Laser Cooling and Spectroscopy of Relativistic C^{3+} Beams at the ESR ◇

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We report on the first laser cooling of a bunched beam of multiply charged relativistic ions. A C^{3+} ion beam was stored at an energy of $E = 1.47\,\mathrm{GeV}$ ($\beta = 0.47$) at the ESR (GSI). At this energy the $2S_{1/2} - 2P_{3/2}$ transition of the Li-like ions ($\lambda \sim 155\,\mathrm{nm}$) is Doppler-shifted into resonance with the frequency doubled (514 nm) line of the Ar-ion laser. Concerning beam energy and charge state, this experiment represents an intermediate step toward the unique laser cooling scheme proposed for relativistic beams of highly charged heavy ions at SIS 300 (FAIR) [2].

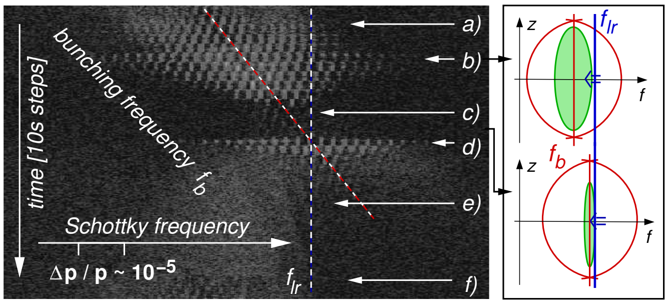

Fig. 1: Schottky noise spectra (47^{th} harmonic) of the laser cooled bunched beam with rising bunching frequency f_b (diagonal dashed line). The decelerating laser beam is operated at fixed frequency and resonant with ions at f_{lr} (vertical dashed line). The bunching frequency $f_b = hf_{rev} = 10 \times 1.295\,\mathrm{MHz}$ is increased in steps of 10 Hz every 10 s. corresponding to the data rows, while the separation of the equidistant peaks corresponds to the synchrotron frequency.

Bunched beam laser cooling [1] relies on the damping of the synchrotron motion by the strong but narrow-band (decelerating) laser force. Its width corresponds to $\Delta p/p \approx 5 \times 10^{-8}$. For matching the initial momentum distribution, the center frequency of the bucket was continuously tuned as depicted in Fig. 1. Starting at a low frequency f_b where ions close to the separatrix come into resonance, the ion beam is cooled into the bucket (a). Within the harmonic range, the number of synchrotron sidebands increases (b) interpreted as a laser cooled bunched beam where individual ions perform synchrotron oscillations with $f_{sync} \sim 100\,Hz$. From the synchrotron frequency (the sideband spacing) a momentum acceptance of about $\Delta p/p \sim 2 \times 10^{-5}$ can be deduced that corresponds to the observed momentum spread (roughly the number of sidebands). Closer to resonance the sidebands suddenly vanish (c) when the beam enters the space-charge dominated regime. When the laser beam comes into resonance with ions at the bucket center (d) the synchrotron motion is driven. Ions are decelerated (e) out of the bucket until the cycle restarts (f).

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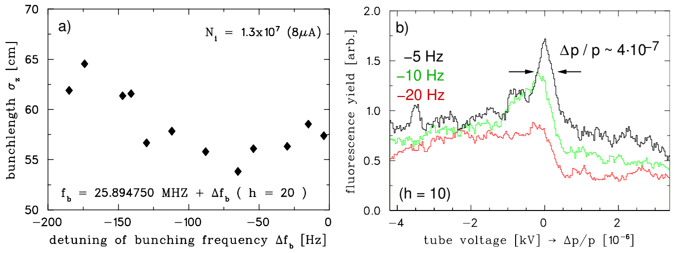

Fig. 2: Bunch length as a function of the detuning of the bucket center with respect to the laser resonance, i.e., the cooling strength (left), and momentum distribution close to optimum cooling (right).

Fig. 2 (left) shows the transition into the space-charge dominated regime in real space, where the bunch length does not decrease any further with increasing cooling strength. This point corresponds to the situation c) in Fig. 1. The right graph depicts the laser induced fluorescence during continuous cooling as a function of the relative momentum deviation in a locally tuned observation region. For a frequency detuning corresponding to $\Delta p/p = 6 \times 10^{-7}$ at $h = 10$ a momentum spread of $\Delta p/p = 4 \times 10^{-7}$ is measured for a cold fraction of the beam. For an ion number of about 1.5×10^6 it corresponds to a plasma parameter of $\Gamma \sim 1$.

A more efficient cooling technique is presently under development, where a dedicated broad band laser system will address the whole ion bunch.

The cooling experiment incorporates the spectroscopy of the $2S - 2P$ transitions of Li-like C^{3+} at a precision limited by the knowledge of the ion energy $\Delta\omega_0/\omega_0 = (1-\beta^2)^{-1}\,\Delta\beta = \beta^{-1}\,\Delta\gamma/\gamma$. This energy has been measured via the electron energy of the cooler at the ion revolution frequency corresponding to the laser resonances [3]. The following transition wavelengths can be deduced, where the first error denotes the calibration accuracy of the electron energy and the second the statistical error.

ref.	$\lambda(2S_{1/2} - 2P_{1/2})$ [nm]	$\lambda(2S_{1/2} - 2P_{3/2})$ [nm]
Exp.	155.0705(39)(3)	154.8127(39)(2)
Th. [4]	155.0739(26)	154.8173(53)

Thus, the accuracy given by theory (second line) can be reached. With an improvement of the voltage calibration or measurements at different ion energies and laser wavelength on the same transition, theory could be readily challenged. At the ESR the method could be extended up to O^{5+} ions while, at FAIR, every element can be reached.

References

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