Three-Dimensional Laser Cooling of Fast Circulating Beams

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A novel method is proposed in order to achieve three-dimensional laser cooling of fast circulating beams in a storage ring. We emply the forced synchrobetatron coupling induced either by dispersion or by a coupling cavity such that the longitudinal cooling effect can be extended to the transverse degrees of freedom through the coupling. It is shown that the transverse cooling rates can be considerably enhanced under linear resonance conditions. Tracking simulations are performed to demonstrate the practical feasibility of the present three-dimensional cooling schemes, in particular, taking into account the lattice parameters of the storage ring ASTRID in Denmark.

Keywords: Laser cooling/ Synchrobetatron coupling/ Linear difference resonance/ Storage ring/ Dispersion/ Coupling cavity

The laser cooling technique has been widely accepted, due to recent experimental success, as a powerful tool to manipulate the longitudinal phase space of stored and circulating ion beams. The beam temperature reachable with this new technique is now, at least, three orders of magnitude lower than that with the traditional techniques like electron cooling and stochastic cooling. In fact, the longitudinal temperature of 1 mK has been obtained in the ASTRID ring in Denmark with 100 keV $^7Li^+$ beams. This is the main reason why laser cooling is often linked to the beam crystallization for which the beam temperature must be reduced to an extremely low level.

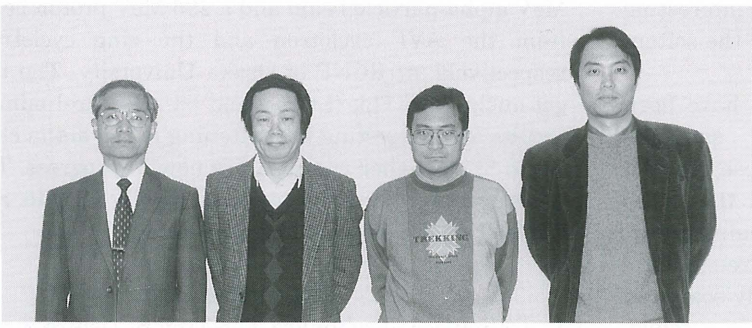
Contrary to this promising potential, laser cooling, if applied to beams in a storage ring, is essentially one-dimensional; namely, it operates only upon longitudinal motion. To overcome this difficulty, we proposed a novel method in the recent papers [1,2]. The idea is based on creating a linear synchrobetatron coupling such that the longitudinal damping action due to the laser cooling mechanism can be transferred into transverse directions. For this purpose, we developed two different schemes; namely, the dispersion-coupling scheme [1] and the coupling-cavity scheme [2].

In the first scheme, the synchrobetatron coupling induced through dispersion at an *ordinary* radio-frequency (RF) cavity was employed, while, in the second scheme, we introduced the so-called coupling cavity excited in a TM_{210} mode. It can be proven that these two schemes are mathematically almost equivalent and, therefore, work in a similar way. In the following, we only describe the first scheme since it is

NUCLEAR SCIENCE RESEARCH FACILITY —Beams and Fundamental Reaction—

Scope of research

Particle beams, accelerators and their applications are studied. Structure and reactions of fundamental substances are investigated through the interactions between beams and materials such as nuclear scattering. Tunable lasers are also applied to investigate the structure of unstable nuclei far from stability and to search for as yet unknown cosmological dark-matter particles in the Universe.



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practically much simpler than the second scheme.

According to the theoretical predictions based on a linear model [1], the transverse cooling rates can be increased up to the same level as the longitudinal cooling rate, provided that the operating point of a storage ring is exactly on resonance; namely, when the conditions

$$\nu_x - \nu_y = \text{integer}, \quad \nu_x - \nu_L = \text{integer},$$

are satisfied (see Fig.1). Here, ν_x, ν_y, and ν_L are, respectively, the horizontal, vertical, and longitudinal tune. These conditions imply that the non-integer parts of the three tunes must be identical. Hence, it is required to set the longitudinal tune as large as possible to avoid the excitation of severe integer resonances in the transverse motions.

The easiest way to increase ν_L is, indeed, the use of a higher RF voltage but it is clearly dangerous

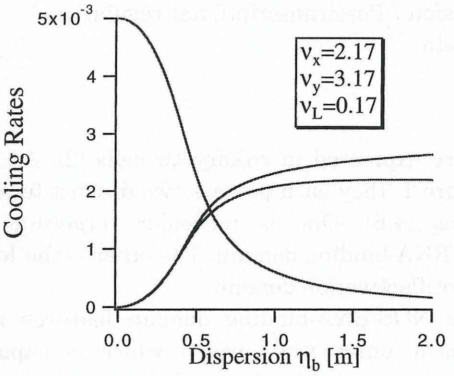

Figure 1. The cooling rates of the horizontal, vertical, and longitudinal direction, under the resonance conditions, plotted as the function of the dispersion η_b at the RF-cavity position. Note that we have the optimum operating point where the three cooling rates are roughly the same. In this example, the optimum value of dispersion is clearly about 0.6 m.

since the longitudinal energy spread of laser-cooled beams eventually reaches even less than 0.1 eV. Further, recalling that the beam is initially continuous, we should adiabatically capture it first, ramping the RF voltage. This adiabatic capturing process causes the initial blowup of the longitudinal emittance where a larger bucket height results in a larger initial $\delta p/p$ to be scanned. A lower RF voltage is thus preferable for shortening the cooling time as well. In ASTRID, the RF voltages of only 70 volts have actually been used for laser cooling experiments of bunched beams.

We now take a look at the result of a numerical simulation, confirming the validity of the proposed three-dimensional cooling method [3]. For this purpose, we here use the tracking code SIMPSONS originally written for the study of space-charge effects in synchrotrons. It is basically a thin-element code but enables us to do realistic investigation of the proposed cooling schemes with a specific lattice design.

Fig.2 shows the result where the exact lattice of the ASTRID ring has been considered, assuming 100 keV $^{24}Mg^+$ beams initially continuous. Although ν_x=2.29 and ν_y=2.73 in the normal operating mode of ASTRID, the machine has been re-tuned here so that the coupling resonance conditions are satisfied; namely we have set the transverse tunes to be ν_x= ν_y=3.1. Further, an RF cavity is turned on to excite the synchrobetatron resonance. Employing the harmonic number h=260 corresponding to 5.8 MHz, we only need 34 volts to obtain ν_L=0.1.

We put a skew quadrupole at the opposite side of the laser cooling section. The strength of the skew field is of essential importance since the cooling rates of the three directions are altered depending on it. The optimum value of the skew field gradient in the present case is $(L/B\rho)\cdot(\partial B/\partial y)$~0.055 [$m^{-1}$] where L is the length of the magnet.

To adiabatically capture the beam into the RF bucket, the RF voltage is linearly increased from 0 to 34 volts in the first 10 mili-seconds. Then, the cooling laser is switched on and is scanned from $\delta p/p$~7.5×10^{-4} down to $\delta p/p$~0 within 0.99 second at a constant speed. The magnitude of a longitudinal momentum kick by a single laser photon is fixed at about dp/p~1.5×10^{-5} in the present simulation.

The result in Fig.2, perfectly consistent with the theoretical predictions, demonstrates the promising possibility of the proposed cooling method. We thus believe that, in order to approach closer to an ultimate limit of cold beams, the present three-dimensional cooling schemes should be tried.

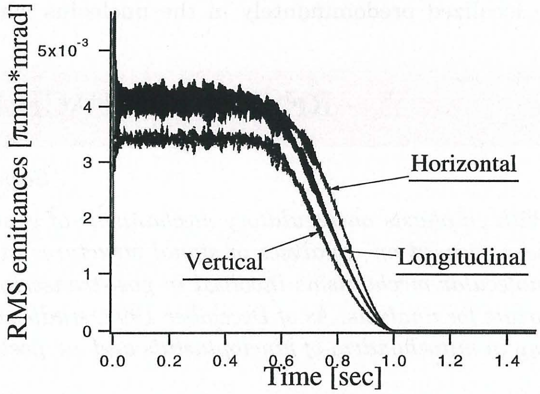

Figure 2. Time evolutions of the RMS emittances of a laser-cooled beam.

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