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Very Fast Kicker for Accelerator Applications

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Abstract

We describe a very fast counter traveling wave kicker with a full pulse width of about 7 ns. Successful test experiment has been done with hi-tech semiconductor technology FET pulse generator with a MHz-range repetition rates and maximum kick strength of the order of 3 G·m. Further increase of the strength seems to be quite possible with the FET pulsers, that makes the kicker to be very useful tool for bunch-by-bunch injection/extraction and other accelerator applications.

1 Introduction

Modern accelerator facilities exhibit a tendency to achieve higher current with increase of number of bunches. The latter varies from a hundred to several thousands in the projects like Tevatron upgrade at FNAL [1], B Factories at SLAC [2] and KEK [3], $\tau - C$ factory at Novosibirsk [4], e^+e^- Linear Colliders [5], LHC at CERN [6], and "Pipetron" project at FNAL [7]. Consequently, the bunch spacing goes down, reaching minimum 0.6 m in the KEK B-factory project. Therefore, the handling of neighbor bunches separately becomes a hard task while it might be necessary for a feedback system or for bunch-by-bunch injection/extraction. The task requires wideband and powerful kickers.

Let us take TESLA Linear Collider as an example [8]. The collider assumes its' low emittance beams to be prepared in a damping ring before injection into linear accelerator. The main complication which arises for the TESLA damping ring design [9] is due to the pulse structure of the linac. The train of 1130 bunches per pulse has a length of 0.8 ms, or 240 km. Since a damping ring of that size would be unreasonable, the bunch train must be stored in the ring in a compressed mode with a bunch spacing smaller than in the linac, and then expanded when extracted out of ring. If one assumes the ejection kicker pulse rise/fall time of τ, then the circumference of the ring is about $C[km] \approx 0.34 \cdot \tau[ns]$.For example, the "dog-bone" proposal for the ring [10] assumes $\tau \simeq 60$ ns and $C \simeq 20$km. An alternative option of the ring in existing PETRA tunnel with $C = 2.3$ km was found to be very attractive, much lower cost and having no significant disadvantages from the multi- and single-bunch dynamics point of view [9]. The key issue for the later option is ejection kicker for a single bunch extraction which has to have $\tau = 7$ ns pulse rise/fall time. The kicker strength for 10 rms bunch size kick amplitude must be about 0.5 G·m in the case of vertical extraction, and about 3 G·m for the horizontal one [11]. As no conventional kicker satisfies the requirements, several novel schemes were proposed including multiple RF cavities [12, 13] and a "beam-beam kicker" with use of external low-energy high current beam from photoinjector [11]. These ideas look to be realizable but rather complicated.

This article is devoted to a very fast counter traveling wave kicker which fits the mentioned above requirements. In Section 2 we describe principle of operation, main components of the device, and preliminary tests. Section 3 is devoted to experimental high-voltage studies of the kicker. Section 4 gives brief summary of the work.

2 The Kicker

The counter traveling wave kicker is designed, built and preliminary tested in Budker Institute of Nuclear Physics(Novosibirsk, Russia). High-voltage pulse generator is based on HTS 50-12-UF high voltage fast transistor switch by Behlke Electronic GmbH (Frankfurt a.M., Germany). Test measurements with the high-voltage generator were held in October 1996 at DESY (Hamburg, Germany).

2.1 Principle of operation

Fig.1 shows the kicker major parts and construction. Two pulses from generator with negative and positive polarities simultaneously go through connection cables and ceramic insulator inputs into two parallel conducting plates (electrodes). Wave resistance of the electrodes inside the vacuum chamber was tuned to be 50 Ohms. An electro-magnetic wave between the electrodes travels with the speed of light c along in the direction *opposite* to an incoming charged particle beam and produces horizontal kick. Then the pulse passes ceramics outputs (similar construction as the inputs) and in ideal case is fully damped in two 50 Ohm loads. Each load contains an in-built 1:120 attenuator for measurements purposes.

Electro-magnetic field between the plates consists of equal amplitude electric and magnetic components. The resulting horizontal force which deflects ultrarelativistic particles is, therefore, twice the electric force for the beam which travels in the direction opposite to the pulse direction, and the electric and magnetic components cancel each other for the beam which goes in the same direction as the pulse. Thus, the traveling wave kicker is a directional device.

Maximum strength of the kicker can be calculated as a product of the effective field $2H$ and the kicker length l:

$$S_0 \approx 2Hl = \frac{2eU_m l}{a}, \qquad (1)$$

where U_m is maximum pulse voltage at the each plate, a is half-aperture. Note, that the dimension of S_0 is G·m, and the beam deflection angle is equal to

$$\theta_m = S_m/(B\rho),$$

where the magnetic rigidity $B\rho$ relates to the beam energy E as $B\rho[G \cdot m] = 3.33 \cdot 10^4 \cdot E[GeV]$.

Let us make a numerical example for the kicker we tested. Applied maximum voltage is about $U_m = 2$kV, the full aperture of the kicker is $2a$ =50 mm and total length l =0.5 m, that yields the kicker strength of $S_0 = 2.67$ G·m. Being installed at the E =3.3 GeV TESLA damping ring such kicker can deflect the positron beam by $\theta_m = 24$ μrad, that corresponds to about $\theta\sqrt{\beta\beta_k} \simeq 5$ mm beam displacement at the point with beta function of about β =200 m if the beta function β_k at the kicker is the same.

2.2 Time structure of the kick

Now we consider the time structure of the kick (or deflection angle) produced by the traveling wave kicker. For simplicity, we take a rectangular input voltage pulse $U(t)$ with maximum amplitude of U_m and pulse duration of t_p – see upper plot in Fig.2. Let us denote $t = 0$ the moment when the front of the pulse enters the kicker input. As the beam passes through the oncoming pulse, the maximum deflection will be seen by test particles which at $t = 0$ are distanced by doubled kicker length $2l$ from the input end of the device. We will call the corresponding time value of $\tau_g = 2l/c$ as "kick growth time". The maximum kick lasts over time interval of $t_f = t_p - \tau_g$ which is supposed to be synchronized with the bunch to extract (see lower diagram in Fig.2). Behind that bunch, the kick amplitude vanishes over the growth time. Analytical expression for the angular deflection is as follows:

$$\theta(t) \equiv S(t)/(B\rho) = \frac{1}{2B\rho}\int_{t_s}^{t} U(t')dt', \quad t_s = -t + 2\max(0, t - l/c). \qquad (2)$$

One can make two remarks: firstly, if the pulse duration is less than the growth time $t_p < \tau_g = 2l/c$, then the beam does not see the maximum deflecting force over the whole passage through the kicker, therefore, the kicker strength can not reach its' maximum value of S_m; secondly, if the bunch spacing in the storage ring is equal to τ, then the kicker length should be less than $l < c\tau/2$, and the generator pulse duration must be less than $t_p < 2\tau - 2l/c$. Again, making numerical example for the TESLA damping ring with $\tau = 7$ ns, we choose $l = 0.5$ m (i.e. $\tau_g = 2l/c = 3.3$ ns $< \tau$) and the requirements on generator pulse length is $t_p \leq 10.7$ ns. In fact, as the pulse shape can not be exactly rectangular, than the one should require the pulse FWHA to be somewhat smaller (but still longer than τ_g), e.g. 6-8 ns.

2.3 Power consumption

The peak power absorbed in both kicker loads is equal to:

$$P_p = 2\frac{U_m^2}{R} \simeq 160\, kW, \tag{3}$$

here we take the maximum voltage of $U_m = 2$ kV, and the load resistance of $R = 50$ Ohms.

The TESLA damping ring kicker should operate with $N_b = 1130$ pulses per train regime with $f_0 = 10$ Hz repetition frequency and $t_p \approx 8$ ns pulse duration, therefore, the average power is:

$$P_a = P_p f_0 N_b t_p \simeq 14\, W, \tag{4}$$

One can see that while the average power is small, the only possible source of load damage trouble can be high peak power.

2.4 Construction features

The kicker is made from materials which are able to work under conditions of "baked-up" high vacuum such as stainless steel, special kind of bronze, ceramics, covar. Copper alloy is used for welding of ceramics insulators.

The electrodes are connected to central conductors of ceramics inputs by use of special fixators. The connection is made when the device ends are open (i.e., conical transition sections are taken out), that allows to set on and off the electrodes easily without welded parts breaking, and align the electrodes precisely.

One expects significant difference in elongations of the electrodes and vacuum chamber during the high-temperature vacuum baking process due to different thermal expansion coefficients of their materials. It may lead to dangerous mechanical stress in the device and even to ceramics insulator inputs damage. To avoid the effect, elastic elements are used for connection of one end of each electrode to central conductor.

The electrodes are not flat, their shape is optimized with *MERMAID-2D* code [14] in order to achieve homogeneous field and the wave resistance of 50 Ohm. Fig.3 presents potential lines in a quadrant, i.e. only a half of one plate is shown because the system has a 4-fold symmetry. Calculated field non-uniformity is less than 10% over 80% of full aperture of $2A_x \times 2A_y = 50 \times 50$ mm^2.

2.5 Preliminary tests

Vacuum testing has been done at Novosibirsk INP in accordance to modern requirements on accelerator elements. The whole kicker was heated ("baked") up to 300°C under continuous vacuuming with use of no-oil magneto-discharge pumps. Input cables and resistive loads were disconnected from the kicker during the "baking". Vacuum of about $1 \cdot 10^{-10}$ Torr was observed after cooling the kicker down to the room temperature.

High voltage test has been done in order to check the kicker electrical performance under high vacuum. 1 ms long, half-sinusoid shape, 15 kV pulses with opposite polarities fed the kicker electrodes through input cables and ceramic inputs. Pulse repetition rate was equal to 1 Hz. The loads were taken off the kicker, therefore, two electrodes, all four ceramic inputs, and two input cables were under the high voltage (see Fig. 4). The test has shown no spark or discharge events over 10 minutes interval.

The kicker element impedances matching, i.e. frequency bandwidth of the device, was checked with use of low voltage short pulse generator – see scheme of the test in Fig.5. The reflected signal comes after the main pulse and can be presented in the same oscilloscope record. An amplitude of the reflected pulse serves as an indicator of the matching: in ideal case the pulse goes to the matched load and there should be no reflected signal, but this condition is hard to maintain over very wide frequency band (i.e. maximum mismatch takes place during rise and fall of the pulse). [1] Fig.6 presents the results of the test with 12 ns long 1.1 V pulse which has 2 ns rise and fall times. The reflected pulse has maximum amplitude of about 60 mV, i.e. 5%, mostly due to reflections of fronts of the initial pulse.

3 Results

Fig.7 shows 120 times attenuated outputs of the kicker fed by high-voltage pulse generator. The scheme of the measurements is the same as presented in Fig.5. High-precision 500 MHz bandwidth HP54542A oscilloscope was used for signal recording. One can see that maximum amplitude of the pulse is about U_m =2.4 kV (ampli-

[1] If an oscilloscope with input resistance of R_i =50 Ohm is used in the scheme, then observed reflected pulse amplitude is 2/3 of the real one. If $R_i \gg 50$ Ohm (e.g. 1 MOhm as in our test) then the reflected pulse is observed in a full scale.

tudes of the positive and negative pulses differ slightly due to unequal output attenuations, and somewhat different amplitudes of the positive and negative input high-voltage pulses from generator; anyway, the effect is not dangerous for the extracted beam). The pulse shape is close to half-period of sine function with zero-to-zero duration of $t_p \approx 6$ ns, i.e. $U(t) \approx= U_m \sin \pi t/t_p$. Using Eq.(2) one can easily estimate the effective kicker strength (deflection pulse shape):

$$S(t) = U_m \frac{ct_p}{\pi a}\Big[cos\Big(\frac{\pi}{t_p}\max(0, t - l/c)\Big) - cos(\frac{\pi t}{t_p})\Big], \quad t \leq t_p/2 + l/c,$$

$$S(t_p/2 + l/c - \Delta t) = S(t_p/2 + l/c + \Delta t). \tag{5}$$

Thus, the maximum kicker strength for the pulses shown in Fig.7 with taking into account the effect of averaging over the passage through the kicker is equal to

$$S_m = S_0\Big(\frac{sin(\pi l/ct_p)}{(\pi l/ct_p}\Big) \approx 2.76G \cdot m. \tag{6}$$

Visually observed pulse-to-pulse amplitude variations were definetely less than 5%, but the stability issue was not studied thoroughly.

Fig.8 demonstrates the reflected pulse (see lower plot). The pulse is delayed on about 100 ns with respect to the initial signal (see upper plot) because we observe both of them at the same attenuated output, i.e. the reflected pulse traveled to the generator and back before recording. One can see, that the reflected pulse is less than 8% amplitude of the initial one. Further improvement in the reflected pulse reduction needs precise mechanical tuning of the plate connections to the output kicker conductors. That is one of the goals of next stage of the kicker test.

As the TESLA damping ring beam extraction requires 1130 pulses spaced by 0.7 microsecond and this pulse train to be repeated 5-10 times a second, we studied the kicker in those conditions. General conclusion is that the pulse generator works well in such regime. The only problem we observed was a monotonous decrease of the pulse amplitude with increasing pulse number. As the result the maximum amplitude of, say, pulse number 11 was some 4% less than of the first one. It is known how to work out this effect with use of larger high-voltage storage capacitance in the pulse generator, and we are going to implement this modification in our further tests. Currently, to avoid the effect we used smaller number of pulses (several dozens) in the train with proportionally increased repetition rate; i.e. generator average power remains the same as required.

4 Conclusions

Very fast kicker for accelerator applications was designed, produced and tested in collaboration of Budker Institute of Nuclear Physics (Novosibirsk, Russia), DESY (Hamburg, Germany) and Fermilab (Batavia, USA). We have found that the counter traveling wave kicker with more than 2 kV voltage, 7-8 ns pulse generator produces some 2.8 G·m deflecting kick strength. The kicker makes possible to work with up to thousand pulses in train with pulse-to-pulse space of 0.7 microseconds, and repetition rate more than 10 Hz. We intend to make further tests and study ultimate kick strength, amplitude stability, ways to reduce pulse reflections and eliminate the decrease of the voltage in long pulse train.

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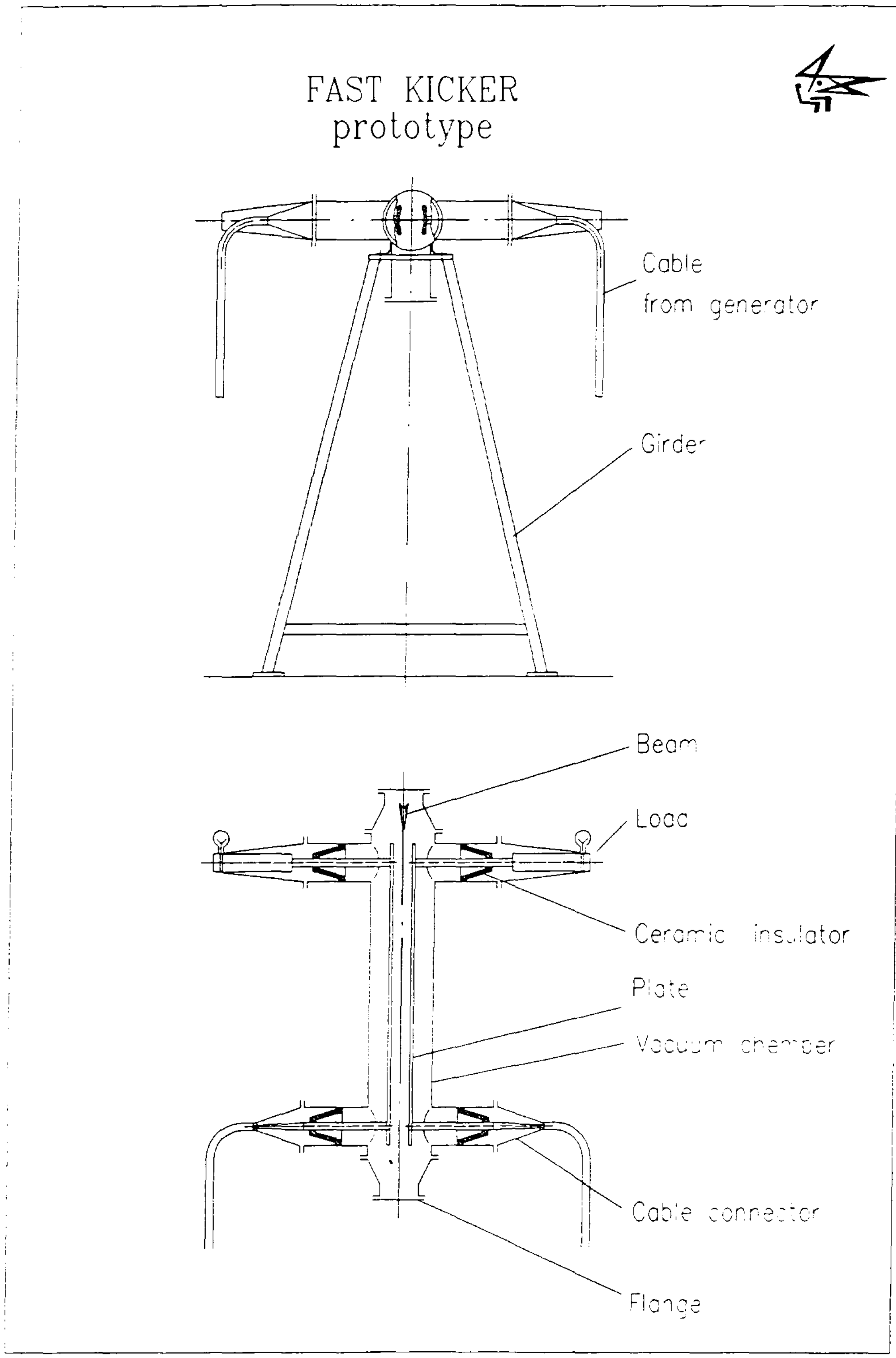


Fig.1: Traveling wave kicker design.

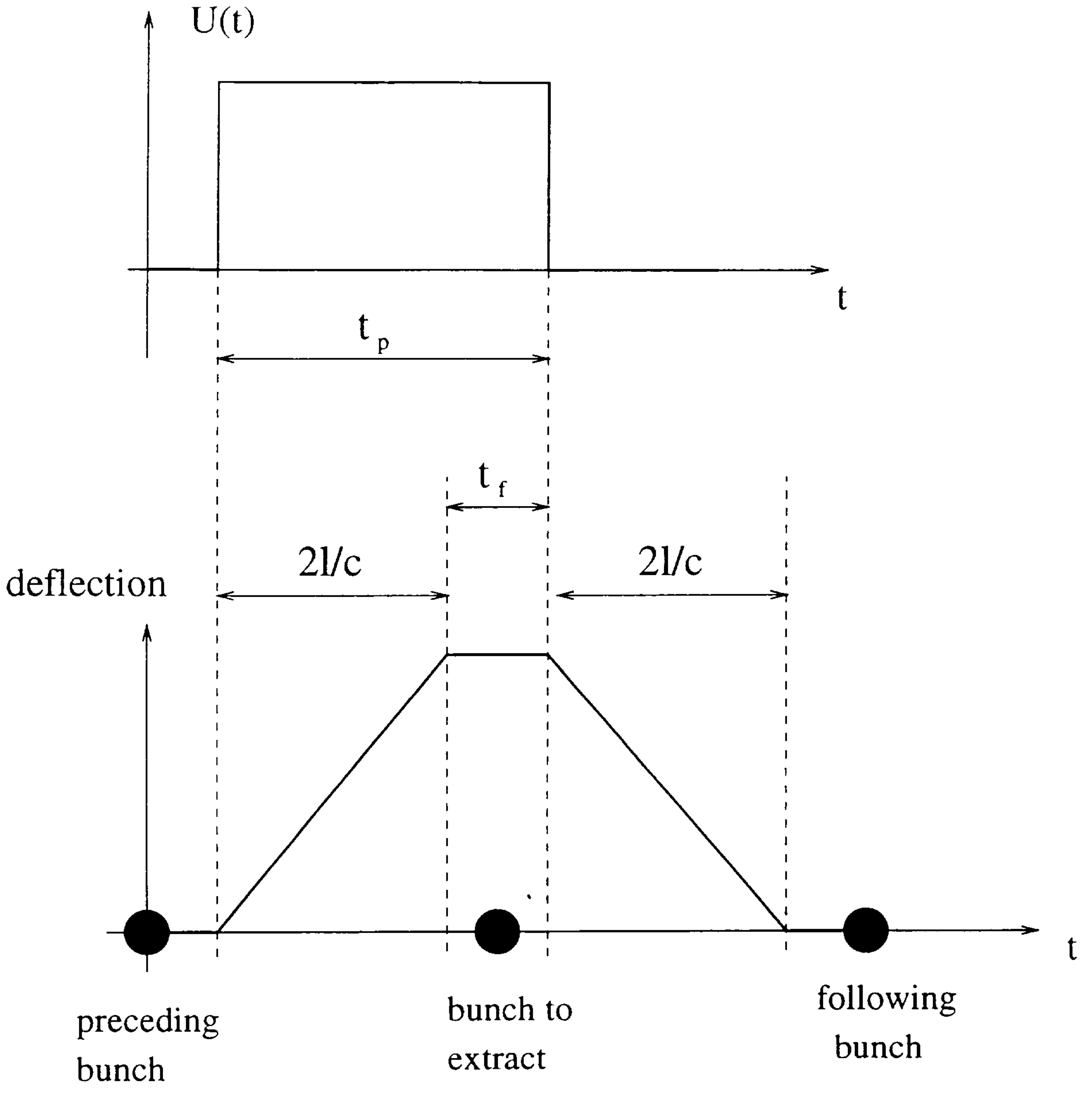


Fig.2 : Operation of traveling wave kicker.
(upper – input pulse, below – particle deflections).

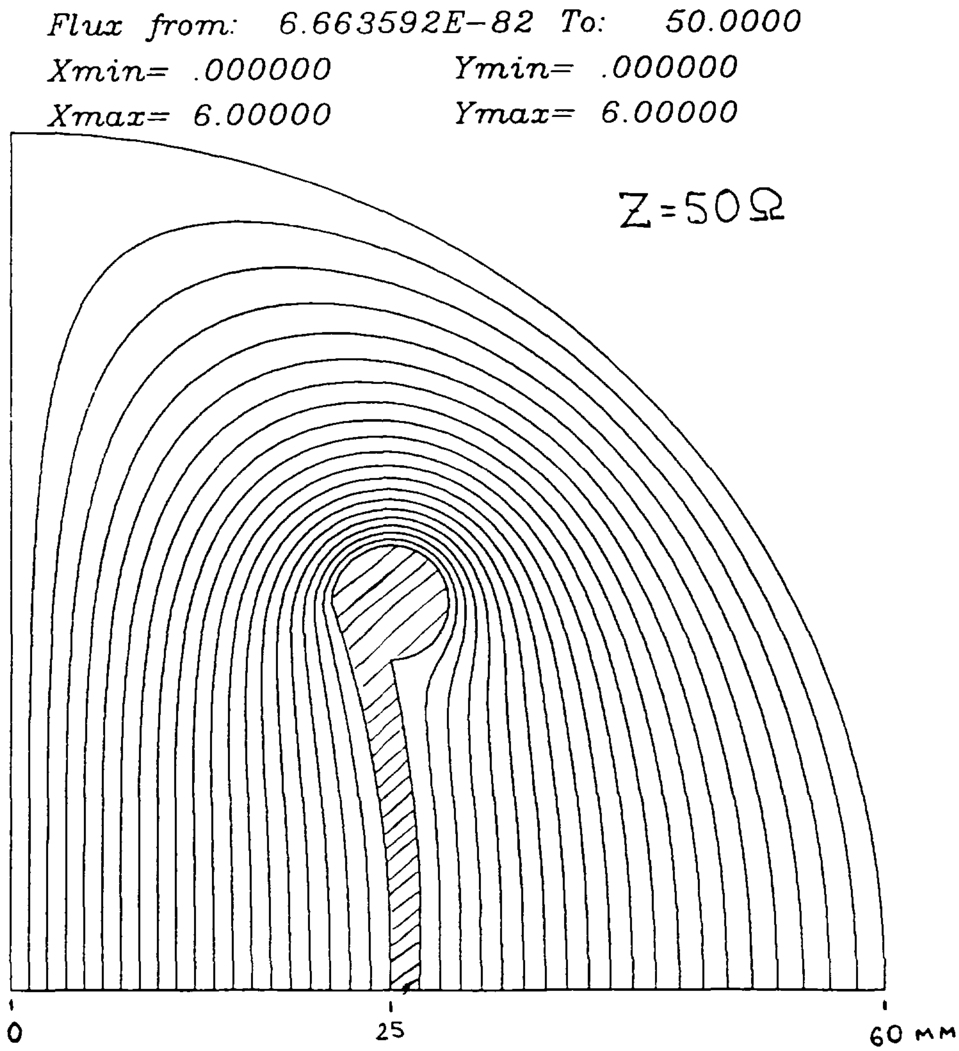


Fig.3: Potential lines in the kicker.

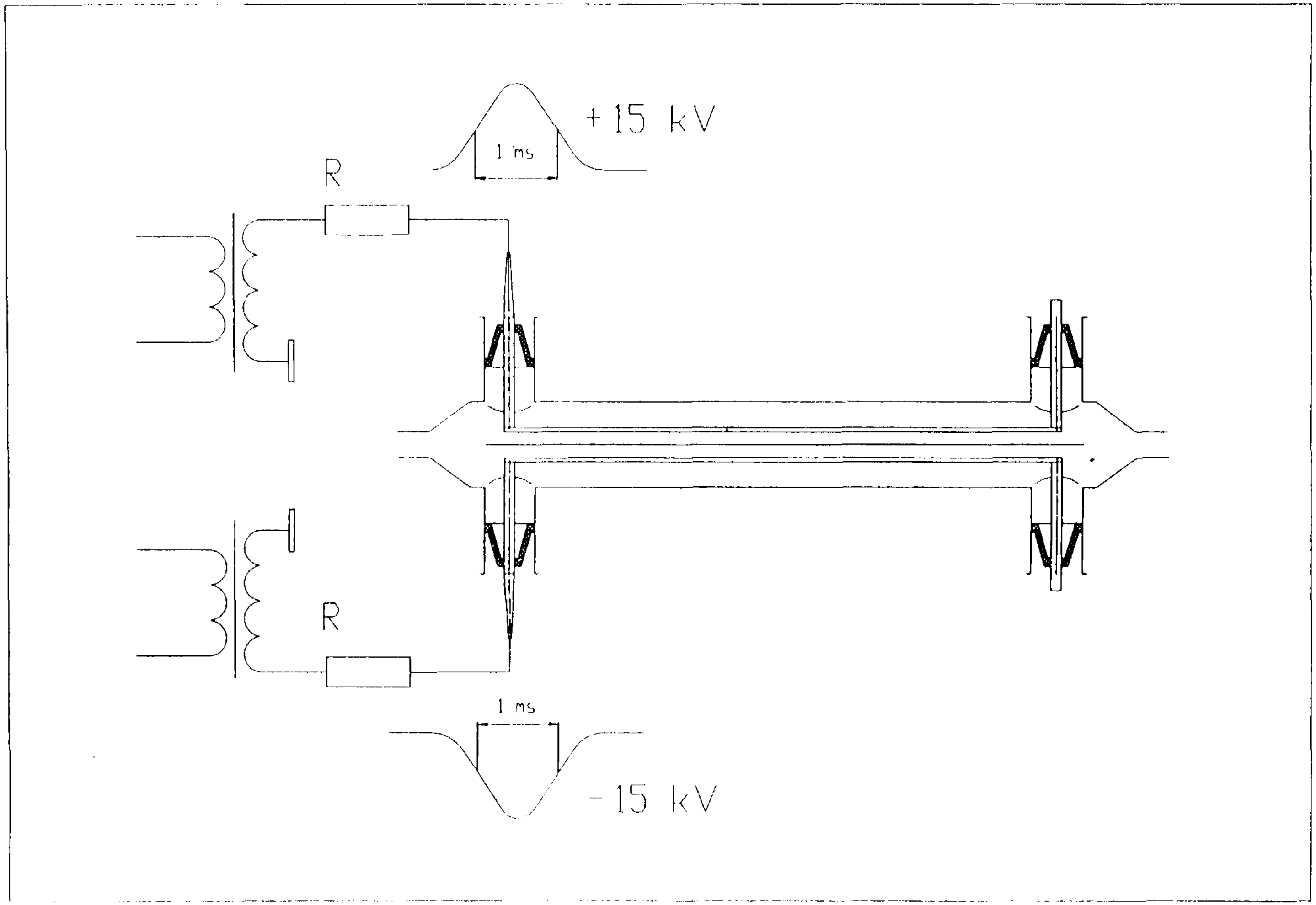


Fig.4: Scheme of the high-voltage kicker test.

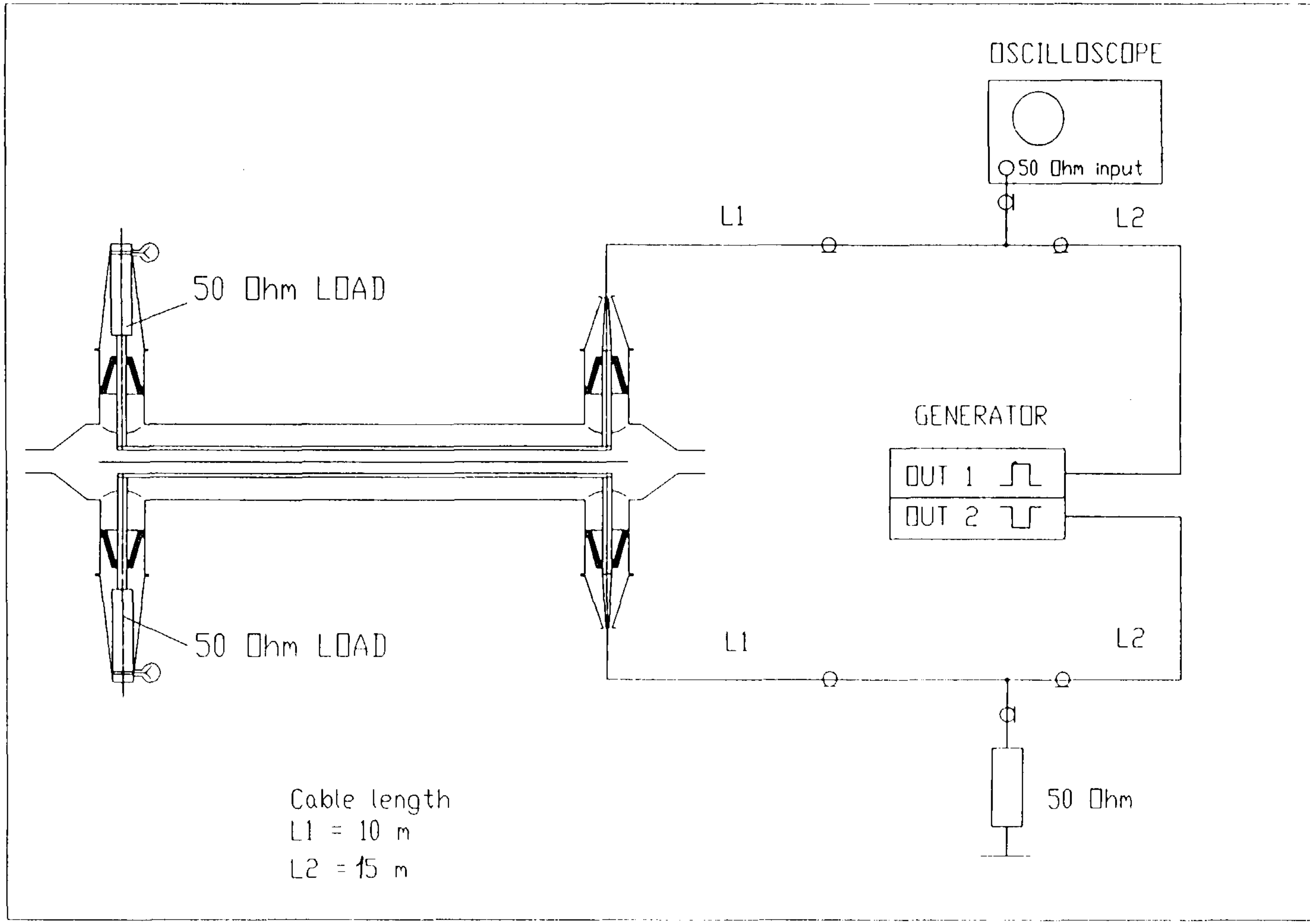
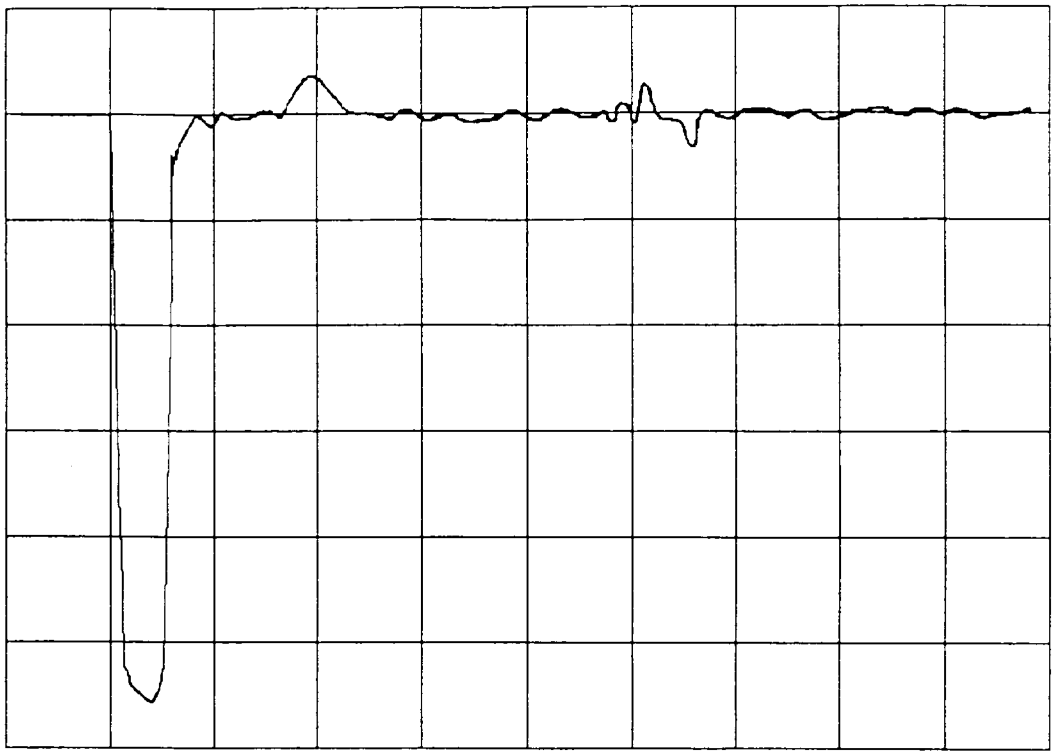


Fig.5: Scheme of the kicker test for reflections.



0.2 V/div 20 ns/div

Fig.6: Low-voltage pulse and reflections.

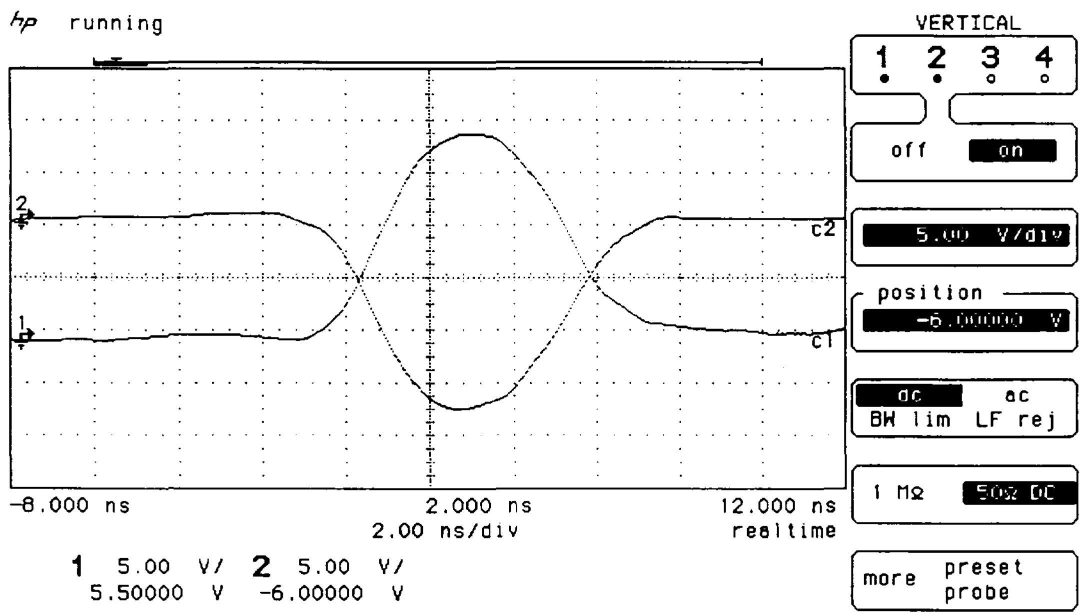


Fig.7: High-voltage pulses at both outputs (attenuation 1:120).

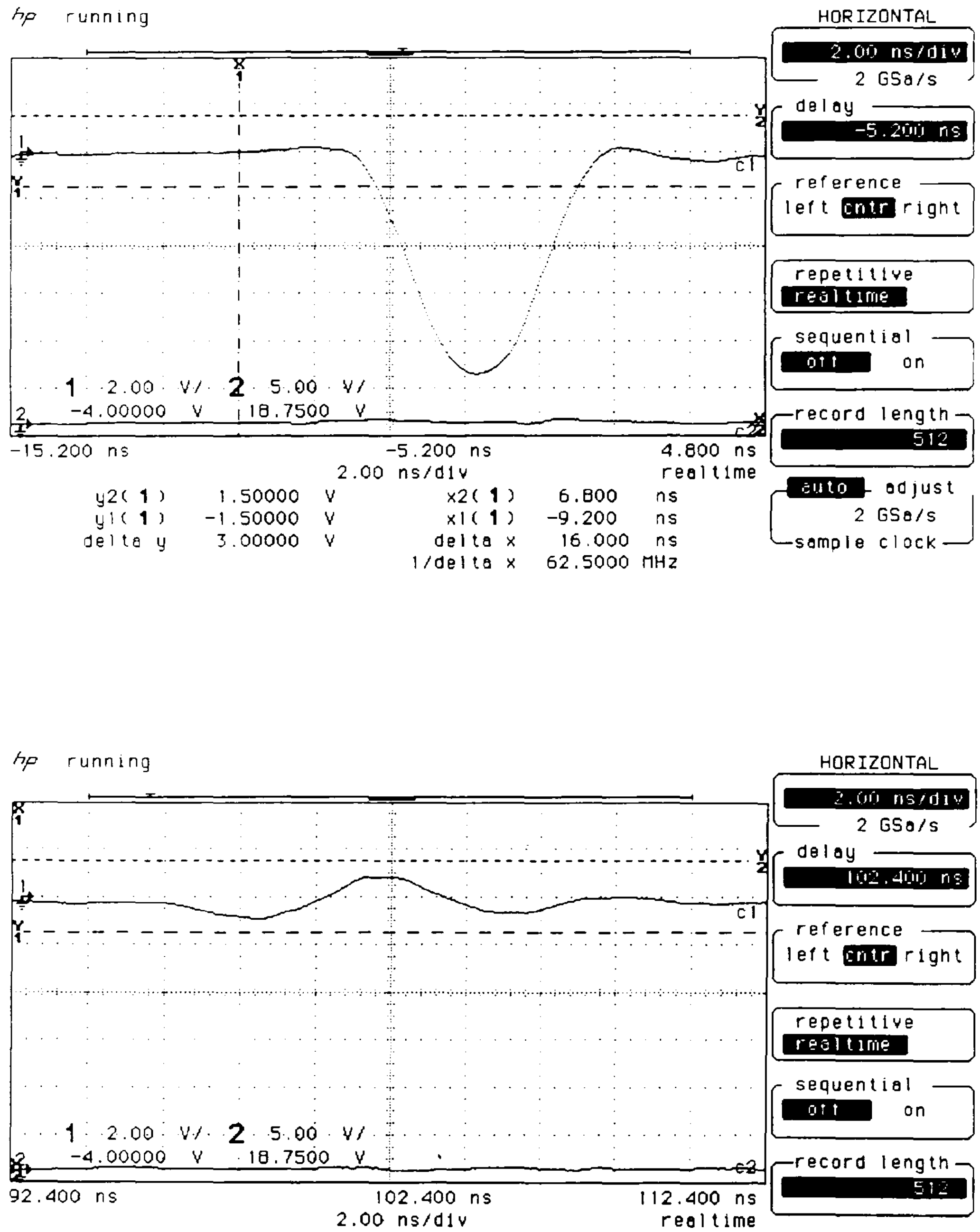


Fig.8: Upper – high-voltage output pulse; lower – reflected pulse. Attenuation 1:120.