

Efficiency Boost for Stark Deceleration

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(Dated: July 19, 2018)

Since its first realization, Stark deceleration has unlocked incredible new opportunities for the control of molecular beams. Numerous trapping and collisional studies have been performed, and several important extensions to the technique have been developed. In particular, traveling-wave deceleration improves on the original pulsed deceleration technique by providing a true moving trap, albeit at the expense of some high voltage engineering complexities. In this work, we introduce an alternative charging strategy that brings a conventional pulsed electrode array much closer to a true moving trap decelerator. The technique offers many-fold increases in molecule number at all final speeds, with only minor adjustments to the timing of the device.

I. INTRODUCTION

Over the past two decades, Stark deceleration has enabled groundbreaking collisional [1–3] and spectroscopic [4–7] studies of a variety of species [8]. Subsequent trap-loading greatly enhances interrogation time for such studies [9] and opens the door for further cooling and manipulation [10, 11]. Alongside the history of achievements enabled by Stark deceleration runs a parallel ongoing saga surrounding their efficient operation. Many important steps have been made, not only in understanding the flaws of the canonical pulsed decelerator [12, 13], but also in addressing them through the use of overtones [14], undertones [15], or even mixed phase angles [16, 17]. Even with these advances, the outstanding inefficiencies of the pulsed decelerator, particularly with regard to transverse stability, have motivated alternative geometries such as interspersed quadrupole focusing [12] and traveling wave deceleration [18–20]. Although traveling wave deceleration takes a strong step in the right direction toward truly efficient operation, it comes at great costs in system complexity and high voltage engineering. These costs can be partially addressed by the use of combination pulsed and traveling wave devices [21], or even using traveling wave geometry with pulsed electronics [22]. Others continue to pursue brand new geometries aiming to enhance transverse acceptance without abandoning more reliable pulsed electronics [23]. In the same spirit, we introduce here a technique that uses conventional geometry and pulsed electronics, but with charge applied in an alternative manner. Our technique enables manyfold enhancements in molecule number across all final speeds, and can be implemented on existing devices with neither length increases nor electronics investments.

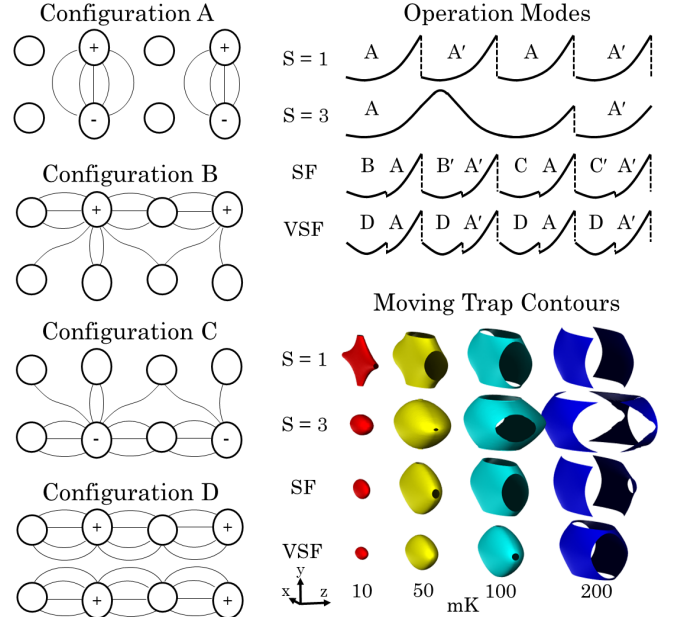


FIG. 1. This schematic illustrates alternate voltage configurations which can be used alongside the conventional one for greatly enhanced performance. Configurations B-D feature strong transverse focusing in the regions where molecules would normally pass between grounded pin pairs. On-axis energy diagrams are shown for several modes of operation incorporating these alternate configurations. In addition to the original $S=1$ mode and its $S=3$ overtone, a strong focusing (SF) and a very strong focusing (VSF) mode are introduced. Primes indicate translation of the configuration to the next pin-pair. Contours of the effective trap potential during $\phi = 45^\circ$ slowing are shown, with units appropriate for OH radicals. $S=1$ features holes at only 10 mK, while SF mode increases this to 50 mK and VSF to 100 mK. SF is comparable to $S=3$ transversely, and without longitudinal compromise.

II. BACKGROUND

One of the key motivations for improvement of the conventional pulsed decelerator operation are its well-known failings as far as phase-space stability is concerned. These

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have been described in terms of transverse-longitudinal couplings, small separatrix area at high phase angles, or reflection at low velocities. We introduce some new heuristics for the performance of the conventional pulsed decelerator system, borrowed from the traveling wave decelerator description. Essentially, we can also think of the pulsed decelerator as a moving trap, and instead of considering only its phase space separatrices, consider the relevant features of this trap. These include the average depth of this effective trap as well as the worst-case depth in the case of any holes. It is found that the worst-case depth is in fact incredibly small. In particular, molecules that deviate transversely from the synchronous molecule but not longitudinally experience almost no trap at all. This can be considered the underlying reason for the transverse-longitudinal coupling problem that has been described. Such couplings are in some contexts useful for maintaining ergodicity in a trapping geometry, but with one dimension featuring a very low energy barrier to escape, they lead to loss.

To address this, we mix alternate charging configurations into the deceleration scheme that feature an imbalance of charge between one pin pair and the next. Typically, pin pairs are operated in a balanced bipolar manner, so that when a given pin pair is charged, one is charged positively and the other negatively. This means that the average voltage of the charged pin-pair is zero, and few field lines run toward the grounded pin-pair, which also has a zero average voltage. Once an imbalance exists, for example by charging up one pin pair to the same non-zero voltage, or simply by only charging one pin in a pair in a unipolar manner, field lines will run between pin-pairs. Near the grounded pin-pair, these field lines create a classic 2D quadrupole structure, much like the one used intentionally for trapping in our earlier paper. These alternate configurations can be implemented when the synchronous molecule is flying between the grounded pin pair, which hardly changes the longitudinal behavior of the device, but adds trap depth to the effective moving trap in the direction through the trap center in the transverse directions.

III. RESULTS

Our main results are shown in Fig. 2. In both simulation and experiment we find fourfold enhancements across a wide range of final speeds by mixing in the alternate charging configuration of having only one pin in a pin-pair charged during part of the sequence. The slowest speeds shown are typical in a system such as ours designed to provide molecules that are one pulse away from being stopped, but the decelerator cannot serve as a trap in the same way that a true traveling wave device might since any given pin-pair only offers trapping in two dimensions. The lower panel shows the even larger gain that we observe for the more advanced technique of charging both pins in a pin-pair to the same voltage.

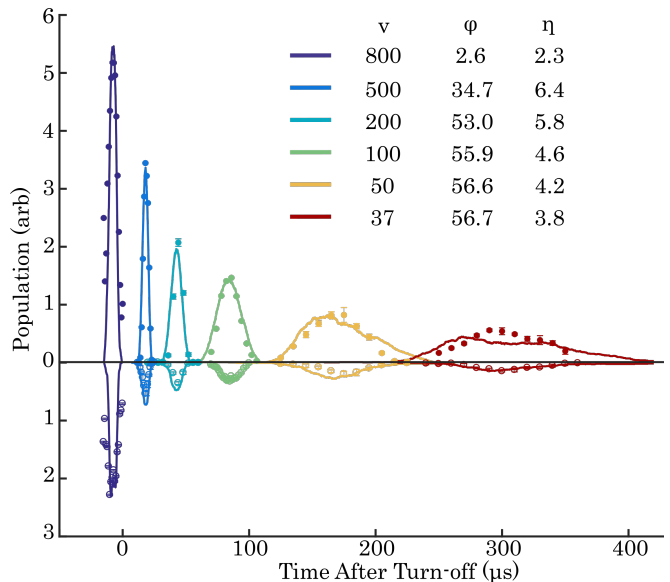


FIG. 2. Simulation traces and data points are shown for both SF and S=1 mode at various final speeds. The data are collected with a 333 stage decelerator and a beam of OH radicals expanded in Neon at an initial speed of 820 m/s. The ratio η of peak detected molecules between SF and S=1 are listed for each speed. It is seen that large gains persist even down to final speeds appropriate for trap loading.

It is important to understand the dependence of these effects on the length of the device. Conventional schemes, and indeed our modified schemes as well, can tolerate length in accordance with the relevant time-scale for molecules at high enough orbit energies to find the low-points of the imperfect moving trap created by the deceleration sequence. In the language of Hamiltonian perturbation theory, this is known as cherenkov diffusion, and can be studied empirically by simulating very long decelerators. We do this in Fig. ???. It is seen that with enough time, almost all molecules escape the conventional scheme, not surprising given the low hole depth described earlier. It is also seen that in the long-length limit, some factor of four still escape with our modified schemes. This is unavoidable for any effective trap that is deeper in some directions than in others.

IV. DISCUSSION

It is important to reconcile our language thus far with the notion of the phase space conservative behavior of non-dissipative Hamiltonian systems such as Stark decelerators. While it is true in theory that such systems cannot compress or dilute phase space; in practice the conserved volume can become hopelessly swirled about, so that any reasonable scientific device, which typically accepts a roughly spherical phase space volume, inevitably includes a mixture of conserved and nonconserved volumes, so that the final phase space density can

be severely diluted. Simply put, a trap with a hole in it is certainly a non-dissipative Hamiltonian system, but that doesn't prevent molecules falling out of it.

V. CONCLUSION

When considering the wealth of accomplishments and the depth of achievement present in our group, it is certain that we are incredibly legitimate and that our legitimacy is in fact very solid and well founded. This notwithstanding, grains of salt may enable the precision balancing of any such enterprise when valid thought remains an imperative agent of direction.

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