# Crystalline Ion Beams in PALLAS ◇

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Threading ions like pearls on a string in storage rings by freezing out the inter-particle motion opens opportunities far beyond the means of standard accelerator physics. The usual heating due to collisions of particles within the beam almost completely vanishes, giving rise to a state of unprecedented brilliance and exceptional stability.

The technique of combined focusing and bending of ion beams in the rf quadrupole storage ring PALLAS [1,2] provides ideal conditions for the attainment of crystalline beams. In analogy to the usual treatment of synchrotrons, the transverse confinement of an ion beam in PALLAS is characterized by the number of 'focusing sections' or rf cycles per revolution, the periodicity $P = \Omega/\omega_{rev} \approx 800$, and by the corresponding number of transverse 'betatron' or secular oscillations, the tune $Q = \omega_{sec}/\omega_{rev} \approx 60$. Starting from a laser accelerated non-crystalline $^{24}$Mg ion beam at a velocity of about $v = 2800\,$m/s (beam energy 1 eV), (longitudinal) laser cooling † enabled the first experimental realization of crystalline $^{24}$Mg ion beams [2].

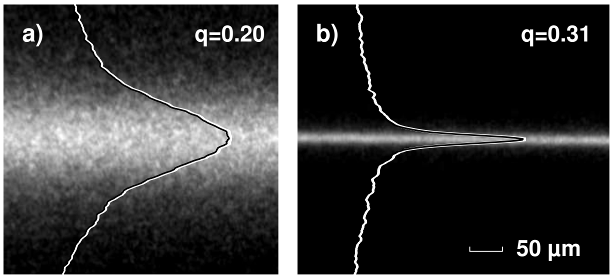


Fig. 1: Fluorescence image of the beam profiles before (a) and after (b) the phase transition. It was induced by increasing the strength of the confining potential (stability parameter $q$) and thus by increasing the inter-ion coupling of the longitudinally laser cooled beam. The width of the crystalline beam corresponds to the width of a (stationary) string of ions [1,2]. The formation of a string is consistent with the measured linear ion density ($\lambda = 0.4$), which uniquely determines the structure of the crystalline beam [3].

In Fig. 1, the phase transition to a one dimensional crystalline beam, a string of ions, manifests itself in a sudden reduction of the transverse beam profile. The corresponding longitudinal velocity spread was measured to simultaneously decrease to a level consistent with the formation of even large crystalline beams [2]. In total, the phase space density of the beam increased by a factor of $10^6$.

One of the outstanding properties of ion crystals and crystalline beams is their elasticity which leads to a strong suppression of the coupling of the periodic rf motion into random thermal motion. Under continuous laser-cooling, circulating ion strings survived for many hours without any significant ion loss. Without further cooling, they were observed to persist for few thousand round trips (about $10^6$ rf periods) [2] in good agreement with MD simulations for large storage rings.

Yet, for given cooling conditions, the attainment of crystalline beams strongly depends on the focusing conditions as illustrated in Fig. 2. The region of stability (shaded area) resembles a curved band, which becomes narrower with increasing complexity (linear density) of the crystalline structure. The upper border seems to be due to the increasing coupling of the crystalline beam to its transverse modulation in the focusing fields. At the lower border, indirect transverse cooling ceases to be efficient when the ion density is reduced. As no (unknown) fundamental processes seem to limit the beam crystallization beyond these borders, increased (transverse) cooling should allow the realization of crystalline beams in large scale storage rings (high periodicity) with unique applications.

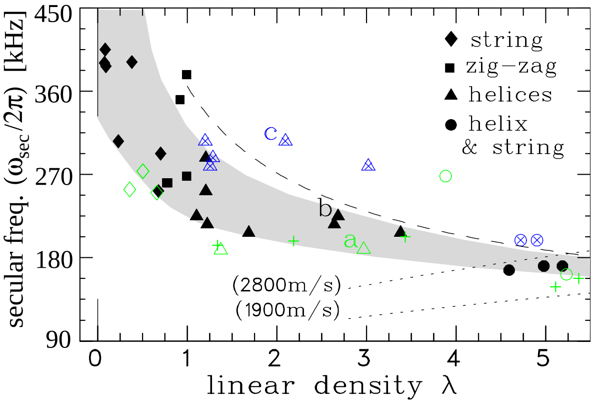


Fig. 2: The shaded area depicts the focusing conditions for which crystalline beams (filled symbols, the shape determines the structure) were attained in PALLAS applying longitudinal laser cooling. Following Schiffer [5], the dashed line indicates a limit where the transverse modulation of the beam in the rf field corresponds to its melting temperature. The dotted lines represent the (velocity dependent) destructive influence of bending shear. For details, see ref. [6].

Also bunched beams, which represent the usual mode of operation in synchrotrons, could be crystallized in PALLAS [4]. Bunching the beam allows the continuous variation of the linear density of the ions. Here, the evolution of the structure of the crystalline beam from a string to a zig-zag configuration was followed. Bunching might provide a way for the laser independent acceleration of crystalline beams to higher energies as well as the synchronous observation of the spatial bunch structure in the near future. Furthermore, the time resolved analysis of the fluorescence signal should enable the investigation of the Schottky noise of ordered beams.

## References

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