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Abstract

We describe a very fast kicker with unique combination of high repetition rate and short pulse width. Constructionally, the device is a symmetrical counter traveling wave stripline 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 very useful tool for bunch-by-bunch injection/extraction and other accelerator applications.

1 INTRODUCTION

The TESLA linear $e^+ - e^-$ collider project (see, e.g. [1]) requires that the train of 1130 bunches with total length of 0.8 ms, or 240 km must be stored in a damping ring in a compressed mode with a bunch spacing smaller than in the linac, and then expanded with use of bunch-by-bunch extraction out of the ring. 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 [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 [3]. The pulse spacing must be 0.7 μs.

Many present-day fast kickers are essentially ferrite kickers fed by thyratrons. They enjoy high voltage abilities of thyratrons but can not work effectively with repetition rate above dozen of Hz and can not provide the kick duration less than 50-100 ns. Here we describe a device which operates with one order of magnitude shorter pulses and five orders of magnitude higher repetition rates. Constructionally, the device is a symmetrical counter traveling wave stripline kicker fed by FET based pulse generator. We present test results of the kicker prototype which fits to the mentioned above requirements.

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). Details of kicker construction and preliminary test results can be found in Ref.[4].

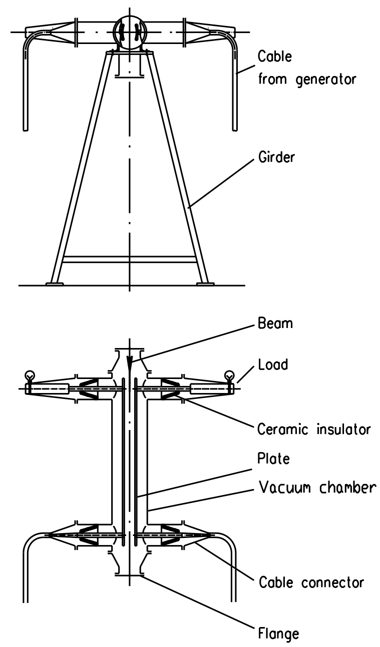

Figure 1: Traveling wave kicker design.

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 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 pulses pass ceramic outputs (the same construction as the inputs) and in ideal case are fully damped in two 50 Ohms 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

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electric and magnetic components cancel each other for the beam which goes in the same direction as the pulse.

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 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”.

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 can not 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 pulse FWHA equal 6-8 ns.

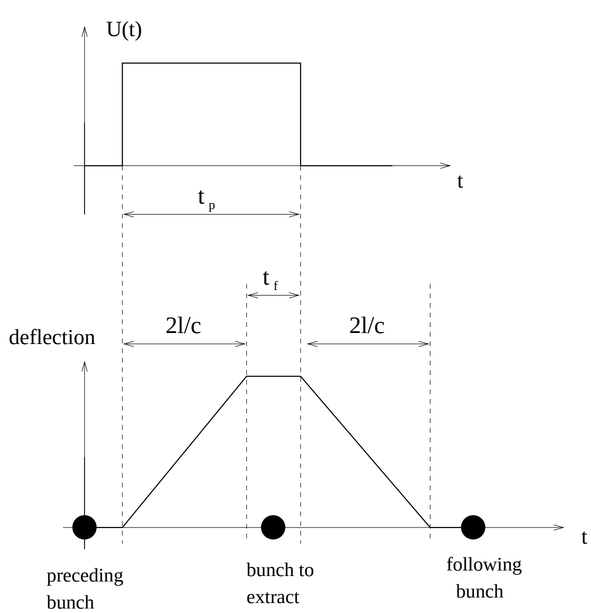

Figure 2: Operation of traveling wave kicker.

2.3 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 electrodes are not flat, their shape is optimized in order to achieve homogeneous field and the wave resistance of 50 Ohms. Calculated field non-uniformity is less than 10% over 80% of full aperture of $2A_x \times 2A_y \approx 50 \times 50$ mm^2.

2.4 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^{o}C under continuous vacuuming with use of oil-free magneto-discharge pumps. 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 at repetition rate of 1 Hz. The loads were taken off the kicker. The test has shown no spark or discharge events over 10 minutes interval.

The kicker element impedances matching was checked with use of low voltage short pulse generator. 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. During the test with 12 ns long pulse which has 2 ns rise and fall times we found that the reflected pulse has some 5.5% in amplitude mostly due to reflections at the initial pulse fronts.

2.5 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 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 $89 \times 64 \times 31$ mm^3. Generator provides 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.

3 RESULTS

Fig.3 shows about 120 times attenuated outputs of the kicker fed by high-voltage pulse generator. High-precision

500 MHZ bandwidth HP54542A oscilloscope was used for signal recording. 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. The pulse shape is close to half-period of sine function with zero-to-zero duration of $t_p \approx 6$ ns. Being installed at the E =3.3 GeV TESLA damping ring such kicker can deflect the positron beam by $\theta_m \approx 30\,\mu$rad, that corresponds to about $\theta\sqrt{\beta\beta_k} \simeq 6$ 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.

Reflected pulse amplitude was found to be less than 8% of the initial one. Further reflected pulse reduction needs precise mechanical tuning of the plate convections to the output kicker conductors. Observed pulse-to-pulse amplitude variations were definitely less that 5%, but the stability issue was not studied thoroughly.

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 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 (few dozens) in the train with correspondingly increased repetition rate, and the kicker works well with the design average power of 18 W.

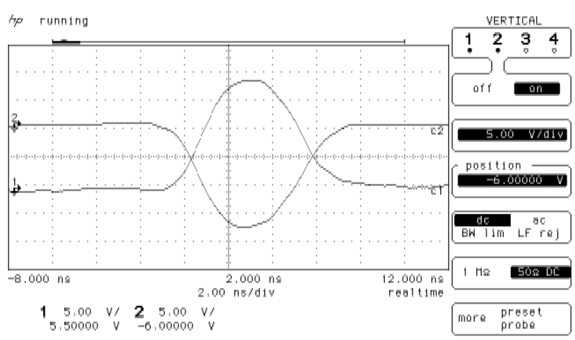

Figure 3: High voltage pulse at both outputs (attenuation 1:120).

4 DISCUSSION AND CONCLUSION

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 3 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.

There are some ways to increase the kicker strength. For that one has 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 no large 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 and possible. 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 with 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.

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