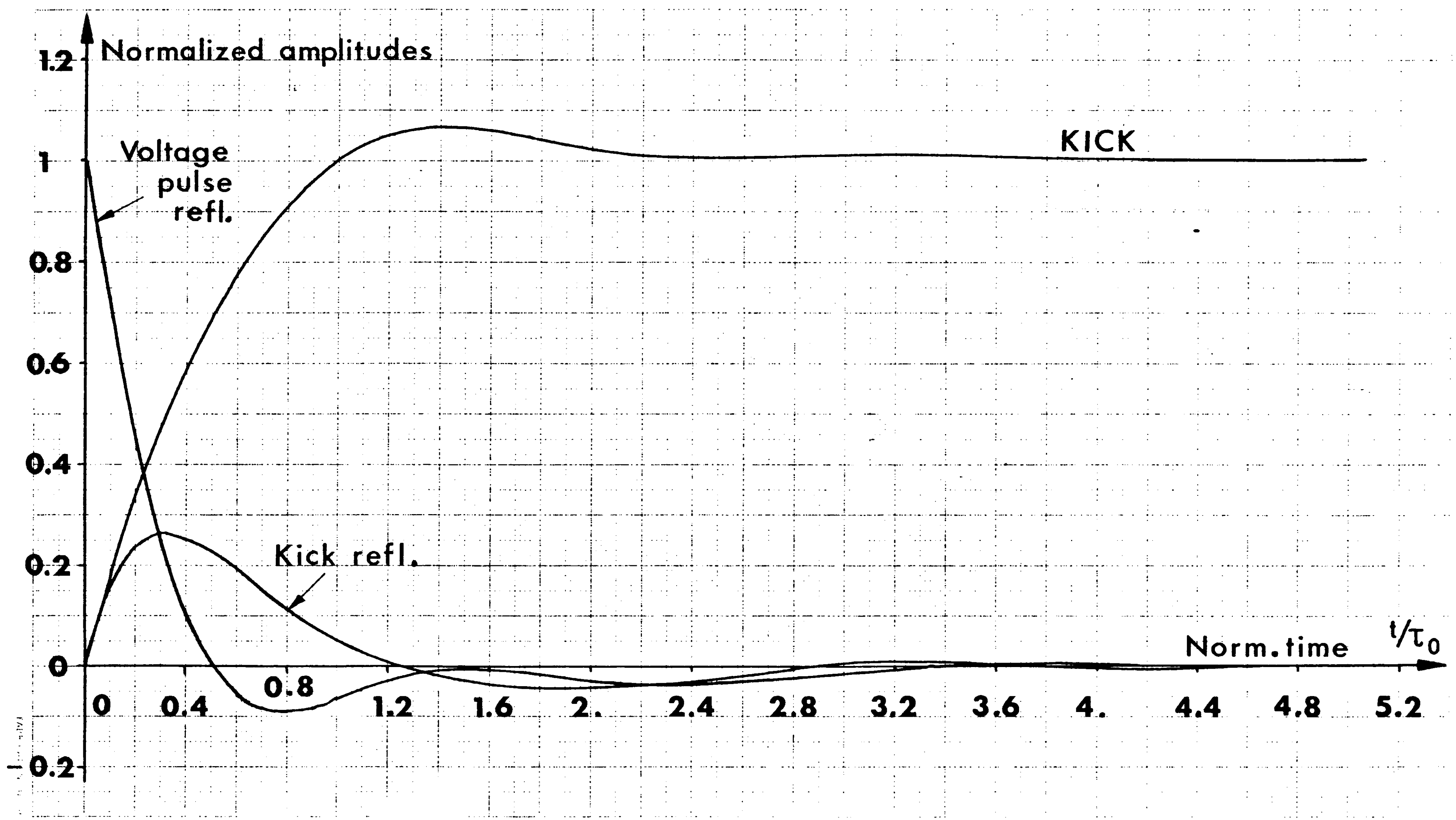
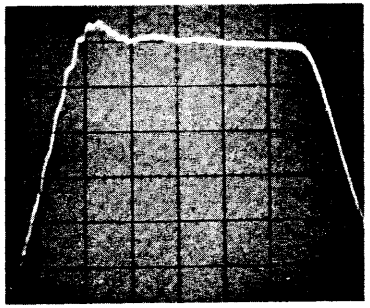
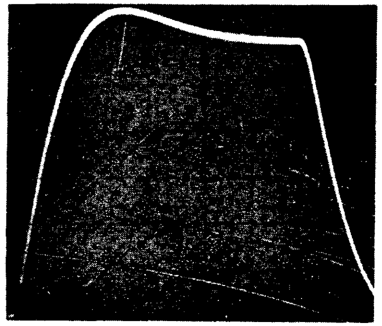


Fig. 8c

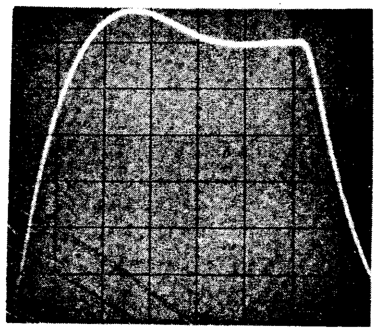
Kick and reflection in voltage and kick of an idealized Janus KM with $L_1 = 1.5\ L_2$, $\beta_1 = 0.5$ and $\beta_2 = 0.25$ as functions of normalized time t/τ_0. $RE = R_0$.



a)



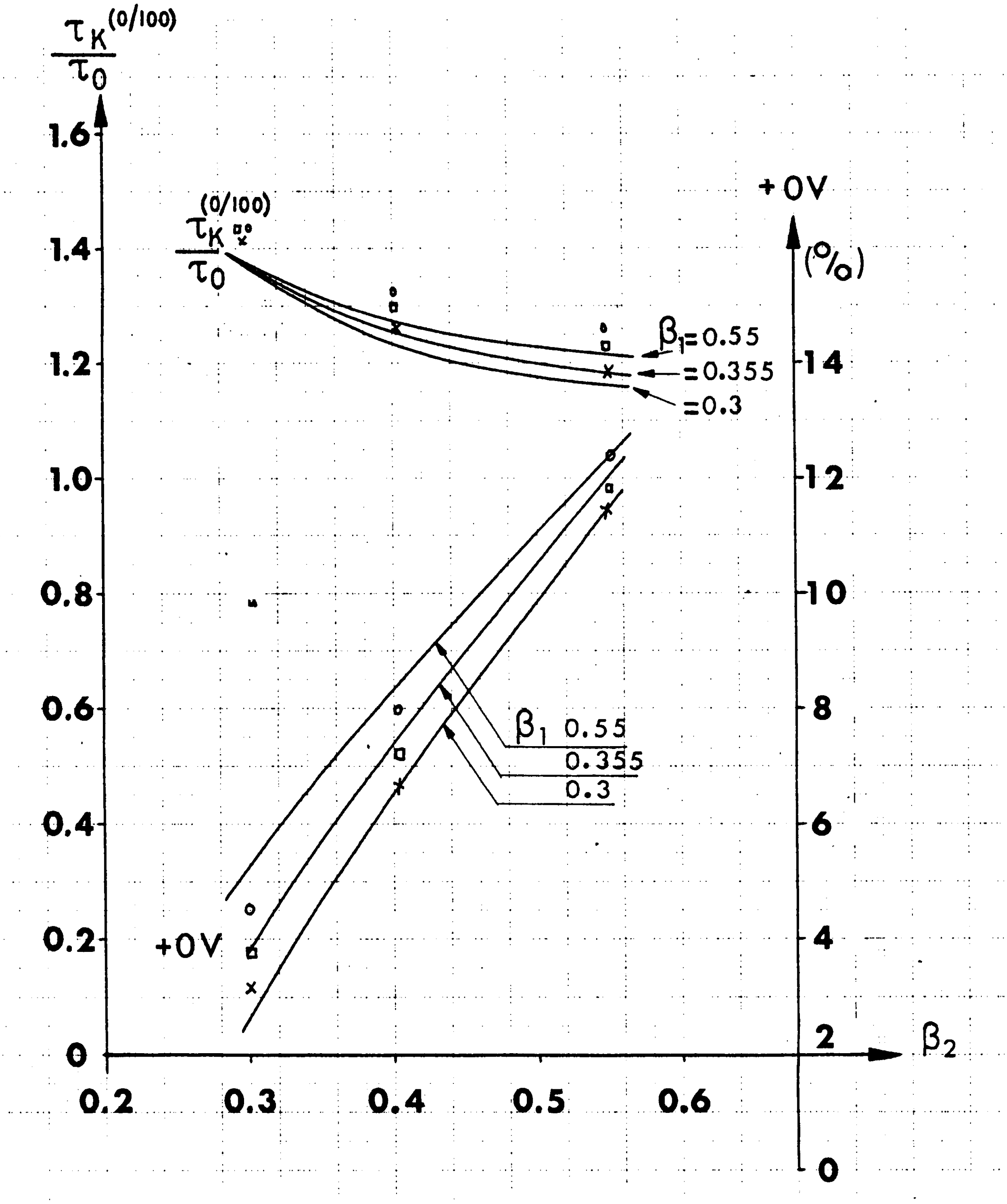
b)



c)

Fig. 9

Typical shapes of kick response measured (a) on a delay line KM model with 11 sections, (b) on a lumped KM with $\beta = 0.7$, and (c) on a Janus KM with $\beta_1 = \beta_2 = 0.55$.



O β_1 = 0.55
□ β_1 = 0.365 } measured values
X β_1 = 0.3

——— computed values

Fig. 10

Measured and computed kick rise-time $\tau_K^{(0/100)}$ and overshoot +ov for a low voltage Janus KM module as a function of $\beta_1 = R_0^2 C_2/L_k$.
Magnet parameters: L_K = 0.55 μH (m); $\ell_a \sim \ell_2 \sim \ell_3 \sim 0.03$ μH(e); ℓ_1 = 0.12 μH(m); M $\sim$ 0; R_0 = RE + 5 Ω (m).
Input pulse: $V_{in}(t)/2 = 1 - \exp(-t/\tau_{in})$ with τ_{in} = 13 nsec (m).

(m) = measured values
(e) = estimated values

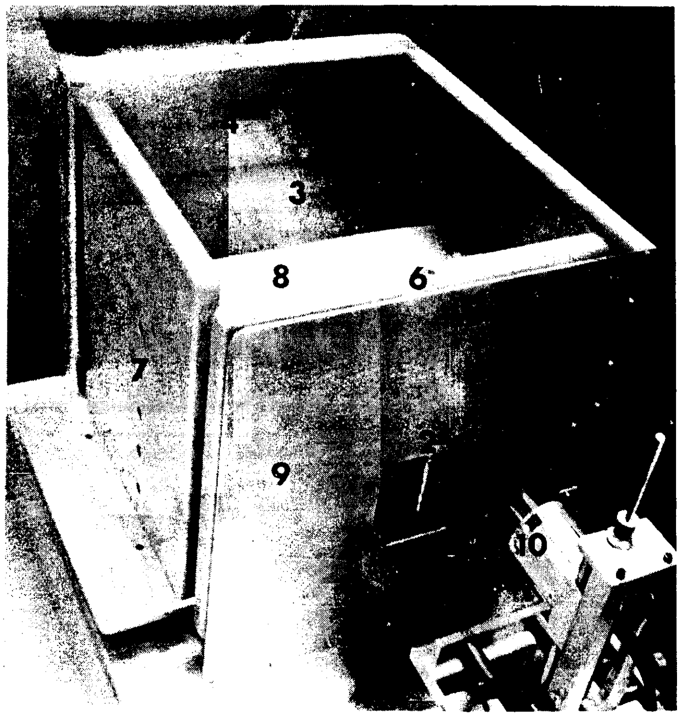


Fig. 11a

High voltage Janus KM module (prototype)

1 = aperture
2 = current conductor
3 = ferrite frames
4 = cold end plate
5 = cold side plate
6 = hot front plate
7 = side plate connected with the separating plate between L_1 and L_2
8 = shielding plate connected with the separating plate between L_1 and L_2
9 = shielding plate at earth for reducing input inductance of the hot conductor
10 = delay line field loop for kick measurement

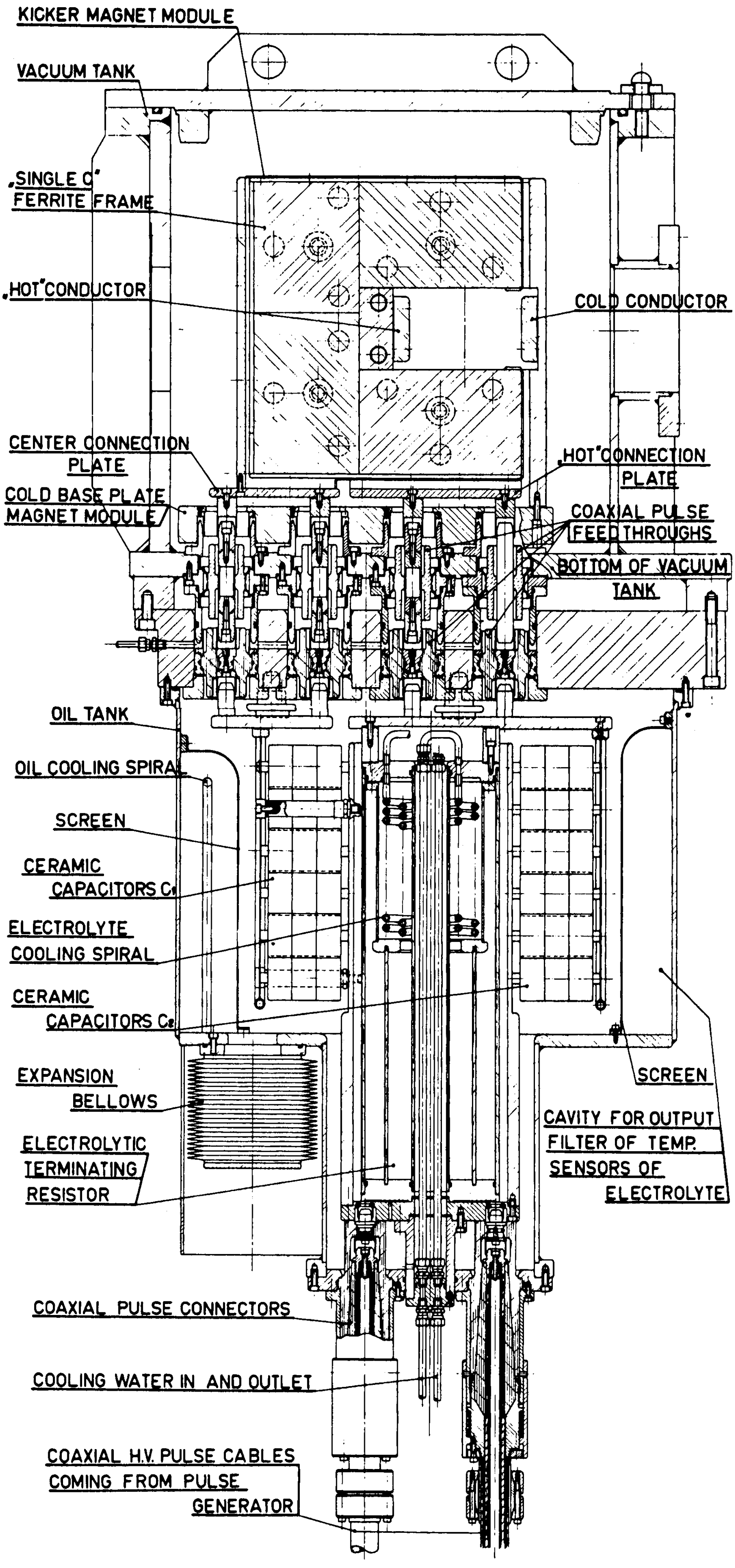
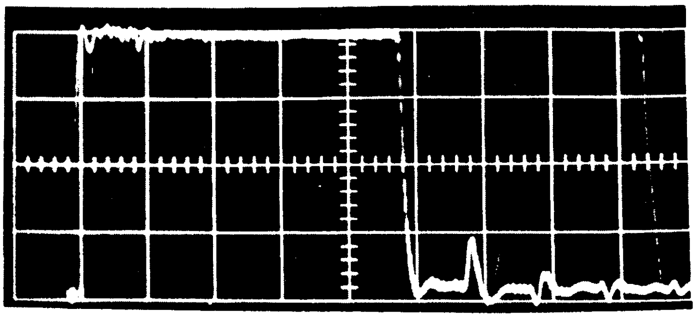


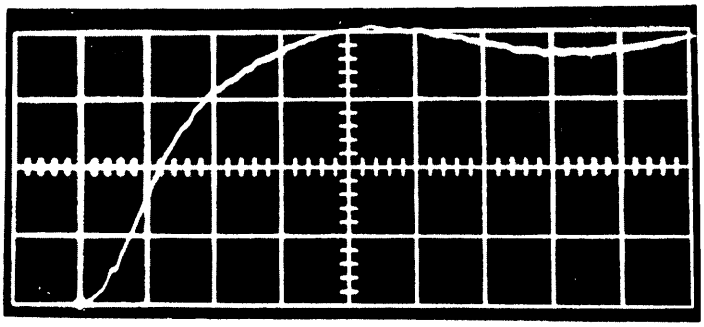
Fig. 11b

Construction of the prototype "single C" Janus KM module for the Serpukhov ejection system.



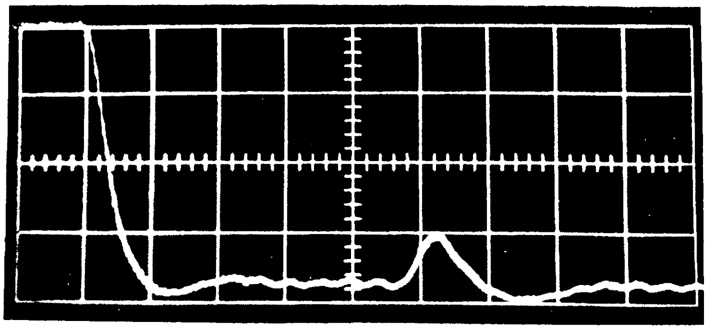
x = 1 μsec/div

a)



x = 40 nsec/div

b)



x = 200 nsec/div

c)

Fig. 12

Kick response of the "single C" Janus KM prototype ($\beta_1 \simeq \beta_2 \simeq 0.5$) for 80 kV charging voltage and 5 Ω impedance of the delay line circuit. Rise-time of the incoming voltage pulse, $\tau_i \simeq 40$ nsec. Fall-time of the voltage pulse $\tau_f \simeq 80$ nsec.

a) Full pulse length of the kick with clipped tail.
b) Initial rise of the kick.
c) Fall-time and first reflection from fall-time.