“White-light” Laser Cooling of a Fast Stored Ion Beam

S. N. Atutov,[1,*] R. Calabrese,[1] R. Grimm,[2] V. Guidi,[1] I. Lauer,[2] P. Lenisa,[1,2] V. Luger,[2] E. Mariotti,[3] L. Moi,[3]
A. Peters,[4,†] U. Schramm,[4] and M. Stößel[2]
[1]*Dipartimento di Fisica dell'Università di Ferrara and INFN-Sezione di Ferrara, 44100 Ferrara, Italy*
[2]*Max-Planck-Institut für Kernphysik, 69029 Heidelberg, Germany*
[3]*Dipartimento di Fisica dell'Università di Siena and INFM-Unità di Siena, 53100 Siena, Italy*
[4]*Sektion Physik, Ludwig-Maximilians-Universität München, 85748 Garching, Germany*
(Received 26 November 1997)

We report the experimental demonstration of “white-light” cooling of a high-velocity $^7\mathrm{Li}^+$ ion beam stored at 6.4% of the speed of light in a storage ring. In a direct comparison with single-mode laser cooling, we show that white-light cooling is much more efficient to counteract strong intrabeam heating and leads to lower longitudinal beam temperatures at higher ion densities, i.e., much higher densities in longitudinal phase space. [S0031-9007(98)05508-2]

PACS numbers: 29.20.Dh, 32.80.Pj, 42.50.Vk

In ion storage rings, established in the past decade as powerful instruments for precision experiments in atomic and nuclear physics [1], cooling techniques [2] play a key role in the production of beams of high brilliance and quality. In accelerator physics, very cold and highly dense ion beams are of great interest for exploring the beam dynamics at highest phase-space densities and for approaching a regime in which the beam behaves as a strongly coupled one-component plasma. Laser cooling [3–8] provides an extremely fast and efficient cooling and thus offers unique possibilities to enter this regime and to attain beams with liquidlike or solidlike Coulomb ordering [9,10].

In order to match the particular requirements of stored high-velocity ion beams, new laser-cooling techniques have to be employed [11,12]. The main problem, which markedly distinguishes the cooling of dense ion beams in storage rings from the cooling of neutral atom beams, is a very strong influence of Coulomb collisions between the stored particles. This intrabeam scattering (IBS) leads to strong heating exceeding thousands of degrees Kelvin per second and, most problematic for laser cooling, to sudden longitudinal velocity changes up to ~ 1000 m/s in single large-angle Coulomb collisions. As single-mode laser radiation does efficiently excite the ions only within the homogeneous linewidth, corresponding to a narrow velocity interval of typically a few tens m/s, these scattering events lead to dramatic losses out of the cooling process [13]. A large velocity capture range, as needed to overcome these losses, can be obtained by Doppler tuning the transition frequency with local electrostatic fields and making use of an adiabatic optical excitation [11]. This method has recently served as a prerequisite for the first transverse laser cooling of a stored ion beam [7], but it has the severe drawback of limiting the applicable cooling rate to values far below the maximum dissipation rates offered by laser cooling.

We have recently proposed a laser-cooling scheme [12] which is based on a specifically tailored broadband laser [14] for the achievement of efficient “white-light” cooling [15–19]. The basic idea of this broadband cooling method is to resonantly interact with different velocity classes at the same time so that the radiation pressure can counteract the influence of IBS much more efficiently as compared to the single-mode case. The crucial point for obtaining optimum cooling results is to realize a broad spectrum with a sharp cutoff, which determines the final cooling velocity and cooling rate.

In this Letter, we report the experimental demonstration of white-light cooling (WLC) in a storage ring in direct comparison with single-mode monochromatic laser cooling. We show that WLC can strongly suppress IBS losses and that it provides lower temperatures at higher densities both for coasting and for bunched ion beams.

The experiments were performed with $^7\mathrm{Li}^+$ at the Heidelberg Test Storage Ring (TSR) where typically 3×10^7 ions are injected at an energy of 13.3 MeV. The $^7\mathrm{Li}^+$ beam consists of both singlet $^1S_0$ and triplet $^3S_1$ states of the heliumlike spectrum. For the triplet ions ($\sim 20\%$ of the beam) we measured a total lifetime of 20 s, which is a result of residual gas collisions leading to a loss rate of $1/35\ \mathrm{s}^{-1}$ and an additional decay of the metastable level $^3S_1$ to the singlet ground state $^1S_0$ with a rate of $1/50\ \mathrm{s}^{-1}$ [20]. The $^3S_1$ state is connected with the $^3P_2$ state through an allowed optical transition at a wavelength of $\lambda = 548.5$ nm in the rest frame. The beam velocity is chosen to be 6.4% of the speed of light so that the cooling transition can be resonantly excited by a copropagating Ar^+ laser emitting the 514.5-nm line. The Ar^+ laser, working in the single-mode regime, is actively stabilized to 1 MHz by locking it to an iodine reference cell. The ion beam is precooled for 7 s by electron cooling in order to provide suitable starting conditions for the laser cooling, i.e., an ion beam diameter of about 1 mm corresponding to transverse temperatures of a few thousand degrees Kelvin.

We have used the passive acousto-optical device described in Ref. [14] to transform the single-mode input light of the Ar^+ laser into a frequency comb [21] with the desired characteristics for the WLC of a stored ion beam (see Fig. 1). The light enters a ring cavity containing an acousto-optical modulator (AOM), which is driven by a radio frequency of $\nu_{\mathrm{AOM}} = 60$ MHz. For input coupling the second diffraction order is used. The output light of this cavity is sent through a second AOM operating at a higher frequency ($\nu'_{\mathrm{AOM}} = 210$ MHz), which allows one to double the total bandwidth of the laser radiation by combining the light from the zeroth and first diffraction order. In this way, a spectrum with a bandwidth of about 500 MHz is generated, as shown in the inset of Fig. 1. Distinctive features of our device are the high efficiency, the absence of any intracavity active medium, and the preservation of the frequency and intensity stability of the input laser. The efficiency, i.e., the ratio between the output intensity and the input intensity, is higher than 80%. A very useful feature is that, when the acousto-optic modulators are switched off, the output beam of our device is the single-mode beam itself. This allows a direct and immediate comparison of the cooling performance between the broadband and the single-mode laser source without any realignment or modification of the apparatus. The only remaining difference is a frequency shift ($\Delta\nu = 330$ MHz) of the sharp edge of the laser spectrum on the high frequency side when switching on the two AOMs, and a slight increase of the beam diameter ($1/e$ intensity drop) from 3 to 4.5 mm.

In a first set of experiments, we have applied WLC to a coasting, i.e., continuous ion beam. Longitudinal laser cooling is performed by counteracting the velocity-selective accelerating force of the copropagating Ar^+ laser, merged with the ion beam in one of the straight sections of the storage ring, with a decelerating auxiliary force [5]. The latter is generated by an induction accelerator (INDAC) [22], which in the present experiments was set to provide a constant ring-averaged deceleration force of -0.36 meV/m. This cooling scheme allows one to capture all ions with velocities above the stable cooling point [see dots in Figs. 2(a) and 2(b)], where the two forces balance each other, and also ions in a limited region of width Δv_c (capture range) below this point, where the accelerating laser force exceeds the INDAC force. In the single-mode case, Δv_c is determined by the homogeneous transition linewidth and the strength of the decelerating force [see Fig. 2(a)]. In the case of WLC, this interval is essentially determined by the bandwidth of the frequency comb, provided that the INDAC force does not exceed the lowest minimum of the radiation-pressure force within the comb [see Fig. 2(b)]. Under the given experimental conditions and with a laser power of 75 mW, the light-pressure force of the frequency comb covers a velocity range of $\Delta v_c \simeq 280$ m/s. Regarding collisional losses out of the velocity capture range by intrabeam scattering, this represents a substantial improvement as compared to the single-mode case, where saturation broadening leads to only $\Delta v_c \simeq 50$ m/s.

Figure 2(c) shows the fluorescence intensity emitted by the ions during the cooling process when the INDAC is active for 8 s. As cooled ions are kept at the stable point in a balance between the laser and the INDAC force with a constant photon scattering rate per ion, the fluorescence count rate is simply proportional to the number of ions in the cooling process. The nonexponential decay of the signal is essentially a result of intrabeam scattering losses out of the velocity capture range [5,13]. A smaller part of the loss (~30%) is due to a $M2$ decay of optically excited ions into the singlet system [23]. The comparison of the fluorescence intensity emitted during WLC and single-mode cooling clearly shows that WLC suffers much less from scattering losses than single-mode cooling: WLC collects a maximum number of ions which is 4 times

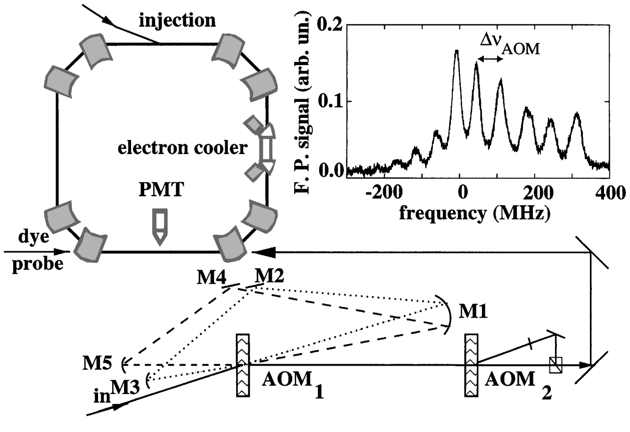

FIG. 1. Sketch of the storage ring TSR (circumference 55.4 m) with the frequency-comb generator cavity used for white-light cooling. AOM, acousto-optic modulator; $M1-M5$, ring-cavity mirrors; PMT, photomultiplier tube. The obtained frequency spectrum is shown in the inset.

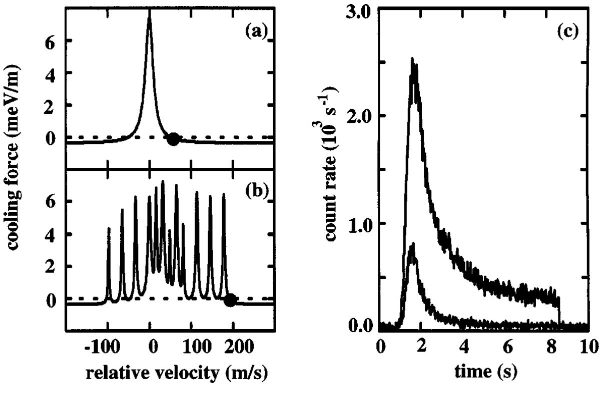

FIG. 2. Illustration of coasting-beam cooling. The total cooling force is a sum of the resonantly accelerating radiation-pressure force of the laser and a decelerating auxiliary force provided by the induction accelerator. In (a) and (b) the cooling forces are shown as calculated for a 130-mW single-mode laser radiation and for a 75-mW frequency comb, respectively. The dots mark the stable cooling point. (c) Shows the fluorescence intensity emitted by the ions during laser cooling with the single-mode light (lower curve) and in the case of the frequency comb (upper curve).

higher as in the single-mode case. After the full 8 s of the INDAC ramp practically no ions are left in the single-mode cooling process, but about 12% are still present in the case of WLC. We point out that a further increase in the velocity capture range is straightforward [24] by further broadening the comb spectrum, e.g., with additional acousto-optical modulators. If the capture interval Δv_c exceeds the velocities in the transverse ion motion, collisional losses will be suppressed completely.

We have probed the longitudinal velocity distribution of the laser cooled ions with a weak dye laser beam ($\lambda = 584.6$ nm) counterpropagating to the ion beam. The probe light was applied with a small duty cycle of ~5% in short 100-μs time intervals alternating with 2-ms cooling intervals. The fluorescence signal was recorded in a gated detection scheme during the probe intervals only. This allows one to probe the velocity distribution without the otherwise very strong fluorescence background caused by the cooling light and without significant perturbations of the cooling process by the probe light. The probe laser scan was performed just after the beginning of the INDAC ramp. Figure 3 shows the detected velocity distributions for 130 mW cooling laser power in a single mode (a) and 75 mW in the frequency comb of WLC (b). The longitudinal temperatures derived from these pictures are 180 and 90 mK, respectively. One clearly sees that WLC leads to lower temperatures although the ion number in the cooling process and thus the heating by intrabeam scattering is about twice as high. This improved cooling performance is due to the steeper slope of the cooling force at the stable point which leads to a higher cooling rate; see Figs. 2(a) and 2(b). These results demonstrate that WLC is a very powerful tool for the longitudinal cooling of stored ion beams as it allows one to combine a large velocity capture range with a high longitudinal cooling rate.

We have studied WLC also for a radio-frequency (rf) bunched $^7\mathrm{Li}^+$ ion beam. Here the ion motion is longitudinally confined in a comoving sinusoidal quasipotential, which is introduced by modulating the beam with an rf field tuned to a harmonics of the revolution frequency. In this “rf bucket” the ions perform synchrotron oscillations, and cooling means damping of these oscillations. Laser cooling in the rf bucket [6] is very promising for attaining ion beams of very high phase-space densities, as it facilitates fast longitudinal cooling without IBS losses. Nevertheless, the cooling performance with a single-mode laser is substantially degraded by the fact that after a large longitudinal velocity change resulting from a large-angle scattering event, it can take a long time to damp the resulting synchrotron oscillation by the laser. The reason is that a single-mode laser covers only a small part of the rf bucket [see Fig. 4(a)], and thus the ion comes into resonance only for a very small fraction of the synchrotron period. WLC overcomes this problem as a much bigger part of the bucket is covered [see Fig. 4(b)] and leads to a much faster damping of the synchrotron oscillations as compared with the single-mode case.

In the case of a $^7\mathrm{Li}^+$ beam, a particular situation arises from the presence of the ground-state singlet ions, which after electron precooling are also confined in the rf bucket but not cooled by the laser. This hot ground-state part of the beam (about 80% of all ions) constitutes a very strong source for heating of the laser-coolable metastable ions. The situation of an rf bunched $^7\mathrm{Li}^+$ beam therefore

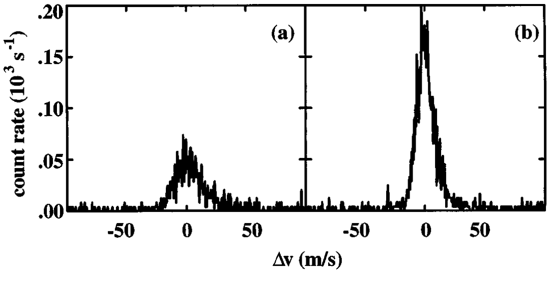

FIG. 3. Velocity distributions recorded for coasting-beam laser cooling with (a) the 130-mW single-mode laser and (b) the 75-mW frequency comb.

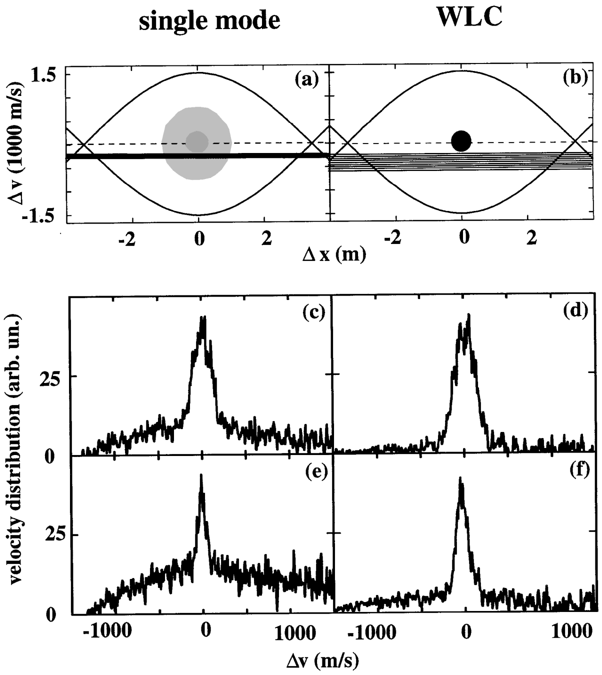

FIG. 4. Bunched beam results comparing single-mode laser cooling with WLC. (a) and (b) show the rf bucket in longitudinal phase space: Δv is the deviation from the synchronous velocity and Δx is the position deviation from the bucket center. The horizontal bars indicate resonant interaction with the laser modes, the dark spot in the middle of the bucket marks the cold laser-cooled distribution, and the gray area in the single-mode case illustrates the background distribution resulting from intrabeam scattering. (c) Shows the velocity distribution observed in the single-mode case with $\nu_{\mathrm{rf}} = 3.451\,045$ MHz, and (d) is the corresponding WLC result for $\nu_{\mathrm{rf}} = 3.451\,065$ MHz. In these cases the synchronous velocity is about 300 m/s above resonance with the laser. In (e) and (f) the rf frequencies are lowered by 20 Hz corresponding to a synchronous velocity that is lower by 130 m/s.

represents an ideal testing ground for laser cooling under the strong influence of intrabeam Coulomb collisions.

We have bunched the 13.3 MeV $^7\mathrm{Li}^+$ beam in the TSR on the 10th harmonics ($\nu_{\mathrm{rf}} \approx 3.451$ MHz) with an effective rf amplitude of 2.5 V. This leads to a synchrotron frequency of 130 Hz and a bucket energy acceptance of ± 2.2 keV, corresponding to ± 1600 m/s [see Figs. 4(a) and 4(b)]. We have studied the cooling results for the single-mode case and the WLC case by probing the resulting velocity distribution with a scanning dye laser as described before. The total laser power was 180 mW in both cases.

Figures 4(c)–4(f) show two pairs of measurements obtained after 5 s of cooling for WLC in direct comparison with the single-mode case. In 4(c) and 4(d) the rf was tuned in such a way that the single laser mode or the highest-frequency mode of WLC, respectively, was in resonance with ions about 300 m/s below the synchronous velocity, i.e., the exact velocity of the moving rf bucket. In 4(e) and 4(f) the rf was lowered to reduce this difference between synchronous and resonant velocity to about 170 m/s. This gives faster cooling in the center of the rf bucket, but also results in an increased rate of IBS kicking ions out of the center. The two single-mode cooling pictures 4(c) and 4(e) show the pronounced two-component velocity distribution which results from the narrow laser-cooling force in the presence of strong IBS [25]: A cold central distribution located in the center of the rf bucket is accompanied by a broad background distribution [see phase-space illustration in Fig. 4(a)]. The closer the laser is tuned to the bucket center the more ions are found in the background distribution. In 4(e) only ~10% of all ions are kept by the single-mode laser in the cold peak. The WLC leads to a markedly different behavior: In Fig. 4(d) the background distribution is completely suppressed and all ions are in the efficiently laser-cooled central part. Closer to resonance [Fig. 4(f)] a small background distribution becomes visible which is much smaller than in the corresponding single-mode case [Fig. 4(e)].

Our experimental results on metastable $^7\mathrm{Li}^+$ ions clearly demonstrate that dense ion beams in storage rings can be cooled much more efficiently with a laser source providing a sufficiently broad spectrum with a well-defined cutoff than with single-mode radiation. For a coasting beam, we have shown that optimized WLC allows one to suppress IBS losses and to reach lower temperatures at higher beam densities. For a bunched beam, where IBS heating leads to a pronounced two-component velocity distribution, we have shown that the hot background part can be strongly reduced in favor of the much colder subensemble in the center of the rf bucket.

We are currently preparing a new class of WLC experiments on $^9\mathrm{Be}^+$ ground state ions. As this species can be cooled from the absolute ground state using a strong and perfectly closed optical transition [5], it facilitates efficient cooling on a time scale which is long enough to observe the transverse cooling that occurs as a result of the thermal coupling of the different degrees of freedom caused by IBS [7,8]. For such a three-dimensional laser cooling, the fast dissipation of thermal energy out of the longitudinal degree of freedom is of crucial importance to obtain high phase-space densities of the stored ion beam. We therefore expect that WLC, substantially improving the three-dimensional cooling performance, will play an important role in future experiments on very cold and dense ion beams, behaving as a strongly coupled and ordered Coulomb plasma.

We thank Helga Krieger for invaluable technical assistance and D. Schwalm and L. Tecchio for support and useful comments on the manuscript.

---

*Permanent address: Institute of Automation and Electrometry-Novosibirsk, 630090, Russia.

†Deceased.

[1] For recent reviews, see the *Proceedings of the Euroconferences on Atomic Physics with Highly Charged Ions I–III* [Hyperfine Interact. **99** (1996); **108** (1997); (to be published)].
[2] *Proceedings of the Workshop on Beam Cooling and Related Topics, Montreux, Switzerland, 1993,* edited by J. Bosser (CERN report No. 94-04, 1994).
[3] S. Schröder *et al.*, Phys. Rev. Lett. **64**, 2901 (1990).
[4] J. S. Hangst *et al.*, Phys. Rev. Lett. **67**, 1238 (1991).
[5] W. Petrich *et al.*, Phys. Rev. A **48**, 2127 (1993).
[6] J. S. Hangst *et al.*, Phys. Rev. Lett. **74**, 4432 (1995).
[7] H.-J. Miesner *et al.*, Phys. Rev. Lett. **77**, 623 (1996).
[8] H.-J. Miesner *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **383**, 634 (1996).
[9] A. Rahman and J. P. Schiffer, Phys. Rev. Lett. **57**, 1133 (1986).
[10] D. Habs and R. Grimm, Annu. Rev. Nucl. Part. Sci. **45**, 391 (1995), and references therein.
[11] B. Wanner *et al.*, in Ref. [2], p. 354.
[12] R. Calabrese *et al.*, Hyperfine Interact. **99**, 259 (1996).
[13] H.-J. Miesner *et al.*, in Ref. [2], p. 349.
[14] S. N. Atutov *et al.*, Opt. Commun. **132**, 269 (1996).
[15] L. Moi, Opt. Commun. **50**, 349 (1984).
[16] P. Strohmeier *et al.*, Opt. Commun. **73**, 451 (1989).
[17] I. C. M. Littler *et al.*, Z. Phys. D **18**, 307 (1991).
[18] M. Zhu, C. W. Oates, and J. L. Hall, Phys. Rev. Lett. **67**, 46 (1991).
[19] T. Engel *et al.*, Max-Planck-Inst. für Kernphysik, Annual Report 1996, p. 149.
[20] M. H. Prior and R. D. Knight, Opt. Commun. **35**, 54 (1980).
[21] P. Jessen and M. Kristensen, Appl. Opt. **31**, 4911 (1992).
[22] C. Ellert *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **314**, 399 (1992).
[23] V. Luger *et al.*, Max-Planck-Inst. für Kernphysik, Annual Report 1996, p. 146.
[24] S. N. Atutov *et al.*, Hyperfine Interact. **109**, 259 (1997).
[25] H.-J. Miesner *et al.*, Max-Planck-Inst. für Kernphysik, Annual Report 1995, pp. 139–142.