APPROACH TO THE LOW TEMPERATURE STATE ORIENTED FOR CRYSTALLINE BEAM*

Akira Noda#, Masao Nakao, Hikaru Souda, Hiromu Tongu, ICR, Kyoto University, Uji-city, Japan
Kouichi Jimbo, IAE, Kyoto University, Uji-city, Japan
Hiromi Okamoto, Kazuya Osaki, AdSM, Hiroshima University, Higashi Hiroshima-city, Japan
Yosuke Yuri, Takasaki Advanced Radiation Research Institute, JAEA, Takasaki-city, Japan
Igor Nikolai Meshkov, Alexander V. Smirnov, JINR, Dubna, Moscow Region, Russia
Manfred Grieser, MPIK, 69029 Heidelberg, Postfach 103980, Germany,
Koji Noda, Toshiyuki Shirai, National Institute of Radiological Sciences, Chiba-city, Japan
Zhengqi He, Tsinghua University, 1 Qinqhuayuan, Beijing, China.

Abstract

With the use of S-LSR, an ion storage and cooler ring at ICR, the approach to attain a low temperature beam has been continued. With electron cooling one dimensional ordered state has been realized for 7 MeV proton beam, resulting in an abrupt longitudinal temperature jump from 2K to 0.3 K at a particle number ≈2000. A transverse temperature at a particle number of 4000 at the observation point with a beta-function of ≈1.7 m is estimated to be 12 K. Laser cooling has also been applied to $^{24}Mg^+$ ion beam with a kinetic energy of 40 keV. The lowest longitudinal temperature of a coasting beam was limited at 3.6 K for a beam intensity of 4 x 10^4 due to intra-beam scattering (IBS) and residual gas scattering, while a transverse temperature is reduced to ≈500 K by IBS for a beam intensity of 2 x10^7, which is accompanied by the increase of the longitudinal temperature to 11K. In order to actively cool down the transverse temperature, synchro-betatron resonance coupling (SBRC) has been applied to a bunched beam. By reduction of the beam intensity with scraping, the average transverse beam temperature has been cooled down to <15-50 K and 7-15 K for the horizontal and vertical directions, respectively, by SBRC for the beam intensity of 1 x 10^4.

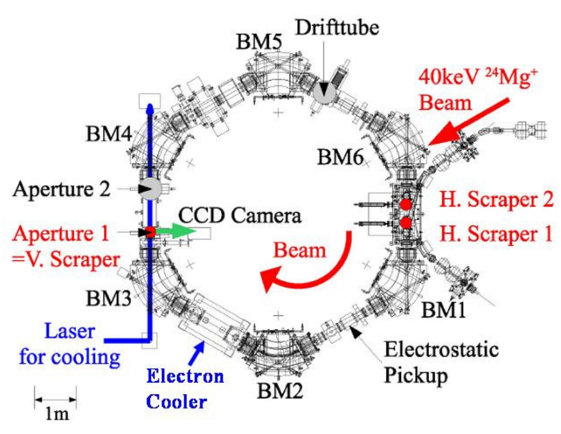

Fig.1 Layout of S-LSR and its beam monitoring and scraping apparatuses.

*Work supported by Advanced Compact Accelerator Development project by MEXT of Japanese government. It is al so supported by GCOE project at Kyoto University, "The next generation of Physics-Spun from Universality and Emergency.
#noda@kyticr.kuicr.kyoto-u.ac.jp

Table 1 Main Parameters of S-LSR

Ion species (energy)	H^+ (7 MeV), $^{24}Mg^+$ (40 keV)
Cooling Methods	Electron beam cooling, Laser cooling
Circumference	22.557 m
Average radius	3.59 m
Length of straight section	2.66 m (including Q mag. parts)
Number of superperiods	6
Betatron tune (ν_x, ν_y) Electron cooling Laser cooling	 (1.64,1.21) (2.07,1.12)
Bending magnet Maximum field Curvature radius Gap height Pole end cut Deflection angle Weight	H-type 0.95 T 1.05 m 70 mm Rogowskii cut + field clamp 60° 4.5tons
Quadrupole magnet Core length Bore radius	 0.20 m 70 mm

INTRODUCTION

A lot of efforts to approach to the low temperature states of a beam have been continued in these two decades so as to improve the beam characteristics which is usually in a gaseous state. At ICR, Kyoto University, an ion accumulation and cooler ring, S-LSR had been constructed and it became in operation in 2005. In Fig.1 and table 1, its layout and main parameters are shown. Originally it was oriented for the realization of compact ion accelerator for cancer therapy by combination of RF accelerator technology and laser plasma interaction [1]. After the successful demonstration of effective electron cooling of a hot ion beam with a relative velocity sweep between the ion and electron beams [2] utilizing TSR at MPIK [3] and S-LSR, the main experimental researches are oriented for the realization of lower beam temperature by application of beam cooling utilizing such a special characteristics of S-LSR lattice satisfying the so-called maintenance condition given by the following relations [4,5],

$$\gamma < \gamma_T \qquad (\gamma_T : \text{the transition gamma}) \qquad (1)$$

ISBN 978-3-95450-125-0

$$\max(\nu_H, \nu_V) < \frac{N_{sp}}{2\sqrt{2}}, \qquad (2)$$

where N_{sp}, ν_H and ν_V are the super-periodicity of the lattice, betatron tunes in the horizontal and vertical directions, respectively.

In the present paper, approaches to low temperature states of the circulating beam at S-LSR with the use of electron cooling and laser cooling are described.

ONE DIMENSIONAL ORDERING OF PROTON BEAM BY ELECTRON COOLING

Stimulated by the report from NAP-M at BIMP [6], particle number dependence of momentum spread of the circulating beam has been studied vigorously in the world and one dimensional ordering has been realized for multi-charge ion beams such as U^{92+}, Au^{79+}, Xe^{54+}, Kr^{36+}, Ni^{28+}, Ar^{18+}, Ne^{10+}, C^{6+} at ESR of GSI [7] and for Xe^{36+} at CRYRING of MSL [8]. Because of a smaller cooling force due to the single charge, the phase transition to the ordered state of a proton beam, had not been observed until its realization at S-LSR with a rather large super-periodicity of 6.

In Fig. 2, the dependence of momentum spread on the particle numbers obtained at S-LSR for 7 MeV protons is given, which shows a sharp jump at the particle number around 2000 [9]. The momentum spread below the transition is estimated to be 1.4 x 10^{-6}, which is close to the minimum longitudinal electron temperature of 1.2 x 10^{-6}. The beam radius at the transition is 17 μm [9] indicating magnetization of the electron beam first pointed out by Derbenev and Skrinsky [10] and experimentally observed at ESR [11].

The longitudinal, $T_{/\!/}$ and transverse, T_u, temperatures can be estimated utilizing the following relations [7, 12].

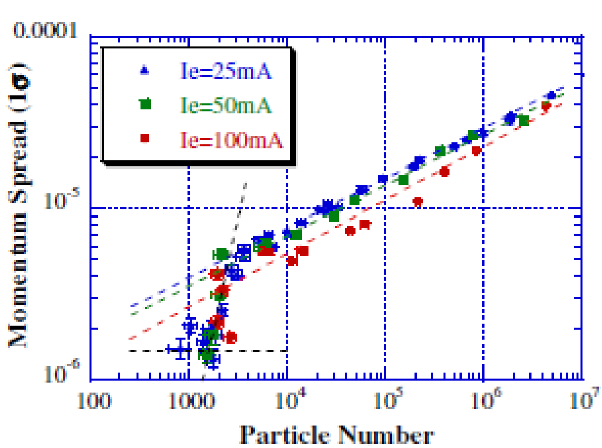

Fig.2 Particle number dependence of the momentum spread (1σ) of 7 MeV proton beam, electron cooled at S-LSR with three different electron currents [9].

$$k_B T_{/\!/} = m_0 c^2 \beta^2 \left(\frac{\delta p}{p}\right)^2, \qquad (3)$$

$$k_B T_u \cong m_0 c^2 \beta^2 \frac{\varepsilon_u}{C} 2\pi\nu_u, \qquad (4)$$

where m_0, c, β, ε_u (u represents either h : horizontal or v: vertical direction) C and ν_u are mass of the ion, velocity of light, the ratio of the ion velocity to the light velocity, the circulating beam emittance in u direction, the circumference of the ring and transverse betatron tune (u =H,V), respectively. The longitudinal temperature was abruptly changed from 2K to 0.3 K at a particle number ≈2000, which is considered to be the evidence of ordering. Transverse temperature with the particle number of 4000 at the observation point with beta -function of ≈1.7 m is estimated to be 12K.

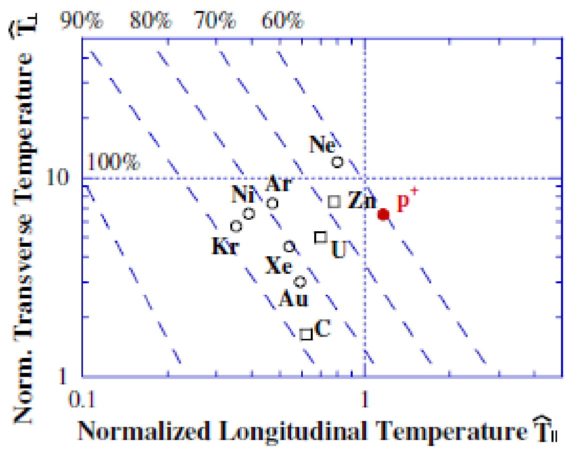

Fig. 3 Reflection probabilities observed for the 1-dimensional phase transition (borrowed from ref.[9])

With the use of the definitions, given by [13]

$$\begin{pmatrix} \hat{T}_{\parallel} \\ \hat{T}_{\perp} \end{pmatrix} = \frac{2}{m_i c^2}\left(2 r_i \beta\gamma \frac{\nu}{R}\right)^{-2/3} \begin{pmatrix} k_B T_{\parallel} \\ k_B T_{\perp} \end{pmatrix}, \qquad (5)$$

$$(T_{\perp} = T_H + T_V)$$

the dimensionless parameters, the normalized temperatures, $\hat{T}_{/\!/}$ and $\hat{T}_{\perp}$ are obtained as shown in Fig. 3 together with the data of other heavier ions measured at ESR [11]. Our data for a 7 MeV proton beam shows that the transition had occurred at a lower reflection probability around 60 %.

The above results are obtained for coasting beams. The importance of such a study to check the capability of similar transition for bunched beam was pointed out [14], which is one item to be studied at S-LSR in the near future.

ISBN 978-3-95450-125-0

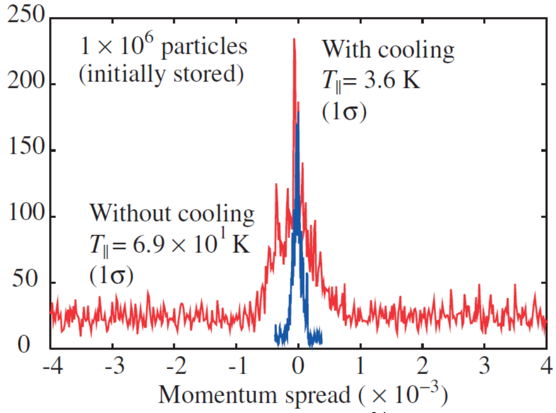

Fig.4 Momentum distribution of the $^{24}Mg^{+}$ ion beam with and without laser cooling.

LASER COOLING

Longitudinal Cooling of Coasting Beam

The laser light co-propagating or counter-propagating with the ion beam can only accelerate or decelerate the ion in the longitudinal direction and can cool down the temperature of the longitudinal direction. Utilizing the heat transfer due to IBS, it was demonstrated that the transverse temperature is also cooled down by performing longitudinal laser cooling. [15, 16] Transverse laser cooling, solely based on single-particle interaction of the ion beam with a laser beam, was also demonstrated. The scheme utilizes the dependence of the horizontal position of the ion on the longitudinal momentum, in combination with a transverse gradient of the light force ("dispersive cooling") [17].

Laser cooling with the use of a ultra-violet laser light (280 nm) co-propagating with the ion beam has been applied to the $^{24}Mg^{+}$ beam with an energy of 40 keV at S-LSR in ICR, Kyoto University. For the counteracting force with the laser cooling force, an induction accelerator was utilized which can generate a decelerating field of 6 mV. In Fig. 4, the momentum distribution of the coasting Mg ion beam with and without the application of laser cooling at an initial beam intensity of 1 x 10^6 is shown. The cooled longitudinal temperature was 3.6 K with a reduced beam intensity of 3 x 10^4 due to IBS and residual gas scattering. IBS effect reduced the transverse temperature to ≈500 K resulting in a higher longitudinal temperature of 11 K at a beam intensity of 2 x 10^7[18].

Indirect Transverse Laser Cooling with SBRC

The degrees of freedom between the longitudinal and horizontal directions can be coupled by accelerating the ion beam at the position with finite dispersion function by the operation point satisfying the following relation (SBRC) [19]:

$$\nu_H - \nu_s = m \text{ (integer).} \qquad (6)$$

Further the horizontal and vertical coupling can be realized with the condition:

$$\nu_H - \nu_V = n \text{ (integer)}, \qquad (7)$$

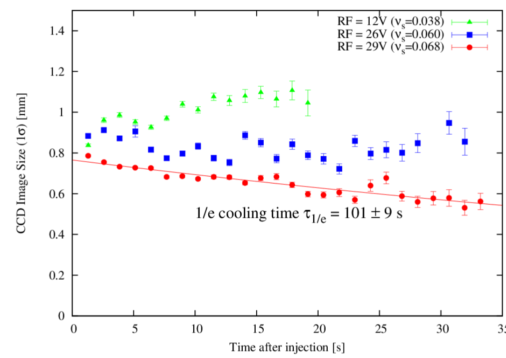

Fig. 5 Time variation of the horizontal beam size for various synchrotron tunes observed by a CCD camera.

satisfying the difference resonance utilizing a solenoidal or a skew magnetic field. Thus the laser cooling force is well expected to be extended to 3 dimensions.

At the first step, the indirect transverse laser cooling with the use of SBRC is experimentally demonstrated as shown in Fig. 5 [20], which gave a rather long cooling time as 101 sec. for a beam intensity of 1x 10^7 due to IBS heating. In Fig. 6, synchrotron tune dependences of cooled momentum spread (red) and the horizontal beam size (blue) are shown. Clear local minimum and maximum appear in these graphs at the SBRC condition.

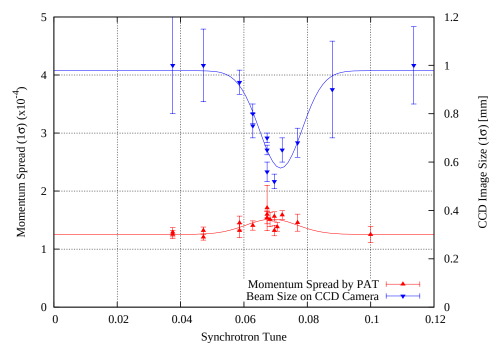

Fig.6. Synchrotron tune dependence of the momentum spread (red) and observed horizontal beam size (blue) after laser cooling.

Controlled Beam Scraping to Suppress IBS

In order to reduce the heating effect by IBS and to increase the efficiency of the indirect transverse laser cooling by SBRC, reduction of the beam intensity with the use of scraping has been proposed [21]. The initial horizontal beam size of 3.9 mm corresponding to the averaged temperature of 8400 K, was cooled down to 1.3 mm and 1.8 mm for SBRC on and off conditions, respectively for a beam intensity of 9 x 10^5 ions. By reducing the beam intensity, the IBS heating is expected to be reduced, however, the signal to noise ratio has also been reduced, which disabled us to perform beam size observation with the use of a standard fluorescence based techniques by a CCD camera described in Ref. [22]. So we utilized another scraper (Horizontal Scraper 2 or Vertical Scraper) to measure the beam profile in addition to the one (Horizontal Scraper 1) to control the beam intensity [23]. By detecting the beam survival ratio at various scraper positions, we could observe the beam

ISBN 978-3-95450-125-0

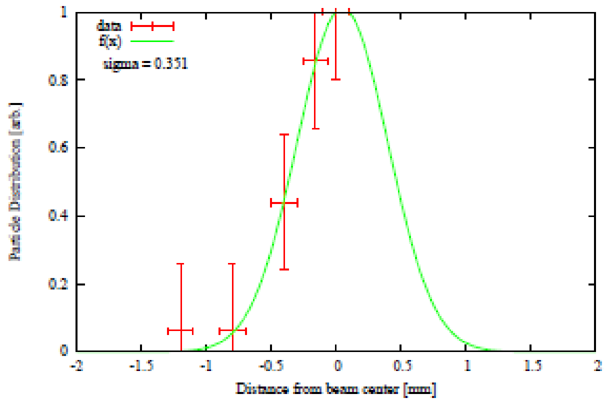

Fig.7 Measured horizontal beam profile with Horisontal Scraper 2.

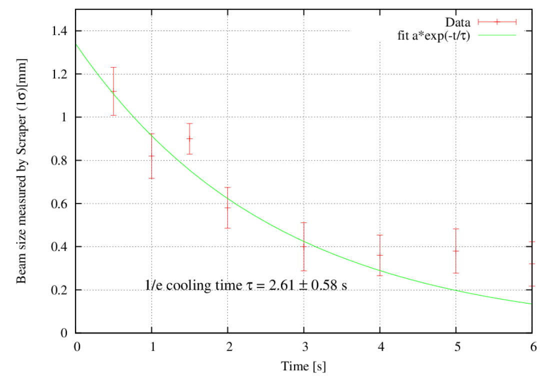

Fig. 9 Time variation of the horizontal beam size after the start of the laser cooling observed with a scraper for the beam intensity of 9 x 10^4 [23].

profile as shown in Fig. 7. We measured the beam sizes for various beam intensities from 1x 10^6 to 1 x 10^4 by changing the insertion position of the first scraper (H Scraper 1 in Fig. 1) which moves in the horizontal direction and after arriving a certain pre-determined position, returns back to its original position, which is 15 mm inner side from the beam center.

In Fig. 8, the beam intensity dependence of the horizontal beam size measured by H scraper 2 (Fig.1), is shown for a laser irradiation power of 8±1mW. By scraping to the intensity of 1 x 10^4, the cooled horizontal beam size was reduced to 0.17-0.30 mm and 0.55-0.61 mm for SBRC on and off, respectively. Taking into account the fractional momentum spread ($\Delta p/p$) measurable by a Post Acceleration Tube (PAT) [24], somewhat smaller horizontal beam size is expected, which, however, is not yet obtained experimentally for such a low intensity at the moment. Horizontal beam size uncorrected for this effect is utilized below, standing at the safety side. Thus the horizontal emittance is estimated to be 3.0-9.3 x 10^{-8} π m·rad for SBRC condition which corresponds to the average temperature of 16-50 K through Eq. (4). It is shown that the horizontal beam size reached by indirect transverse laser cooling is reduced by reduction of the beam intensity due to suppression of IBS, resulting in an increase of the indirect laser cooling efficiency. In Fig. 9, the time variation of the horizontal beam size indirectly laser cooled with the scraped beam intensity of 9 x 10^4 is shown, which gives us a cooling time of 2.6 sec, more than one order of magnitude shorter compared with the beam of the intensity of 1 x 10^7. It, however, seems to be still not so good enough to be able to realize the transition to a beam string. Further reduction of the beam intensity attaining enough S/N ratio might be needed for phase transition to a string state.

In Fig. 10, similar beam intensity dependence of the vertical beam size is shown. In the present case, the operation point of (2.07, 1.12) does not satisfy the difference resonance condition given by Eq. (7) and neither a solenoidal nor skew field was applied. So no coupling between the horizontal and vertical motions other than IBS is expected. The vertical heat is considered to be transferred mainly to longitudinal direction through IBS. As is known from Fig.10, the initial vertical beam size of 3.9 mm corresponding to the emittannce of 4.1 π mm·mrad is reduced to 1.9 mm and 3.3 mm by application of indirect transverse laser cooling for 3 sec. for beam intensity of 9 x 10^5 with and without SBRC condition, respectively. With SBRC condition on,

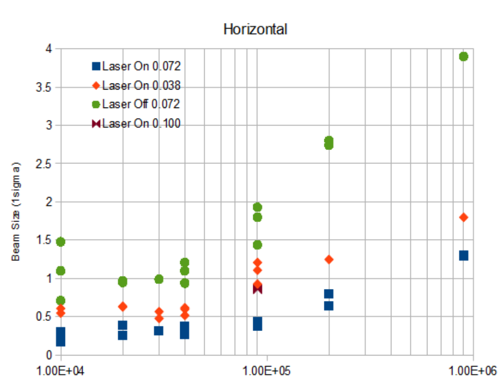

Fig.8 Ion number dependence of the horizontal beam size measured 3 sec. after the start of the indirect transverse laser cooling with the irradiated laser power of 8±1mW.

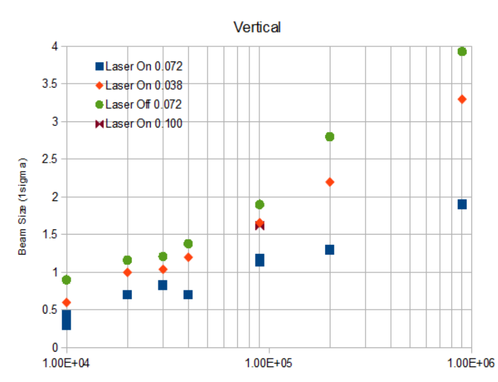

Fig.10 Ion number dependence of the vertical beam size measured 3 sec. after the start of the indirect transverse laser cooling with the irradiated laser power of 8±1mW.

ISBN 978-3-95450-125-0

Table 2 List of transverse temperatures attained by the indirect transverse laser cooling

Year	Method	Ion	Kinetic Energy	Intensity	$T_{//}$	T_H	T_V	Ref
1996	IBS	$^9Be^+$	7.3 MeV	2.0 x 10^7	15	4000	500	[15]
1998	Dispersive cooling	$^9Be^+$	7.3 MeV	1.0 x 10^7	few tens	≈500#	≈150#	[17]
2001	RFQ	$^{24}Mg^+$	1 eV	1.8 x 10^4	<3 m	$T_\perp$<0.4		[25]
2008	IBS	$^{24}Mg^+$	40 keV	1.0 x 10^7	11	-	500	[18]
2009	W SBRC	$^{24}Mg^+$	40 keV	1.0 x 10^7	27	220$		[20]
2009	WO SBRC	$^{24}Mg^+$	40 keV	1.0 x 10^7	16	-%		[20]
2012	W SBRC	$^{24}Mg^+$	40 keV	1 x 10^4	-	<16-50	7-15	[23]
2012	WO SBRC	$^{24}Mg^+$	40 keV	1 x 10^4	-	<150-190	30	[23]

(unit of the temperature is K, #,$ estimated from the data in the figures of the reference [17] and [20], respectively. % laser size is too small to give the correct beam size.)

the horizontal beam size is cooled down rapidly compared with the off case and the line density of the ion becomes larger, which results in more efficient cooling of the vertical beam temperature by increase of IBS. For scraped beam intensity of 1 x 10^4 ions, cooled vertical beam size becomes 0.30-0.44 mm and 0.6 mm for SBRC on and off, respectively. These values correspond to the vertical emittances of 2.4-5.2 x 10^{-8} π m·rad and 9.6 x 10^{-8} π m·rad, respectively. Thus the average vertical temperature has come down to 7-15 K with SBRC on for the beam intensity of 1 x10^4.

As shown in table 2, among the data ever obtained through transverse laser cooling, the above transverse temperatures attained at S-LSR by indirect transverse laser cooling are lower than the others except for PALLAS at Munich which realized crystallization for very slow (1eV) ions [25].

SUMMARY AND DISCUSSION

We have tried to attain the lowest possible temperature of a $^{24}Mg^+$ ion beam with the kinetic energy of 40 keV with the use of laser cooling technique to extend a strong laser cooling power for 3 dimensions. Experimental demonstration of SBRC has been performed at S-LSR and an intensity reduction with the use of controlled scraping results in the reduction of the transverse temperature down to 16-50 K for the horizontal direction and 7-15 K for vertical direction, which is the lowest temperature ever realized through laser cooling at storage rings with rather high energy. The longitudinal temperature at our experiment, however, remains at rather high level higher than a few tens K for the intensity of 1 x 10^7 as shown in Table 2, obstructed by the limitation of the available laser power.

Computer simulation assuming S-LSR lattice predicts a formation of a string for the 35 keV $^{24}Mg^+$ ion beam at a intensity of 10^3 (10 ions per bunch for harmonic number of 100) [26], which, we hope will be demonstrated in a near future experimentally at S-LSR by improvement of the laser power and sensitivity of the beam observation system.

REFERENCES

[1] A. Noda et al., Proc. of EPAC2002, Paris, France, (2002), 2748-2750.
[2] Originally proposed by Y.A.S. Derbenev, A.N. Skrinsky, Sov. Phys. Rev. **1** (1979), 165.
[3] H. Fadil et al., Nucl. Instr. Meth. in Phys. Res. **A517** (2004), 1.
[4] J. Wei, X.-P. Li and A M Sessler *Phys. Rev. Lett.* **73**, (1994), 3089.
[5] X.-P Li, H. Enokizono, H. Okamoto, Y. Yuri, A.M. Sessler and J. Wei Phys. Rev. ST Accel. Beams **9**, (2006), 034201.
[6] V. Parkhomchuk, Proc. Workshop on Electron Cooling and Related Applications (ECOOL84) (KfK Report No3846) ed H. Poth (Karlsruhe) pp71–83.
[7] M. Steck et al., Phys. Rev. Lett. **77**, (1996), 3803.
[8] H. Danared et al., J. Phys. Bat. Mol. Opt. Phys. **36**, (2003), 1003-1010.
[9] T. Shirai et al., Phys. Rev. Lett. **98**, (2007), 204801.
[10]Ya. S. Derbenev and A.N. Skrinsky, Sov. Sci. Rev., Sect. **A3**, (1981), 165.
[11]M. Steck et al., Nucl. Instrum. Methods Phys. Res., Sect. **A532**, (2004), 357.
[12] U. Schramm and D. Habs, Progress in Particle and Nuclear Physics, **53**, (2004), 583-677.
[13] H. Okamoto et al., Phys. Rev. **E69**, (2004), 066504.
[14] H. Danared, private communication at IPAC11.
[15] H.J. Miesner et al., Phy. Rev. Lett., **77**, (1996), 623.
[16] H.J. Miesner et al., Nucl. Instr. Meth. **A393**, (1996), 634.
[17] I. Lauer et al., Phys. Rev. Lett. **81**, (1998), 2052.
[18] M. Tanabe et al., Appl. Phys. Express , **1**, (2004), 028001.
[19] H. Okamoto, A. Sessler and D. Möhl, Phys. Rev. Lett. **72**, (1994), 3977.
[20] M. Nakao et al., submitted to Phys. Rev. ST-AB.
[21] A. Noda et al., Proc. of IPAC12, New Orleans, Louisiana, USA, (2012), MOPPD012.
[22] M. Nakao et al., Proc. of IPAC10, Kyoto, Japan, (2010), MOPD072.
[23] H. Souda et al., submitted to Appl. Phys. Express.
[24] J.S. Hangst et al., Phys. Rev. Lett. **74**, 86 (1995).
[25] T. Schätz, U. Schramm and D. Habs, Nature, **412**, (2001), 717-720.
[26] Y. Yuri and H. Okamoto, Phys. Rev. ST-AB **8** (2005) 114201.

ISBN 978-3-95450-125-0