Beam-Beam Kicker for Superfast Bunch Handling

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Abstract

A novel method of a very fast kicker based on beam-beam forces is suggested. The method assumes impact of a high pulse current, low energy beam on the bunches which circulate in a storage ring. The kicker allows to handle separately the bunches spaced by only a few tens of centimeters. The article is devoted to the technical consideration of the kicker construction, its' ultimate possibilities and the choice of its' parameters. Two schemes with head-on and perpendicular crossing are considered. The possible applications of the beam-beam kicker as an injector/extractor for the TESLA damping ring and as a diagnostic tool at multibunch storage rings are discussed.

1 Introduction

In recent years, the tendency of increasing current in modern accelerators had lead to projecting of storage rings that should operate with up to some hundreds of bunchs. The examples include B-Factories [1], $\tau - C$ Factories, damping rings for linear colliders [2] and some others. Growing number of bunches takes place in parallel with decreasing of the bunch-to-bunch distances, that arises serious wakefields issues at high mean currents and produce difficulties with multiturn ejection/injection. The multibunch instability is cured by a feedback system which has to have a large band width and high power. The multiturn ejection/injection (necessary, for example, in the TESLA damping ring) needs a very broad band and powerful kicker. If the bunch-to-bunch spacing is only several meters then conventional kickers (with the rise-and-fall time of the order of 50 ns) can not handle the bunches separately.

This article describes a novel scheme for a superfast kicker. The deflecting force of the kicker is produced by high pulse current, low energy beam. This kicker beam can be injected inside the vacuum chamber of the storage ring along or across the orbit. The beam-beam kicker (BBK) with quite reasonable parameters can provide the kick duration of about fractions of a nanosecond.

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The ejection/injection problem is a great issue for the damping ring of the linear $e^+ - e^-$ collider TESLA [4]. Basic parameters of the ring are given in the Table 1.

Table 1: Basic Parameters of TESLA Damping Ring

Energy	E	3.3	GeV
No. of bunches	N_b	~ 1100	
Particles/bunch	N_e	$3.6{\cdot}10^{10}$	
Bunch length	$\tilde{\sigma}_s$	~ 1	cm
Damping times	$\tau_s/\tau_{x,y}$	18.5/37	ms
Norm. emittances			
at injection	$\epsilon_x^0/\epsilon_y^0$	$10^4/10^4$	μm
at ejection	ϵ_x/ϵ_y	10/0.2	μm

The TESLA design intends a bunch train duration of about 800 μs (or about 240 km length) in the main linac. The bunch train must be compressed in a storage ring and then expanded when extracted out of it. If one assumes to use a kicker for the ejection with rise/fall time τ, then the circumference of the ring is about $C[km] \simeq \tau[ns]/3$. For example, the "dog-bone" proposal for the damping ring assumes $\tau \sim 60$ ns, and therefore, $C \simeq 20$ km [3]. As we'll see below, the beam-beam kicker allows to get $\tau \leq 1$ ns; thus, the ejection requirement plays no role for the choice of the circumference. A low-cost solution could then be a much smaller ring in an appropriate existing accelerator tunnel, e.g. the PETRA tunnel with $C \approx 2.3$ km. In that case, the required $\tau \simeq$7 ns could be easily provided by the BBK.

Another important parameter is the strength of the kicker. It depends on the DR energy, the thickness of magnetic or/and electric septum, the bunch sizes. Let us estimate the kicker strength for the TESLA DR injection/ejection schemes assuming beta function at the kicker $\beta \approx 200$ m and requiring beam kick of about $5\sqrt{\epsilon/\gamma\beta}$ at injection and about $10\sqrt{\epsilon/\gamma\beta}$ at ejection. The results for vertical and horizontal schemes are presented in Table 2.

The possibility of the beam-beam kicker to achieve these goals will be discussed in this work.

Aside the introduction, the article consists of four sections. Section 2 is devoted to general consideration of the kicker schemes. Estimations of stability requirements, the emittance growth at the ejection and the effect of resistive vacuum chamber wakefields are considered in Section 3. Ultimate possibilities of the kicker which comes from the

Table 2: Kicker Strength for the TESLA DR

		Injection	Ejection
Vertical	θ	435 μrad	3.9 μrad
	P	48 $Gs \cdot m$	0.43 $Gs \cdot m$
Horizontal	θ	435 μrad	27.5 μrad
	P	48 $Gs \cdot m$	3 $Gs \cdot m$

analysis of the appropriate sources are estimated in Section 4. Finally, in Section 5 we discuss advantages and disadvantages of the BBK in comparison with some other fast kicker schemes, and possible application of the beam-beam kicker scheme for beam diagnostic at accelerators.

2 Beam-Beam Kicker

2.1 Head-On Beam-Beam Kicker

Fig.1 illustrates the principle of the beam-beam kicker operation. The low energy, high pulse current (electron) bunch is injected into the vacuum chamber of the storage ring. It moves at some the distance of d along the orbit of the high energy beam (HEB) circulating in the ring. Both the electric and magnetic forces of the low energy beam (LEB) kick the HEB while the two bunches pass each other. Then the low energy beam (LEB) leaves the vacuum chamber to the beam dump before the arrival of the next high energy bunch. Therefore, the beam-beam kicker interacts with only one bunch in the ring, and the kick duration is $\tau_0 \approx l/c$ where l is the LEB length, c is the speed of light. For the few-cm long LEB the value of τ_0 could be as small as some hundreds of picosecond. However, one must take into account that some space is necessary for the LEB injection and ejection, so, if the total length of the vacuum chamber segment for the BBK is l_{BBK} then the effective kicker time is $\tau \approx l_{BBK}/c$. This time could be in the order of few nanoseconds – let us take for the numerical example, that the energy of the LEB is about 2 MeV, then 200 Gs magnetic field over the distance of 30 cm allows to eject the kicker beam out of the vacuum chamber aperture of about 3 cm. Thus, $l_{BBK} \simeq 60$ cm, and $\tau \simeq 2$ ns.

Let us calculate the strength of the beam-beam kicker. We'll consider the relativistic LEB with round Gaussian transverse charge distribution and linear charge distribution $\lambda(z)$:

$$\rho(x,y,z) = \frac{\lambda(z)}{2\pi\sigma_r^2} e^{-\frac{x^2+y^2}{2\sigma_r^2}}, \quad (1)$$

$$\int_{-\infty}^{+\infty} \lambda(z)dz = Ne, \quad (2)$$

here Ne is the total bunch charge, and σ_r is the rms bunch size. Radial electric and azimuthal magnetic fields of the bunch are equal to (see also Fig.2):

$$E_r = \frac{2\lambda(z)}{r}(1 - e^{-\frac{r^2}{2\sigma_r^2}}), \quad r^2 = x^2 + y^2, \quad (3)$$

$$H_\theta = \beta E_r, \quad \beta = 1 - \frac{1}{\gamma^2}. \quad (4)$$

The fields have a maximum at $\zeta = (r/\sigma_r) \approx 1.586$:

$$E_r^{max} = \frac{2\lambda(z)}{\sigma_r}\frac{\zeta}{1+\zeta^2} \approx 0.9\,\frac{\lambda(z)}{\sigma_r}. \quad (5)$$

We assume that the length of the high energy bunch in the DR (that is typically of the order of 1 cm) is less than the length of kicker bunch, then the angle kick provided by the BBK is equal to:

$$\theta(d) = \frac{e\int[E_r + \beta^2 H_\theta]dz}{\gamma mc^2} \approx \frac{2e}{\gamma mc^2}\int E_r dz = \frac{4Nr_0}{\gamma}\,\frac{1 - e^{-d^2/2\sigma_r^2}}{d}, \quad (6)$$

here $r_0 = e^2/mc^2$ is the classical electron radius.

Choosing the optimum value of $d_0 = \zeta\sigma_r$ one gets:

$$\theta_0 = \frac{4Nr_0}{\gamma\sigma_r}\frac{\zeta}{1+\zeta^2} \approx 1.8\,\frac{Nr_0}{\gamma\sigma_r}. \quad (7)$$

Using the last equation, useful formulas can be derived for the kick angle θ_0 and for the kicker strength P_{BBK}:

$$\theta_0[\mu rad] = 250\frac{N[10^{11}]}{\sigma_r[mm]E[GeV]}, \qquad P_{BBK}[Gs\cdot m] = 8.4\frac{N[10^{11}]}{\sigma_r[mm]}. \quad (8)$$

Operation of the BBK at the optimum distance of $d = \zeta\sigma_r$ allows to minimize the required charge of the kicker beam. Another advantage is minimization of the kick spread in the HEB with finite transverse sizes $\tilde{\sigma}_{x,y}$. Such spread comes from unequal kicks for different particles and leads to the growth of the bunch transverse emittance. The effect is a point of concern at the ejection out of the DR.

If we suppose the vertical ejection at the optimum distance $y = d_0$ and $x = 0$, then the variations of the fields are quadratic forms of the coordinates:

$$\Delta E_y \approx \frac{(y-d_0)^2}{2}\frac{\partial^2 E_x}{\partial x^2} = -\frac{(y-d_0)^2}{2}\frac{E_r^{max}}{\sigma_r^2}\frac{\zeta^2-1}{\zeta^2}, \tag{9}$$

$$\Delta E_x \approx (y-d_0)\cdot x\frac{\partial^2 E_x}{\partial x \partial y} = -(y-d_0)\cdot x\frac{E_r^{max}}{\sigma_r^2}\frac{1}{\zeta^2}. \tag{10}$$

The integration over the HEB cross section gives the increase of emittances:

$$\Delta\epsilon_y = \gamma\beta_y\theta_0^2\frac{3\tilde{\sigma}_y^4}{4\sigma_r^4}\frac{(\zeta^2-1)^2}{\zeta^4}, \tag{11}$$

$$\Delta\epsilon_x = \gamma\beta_x\theta_0^2\frac{\tilde{\sigma}_y^2\tilde{\sigma}_x^2}{\sigma_r^4}\frac{1}{\zeta^4}. \tag{12}$$

Let us take as a numerical example the parameters of the TESLA DR at vertical $10\sigma_\theta$ ejection with β_y=200 m and β_x=20 m. The size of the kicker beam is chosen to be about σ_r=3 mm and the LEB population should be about $N \approx 1.5 \cdot 10^{10}$ (i.e. the total bunch charge of about 2.4 nC). The vertical and radial rms sizes of the HEB are equal to 78 μm and 174 μm correspondingly, and the increases of emittances can be estimated as:

$$\frac{\Delta\epsilon_y}{\epsilon_y}[\%] \approx 2.7\cdot 10^3\left(\frac{\tilde{\sigma}_y}{\sigma_r}\right)^4 \approx 0.001\%, \tag{13}$$

$$\frac{\Delta\epsilon_x}{\epsilon_x}[\%] \approx 3.2\left(\frac{\tilde{\sigma}_y\tilde{\sigma}_x}{\sigma_r^2}\right)^2 \approx 10^{-5}\%. \tag{14}$$

These reasonable numbers let us to consider the BBK scheme as very promising for the ejection purposes. If the parameters of other machines lead to the dangerous emittance increase then the flattened kicker beam can be used.

As the emittances of the TESLA DR are some thousands times larger at the injection then the kicker strengths is needed to be almost hundred times larger. Thus beam-beam kicker must operate with very high charge of the order of 300 nC. In Section 4 below we'll overview the ability of modern sources to provide such kicker beam.

2.2 "Cross" Scheme of the Beam-Beam Kicker

Let us consider another possible scheme – namely, when the kicker beam travels across the orbit of the storage ring (see Fig.3). The scheme needs no additional magnets for the kicker beam injection and ejection.

We again will denote the distance between the kicker beam trajectory and the orbit as d and the charge distribution of the kicker bunch is as in Eq.(2) above. Then the vertical electric force that acts on the high energy particle placed at x is equal to:

$$F_y = \frac{2e\lambda(z)d}{r^2}(1-e^{-\frac{r^2}{2\sigma_r^2}}), \quad r^2 = d^2 + x^2. \tag{15}$$

and, therefore, the kicker strength and angular kick:

$$P_{\perp BBK} = \frac{1}{e}\int F_y dx, \qquad \theta_\perp = \frac{eP_{\perp BBK}}{\gamma mc^2}. \tag{16}$$

(Note, that here z is for the coordinate along the kicker beam, and x is the coordinate along the HEB orbit). The kick is produced only by the electric field while the magnetic force gives zero contribution as integrating over the x axis.

The integration of the Eq.(16) is trivial in the case of constant linear charge distribution $\lambda(z) = \lambda_0$:

$$P_{\perp BBK} = 2\lambda_0\pi\Phi(\frac{d}{\sqrt{2}\sigma_r}), \qquad \Phi(x) = \frac{2}{\sqrt{\pi}}\int\limits_0^x e^{-t^2}dt. \tag{17}$$

As the *error function* $\Phi(x)$ exponentially small differs from 1 if $d/\sigma_r \gg 1$, then one can get following formulas:

$$\theta_\perp[\mu rad] = 183\,\frac{J[kA]}{E[GeV]}, \qquad P_{\perp BBK}[Gs\cdot m] = 6.1\,J[kA]. \tag{18}$$

Applying these formulas to the TESLA damping ring, one can obtain that the current of about $J \simeq 70$ A is necessary for vertical ejection, 500 A is enough for horizontal ejection, and 7.9 kA kicker beam current can provide the injection.

A big advantage of the cross scheme is that the kick angle doesn't depend on the beam-beam distance d if the distance is much bigger than σ_r (say, $3\sigma_r$ is quite enough for that).

The cross scheme requires a comparatively long kicker bunch with smooth linear distribution function, otherwise the particles at the head of the high energy bunch will get the kick that is different of the center particles kick. Let us assume Gaussian distribution for the kicker beam with the rms longitudinal size σ_z:

$$\lambda(z) = \frac{Ne}{\sqrt{2\pi}\sigma_z}e^{-\frac{z^2}{2\sigma_z^2}}. \tag{19}$$

Then the integral of Eq.(16) for the particle of the HEB that is at the distance of s out of the HEB center, will take form:

$$P_{\perp BBK}(s,d) = \frac{2eNd}{\sqrt{2\pi}\sigma_z}\int\limits_{-\infty}^{+\infty}\frac{1-e^{-\frac{x^2+d^2}{2\sigma_r^2}}}{x^2+d^2}e^{-\frac{(x-s)^2}{2\sigma_z^2}}dx. \tag{20}$$

Under the condition that the LEB length is much bigger than the length of the HEB $\sigma_z \gg \tilde{\sigma}_s \gg (\sigma_r, d)$, the integration can be easily performed, and in the lowest order of smallness we obtain:

$$P_{\perp BBK}(s,d) \approx \frac{2\pi eN}{\sqrt{2\pi}\sigma_z}e^{-\frac{s^2}{2\sigma_z^2}}\Phi(\frac{d}{\sqrt{2}\sigma_r})\Big(1-\Phi(\frac{d}{\sqrt{2}\sigma_z})\Big). \tag{21}$$

Thus, the emittance increase during the ejection of the Gaussian HEB with rms length $\tilde{\sigma}_s$ can be calculated as:

$$\frac{\Delta\epsilon_y}{\gamma\beta_y\theta_0^2} = \int_{-\infty}^{+\infty}(1-e^{-\frac{s^2}{2\sigma_z^2}})e^{-\frac{s^2}{2\tilde{\sigma}_s^2}}\frac{ds}{\sqrt{2\pi}\tilde{\sigma}_s} = 3(\frac{\tilde{\sigma}_s^2}{\sigma_z^2} - 2 + \frac{2}{\sqrt{1+\frac{\tilde{\sigma}_s^2}{\sigma_z^2}}}) \approx \frac{3\tilde{\sigma}_s^4}{4\sigma_z^4}. \tag{22}$$

Therefore, to keep the emittance increase within 1% one must have kicker bunch length $\sigma_z \geq 10\tilde{\sigma}_s \simeq 10$ cm. The BBK with such bunch can be used if the bunch spacing in the storage ring is more than $3\sigma_z \simeq 30$ cm.

The obvious disadvantage of the cross scheme is that for the same kick is needs about $\sigma_z/\sigma_r \sim 20$ times more charge of the kicker beam.

Before finishing the Section, let us note that the ultimate possibility of the BBK to operate with some centimeters distanced bunches can not be applied in the TESLA damping ring because the bunch spacing is restricted by multibunch dynamic issues at high mean current in the ring (the single bunch population is considered to be fixed). If one takes the maximum value of the mean current to be handled with a multibunch feedback system of the order of 1 A, then the minimum circumference is $C \approx 2$ km, and the bunch-to-bunch distance is about 2 m. As we have shown above, it is far within the abilities of the beam-beam ejection.

3 Kick Imperfections

3.1 Charge stability of the kicker beam

There are some sources of the kick imperfections in the BBK schemes. First of all, the shot-to-shot variation of the total charge (or current in the "cross" scheme) will lead to the jitter of the kick deflection angle. For kick strength of $10\sigma_\theta$, the desired stability of the kick $\Delta\theta_0/\theta_0 = 0.1 \cdot \sigma_\theta$ requires to keeping the variations of the kicker beam charge (current) within $\Delta Q/Q = 1\%$. If the requirement can not be satisfied with a chosen kicker beam source, then the BBK scheme offers an opportunity to make a feedback for the compensation of the kick jitter. The charge (or current) can be measured in the kicker beam dumper (Faraday cup) with a precision better than 1%, the signal to be included in the feedback loop and the difference can be compensated in the bunch length compressor scheme or in the main linac.

3.2 Resistive wall wakefields

When the LEB travels through the vacuum chamber, it will generate a wake field if the chamber is not perfectly conductive. A finite conductivity allows the induced magnetic field to penetrate into a metal wall with the result that the magnetic force decays more slowly than the electric force. This gives rise to a net wake field force on the later bunches. The transverse wake field has been investigated in [6]. Here we'll use an approximate formula [7] for the magnetic field B_y behind a short δ-function bunch with total charge of Ne that gives wake kick vs. time t after passing the beam:

$$B_y(t) \approx -\frac{2Ned}{\pi b^3(\sigma t)^{1/2}}, \tag{23}$$

where σ is conductivity of the vacuum chamber ($5.2{\cdot}10^{17}s^{-1}$ for copper), b is the beam pipe radius, d is for the beam-beam distance as it was introduced above. The approximation (23) is valid if the bunch spacing is much longer than the bunch length. After characteristic *diffusion* time T_d :

$$T_d \approx \frac{2\pi\sigma b\Delta}{c^2}, \tag{24}$$

where Δ is the thickness of the pipe, the $t^{-1/2}$ law changes to the exponential one with the decay time T_d. For the copper pipe with $b = 3$ cm, $\Delta = 0.2$ cm $T_d \approx 0.73$ ms.

The effect of the parasitic kick due to the wake fields with respect to the main kick (7) can be estimated as:

$$\eta(t) = \frac{\Delta\theta_{wake}(t)}{\theta_0} \approx \frac{d^2}{2\pi b^2}\frac{l_{pass}}{b(\sigma t)^{1/2}}\frac{\zeta^2}{1+\zeta^2} \tag{25}$$

where where l_{pass} is the length of the vacuum chamber from the injection of the LEB to its' extraction.

Let us estimate the effect of wakes induced by the LEB in the TESLA damping ring. As the value of T is about full ejection time for the ring (0.8 ms), so the formula (23) is applicable for all ejected bunches. The maximum relative kick $\eta_{max} \simeq 2.4 \cdot 10^{-6}$ will be experienced by the bunch that comes next after the ejected one ($L_{bb} \approx 2$ m, $l_{pass} \approx 60$ cm). This value can be considered as negligible.

3.3 Position jitter and emittance growth

As the kick (6) depends on the distance d, then one should consider the jitter effect [1].

Using formulae Eq.10, one can derive the requirement on the d-jitter :

$$\frac{\Delta d}{d} \leq \sqrt{\frac{\Delta\theta_0}{\theta_0}\frac{2}{\zeta^2-1}} \simeq 1.14\sqrt{\frac{\Delta\theta_0}{\theta_0}}. \tag{26}$$

If we assume allowable value of the kick jitter of the order of $\Delta\theta_0/\theta_0 \simeq 0.5$ %, and $d \simeq 5$ mm, then beam-beam distance d should be stabilized within $\Delta d \simeq 0.4$ mm. Similar estimation gives that kicker beam rms transverse size σ_r must not vary more then 13% of its' value.

One must also take into account that the LEB is also deflected while passing by the high energy bunch. The deflection angle of the LEB is equal to (compare with Eq.(8)):

$$\theta_{LEB}[mrad] = 35\,\frac{N_e[10^{10}]}{\sigma_r[mm]E_{LEB}[MeV]}, \tag{27}$$

where N_e is the storage ring bunch population. Thus, the deflection distance $\Delta d \simeq \tilde{\sigma}_s\theta_{LEB}$, and for the parameters of the TESLA DR we have:

[1] I'd like to mention once more that these effects do not exist in the "cross" scheme, because there is no dependence of the kick on the distance between the LEB and the HEB while that distance is much more than the kicker beam radius.

$$\Delta d[mm] \simeq \frac{0.4[mm]}{E_{LEB}[MeV]}. \tag{28}$$

Therefore, $E_{LEB} \sim 2\div 4$ MeV will be enough to satisfy the beam-beam jitter requirements which we considered above. Note, that as the HEB passes the region where the kicker beam density is about $e^{-\zeta^2/2} \simeq 0.29$ of its maximum value, then some particles of the LEB gets $(\sigma_r/\tilde{\sigma}_{x,y} \sim 30$ times bigger kick than (27). Although the number of the overkicked LEB particles is about $0.29\times(\tilde{\sigma}_x\tilde{\sigma}^y)/\sigma_r^2 \sim 10^{-4}$ times of the total number of N, one must take care to collect them in the kicker beam dump.

4 Kicker Beam Source

The ultimate possibilities of the proposed kicker are determined by the source of the low energy beam. Below, the strengths and needs of the two BBK schemes are briefly summarized:

	"Head-On" BBK	**"Cross" BBK**
Strength	$P_{BBK}[Gs \cdot m] = 0.53\frac{Q[nC]}{\sigma_r[mm]}$	$P_{\perp BBK}[Gs \cdot m] = 0.073\frac{Q[nC]}{\sigma_z[cm]}$
Needs	high charge	high current
	short pulse $\leq 300ps$	pulse length $\geq 300ps$
	small transverse size	

(Here kicker beam parameters are: Q is for the total charge, σ_z is the rms length, σ_r is the rms transverse size).

Contemporary RF photo-injectors look like the most appropriate candidates to be the source. Below we'll follow the RF injectors design strategy and simple formulas presented in Ref.[8].

The space charge forces at the cathode limit restrict the maximum charge by the value of:

$$Q_{max}[nC] = \frac{E_0[MV/m]\sigma_r^2[mm]}{20}, \tag{29}$$

where E_0 is the electric field at the cathode. The maximum gradient depends on the RF frequency of the injector. The review [8] of the achieved values can be summarized in the "2 times Kilpatrick criterion" that satisfactory fits the expression:

$$E_0[MV/m] = 8.47 + 1.57\sqrt{f[MHz]}. \tag{30}$$

The maximum beam size at the entrance of the injectors also depends on its' RF frequency f:

$$\sigma_r[mm] \leq \Sigma(f) = minimum\left(10, \frac{10^4}{f[MHz]}\right). \tag{31}$$

Optimizing the kick strength over f, one finds that the RF frequency of the injector should be $f \approx 1$ GHz, $\sigma_r \approx 10$ mm, $E_0 \approx 60$ MV/m, and then the maximum charge is equal to $Q \approx 300$ nC. Thus the ultimate strength:

$$P_{BBK}^{max} \simeq 16[Gs \cdot m]. \tag{32}$$

The choice of these parameters allows to describe other parameters of the source. Such high gradient as 60 MV/m can be achieved only with normal conducting RF system. To obtain as low as 13% rms energy spread of the bunch, its' length should be less than:

$$\sigma_z[cm] \leq \frac{3 \cdot 10^3}{f[MHz]} \tag{33}$$

that is 3 cm if $f = 1$ GHz. The energy of the LEB can be found from the formula:

$$\gamma = 1 + 147(n + 1/2)\frac{E_0[MV/m]}{f[MHz]} \tag{34}$$

(n is number of accelerating RF cavities) and for 3/2 cell design the energy is about 6.6 MeV. To extract such as big charge from the metallic (Cu) cathode one should have about 1 mW 193-nm wavelength laser micropulses with about 1 mJ energy in each (for the alkali cathode (CsI) – about 20 μJ).

As it is seen from Eq.(32) the strength of the kicker with the maximum charge is some dozen times more that it is necessary for the TESLA DR ejection, but it is still factor of 3 less than the injection requirement of 48 Gs·m. This value can be achieved by reducing the transverse bunch size at the entrance of the injector by using a post-accelerator or with an additional focusing to the value of about 3 mm.

For the "cross" BBK the RF photoinjector with 300 nC charge and 10 cm bunch length will produce the strength of about:

$$P_{\perp BBK}^{max} \simeq 2.2[Gs \cdot m]. \tag{35}$$

Looking for another sources of the kicker beam, the *ferroelectric* cathode guns look quite promising [9]. The ferroelectric (FE) materials need fast switching of its' spontaneous polarization and then the surface charge is repelled out of the cathode. Therefore, the space charge forces give no restriction on the extracted charge. Recently started R&D over the world labs have shown, that, in principle, the FE sources can provide as much as 500-1000 nC charge. As the minimal achieved pulse duration is some dozens of ns, then a post accelerator is necessary to shorten the pulse length.

5 Discussion

5.1 BBK as Electron Beam Monitor

The beam-beam kicker method can be used for the beam diagnostic. Let us consider the dc low-current "test" electron beam passing across the orbit of the storage ring. The beam-beam forces deflect the "test" beam on the angle that depends on the storage ring beam size σ, current $J(t)$ and the beam-beam distance x (compare with formulas for the "cross" BBK above):

$$\theta \approx \frac{2\pi r_0(J(t)/ec)}{\gamma_0}\Phi(\frac{x}{\sqrt{2}\sigma}) \tag{36}$$

here γ_0 denotes the electron beam relativistic factor. Thus, the measured test beam deflection contains (and allows to extract it) the following information on the circulating beam: a) total current; b) bunch length; c) longitudinal charge distribution; d) beam position; e) transverse beam size; f) transverse charge distribution; g) transverse displacement along the beam (similar idea as the last item was recently discussed for the very broad band stochastic cooling pick-up and kicker [10]). Such a device can be very useful for a diagnostics especially at proton accelerators (all the parameters at electron machines can be obtained with use of synchrotron radiation).

Let us take for numerical example parameters of the HERA-p bunch with $4{\cdot}10^{10}$ protons and the rms bunch length of about 25 cm. Then, for $\gamma_0 \sim 3$ one gets $\theta_{max} \sim 0.4$ mrad, that can be easily detected.

5.2 Alternative Kicker Schemes for TESLA DR

Recently, another ejection scheme was suggested in [11] for CLIC and TESLA linear colliders damping rings and it was somewhat modernized in [12] for the TESLA DR. The scheme is based on two deflecting cavities which operates at two appropriate harmonics of the extraction frequency (1.41 MHz for TESLA). While the sum of the two harmonics makes beating, it allows to separate corresponding bunch from the others. Another set of 2 identical deflectors is placed in the ring at π betatron phase advance with identical deflections, therefore, their kicks cancel the kicks of the first pair outside the ejection area. To increase the kick difference for two closely spaced bunches the number of deflectors can be increased, or extreme fast kickers can be added [11].

It was shown in the cited papers that these schemes, in principle, can be adequate for the TESLA damping ring with circumference of 20 km (so-called "dog-bone" version) and 6.3 km (the circumference of the HERA-e).

Nevertheless, if the circumference is down to about 1-2 km, the application of these schemes sees some difficulties. First of all, in order to separate properly the ejected bunch and the next coming one it will need maximum deflection of almost $100\sigma_\theta$ when using only two harmonic deflectors. Beside that at the injection the 100σ value is far above acceptance of the ring, such a big value means big kicker power and high stability requirement of the kick of about 0.05%. Moreover, the cancellation errors of the two pairs of cavities should be down to about 0.01%. One also can note that installation of (at least) 4 additional low frequency deflectors will cost some impedance increase that is undesirable in the ring where the beam stability is a great issue. In addition, the requirement to have π betatron phase advance between the deflectors reproduce some "rigidity" of the ring lattice.

From this point of view, the proposed beam-beam kicker scheme seems almost free of these disadvantages. The BBK produces the necessary kick, needs no cancellation devices, shows very easy requirements and costs quite tiny addition to the ring impedance budget.

As we demonstrated above, there are no physical and technological limitations to construct the BBK for the ejection. The injection BBK scheme needs extremely high charge sources and needs further R&D, but does not seem impracticable.

6 Conclusions and Acknowledgments

The idea of the Beam-Beam Kicker looks very promising for the accelerator applications. The present level of the electron sources development allows to propose the BBK as the basic scheme for single bunch injection/extraction at the accelerator facilities where bunch spacing is too small for conventional kickers. It could be the damping ring(s) for the TESLA $e^+ - e^-$ project, microbunch accelerators, etc. The two discussed variants of the BBK - "head-on" and "cross" - can be chosen for different applications. In particular, the device with tiny electron beam crossing the orbit of the high energy bunch (*Electron Beam Monitor*) can be very useful as a diagnostic tool.

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References

[1] *PEP-II, An Asymmetric B-Factory*, Conceptual Design Report, LBL-PUB-5379, SLAC-418, CALT-68-1869, UCRL-ID-114055, UC-IIRPA-93-01, 1993.

[2] J.Rossbach, *Nucl. Instr. Meth.*, A309, p.25 (1991).

[3] K.Flottmann, J.Rossbach, DESY Internal Report 94-03-K (1994).

[4] R.Brinkmann, *Proc. of IEEE PAC'95*, Dallas, 1995, see also DESY Internal Report M-95-08 (1995), pp.57-59.

[5] P.R.Zenkevich, DESY Print, TESLA 95-15, 1995.

[6] S.Bodner, V.K.Neil, and L.Smith, *Part. Accel.*, 1, p.327 (1970).

[7] G.Rangarajan, K.C.D.Chan, *Phys. Rev. A*, V.39, No.9, p.4749 (1995).

[8] C.Travier, *Nucl. Instr. Meth.*, A340, p.26 (1994).

[9] H.Riege, *Nucl. Instr. Meth.*, A340, p.80 (1994).

[10] F.Willeke, DESY HERA 95-03, p.531 (1995).

[11] J.P.Delahaye, J.P.Potier, *Proc. of EPAC'94*, London, 1994, and CERN/PS 94-15 (LP).

[12] D.G.Koshkarev, DESY Print, TESLA 95-16, 1995.

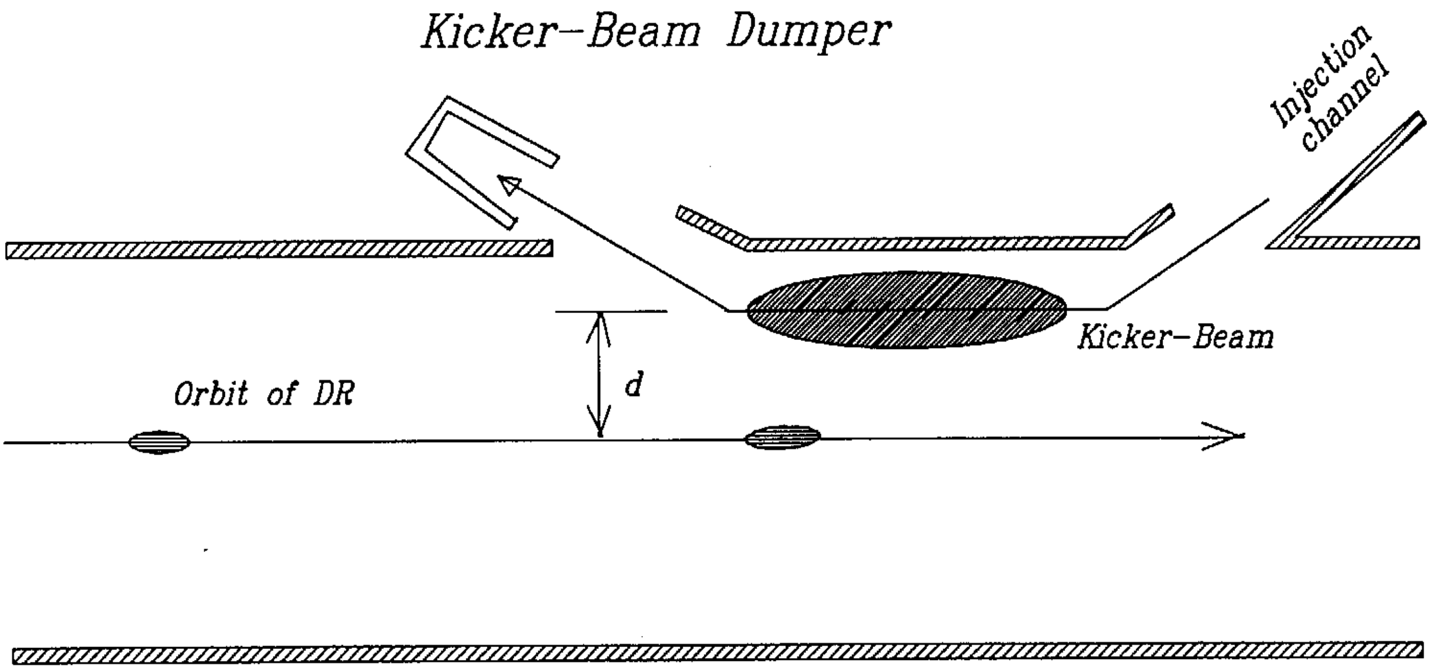

Fig.1: General scheme of the "head-on" beam-beam kicker.

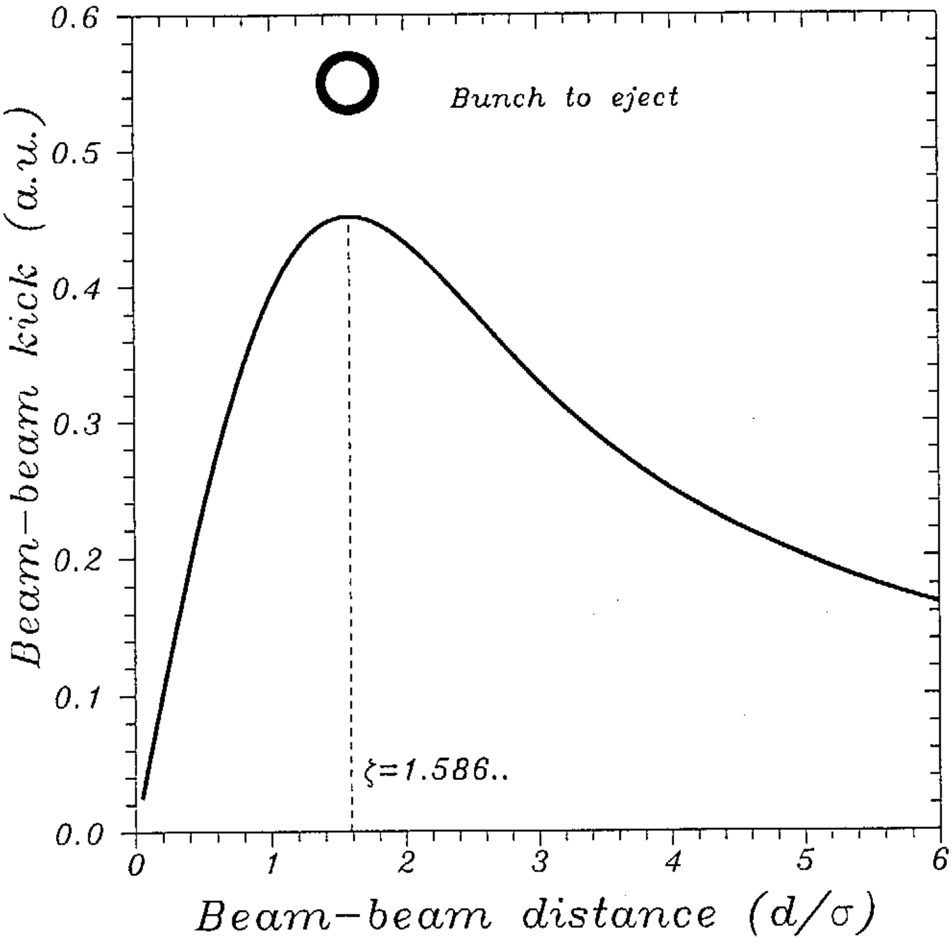

Fig.2: The transverse force vs. beam-beam distance.

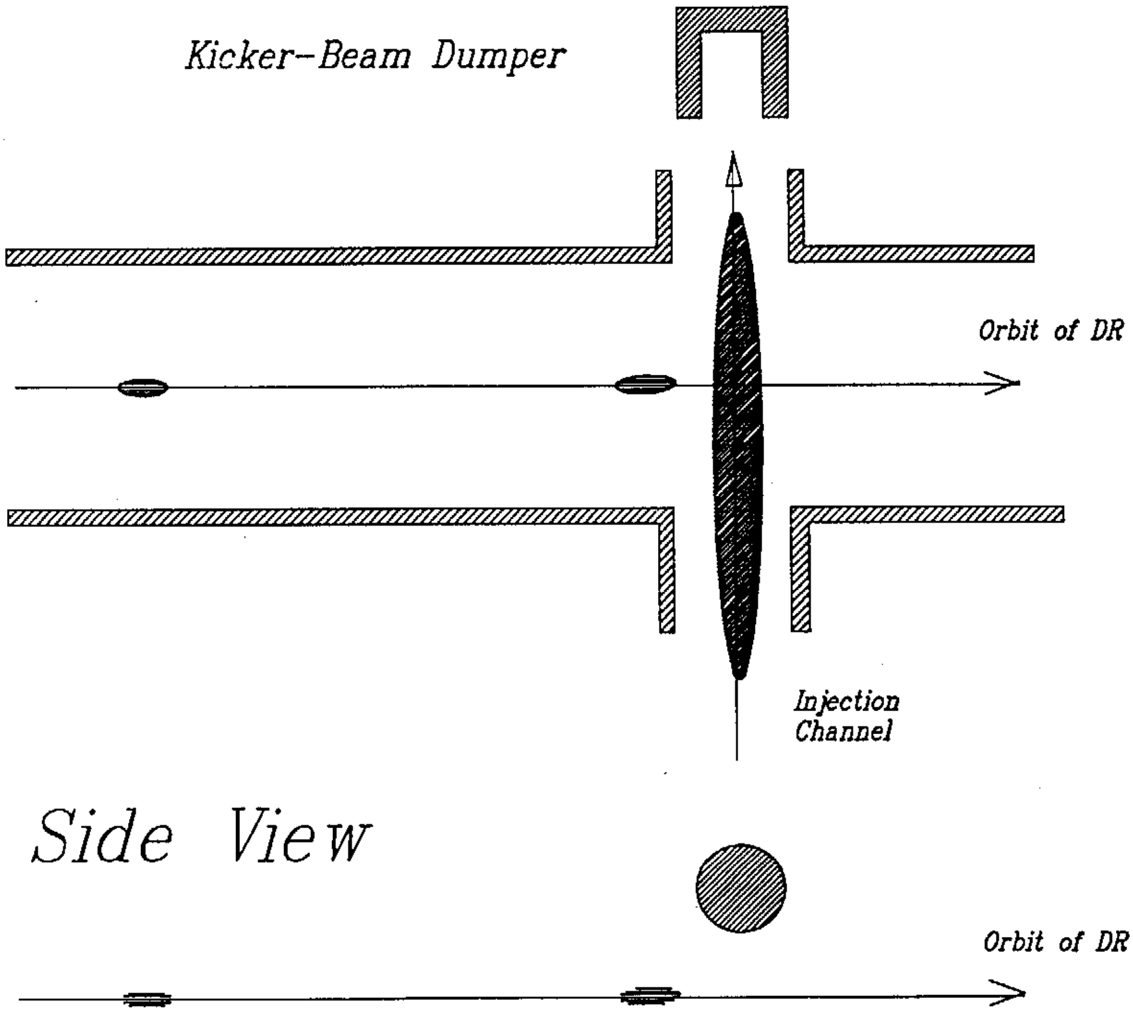

Fig.3: The scheme of the "cross" beam-beam kicker.