<table>
<thead>
<tr>
<th>Title</th>
<th>One-dimensional beam ordering of protons in a storage ring</th>
</tr>
</thead>
<tbody>
<tr>
<td>Author(s)</td>
<td>Shirai, T; Ikegami, M; Fujimoto, S; Souda, H; Tanabe, M; Tongu, H; Noda, A</td>
</tr>
<tr>
<td>Citation</td>
<td>PHYSICAL REVIEW LETTERS (2007), 98(20)</td>
</tr>
<tr>
<td>Issue Date</td>
<td>2007-05-18</td>
</tr>
<tr>
<td>URL</td>
<td><a href="http://hdl.handle.net/2433/50396">http://hdl.handle.net/2433/50396</a></td>
</tr>
<tr>
<td>Copyright</td>
<td>Copyright 2007 American Physical Society</td>
</tr>
<tr>
<td>Type</td>
<td>Journal Article</td>
</tr>
</tbody>
</table>
One-Dimensional Beam Ordering of Protons in a Storage Ring

Institute for Chemical Research, Kyoto University, Gokasho, Uji, Kyoto 611-0011, Japan

K. Noda
National Institute of Radiological Sciences, 4-9-1 Anagawa, Inage, Chiba 263-8555, Japan

T. Fujimoto, S. Iwata, and S. Shibuya
Accelerator Engineering Corporation, 4-9-1 Anagawa, Inage, Chiba 263-8555, Japan

A. Smirnov and I. Meshkov
Joint Institute for Nuclear Research, Joliot Curie 6, Dubna 141980, Russian Federation

H. Fadil and M. Grieser
Max-Planck-Institut für Kernphysik, D-69029 Heidelberg, Germany

(Received 21 November 2006; revised manuscript received 25 February 2007; published 16 May 2007)

The ordering of protons has been observed at a new storage ring, S-LSR, at Kyoto University. Abrupt jumps in the momentum spread and the Schottky noise power were observed for protons for the first time at a particle number of \( \sim 2000 \), upon applying electron cooling with electron currents of 25, 50, and 100 mA. The transition temperature was 0.17 and 1 meV in the longitudinal and transverse directions, respectively. The transverse temperature of the proton beam was much below that of electrons at the transition, which played an essential role in the ordering of protons.

DOI: 10.1103/PhysRevLett.98.204801 PACS numbers: 29.20.Dh, 29.27.Fh, 41.75.5, i

There have been many efforts in the past two decades to achieve Coulomb crystal beams. In the crystalline state, ions are cold and remain ordered in the particle rest frame. A crystal beam has an extremely small emittance and momentum spread. The first indication of ion ordering was reported from NAP-M for a proton beam [1]. However, there have been discussions about the results. The Coulomb crystal beam was studied theoretically by Schiffer and Kienle using molecular dynamics simulations, and they showed the possibility of a Wigner crystal [2]. In an experimental study, Steck et al. found new evidence of beam ordering for highly charged heavy ions using electron cooling at ESR [3]. The momentum spread of the ions dropped abruptly when the particle number reached some thousands. It was studied by Hasse using a Monte Carlo simulation [4], and interpreted as a longitudinal string-like ordering, where the ions did not pass through each other in the longitudinal direction. It might not be a Coulomb crystal beam in a strict sense, because the line density and the plasma parameter are very low; nevertheless, ions have a sort of order and intrabeam scattering (IBS) is suppressed. Similar phenomena for highly charged ions were found at CRYRING by Danared et al. [5]. The ordering of U\(^{92+} \), Pb\(^{55+} \), Au\(^{79+} \), Xe\(^{54+} \), Kr\(^{36+} \), Zn\(^{30+} \), Ni\(^{17+} \), Ar\(^{18+} \) was found at ESR, SIS, and CRYRING [3–6]. Recently, the ordering of C\(^{6+} \) was found at ESR, which was the lightest ordered ion [6]. However, the ordering of single charged ions and lighter ions than carbon was not found due to the small Coulomb interaction between ions.

In the Autumn of 2005, a storage ring, S-LSR, at ICR, Kyoto University, went into operation [7]. It is a compact ring with a circumference of 22.557 m and is equipped with an electron cooler and a laser cooling system. An indication of proton ordering at S-LSR was reported in Ref. [8] on the basis of a theoretical study. We have experimentally confirmed the ordering of protons for the first time. This Letter presents the details of the measurements and a discussion of the experimental results.

Table I gives the major parameters of the ring and the electron cooler. The stored 7 MeV proton beam was coasting. We had to measure three types of beam information: the particle number, the momentum spread \( \delta p / p \), and the transverse emittance \( \epsilon \). We define the effective longitudinal and transverse beam temperature, \( T_{||} \) and \( T_{\perp} \), following Ref. [3],

\[
k_B T_{||} = m_p c^2 \beta^2 \left( \frac{\delta p}{p} \right)^2.
\]

TABLE I. Parameters of S-LSR and the electron cooler.

<table>
<thead>
<tr>
<th>Ion</th>
<th>Proton, 7 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference of ring</td>
<td>22.557 m</td>
</tr>
<tr>
<td>Betatron tune</td>
<td>(1.645, 1.206)</td>
</tr>
<tr>
<td>Momentum compaction</td>
<td>0.502</td>
</tr>
<tr>
<td>Average vacuum pressure</td>
<td>( 1 \times 10^{-8} ) Pa</td>
</tr>
<tr>
<td>Electron energy</td>
<td>3.8 keV</td>
</tr>
<tr>
<td>Electron density</td>
<td>( 2.2 \times 10^{6} ) cm(^{-3} ) (( I_e = 25 ) mA)</td>
</tr>
<tr>
<td>Effective cooler length</td>
<td>0.44 m</td>
</tr>
<tr>
<td>Expansion factor</td>
<td>3</td>
</tr>
</tbody>
</table>
where \( k_B \) is the Boltzmann constant, \( m_p \) is the mass of protons, \( R \) is the average radius of the ring, \( \nu_h \) and \( \nu_v \) are the betatron tunes, \( T_h \) and \( T_v \) are the horizontal and vertical temperatures, respectively, \( \epsilon_h \) and \( \epsilon_v \) are the horizontal and vertical emittance, and it is assumed that they are equal. It was confirmed experimentally by a profile measurement of the extracted beam at a particle number of \( 10^6 \). Because the transverse temperature varies in the ring due to the focusing structure, the ring-averaged temperature is used. Since the typical particle number at the ordering transition is expected to be some thousands, special beam diagnostics are necessary for such a very low intensity, especially for singly charged protons.

The particle number was measured by an ionization residual gas monitor. The residual gas ionized by the proton beam was collected by an electrostatic voltage and counted by a microchannel plate \([9]\). The count rate is proportional to the particle number. The particle number was also measured by a bunched beam signal from the Schottky pickup. The absolute number of particles was calibrated by a dc current transformer at a high intensity (about \( 10^8 \) protons) for both methods. The results of the two methods agreed within \( \pm 10\% \) from \( 1 \times 10^6 \) to 500 protons.

The momentum spread of the protons was measured from the Schottky noise spectrum. When the particle number was less than \( 10^7 \), the collective effect became negligible and the momentum spread was obtained by \( \delta p/p = -\delta f/f \eta \) from the frequency spread \( \delta f/f \). The slip factor \( \eta \) was \(-0.5\) at S-LSR. Note that a careful treatment is necessary for an application of the relation below the ordering transition. The Schottky pickup is a traveling-wave type with a helix structure, optimized for a velocity of 7 MeV protons \([10]\). The center frequency is \( 48.29 \) MHz, which is the 30th harmonic of the revolution frequency. The head amplifier has a gain and a noise figure of \( 46 \) and \( 0.6 \) dB, respectively. The momentum spread could be measured down to 1000 protons.

The beam radius could be measured by the ionization residual gas monitor, but the resolution was rather limited. The smaller beam radius was measured by a scraper \([3]\). Both methods gave consistent results (see Fig. 4). The scraper was controlled by a stepping motor with the minimum step of the motion of \( 0.8 \) \( \mu m \). It was moved into the circulating beam and stopped at a certain position for 0.1 s, and then removed back away. The rms beam radius, \( \sigma_{\text{beam}} \) (1\( \sigma \) of the transverse profile), was determined from the distance \( L_s \) between the stopped position of the scraper for the measurement and that where the beam was completely lost. The relation between \( \sigma_{\text{beam}} \) and \( L_s \) was estimated from the beam simulation by the BETACOOL \([11]\), which included the measured electron cooling force, the IBS effect (Martini model), and the effect of the residual gas scattering. The distance \( L_s \) was found to correspond to \( 3.5 \sigma_{\text{beam}} \). The measurement errors of the beam radius came from the drift of the beam center and the reproducibility of the mechanical positioning of the scraper. The error of \( \sigma_{\text{beam}} \) is estimated to be \( \pm 7 \) \( \mu m \).

Figure 1 shows the momentum spread of the proton beam as a function of the particle numbers \( N \) in the ring. The momentum spread is defined as \( 1\sigma \) of the fitted Gaussian function to the momentum distribution. The momentum spread was proportional to \( N^{0.29} \) above a particle number of 4000. The momentum spread dropped abruptly from \( 3.5 \times 10^{-6} \) at a particle number of 2000. From Eq. (1), the corresponding longitudinal transition temperature is 0.17 meV. This abrupt drop of the momentum spread is evidence of ordering of the proton beam. In contrast, the momentum spread of protons was constant below certain particle numbers, instead of the abrupt drop at NAP-M and COSY \([12]\). Figure 2 shows the Schottky noise power as a function of the particle number. The Schottky noise power is defined as the integrated area of the Schottky noise spectrum. It is proportional to \( N^{0.99} \) above a particle number of 6000. It drops by 1 order of magnitude at the transition point. Similar phenomena were also observed for highly charged heavy ions at CRYRING \([5]\).

Figure 3 shows the momentum spread with three different electron currents: 25, 50, and 100 mA. The transitions were observed with all electron currents. Above the transition, the momentum spread with an electron current of 100 mA is smaller than those of the lower currents because of the larger cooling force. Below the transition, the momentum spread was estimated to be \( 1.4 \times 10^{-6} \) with electron currents of 25 and 50 mA. The minimum longitudinal temperature of protons is determined by the longitudinal electron temperature \( T_{e\parallel} \) \([13]\),

\[
k_B T_{e\parallel} \approx \frac{(k_B T_{\text{cath}})^2}{\beta^2 \gamma^2 m_e c^2} + \frac{e^2 n_e^{1/3}}{4 \pi \epsilon_0^2}.
\]
where $T_{\text{cath}}$ is the temperature of the electron gun cathode and $n_e$ is the electron density. With an electron current of 25 mA, it is $20 \mu$eV, which corresponds to a momentum spread of $1.2 \times 10^{-6}$ for protons from Eqs. (1) and (3). The calculated momentum spread below the transition is close to this limit.

Figure 4 shows the horizontal beam radius ($1\sigma$) as a function of the particle numbers, measured by the scraper and the ionization residual gas monitor. The variation of the function at the two monitors made a 2% difference of the beam radius. The results of the two methods are consistent in Fig. 4. The beam radius was proportional to $N^{0.28}$, and monotonically decreased even below a particle number of $10^4$. The beam radius was 17 $\mu$m at a particle number of 4000. The transverse transition temperature is 1 meV from Eq. (2). On the other hand, the optics of the electron gun has no aberrations, the transverse electron temperature $T_{e\perp}$ is

$$k_B T_{e\perp} = \frac{k_B T_{\text{cath}}}{\alpha},$$

where $\alpha$ is the magnetic expansion factor. For expansion factor 3, the transverse electron temperature is 34 meV. The transverse temperature of the proton beam is much lower than that of the electrons. This is evidence that the minimum temperature of the ion beam is determined only by the longitudinal electron temperature, because the electron beam is magnetized by a strong solenoid field (500 G) in the cooler. This was pointed out by Derbenev and Skrinsky [14], and experimentally observed in the cooling of $^{12}$C at ESR [6]. This fact is the key for the transition of the proton beam, which is discussed later.

As we described previously, the essential point of beam ordering is reflection between the ions in the longitudinal direction [4]. Therefore, the condition of ordering is determined by the Coulomb interaction between the ions and the kinetic energy of the relative ion motions. Some theories and simulations have been proposed to explain this phenomenon quantitatively. Meshkov et al. proposed the criteria $\Gamma_2$ [15], which determines the condition where the ions do not pass each other without an appropriate scatter-

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|}
\hline
ion & $T_{||}$ & $T_{\perp}$ & $\Gamma_2$ \\
\hline
$^1$H & 0.17 meV & 1 meV & 0.5 \\
$^{12}$C$^{6+}$ & 4.0 meV & 11 meV & 1.8 \\
$^{70}$Zn$^{30+}$ & 78 meV & 0.64 eV & 0.70 \\
$^{238}$U$^{92+}$ & 470 meV & 3.4 eV & 0.88 \\
\hline
\end{tabular}
\caption{Longitudinal and transverse transition temperatures and the $\Gamma_2$ parameters for protons at S-LSR and the other three kinds of ions at ESR, which were extracted from Table 1 in Ref. [6]. It is assumed that the transverse temperature is twice the horizontal one.}
\end{table}
In summary, we succeeded in realizing the ordering of protons at S-LSR with a particle number of 2000, while the ordering of highly charged ions had been achieved at ESR and CRYRING. The longitudinal and transverse transition temperatures were 0.17 and 1 meV, respectively. The $\Gamma_2$ parameter and the normalized temperature of protons at the transition were comparable with those of other ions at ESR.

The authors would like to thank Dr. E. Syresin, Dr. I. Seleznzev, and the electron cooler team of TOSHIBA for their significant contribution to the design, construction, and commissioning of the electron cooler. We also thank Dr. R. W. Hasse and Dr. H. Okamoto for their suggestions about the ordering conditions. We further thank Dr. J. Dietrich, Dr. M. Wakasugi, and Dr. F. Caspers for their helpful advice about the measurements. This work was supported by the Advanced Compact Accelerator Development project by MEXT of the Japanese Government and 21st Century COE at Kyoto University-Diversity and Universality in Physics.

*Electronic address: shirai@kyticr.kuicr.kyoto-u.ac.jp

16. The threshold constant $C$ was $\pi$ in Ref. [15], but it was found to be 1 in the recent study.