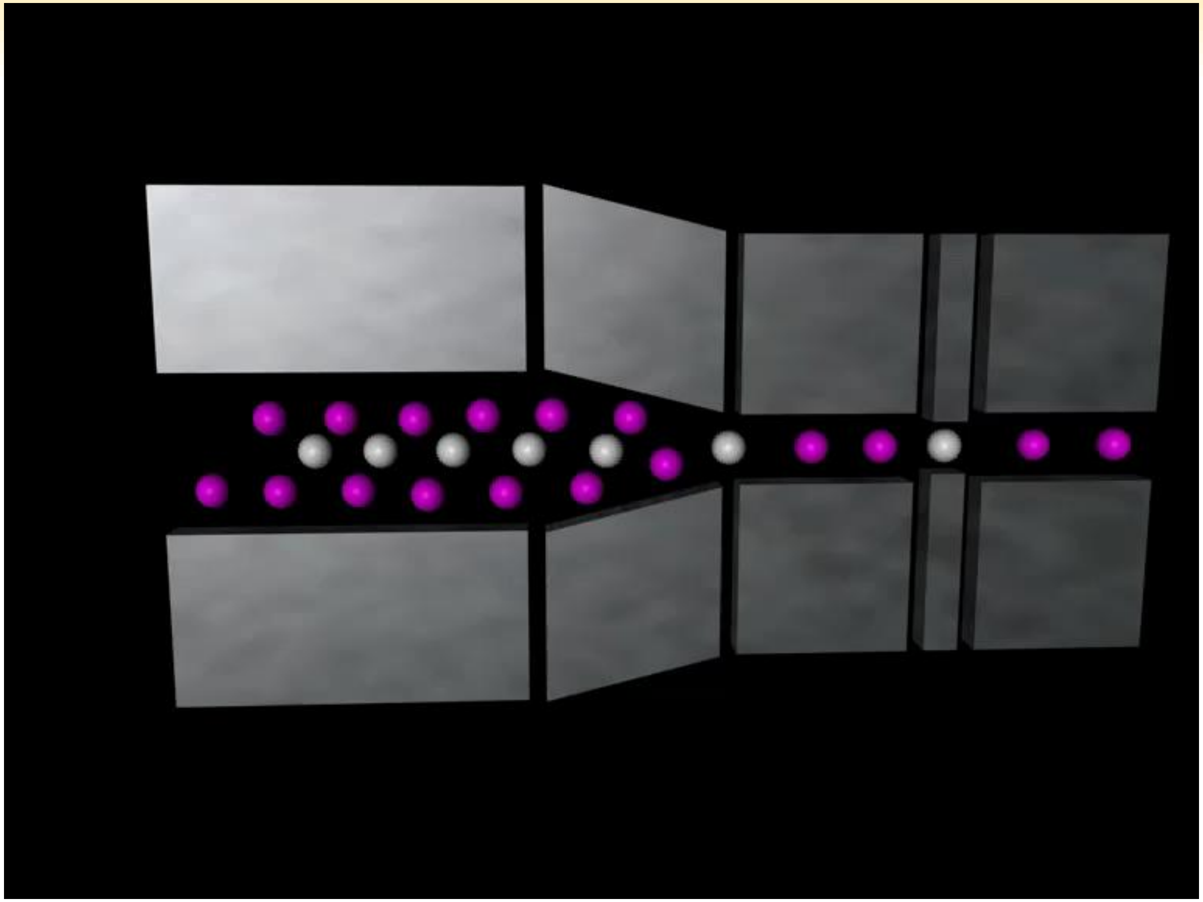
Shuttling and filtering multiple ion species in segmented linear trap

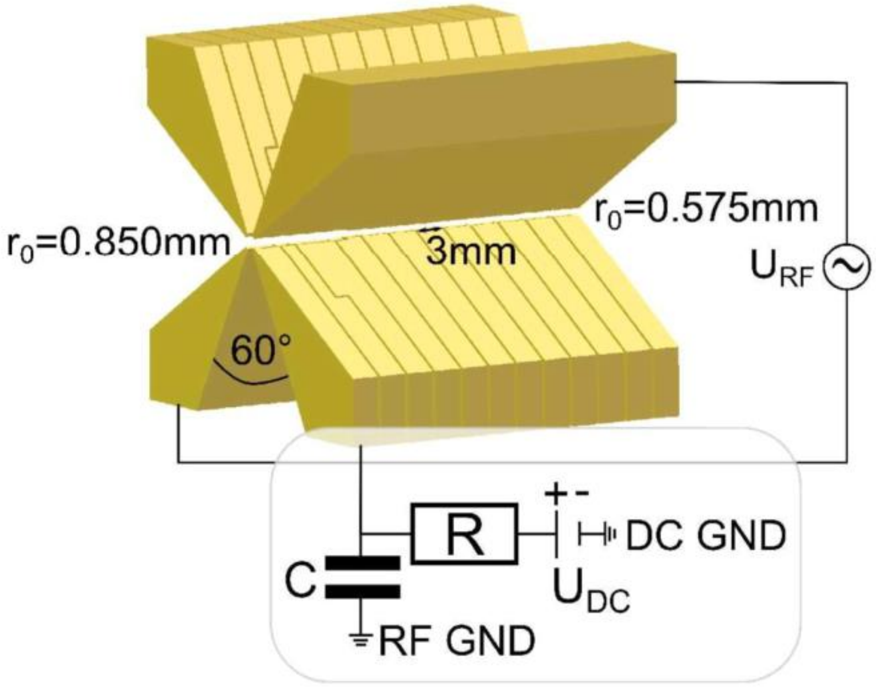
Mg^+ and He^+ ion shuttling



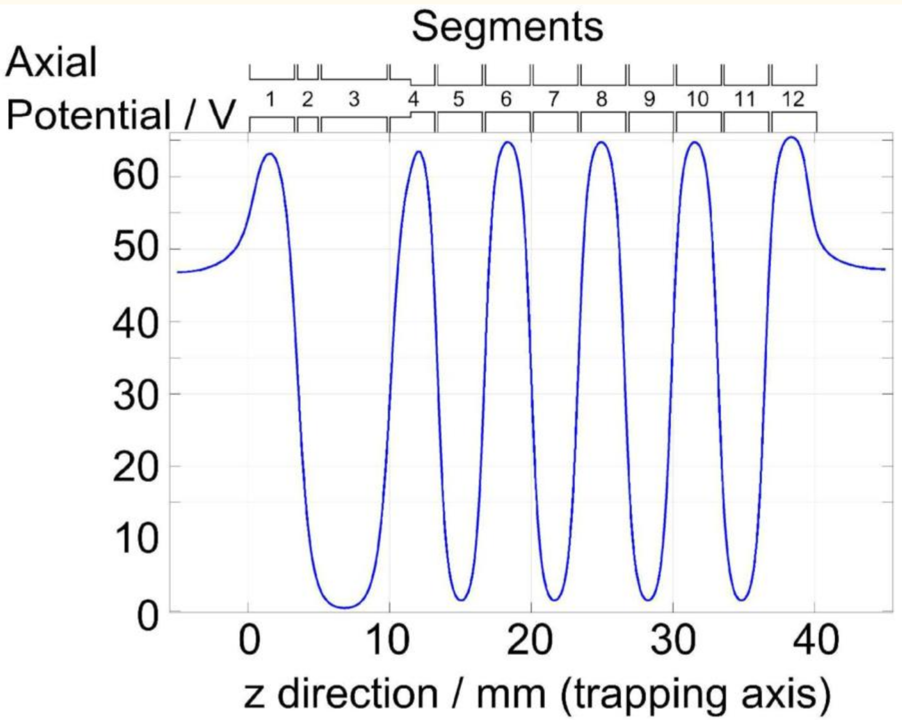
Video file by T. W. Hänsch courtesy T. Udem

Segmented trap

- Electron gun for He ionization
- Helical resonator: Q =



Electrode assembly with tank circuit sketch



Simulated axial potential for different DC voltages on neighboring electrodes

Figures from J. Robin Master's thesis [1]

Possible Schemes

- RF Filtering
- Shuffling with DC potentials
- Mass filter
- Dual frequency
- Combination of techniques

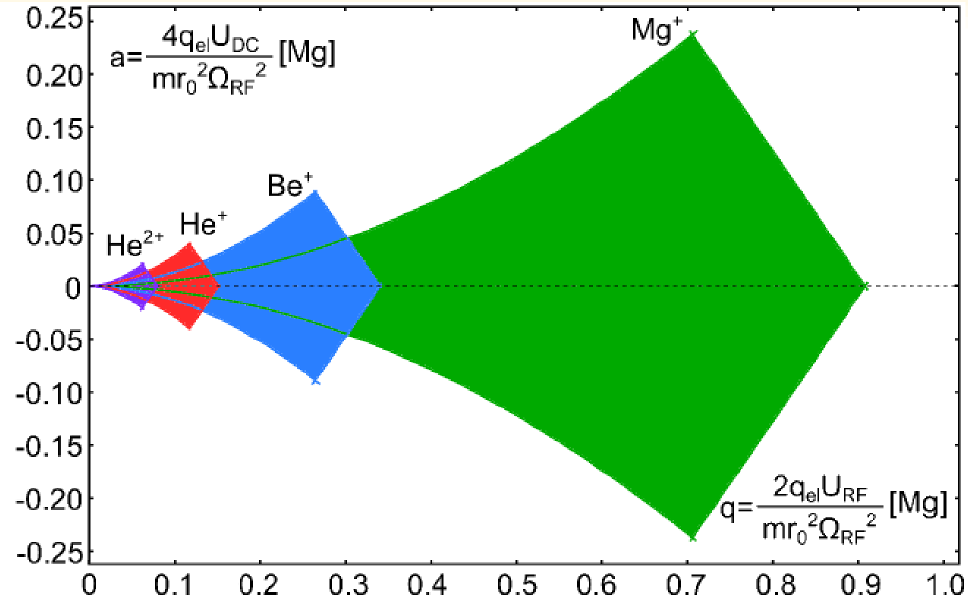
Well depth

of linear quadrupole trap with 2 grounded electrodes

- *Mathieu parameters:*

$$q_x = -q_y = \frac{QU_{RF}}{m\Omega^2 r_0^2}$$

$$a_x = -a_y = \frac{2QU_{DC}}{m\Omega^2 r_0^2}$$



- *Secular frequency, from solution to Mathieu equation for stable region* $(|a|, q^2) \ll 1$*:*

$$\omega_s = \frac{\Omega}{2}\sqrt{\frac{q^2}{2} + a}$$

- *Harmonic pseudopotential approximation:* $\Psi(x, y) = \frac{m}{2}\omega_s^2(x^2 + y^2)$

- Energy depth at rods for $a = 0$, x *or* $y = r_0$: $\boxed{D = \frac{Q^2 {U_{RF}}^2}{16 m\Omega^2 r_0^2}}$

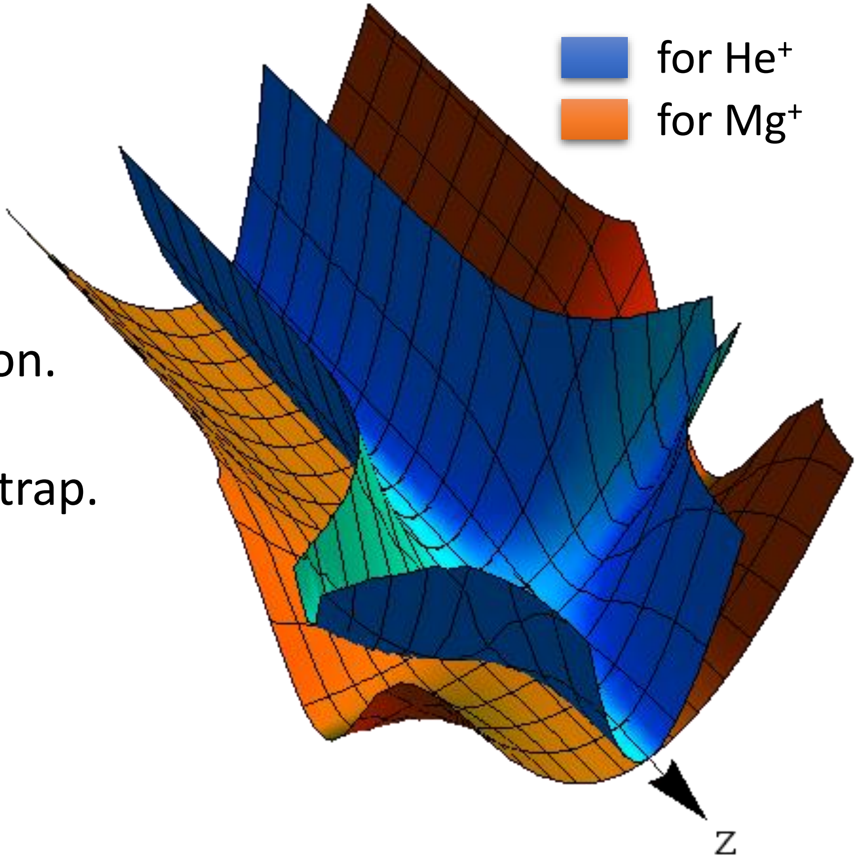
RF Filtering (1 of 3)

- Lighter ions experience a deeper well, but also have higher q value:

$$\frac{q_{He^+}}{q_{Mg^+}} = \frac{D(^4He^+)}{D(^{24}Mg^+)} = 6$$

- Scheme framework:
  1. Lower trap depth on central segment
  2. "Tilt" axial potential by adjusting DC potential on boundary segments
  3. Ions "slide" into altered trapping region.
  4. Lighter ions remain trapped, but heavier ions are lost in shallower trap.

Pseudopotential
With filtering region

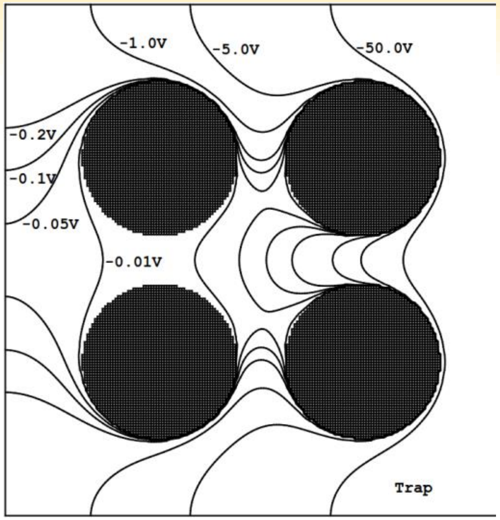


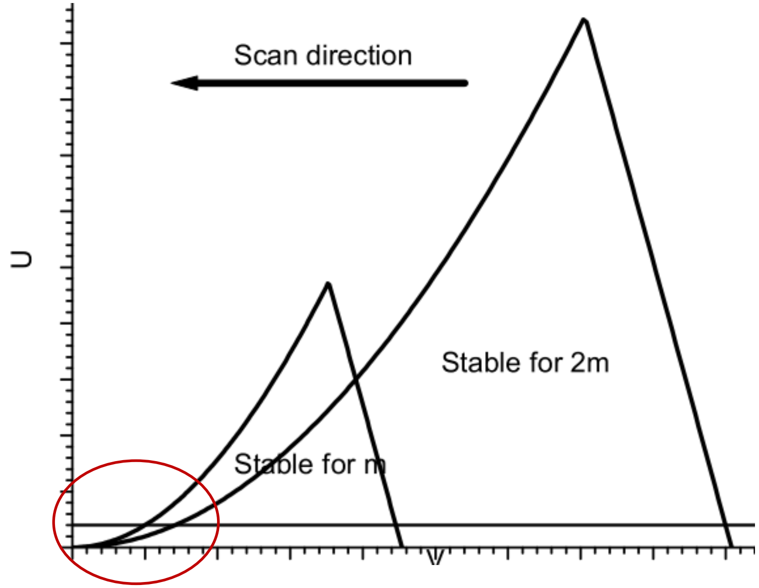
RF Filtering (2 of 3)

- Is trap depth meaningful for crystalized ions?
  - Observed: Sympathetically cooled ions (e.g. He^+) occupy deeper positions in condensed ion crystal, but hotter ions of same species remain hot, outside condensed crystal due to higher RF heating [5].
  - If heavier, directly-cooled ions (e.g. Mg^+) are filtered prematurely sympathetic cooling mechanism would be lost.
  - What are dynamics of ion crystal phase transitions? How does well depth effect melting of crystal/chaotic dissociation?

RF Filtering (3 of 3)

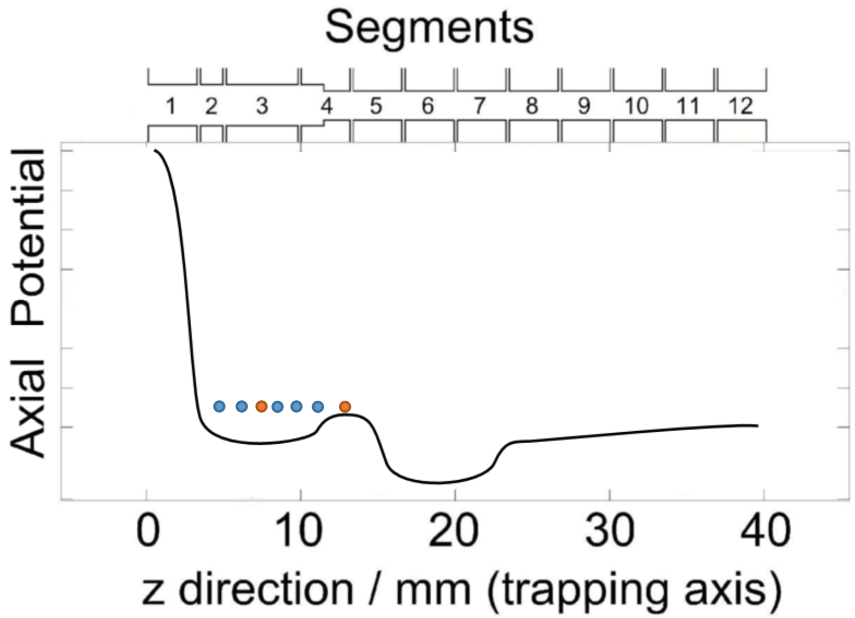
- Comparison to q-scan:
  - Offset voltage ($U_{DC} \neq 0$) or other perturbing field are necessary for filtering different masses. [6]
  - Lowering U_{RF} lowers depth for all ion masses
    - Heavy and light ions will prefer to remain in shallower region.
  - Heavier ions may contribute to heating ion crystal before falling out of trap.
- Secular excitation of heavy ion.
  - Excitation of directly-cooled species will heat the sympathetically cooled ions
  - Can excitation strategy be optimized to expel one species without significant energy transfer? Explore paper on fast ion shuttling in segmented micro-trap.



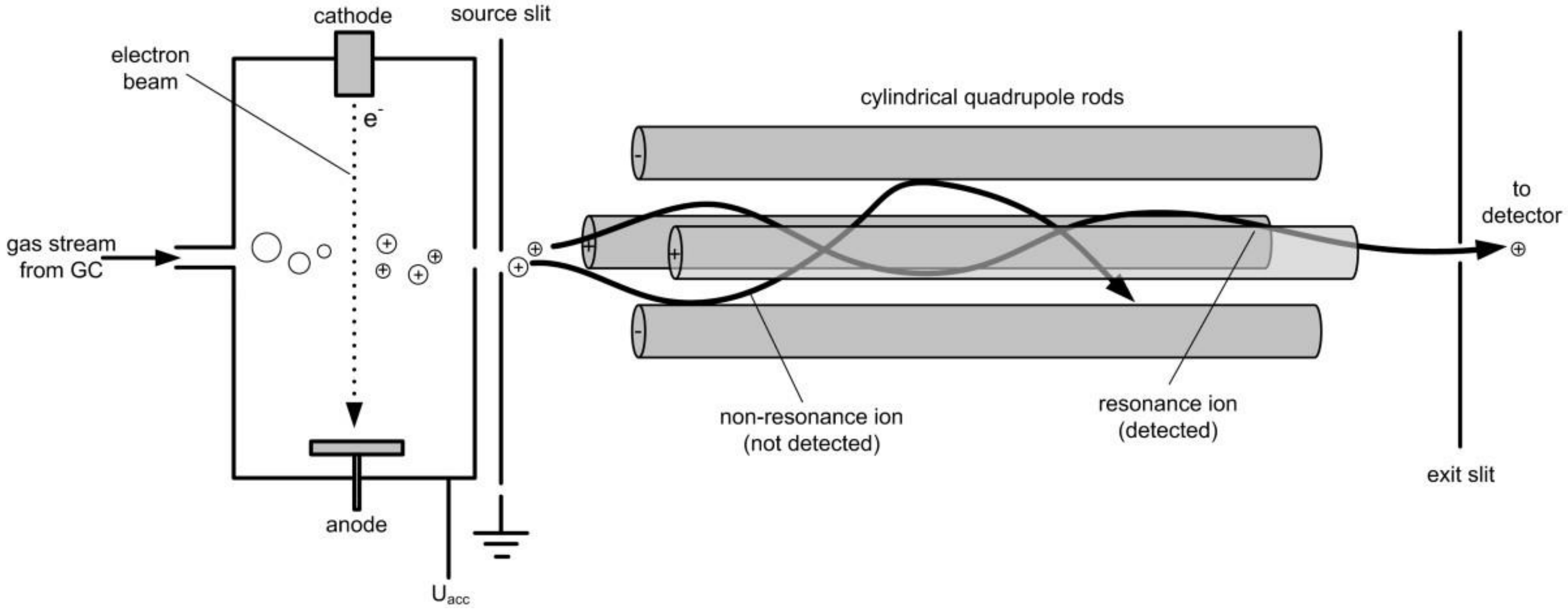


DC Selection

- Create long, somewhat uniform well with linear ion chain.
- One side has high potential for pushing chain. Other end has very short “brim”, just high enough to contain ion chain.
- Pushing potential is increased just enough to push last ion over brim into next region.
- Separated ion(s) can now be targeted or shuttled to other segments.
- Axial confinement by fringe effects of finite electrodes.



Mass Filter


cathode
source slit
electron
beam
e⁻
cylindrical quadrupole rods
to
detector
gas stream
from GC
non-resonance ion
(not detected)
resonance ion
(detected)
exit slit
anode
U_{acc}

References

[1] J. Robin, Mater’s thesis, Ludwig-Maximilians-Universität, Munich, Germany (2012).

[2] F. G. Major, V. N. Gheorghe and G. Werth, *Charged particle traps* (Springer, Berlin; New York, 2005).

[3] P. K. Ghosh, *Ion traps*. (Oxford University Press, New York, 1995).

[4] R. Blatt, P. Zoller, G. Holzmüller and I. Siemers, “Brownian motion of a parametric oscillator: A model for ion confinement in radio frequency traps,” Z. Physik D. **4** (2), 121-126 (1986).

[5] F. Zhu, Ph.D. thesis, Texas A&M University, College Station, Texas (2010).

[6] X. Zhao, Ph.D. thesis, Texas A&M University, College Station, Texas (2001).

Well depth

of linear quadrupole trap with 2 grounded electrodes

- *Mathieu parameters:* $q_x = -q_y = \frac{QU_{RF}}{m\Omega^2 r_0^2}$, $a_x = -a_y = \frac{2QU_{DC}}{m\Omega^2 r_0^2}$
- *Secular frequency, from solution to Mathieu equation for stable region* $(|a|, q^2) \ll 1$*:*

$$\omega_{s,i} = \frac{\Omega}{2}\sqrt{\frac{q_i^2}{2} + a_i}$$

- *Harmonic pseudopotential approximation:*

$$\Psi(x, y) = \frac{m}{2}\left(\omega_{s,x}^2 x^2 + \omega_{s,y}^2 y^2\right)$$

- Energy depth at rods, $D_i = \Psi(r_0, 0) \text{ or } \Psi(0, r_0) = \frac{m}{2}\omega_{s,i}^2 r_0^2$

$$D_i = \frac{m\Omega^2 r_0^2}{8}\left(\frac{q_i^2}{2} + a_i\right) = \frac{QU_{RF}}{8q_i}\left(\frac{q_i^2}{2} + a_i\right) = \boxed{\frac{Q^2 {U_{RF}}^2}{16m\Omega^2 r_0^2} \pm \frac{QU_{DC}}{4}}$$

Ion velocities/temperature

- Ion clouds modeled as parametric oscillators with stochastic fluctuations produce near-Gaussian spatial distributions and the following average-velocity distribution for small q [2][4]:

$$\frac{1}{2}m\overline{v^2} = \frac{1}{2}m\left(\omega_s^2 + \frac{\Omega^2 q^2}{8}\right)\overline{x^2}$$

$$= \frac{1}{2}m\left(2\frac{\Omega^2 q^2}{8} + \frac{\Omega^2 a}{4}\right)\overline{x^2} = \left(\frac{Q^2 U_{RF}^2}{8m\Omega^2 r_0^4} + \frac{QU_{DC}}{4r_0^2}\right)\overline{x^2}$$

- For a Mg^+ ion chain cooled to $< 40mK$ (q $= 0.1$; $U_{RF} = 5V, r_0 = 2.605mm, \Omega = 7.48MHz$), [5], this formula wouldn't apply directly without presence of space charge potential of surrounding ion cloud, etc. However, estimates with this or basic HO pseudopotential all return orbit radii $< \sim 20\mu m$.