Dynamics and Structural Properties of Crystalline Ion Beams ◇

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In coasting [1] and bunched [2] crystalline ion beams the inter-particle motion is frozen out so that the ions arrange themselves into an ordered state, representing the most brilliant beams achievable in storage rings. First realized at the storage ring PALLAS [3,4] these beams are currently investigated in more detail. Here, systematic studies of the influence of the confining forces and the cooling scheme on the stability of crystalline beams and of their structural properties are presented.

In the PALLAS storage ring $^{24}Mg^+$ ions are confined on a closed orbit by quadrupole ring electrodes [1,2,3,4,5]. Equivalent to the technique of strong focusing an rf voltage is applied and the transverse motion of the ions circulating in this alternating quadrupole field is described by an oscillation around the closed orbit (circumference $C = 2\pi \times 57.5$ mm) at the secular frequency ω_{sec}. Laser cooling of the $^{24}Mg^+$ ion beam reduces the velocity spread of the ions to the mK range which allows for the routine generation of crystalline beams with a typical velocity of $v = 2600\,\mathrm{m/s}$ and particle numbers of $N = 10{,}000 \ldots 100{,}000$.

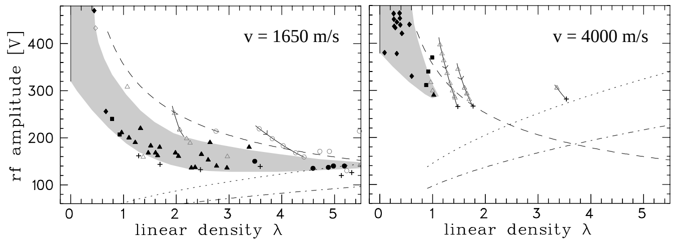

Fig. 1: Focusing conditions for which crystalline ion beams of different linear density were attainable in PALLAS are illustrated (grey-shaded area) for two beam velocities. Filled symbols stand for crystalline beams, open for non-crystalline ones and crosses for beam losses (see [6,7] for details).

The structure of crystalline beams depends on the linear density $\lambda = (N/C)a_{WS}$, expressed in terms of the Wigner-Seitz radius a_{WS}. With increasing λ, strings, zig-zags and helices can be realized in the PALLAS storage ring [6,7].

Helical structures are subject to bending shear, since ions closer to the center of the ring need less time to complete one revolution than those farer away when cooled to constant linear velocity v. The difference in traveling time increases with the beam velocity. As a consequence, for higher beam velocities only one-dimensional crystalline strings could be attained (fig. 1), while for lower velocities larger structures have been reached [6,7]. Simply assuming that the velocity mismatch due to shear is transferred into thermal motion nicely explains this observation (dotted lines in fig.1). Thus no shear elasticity could be observed. Cooling the beam to constant angular velocity – which is anticipated in the near future – should enable the creation of larger crystalline structures at higher beam velocities.

Additional control over the longitudinal ion distribution can be gained if a sinusoidal voltage U_b at a harmonic frequency $\omega_b = h\omega_{rev}$ of the revolution frequency ω_{rev} acts on the ion beam. A pseudo-potential co-moving with the ion beam is formed. In this bucket the ions oscillate with the frequency ω_{syn} unless their motion is damped by laser cooling and they finally crystallize in separated circulating bunches [8]. As for the case of a linear Paul trap the ions in the bunch should form a spheroid with an aspect ratio that depends on the ratio of the confining forces characterized by the anisotropy parameter $\beta = \omega_{sec}^2/\omega_{syn}^2$.

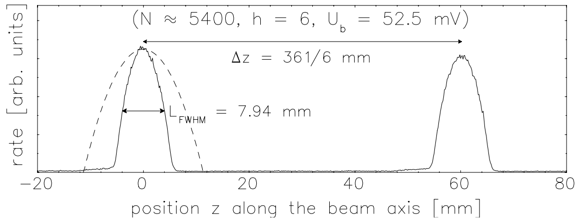

Fig. 2: Longitudinal spatial profile of a bunched crystalline beam, compressed by a factor of $\Delta z/L_{FWHM} = 7.6$. The solid line shows the measured profile, the dotted the predicted one.

However, the length of the bunches can be much larger than for the situation in traps. Predictions of the length of such ensembles, either from analytical theory [9] or by simulation, give bunch lengths L_b exceeding experimental results [10] by a factor of 2 to 3 as demonstrated in fig. 2. Furthermore, bunch lengths measured for different U_b show deviations from the predicted $L_b \propto U_b^{-1/3}$ scaling [10]. Accordingly, the transition from string-like to zig-zag structures was found at a value of $\beta = 880.000$ ($N = 11000$) [10], while theoretical values range from $\beta = 175.000$ to $\beta = 237.000$.

To clarify this obvious problem, we plan to continue systematic measurements on bunched beams. These will be complemented by a new frequency stabilization of the laser system improving the long term stability of the ion velocity and thus allowing for stroboscopic measurements of crystalline beams. Accompanying these experimental efforts a parallel molecular-dynamics simulation [1] of the PALLAS ring (in collaboration with the Univ.of Mainz) will be implemented on our Linux-cluster [11].

References

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