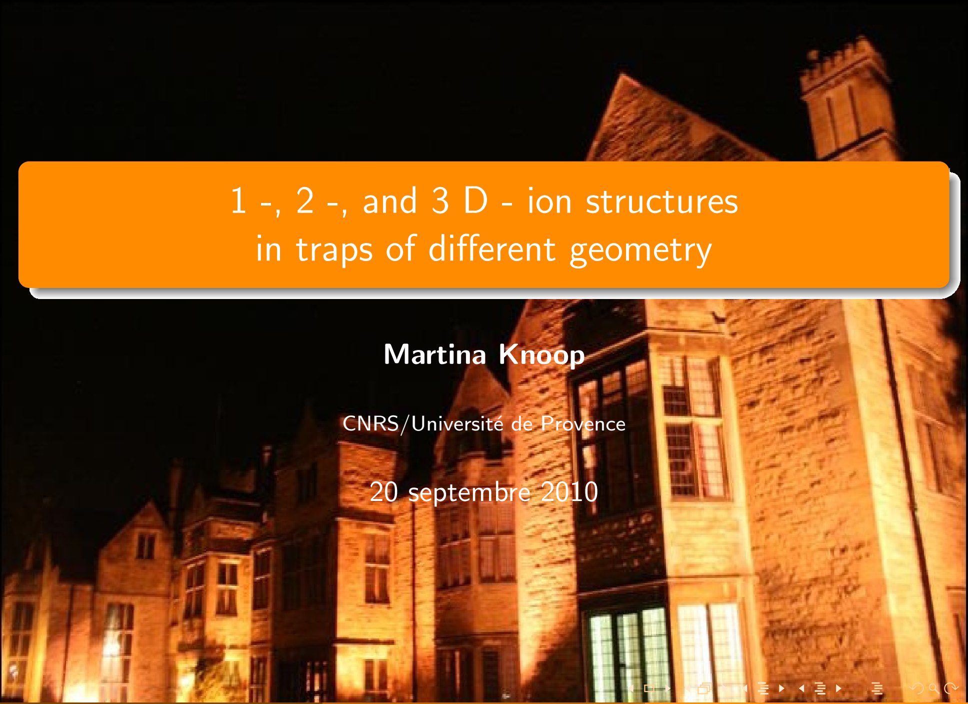


1 -, 2 -, and 3 D - ion structures in traps of different geometry

Martina Knoop

CNRS/Université de Provence

20 septembre 2010

Motivation

Dynamics of large ion clouds

- ion numbers from a few particles to 10 million ;
- to study long-range interactions ;
- in a highly controlled environment ;
- for metrological applications (micro-wave) ;

Motivation

Dynamics of large ion clouds

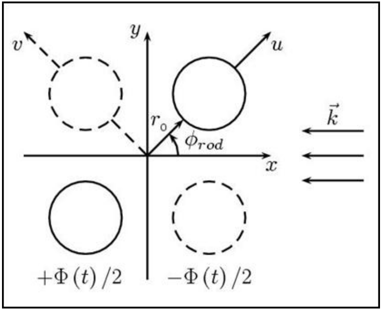
- ion numbers from a few particles to 10 million ;
- to study long-range interactions ;
- in a highly controlled environment ;
- for metrological applications (micro-wave) ;

Outline

1. Numerical simulations
2. Experiment

Molecular Dynamics

- time is divided in steps δt
- for each $t_j = j\delta t$ all the forces $\overrightarrow{F}[x(t_j)]$ are calculated *(trapping, Coulomb, etc)*
- position and velocity for every ion at time t_{j+1}
- integration algorithm Velocity Verlet



Environment

- ideal potential
- negligible residual pressure
- Coulomb interaction
- homogeneous laser beam profile

Modeling of laser cooling

Ion-laser interaction at EACH time step and for EACH ion

TEST : Excitation of the ion ?

NO

TEST : Excitation ?

$$rdm < \frac{1}{2} \frac{\Omega_r^2/2}{\left(\delta\omega_l + \vec{k}\cdot\vec{v}\right)^2 + (\gamma_0/2)^2 + \Omega_r^2/2}$$

If YES

$$\vec{v} = \vec{v} - \frac{\hbar k}{m}\hat{x}$$

$$\gamma_0 \gg \omega_r ; \frac{\hbar k^2}{2m}$$

YES

TEST : De-excitation ?

$$rdm > exp(-\gamma_0 \Delta t_{ex})$$

If YES

$$\vec{v} = \vec{v} + \frac{\hbar k}{m}\hat{u}$$

où $\hat{u} \in \overrightarrow{rdm}(sphere)$ et $|\hat{u}| = 1$

R. Blümel et al., Nature **334**, 309 (1988)

Numerical simulations

Examples

1. Laser cooling with a single laser beam
    - in a linear quadrupole trap
    - cloud size > 35 ions

Numerical simulations

Examples

1. Laser cooling with a single laser beam
   - in a linear quadrupole trap
   - cloud size $>$ 35 ions

2. Ion rings in a multipole trap
   - in a linear octupole trap
   - more than 10 ions
   - for metrology ?

Cooling dynamics of an ion cloud in a linear quadrupole

$$V_{lin} = [V_{st} + V_r cos(\Omega t)]\,(r/r_0)^2 + V_z(2z^2 - r^2)/z_0^2$$

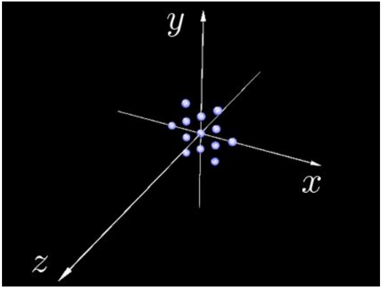
Laser cooling dynamics

- different crystal structures (T=0K) J. P. Schiffer, Phys. Rev. Lett. 70, 818 (1993)
- heating in a plane orthogonal to the laser beam

D. J. Wineland and W. M. Itano, Phys. Rev. A 20, 1521 (1979)
G. C. Hegerfeldt and A. W. Vogt, Phys. Rev. A 41, 2610 (1990)

In a linear quadrupole trap

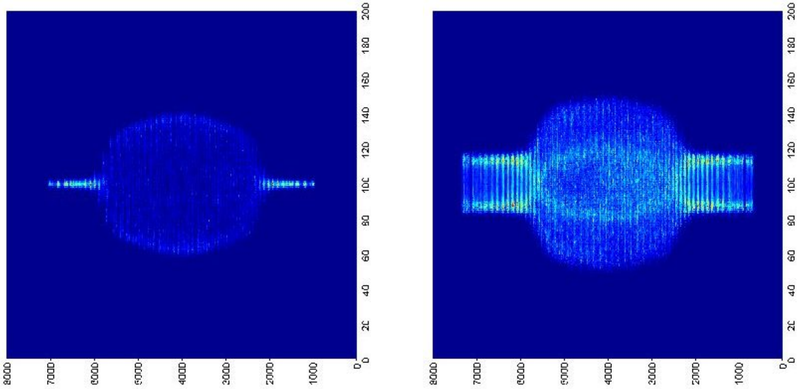
- $\alpha = (\omega_z/\omega_r)^2$
- for $\alpha \nearrow$
  structures 1D $\rightarrow$ 2D $\rightarrow$ 3D $\rightarrow$ 2D



Coupling efficiency in the pseudo-potential

$\alpha = (\omega_z/\omega_r)^2$

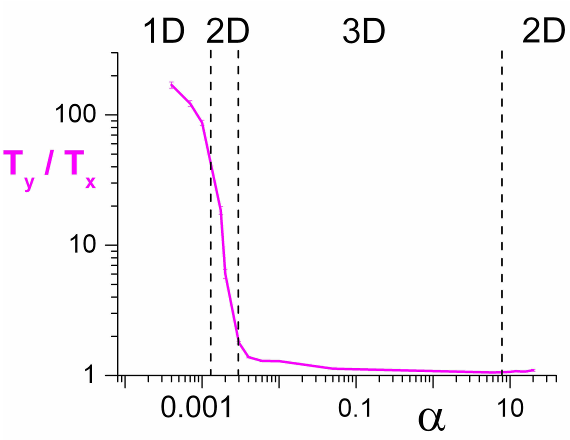
70-ion cloud, pseudo-potential, $\alpha = 10^{-3}$, laser along x



xz **yz**

Coupling efficiency in the pseudo-potential

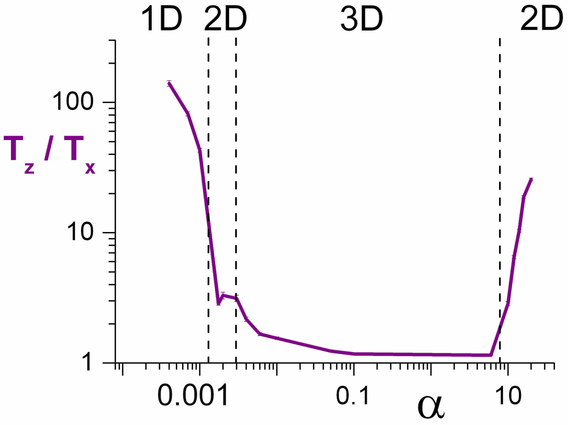
$\alpha = (\omega_z/\omega_r)^2$



M. Marciante, et al. Phys. Rev. A 82, 033406 (2010), arXiv :1004.5202v1 [physics.atom-ph]

Coupling efficiency in the pseudo-potential

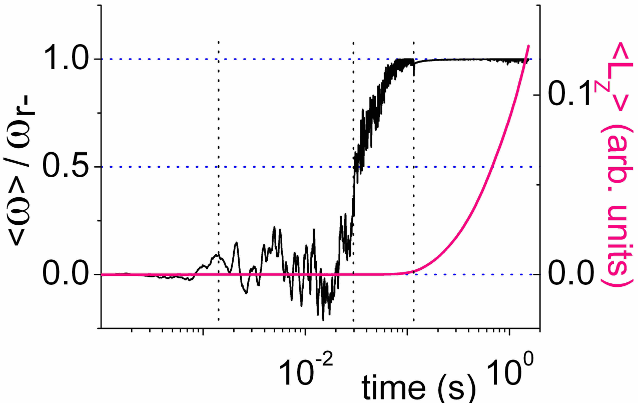
$\alpha = (\omega_z/\omega_r)^2$



M. Marciante, et al. Phys. Rev. A 82, 033406 (2010), arXiv :1004.5202v1 [physics.atom-ph]

Coupling efficiency in the rf potential

$\alpha = (\omega_z/\omega_r)^2$

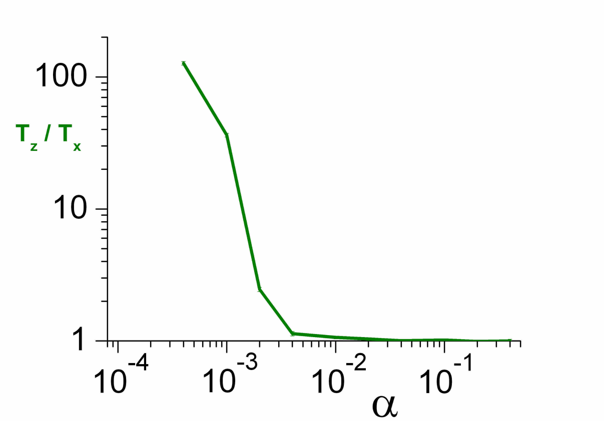


M. Marciante, et al. Phys. Rev. A 82, 033406 (2010), arXiv :1004.5202v1 [physics.atom-ph]

Coupling efficiency in the rf potential

$\alpha = (\omega_z/\omega_r)^2$

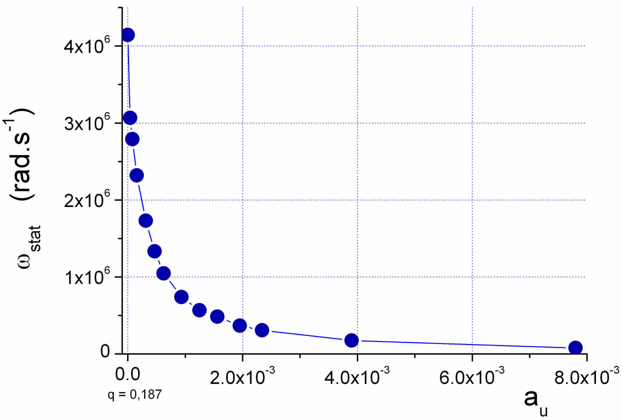
with $a_u = 8 \times 10^{-3}$ $(T_y/T_x \simeq 1)$



M. Marciante, et al. Phys. Rev. A 82, 033406 (2010), arXiv :1004.5202v1 [physics.atom-ph]

Coupling efficiency in the rf potential

$\alpha = (\omega_z/\omega_r)^2$



M. Marciante, et al. Phys. Rev. A 82, 033406 (2010), arXiv :1004.5202v1 [physics.atom-ph]

Numerical simulations

Examples

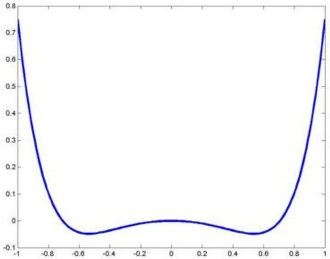
1. Laser cooling with a single laser beam
    - in a linear quadrupole trap
    - cloud size $>$ 35 ions
2. Ion rings in a multipole trap
    - in a linear octupole trap
    - more than 10 ions
    - for metrology ?

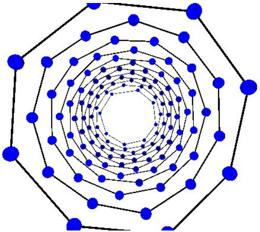
Multipole potential

$$V_{multipole} = V^*(r) + V_{stat}$$

$$\text{with } V^*(r) = \frac{k^2 q^2 V_0^2}{16 m \Omega^2 r_0^2} \left(\frac{r}{r_0}\right)^{2k-2} \text{ and } V_{stat} = \frac{1}{2} m \omega_z^2 \left(z^2 - \frac{r^2}{2}\right)$$

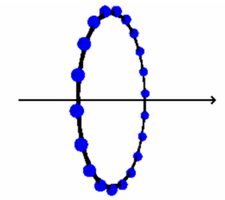
Octupole pseudo-potential well





Ion rings

For 20 Ca^+-ions with $\omega_z/2\pi = 1$ MHz and $\Omega_z/2\pi = 20$ MHz

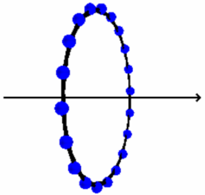


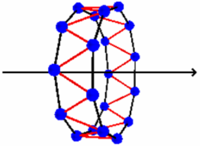
$V_0 = 3142V$ and $r_0 = 400\mu m$
$\Rightarrow r_{min} > R_l$,
the one-ring configuration is stable
(R $= 28\mu m$).

C. Champenois, et al., Phys. Rev. A 81, 043410 (2010), arXiv :1003.0763v1 [quant-ph]

Ion rings

For 20 Ca^+-ions with $\omega_z/2\pi = 1$ MHz and $\Omega_z/2\pi = 20$ MHz





$V_0 = 3142V$ and $r_0 = 400\mu m$
$\Rightarrow r_{min} > R_l$,
the one-ring configuration is stable (R $= 28\mu m$).

$V_0 = 5771V$ and $r_0 = 400\mu m$
$\Rightarrow r_{min} < R_l$,
stable double-ring configuration with a plane of separation 3 μm, (R $= 21\mu m$).

C. Champenois, et al., Phys. Rev. A 81, 043410 (2010), arXiv :1003.0763v1 [quant-ph]

An ion ring for precision spectroscopy

For a 10-ion ring ; $R = 20\mu m$ | For a 20-ion ring ; $R = 40\mu m$

effect	conditions	long term instability
Doppler(2^e)	$R = 20\mu m$	8×10^{-17}
Stark	$R = 20\mu m$	6×10^{-17}
Doppler(2^e)	$R = 40\mu m$	5×10^{-17}
Stark	$R = 40\mu m$	3×10^{-17}
Zeeman	$\delta B \leq 6 \times 10^{-7}$ G	2.5×10^{-15}
BBR	$T = 300 \pm 10$ K	$< 10^{-16}$
quadrupole	trapping field	$\leq 10^{-17}$
quadrupole	extra dc	$\leq 10^{-16}$
total	$R = 20\mu m$	2.5×10^{-15}
total	$R = 40\mu m$	2.5×10^{-15}

C. Champenois, et al., Phys. Rev. A 81, 043410 (2010), arXiv :1003.0763v1 [quant-ph]

Experimental set-up

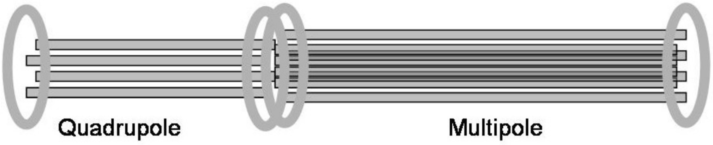
Linear ion trap(s)

- very large cloud (10^7ions)
- different trapping potentials
- open structure for optical access

Double trap

Potential

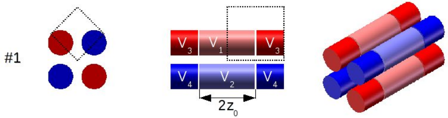
PI : $V_2(r) = \frac{q^2 V_0^2}{m\Omega^2 r_0^2} r^2$ PII : $V_k(r) = \frac{k^2}{16} \frac{q^2 V_0^2}{m\Omega^2 r_0^2} r^{2k-2}$ $2k$-pole

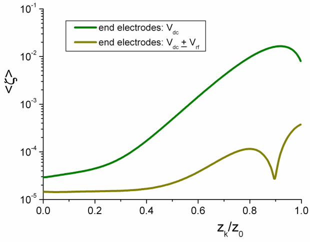


Shuttling of the ions

Minimization of anharmonic contributions

$$\phi(x,y) = C_0 + Real\left\{\sum_{m=0}^{\infty} C_{(4m+2)}\xi^{(4m+2)}\right\}; \qquad \xi = x + iy$$

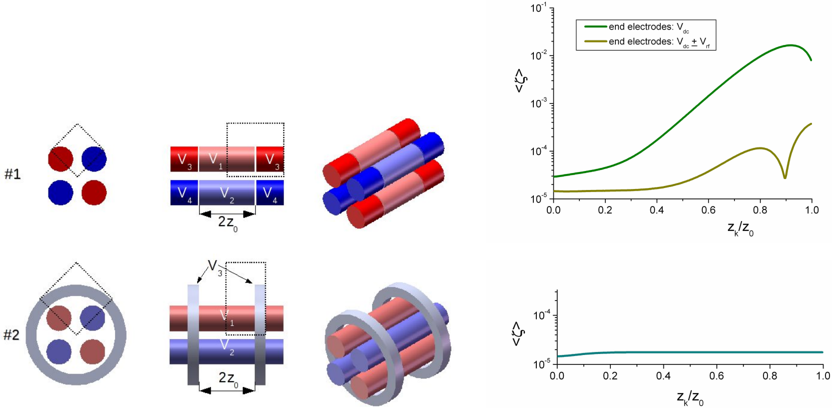




J. Pedregosa et al.,International Journal of Mass Spectrometry 290, 100-105 (2010), arXiv :1001.1403v1[physics.ins-det]

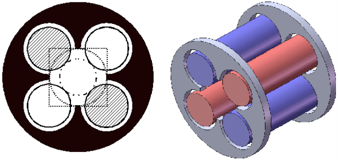
Minimization of anharmonic contributions

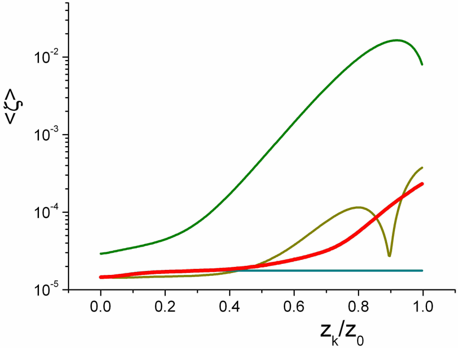
$$\phi(x,y) = C_0 + Real\left\{\sum_{m=0}^{\infty} C_{(4m+2)}\xi^{(4m+2)}\right\}; \qquad \xi = x + iy$$



J. Pedregosa et al.,International Journal of Mass Spectrometry 290, 100-105 (2010), arXiv :1001.1403v1[physics.ins-det]

Hybrid Electrode Geometry

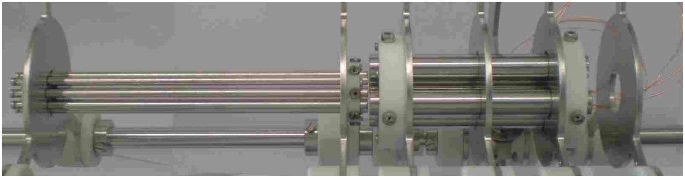




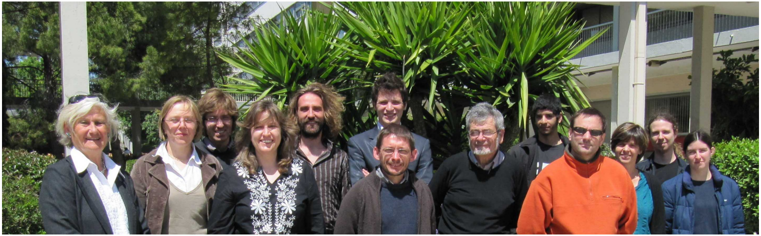
J. Pedregosa et al.,International Journal of Mass Spectrometry 290, 100-105 (2010), arXiv :1001.1403v1[physics.ins-det]

Experiment

Double trap, quad + octupole



Credit



PIIM

Mathieu Marciante
Annette Calisti, *plasma physics*
Caroline Champenois
Gaëtan Hagel
Marie Houssin
Olivier Morizot [POSTER]
Jofre Pedregosa [POSTER]
MK
F Vedel, *M Vedel*

Collaboration

Masatoshi Kajita, NICT/Jpn

€€€

Agence Nationale de la Recherche, CNES, Région Provence-Alpes-Côte d'Azur

Discussion - Tuesday 14h

n + 1

The speed of light