OBSERVED LIMITS TO LASER-COOLING OF A STORED ION BEAM

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Abstract

At the ASTRID storage ring we have recently developed a high resolution technique to monitor the transverse size of a stored ion beam utilizing the fluorescent light from a laser-excited ion beam. With this novel technique we have studied the transverse size of a coasting ion beam during longitudinal laser-cooling to ultra low temperatures. We observe that we can obtain a constant (high) density as a function of beam current, which suggests that the beam is space charge limited with zero emittance. However the limiting densities does not comply with this conclusion, and the beam shapes does not deviate from Gaussians as one would expect in a zero emittance beam. We suggest as a possbile mechanism, that large space charge tune shifts changes the beam tune to be close to a resonance, thus causing strong heating in the beam. These observations may have implications for attaining a crystalline beam, as well as to the ultimate limits to beam quality of a stored ion beam.

1 INTRODUCTION

Laser-cooling [1] offers high cooling rates and low temperatures. Since it's first demonstration on stored ion beams [2, 3], it has risen much interest due to it's potential for obtaining high phase-space densities in stored ion beams [4]. In the extreme case where the emittance approaches zero, one has predicted that the beam will eventually crystallize [5].

In this paper we present recent results from experiments on laser-cooling of coasting ion beams. As laser-cooling in a storage ring is only applicable in the longitudinal dimension it is of major interest how strong the coupling to the transverse dimensions is, and whether it can be strengthened. We have therefore studied how the size of a laser-cooled beam changes as a function of the number of particles in the beam. We observe that the size scales as a squareroot of the number of particles, i.e. we have a constant density as a function of the beam current. This is what would be expected for a zero-emittance space charge limited beam, however the limiting density observed does not comply with what would be expected for the given lattice.

For these experiments we have developed a new type of transverse beam size measurement, which relies on the fluorescent light from the laser-excited ion beam. The fluorescent light is imaged onto a high-resolution CCD, and in this way the transverse density distribution is measured.

2 TRANSVERSE DIAGNOSTICS

Non-destructive measurements of the transverse degree of freedom can, in some cases, be done by studying the noise spectrum in the beam, working on the sidebands of the natural (betatron) oscillation frequency of the beam in the focusing lattice of the storage ring, the amplitude of the so-called Shottky-noise spectrum [6]. This method, however, requires fairly high beam currents, and does not determine the beam profile. Furthermore the application of laser cooling, induces large distortions in the Schottky noise spectrum [7]. A residual-gas ionization beam-profile monitor (BPM) detects the ionization products from collisions between beam particles and rest gas. This technique has for instance been employed at the TSR storage ring in Heidelberg [8]. However, the resolution of this technique, is not sufficient for detailed study of the small beams studied here. We have therefore implemented a system to measure the beam profile by imaging the flourescent light from the laser-excited ion beam onto a high-resolution, low-noise CCD camera.

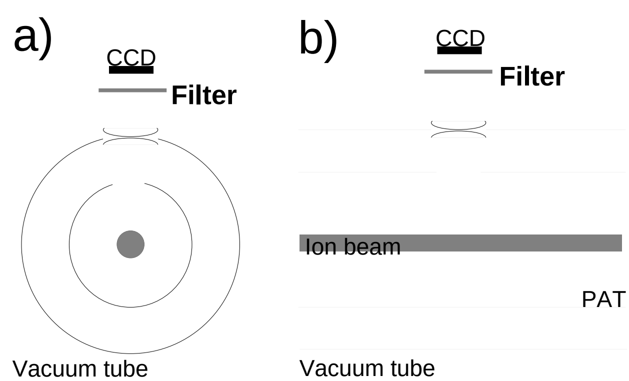

Figure 1: Schematic drawing of the experimental arrangement for imaging the horizontal beam size. a) Downstream view, b) Side view. The filter is a UV filter to block out most of the light coming from other sources than the beam.

Figure 1 shows a schematic drawing of the experimental arrangement. The camera can be set to observe the ion beam vertically or horizontally (only the horizontal configuration is drawn on figure 1). In front of the CCD is a mechanical shutter which can be controlled externally, thereby making it possible to image the ion beam at different times after injection. The current CCD system consists of two CCD cameras (one for each transverse dimension) with 1024x1024 pixels with a side length of 24 microns.

Thus the limiting resolution is $\sim$ 24 microns with a magnification of 1, more than adequate for the observed beam sizes of 1 to 12 mm (FWHM). The CCDs are cooled with liquid Nitrogen to reduce the thermal noise. In order to produce a spatially flat laser light distribution the strongly focused (FWHM $\sim$ 1.0mm) laser beam was actively swept (with a frequency of $\sim$ 100 Hz) in the desired plane.

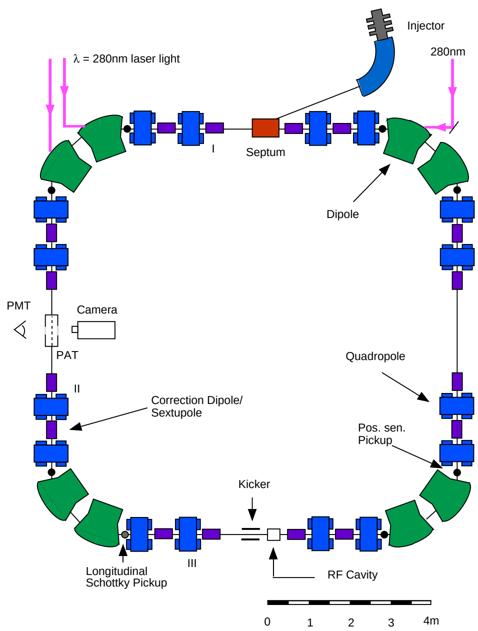

Figure 2: The ASTRID Storage Ring. One of the cooling lasers is split to provide light for the probe section (II) in which both the velocity profiles, and the transverse spatial profiles are measured.

3 EXPERIMENT AND DISCUSSION

We have used the ASTRID storage ring (figure 2 [9]) in Aarhus to store a beam of 100 keV $^{24}Mg^{+}$ ions. Copropagating laser light, overlaps the ion beam in two straight sections of the storage ring, in one section it is overlaped by a counterpropagating laser, and both lasers have in this section sizes of order $\sim$ 3mm. The copropagating laser light in the second ring section is focused strongly and is overlapping with the ion beam in a Post Acceleration Tube (PAT)[1] in front of the transverse imaging system. In figure 3 we have shown some examples of transverse beam profile measurements.

As the ion beam is rather cold at injection we can cool the beam by detuning the two lasers slightly red from resonance with the center of mass velocity of the beam before injection. At injection the lasers then prevent the beam from heating up in the longitudinal dimension. Using

[1]The PAT is a drift tube which can be excited by a DC voltage. Exciting the PAT changes the local velocity of the ions, and thus the velocity class of ions in resonance with the laser. By sweeping the voltage on the PAT and simultaneously monitoring the fluorescence we can measure the longitudinal velocity distribution [7].

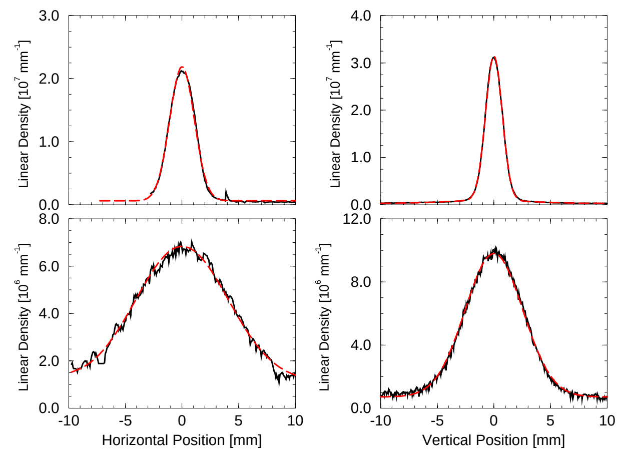

Figure 3: Horizontal and vertical particle distributions for uncooled (bottom) and cooled (top) beams of $\sim 5.8{\cdot}10^7$ particles. The distributions have been normalized to have an area of $5.8{\cdot}10^7$. The dashed lines are gaussian fits to the distributions.

this cooling procedure we have then studied the transverse beam sizes as a function of current for beams with longitudinal momentum spread $\Delta p/p \sim 5{\cdot}10^{-5}$. The current was extracted from a measurement of the injected beam and the beam lifetime, thus we varied the current by both changing the injected current, and changing the time after injection at which the measurement was done.

In figure 4 we have shown the results of these measurements. We observe a good agreement with a squareroot fit to the transverse sizes. This means that the beam density is constant as a function of the current. In the figure we have also drawn the transverse size of a beam of uniform density, which is how a zero emittance beam would be in the focusing potential of the storage ring. The confinement potential used for this calculation is given by the average focusing force of the storage ring in terms of the average tune.

It's evident from the figure that we have not reached the maximum density we would expect possible. Furthermore, as we could see from figure 3, the beam profiles are Gaussian, which is not to be expected if we project a uniform density beam into a plane (which is what we do when we images the beam onto the camera) [10].

The ring averaged (constant) density in the beam center we can extract from the measurements is $4.7{\cdot}10^5$cm^{-3}, where we have assumed that the beam size scales with the local beta function, which wouldn't be the case if we were in a space charge limited situation. This density is about 15% of what we would expect for the uniform beam, thus space charge must be an important factor, even though we are not limited by it alone.

Using this density we can calculate the first order space charge tune shift of the beam to $\sim$ 0.2, which is rather large compared to the betatron tunes in this experiment (Q_h = 2.27, Q_v = 2.83). It therefore seems that the beam might

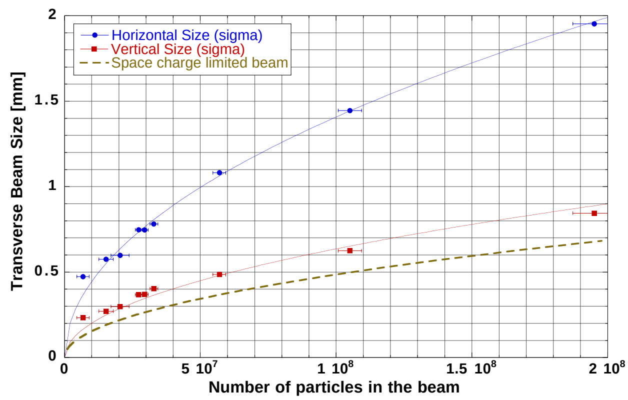

Figure 4: Transverse beam dimensions for a laser-cooled ion beam, as a function of the number of particles in the beam. The betafunctions at the camera position where β_x=12.13m and β_y=2.61m. The solid curves are fits to the data, assuming the beam size varies as the squareroot of the number of ions. The dashed curve is the size of a space-charge limited beam for a betatron tune of $Q_\perp$ = 2.5.

be limited by the space charge tune shift, which brings the tune close to a resonance, and thus heats the beam. This indicates that the density limit is an equilibrium between the cooling from the lasers and the heating due to the resonances. As the first order tune shift only depends on the beam density this explains the constant density as a function of current.

One other mechanism which might limit the attainable densities is dispersion. It was early realised [11] that because of the different path lengths of particles with different horizontal position in the ring, shear might prevent crystallization in a storage ring. However simulations showed that under certain conditions they could survive [12]. However as the stable situation requires the particles to have a constant *angular* velocity and laser-cooling tends to give a constant *linear* velocity it's not certain that laser-cooling is the tool the reach crystallisation. If however we assume that it's this effect which limits the density in our experiments, we would expect that as we have less current and the beam becomes smaller, dispersion would lead to less heating, thus the density should increase - since we don't observe this, this mechanism is not likely to be the problem yet.

Thus everything seems to suggest that we have a tune limited beam. However, as we expect that this limitation might be overcome, and we'll then face the limitation due to dispersion, we need a way to generate a 'dispersive' laser beam, or what has been called tapered cooling [12]. In Astrid the dispersion in most of the cooling section is about 2.7m, thus a 1mm displacement equals a velocity offset of about 360 m/s., which corresponds to a frequency change of the laser of 1.3 GHz. It's most likely not possible to generate a laser beam with a frequency gradient of 1.3 GHz/mm, thus we propose to compensate for the dispersion in the cooling section by introducing a horizontally varying potential which will change the local velocity as a function of position. The bending introduced by the horizontal electric field could be compensated by a magnetic dipole field. The proposed setup is illustrated in figure 5.

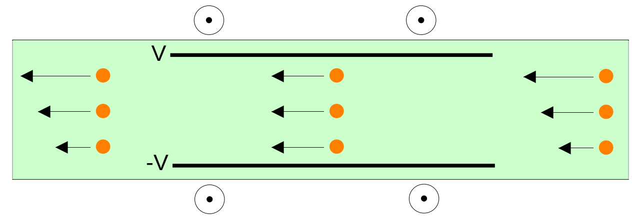

Figure 5: Tapered cooling by introducing a horizontally varying potential by exciting two parallel plates around the beam. The magnetic field compensates for the bending that the electric field would otherwise cause.

4 CONCLUSIONS

We have observed that an ion beam laser-cooled to a longitudinal momentum spread of $\Delta p/p \sim 5{\cdot}10^{-5}$ has a constant density as a function of the number of particles. We argued that this must be due to the large space-charge tune shifts induced by the reduction of the transverse beam size due to intra beam scattering. For these studies we used a novel technique for transverse beam size measurements, which images the fluorescent light from the laser-excited ion beam onto a high-resolution CCD. These observations may have implications for the possibility of attaining beam crystallisation using laser-cooling.

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