

# FAST KICKER

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*Abstract.* We analyze the possibilities for minimizing the kicker rise time down to the rise time of the feeding pulse. For this we are suggesting a 90° orientation of the strip line kicker and the beam. As a pulser we are suggesting a device using many vacuum tubes working in parallel.

In particular, we are proposing a scheme able to provide a kick to 5 GeV bunch, removing it from its orbit in a ~10nsec time window. Establishing/dropping time for the system is estimated to be ~ 0.1 nsec with the ability for a repetition rate up to 3 MHz supported by the suggested pulser.

However, relaxed conditions for ERL allow usage of traditional kicker system with counter propagation of beam and kicking pulse.

## 1. OVERVIEW

Kicker is a device for delivering transverse (typically) momentum to the charged particle beam. Basically, the kicker acts through the electromagnetic (EM) field generated by currents running in its electrodes. As a rule, field in a kicker lasts for a rather short period of time, so it acts to the selected part of the beam only (typically to a selected bunch in a sequence). So the pulsed power supply for this kicker plays an important role in all processes as well as configuration of electrodes and conductors in the kicker itself. So to speak, the kicker electrodes (conductors) and the source of short EM pulse for feeding these electrodes represent an integrated unity. By having the powerful source of short pulses in hand one can simplify the task for designing such pulsed system able to act in a short time.

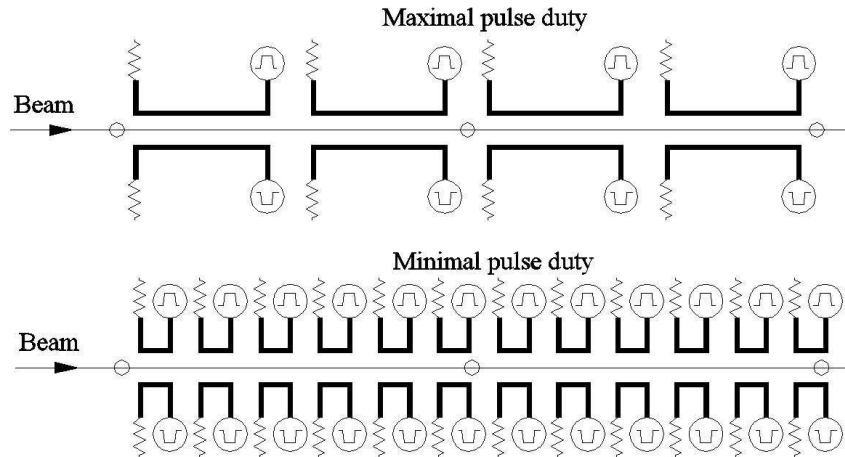


Figure 1: Long kickers (top) and short ones (bottom).

All fast kickers described so far are strip-line electrodes fed by counter propagating EM pulse. As the length of such kicker could not be longer than the half of distance between bunches, the kicker typically sectioned by many units having short length each, Fig. 1. There is no limit for the minimal length of kicker. For matching the impedance of strip line

electrodes immersed in a vacuum chamber, some tapering is required. However, tapering reduces the effective length of a kicker. Also in a region of taper, the higher order modes are excited, which in a time dependent case (as it is) generated substantial nonlinear components [1]. Fortunately parts of pulse changing in time are not suitable for kick so must be excluded from interaction with the beam in any case.

Time duration of the feeding pulse for the kicker of maximal allowed length (which comes to a half the distance between the neighboring bunches) is twice the kicker length i.e. it is coinciding with the time sequence of bunches, which considered as short, compared with the distance between them.

Other example of a sectioned kicker is the able to deflect ILC high energy beam described in [2]. Here, the sectioned kicker is arranged with C-type pulsed magnets having laminated yoke. However, the presence of laminated yoke yields a relatively long time of establishing (ns level at the best, [3]) and, what is more important, the presence of tails of pulse associated with currents captured by laminations within skin-layer. Better results one could expect from the yoke filled by ferrite (see [4], [5] for practical realization of kickers with  $\sim 2$ nsec rise time). Even so, if the kicker deflects only one bunch from the beam sequence, the problems associated with its design are much more difficult, that if the kicker removes the entire beam in a single turn: after-pulse voltage present in a kicker can not do any harm as there is no beam anymore.

Usage of a series of short kickers is profitable from the point of minimization of energy stored in all systems. Really as the bunch planned to be kicked off is short (typically less than a mm) only a fraction of all EM pulses are interacting each moment with the bunch, although the kicker pulse must fill all the space inside kicker. So to speak, for minimal energy consumption the kicking pulse must just be present in space-time only where the (short) bunch is present.

As far as the pulser itself, in [6] there was described a multi-kicker system able to generate 150 kV travelling wave EM pulse in 10-m long ensemble of kickers arranged with  $\sim 30$ -cm long strip line electrodes. The HV generator described there consists of a high-current electron accelerator equipped with the sweeping unit, which directs the electron beam to series of targets each connected to the individual strip line kicker. The accelerator produces 1 kA electron beam with 0.3 ms flat top duration and operates at 100Hz. Kickers composed by many short counter-traveling wave units separately fed by couple pulses having opposite polarities obtained from HV generator described above. The system of targets located at the circle, having its center on the line to the output orifice of accelerator. Girocon-type sweeping device is a RF cavity operating at  $E_{110}$  ( $TM_{110}$ ) with two polarizations shifted by  $90^\circ$  [7]. This project could be considered as absolutely feasible on the grounds of achieved and tested technologies, but requires some investment. We analyze this system (see section 4.1) for the purposes of completion of the search for the best pulser.

We intend, however, to suggest a concept of kicker which has a substantial difference with all ones proposed before in one instance-namely in relative direction of propagation of high energy beam of charged particles and the HV EM pulse. For some particular reason we suggesting a  $90^\circ$  orientation between these two. In this case the time of establishing coincides with the rise time of EM pulse, as the beam size is very small in a typical case.  $90^\circ$  kicker also has no problems with tapering as the tapering and matching impedances does not occupy the space along the beam trajectory, but located aside. The price for these

excellent timing characteristics is half the strength of this device compared to counter-propagating beam and pulse.

Other innovation –we are suggesting to implement long time used vacuum tubes for the purposes of short pulse generation for feeding this kicker, although the pulser with vacuum tubes could be used with any kicker as well.

## 2. INTERACTION OF EM WAVES WITH RELATIVISTIC ELECTRON

Electromagnetic wave in multiply connected waveguide propagates with the speed of light if the wave guide is not filled with media (i.e. its permittivity and permeability coincides with these for vacuum). In this case the time required for the pulse to establish the field equates to the propagating time of pulse front along the kicker. But as the beam could not appear in a kicker a prior the front reaches the end, dead time for this system counted from the moment of pulse front appearance in a kicker comes to be two times the time required for the pulse front to reach the end. This factor of two appears due to the beam and kicker pulse counter-motion with the speed of light practically.

The wave propagating inside multiply connected waveguide (strip-line) –so called general wave can be considered as a plane one [8]. For this wave (CGS units)

$$H_x = -E_y, \quad H_y = E_x, \quad E_z = H_z = 0, \quad (1)$$

and longitudinal dependence could be described as  $H_x(z) = H_{x0}(z - ct)$ , where  $z$  stands for longitudinal coordinate linked with waveguide,  $c$  –is a speed of light. Basically the field distribution could be described here as a solution of 2D problem. The instant transverse force acting to the particle propagating through the waveguide defined by equation (CGS system)

$$\vec{F}_\perp = e\vec{E}_\perp + \frac{e}{c}[\vec{v} \times \vec{H}]_\perp \quad (2)$$

where instant particle's velocity  $\vec{v}$  defined with respect to the coordinate system of the waveguide. In simplest case the particle's trajectory coincides with coordinate  $z$  and could be co-directional or counter-directional with respect to direction of propagation of EM wave. Now let us axis  $z$  directed along particle's trajectory. Forces acting to the particle arising from electric and magnetic components either add one to another or subtract one from the other (with accuracy  $\sim 1/\gamma^2$ ).

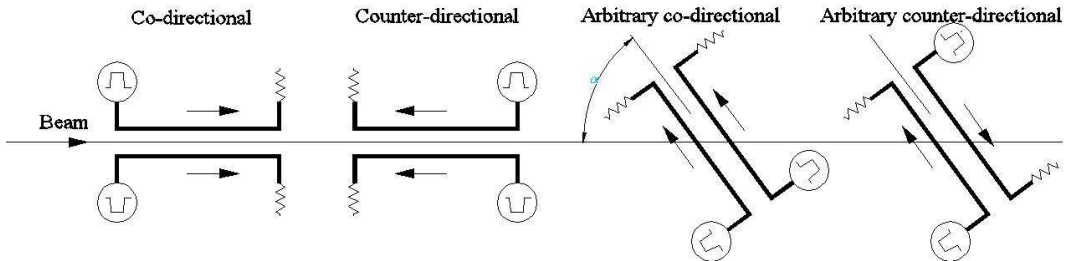


Figure 2: Relationship between direction of the beam and direction of propagation EM in strip line kicker.

The last scheme in Fig.2 allows subtract magnetic field value (at least at median plane) as the currents physically are running in the same direction (positive and negative pulses are running in opposite direction). Kicker with arbitrary orientation could operate by electric or by magnetic field only if the angle  $\alpha = 90^\circ$ . This depend on azimuthal orientation of

strip-lines: for electrostatic operation the beam is going between plates, for magnetic operation it goes through the plates, the last must have appropriate holes in this case (pretty similar as ordinary RF cavity has).

We will be interesting in strip-line kickers acting to the beam trough electric field. We accept that the kick value is reduced at least two times, if compared with counter-propagating case. In return one can get the possibility of very fast establishing fields on particle's trajectory, relaxed condition for tapering lowering total power required from pulser. To compensate weakness of 90o kicker few pulsers must deliver pulses to each kicker so the short pulse must appear at the kicker when the bunch is there (Fig.7).

### 2.1. Kick strength.

In case of extraction of fraction of the beam, some portion of the beam receives a kick and goes to the septum magnet, located downstream. Minimal value of displacement required is a transverse beam size plus the thickness of the septum knife. In case of just elimination of selected bunch the collimator used in place of septum; so the value of kick might be smaller as there is no necessity for the knife; but the difference is small.

Propagation of kick  $x'(s_0) = \alpha$  from its origin at location  $s_0$  to the point located at  $s_1$  counted from the kicker, described by sin-like trajectory  $S(s, s_0)$  having starting point at the kicker location  $s_0$

$$x(s_1) = x'_0(s_0)S(s_1, s_0) = \alpha \cdot S(s_1, s_0), \quad (4)$$

where  $S(s_0, s_0) \equiv S(s_0) = 1$ ,  $\alpha$  is a kick angle; with similar equation for the other transverse coordinate  $y$  if kick happen in other direction too. By introduction of usual envelope function and the phase change as

$$\Delta\Phi \equiv \Delta\Phi_x(s_1, s_0) = \int_{s_0}^{s_1} ds / \beta_x(s), \quad (5)$$

displacement and the slope of the beam centroid at the septum come to

$$x(s_1) = \alpha \sqrt{\beta_x(s_1)\beta_x(s_0)} \text{Sin}(\Delta\Phi), \quad x'(s_1) = \alpha \sqrt{\beta_x(s_0)/\beta_x(s_1)} [\text{Cos}(\Delta\Phi) + \frac{1}{2} \beta'_x(s_1) \text{Sin}(\Delta\Phi)] \quad (6)$$

where  $\beta_x(s_1)$ ,  $\beta_x(s_0)$  stand for envelope functions values at the septum and at the kicker locations respectively (for other coordinate,  $y$ , the functions are  $\beta_y(s_1)$ ,  $\beta_y(s_0)$ ). As the septum located at the betatron phase changed to  $\Delta\Phi \equiv \pi/2$ , so  $\text{Sin}(\Delta\Phi) \equiv 1$ .

So the angular kick required comes to be

$$\alpha = \frac{\sigma_x + \delta}{\sqrt{\beta_x(s_1)\beta_x(s_0)}}, \quad (7)$$

where  $\sigma_x$  stands for the beam size (with appropriate margins) and  $\delta$ - for the septum thickness (this also includes the spatial separation of the steady orbit and the septum edge). Suggesting  $\delta \geq 20\sigma_x$ , one can re-write (7) as the following

$$\alpha = \frac{\sigma_x + 20\sigma_x}{\sqrt{\beta_x(s_1)\beta_x(s_0)}} \equiv \frac{21 \cdot \sqrt{(\gamma\epsilon_x)\beta_x(s_1)}/\gamma}{\sqrt{\beta_x(s_1)\beta_x(s_0)}} = 21 \cdot \sqrt{\frac{(\gamma\epsilon_x)}{\beta_x(s_0) \cdot \gamma}}, \quad (8)$$

where  $\gamma\epsilon_x$  stands for invariant emittance in the direction of kick ( $x$ -direction in this example). One can see that angular kick is just four times the angular spread at kicker location. Substitute here  $\gamma\epsilon_x \cong 0.1 \text{ mm} \cdot \text{mrad}$ ,  $\beta_x(s_0) \cong 5 \text{ m}$ ,  $\gamma \cong 10^4$  ( $5 \text{ GeV}$ ) the angular kick strength goes to be  $\alpha \cong 2.8 \cdot 10^{-5} \text{ rad}$ . Beam size at septum location for  $\beta(s_1) \cong 10 \text{ m}$  comes to  $\sigma_x \cong \sqrt{(\gamma\epsilon_x) \cdot \beta(s_1) / \gamma} \cong \sqrt{0.1 \cdot 10^{-6} \cdot 10 / 10^4} = 10^{-5} \text{ m}$ , so  $20\sigma_x \cong 0.2 \text{ mm}$  only. As the angular kick defined by the

$$\alpha \cong \frac{1}{(HR)} \int H_k(s) ds \cong (H_{k \max} \Delta_{\text{eff}}) / (HR), \quad (9)$$

where  $H_k(s)$  is longitudinal distribution of field in kicker,  $(HR)$   $[G \cdot \text{cm}] = pc[eV]/300$  stands for magnetic rigidity,  $H_{k \max}$  stands for maximal field value in a kicker,  $\Delta_{\text{eff}}$  it effective length. Substitute here  $\Delta_{\text{eff}} = 1 \text{ m}$ ,  $(HR) = 1.67 \cdot 10^2 \text{ kG} \cdot \text{m}$  one can obtain

$$H_{k \max} \cong \alpha \frac{(HR)}{\Delta_{\text{eff}}} \cong \frac{2.8 \cdot 10^{-5} \cdot 1.67 \cdot 10^2}{1} \cong 4.7 \cdot 10^{-3} \text{ kG} \cong 4.7 \text{ Gauss}$$

Although the beam losses for separation  $\delta \geq 20\sigma_x$  is minimal, from the point of heating the septum edge by imaginary currents by steady beam, the distance must be increased from  $0.2 \text{ mm}$  to  $\sim 1 \text{ mm}$  i.e. five times. So the kick angle and magnetic field value required come to

$$\alpha \rightarrow 5\alpha \cong 2.8 \cdot 10^{-4} \text{ rad}; \quad H_{k \max} \rightarrow 5H_{k \max} \cong 47 \text{ Gauss}.$$

For reduction of heating by induced currents, the side of septum opposing to the steady beam could be galvanized by metal having high conductivity (Copper). So the feeding current comes to  $I = 150 \text{ A}$  for field line path length  $w = 4 \text{ cm}$ . For impedance of strip line  $\sim 30 \Omega$  the voltage required is about  $4.5 \text{ kV}$ .

As the transverse size of the beam is small, further reduction of width  $w$  down to  $2 \text{ cm}$  is possible;

This will yield a possibility for rise the field two times.

## 2.2. Electrostatic septum.

Electrostatic septum serves for further separation of kicked bunch from main train, with help of electrostatic field, Fig.3. Fig.4. Electrostatic septum delivers less perturbations to the resting beam, than the magnetic one with equivalent action force.

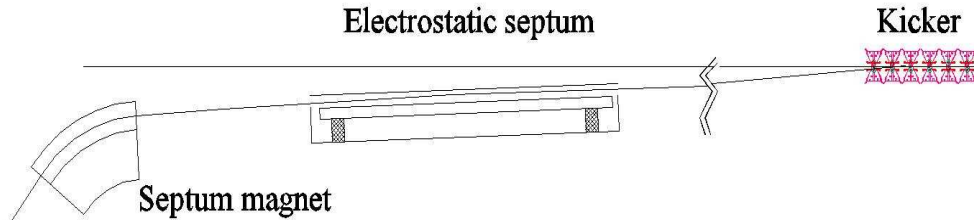


Figure 3: Arrangement of fast bunch kick-off/kick-in. For kick-off the beam is coming from the right. For injection to the orbit the beam is coming from the left in reversed order.

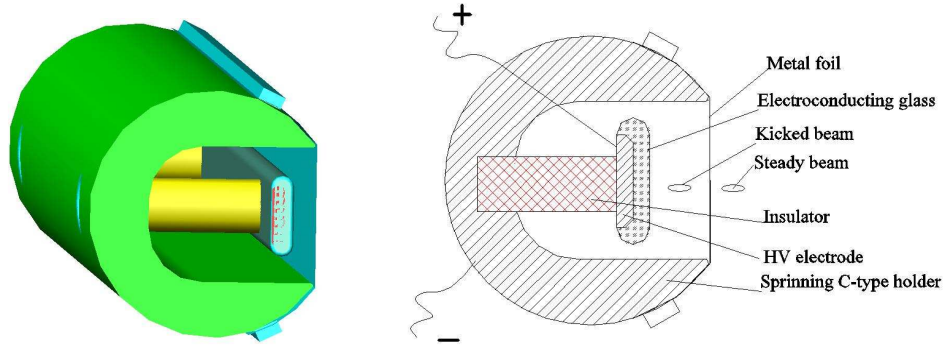


Figure 4: Cross section of electrostatic septum.

Usage of HV electrode covered by conducting glass allows having electric field strength in the gap up to  $100 \text{ kV/cm}$ .

### 3. KICKERS

One needs to distinguish between electric pulse duty, recalculated to the pulse length and the geometrical length of kicker. If the pulse generator in hand, which is able to generate single pulses

For ERL machine three types of kicker regimes might be foreseen. The first one will be able to kick a single bunch in sequence, the second one will be able to kick a train of 13 bunches and the third one must kick off single bunch running in  $\sim 10 \text{ nsec}$  time window. Although there is no difference in the length of the kicker, the pulse pattern might be different. Maximal length of kicker for the first two regimes (even the many of them) remains corresponding to  $0.77 \text{ ns}$  i.e.  $L_{kicker} \leq 3 \cdot 10^{10} [\text{cm/sec}] \cdot 0.77 \cdot 10^{-9} [\text{sec}] \cong 23 [\text{cm}]$ . For kicking off single bunch running in  $10 \text{ nsec}$  the length of kicker might be  $1.5 \text{ m}$  max.

#### 3.1 $90^\circ$ Stripline electrostatic kicker

The case of our particular interest is when the strip-line kicker and the beam have  $90^\circ$  orientation, see Fig 5 and Fig.6.

This type of kicker has input and output tapering out of beam way, so they do not reduce the length with good field in a kicker.

Kick is much less sensitive to the beam position while the pulse duty allows this. This is because the field is homogenous at longitudinal distance, rather than in transverse direction as it is in usual kicker.

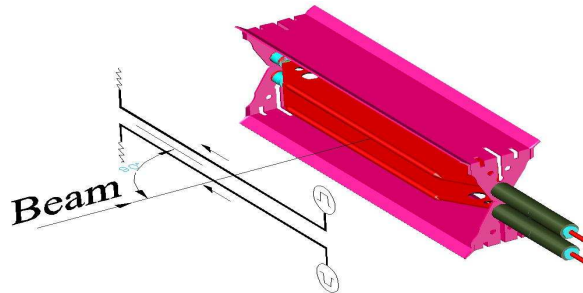


Figure 5:  $90^\circ$  electric strip-line kicker unit. Loading resistors are visible at the ends opposite to the input ones.

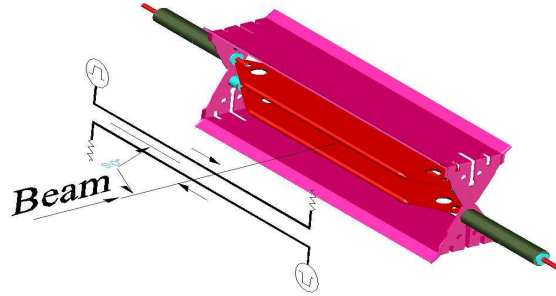


Figure 6: 90° electric strip-line kicker unit with counter-directional waves in strip lines. In this kicker magnetic field at medial plane comes to zero.

Some holes in strip-line electrodes visible in Fig. 6 and Fig.7, made for the EM phase correction, so the wave front positioned evenly across the strip-line electrode while propagating to the load through the strip line (EM lens).

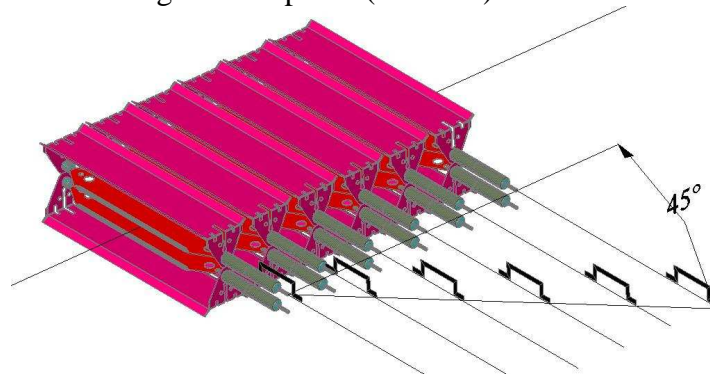


Figure 7: Kicker assembly with transversely moving EM waves. Pulses are shown here schematically also.

Pulse sequence arrives to the kicker with appropriate delay which takes into account that velocity of propagation in cables might be less than the speed of light. So 45 degrees corresponds to the situation when these velocities are equal. Direction of pulse propagation within 90° is not important (left-right invariance).

### 3.2 Counter directional kicker.

As we mentioned already this type of kicker could be used for kicking single bunch in 10 ns time frame. Width of electrodes across the field line ~4 cm is big enough for delivering homogeneity.

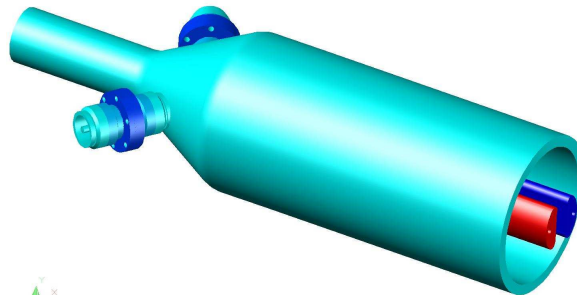


Figure 8: Kicker with counter propagating beam and pulse.

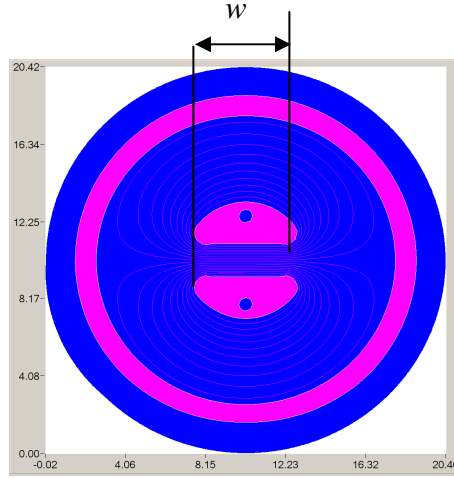


Figure 9: Electric field lines in the kicker from Fig.8 calculated with MERMAID.

Let us compare the strength of kickers with counter propagating beam/pulse and theirs with  $90^\circ$  orientation.

Magnetic field value between strips defined by the width of the stripline conductors in Fig.11. So the magnetic field  $H_\perp \cong I/w$ , where  $I$  is the current running in the conductor and  $w$  stands for its width. This magnetic (and electric) field weakly depends on the distance between the strips (until it remains less that the width). Impedance of this system seen from one input is  $Z \cong 377h/(w+h)[\Omega]$  where  $h$  is the half of the distance between strips. So the electric field is about  $E \cong I \cdot Z/h = I \cdot 377/(w+h)$ . Electric and magnetic force are the same. Let the length of a stripline in case of counter-directional propagation will be  $l$ . Then if the same kicker rotated by  $90^\circ$ , the total integral of transverse kick will be less in the ratio  $\frac{1}{2}w/l$ . So one can see that  $90^\circ$  system has advantage in case when the pulse is short, when  $l < \frac{1}{2}w$ . In its turn the value of  $w$  defined by homogeneity of field desired in case of counter propagation. Remember also, that the length of kicker  $l$  is limited by the half of the distance between bunches. Although for mostly cases counter directional kicker has advantage is strength,  $90^\circ$  system might be useful from the point of reduction of power. Really, to generate the same strength kick there must be many  $90^\circ$  systems installed one by one, so theirs total length must be about  $l \cdot 2l/w$  i.e. the number of  $90^\circ$  kickers goes to be  $n \cong 2l^2/w^2$ . For the bunch length  $\sigma_b \ll l$  (typical case of our interest) the total energy in  $90^\circ$  kicker must stored only at the distance  $\sim \sigma_b$  in each  $90^\circ$  kicker, so the total energy will be less than in counter directional kicker in a ratio  $n\sigma_b/l \cong 2l\sigma_b/w^2$ . For typical case,  $l=10cm$ ,  $\sigma_b \cong 0.03cm$  (1ps),  $w=2cm$  this factor comes to 0.15 i.e. the power for feeding array of  $90^\circ$  kicker which provide the same kick will be  $\sim 15\%$  if the kick delivered by counter-directional kicker.

This advantage could be realized only if the pulser able to generate short pulses is in hand.

#### 4. PULSER

Now we can turn to the second important component of system-pulser itself. Pulse sequence used in ERL represented in Fig. 10.



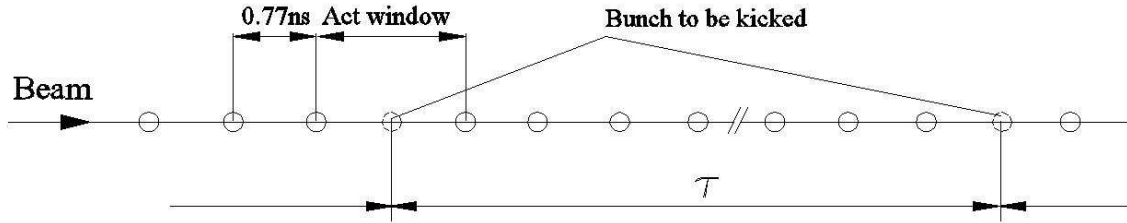


Figure 10: Pulse sequence required for ERL~0.77 ns corresponds to ~23 cm.

As the 90 degree kicker is chosen as a baseline we can concentrate now on device for proper feeding this kicker-the pulser. This pulser must be able to generate <2 ns-long pulses with repetition rate up to 100 MHz. This pattern required by ERL some special regimes for diagnostics. So the kicker eliminates some selected bunch in sequence. Kicker for ILC Damping Ring (DR) operates with repetition rate 5 Hz but must generate ~2820 pulses separated by 330 nsec. Time duration of pulse is strongly associated with the bunch pattern in the ring and defines, hence, the total circumference of the ring. Kicker for ERL must operate with beam of 10MeV i.e. in injection region, while ILC damping ring kicker operates with 5-GeV beam.

Few types of pulser could satisfy demands of ERL and ILC. Due to low energy of operation, kicker for ERL has much less integral than ILC DR, but repetition rate (100 MHz) makes it a very challenging device.

Basic principles of fast pulser interesting for us are represented in Fig.11.

The lines in Fig. 11 commutated with switch K located either in central electrode or in ground one. Each of these schemes characteristics which might be interesting for some specific applications. For example, scheme on Fig. 11 (b), (d) has a switch K which is attached to the ground; this scheme requires careful matching for reduction of reflections and influence of charging current to the output voltage however.

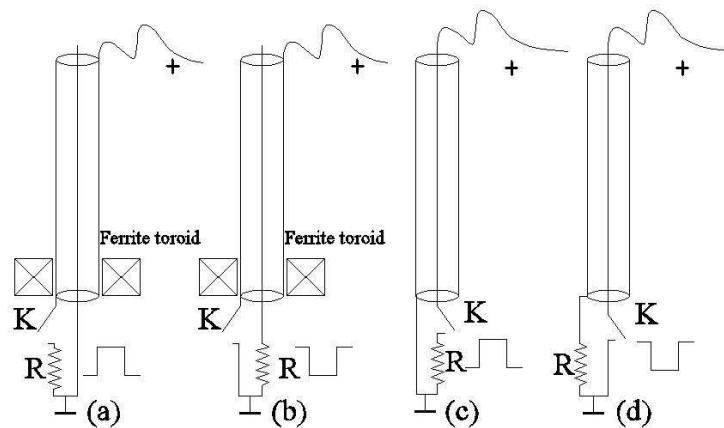


Figure 11: Principle of fast pulser operation with switch installed in ground electrode (a), (b) and in central electrode (c), (d).

#### 4.1. Pulser with electron beam

As we already mentioned, in [6] a pulser described which uses a  $E_{110}$  mode for generation of circularly swept beam with many collectors irradiated by swept beam in sequence defined by frequency of swiping RF [7].

For the purposes of feeding just single kicker the klystron-type system could be used as well. We will consider here a pulser represented in Fig. 12 below.

So basically this is a klystron with removed output cavity. Instead of this last cavity a beam collector located there. Electronics located in HV rack serves for triggering the grid, which opens the current.

One disadvantage of this device is that it is not possible to change the pulse pattern. This defined by resonant frequency of the cavities.

To increase contrast ratio of current reaching the collector, some modifications could be suggested. This might be a usage of  $E_{110}$  mode in cavities, so the beam will have a circle-type sweep [6]. In this case collectors located at the circle. Radius defined by the level of excitation.

In principle one can suggest sweeping with magnetic fields generated by coils (similar to old fashion TV raster sweeping system) rather than by RF fields

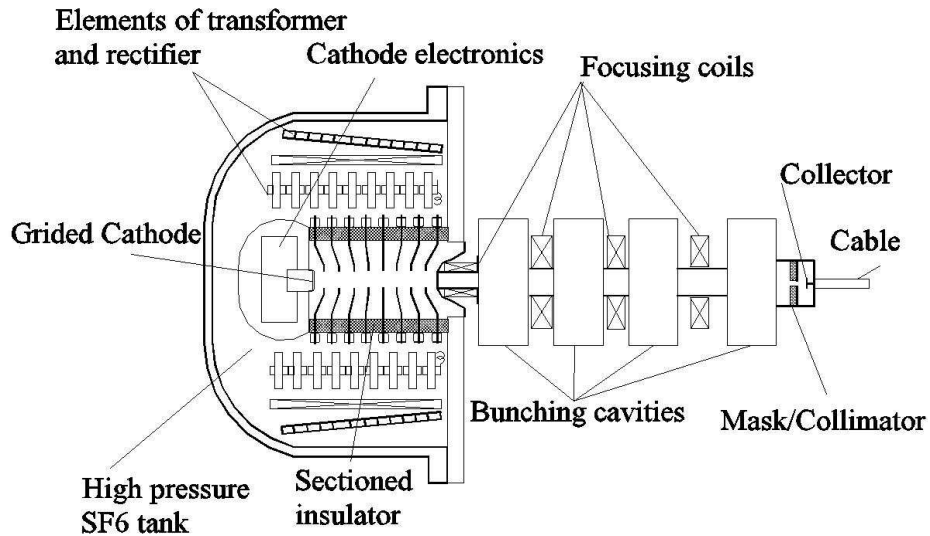


Figure 12: Pulser able to generate series of pulses in single cable with repetition rate up to 3 GHz in DC regime.

#### 4.1.1 Inverters

In principle the kicker is a system of strip line electrodes, so mostly adequate here might be strip line transmission line also. However for practical reasons the cable transmission mostly in use for these purposes. In our case it is convenient to prepare bi-polar pulses with inverter. Lot of practical schemes of cable/stripline inverters are known.

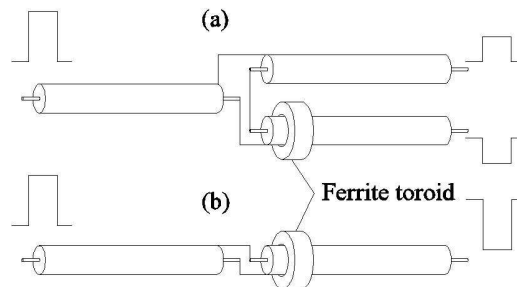


Figure 13: Schematics of inverter with split (a), simple unipulse inverter (b).

Instead of ferrite ring sometimes just roll the cable into loop serves for the same purposes. In principle schemes in Fig.13 operate in both directions, so the scheme in Fig. 13(a) can sum two pulses with opposite polarity coming from left/right in single pulse and so on.

So, usage of cable invertors allow simplify the pulser design, as there is no necessity for inversion polarity in the switch (like vacuum tube).

#### 4.2. Pulser with vacuum tubes.

Vacuum tubes are mostly adequate for pulsing in this case. They are specially designed for operation up to GHz bandwidths with low capacitance and inductance. Schemes with DSRD (Drift Step Recovery Diodes) could be used for usage for manipulating the grid voltage. By itself the DSRD electronics is powerful in generation of short pulses of sub-nanosecond duty. The only disadvantage what might be seen here with DSRD is that it is not easy to exclude post-pulse ringing of pulser as the energy stored in inductance one switched to the load carries tails of oscillations. But as a triggering device for vacuum tube DSRD technology looks as ideally matched.

There is one significant peculiarity of vacuum tube used as a switch. Namely, the vacuum tube is transmitting current only if anode voltage applied, so even in “on” position the grid voltage remains. This might be reflected by saying that vacuum tube switch has substantial internal impedance. Indeed in idealized switch the voltage across the commutated gap becomes ~zero, the same is valid for spark switch or thyratron. For thyristor switch remaining voltage is ~0.3-0.5 V only.

For usage of vacuum tube, (triode or tetrode), scheme from Fig.11 (a) looks like represented in Fig.14. Triggering and application of negative voltage to the grid arranged through the sidewall with installation of ferrite toroids for prevention of leakage of main pulse to the triggering electronics.

Parameters of vacuum tubes represented in Table 1.

Table 1. Vacuum tubes for pulser.

Type	Power	Freq	Voltage	Current	Cooling
Triode 3CX20	84 kW	90 MHz	12 kV	12 A	air
Triode 3CX15	56.2 kW	90 MHz	12 kV	6A	air
Planar triode Y-820	750W	-	32 kV	15(20) A	oil/air
Triode GI7B	1 kW	3GHz	9kV	9A	air
Tetrode 8973	1,000 kW	110 MHz	22.5 KV	110A	water
Tetrode 8974/X-2159	2,158 kW	30 MHz	21.5 KV	125A	water

So called planar triode Y-820 (YU-114) designed specially for fast commutation purposes.

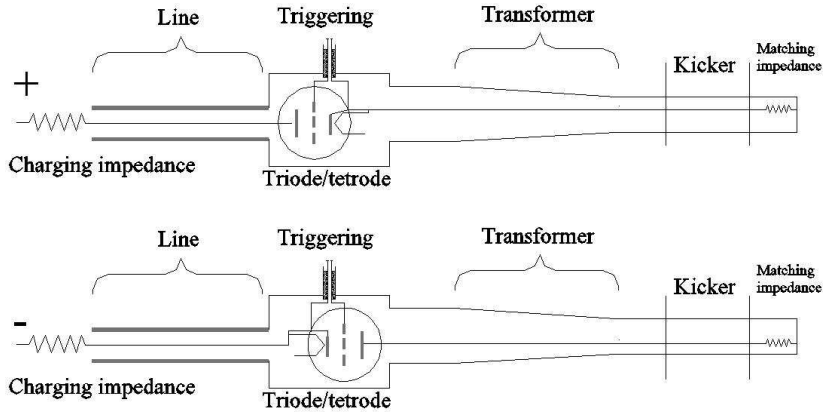


Figure 14: Pulser with vacuum tube according to Fig. 13(c). Transformer as a tapered transmission line described below.

In short pulse operation some parameters, indicated in Table 1 could be overloaded. Mostly limiting for our business is saturation (three-half power law) current for given anode voltage. For example for planar triode Y-820 for 32 kV indicated current 15 A – maximal value represented in technical passport for 25 kV; if approximated for 32 kV, the current could reach ~20 A.

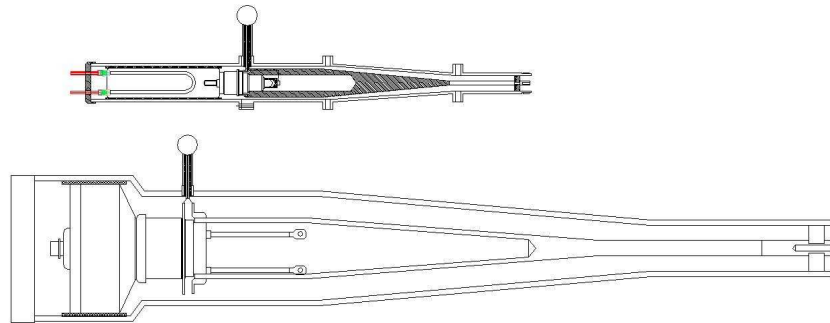


Figure 15: Pulser from Fig.14 realized with vacuum tube GI7B (top) and 3CX15 (bottom). Proportions are kept right. Diameter of anode block of 3CX15 is 7".

System with similar garb described in [13], the thyatron used as a switch there however.

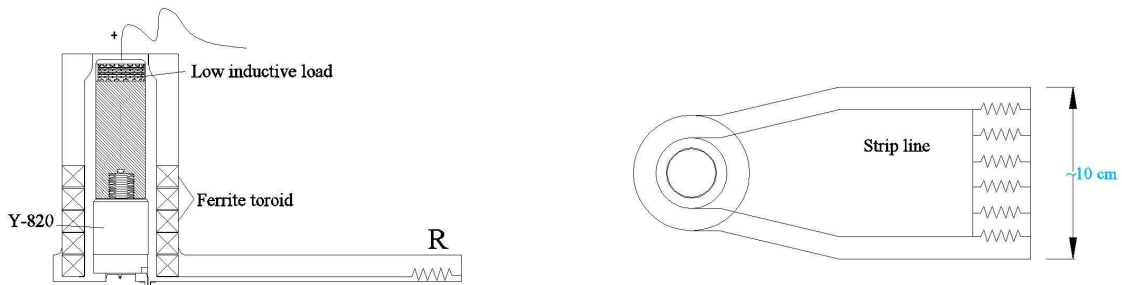


Figure 16. Scheme from Fig.11(d) with planar triode Y-820 and strip-line transmission system.

More interesting for us will be the schemes based on Fig.11(b). The scheme uses few (six in our case) vacuum tubes operating in parallel.

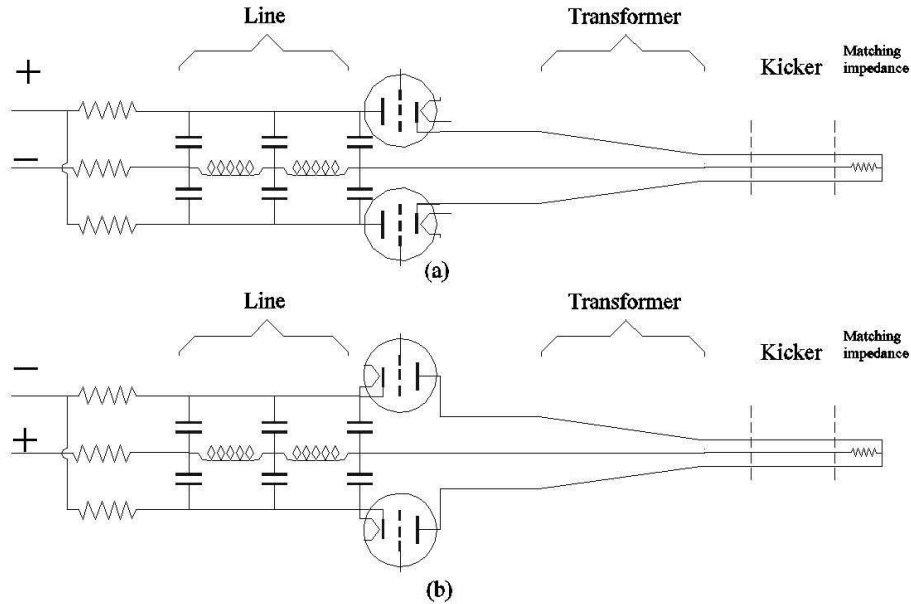


Figure 17: Developed schemes suggested for usage as pulsers.

Operation in parallel is less disadvantageous than operation of single vacuum tube as here propagation of triggering pulse across grid-cathode gap could be minimized by parallel feeding of grids.

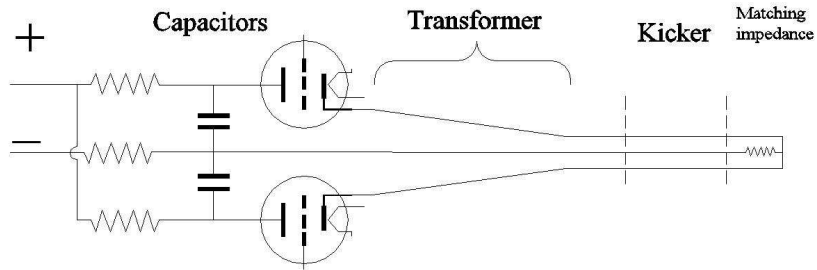


Figure 18: Scheme in Fig.19 (a) when capacitive impedance dominates over inductive one

Realization of scheme from Fig. 11(b) with triodes GI7-B represented in Fig. 19. Triodes are rather compact, so there is no apparent limitation in usage of many of these in parallel.

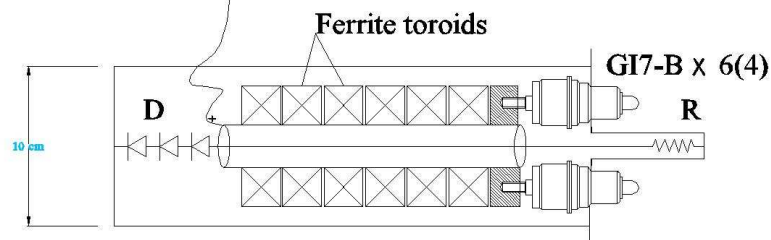


Figure 19: GI7B in scheme from Fig.11(b), Fig.17 (a). Diodes D serve in charging loop.

Ferrite toroids serve for electrical insulation of outer coaxial from the processes of pulse creation by the EM energy stored in inner coaxial only.

Finally, the scheme recommended for pulser represented in Fig.20. Basically this is the one from Fig.17 (a). It uses Y-820 allowing out voltage 30 kV and 120 A (six tubes in

parallel) with expected duty time  $\sim 1\text{ns}$  and sub-nanosecond rise/fall times. Scheme is rather compact  $\sim 10\text{cm}$  in diameter by  $20\text{cm}$  high. Each of these pulsers could feed one section of kicker of  $10\text{cm}$  long so  $\sim$ ten of these required for  $5\text{GeV}$  beam. If the spacing allows, with usage of RF capacitor as a HV line the pulser could be rearranged to be able providing a high voltage pulse with multi-nsec duty.

As we mentioned already, usage of many small size triodes in parallel instead of one tetrode (such as 8973/8974) might have advantage as the geometrical size of grid is smaller, so propagation of electrical field across grid/cathode gap goes proportionally faster. Separate feeding of each grid could be arranged easily by individual cables having the common source (based on DSRD, see paragraph 4.3 below). Usually the time of establishing the output signal is defined by the time required for charging capacity grid-cathode and electron cathode-anode propagation time. For Y-820 the grid/cathode capacity is  $\sim 16\text{pF}$ . In case of fast pulse feeding the process of establishing is bit more complicated as the inductance is also playing its role. But the combination of capacitance and inductance in bi-connected line, (what are the grid-cathode electrodes), acts as active impedance, so time of establishing defined by (doubled) time required for propagation of triggering pulse across the grid. While establishing, the feeding pulse doubles its voltage at vicinity of grid (due to boundary conditions corresponding reflection of propagating pulse from the open end of the line). This helps in fast rise time.

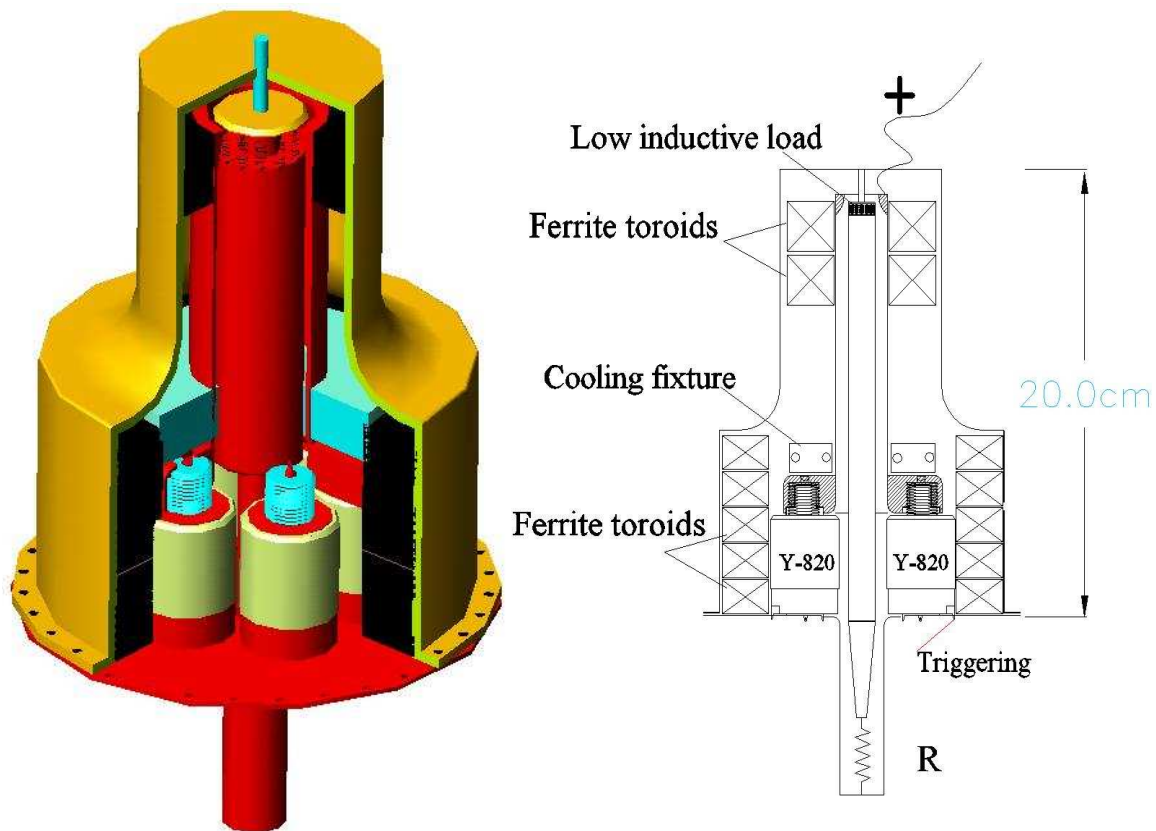


Figure 20: Realization of the scheme recommended. It generates  $\sim 30\text{kV}$ ,  $120\text{A}$  in  $\sim 1\text{ns}$  pulse at the bottom level. Shown is transformer for increase the output voltage.

Transformer could either increase or decrease the voltage/current ratio by changing the ratio of diameters of co-axial output conductors.

During operation X-ray production is possible, as the voltage is significant. Basically electrons bombarded anode with ~30kV having 120 A total, or 3.6 MW pulsed power acting in ~1nsec, coming to 3.6 mW per 1Hz repetition rate, however. For 1 kHz this comes to 3.6W. Only few percent of this amount could be transformed in X-ray flux. So this system remains self protected due to thickness~ 4mm of outer cover, made from Copper. Some Lead wrapping is possible here.

#### 4.2.1 Tapered transformer

So, typical vacuum tube is able to commutate ~30A current at voltage ~30 kV, i.e. with internal impedance ~1 kOhm.

To drive specific voltage in a strip-line kicker the voltage in a pulse required is just  $V=IZ$ , where  $Z$  stands for impedance of line. Typically it is 100Ohm, so if generator is able to provide current  $I=30A$  the voltage could be developed comes to  $V\sim 3kV$  only. So usage of transformers becomes inevitable here.

Equations governed the propagation of pulse in tapered transmission line are the following

$$\frac{d^2V(z,t)}{dz^2} - \frac{1}{L(z)} \frac{dL(z)}{dz} \frac{dV(z,t)}{dz} + L(z)C(z) \frac{d^2V(z,t)}{dt^2} = 0 \quad (10)$$

$$\frac{d^2I(z,t)}{dz^2} - \frac{1}{C(z)} \frac{dC(z)}{dz} \frac{dI(z,t)}{dz} + L(z)C(z) \frac{d^2I(z,t)}{dt^2} = 0 \quad (11)$$

where  $V(z,t)$  stands for voltage and  $I(z,t)$  for current at local position  $z$  along the line,  $L(z)$  and  $C(z)$  are local inductance and capacitance per unit length accordingly. Solutions of these equations given by Slater [13] are the following

$$V(z,t) = V(0,t) \sqrt{\frac{Z(z)}{Z(0)}} \exp\left(-it \int_0^z T(z') dz'\right) \quad (12)$$

$$I(z,t) = I(0,t) \sqrt{\frac{Z(0)}{Z(z)}} \exp\left(-it \int_0^z T(z') dz'\right), \quad (13)$$

where  $T(z) = \sqrt{L(z)C(z)}$ ,  $Z(z) = \sqrt{L(z)/C(z)}$ . The last expression is a characteristic local impedance. Out impedance of line coincides with impedance of kicker, which is about 150Ohm. If impedance of line in Fig.17 is chosen to be~1.5 Ohm, then the transformer ratio comes to ~10. So the voltage at the kicker one can expect ~100kV at max. This voltage is limited by the current available from triode package, however. Analyses of tapered transmitting line one can find in [9].

#### 4.3. Triggering of vacuum tube pulser.

Principle of operation of triggering system is represented in Fig.21. This system uses DSRD diodes [10], [11], [12]. Scheme in Fig.14 (a) operates as the following. First key K1 is closed and the capacitor C1 discharged through inductance and DSRD. After half period of discharge the key K2 closed and discharge current trough C2 and L2 add to the current

of first loop. So the current, which is reversed to normal direction of DSRD is  $\sim$ doubled, which makes  $\sim$ twice faster charge dissolution from the body of diode and the current interrupts faster, see Fig 21 (b). The time of pulse existence is defined by ratio  $L/R$ , Fig 23.

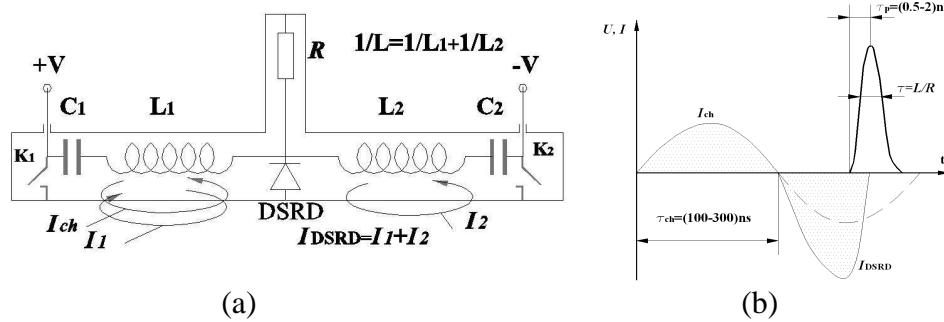


Figure 21: Principal of operation (a). Currents and voltage running in scheme (b).

Detailed scheme represented in Fig.22. The only difference between scheme in Fig.21 and Fig.22 is in additional stage in pumping inductance  $Ls3$ . Also two transistors operating by Darlington scheme deliver a short close up, so capacitors  $Cs1$  and  $Cs3$  become connected to the ground electrode with minimal time. The rate of operation is defined by frequency of transistors arranging  $Tc1$ - $Tc3$  and adequate cooling.

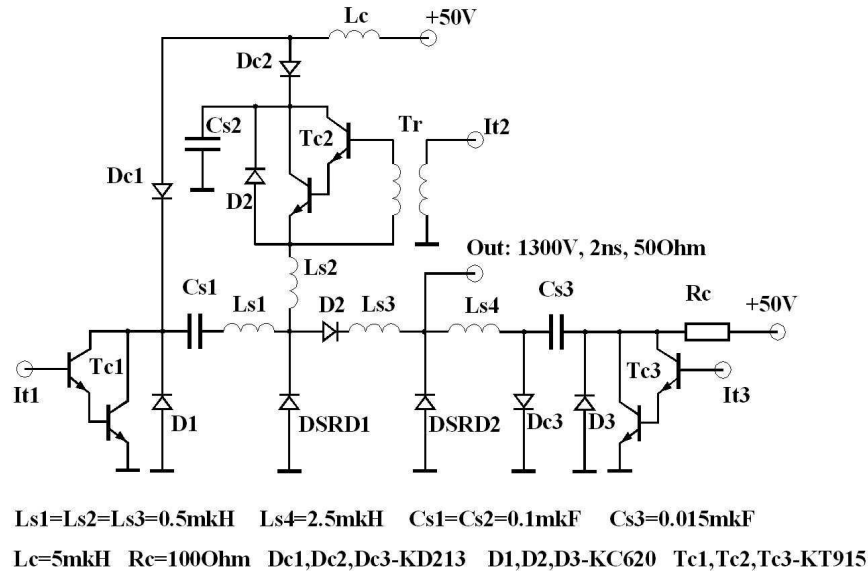


Figure 22: Two-stage generator with DSRD [11]. This generator could be used for triggering pulser with vacuum tube after sharpening with technique described in [11], [15].

This triggering generator might be interesting by itself for feeding fast kickers of appropriate timing. Usage of system with DSRD from Ioffe Institute for ILC kicker described in [14]. For further sharpening, known technique can be used [11], [15]. This technique allows formation of pulse with sub-nanosecond rise time. Presence of bi-polar tails in pulses generated by DSRD, is not affecting quality of pulse formed by vacuum



tubes, as the reaction time for blocking pulses with opposite polarities is very short. Scheme for spitting the triggering pulse is represented in Fig.23.

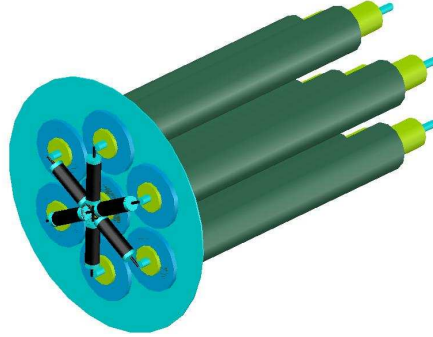


Figure 23: Principle of preparation of six triggering pulses. Pulse from generator comes at the center. This device could be realized as a micro-strip line.

This divider sacrifices of pulse amplitude in a favor of short establishing time while dividing the pulse. As the voltage in this triggering splitter is relatively low (1.3kV at the entrance) realization of this splitter as a strip-line system with micro-resistors is mostly adequate here.

Just to remind that maximal grid voltage for this tube (fully open) is about 60V . Some negative voltage need to be applied for locking the tube (~ minus100 V).

We would like to mention here that similar technique could be used for generation of microsecond-long pulses with nsec rise/drop time as well [16].

#### 4.4. Kicking of sequence of 1.3 GHz.

For kicking the 1.3 GHz sequence one can use some power from klystron feeding SC structure to prepare the triggering pulse. Additional fast time gate chopping for this sequence required. After desirable time sequence obtained it could be used for feeding the pulser. One positive property of vacuum tube as a switch is that it is not reacting on negative polarity and could be opened only if the opening pulse overwhelms the negative potential applied to the grid.

### 5. SYSTEM OF KICKERS FOR ERL/ILC

ERL has a regime with missing 13 regular bunches in a sequence of 1.3 GHz. This elimination surpassingly will be done after acceleration of the beam, generated in the photocathode, to 10 MeV level in linac-injector. Elimination of bunches after acceleration done for prevention of excitation of parasitic modes in injector linac, operating for acceleration from ~700kV to 10 MeV. In freed space a 1 nC bunch from additional source will be positioned [17]. That will be either the same 10MeV energy or 50 MeV one. In last case the combining to the main beam trajectory could be done with the help of merging magnet techniques. After reaching 5 GeV this 1 nC bunch should be extracted without perturbations affecting remaining bunch sequence. In this instance it is pretty much the same as required for ILC regime.

For relatively long acting window allowed, ~10 nsec counter propagation of pulse and bunch is mostly adequate here, although for kicking sequence of 13 ERL bunches after injector the length of kicker could not be more than  $23/2=11.5$  cm.

Parameters of kicker system required for accomplishing the task is represented in Table 2.

Table 2. Parameters of kicker systems for ERL.

Energy	10MeV	10MeV	50 MeV	5GeV
Location	After injector	After injector	Close to previous	After second linac
(HR)	0.33 kGxm	0.33 kGxm	16.7 kGxm	167kGxm
Kicking angle	$10^{-2}$ rad	$10^{-2}$ rad	$10^{-2}$ rad	$10^{-3}$ rad
Type	180°	90°	180°	180°
Length	10 cm	10 cm	50cm	4x75cm
Magnetic field	16 G	32 G	16 G	32 G
Current	68 A	136 A	68 A	136 A
Voltage	4.8kV	9.6 kV	4.8kV	9.6 kV
Duty	<10 nsec	<10 nsec	<10 nsec	<10 nsec
Rep. rate	1 pulse/1MHz	1 pulse/1MHz	1 pulse/1MHz	1 pulse/1MHz

180° means counter propagation of beam and kicker pulse. Injector and ejector system are practically identical.

For ILC the repetition rate must be ~3 MHz, which is not a problem for the pulser described.

## 6. SUMMARY

We suggested for the first time to use a stripline kicker with rectangular orientation of beam trajectory to the kicker (90°). Utilization of kicker with orthogonal direction of propagation of pulse with respect to the beam has advantages in situations where generation of pulse with fast rise/drop time is a difficult task. For this case influence of high order modes is eliminated and space not occupied by tapering.

The system described could be transformed into injection system by proper location of input/output connectors and by reversing the sequence of septum magnet-electrostatic septum-kicker. For 90° kicker direction of propagation of pulse is irrelevant.

We claim also, that vacuum tubes could serve as pulser devices for such kickers. We suggested usage of few small vacuum tubes in parallel for generation of pulses with sub-nsec duty. Adequate coaxial garb must be used for these tubes. Usage of few small size high frequency tubes operating in parallel has advantage with single big-size tube in sub-nanosecond region.

Tapered coaxial line with slow changing parameters can serve as a transformer.

Schemas with DSRD could be used for triggering generators based on usage of vacuum tubes. For triggering with 1.3 GHz sequence one can use some power from main klystron feeding RF structure.

For usage in ERL, the generator and the kicker are compact size devices required <0.5 meter of beam line will be able to kick individual bunches with repetition rate 1-10 MHz. Injection of bunch from second electron source (with increased charge) into orbit could be made directly with the kicker system (Fig. 3).

Results of this publication could be used for any specific design of fast pulsed kicker, for example in ILC damping ring injection/ejection system.

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