Lasers and Laser-Cooling used for studies of Beam Dynamics

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Abstract

A new technique for measuring ion beam profiles using laser induced flourescence is presented. The technique employs the resonant interaction of laser light with a beam of circulating ions in a storage ring. The light from the spontaneous decay of the excited ions is imaged by an optical system onto a high resolution CCD, making it possible to extract the beam's transverse spatial distribution. The first results from this technique, including studies of the transverse to longitudinal coupling in a circulating, laser-cooled ion beam, are presented.

1 INTRODUCTION

The creation and behavior of dense cold (i.e. having a very small velocity spread) ion beams in storage rings are of interest for many storage ring applications. In this paper we present a new technique for diagnosing the transverse degrees of freedom of an ion beam. The technique is especially applicable for ions sutable for laser cooling [1], as it utilizes the flourescence from the electronic transition of these ions, when they are resonantly interacting with laser light.

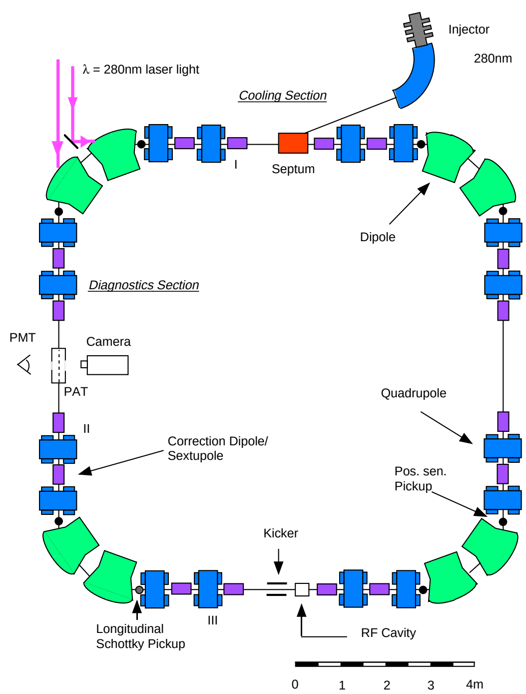

Figure 1: The ASTRID Storage Ring

2 LASER-COOLING IN ASTRID

At the ASTRID storage ring (figure (1) [3]) we have applied the technique of laser cooling to create and study dense, cold ion beams. Two means are used for the study of the longitudinal degree of freedom. The technique of laser induced flourescence (LIF) involves an ion beam which passes through a cylindrical tube (called Post Acceleration Tube (PAT)) which can be excited by a dc voltage, thereby locally changing the ions velocity and thus the Doppler-shifted resonant frequency of the optical transition. By sweeping the voltage on the tube we can bring different velocity classes of the ion beam into resonance with the laser, and thereby measure the longitudinal velocity distribution [4]. An alternate method monitors the fluctuations induced on a longitudinal pickup (Schottky-noise [5]) by fluctuations in the total beam intensity. From the frequency spectrum of these fluctuations we can under certain conditions extract the longitudinal velocity distribution. This technique is sensitive to coherent behavior in the beam, ideal for the study of charge density waves etc. [4]. The attainment of an ultra cold ion beam via laser cooling is strongly coupled to the degree of sympathetic cooling in the beam. As the laser cooling force, in contrast to atom traps, in a storage ring only applies to the longitudinal degree of freedom, the coupling to the transverse degrees is of major interest, and several schemes to enhance this coupling have been proposed [6]-[7].

3 TRANSVERSE DIAGNOSTICS

To be able to optimize this coupling it is important to be able to study it. Non-destructive measurements of the transverse degree of freedom can, in some cases, be done by extracting the amplitude of the betatron sidebands in the Shottky-noise spectrum of a coasting beam induced in a transverse pickup [5]. This method, however, requires fairly large beams, and furthermore doesn't directly reveal the shape of the beam. A final limitation is induced by the application of laser cooling, which induces large distortions of the Schottky-noise signal [4]. A residual-gas ionization beam profile monitor (BPM) can be used to detect the ionization products from collisions between beam particles and rest gas. This technique has been employed at the TSR storage ring in Heidelberg [8]. The technique has a reported spatial resolution of 260(50)μm, and a typical count rate for laser cooling conditions (singly charged ions, $\sim 1\mu$A current) of $\sim 300\ \mathrm{s}^{-1}$. An estimate (using the betatron tune to define a harmonic confining force constant K) of the average beam size for a space charge dominated beam of $\sim 10^8$ particles in ASTRID is 1mm, thus the resolution of the rest-gas BPM is not sufficient for detailed study of space charge dominated beams, and definitely not for future studies of crystalline beams. Furthermore it is not desirabel for the study of ultra-cold beams that the technique relies on collisios with the (hot) rest gas. In the light of these considerations we have 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.

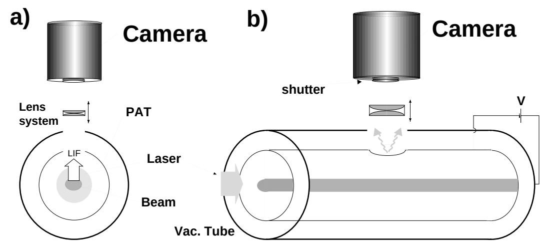

Figure 2: Schematic drawing of the setup. a) Downstream view, b) Side view

Figure 2 shows a sketch of the setup. The camera can be set to observe the ion beam vertically or horizontally (only the horizontal view is sketched on figure 2). The section of beam observed by the camera passes through the above mentioned PAT. 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 shutter has an open/close time of order 6ms. The magnification and focus of the system can be calibrated by inserting a plate with marks of known distances. This is also the way to measure the laser profile, i.e. by making the laser incident on a diffuser, and imaging the distribution on the CCD.

The current CCD system consists of a cryogenically cooled CCD camera with 1024x1024 square pixels with a side length of 24 microns. Thus the limiting resolution is $\sim$ 24 microns with a magnification of 1, which is a resonable magnification as the beam sizes observed are between 2 and 10 mm wide (FWHM). As explained above the system images the flourescent light from the ion beam interaction with an overlapping resonant laser in the beam pipe. In order to avoid difficult interpretation of the images the spatial intensity distribution of the laser beam needs to be uniform in the plane we want to image. This is done by actively sweeping a strongly focused (FWHM $\sim$ 1mm) laser beam spatially in the desired plane.

The sensitivity of the described system relies on the available laser power, as more laser power generates more flourescent light. To avoid the laser exerting a force on the ion beam while probing, the CCD system images the ion beam inside the PAT. The PAT is held at a voltage ($\sim$ 400 V) thus making it possible to have the ions on resonance inside the PAT and far off resonance outside. The PAT is rather short compared to the cooling section, and no influence of the laser on the ion beam has been observed. Uncooled ion beams with linear densities down to $1.6{\cdot}10^5$m^{-1} have been imaged. The main limiting factor for the system is the readout noise of the CCD, as the dark current is extremely low ($\sim$ 0.3e$^-$/hour/pixel). This means that the present system, by binning the CCD pixels in the beam direction[1], easily can measure beams of one order of magnitude lower linear density, which is in the string regime [2]. Thus this method of transverse beam diagnostics offers high sensitivity and resolution and is at the same time completely nondestructive.

A further feature of the described system is that the measurements are dispersion free. As the width of the electronic transition is small compared to the uncooled longitudinal velocity spread (in our case an uncooled beam has a spread of order 700 m/s where as the ion fraction in velocity space resonant with the laser has a FWHM of order 13 m/s), the system probes only a narrow velocity class, and the imaged beam profile is thus directly an expression for the horizontal beam emittance without the need to consider dispersion (the position deviation covered by the laser is of order 15 microns (D = 2.7m)). This of course also means that we can measure the dispersion by detuning the laser and probing the horizontal distribution of different velocity classes, this is illustrated in figure 3.

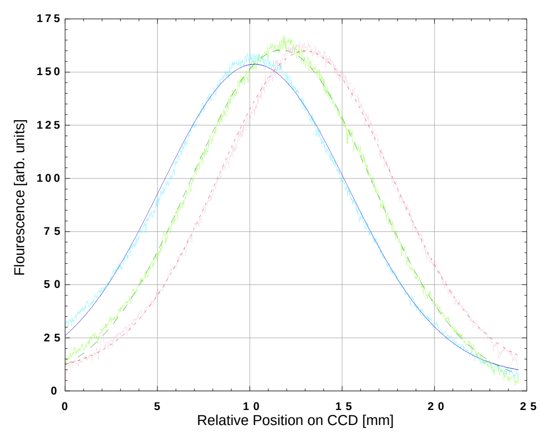

Figure 3: Horizontal Beam Profiles measured for different longitudinal velocities. The strong lines are gaussian fits to the data. Solid Line Δv = -279.6m/s. Long dashed line Δv=0. Short dashed line Δv = 279.6m/s.

4 LASER COOLING RESULTS

The ASTRID storage ring (figure 1) [3] was used to store 100 keV ^{24}Mg$^+$ ions. The beam is bunched by a sinusoidally varying longitudinal electric field in the beam path. The frequency of this signal is the 16th harmonic of the revolution frequency. One counterpropagating laser, produced by frequency-doubling 560 nm light from two ring-dye lasers, overlaps the ion beam in one straight section (8 m) of the storage ring (figure 1). The ultraviolet light, which can be frequency-tuned over a range of 20 GHz, drives the $(3^2S_{1/2}) \leftrightarrow (3^2P_{3/2})$ electronic transition used

[1] Binning means that the charges in a given number of adjecant pixels are added before readout.

for laser cooling [9]. By scanning the laser frequency from large red detuning (with respect to the resonant frequency of an ion circulating at the ideal orbit) the particles can be cooled to temperatures of order 1 Kelvin [10].

The first investigations studying the behavior of the transverse phase space as a function of longitudinal cooling has been undertaken. In figure 4 we first show results from observing an uncooled beam of ions. This plot clearly shows the expected nondependence on the number of particles of the transverse size for an uncooled beam. Furthermore we can observe that the difference in size between the two dimensions is ~ 2.2, in good agreement with expections from the calculated betafunctions of β_x =11.56m and β_y =2.64m.

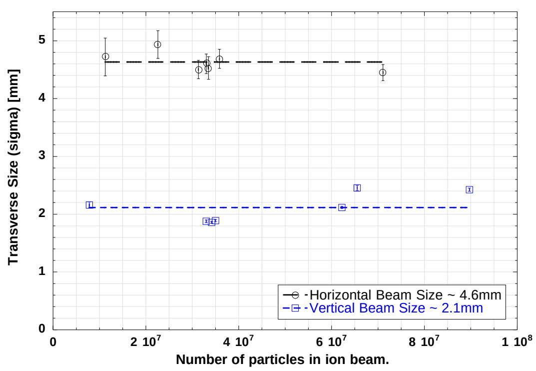

Figure 4: Horizontal and vertical beam sizes measured for uncooled beams having varyious particles numbers (bunch lengths = 1.00m$\pm$0.05). The longitudinal velocity spread is of order 600 m/s for all measurements.

When laser cooling is applied to the above beams, a dramatic decrease of the transverse sizes has been observed. This is shown in figure 5. This figure shows how the transverse dimensions of the ion beam decreases with decreasing longitudinal velocity spread, thus demonstrating the existance of sympathetic cooling in a bunched ion beam, earlier demonstrated in a coasting beam [11]. The measurements were done with betatron tunes of Q_x =2.282 and Q_y =2.821. The strength of the sympathetic cooling was observed to depend strongly on the betatron tunes.

5 CONCLUSION

We have demonstrated a new velocity selective technique for measuring ion beam profiles. The technique is applicable for any ion having a closed electronic transition for interaction with laser light. In fact, by utilizing the Doppler shift of the fast circulating ions, this technique could be used for highly charged ions having transitions in the X-ray regime in the moving frame, giving this technique quite broad application possiblities. The technique is a major step forward in the study of dense cold ion beams, for which the possiblity of beam crystallization has been proposed [12]. It is completely nondestructive, and offers resolutions in the μm regime, which is necessary for observing

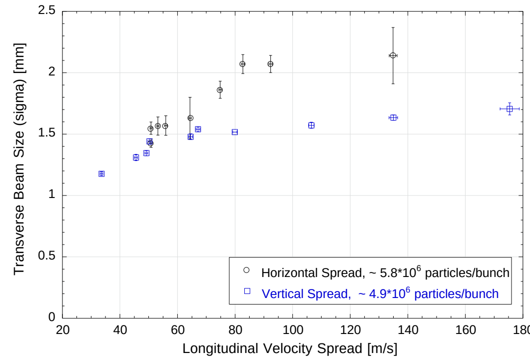

Figure 5: Horizontal and vertical beam profiles measured for different longitudinal velocity spreads. The beam currents are not the same because the measurements weren't done simultaneously. Other measurements showed that this does not alter the overall behavior.

beam crystallization (shell structures), as has already been done in ion trap experiments [13].

We have furthermore confirmed the presence of sympathetic cooling in a laser-cooled ion beam, and observed that the strength of sympathetic cooling depends strongly on the betatron tunes. We are currently working on gaining more insight into the behavior of the sympathetic cooling under varying conditions, which has implications for the ultimate limit for cold ion beams and thus beam crystallisation.

6 ACKNOWLEDGEMENTS

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