Report on Ip et al. “Phonon lasing from optical frequency comb illumination of a trapped ion”

The authors describe Doppler cooling of a trapped Yb^+ ion using a mode-locked laser with a repetition time comparable to the excited state lifetime of the atom. In agreement with previous work, they find that the detuning of the nearest comb tooth to the atomic resonance plays an important role, resulting in either cooling or saturated phonon lasing. The nonlinear interaction between micromotion and the red and blue detuned comb teeth results in discrete fixed points of the oscillation amplitude that depend on the sign of the detuning.
According to the authors, this effect allows loading and crystallization of a single ion without the need for precooling with a cw laser. Furthermore, the authors claim that phase coherence and the spectral comb structure play a crucial role in the cooling performance.
The paper is well written and scientifically sound. The author’s findings of stable fixed points in oscillation amplitude as a consequence of the blue- and red-detuned comb teeth interacting with the amplitude-dependent micromotion sidebands, is an interesting and novel finding. It is also well-derived and substantiated with convincing data that demonstrates agreement between experiment and theoretical predictions from a simple model.
All other effects have been observed before: Doppler cooling using a frequency comb [5,7,8], and phonon lasing using two red- and blue-detuned laser beams [9,11], or by generating a comb structure through micromotion [10]. In contrast to previous work, no temperature measurement has been performed.
Furthermore, two of the other important claims are less well substantiated. It is not clear why direct loading and crystallization is possible in their system, but not e.g. in the similar situation of Ref. [5] or even Ref. [7], where the comb teeth are even much better resolved. I could not find a convincing argument or explanation for this observation. In the end, the ability to crystalize with only comb cooling could be related to a different system parameter and completely unrelated to the observed fixed points of the motional amplitude. Similarly, the interplay between comb structure and single-pulse cooling as discussed in Ref. [5] is not convincingly developed. The invoked visibility of the comb structure illuminates just one aspect. If I understood Ref. [5] correctly, Doppler cooling in the single pulse regime is based on the spectral pulse envelope being centered on the red side of the atomic resonance. In this situation, the linewidth of the pulse envelope takes the role of the Doppler cooling linewidth. Therefore, the duration of the pulse is another important parameter. I would assume that, as soon as the additional slope induced be the comb structure becomes steeper than the pulse envelope slope, the model developed by the authors applies. It should be possible to either find a simple unified model of the comb and single pulse cooling, or at least identify regimes that will depend on the comb visibility, the pulse duration, and the atomic linewidth. Also, the achievable temperature as a function of the cooling parameters should be provided, since it is an important aspect for future applications.

Since the interaction of trapped ions with a frequency comb is an emerging field with many applications ranging from cooling species such as He^+ in the VUV regime or molecular ions with their many transitions, the findings are relevant to a larger community. Furthermore, the nonlinear coupling may be of interest in other fields, since it is a variant of the van der Pol oscillator, implemented in a fairly clean, but rich setting. Therefore, the present work could in principle meet the requirements for publication in PRL, but for the reasons state above, not in its current form.

In addition to this major criticism, the following minor points should be addressed:

- The dependence of fixed point amplitudes on the detuning δ should be discussed. The prediction of Eq. (3) for a fixed detuning seems to agree well with the experimental data in Fig. 1. However, according to Eq. (5), there should be at least a weak dependence on the detuning.

- I find the statement "…each decay makes the ion insensitive to the optical phase of the next pulse, suggesting that the comb teeth will not be well resolved" on page 2 misleading. The comb structure is established according to the coherence between successive laser pulses with a comb tooth width that ideally scales with the inverse of the number of pulses. The atom acts like a spectral filter with a width corresponding to the linewidth γ of the transition. The more comb teeth lie within a linewidth of the transition, the less resolved is an individual comb tooth. In this picture it is much less surprising that the comb structure actually has an effect on the atomic fluorescence, since $\gamma \sim f_r/4$.
- $\mathbf{F}$ and $\mathbf{v}_{\mathbf{sec}}(\xi)$ before Eq. 5 should be defined, and ω in Eq. 5 should be ω_x.
- Caption of Figure 1: The statement "… the ion is Doppler cooled near the ground state." is misleading, since i) no temperature measurement has been performed ii) it is not expected that for the presented parameters Doppler cooling to the ground state is possible.
- Why is the $x_0^* \approx 0\,\mu$m fixed point in Fig. 2, 3 and the describing text missing? As stated above, an expression for the achievable temperature as a function of detuning should be provided.
- The authors should comment why no temperature measurement has been performed in their system, which seems to offer a similar imaging resolution compared to Ref. [5].
- Ref. [24] is incomplete