ELECTRON BEAMS AS STOCHASTIC 3D KICKERS

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Abstract

This article describes an idea combining electron and stochastic cooling in one device. The amplified signal of displacements of the ion from the pick-up electrode is applied to the control electrode of an electron gun. Thus, a wave of space charge in the electron beam is induced. This wave propagates with the electron beam to the cooling section. The space charge of the electron beam acts on the ion beam producing a kick. The effectiveness of the amplification can be improved with using a structure similar to a traveling-wave tube.

INTRODUCTION

Stochastic cooling is a typical feedback systems used in accelerators [1]. A displacement of a particle induces a signal on a pickup electrode. This signal from the pickup is amplified and applied to the kicker device acting on the particle. With a proper choice of the feedback parameters the oscillations of the target particle are damped. Other particles of the beam cause a parasitic noise and limit the maximum cooling rate. A typical kicker device is an electrodynamics structure like a strip line or slow-wave array. The bandwidth of the system is about 1 GHz with a power of few kW.

Experiments [2-4] with electron beams show that the space-charge field can be an effective tool for impacting on an ion. The space charge of the electron beam can be used as the kicker in stochastic cooling systems. A sketch of such a device is shown in Figure 1. The signal from the pick-up or array of pick-ups is applied to the amplifier system. The signal from the amplifier is applied to the control system of the electron gun which produces a fluctuation of the electron current of required form. After that the electron beam is accelerated and the space charge fluctuation proceeds to the cooling section. Here the fluctuation moving together with an ion acts via the electrical field of the space charge.

The effective kicker device should satisfy many requirements. The rate of cooling depends on the system bandwidth. The bandwidth is limited by its highest frequency. Aside from technological issues, there is a limit of the typical aperture of the kicker. Problems appear when the kicker aperture becomes comparable to the wavelength at high frequencies when the particle with $\beta<1$ does not have time to fly through the kicker during the impulse. Most of the problems are easily solved in high-energy accelerators but for low and medium energy range new criteria may be useful. The physical size of the electron kicker is small. The size may be easily changed in proportion to the size of the ion beam, thus the kicker parameters will be optimal. The size of the electron kicker does not depend on the aperture of the vacuum pipe. It is not necessarily a plunging device.

From the physical point of view the electron cooler device as kicker enables one to obtain 40 GHz ranges of frequencies. One of the imiting factors is the size of the electron beam. A wave with wave-length about thr transverse size of the beam is difficult to inject by usual RF methods and may have strong dispersion and damping.

The electron kicker is effective for the velocity matching of kick impulse and ion. Adjusting the energy of the electron beam the phase velocity of the space-charge wave may be equalized to the ion velocities with high accuracy. This result may be obtained at large variation of the ion velocities $0<\beta<1$.

The space charge of the electron beam enables one to obtain the 3D distribution of the electric field at the same time. So, if the control structure of the electron gun can modulate the electron gun axial-asymmetrically then all 3D kick types (vertical, horizontal and momentum) are available in one single device.

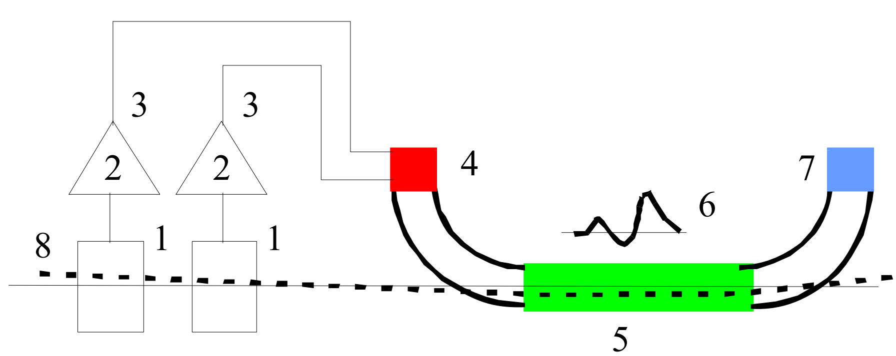

Figure 1: Scheme of stochastic cooling with electron cooler as 3D kicker. 1 – pick-up system, 2 – hybrid and amplifier, 3 – cable system, 4 – electron gun with the current modulation, 5 – cooling section, 6 – modulation of the space-charge density in the cooling section, 7 – collector of the electron beam, 8 – ion trajectory.

This idea is a variant of Derbenev's idea [5] about the use of instability for the amplification of the cooling force.

STRENGTH OF THE ELECTRON KICKER

The performance of some stochastic cooling systems may be limited not only by the system bandwidth but also by the strength of the kick. The maximum value of the electron current fluctuation is limited. In order that the electron kicker works in the linear regime the condition $\sqrt{(\Delta I)^2} = \Delta i_{\max} << I_0$ is desirable. Here $\Delta i_{\max}$ is the r.m.s. value of the possible fluctuation of the electron current, I_0 is the total current of the electron beam.

The electric fields of the space charge fluctuation can be written as

$$E_\perp = \frac{2}{\gamma \beta c} \frac{\xi}{a^2} i \,, \qquad E_{||} = \frac{1}{\gamma \beta c}\left(2\ln\left(\frac{b}{a}\right)+1\right)\frac{\partial i}{\partial z} \,,$$

where $E_\perp$ and $E_{||}$ are the transverse and longitudinal electric fields the in co-moving reference system, i is the electron current, b and a are the radii of the vacuum pipe and electron beam, respectively, ξ is the "pseudo"-displacement of the center of space charge describing the amplitude of the dipole fluctuation, and z is the longitudinal coordinate.

If the transverse and longitudinal momenta of the single particle before and after a kick can be described by the equation

$$A_c = A - \lambda A \,,$$

then the minimal stochastic cooling time τ_{cool} of a single particle is

$$\tau_{cool}{}^{-1} = 2\lambda f_0 \,.$$

Here we do not take into account effects related to the role of the rest particle in the interaction region, "bad" and "good" mixing and so on. The maximum strength of the kicker is limited to

$$\lambda_{\max} A = \delta A_{\max} \,.$$

The signal from the pickup is formed by the all other passing particles within the time $1/\Gamma$, where Γ is the bandwidth of the system. Thus, the useful part of the kick is only $1/\sqrt{N_s}$ part of total value. The term $N_s = N \cdot f_0/\Gamma$ is the conventional value for the particle numbers per sample at revolution frequency f_0 and the particles in the beam N. The resulting equations for the kicker strength of the electron beam are

$$\lambda_{||}^{\max}\frac{\Delta p_{||}}{p} = \frac{1}{\gamma^2 \beta^4} r_q \frac{\Gamma\, l_{cool}}{q \cdot c^2} \frac{\Delta i_{\max}}{\sqrt{N_s}} \left(2\ln\left(\frac{b}{a}\right)+1\right)$$

and

$$\lambda_{\perp}^{\max}\frac{\Delta p_{\perp}}{p} = \frac{2}{\gamma^3 \beta^3} r_q \frac{l_{cool}}{qca} \frac{\Delta i'_{\max}}{\sqrt{N_s}} \,.$$

Here $\lambda_{||}^{\max}$ and $\lambda_{\perp}^{\max}$ are the maximum rates of transverse and momentum cooling of the particle, l_{cool} is the length of the cooling section, $\Delta p_\perp/p$ and $\Delta p_{||}/p$ are the initial spreads of the transverse and longitudinal momenta of the particle, $\Delta i'_{\max} = I_0\, \xi/a$ is the amplitude of dipole fluctuations of the electron beam, and r_q is the classical charge radius.

Table 1

Parameter	Value
modulation of electron current $\Delta i'_{\max}$ and $\Delta i_{\max}$	50 mA
cooler length	4 m
bandwidth of the amplifier	2 GHz
radius of electron beam	0.5 cm
radius of vacuum pipe	5 cm
β-function in cooling section	15 m
revolution frequency	1 MHz
initial normalized emittance (1σ value)	10 π·mm·mrad
initial momentum spread (1σ value)	5 10^{-3}

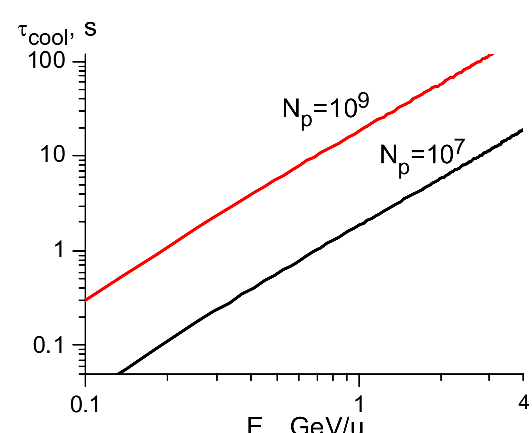

Figure 2: Maximal value of the longitudinal cooling rate versus energy of the cooled particle.

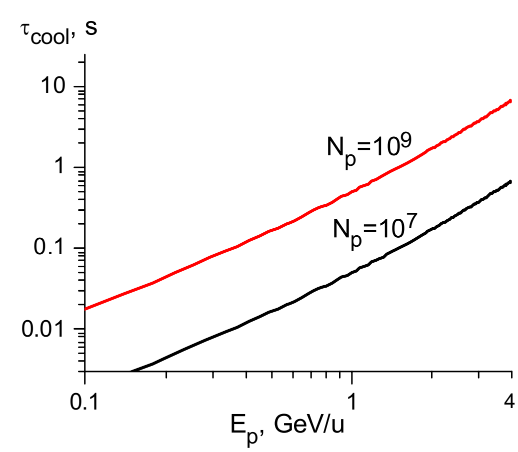

Figure 3: Maximal value of the transverse cooling rate versus energy of the cooled particle.

The figures 2 and 3 show the cooling rate versus the energy of the cooled particles. The other parameters of the estimation are listed in Table 1. One can see that a reasonable cooling rate is obtainable in the energy region 0.1 – 1 GeV/u or less. The corresponding energy of the electron beam is 50 – 500 keV.

DISPERSION AND ROTATION OF THE KICKER PULS IN ELECTRON BEAMS

One of the characteristic problems related to this type of kick is a distortion of the kick impulse induced by wave dynamic. The dispersion equations of the space-charge fluctuation propagating in the electron flow are

$$\omega_l = kv_e \mp k\frac{\omega_{pe}a}{\sqrt{2}}\sqrt{\ln\left(\frac{b}{a}\right)+\frac{1}{2}},$$

$$\omega_t = kv_e \mp \frac{\omega_{pe}}{\sqrt{2}}\frac{a^2}{b}k$$

for longitudinal and transverse fluctuations. A perturbation propagates with the group velocity v_e and diverges because of the action of space charge. If no particular care is taken against excitations only one oscillation mode exists with velocities $v_e \pm u$. The widening δl of the initial impulse with length l_0 is about

$$\frac{\delta l}{l_0} = \frac{u\Gamma\, l_{cool}}{(\gamma\,\beta\,c)^2}.$$

Figure 4 shows numerical estimates of the impulse splitter for typical parameters of the electron beam. One can see this effect may be essential for the longitudinal wave at low energy that limits the maximum electron current at such condition. This effect is negligible for propagaton of the transverse kick pulse.

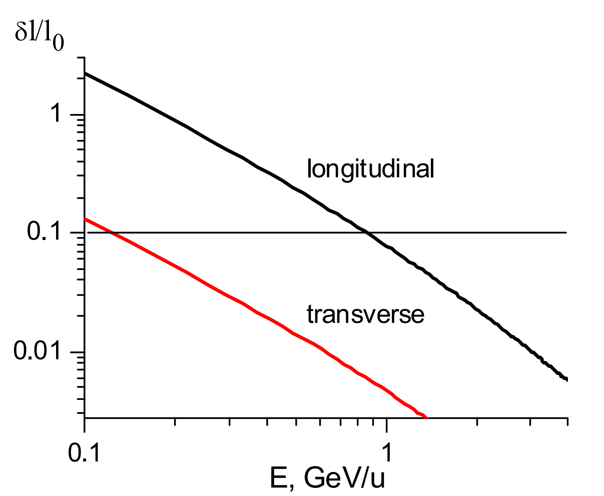

Figure 4: Widening of the kick pulse induced by diverging of two waves. Electron current is I_0=0.5 A, radius of electron beam is a=0.5 cm, frequency bandwidth is Γ=2 GHz.

This problem can be resolved if the modulation system excites fluctuations only in one mode. For example, the modulation system contains the slow-wave electromagnetic structure. So, the traveling wave of the input impulse interacts with an oscillation mode of the electron beam. A theory of such interactions has been developed in detail for the description of a traveling tube device [6]. An example of such a device is the Kompfner splitter [6] that transfers energy from the structure to the beam without amplification.

In this case, the problem of pulse dispersion remains in any case but moves to the term $\propto k^2$ in the dispersion equation. An expansion of the dispersion equation to higher powers of k for the longitudinal wave can be found in [7],

$$\omega = kv_e \mp k\frac{\omega_{pe}a}{\sqrt{2}}\sqrt{\ln\left(\frac{b}{a}\right)}\cdot\left(1-\frac{k^2b^2}{4\ln\left(\frac{b}{a}\right)}\right).$$

The widening of the initial impulse described by the set of equations

$$D = \frac{1}{2}\frac{\partial^2\omega}{\partial k^2}, \qquad l_0+\delta l = l_0\sqrt{1+\frac{4D^2t^2}{\sigma^4}},$$

$$t = \frac{l_{cool}}{\gamma\,\beta\,c},\quad \sigma = \frac{\gamma\,\beta\,c}{\Gamma}, \qquad k \approx \frac{\pi}{\sigma}$$

is shown in Figure 5. So, it enables to use larger values of the electron current for the kick with minimal pulse widening. In the range of small energies a decrease of the bandwidth of the electron current is possible.

The rotation of the kick at the combined action of crossed electrical and magnetic fields is nonessential. The radial electric field of the electron beam,

$$E_r = \frac{2}{\gamma\,\beta\,c}\frac{r}{a^2}J_e,$$

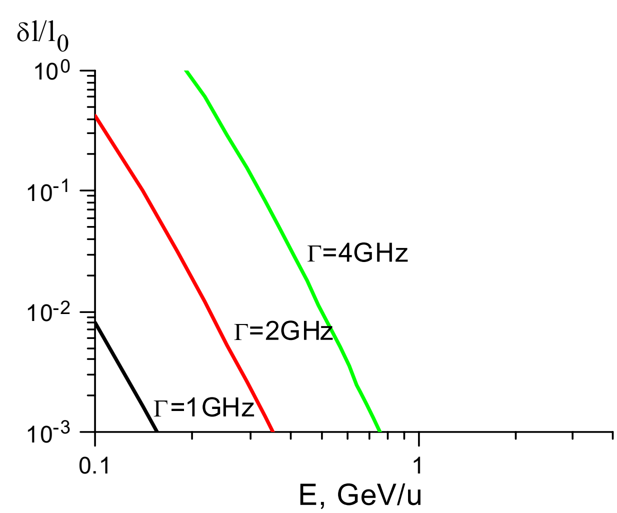

Figure 5: Widening of the kick pulse induced by dispersion of the longitudinal wave. Electron current I_0=0.5 A, radius of electron beam a=0.5 cm, frequency bandwidth Γ=1, 2 and 4 GHz.

leads to a rotation of the kick in the longitudinal magnetic field on the angle

$$\Delta\theta_M = c\frac{E_r}{B_{cool}}\frac{\tau_{flight}}{r}.$$

At electron energy 50 keV and ion energy 0.1 GeV/u the rotation angle is $\Delta\theta_M = 0.6$. The remaining parameters are taken from Table 1. At the highest energy this effect is negligible.

ESTIMATION OF COOLING RATE FOR A REAL ELECTRON GUN

In order to estimate the usefulness of such kicker device the authors tested the electron gun of the EC-35, EC-300, EC-40 coolers from this point of view. Fig. 6 shows the modulation capability of the electron gun versus frequency. The simulations were performed by RF modification of the UltraSAM code [8]. Obviously, this existing construction is not a high frequency device (curve 1) but the situation may be improved slightly by decreasing the geometrical size of the gun by a factor of tow (curve 2). The response of the control grid is 1-1.5 mA per V, the typical frequency is about 1 GHz., the maximal input RF power applied to the gun may be about 50 W at the maximal fluctuation current 50 mA.

Figure 7 shows estimates of the cooling time for fixed total amplifier coefficients. One can see that the not well matched electron gun can produce a kick sufficient for obtaining a reasonable cooling time of about 1 s or less in the medium energy range. So, it may be expected, that a special RF gun may be more successful.

SUMMARY

The use of an electron cooler as kicker in the medium range of the energy (0.1 – 1 GeV/u for heavy charged particles) may have the following advantages: one device

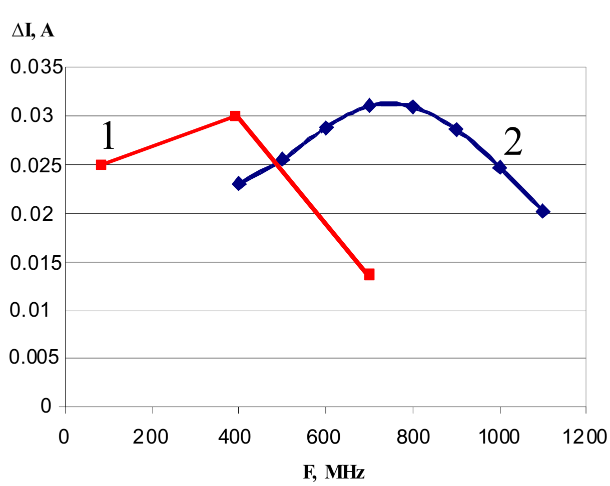

Figure 6: Modulation current versus frequency at 20 V modulation voltage. The curve 1 corresponds to usual BINP electron gun used in EC-35 (CSRm), EC-300 (CSRe), EC-40 (LEIR), curve 2 is variant 1 decreases in scale 2.

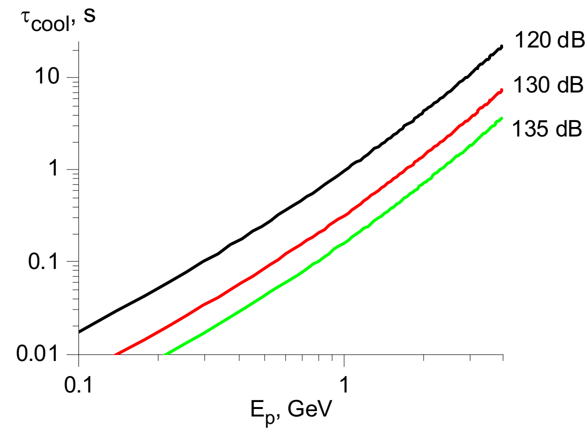

Figure 7: Transverse cooling time versus energy at the different values total amplifier gain. The rest parameters of the estimation are $N_p=10^9$, Γ=1 GHz, f_0=1 MHz, ρ=50 Ohm, T_{ampl}=60 K, L_{cool}=4 m, $\beta cool$=15 m, Z_{gun}^{-1}=1 mA/V.

providing a 3D kick at the same time; velocity matching of kicking pulse with ion in the wide range of charges; free aperture; using existing devices (certainly, if electron cooler exists yet); frequency bandwidth may be very high; such type of the kicker does not restriction on frequency bandwidth at low ion velocities when the time-of-flight factor becomes essential.

Further improvement of the gun construction may follow the way of the traveling wave tube (TWT) device. An electron cooler contains all main components of TWT device: cathode, control electrode, longitudinal magnetic field and collector. It is necessary to provide an electron flow by the special slow-wave structure at intermediate energies of a few kV only. Amplification of the RF signal and modulation of the electron current can be obtained in such type of control system. The RF power of the electrostatic fluctuation with the electron beam is delivered straight on to the ion beam. The electrostatic fields of the space charge induce the required kick on an ion during the time of the joint flight of electron and ion beams in the cooling section. The parameters of a TWT tubes are comfortable for an electron cooler. For example, the kinetic energy of the electron beam is typically 3-10 keV and beam currents in the range 200-500 mA are produced from the TWTs by useing the antiproton source of FERMILAB. The output parameters of a compact Industrial TWT are sufficient. The amplifier gain is up to 30-50 dB, the bandwidth is up to 20 GHz and the power is up to 50 W in the continuous regime. If one supposes a 30 dB RF signal amplification directly in the modulation system, then the requirement on the amplifier of the pick-up signal becomes very low. The noise loading of the amplifier can be 0.1 W or less at the effective amplifier temperature 60 K.

Thus, the use of an electron cooler as a 3D kicker may be very perspective in the medium energy region. It is possible to construct a very low power device which is able to cool ions in about one second or less.

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