Nuclear Instruments and Methods in Physics Research A 396 (1997) 28–34

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

Very fast kicker with high repetition rate for accelerator applications

B.I. Grishanov[a], F.V. Podgorny[a], J. Rümmler[b], V.D. Shiltsev[c,*]

[a] Budker INP, Novosibirsk, 630090, Russian Federation
[b] DESY, Notkestrasse 85, Hamburg 22603, Germany
[c] Fermi National Accelerator Laboratory[1] M.S.345, P.O. Box 500, Batavia, IL 60510, USA

Received 18 February 1997; received in revised form 4 April 1997

Abstract

We describe a very fast kicker with unique combination of high repetition rate and short pulse width. Constructionally, the device is a counter traveling wave strip-line kicker fed by semiconductor high-voltage pulse generator. Experimentally tested kicker has a full pulse width of about 7 ns, 1.4 MHz repetition rate and maximum kick strength of the order of 3 G m. Recent achievements in high-voltage semiconductor field-effect-transistors (FET) technology and goal-specific optimization of the kicker parameters allow many-fold increase of the strength, and the kicker can be a 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 up to hundreds and even several thousands. Consequently, the bunch spacing goes down, and 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 wide band and powerful kickers. Many present-day fast kickers are essentially ferrite kickers fed by thyratrons. They enjoy high-voltage abilities of thyratrons, but cannot work effectively with repetition rate above dozen of Hz and cannot provide the kick duration less than 50–100 ns.

This article is devoted to a device which operates with one order of magnitude shorter pulses and five orders of magnitude higher repetition rates. Constructionally, the device is a counter traveling wave strip-line kicker fed by an FET-based pulse generator. We present here test results of the kicker prototype for linear collider TESLA damping ring.

The TESLA linear e^+–e^- collider project (see, e.g. Ref. [1]) 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 is due to the pulse structure of the linac. The train of 1130 bunches 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, i.e. single-bunch extraction is needed. Thus, the circumference of the ring is proportional to the minimum rise/fall time of the ejection kicker used, e.g. 60 ns-kicker yields 20 km long ring, while the circumference of about 2.3 km (the ring in existing PETRA tunnel, Ref. [2]) requires rise and fall times of the kicker to be less than 7 ns. Some 3 G m of the kicker strength is needed for the 10 rms bunch-size kick amplitude, Ref. [3]. As no conventional kicker satisfies the requirements, several novel schemes were proposed including multiple RF cavities, Refs. [4,5] and a "beam–beam kicker" with use of external low-energy high-current beam from photoinjector, Ref. [3]. These ideas look to be realizable but rather complicated.

This article is devoted to 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 test results. Section 3 is devoted to experimental high-voltage studies of the kicker. A discussion on ultimate possibility of the kicker and a brief conclusion of the work are given in Section 4.

* Corresponding author. E-mail: shiltsev@fnal.gov.

[1] Operated by URA under Contract No. DE-AC02-76CH03000 with the US Department of Energy.

PII S0168-9002(97)00739-0

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 fast field effect transistor (FET) 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 is tuned to be 50 Ω. 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 pulses pass ceramic outputs (similar construction as the inputs) and in ideal case are fully damped in two 50 Ω loads. Each load contains an in-built 1 : 120 attenuator for measurement purposes.

The electro-magnetic field between the plates consists of equal amplitude and perpendicular electric and magnetic components. For ultra-relativistic particles moving along the electrodes, the resulting horizontal deflecting force is twice the electric force for the beam traveling in the direction opposite to the pulse propagation 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

$$S_0 \approx 2Hl = \frac{2eU_m l}{a}, \tag{1}$$

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

$$\theta_m = S_0/(B\rho),$$

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

Let us make a numerical example for the kicker we tested. The maximum voltage applied to each plate is about $U_m = 2.4$ kV, the full aperture of the kicker is $2a = 50$ mm and total length $l = 0.5$ m, that yields the kicker strength of $S_0 = 3.2$ G m. Being installed at $E = 3.3$ GeV, TESLA damping ring such a kicker can deflect the positron beam by $\theta_m \approx 30$ μrad, that corresponds to about $\theta_m\sqrt{\beta\beta_k} \simeq 6$ mm beam displacement at the point with beta function of about $\beta = 200$ m if the beta function β_k at the kicker is the same.

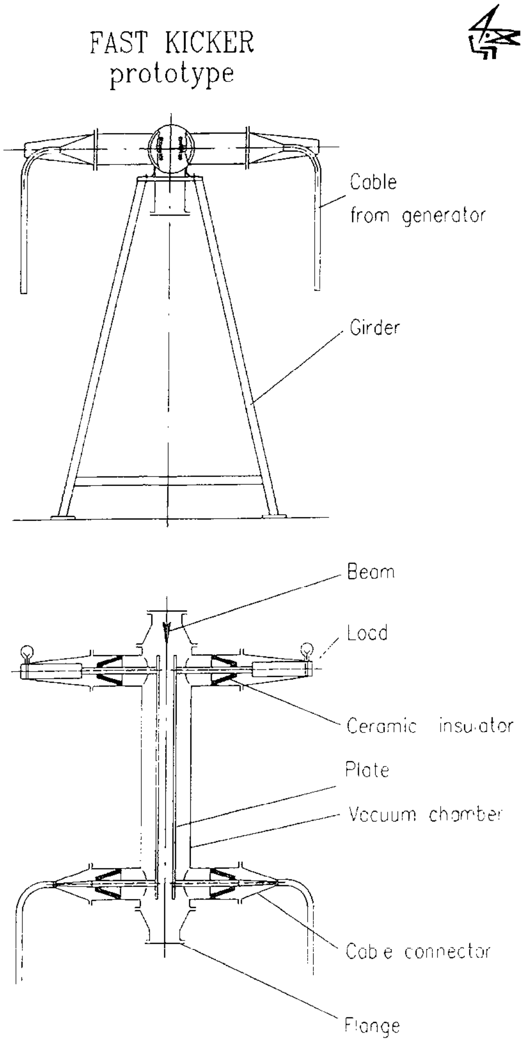

Fig. 1. Traveling wave kicker design.

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 of time when the front of the pulse enters the kicker input. As the beam passes through the oncoming wave, the maximum deflection will be seen by test

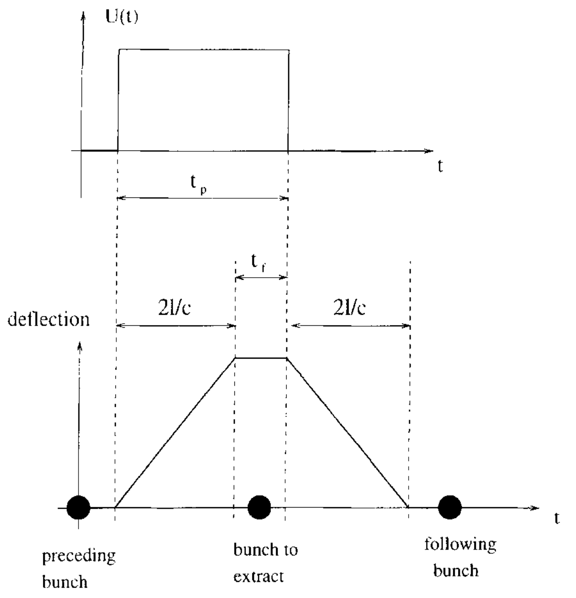

Fig. 2. Operation of traveling wave kicker (upper – input pulse, below – particle deflections).

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 the "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 amplitude vanishes over the same "kick growth time". Analytical expression for the angular deflection is as follow:

$$\theta(t) \equiv S(t)/(B\rho) = \frac{ec}{aB\rho} \int_{t_s}^{t} U(t')\,dt',$$

$$t_s = -t + 2\max(0, t - l/c). \qquad (2)$$

One can make two remarks: firstly, if the pulse duration is less than the growth time $t_p < \tau_g = 2l/c$, then the kicker does not work in full strength; secondly, if the bunch spacing in the storage ring is equal to τ, then the generator pulse duration must be less than $t_p < 2\tau - 2l/c$ otherwise neighbor bunches will be deflected too. As the result, one can conclude, that the duration of the rectangular pulse equal to the bunch spacing $t_p = \tau$ corresponds to maximum kicker strength. The kicker length has to be less than $l < c\tau/2$ because the pulse shape cannot be exactly rectangular, besides that, some flat top of the kick is usually required. 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 cannot be exactly rectangular, then 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:

$$P_p = 2\,\frac{U_m^2}{R} \simeq 230\,\text{kW}, \qquad (3)$$

here we take the maximum voltage of $U_m = 2.4$ kV, and the load resistance of $R = 50\,\Omega$.

The TESLA damping ring kicker should operate with $N_b = 1130$ pulses per train regime with $f_0 = 10$ Hz repetition frequency and $t_p \approx 7$ ns pulse duration, therefore, the average power is

$$P_a = P_p\, f_0\, N_b\, t_p \simeq 18\,\text{W}, \qquad (4)$$

while the average power over the full extraction duration is $P_t = P_p t_p / T_0 \simeq 2.3$ kW, where $T_0 \approx 710$ ns is the bunch spacing in the linac.

One can see that while the average power is small, the only possible source of load damage trouble can be high-peak power P_p and average power P_t in the 0.8 μs long train.

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 ceramic insulators.

The electrodes are connected to central conductors of ceramic 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 elongation of the electrodes and the 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 ceramic 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 [6] in order to achieve homogeneous field and the wave resistance of 50 Ω. Fig. 3 presents potential lines in a quadrant, i.e. only a half of one plate is shown because of system symmetry. Calculated field non-uniformity is less than 10% over 80% of full aperture of $2A_x \times 2A_y \approx 50 \times 50\,\mathrm{mm}^2$.

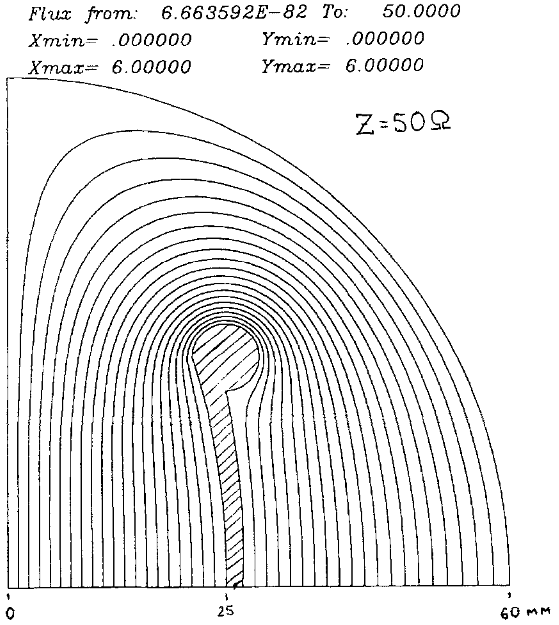

Fig. 3. Potential lines in the kicker.

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 oil-free magneto-discharge pumps. Input cables and resistive loads were disconnected from the kicker during the "baking". Vacuum of about 1×10^{-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. The kicker electrodes were fed 1 ms long, half-sinusoid shape, 15 kV pulses with opposite polarities 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. The test has shown no spark or discharge events over 10 min interval.

The kicker element impedances matching, i.e. frequency bandwidth of the device, was checked using a low voltage short-pulse generator – see scheme of the test in Fig. 4. 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

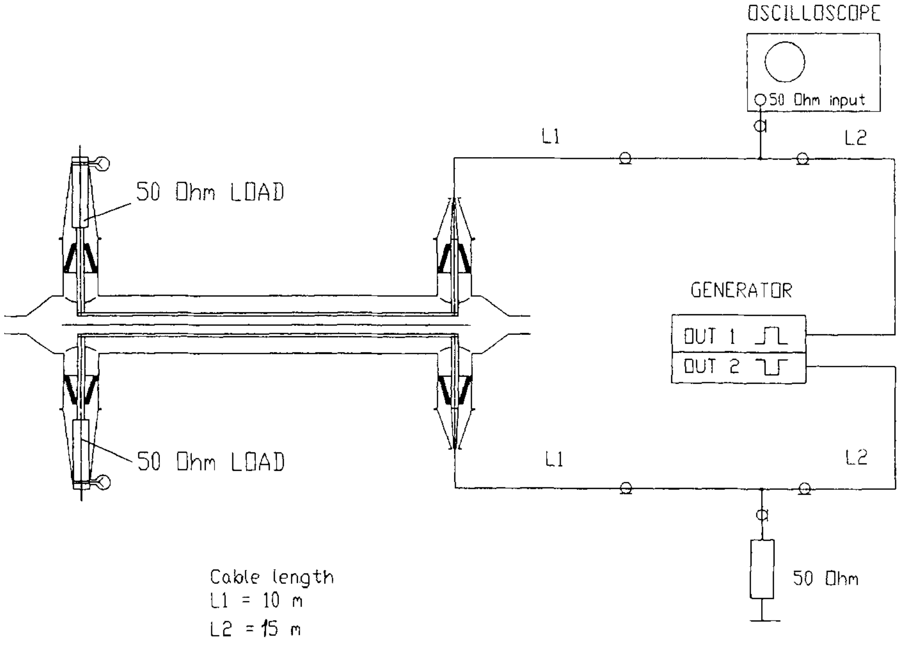

Fig. 4. Scheme of the high-voltage kicker test.

mismatch takes place during rise and fall of the pulse).[1] During the test with 12 ns long 1.1 V pulse which has 2 ns rise and fall times we found that the reflected pulse has maximum amplitude of about 60 mV (some 5.5% in amplitude) mostly due to reflections at the the initial pulse fronts.

2.6. High-voltage pulse generator

The high-voltage (HV) short-pulse generator is based on the solid state field-effect transistor switch HTS 50-12-UF by BEHLKE Electronic GmbH (Germany). It has been specially designed for HV generators with a short pulse duration and extreme edge steepness, and has a very low jitter (with respect to cold cathode tubes) and the lifetime typical of semiconductor devices. Major technical parameters of the switch are as follow: maximum operating voltage 5000 V, maximum peak current 120 A, turn-on rise time (10–90% in amplitude) $\simeq$ 1.6 ns, minimum pulse spacing is less than 1 μs, dimensions $89 \times 64 \times 31\ \mathrm{mm}^3$. Fig. 5 schematically shows the HV generator with HTS 50-12-UF (for simplicity, only the positive pulse part is presented, the negative one looks the same way). A conventional 5 V TTL pulse generator was used for external triggering, which provided the necessary time structure of the signal: variable number of pulses in train – from 10 to 1130, pulse spacing – typically 700 ns (frequency of about 1.4 MHz), and the pulse train repetition frequency of 10 Hz.

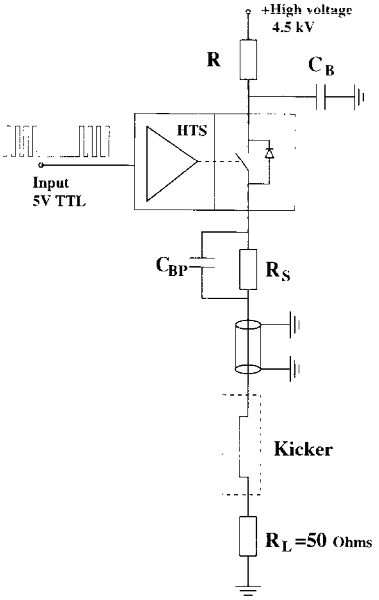

Fig. 5. Schematic sketch of the high-voltage pulse generator ($R = 100\,\Omega$, $C_B = 10\,\mu$F, $C_{BP} = 33$ pF, $R_S = 47\,\Omega$).

3. Results

Fig. 6 shows output signals of the kicker fed by the high-voltage pulse generator. The signals are taken from 1 : 120 attenuator. The scheme of the measurements is the same as presented in Fig. 4. High-precision 500 MHz bandwidth HP54542A oscilloscope is used for the signal recording. One can see that maximum amplitude of the pulse is about $U_m = 2.4$ kV. It is obtained with the input DC voltage on the switch of about 4.5 kV. Amplitudes of the positive and negative pulses are somewhat unequal, probably due to unequal output attenuations, and somewhat different amplitudes of the positive and negative high-voltage pulses from the 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)

$$S(t) = U_m \frac{ct_p}{\pi a}[\cos(\pi/t_p \max(0, t - l/c)) - \cos(\pi t/t_p)],$$
$$t \le t_p/2 + l/c,$$
$$S(t_p/2 + l/c - \Delta t) = S(t_p/2 + l/c + \Delta t). \qquad (5)$$

Thus, the maximum kicker strength for the pulses shown in Fig. 6 with taking into account the effect of averaging over the passage through the kicker is equal to

$$S_m = S_0\left(\frac{\sin(\pi l/ct_p)}{\pi l/ct_p}\right) \approx 2.76\ \mathrm{G\,m}. \qquad (6)$$

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

Fig. 7 demonstrates the negative input signal (upper plot) and the reflected pulse (see lower plot). The reflection is delayed by about 100 ns with respect to the initial signal 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% of the initial amplitude. Further improvement in the reflected pulse reduction needs the precise mechanical tuning of the plate connections to the output kicker conductors. That is one of the goals of the next stage of the kicker improvement.

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

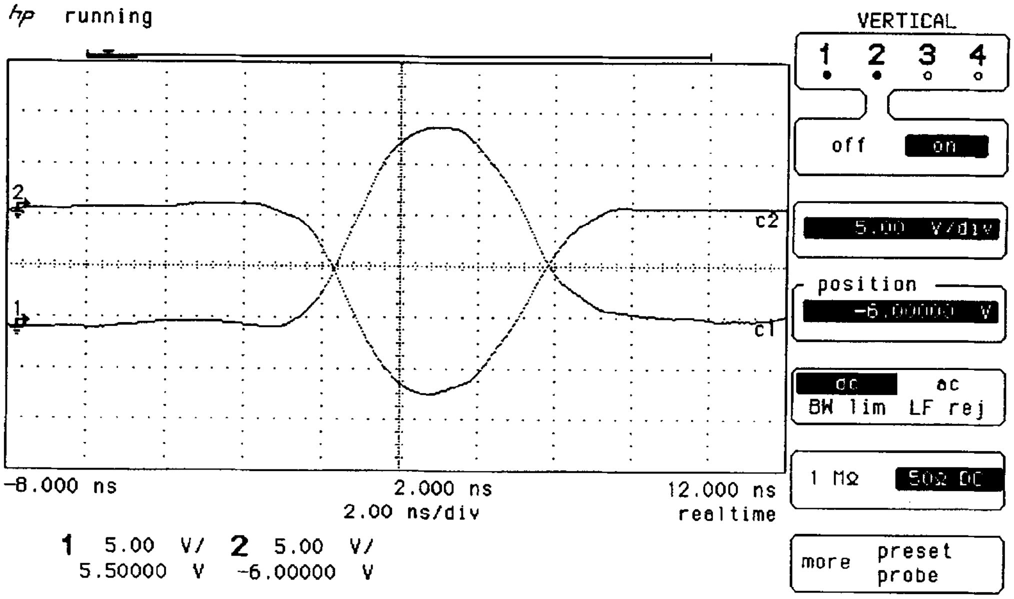

Fig. 6. High-voltage pulses at both outputs (attenuation 1 : 120).

As the TESLA damping ring beam extraction requires 1130 pulses spaced by 0.7 μs and this pulse train to be repeated 5–10 times a second, we studied the kicker in such conditions. General conclusion is that the pulse generator works well in this regime. The only problem we observed was monotonically decreasing 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. To carry out the mean power maintenance test, we used smaller number of pulses (several dozens) in the train with correspondingly increased repetition rate, and the kicker works well with the design average power of 18 W.

4. Discussion and conclusion

A 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 μs, 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.

The ways to increase the kicker strength are immediately seen from Eq. (1). For that one has to either increase the maximum voltage U_m, or decrease the device aperture a, or increase the kicker length l. The maximum voltage is limited by FET breakdown in HV switches. Nevertheless, there are existing switches with U_m of about 8–10 kV, while, at the sacrifice of pulse spacing and repetition rate, the voltage can be increased up to 15–25 kV. Usually, there is very little freedom in decreasing the kicker aperture in circular accelerators, nevertheless, for some applications which use single passage tiny beams (e.g. in linacs), the shrinking of a can be useful. Finally, making longer kicker one has to take into account the required kick duration because the traveling wave kicker has intrinsic kick growth time proportional to the length $\tau_g = 2l/c$ which should be less than bunch spacing in accelerator. Thus, fast and strong deflection can be done by the use of several short kickers, e.g. the bunch spacing of $\tau = 20$ ns requires the kicker to be sectioned into several parts each of them has to be shorter than $l = \tau c/2 = 3$ m.

All together, one can estimate maximum strength of the fast kicker for accelerator applications – which we think can be realized at the moment – taking the parameters of $U_m = 12$ kV, $2a = 4$ cm and total length of $l = 10$ m, that results in the strength of $S_m = 400$ G m. This value indicates that fast traveling wave kickers with semiconductor pulse generators can be widely used at medium- and high-energy accelerators.

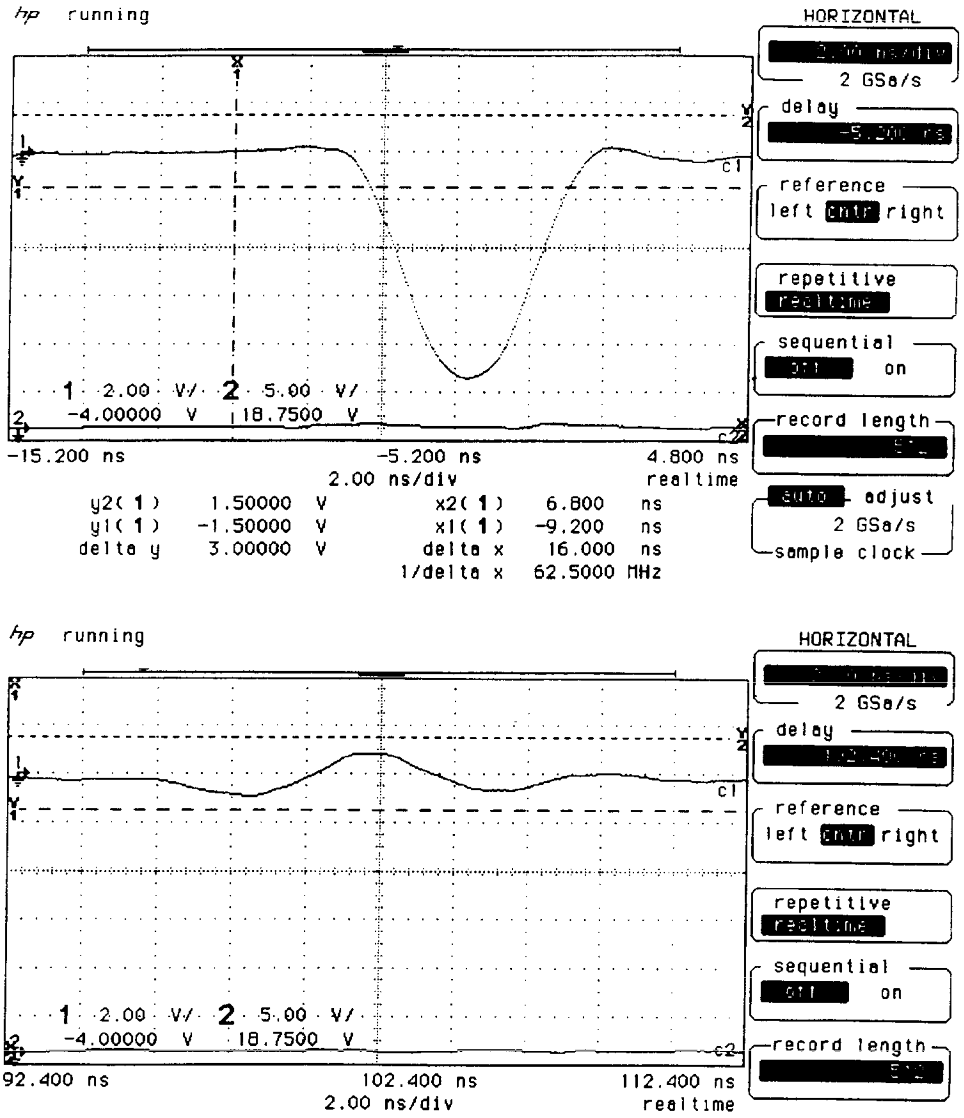

Fig. 7. Upper – high-voltage output pulse; lower – reflected pulse. Attenuation 1 : 120.

Acknowledgements

We would like to thank A.I. Butakov, R.V. Melekhova, L.V. Mironenko and V.V. Anashin (Novosibirsk INP) for their help in designing, production and preliminary testing of the fast kicker, and H. Gundel (TU Berlin) for assistance in the pulse generator handling. We acknowledge useful discussions with J. Marriner, P. Colestock, and C. Jensen (FNAL). We are indebted to N. Dikansky (INP), D. Finley (FNAL), R. Brinkmann, R. Kose and D. Trines (DESY) for their steady interest and support of this work.

References

[1] R. Brinkmann, Proc. IEEE PAC'95, Dallas, 1995, pp. 674–676.
[2] V. Shiltsev, DESY Print, TESLA 96 (02) 1996.
[3] V. Shiltsev, Nucl. Instr. and Meth. A 374 (1996) 137.
[4] J.P. Delahaye, J.P. Potier, CERN/PS 94-15 (LP), and Proc. of EPAC'94, London, 1994, pp. 2373–2375.
[5] D.G. Koshkarev, DESY Print, TESLA 95 (16) 1995.
[6] A. Dubrovin, MERMAID 2D and 3D Codes, Budker INP, Novosibirsk, 1995.