Large Ion Crystals and First Beams in PALLAS ◇

T. Schätz, D. Habs, and U. Schramm

The table-top RF-Quadrupole storage ring PALLAS, dedicated to the experimental realization of crystalline ion beams, primarily resembles a linear Paul-trap bent to a circle of 360 mm circumference. Additionally, 16 drift tubes allow to position, transport and accelerate ions within the ring [1,2]. Two independent laser systems† enable laser cooling of Mg^+-ions at rest as well as at ion beam velocities of presently up to several 1000 m/s.

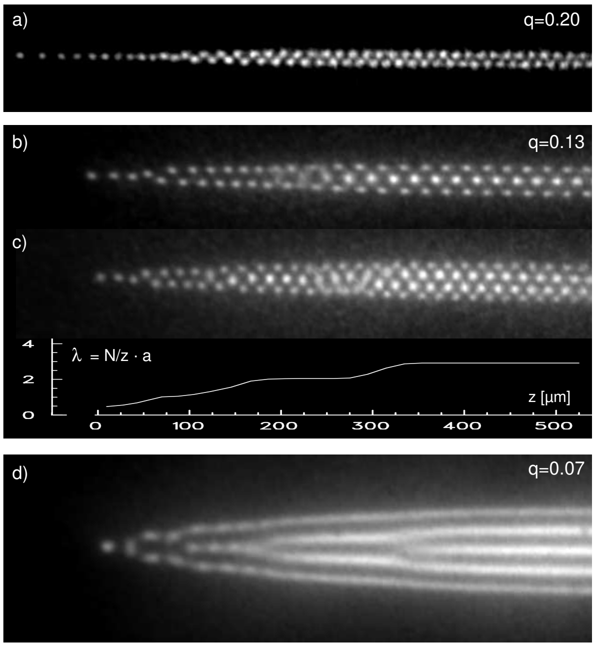

Fig. 1: Series of images of very prolate ion crystals subject to weak axial confinement. From a) to d) the radial focusing strength q is decreased while the total particle number is increased, continuously raising the linear density λ in the center of the axial potential well. In c) the step-like rise of λ as a function of the axial position z, characteristic for the evident change in the crystal structure, is sketched (recording time 0.4 s).

For the investigation of large Mg^+-ion crystals at rest, the drift tubes provide precise axial confinement [1,2]. Since the axial potential is weak compared to the radial (the axial single particle frequency amounts to 650 Hz compared to the secular frequency of 250 kHz), laser cooling of the ion ensemble leads to the formation of very prolate ion crystals, as depicted in fig. 1. The structure of these elongated crystals was predicted [3] to develop from a linear ion chain over a zig-zag band to single- and multiple-shell helices, characterized only by the dimensionless linear density $\lambda = a \cdot N/z$ in units of the Wiegner-Seitz radius $a^3 \propto 1/q^2$ (N being the number of ions per unit length z). Although these structures were confirmed experimentally earlier in ring [4] and linear [5] Paul-traps, their realization is a key requirement preparing the first generation of crystalline beams in PALLAS. Moreover, the transition between two different, almost degenerate states of a single shell structure in the range of $\lambda = 1.9$ to $\lambda = 2.9$ is nicely resolved in a single crystal.

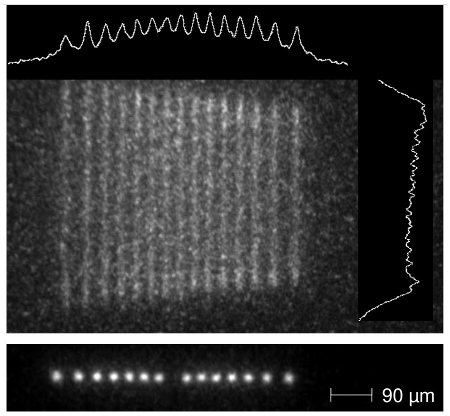

Fig. 2: Image of a linear ion crystal (14 Mg^+-ions and one "dark" impurity ion) exhibiting strong radial oscillations of up to $\pm 200\,\mu$m, but maintaining the full crystalline order (upper figure and corresponding projections). In the lower figure, the "dark" ion has jumped into the middle of the structure, stabilizing the ion chain (time resolution 50 ms).

A puzzling effect was often found observing only few Mg^+-ions. Instead of forming a localized linear chain, the crystal starts to oscillate radially while remaining perfectly ordered axially (fig. 2). Inserting a "dark" impurity ion immediately stabilizes the structure. It possibly enhances the otherwise small coupling between the externally excited (collective) radial motion and the laser cooled axial motion. A related problem was treated theoretically recently [6], predicting almost no coupling between the rf-driven micro-motion of ions in a crystal (similar to the excitation discussed above) and the random ion motion around their time-averaged positions (commonly interpreted as their temperature). As a consequence the ion crystal, once formed, should survive for minutes without further cooling as confirmed for large crystals in PALLAS.

Furthermore, ions of interest (e.g., of rare super-heavy elements) can be implanted and cooled sympathetically in a small ion crystal, as presented for the case of a nitrogen-ion in the lower fig. 2). Fundamental quantities like, e.g., the mass of the potentially unknown ion could be identified in a non-destructive way employing the laser fluorescence of the directly cooled ions as the monitor signal for, e.g., a resonant mass dependent excitation.

Very recently, the first Mg^+-ion beams were efficiently accelerated to typical velocities of 2000 m/s and laser cooled applying two counterpropagating laser beams, Doppler-shifted by approximately $\pm 10\,$GHz.

References

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