

# ONE-DIMENSIONAL ORDERING OF PROTONS BY THE ELECTRON COOLING\*

T. Shirai<sup>#</sup>, M. Ikegami, H. Souda, M. Tanabe, H. Tongu, A. Noda  
ICR, Kyoto-U, Uji, Kyoto, Japan

I. Meshkov, A. Smirnov, JINR, Dubna, Moscow Region, Russia

M. Grieser, MPI Kernphysik, Spaupfercheckweg, Heidelberg, Germany

K. Noda, NIRS, Anagawa, Inage, Chiba, Japan

## Abstract

The one-dimensional ordering of protons has been studied at S-LSR, while the ordering of the highly charged heavy ions has been found at ESR and CRYRING. Abrupt jumps in the momentum spread and the Schottky noise power have been observed for protons at the particle number of around 2000. The beam temperature was 0.17 meV and 1 meV in the longitudinal and transverse directions at the transition, respectively. The normalized transition temperature of protons is close to those of heavy ions at ESR. The lowest longitudinal beam temperature below the transition was 0.3 K. It is close to the longitudinal electron temperature.

## INTRODUCTION

Anomalous behaviour of Schottky signal as a function of the particle number for the electron-cooled proton beam was firstly reported at NAP-M [1]. Later, the abrupt jump of the momentum spread was found at ESR for highly charged heavy ions [2]. The similar jump of the momentum spread was also confirmed at CRYRING for other heavy ions [3]. Such phenomena are now called one-dimensional ion ordering. However, the jump of the momentum spread has not been found for protons. Even if the phase transition of the proton ordering occurs, the lower transition temperature is expected, because the Coulomb interaction of protons is much smaller than that of the highly charged heavy ions, which is proportional to  $Z^2$ . For the proton ordering, the low electron temperature in the cooler and the small heating in the ring are necessary. The high stability of the cooler and the ring is also required.

We have performed the experiment of the one-dimensional ordering of protons at Small-Laser Storage Ring (S-LSR) at Institute for Chemical Research, Kyoto University [4]. It is the first storage ring optimized for the high space charge beam. The lattice of the ring is designed so that the betatron tune in a superperiod becomes as small as possible. It is essentially important to avoid the resonance heating due to the space charge. It also has a small magnetic field error and a stable power

supply. As the results, the closed orbit distortion and the stopband of the resonance become small. The parameters of the one-dimensional ordering experiments for protons at S-LSR are shown in Table 1.

Table 1: Parameters of the one-dimensional ordering experiments for protons

Beam	Proton, 7 MeV
Revolution frequency	1.61 MHz
Lifetime with cooling	$1.7 \times 10^4$ sec
Ring	
Betatron tune	(1.645, 1.206)
Max. $\beta$ -function	(3.9 m, 3.2 m)
Max. dispersion	1.8 m
Electron Cooler	
Energy	3.8 keV
Electron Beam Current	25, 50, 100 mA
Expansion Factor	3

## ONE-DIMENSIONAL ORDERING EXPERIMENT FOR PROTONS

### Longitudinal Beam Temperature

The longitudinal beam temperature  $T_{||}$  is defined by the momentum spread ( $\delta p/p$ ).

$$k_B T_{||} = m_i \beta^2 c^2 \left( \frac{\delta p}{p} \right)^2, \quad (1)$$

where  $\beta c$  is the velocity of the particle. The momentum spread is calculated from the frequency spectrum of the Schottky noise, which is measured by the helical pickup. The minimum particle number for the momentum spread measurement is around 1000 protons. It is limited by the noise of the pre-amplifier (SA-230F5, NF Corporation).

The Figure 1 shows the momentum spread and Schottky noise power as a function of the particle numbers [5]. The electron current in the cooler is 25 mA. The particle number is measured by the ionization residual gas monitor. The momentum spread is proportional to  $N^{0.29}$  above a particle number of 4000. At the particle number of around 2000, the momentum spread drops abruptly. The transition momentum spread is  $3.5 \times 10^{-6}$ , which corresponds to the ion temperature of 0.17 meV from eq.(1). It is considered that this abrupt drop is evidence of ordering of protons. The lowest

\*Work supported by Advanced Accelerator Development Project of Ministry of Education, Culture, Sports, Science and Technology (MEXT) and the 21st COE program, Centre for Diversity and Universality in Physics at Kyoto University

<sup>#</sup>Present address: NIRS, Anagawa, Inage, Chiba, Japan  
t\_shirai@nirs.go.jp

momentum spread below the transition is  $1.4 \times 10^{-6}$ , which corresponds to the longitudinal ion temperature of  $26 \mu\text{eV}$  (0.3 K). It is close to the longitudinal electron temperature. The Schottky noise power in Fig.1(b) is proportional to  $N^{0.99}$  above a particle number of 6000. At the transition point, it drops by one order of magnitude. Similar phenomena have been observed for highly charged heavy ions at CRYRING [3].

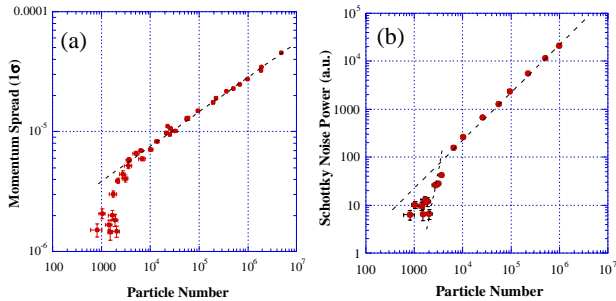


Figure 1: Momentum spread (a) and Schottky noise power (b) as a function of the particle numbers with the electron current of 25 mA. The momentum spread is defined as  $1\sigma$  of the fitted Gaussian function to the momentum distribution. The Schottky noise power is defined as the integrated area of the spectrum.

The transition of the momentum spread depends on the various experimental conditions. Figure 2(a) shows the momentum spread with three different electron currents of the cooler: 25 mA, 50 mA and 100 mA. The transitions are observed with all electron currents. Above the transition, the momentum spread with an electron current of 100 mA is smaller than others. On the other hand, below the transition, the momentum spread is  $1.4 \times 10^{-6}$  with electron currents of 25 mA and 50 mA. The momentum spread with the electron current of 100 mA is higher.

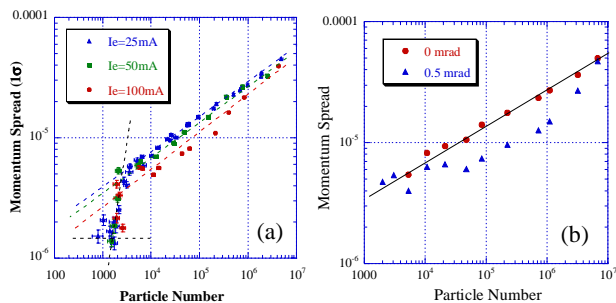


Figure 2: Momentum spread as a function of the particle numbers with the various electron current (a) and the proton-electron orbit misalignment (b).

Figure 2(b) shows the momentum spread with two alignment conditions. The “0 mrad” is an exact alignment

condition between the proton and electron orbit. The “0.5 mrad” means the artificial misalignment of 0.5 mrad. The electron misalignment induces the beam heating and the momentum spread is saturated.

### Transverse Beam Temperature

The transverse beam temperature is defined from the beam size measurements,

$$k_B T_{\perp} \cong \frac{1}{2} m_i \gamma^2 \beta^2 c^2 \frac{v_x + v_y}{R} \epsilon, \quad (2)$$

where  $R$  is the average radius of the ring, and  $v_{x,y}$  are the horizontal and vertical betatron tunes, respectively.  $\epsilon$  is the transverse emittance. Figure 3 shows the horizontal beam size as a function of the particle number [5]. The beam radius is proportional to  $N^{0.28}$ , and monotonically decreased. The beam radius is  $17 \mu\text{m}$  at a particle number of 4000. It is impossible to determine whether there is an abrupt jump of the beam size, because of the insufficient resolution of the scraper. The corresponding horizontal emittance is  $1.7 \times 10^{-4} \pi \cdot \text{mm} \cdot \text{mrad}$  with the  $\beta$ -function of 1.7 m at the scraper. If it is assumed that the horizontal and vertical emittances were equal, the transverse temperature is 1 meV from eq.(2).

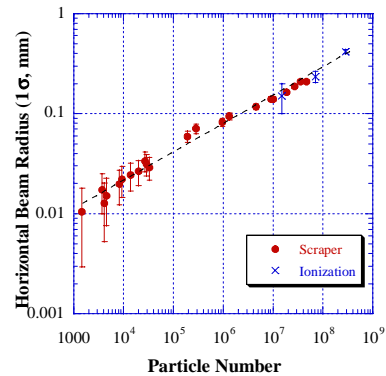


Figure 3: Horizontal beam radius as a function of the particle number with the electron current of 25 mA. They were measured by the scraper and the ionization residual gas monitor.

## ORDERING CONDITIONS BETWEEN PROTONS AND HEAVY IONS

The conditions of the one-dimensional ion ordering for heavy ions can be explained by the reflection probability between two particles [6]. The momentum spread of the heavy ions has a transition at the reflection probability between 60 % and 80 %. In order to compare the heavy ions and proton, the normalized temperature was introduced as the following definition [7],

$$\hat{T}_{\perp,\perp} = \frac{2}{m_i c^2} \left( 2r_i \beta \gamma \frac{v}{R} \right)^{-2/3} k_B T_{\perp,\perp}, \quad (3)$$

where  $m_i$  is the mass of the ion,  $r_i$  is the classical ion radius,  $\beta\gamma$  is the relativistic factor,  $v$  is the betatron tune and  $R$  is the average radius of the ring. Table 2 shows the transition temperatures and normalized ones for the proton at S-LSR [5] and for the heavy ions at ESR [8]. Although the transition temperatures are different by a factor of 1000 between  $U^{92+}$  and  $p^+$ , the normalized transition temperatures are very close and both have the similar reflection probabilities. It suggests that the transition of the momentum spread occurs by the same mechanism from highly charged heavy ions to proton. It is a general phenomenon for the ion beam.

Table 2: Transition temperatures  $T_{//,\perp}$  and the normalized temperatures  $\hat{T}_{//,\perp}$  for heavy ions and protons.

Ions	$T_{//}$	$T_{\perp}$	$\hat{T}_{//}$	$\hat{T}_{\perp}$
$p^+$ [5]	0.17 meV	1 meV	1.2	6.5
$C^{6+}$ [8]	4.0 meV	11 meV	0.62	1.6
$Zn^{30+}$ [8]	78 meV	0.64 eV	0.78	7.6
$U^{92+}$ [8]	470 meV	3.4 eV	0.70	5.1

The molecular dynamics simulations were carried out for the proton ordering to analyze more precisely. The program code was BETACOOOL [9] and the electron cooling was treated as the constant cooling rate, which was calculated from the cooling force measurements. Figure 4 shows the trajectories in the cooling process on the phase space of the horizontal emittance and the momentum spread. The particle numbers are 2000 and 6000, respectively. In both cases, the beams are cooled down along the similar trajectories but the beam at the particle number of 6000 stops at the point with the momentum spread of  $6 \times 10^{-6}$ . It reaches the equilibrium state, where the electron cooling rate and the IBS heating rate are equal. On the other hand, the momentum spread at the particle number of 2000 decreases monotonically and there is no limit of the lowest momentum spread. The reduction rate of the momentum spread is almost the same as the input cooling rate.

These simulations suggest that the cooling rate exceeds the maximum heating rate at the particle number of 2000. Concerning the transition, the mechanism in the one-dimensional ordering is similar to that of the crystalline beam. This result explains why the one-dimensional ordering occurs at the very small particle number. Because of the small cooling rate of the electron cooling, it can exceed the IBS heating rate only with the very small particle number. It is different from the crystalline beam simulation by laser cooling. The laser cooling has a higher cooling rate and can overcome the intrabeam scattering even with the large particle number.

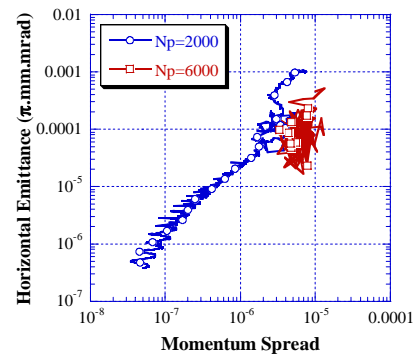


Figure 4: Beam trajectories in the cooling process on the phase space of the horizontal emittance and the momentum spread. The particle number is 2000 and 6000.

## CONCLUSION

From the particle reflection model, the transition temperature of the proton coincides with those of the highly charged heavy ions at ESR using the appropriate scaling. It shows that the one-dimensional ordering is the common phenomena of the electron-cooled ion beam from the heavy ions to the proton. The molecular dynamics simulation gives the consistent result with the measurement.

## REFERENCES

- [1] V. V. Parkhomchuk, “Physics of Fast Electron Cooling”, Proc. of ECOOL84, Karlsruhe (1984) p.71.
- [2] M. Steck et al., “Anomalous Temperature Reduction of Electron-Cooled Heavy Ion Beams in the Storage Ring ESR”, Phys. Rev. Lett., **77** (1996) p.3803.
- [3] H. Danared et al., “Model and Observations of Schottky-Noise Suppression in a Cold Heavy-Ion Beam”, Phys. Rev. Lett., **88** (2002) 174801.
- [4] A. Noda, “Ion beam cooling at s-lsr project”, Nuclear Instruments and Methods in Physics Research Section A, **532**, (2004) p.150.
- [5] T. Shirai et al., “One dimensional beam ordering of protons in a storage ring”, Phys. Rev. Lett., **98** (2007) 204801.
- [6] R. W. Hasse, “Theoretical Verification of Coulomb Order of Ions in a Storage Ring”, Phys. Rev. Lett., **83** (1999) p.3430.
- [7] H. Okamoto et al., “One-dimensional Ordering of Ultra-Low-Density Ion Beams in a Storage Ring”, Phys. Rev. E, **69** (2004) 066504.
- [8] M. Steck et al., “Electron cooling experiments at the ESR”, Nucl. Instrum. Methods Phys. Res. Sect. A, **532** (2004) p.357.
- [9] I. Meshkov et al., “Physics guide of BETACOOOL code Version 1.1”, BNL Note C-A/AP/262 (2006).