RECENT RESULTS WITH STOCHASTIC COOLING IN THE ISR

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Cooling of Vertical Betatron Oscillations

a) Introduction

Stochastic cooling of vertical betatron oscillations was first proposed by S. Van der Meer[/1/]. H.G. Hereward extended the theory and took into account a general system gain $g \leq 1$ (correction per turn) as well as the influence of a finite signal-to-noise ratio $1/\eta$ [/2/,/3/]. For a system with constant g over the bandwidth W, the cooling rate for N particles is

$$\frac{1}{\tau} = \frac{W}{2N}\left(2g - g^2(1+\eta)\right)$$

In view of a possible application in the ISR[/4/] an experimental system was built and provided first evidence for stochastic cooling[/5/]. Practical experience gave rise to the development of the 1-2 GHz system described in the next section[/9/,/10/].

Since then the interest in cooling of low-intensity beams has grown steadily[/6/,/8/]. Cooling time constants of the order of 1 h were found to be possible at ISR energies with a system in the range 100-300 MHz[/7/]. This led to the construction of the 80-360 MHz system[/9/,/13/] described below. Later it was found that the 1-2 GHz system could give similar results.

b) 1-2 GHz system

The lack in performance of the loop-type pick-up (PU) and the kicker (K) used in the first experimental system[/4/,/5/] (insufficient common mode rejection, sensitivity against waveguide modes and restricted bandwidth) was overcome by a distributed PU and K structure where the coupling is provided by an array of 30 rectangular slots. Both PU and K are operated in push-pull mode. The PU amplitude response is proportional to f; the K response is f-independent. Though PU and K are useful over the range 1-4 GHz, the presently available amplifiers restrict the band covered by the system to 1-2 GHz[/9/,/10/,/13/].

Experimental results on both medium- and low-intensity cooling, obtained with 1 W K-power, have been reported earlier[/10/,/11/,/13/]. Since low-intensity work is now considered to be more important, the K-power recently was increased to 20 W, delivered by a travelling wave tube amplifier. This increased the correction factor g up to a point where the term $g^2 \cdot \eta$ in the formula given above became significant. On the other hand, the expected cooling rates are high enough to reduce the effective beam height, and consequently $1/\eta$, considerably over a few hours. Hence, the cooling rate should decrease continuously[14] according to

$$\frac{1}{\tau(t)} = \frac{W}{2N} (2g - g^2(1+\eta))(1 + \eta \frac{g}{2-g} (\exp(t \frac{W}{N} (2g-g^2)) - 1))^{-1}$$

Fig. 1 shows the experimental result obtained with a 4.3 mA beam at 26.6 GeV/c in comparison with the theoretically expected performance. The experimental rates were found from exponential least square fits over approximately ten consecutive vertical Schottky scans every 30 minutes. The agreement is seen to be reasonably good.

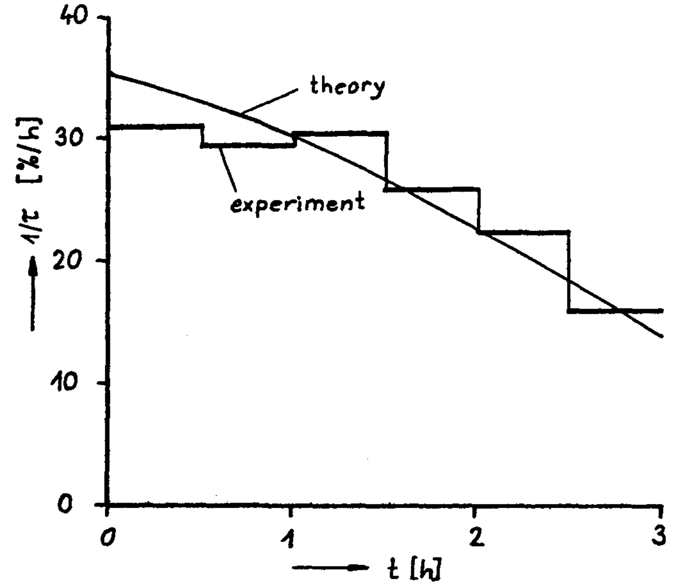

Fig. 1. Theoretical and measured cooling rate $1/\eta$ versus t.
(4.3 mA, 26.6 GeV/c, 1-2 GHz system)

At present the PU is being modified to give tighter coupling with the beam which should yield an improvement in cooling rate by a factor of 3. Another factor of 3 should be possible if the K is modified in the same way.

c) <u>Low-frequency betatron cooling</u>

For frequencies with no microwave propagation inside the vacuum chamber, simple directional loop couplers provide an echo-free and sensitive pick-up. Several electrodes can be used to increase the signal power prior to amplification. The pick-up response is proportional sin x ($x = 2\pi \ell f/c$, ℓ : loop length). To simplify construction the PU plate is short-circuited at the far end. Similar loops can also be used as a kicker, whose frequency response is proportional sin x/x.

The parameters for the 80-360 MHz vertical cooling system tried out in the ISR are similar to those proposed in ref. /7/ for low-intensity cooling. Particles complete almost one turn between observation and correction. In an experiment at 11.7 GeV/c a cooling rate of 71% per hour was measured over 30 min. The Schottky signals within the bandwidth decrease by $\sim$50% when the feedback loop is closed since the mixing per turn at the low frequencies is incapable of restoring the uncorrected statistical error. (The incomplete mixing represents a serious limitation, for currents above 1 mA, due to the small revolution frequency spread at 11.7 GeV/c in the ISR. For higher ISR momenta this spread is doubled. In different machines it could be considerably higher.) To observe the change in vertical betatron oscillations the loop is opened (Fig. 2).

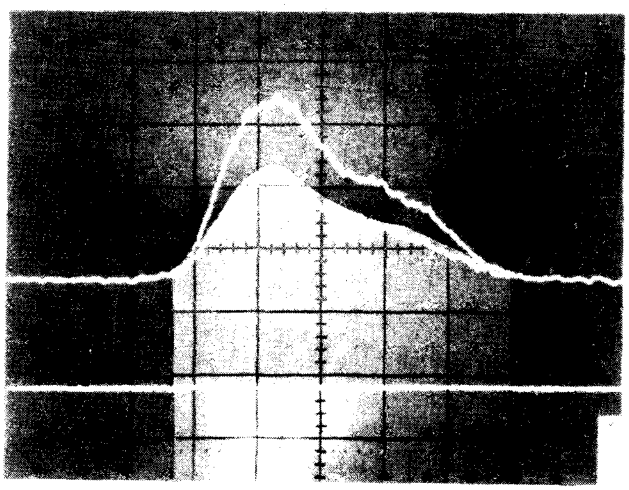

Fig. 2. Vertical Schottky signal before and after 30 min stochastic cooling. (750 μA, 11.7 GeV/c, 80-360 MHz system)

Stochastic acceleration and cooling of momentum spread in the ISR

a) Acceleration

Assume the PU consists only of the inner lefthand side electrode in Fig. 3. When a particle passes inside this inner electrode (connected as a loop) and the feedback bandwidth is conveniently chosen, it will induce at each passage a peak current $i_p \sim 2$ eW and a peak voltage 2 ReW in an R = 50Ω system. This voltage is furthermore increased by a factor of 2 by adding the signal power from four inner loops. The single particle signal is amplified by ρ and timed in such a way that it accelerates the particle by 8 eWRρ at each passage through four accelerating gaps. (A factor 2 in accelerating voltage is gained by distributing the power on four 50Ω gaps.) With 1 kW total power on the accelerating gaps and a preamplifier noise figure of 3 dB the acceleration should be 247 mV/turn.

b) Cooling

Cooling is obtained by feeding signals in antiphase, via a hybrid transformer, into the feedback system from the four outer PU electrodes (loops). For particles with momenta above the nominal the outer loop signal dominates and they are decelerated.

In the case of low intensities and a beam situated between the two electrodes the cooling time is approximately given as the acceleration × e at the mouth of the electrode divided by the difference in kinetic energy of an orbit at the mouth and at the nominal orbit. For 26 GeV/c this yields a cooling time of about 1 h.

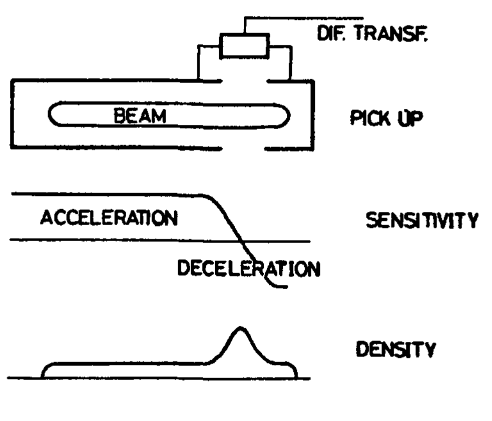

Fig. 3. Stacking in momentum and cooling with a radial difference PU, schematically. In reality, the particles pass four identical electrodes consecutively.

c) <u>Acceleration, 1-2 GHz system</u>

Similarly to what was said under a), the distributed PU will detect longitudinal Schottky signals when operated in common mode. Moreover, it has been shown theoretically[10] that the K produces a longitudinal kick when operated in common mode too. This kick is proportional to f and the energy change of a passing particle may equal or even exceed that of a conventional cavity for the same voltage applied. With the presently-used K, and at 2 GHz it is 1.5 eV per V (peak). An acceleration rate of 4.6 MeV/h is to be expected with the present system.

Fig. 4 shows the result of an experiment carried out with a 10 μA beam at 11.7 GeV/c[12]. The longitudinal Schottky signal at the 300th harmonic of the revolution frequency was expected to shift to the left with a rate of -247 Hz/h; the rate actually observed was -440 Hz/h, i.e. about 80% higher. It is not yet clear where this discrepancy might come from.

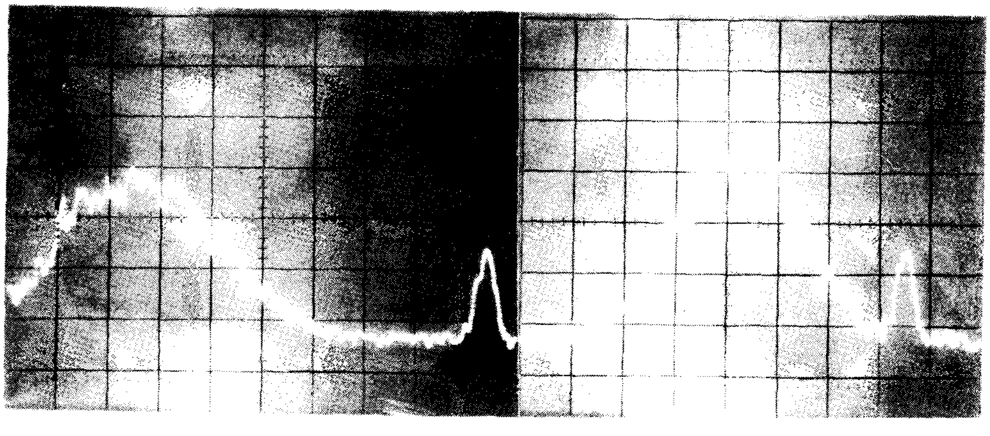

Fig. 4. Longitudinal Schottky signal at 300 × f_R before (right) and after (left) 2.75 h stochastic acceleration (10 μA, 11.7 GeV/c, 1-2 GHz system).

Vertical: rms amplitude, arbitrary units

Horizontal: frequency - 100 Hz/cm, left marker - 95103300 Hz, right marker - 95104100 Hz.

It should be possible to use both the distributed PU and the K for momentum cooling, following the same principles as those outlined under b). The PU and K used for momentum cooling could be operated in push-pull mode simultaneously, thus permitting betatron cooling at the same time.

For the present system, improvements by the same factors as expected for vertical cooling should be possible in acceleration mode.

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