# LIMITS TO BUNCHED BEAM LASER COOLING

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*Abstract*

Laser-cooling of bunched beams have been proposed as a means to increase the coupling between the transverse and longitudinal degree of freedom necessary because laser-cooling in storage rings only operate in the longitudinal dimension [1]. We have studied the longitudinal bunch shapes and temperatures, as well as, using a novel technique [2], the transverse beam sizes during laser-cooling. The bunch lengths for various temperatures seems to comply with what would be expected when the transverse dimensions are ignored. However in the longitudinally space charge limited case, which has been studied before [1, 3], the vertical dimensions seems to decouple somewhat from the cooling, causing a decreasing maksimum attainable density with increasing current. These observations might be important for the beam quality obtainable with laser-cooling.

## 1 INTRODUCTION

Beam cooling is important for many storage ring applications. The introduction of laser-cooling in a storage ring has, because of it's relatively short cooling times, and high cooling force, arisen much interest [4]. Especially in work on inertial confinement fusion, the ability of cooling bunched beams is of interest, due to the high currents and hence instability problems during acceleration in some of the proposed methods [5].

In this article we present recent results from studies of the longitudinal as well as transverse density profiles of a bunched beam during laser-cooling. The most simple assumption is that the longitudinal density distribution is a Boltzmann distribution with only a weak (logaritmic) dependence on the transverse beam size [7]. Our measurements does indeed agree with this assumption for beams which are not space charge limited in the longitudinal dimension. However we need to take into account that laser cooling induces parabolic longitudinal velocity distributions and not Gaussian as in the Maxwell-Boltzmann distribution.

In the longitudinally space charge limited case we observe deviations from the simple model. A novel technique for transverse beam profile diagnostics, which images the fluorescent light from the laser excited ion beam onto a high resolution CCD [2], has made us able to simultaneously monitor the transverse beam profiles. These measurements reveal that the vertical dimension tends to increase faster than the cuberoot scaling in current expected for a constant density beam. Furthermore the transverse sizes are far from what would be expected in a 3D space charge limited beam. These observations are compared to the situation in a coasting beam [2], where the density was observed to be a constant as a function of current. These deviations and limitations we suspect are due to tune resonances, and they might be important for the attainable beam quality with laser-cooling.

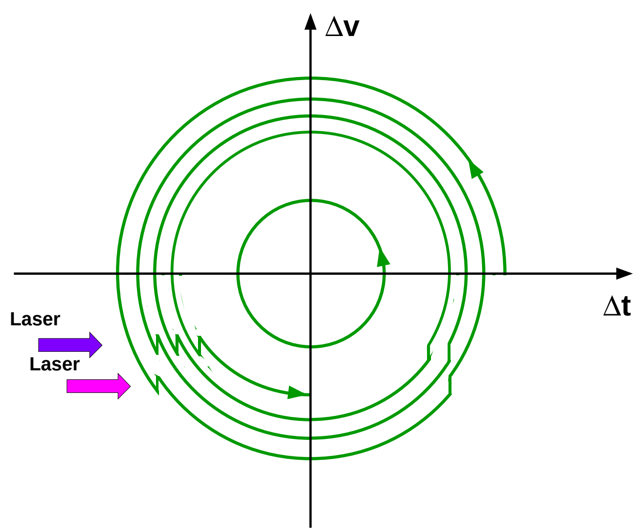


Figure 1: Laser-cooling of a bunched beam. The figure shows the longitudinal phase space oscillations induced by the longitudinal bunching potential. The arrows shows what happens when the particles have a velocity at which they interact resonantly with the laser. As long as the particle emittance is above a certain level it will be damped by the laser at least once pr. syncrotron period.

## 2 LONGITUDINAL SHAPES

At the ASTRID storage ring we have laser-cooled a bunched beam of 100 keV $^{24}Mg^{+}$ ions by overlapping the ion beam with a counterpropagating laser-beam detuned slightly red from resonance with the mean ion beam velocity. In figure 1 the cooling process is illustrated. We bunch the beam by exciting a drift tube with a sinusoidally varying potential with a frequency of $h$ times the revolution frequency. This splits the beam into $h$ bunches by generating a longitudinal confinement force described in the bunch frame of reference by

$$F(x) = -F_0 \cdot \sin(\frac{2\pi h}{C}x) \ ; \ F_0 = q\frac{2V_{rf}}{C}\eta\sin(\frac{\pi h}{C}L) \quad (1)$$

where $q$ is the charge of the circulating particles, $V_{rf}$ is the amplitude of the applied sinusoidal voltage, $C$ is the ring circumference, $L$ is the tube length, $x$ is the relative displacement of the particle from the center of mass of the bunch, and the slip factor $\eta = 1/\gamma^2 - \alpha$ where $\gamma$ is the relativistic factor and $\alpha$ is the momentum compaction factor.

We have monitored the transverse and the longitudinal beam profiles, as well as the longitudinal velocity distribution. The transverse profiles were measured using a novel technique employing the fluorescent light from the laser-excited ion beam. This technique is described elsewhere in these proceedings [2]. The longitudinal profiles where measured by measuring the induced sum signal on a beam position pickup. Finally the longitudinal velocity distribution was measured by letting the beam pass through a drift tube which can be excited by a DC voltage. When excited the particles local velocity in the tube is shifted, thus the Doppler shifted resonance frequency is shifted. Thus by sweeping the voltage on the tube and at the same time monitoring the fluorescence from the laser-excited beam with a photomultiplier we can measure the longitudinal velocity distribution [6].

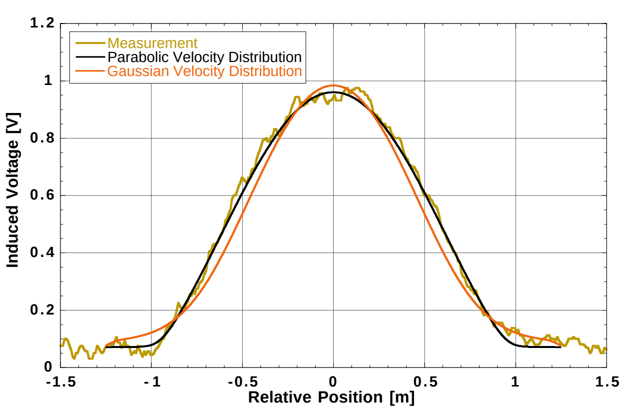


Figure 2: Measured bunch profile together with the two discussed model distributions. The longitudinal velocity spread is $\sqrt{\langle v^2 \rangle}$ = 100 m/s.

Following the arguments of [7] we compare the results of the measurements to the bunch shape expected by a self consistent solution to the Maxwell-Boltzmann distribution, including the confinement and the space-charge potential. In our case the distribution is given by

$$\frac{\rho_L(z)}{\rho_L(0)} = \exp\left\{-\frac{F_0 C}{2\pi h k_B T_{||}}\left[1-\cos\left(\frac{2\pi h}{C}z\right)\right] + \frac{g_0 q}{4\pi\epsilon_0 k_B T_{||}}\left(\rho_L(0)-\rho_L(z)\right)\right\} \qquad (2)$$

where $\rho_L(z)$ is the line charge density in the beam, $T_{||}$ is the longitudinal temperature and $g_0$ is a geometric factor given by $g_0 = 1 + 2\ln(b/a)$. Where $b$ is tbe radius of the vacuum chamber and $a$ is the beam radius.

In this equation we have assumed that the only influence from the transverse dimension is the logaritmic dependence on the transverse size in the geometric factor $g_0$.

In figure 2 is an example of a longitudinal bunch profile. The assumption of a Gaussian velocity distribution inherent in the Maxwell-Boltzmann distribution is seen to fit worse than if we assume a parabolic one.

As is confirmed by the velocity and spatial distributions shown in figure 3, the longitudinal velocity distribution induced by laser-cooling is more parabolic than Gaussian. The reason is that laser-cooling tends to reduce the tails, as the syncrotron oscillations oscillate all particles which are too warm into resonance with the lasers at least once per oscillation, thus slowly cooling the particles that may have been lost by collisions. As the rate of collisions causing particles to be lost decreases fast with increasing capture range the tails at higher velocity spreads are vanishing [8].

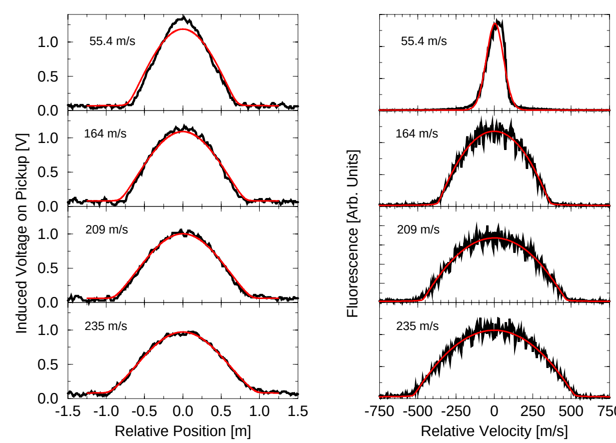


Figure 3: Longitudinal bunch and velocity profiles for bunches of $4.06 \cdot 10^6$ particles. The dashed lines in the velocity profiles are parabolic fit to the data (folded with the laser line shape), and in the bunch profiles it's the theoretical profile extracted from the parabolic modification of the Maxwell-Boltzmann distribution.

In figure 4 we have shown the results of a measurement of many bunches at different longitudinal velocity spreads and particle numbers. Each dot represents an average of bunches with the same number of particles and the same longitudinal velocity spread. The longitudinal velocity profile is measured as an average of several injections (typically 20) whereas the bunch profiles are measured in one shot.

The agreement of the parabolic modified distribution with the measurements is quite good. However we observe, as was earlier done in [1], that for the coldest beams there's a slight tendency of the bunches to be shorter than expected in the high current regime. One possibility for the discrepancy could be that the beam was space charge limited in the transverse dimensions too, but then one would expect the bunches to become slightly longer than in the uncoupled case, thus this seems not to be the explaination [9, 10].

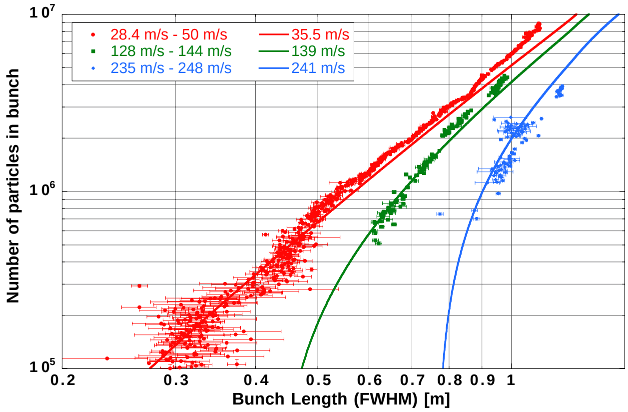


Figure 4: The number of particles in each bunch versus the bunch length. The solid lines are results from the parabolic model, which in the cold limit, as well as in the low density limit coincides with the Maxwell-Boltzmann result. The deviation of the space charge limited sizes is discussed in the text.

## 3 TRANSVERSE BEHAVIOR

In order to understand the deviations we must look at the simultaneous transverse profile measurements done during these studies. In figure 5 we have shown all three spatial dimensions of the ion beam as a function of current. If the density was constant we would expect all of them to scale at a cube root of the number of particles. This seems also to be the case for both the horizontal and the longitudinal dimension, however the vertical dimension blows up faster when the current is increased. This drop in density as the current goes up correlates well with the bunches being shorter, as that means we would expect a drop in the space charge repulsion.

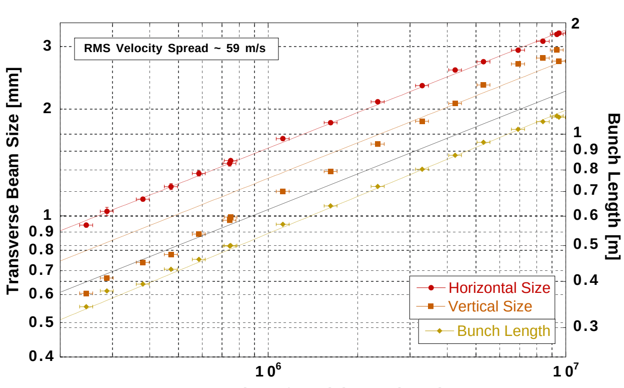


Figure 5: The transverse and longitudinal dimensions of the laser-cooled beam as a function of the current. The colored lines are cuberoot fit to the data, whereas the black line is a parallel translation of a cuberoot fit to guide the eye. The beta functions at the point of measurement are $\beta_x$ = 12.1m and $\beta_y$=2.6m.

However it's not clear what makes the beam blow up, or what makes the beam density in the densest cases be what it is, at the low currents the density is about $2{\cdot}10^5$ cm$^{-3}$, about an order of magnitude below what we would expect to be the highest possible density with the given potential [2]. As in [2] we presume that this limitation is due to space charge tune shift. This might also account for the blow up of the vertical dimension, as high beam currents might make the beam harder to cool, and as the coupling of heat from the horizontal to the longitudinal motion (where we are cooling) is aided by dispersion, which the vertical to longitudinal coupling is not.

## 4 CONCLUSIONS

We have studied the longitudinal and transverse spatial profile of a laser-cooled bunched beam in a storage ring. The longitudinal shapes showed good agreement with a Maxwell-Boltzmann distribution modified to account for the parabolic longitudinal velocity distributions induced by laser-cooling.

However, at the lowest temperatures, where the density was highest, deviations from the expected bunch lengths was observed for high currents. The bunches was observed to be shorter than expected. This behavior has not earlier been accounted for [1], but the transverse beam profiles revealed that it might be due to a blowup of the vertical dimension of the beam that the bunch lengths are allowed to become shorter than expected. As also observed in coasting beams [2] we furthermore observe that the highest densities reached are an order of magnitude below what would be expected for a zero emittance beam. We assume that this is due to the large space charge tune shifts induced in the rather dense beams. These results might indicate important limitations the the beam quality obtainable by longitudinal laser-cooling of bunched beams.

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