Ion cooling simulations

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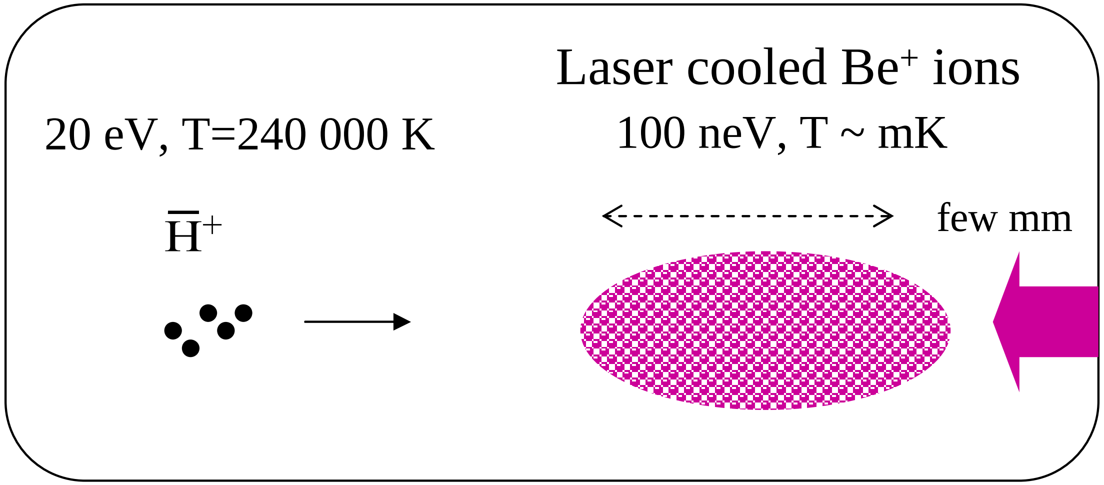
$\bar{H}^+$ sympathetic cooling challenges

First step



20 eV, T=240 000 K

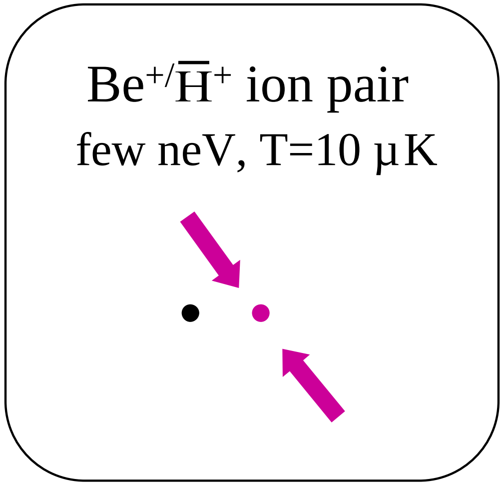
$\bar{H}^+$

Laser cooled Be^+ ions

100 neV, T ~ mK

few mm

Second step



$Be^{+}/\bar{H}^{+}$ ion pair

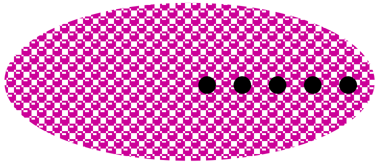
few neV, T=10 μK

Why $^9Be^+$? $\bar{H}^+$ is light and needs the lighter laser cooled ion mass ratio 9/1

Which cooling laser ? λ = 313 nm, ~ mW/mm^2

What about UV $\bar{H}$+ photodetachment ? Cooling time < 1 s

Objectives of the simulations



- Estimate the sympathetic cooling time and final temperature

- Design the ion pair trap and estimate the cooling time

Ion cloud dynamics simulations

- N_{LC} Be^+ ions and N_{SC} $\bar{H}^+$ ions

- Trap RF and DC electric fields

$$V(\vec{r},t)=V_{RF}\cos(\Omega\, t)\overbrace{\frac{x^2-y^2}{2r_0^2}}^{\text{Radial confinement}} + \frac{m}{q}\frac{\omega_z^2}{2}(\overset{\text{Longitudinal confinement}}{z^2}-\underbrace{x^2-y^2}_{\text{Radial de-confinement}})$$

- Coulomb interaction

$$\vec{F}_{i,Coul}=\sum_{j\neq i}\frac{q_i q_j}{4\pi\varepsilon_0}\frac{\vec{r}_i-\vec{r}_j}{r_{ij}^3}$$

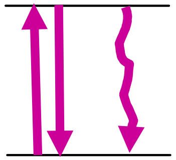
$(N_{LC}+N_{SC})^2$ terms

- Leap frog (velocity Vernet) integration algorithm

$\delta t = 2\ 10^{-10}$ s

- Laser cooling process

  Absorption,
  Spontaneous emission
  Stimulated emission



Evaluated each time step

- No heating process

Implementation FORTRAN F90
parallel computing with openmp →

$$E_{macro,sc}=\frac{1}{N_{sc}}\sum_{i=1}^{N_{sc}}\frac{1}{2}m\langle\vec{v}_i(t)\rangle_{RF}^{\ 2}$$

Computer requirements

- RAM

Position, velocity, acceleration, mass, charge
LC/SC, internal state, dead/alive, …

11 double precision / ion
4 integers and 2 boolean / ion

< 1000 bit / ion   < 1.25 Mo for 10 000 ions

< cache memory size

- Disk storage

1000 trajectories (t,**r**,**v**) ~ 56 ko / saved step

files < few Go

- CPU

Coulomb force dominates CPU time

$\underbrace{\text{(5+, 6x, 1÷, 1 power)}} \ (N_{LC}+N_{SC})^2$

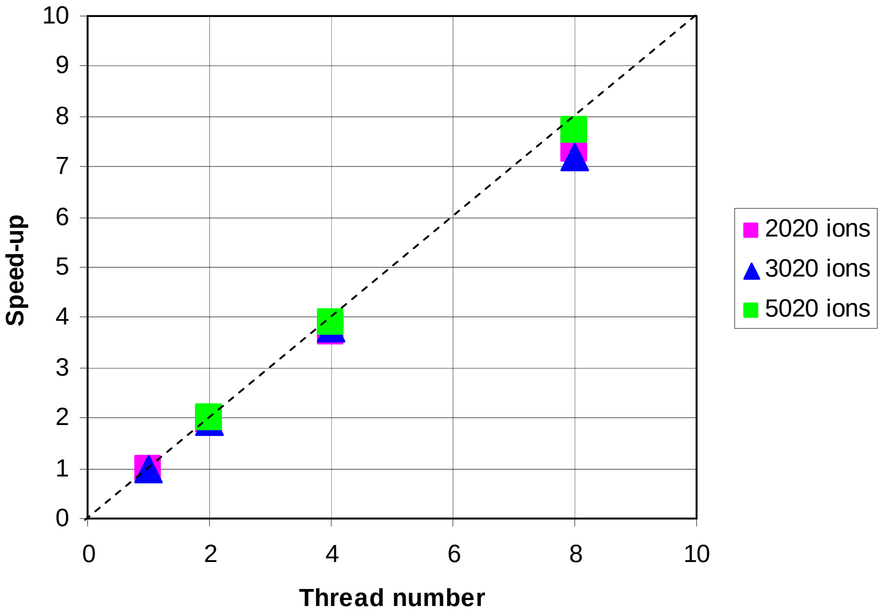
with 2.7 GHz CPU : 50 000 000 term/s

Performances

1 thread

$N_{LC}+N_{SC}$	step/s	T_{simul} for 1 ms
520	205	7 hours
1020	53.5	26 hours
3020	6.1	9 days 1/2
10020	0.5	3-4 months

OMP parallel library



10 ms / week

ions	Threads
1000	2
5000	41
10000	165

LKB max thread nb = 24

State of the art

- S. Schiller group, Be^+ / HD^+

  S. Schiller, C. Lammerzahl, Phys. Rev. A 68, 053406 (2003)
  C.B. Zhang, D. Offenberg, B. Roth, M.A. Wilson, S. Schiller, Phys. Rev. A 76, 012719 (2007)

  ~ 1000 Be^+ ions, ~100 SC ions

  Steady state, ion cloud image, heating and cooling rates, RF heating

- M. Bussmann, U. Schramm, D. Habs, V.S. Kolhinen, J. Szerypo, IJMS **215**, 179 (2006)

  - 100 000 $^{24}Mg^+$ ions, 1 $^{100}X^{40+}$ ion
  - no RF (effective potential) ↔ $$\frac{m_1/q_1}{m_2/q_2} = 9.6$$
  - $\delta t = 10^{-9}$ s

  ➡ 400 meV $^{100}X^{40+}$ ion is stopped within 0.1 – 1 ms

  But what about RF heating ?

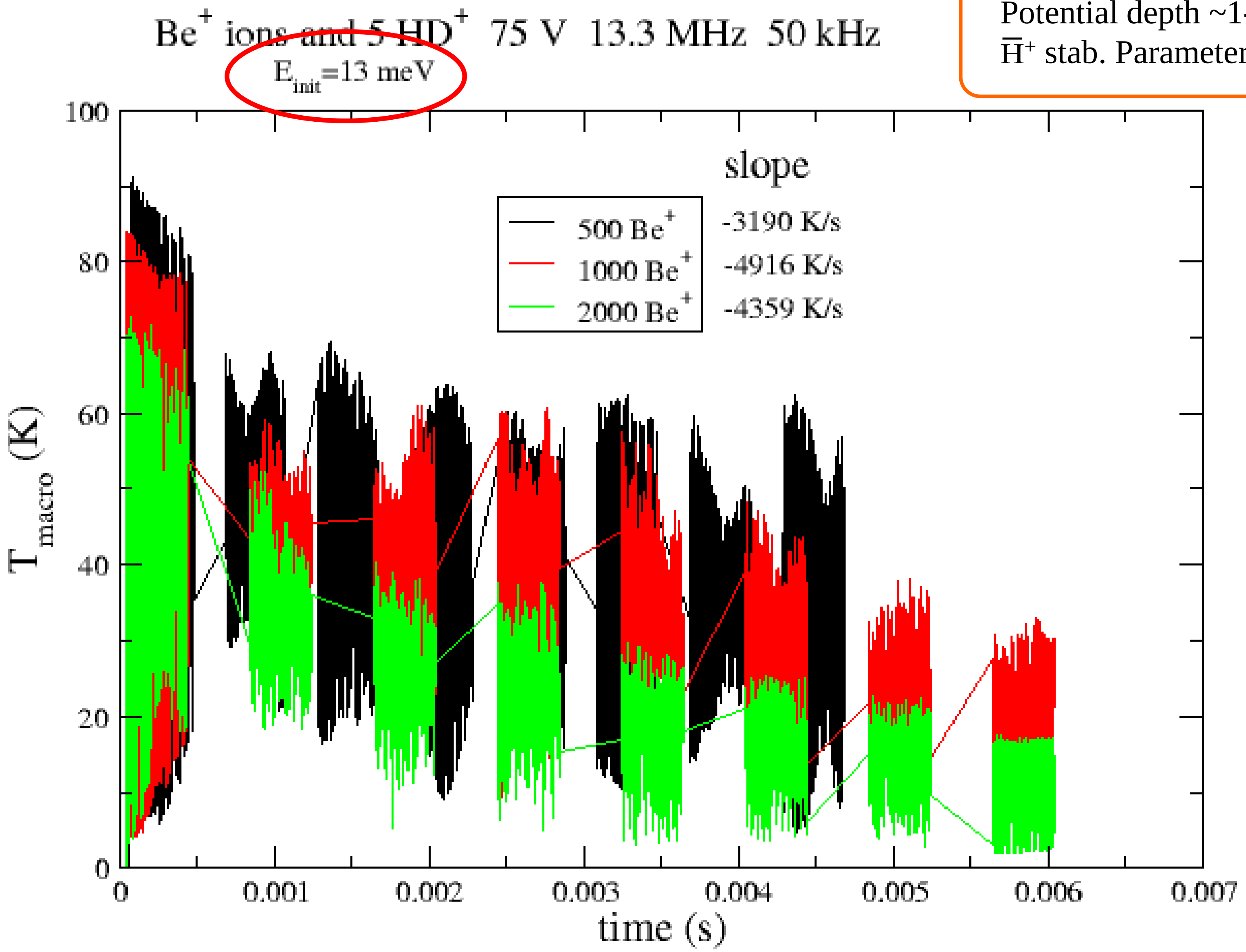
- J. B. Wübbena, S. Amairi, O. Mandel, P.O. Schmidt, Phys. Rev. A **85**, 043412 (2012)

  Ion pair sympathetic cooling

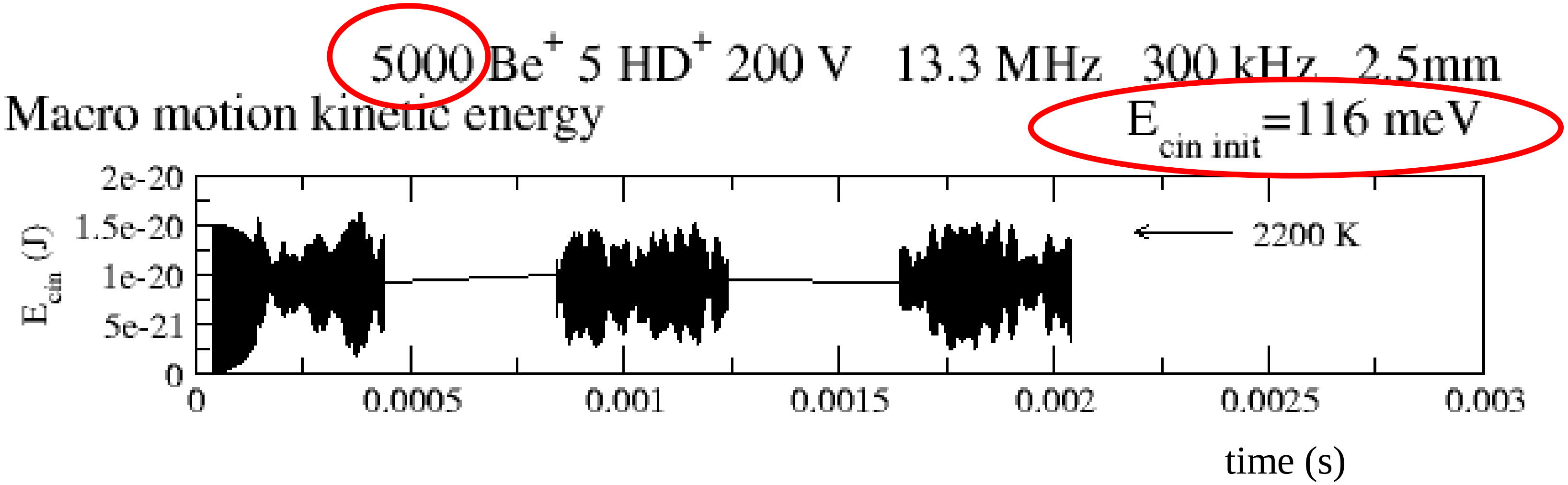
First results

Let’s start with Be^+ and HD^+, 9/3 mass ratio

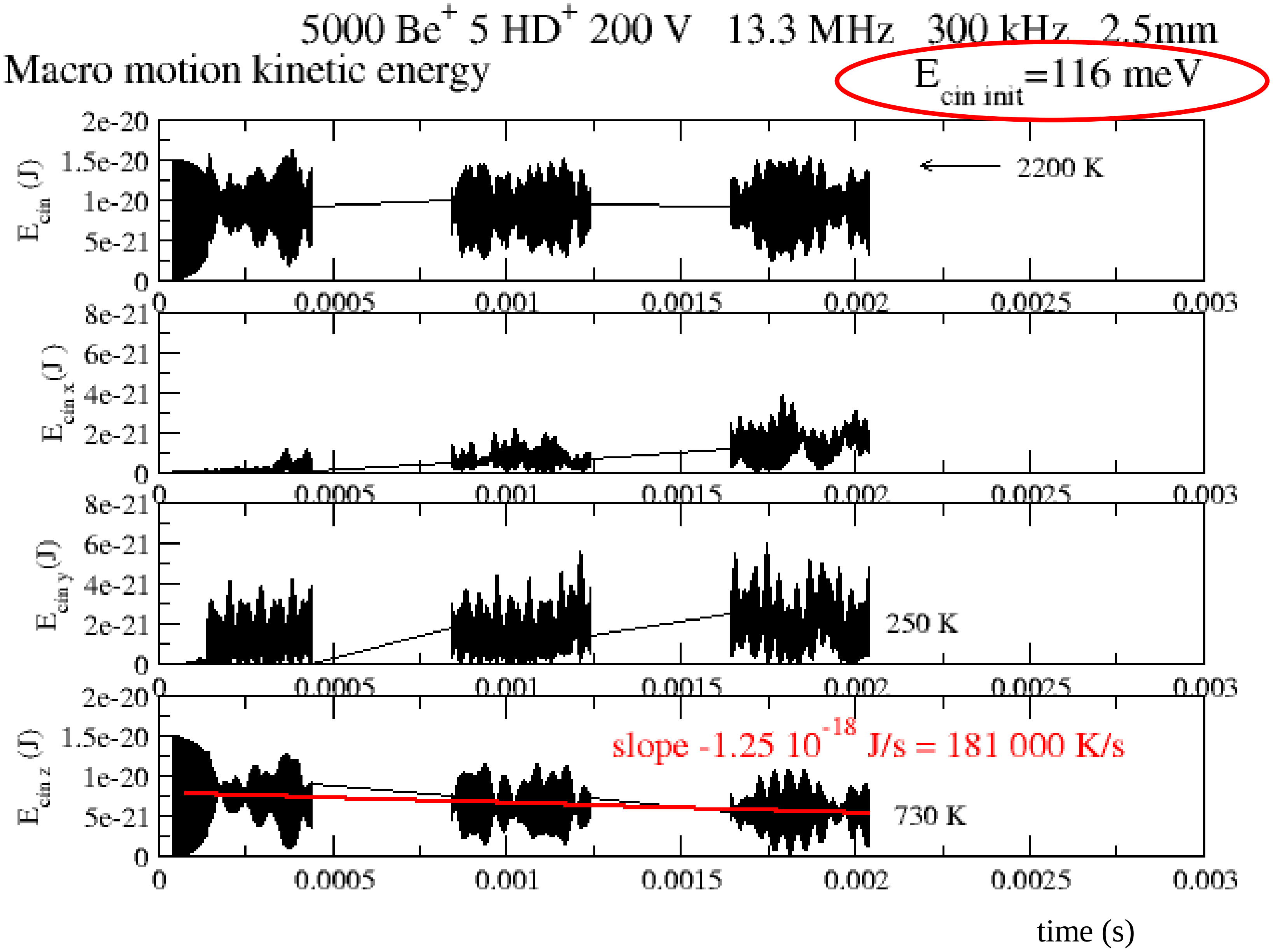
Potential depth ~1-10 eV
$\overline{H}^+$ stab. Parameter q ~ 0.4



Let’s try more energetic HD^+ ions and more Be^+ ions

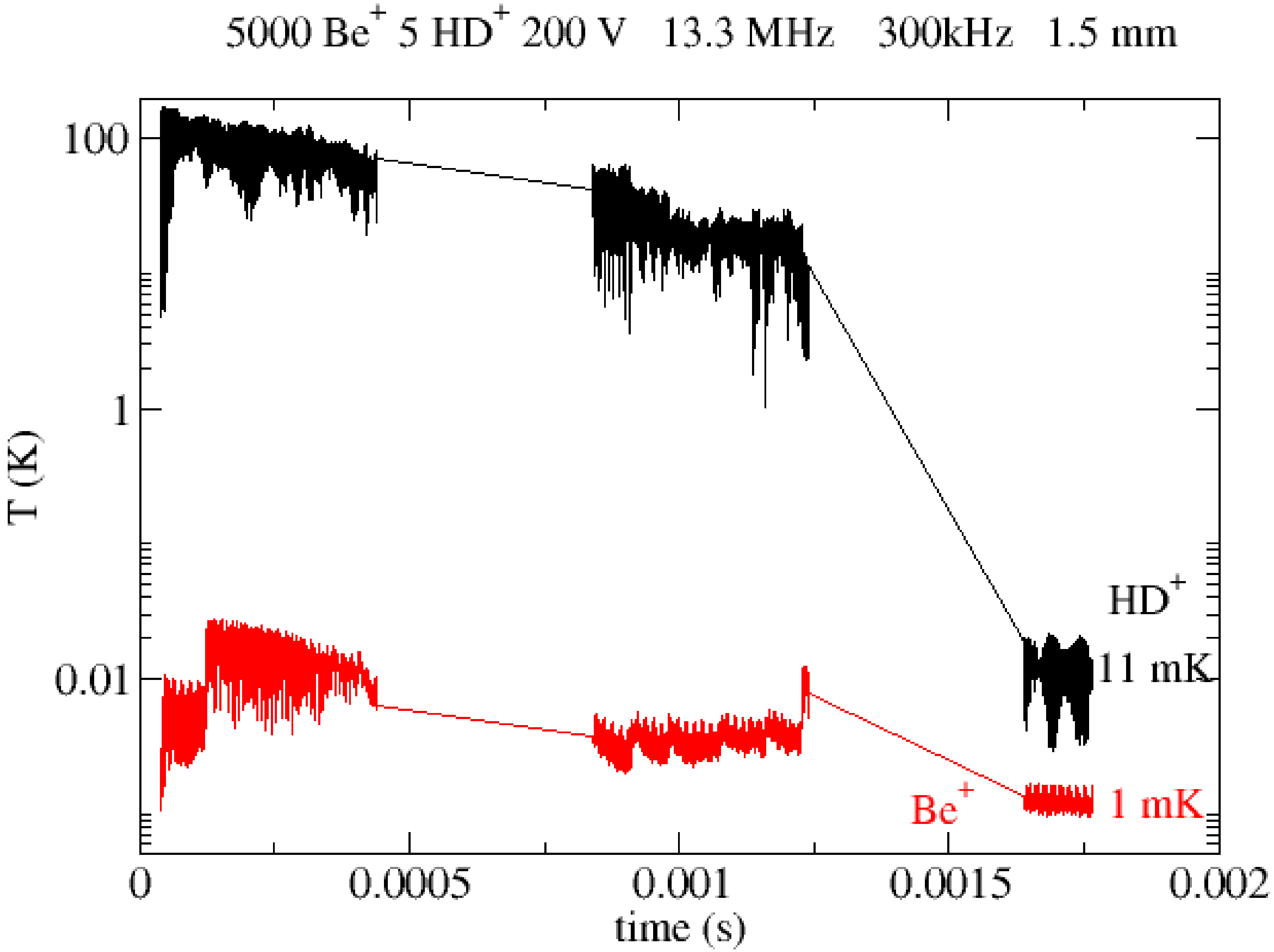


Let’s try more energetic HD$^+$ ions and more Be$^+$ ions

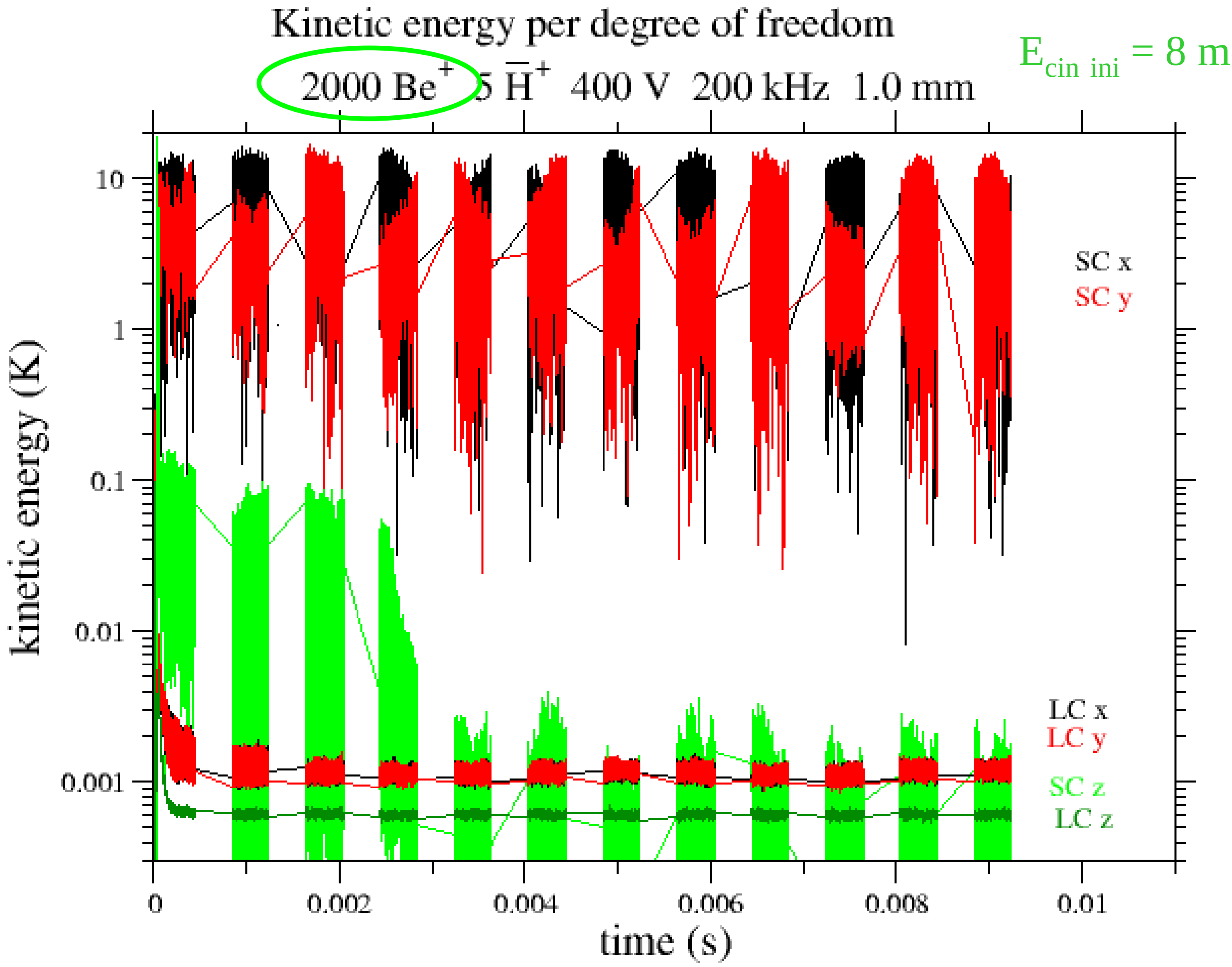


Let’s try less energetic HD$^+$ ions …

$E_{cin\ ini} = 41$ meV



Be$^+$ / $\overline{\mathrm{H}}^+$ now, 9/1 mass ratio …

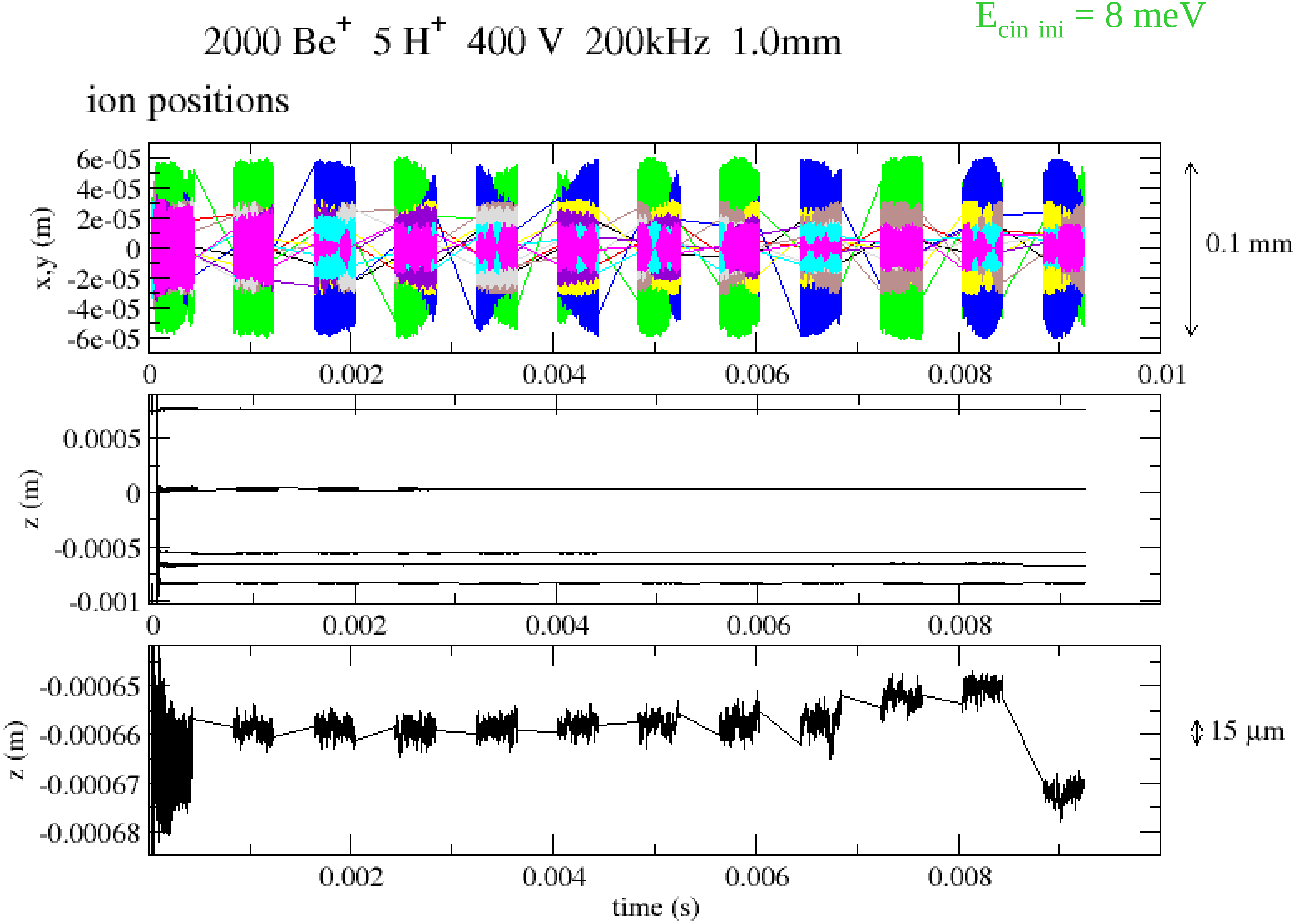


$E_{\mathrm{cin\ ini}} = 8$ meV

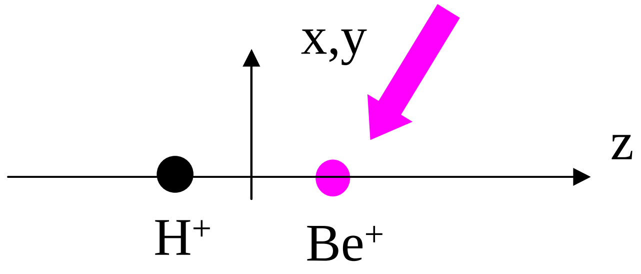
What about $\overline{\mathrm{H}}^+$ capture ?

$\overline{H}^+$ ion trajectories

$E_{cin\ ini} = 8$ meV



Ion pair Doppler cooling



Two coupled oscillators in an external potential

in phase mode
out of phase mode

normal modes

individual ion modes
x, y, z

$$q_1(t) = b_1 \overbrace{z_{in}\sin(\omega_{in}t+\varphi_{in})} + b_2 \overbrace{z_{out}\cos(\omega_{out}t+\varphi_{out})}$$

$$q_2(t) = b_2 \frac{z_{in}}{\sqrt{m_2/m_1}}\sin(\omega_{in}t+\varphi_{in}) - b_1 \frac{z_{out}}{\sqrt{m_2/m_1}}\cos(\omega_{out}t+\varphi_{out})$$

$$b_1^2 + b_2^2 = 1$$

m_{SC}/m_{LC} ? → sympathetic cooling efficiency

T. Hasegawa, Phys. Rev. A 83, 053407 (2011)
J. B. Wübbena, S. Amairi, O. Mandel, P.O. Schmidt, Phys. Rev. A **85**, 043412 (2012)

1D
3D

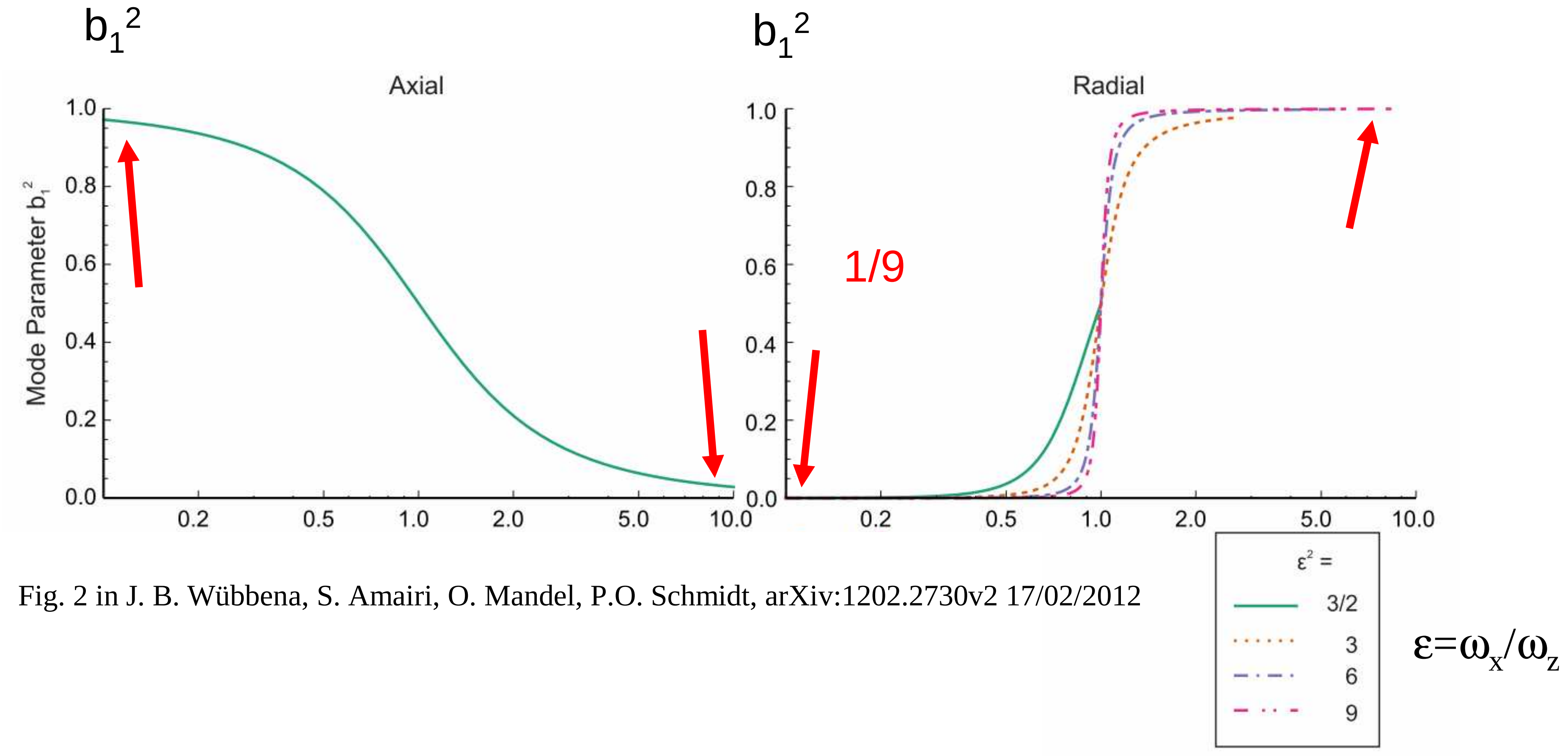


Fig. 2 in J. B. Wübbena, S. Amairi, O. Mandel, P.O. Schmidt, arXiv:1202.2730v2 17/02/2012

Design a ion pair trap with similar ω_z → planar microtrap

ω_x → dual RF trap

Conclusion

Doppler sympathetic cooling

capture seems realistic
needs intense simulations
captured $\overline{H}^+$ with K range final temperatures

100 - 1000 threads

Ion pair trap design

dual frequency RF planar microtrap

Mainz group

313 nm cooling laser : on the way

$\left\{ \begin{array}{l} H_2^+ \\ \text{HCI} \\ \text{Gbar} \end{array} \right.$