Structural and Temporal Analysis of Crystalline Ion Beams ◇

M. Bussmann, D. Habs, F. Horak, and U. Schramm

Recently, experimental studies of bunched crystalline beams [1] in PALLAS have shown that the bunch length and the confinement parameters determining the transition between string and zigzag configurations of the crystal structure differ from theoretical expectations [2]. A further investigation of this problem requires new experimental and theoretical approaches to investigate the structure of crystalline ion beams, two of which are outlined in the following text.

Inside the PALLAS storage ring $^{24}Mg^+$ ions are confined in the transverse direction by quadrupole ring electrodes. They can propagate freely in the longitudinal direction, following a closed orbit of circumference $C = 2\pi \times 57.5\ mm$ along which they are accelerated and cooled by the combined force of two laser beams. The transverse motion of the ions in the alternating quadrupole field can be approximated by an oscillation around the closed orbit at a secular frequency ω_{sec}. If the mutual Coulomb repulsion between the ions overcomes their mean kinetic energy they can arrange themselves in a long-range order.

Consider a string of N ions of equal spacing revolving in the storage ring, emitting fluorescent light. Assuming a constant beam velocity the ions pass a photomultiplier at regular intervals. If the size of the detection region is sufficiently small the Fourier-spectrum of the photon current should exhibit a pronounced peak at $N \times v/C$, namely N times the revolution frequency $f_{rev} = v/C$.

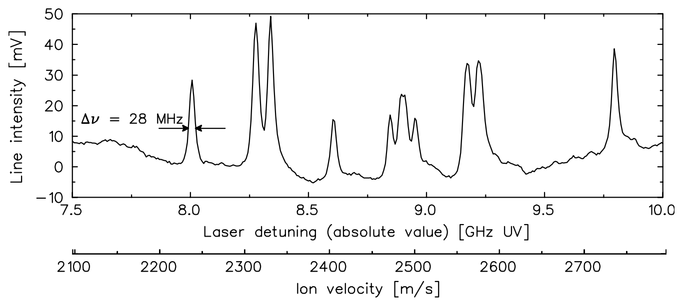

Fig. 1: Spectral lines of the iodine molecule relevant for laser frequency stabilization. The two x-axis legends show the absolute laser frequency detuning in GHz relative to the $3s^2S_{1/2} - 3p^2P_{3/2}$ transition [4] in $^{24}Mg^+$ for ions at rest and the corresponding beam velocity.

The frequency ν_L of the laser beam counter-propagating to the ion beam determines the final ion velocity v, thus a stable frequency of this laser beam is required to obtain constant beam velocity. On a short time scale of some milliseconds or less the laser wavelength variation amounts to less than $\pm 1\ MHz$ in the UV.

On a scale of some minutes or longer an active stabilization of the laser beam wavelength using an optical transition in iodine as a stable reference wavelength has recently been realized at PALLAS using Doppler-free polarization spectroscopy [5]. To characterize the frequency stability the error signal of the feedback control has been recorded every 0.2 s over a time interval of 100 minutes (see fig. 2).

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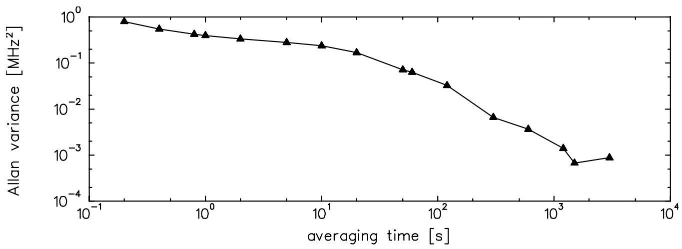

Fig. 2: Allan variance of the error signal of the laser stabilization for different time averages.

If the laser beam frequency changes by $\Delta\nu_L$ on a time scale comparable to the photon current measurement time it will cause a change in the revolution frequency Δf_{rev}, limiting the resolution of the revolution frequency measurement. The relative accuracy of the revolution frequency measurement is given by $\Delta f_{rev}/f_{rev} = \Delta\nu_L/\Delta\nu_{det}$ where $\Delta\nu_{det}$ is the detuning of the laser as plotted in figure 1. For the line selected in figure 1 this leads for long time scales of several minutes to a relative accuracy of $\Delta f_{rev}/f_{rev} \approx 10^{-6}$. As the next step it is foreseen to test the stabilization scheme with a coasting crystalline beam in PALLAS.

For the analysis of the experimental results a comparison with model calculations is vital. For this purpose a new parallel MD simulation code suitable for both ions at rest and coasting as well as bunched ion beams has been developed for the PALLAS experiment.

It is based on the computation of the direct inter-particle Coulomb interaction and includes realistic laser cooling and acceleration forces. Thus – like MD simulations of ion crystallization at rest [6,7] – it becomes possible to compute realistic cooling rates and study the Coulomb coupling between the degrees of freedom. Furthermore, unlike MD simulations specialized for coasting beams which are based on approximating the Coulomb interaction via Ewald summation [8], the code allows to simulate the behaviour of charged particles confined in a ring subjected to cooling and accelerating forces even if the beam density is modulated by a bunching force.

In a first test a series of simulations of ions strings confined in a longitudinal harmonic potential has been started. For small ion numbers $N < 200$ the simulation results will be compared to analytical calculations of the ion positions and with data taken for string-like crystal structures at rest in PALLAS.

References

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