SCHOTTKY NOISE SIGNAL AND MOMENTUM SPREAD FOR LASER-COOLED BEAMS AT RELATIVISTIC ENERGIES

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Abstract

We present results on laser-cooling of relativistic bunched $C3^+$ ion beams at the the Experimental Storage Ring at GSI, Darmstadt. With moderate bunching at a few volts, beams of triply charged carbon ions with a beam energy of 122 MeV per nucleon have been laser-cooled to relative longitudinal momentum spreads of about 2×10^{-6} and below at beam currents of the order of several μA. By detuning the bunching frequency relative to the laser frequency, the acceptance range of the laser force can be increased to match the beam momentum spread. Subsequently decreasing the detuning reduces the momentum spread to values below the resolution of the Schottky noise spectrograph. The reduction of the beam momentum spread is accompanied by a drop in the Schottky noise power by seven to eight orders of magnitude until the signal vanishes completely.

INTRODUCTION

The Experimental Storage Ring (ESR) (see Fig.1) establishes an ideal testbed for laser-cooling experiments at relativistic energies using standard laser equipment (see Tab. 1 for experimental parameters). Exploiting the relativistic Doppler-shift of the laser frequency from the laboratory frame to the rest frame of the ions, a variety of ions can be directly laser-cooled using a single laser system and choosing the appropriate beam energy [1]. The results presented in the following serve as a valuable input for laser-cooling experiments at the future FAIR facility [1, 2].

Different to typical laser-cooling setups in traps, for laser cooling of ion beams at relativistic energies, moderately bunching the beam is necessary to provide for a counter-acting force to the laser force [3] (see Tab. 1 for a listing of all experimental parameters). The combined force of the bucket and the laser results in a momentum-dependent force with a controllable, stable cooling point in momentum space. For the data sets discussed here, bunching of a few volts was applied at the 20th harmonic of the revolution frequency f_{rev}, while the mixing frequency at which the Schottky signal was observed was set to the 47th harmonic.

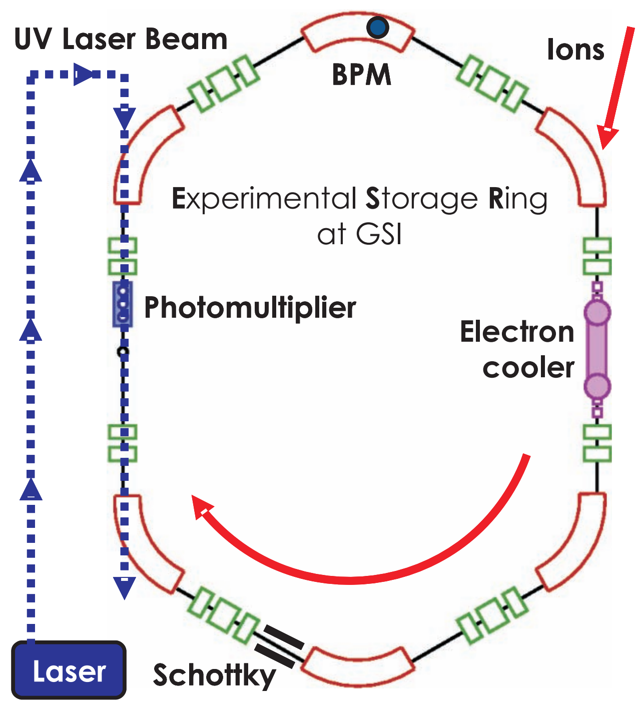

Figure 1: View of the ESR at GSI, Darmstadt. Laser beam and ion beam are brought in overlap in a straight section of the ring. The focus of the laser beam is adjusted to the position of the photomultiplier where the fluorescence signal of the ion beam is recorded. Also marked are the position of the electron cooler, the beam profile monitor (BPM) and the pickup electrode (Schottky). The ions revolve clockwise in the ring, the laser beam is counterpropagating to the ion beam.

A combination of two laser systems, namely two frequency-doubled argon ion lasers, has been used for laser cooling. While the first of the two laser beams is frequency-stabilized by measuring the absorption signal of the beam passing through an iodine vapor cell, the frequency of the

Table 1: Experimental parameters for the storage ring, ion beam and laser system.

ESR	
circumference	108 m
betatron tune	2.3
slip factor	0.6
Beam	
ion species	C^{3+}
beam energy	1.47 GeV
revolution frequency	1.295 MHz
relativistic β,γ	0.47, 1.13
beam lifetime	300 s to 450 s
Laser	
laser source	Ar^+ ion laser
operational mode	cw, single mode
wave length	257.34 nm (SHG)
power	40-100 mW
Cooling Transitions	
$2S_{1/2} \rightarrow 2P_{1/2}$	155.07 nm
$2S_{1/2} \rightarrow 2P_{3/2}$	155.81 nm

second beam is scanned relatively to the frequency of the first. The frequency offset Δf_{beat} between the two laser beams is determined by overlapping the beams and measuring the beat signal. Both beams are brought in overlap with the ion beam in a straight section of the ring. (see Fig. 2). The fixed-frequency laser beam is used to cool the ions to their ultimate small momentum spread, while the other laser-beam is applied to increase the momentum acceptance of the laser force, especially addressing those ions which escape the momentum acceptance of the first laser beam due to intra-beam scattering.

The initial momentum spread of the bunched beam is about three orders of magnitude bigger than the momentum acceptance of the force of the fixed-frequency laser beam. Although the scanning laser system increases this acceptance range by almost one order of magnitude [4] (the maximum detuning of both lasers is about 400 MHz in the UV for all data sets presented here), the momentum mismatch is still to large to cool all ions confined in the bucket. To directly cool all ions, the bunching frequency is detuned relatively to the fixed laser frequency, thus subsequently bringing different velocity classes of ions in overlap with the laser force. A reduction of the detuning reduces the total longitudinal momentum spread until the laser frequency is close to the cooling transition frequency for those ions resting in the bucket center as shown in Fig. 3.

Finally, additional moderate electron cooling at a few mA electron current is used to increase the coupling of the transverse to the longitudinal degree of freedom of the ion motion in the bucket. In all cases, electron cooling is switched on for only a few seconds until the coupling has been increased to the desired degree. With a combination of these two cooling techniques, three-dimensional cold beams can be attained [5].

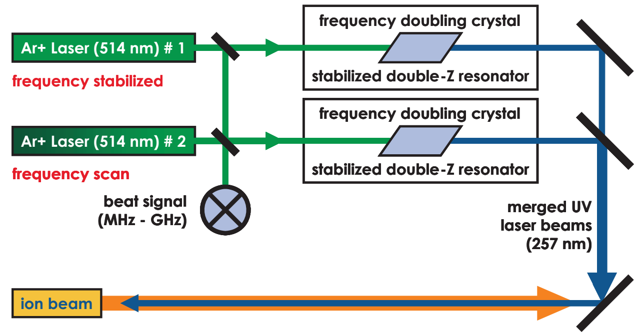

Figure 2: Laser system used for laser-cooling. The frequency of one laser beam is scanned relatively to the fixed frequency of another laser system. The scanning is controlled by measuring the beat signal of the two laser beams. Both laser beams are frequency-doubled separately using beta-barium borate crystals placed in a double-Z resonator geometry. After frequency-doubling, both beams are merged to one and brought in overlap with the ion beam.

SCHOTTKY NOISE SPECTRA

At the ESR, Schottky noise spectra provide a relative longitudinal momentum resolution for a single bunched beam to about 2×10^{-6}. A further increase in resolution is possible using optical detection of the fluorescence signal of the laser-cooled beam [6]. Here, we concentrate on the dynamics of ions confined in the bucket which can be deduced from the Schottky noise signal.

The spectrum of the Schottky noise signal of a bunched laser-cooled ion beam shows sharp, pronounced peaks at a spacing determined by the synchrotron oscillation frequency of the ions in the bucket pseudo-potential. The center peak marks the center of the bunch in frequency space. The spread Δf_{b} of the satellite peaks, which are symmetrically distributed around the center peak, determines the longitudinal momentum spread of the ions. The momentum spread is then given by the frequency spread as [5]

$$\frac{\Delta p_{\text{long}}}{p_{\text{long}}} = \frac{1}{\eta} \frac{\Delta f_{\text{b}}}{f_{\text{b}}}. \quad (1)$$

The limitation of the momentum spread measurement stems from the fact that the determination of the frequency spread requires the existence of at least one sideband on each side of the carrier peak. Momentum spreads smaller than the resolution limit determined by these two first order sidebands of the spectrum thus cannot be resolved.

Recently, the dynamics of laser-cooled bunched beams have been discussed in detail [4], showing qualitatively new features at the transition from the intra-beam scattering dominated regime to the space-charge dominated regime [5]. At this transition, the momentum spread of the beam reaches the resolution of the Schottky measurement.

As in the case of the momentum spread, the Schottky signal intensity is derived from the Schottky spectrum by first subtracting the constant signal background before

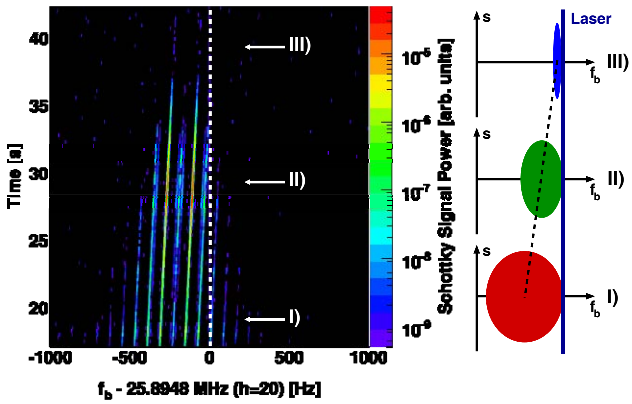

Figure 3: Schematic view of the cooling scheme. The bunching frequency f_b is detuned continuously relative to the laser frequency marked by the dashed white line in the middle of the color-coded Schottky noise spectrum. The Schottky noise signal strength is plotted logarithmically, the X-axis showing the detuning of the bunching frequency, the Y-axis showing the time in which the detuning is reduced. Three steps indicated by the numbers I, II and III are marked in the spectrum. On the right side of the figure, the phase space volume of the ion distribution in the bucket at each of these steps is illustrated by three ellipses. When the detuning is reduced, the momentum spread decreases with the position of the laser beam marking the maximum momentum spread.

summing up the intensity of all individual peaks. At low Schottky signal intensities, a longer signal integration time is used to clearly distinguish the signal from the background. All the intensities were weighed by this integration time.

SCHOTTKY NOISE INTENSITY AND MOMENTUM SPREAD

Previous experiments using electron-cooled coasting beams [7, 8, 9] have shown a drop in the Schottky intensity by several orders of magnitude at low ion beam currents, meaning low ion densities. This drop has been attributed to an onset of beam ordering [8].

While in these experiments the ion current has to be varied in order to determine the ion density at which the drop of the Schottky signal intensity is observed, in laser-cooling experiments, the momentum spread is simply controlled varying the detuning Δf_b of the bunching frequency relatively to the fixed laser frequency. This offers additional experimental control over the longitudinal momentum spread, which in turn becomes almost independent of the ion current.

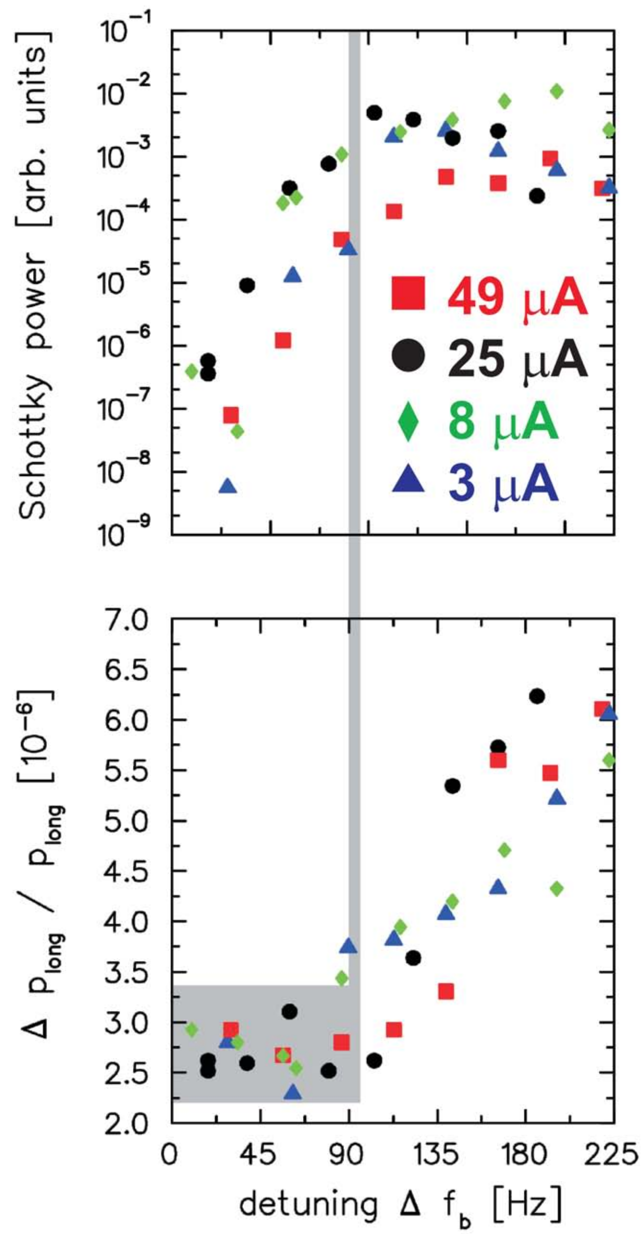

Figure 4: **Upper Part:** Integrated Schottky signal power versus detuning of the bunching frequency. The power of the Schottky signal is extracted from the Schottky spectrum, removing the constant background noise value and summing the signal for all peaks. For each detuning value a short time integration (usually 0.1 s) of the Schottky signal has been used to extract the corresponding power signal. The total signal power has been normalized to this integration time.

Lower Part: Corresponding momentum spread. The resolution limit of the Schottky measurement is indicated by the gray bar. At this point, the ion beam typically enters the space-charge dominated regime. The position marking the onset of the drop in Schottky power is indicated by the gray line.

The upper part of Fig. 4 shows a plot of the Schottky signal intensity extracted from the spectrum as described in the previous section. The intensity is plotted versus the detuning Δf_b. The various markers indicate various beam currents. All data points follow the same trend. At large detuning the intensity of the Schottky signal decreases only weakly with decreasing detuning. At a detuning of about 90 Hz, as indicated by the gray line in Fig. 4, the signal intensity drops rapidly until the level of the background noise is reached. The relative reduction of the signal strength is about seven to eight orders of magnitude. It has to be pointed out that the reduction is not caused by ion loss, instead the ions reside in the bucket center and the beam current remains almost constant during the scanning of the bunching frequency.

Interestingly, the drop occurs at the same detuning value at which the measured momentum spread of the ion beam, as shown in the lower part of Fig. 4, becomes limited by the resolution of the Schottky measurement. The reduction of the momentum spread below the limit of the Schottky measurement has been previously found to mark the transition of the bunched beam to the space-charge dominated regime [4, 5, 6].

The decrease in Schottky signal power sets a severe limitation to the observation of ultra-cold beams. It shows, that as soon as coherent movement of the ions due to an increase in coupling between the ions in the bucket could be observed, the Schottky signal is reduced by several orders of magnitude, thus limiting the amount of information on the dynamics of ultra-cold bunched beams which can be extracted from the Schottky signal.

Fortunately, with laser-cooling, the fluorescence intensity of the laser-cooled ions, which depends on the Doppler-shift of the cooling transition frequency relative to the laser frequency, can serve as a high-resolution diagnostic tool complementary to the Schottky noise signal. Unfortunately, with the current experimental setup, the observed fluorescence rate was in most cases too low for high precision measurements of the momentum spread.

Nevertheless, recent measurements of the fluorescence signal of a laser-cooled bunched beam [6] indicate that the longitudinal momentum spread could be at least one order of magnitude smaller than the value measured using the resolution-limited Schottky signal.

CONCLUSION AND OUTLOOK

We have shown that laser-cooling of relativistic ion beams is possible in a typical storage ring using a standard laser system and moderate bunching. Our main focus in this paper was on the information which can be extracted from the Schottky noise spectrum at low momentum spread. In the space-charge dominated regime, the information on the ion dynamics which can be deduced from the Schottky noise spectrum is sparse. Yet, all data indicate that collective ion motion due to increased inter-ion coupling dominates the ion dynamics in the bucket.

A clear fluorescence signal from the laser-cooled ions can provide a much higher resolution for determining the longitudinal beam momentum spread. Thus, for future experiments, a new experimental setup including at least two photomultipliers placed inside the beam tube in vacuum, near to the ion beam, is proposed.

In addition to extending the resolution of the beam diagnostics, it is foreseen to complement the single-frequency laser system by a pulsed laser system with high repetition rate and a pulse length comparable to the ion bunch length. The energy spread of the pulsed laser beam will then match the acceptance of the laser force to the initial ion momentum spread without the need for detuning the bunching frequency, while the high repetition rate increases the integrated cooling strength of the laser force.

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