LASER COOLING OF RELATIVISTIC C^{3+} ION BEAMS WITH A LARGE INITIAL MOMENTUM SPREAD

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Abstract

We present results on laser cooling of stored relativistic C^{3+} ion beams at the Experimental Storage Ring (ESR) in Darmstadt. For the first time, laser cooling of bunched relativistic ion beams using a continuous-wave UV-laser that was widely tunable over a large frequency range has been demonstrated. This new scheme allows to address the complete, initially broad momentum distribution of the ion beam without the need of additional electron cooling. Most importantly, this new method can be directly adopted to future high-energy ion storage rings where a previous scheme, based on varying the bunching frequency, can no longer be employed. As conventional beam diagnostics reach their limit at the ultra-low momentum spreads achievable with laser cooling, we show that with in-vacuo detectors the fluorescence emitted by the laser-cooled ions can be used instead for optical beam diagnostics.

INTRODUCTION

Future accelerator facilities, such as FAIR (Germany) [1] and HIAF (China), will provide high-energy beams of stable and rare (heavy) ions for fundamental research. Many of the experiments planned at these facilities, such as in-ring mass spectrometry of short-lived rare nuclei, tests of strong-field quantum electrodynamics with highly-charged ions, or in-beam x-ray spectroscopy of atomic transitions in heavy nuclei, will greatly benefit from ion beams with ultra-low momentum spread. Most of the existing storage ring facilities employ electron cooling to obtain ion beams with a low momentum spread ($\Delta p/p$) and a small diameter. However, at highly-relativistic energies or high γ (γ^2=$1/(1-\beta^2)$, β=v/c), there are two major challenges to achieve electron cooling. The first challenge deals with the creation of high-current electron beams of several hundred mA and energies of several MeV [1, 2]. The second challenge comes from the fact that the cooling time increases as $\tau_e \propto \gamma^{3/2}$ [3]. For an electron beam energy of 8 GeV and a beam current of 1 A, this can lead to cooling times of above one minute to reach $\Delta p/p \approx 10^{-5}$ [4]. The high cost and the demanding technical efforts to perform electron cooling at such high energies are the main reasons why other methods are sought for. Schramm *et al.* [5] have suggested laser cooling as a promising alternative, and listed several advantages. Most importantly, for appropriate cooling transitions in highly charged ions, the laser cooling force scales with γ^3 and thus becomes very strong, yielding cooling times as short as milliseconds. Many different ion species can be laser-cooled due to the large Doppler-shift of the cooling transition frequency f_0 in the ion rest frame (f=$f_0\gamma(1-\beta)$, f=c/λ) and state-of-the-art laser systems of appropriate power [6]. Furthermore, at high γ-values, the fluorescence photons from the ions are emitted into a Lorentz-boosted cone of opening angle θ=$1/\gamma$ [7]. This yields high photon rates and supports fluorescence detection of the laser-excited cooling transition, which, in turn, can be used for optical beam diagnostics and spectroscopy.

ESR EXPERIMENT

After several years of planning [8], development [9], and tests [10], in August 2012 a laser cooling experiment using a cw laser system with a broad detuning range has been performed at the ESR [11]. The first goal of this beamtime was to demonstrate that the initially 'hot' ions in the bucket can be cooled by a single laser with a relative frequency scanning range surpassing the rf bucket acceptance, *i.e.* without changing the bucket frequency and without initial electron cooling. A second goal was to demonstrate *in-vacuo* optical detection of the UV-fluorescence from the laser-excited ions. Finally, systematic studies of the 'dynamics of laser cooling' with varying bunch lengths, rf-bucket amplitudes,

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ion number per bunch, laser power, laser scan time, etc. have been performed. This required the development of a synchronized data acquisition system combining state-of-the-art ion beam diagnostics (Schottky resonator, ionization profile monitor) with optical detectors (*e.g.* UV-channeltron [10]) and laser diagnostics.

As in the two previous ESR laser cooling experiments (2004 and 2006), a beam of $^{12}C^{3+}$ ions[1] with a kinetic energy of 122 MeV/u (β=0.47, γ=1.13) was used. For laser-cooling we used the $2s_{1/2} \rightarrow 2p_{1/2}$ cooling transition at λ_0=155.07 nm. Typically 10^6 to 10^8 ions were stored in the ring and beam lifetimes were well above hundred seconds.

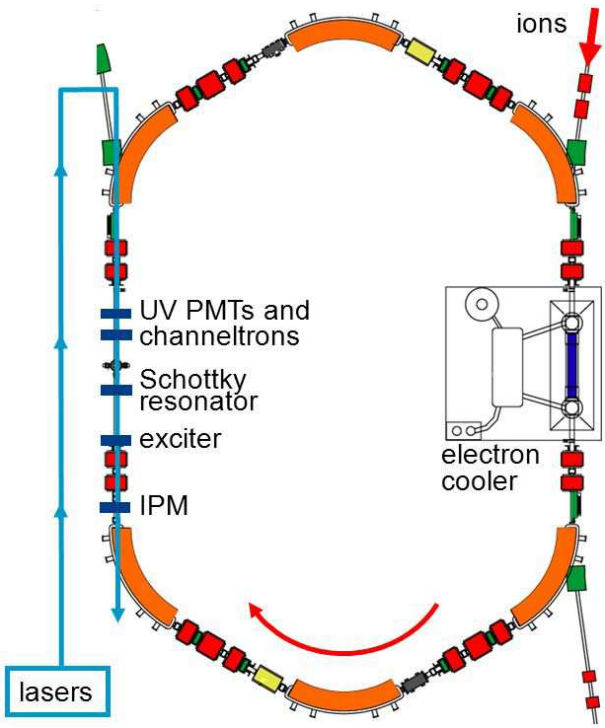

Figure 1: The experimental storage ring at GSI. The paths of the ion and laser beams and the employed diagnostics are indicated (see text).

A schematic drawing of the ESR and the used diagnostics is shown in Figure 1. The ion beam revolves clockwise and was bunched with a moderate sinusoidal rf-signal (amplitudes of a few V) on beam axis, provided by a broadband exciter. The laser beam was overlapped with the ion beam in an anti-collinear geometry in a straight, field-free region of the ESR. The laser had a focal spot size (FWHM) of several hundred μm and several tens of mW power.

In order to observe the fluorescence from the laser-cooled ions, two UV-channeltrons were placed at strategic positions along this overlap section. The channeltrons (PHOTONIS) have a horn-like shape and a CsI-coated active area with a diameter of one inch. Via the photoelectric effect the CsI coating 'converts' UV-photons into electrons,

[1]With about 10% of $^{16}O^{4+}$ contamination from the ECR ion source.

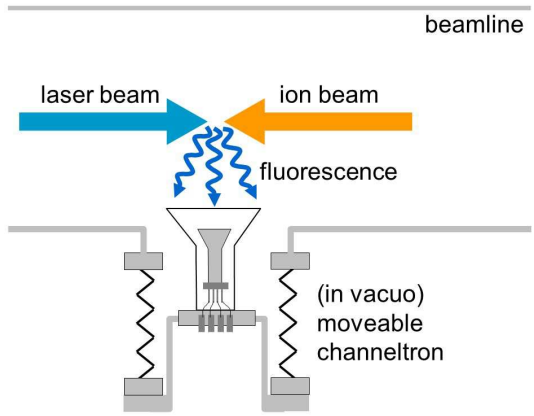

Figure 2: Schematic representation of the fluorescence detection with a moveable UV-channeltron at the ESR.

which are then collected and amplified by the channeltron. Each channeltron was mounted inside a bellows such that it could be moved close to the ion beam by a linear drive. A metal cone, which could be biassed, was used to shield the UV-channeltron from stray light of the laser and from stray electrons or ions. This design, schematically shown in Figure 2, also assured that the electrical connections were kept as simple and short as possible [10]. The overall background could thus be kept very low. The UV-PMTs, installed at the same diagnostic chambers, were mounted directly onto DN40CF CaF2 viewports, which have a relatively high transmission in the UV.

Laser cooling of relativistic ions in a storage ring can be performed using only one anti-collinear laser beam and a bunched ion beam, using the bucket force to counteract the laser force. The bandwidth of the laser in this experiment was in the kHz range, and thus orders of magnitude too small to collect the initially 'hot' ions with a typical momentum spread of $\Delta p/p \approx 10^{-4}$.

If the laser frequency is fixed, as was the case for the ESR beamtime in 2006, the bunching frequency needs to be changed, a technique developed at the ASTRID storage ring [12]. As a result, the typical multiple, equally-spaced lines in the Schottky spectra, which originate from the synchrotron motion of the ions inside the rf-bucket, appear slanted [13]. Although this scheme works quite well, changing the bunching frequency is not practical at high beam energies. It also induced small changes in the revolution frequency of the ions, which could influence high-precision experiments requiring stable beam conditions. A more promising and flexible approach is to keep the bunching frequency fixed and change the laser frequency [8]. However, since the initial momentum distribution of the ions is quite large, the laser needs to be scanned continuously over a very large range, *i.e.* about 10 GHz, without mode-hopping or a significant change in the laser power. Here, we demonstrate for the first time laser cooling using a fast scanning, narrow-band cw laser system, based on a seeded fiber amplifier (1028 nm) with two frequency dou-

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bling stages (514 and 257 nm) [14], which was operational during the complete 8 days of beamtime.

Figure 3 shows a typical Schottky spectrum of a coasting $^{12}C^{3+}$ beam, recorded at the 189^{th} harmonic (ca. 244 MHz) of the ion revolution frequency in the ring. For this beam, no electron cooling was employed and the cw laser was scanned over 12 GHz in 10 s. It can be seen that the laser slows down the ions (*i.e.* they obtain a lower revolution frequency) as it is scanning through its range. Since the ion beam is not bunched, there can be no effective laser cooling as no velocity-dependent force counteracts the laser force. Thus, those ions interacting with the laser are effectively decelerated by the laser force, leaving a certain energy band in the beam almost void of ions. The width of this band illustrates the large scanning range of the laser frequency.

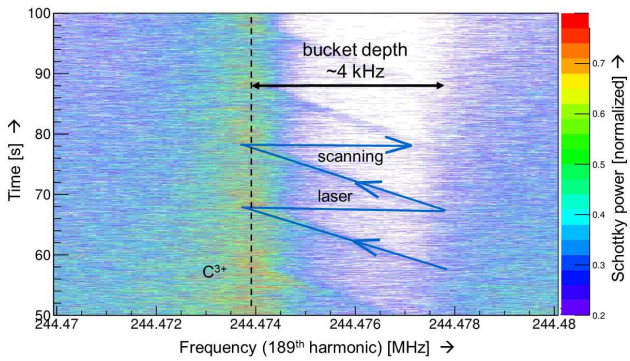

Figure 3: Schottky spectrum of a coasting C^{3+} beam: time vs. frequency, the color scale represents the intensity of the Schottky signal. The electron cooler was switched off. The cw laser scans over a frequency range of 12 GHz at 257 nm in 10 s, as indicated by the arrows, effectively decelerating a certain velocity class of ions.

In order to achieve laser cooling, the ion beam has been moderately bunched. The corresponding Schottky spectrum is shown in Figure 4. As the cw laser frequency slowly approaches the transition frequency of ions resting in the center of the bucket, the momentum spread of the ion beam continuously decreases, as indicated by the vanishing synchrotron sidebands. In order to mark the position of the bucket center, the laser frequency was scanned over the transition frequency of the ions resting in the bucket. At this point, the laser force drives the ion motion in the bucket, which leads to a rapid heating of the bunch and a fast appearance of a large number of synchrotron sidebands. Then, the cooling cycle starts again. This operational mode was used to study the cooling dynamics as a function of the number of ions stored in the ring. For continuous cooling, the laser frequency would only be scanned close to the resonant frequency on the cooling side of the bucket. The Schottky signal intensity, as indicated by the color bar (right axis), does not exhibit a smooth pattern. This is most likely due to intrabeam scattering, which is always present and acts as a heating force on the ions counteracting the laser cooling. The integrated Schottky intensity decreased with decreasing momentum spread, while the number of ions stored in the bucket remained almost constant.

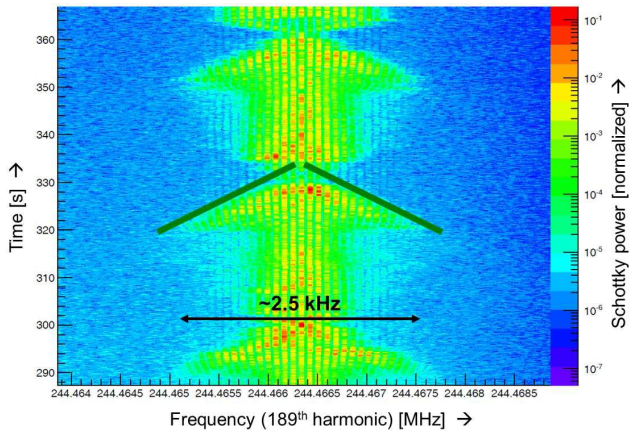

Figure 4: Schottky spectrum of a bunched C^{3+} beam. When the laser scans (scan time = 10 s) the number of synchrotron sidebands (vertical lines) is reduced, as indicated by the slanted green lines, giving a clear sign of laser cooling. The cooling time was set by the scanning time of the laser and was much shorter than the beam life time, resulting in an effectively constant number of ions stored in the bucket potential during one cooling cycle.

Fluorescence from the laser excited ions has been recorded with the UV-channeltron detectors [10] throughout the whole beamtime. The fluorescence was found to depend only on the laser power, the laser focus/overlap, and the ion number. The background could be kept rather low. An example is shown in Figure 5. Here, the ion

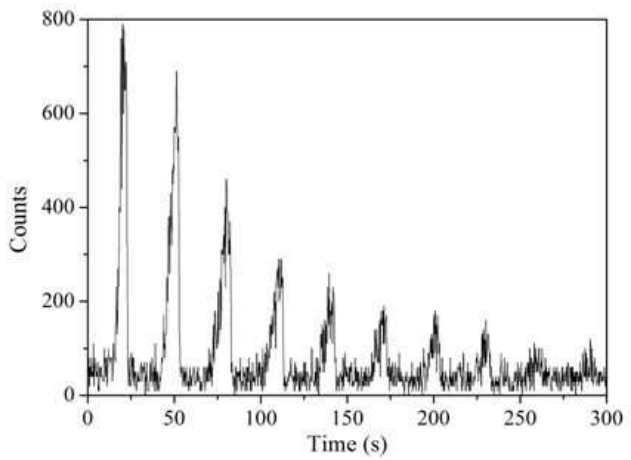

Figure 5: Fluorescence signal measured with the UV-channeltron. As the laser frequency is scanned (scan time = 30 s) fluorescence peaks appear when the laser frequency becomes resonant with the $2s_{1/2} \rightarrow 2p_{1/2}$ transition frequency of the C^{3+} ions. The overall background could be kept very low.

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beam was bunched and the electron cooler switched on. As the laser is scanned over 12 GHz in 30 s, the fluorescence strongly increases when the laser frequency approaches the resonance frequency of the ions, i.e. the $2s_{1/2} \rightarrow 2p_{1/2}$ transition at about 155 nm. The peak intensity decreases exponentially with time, directly following the ion beam current, which is due to charge-exchange with the residual gas. The observed fluorescence was strongest when the electron cooler was switched on. We attribute this to the increased phase space density of the three-dimensional cold ion beam. However, small shifts in the beam orbit due to electron cooling, and therefore a better overlap of ion and laser beam, might also increase the fluorescence yield.

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