Ecole Thématique FTMS 2018
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Orbitrap Mass Analyzer (how does it work ??)

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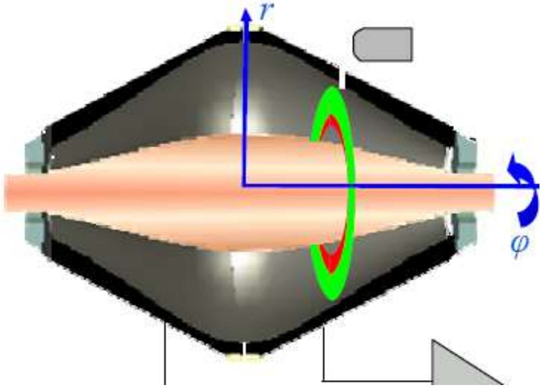
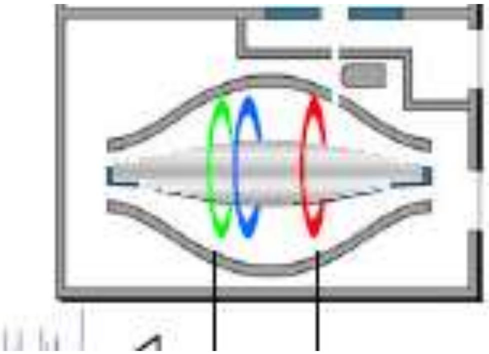
Plan (1:30)

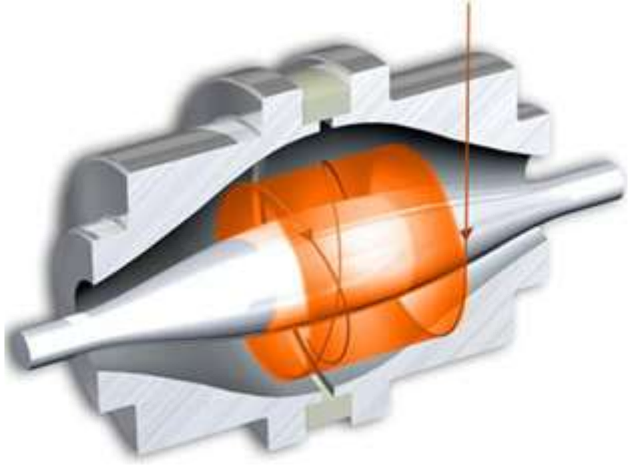
1. Introduction
   a. SIMION, a tool to simulate ionic trajectories on PC, a tool to understand what is happening in your instrument
   b. Representation of Orbitrap in SIMION
2. Birth of the Orbitrap concept, historical steps ;
   a. Other types of electrostatic ion traps
   b. 1923 : the Kingdon trap
   c. 1981 : the Knight trap
   d. 1996 : the ideal Gillig trap
   e. 2000 : the Orbitrap of A. Makarov
3. Physical principle behind the measurement concept,
   a. The harmonic oscillator
   b. The important process of injection: how to enter a perfect medium ?
   c. Pulsed injection - Importance of the C-TRAP
   d. How much is pressure ?
4. Orbitrap, simulation of performances in SIMION
   a. Illustration of the FFT
   b. Dephasing during injection
   c. (In)sensitivity to source effects
5. Evolutions of Orbitrap
   a. Improvement of performances
   b. Manipulation of ions in Orbitrap
   c. Cassinian analyser
   d. Spacebound instrument, Cosmorbitrap
   e. Isotopic measurements with orbitrap ?

I. Introduction

Representations of orbitrap and ionic trajectories: great diversity







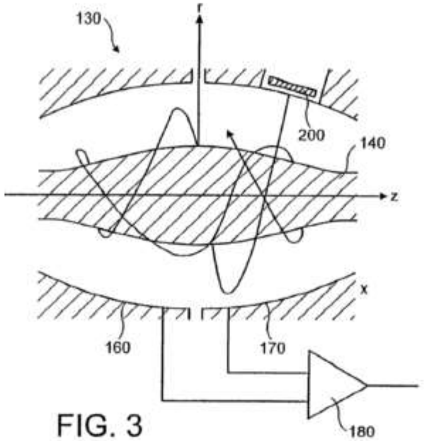
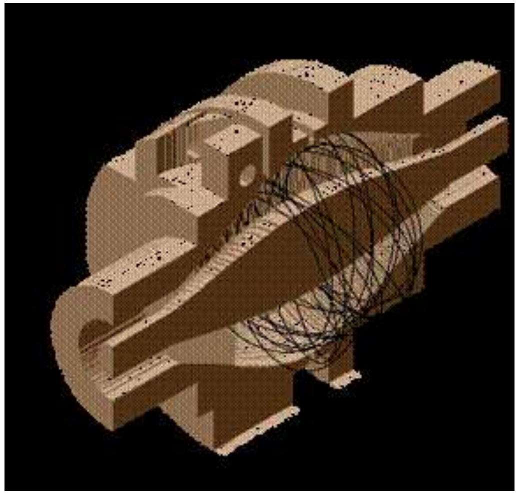
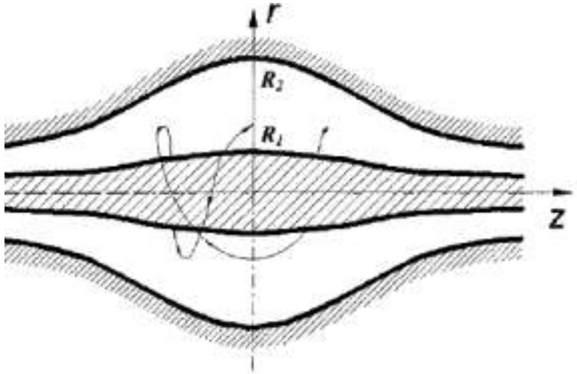


FIG. 3





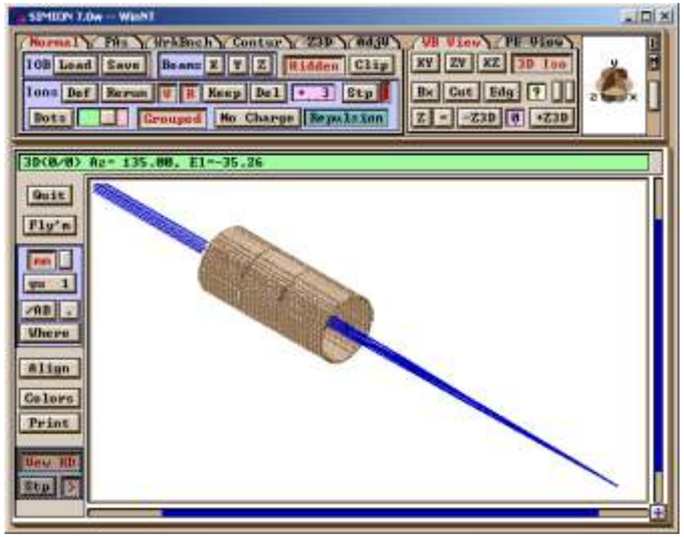
SIMION, nice tool to apprehend the behaviour of charged particle inside electromagnetic device

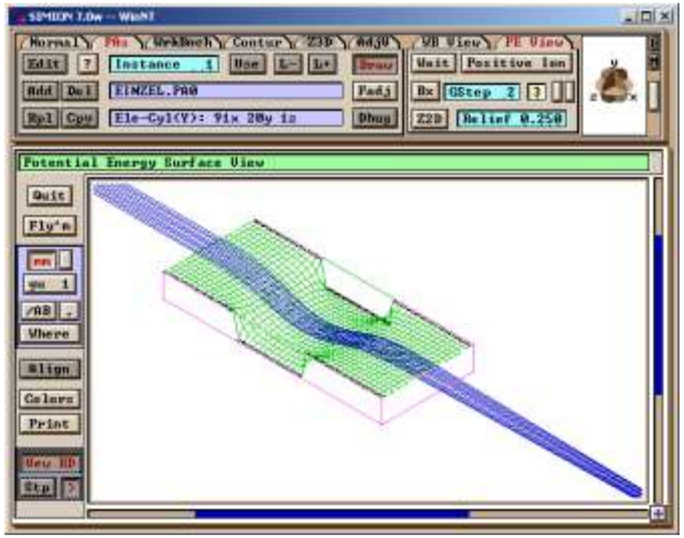
Simion is a software simulating ion optics by calculating the local fields (E and B) in 3D matrix and able to launch charged paticles to simulate trajectories.

Solves the Laplace equation in a 3D space with constant grid size.
Can propagate ions

- calculation of local field and associated Force applied to the ion
- calculation of the acceleration induced by the Force on ion
- propagate the ion with time steps inversely proportional to the local field strength
- Scriptable, therefore possible to perform time dependent modulation of elements (RF, pulsed voltage, etc)

Software developed since 1970.

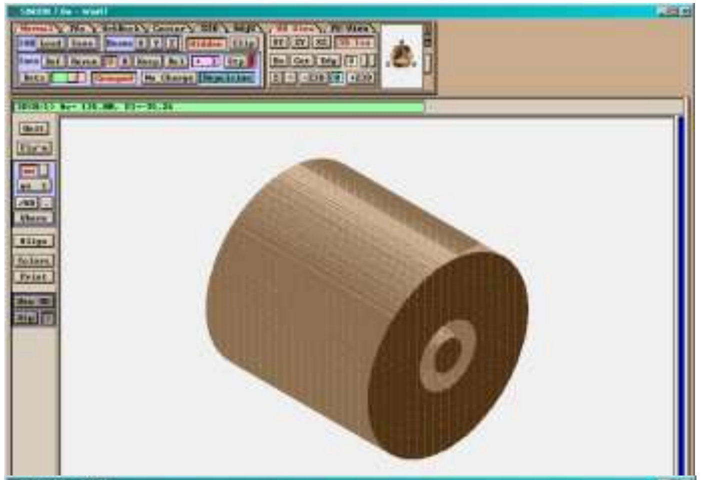


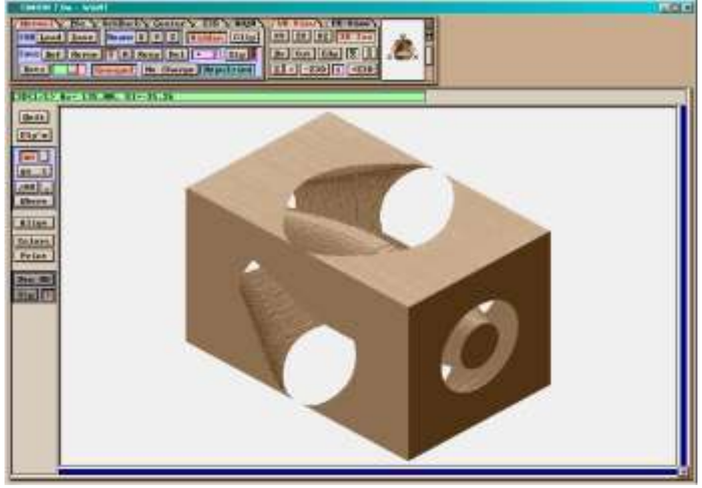


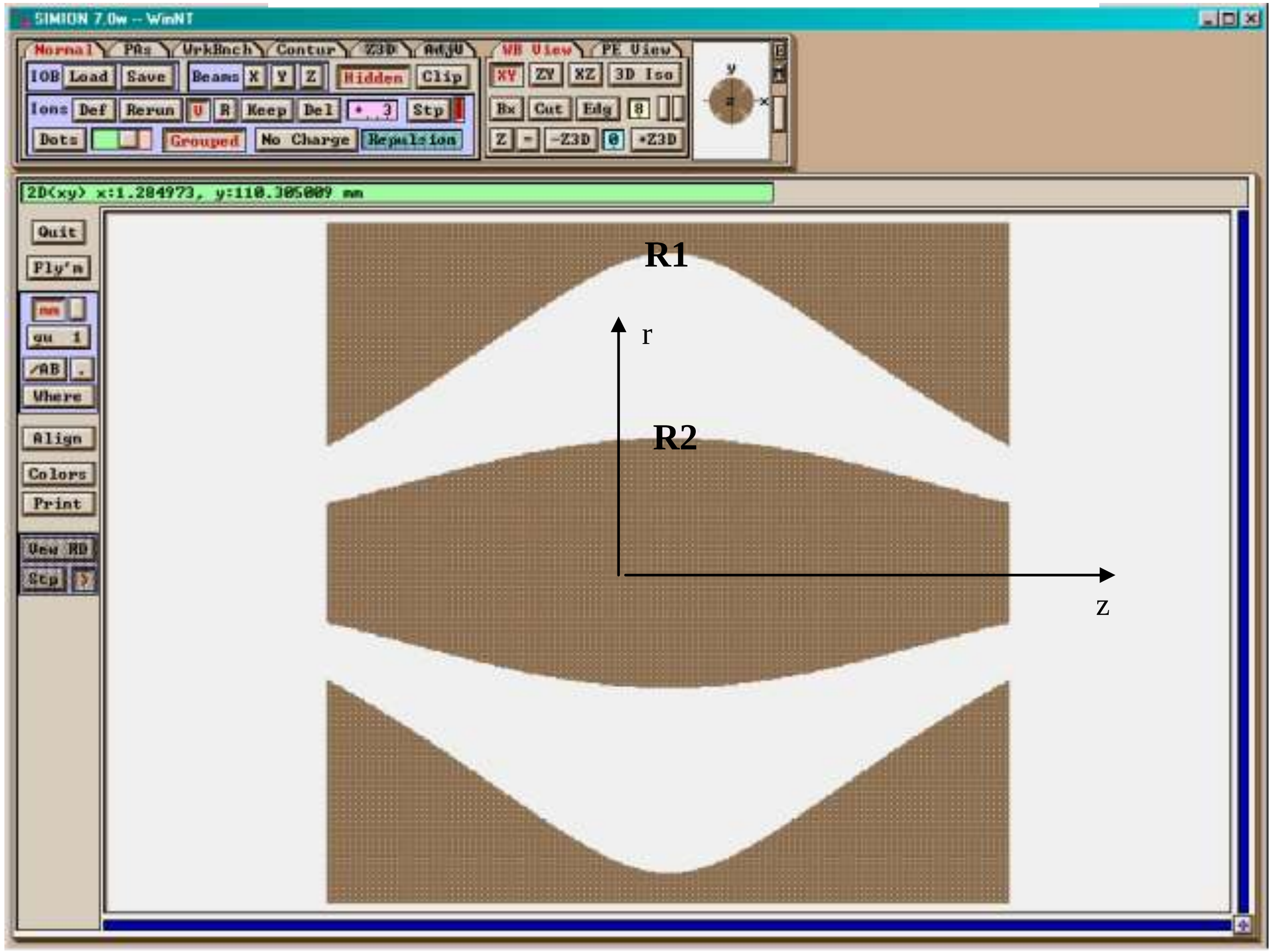
Dahl, D. (2000). "SIMION for the personal computer in reflection". International Journal of Mass Spectrometry 200 (1-3): 3.

Representation of Orbitrap in SIMION

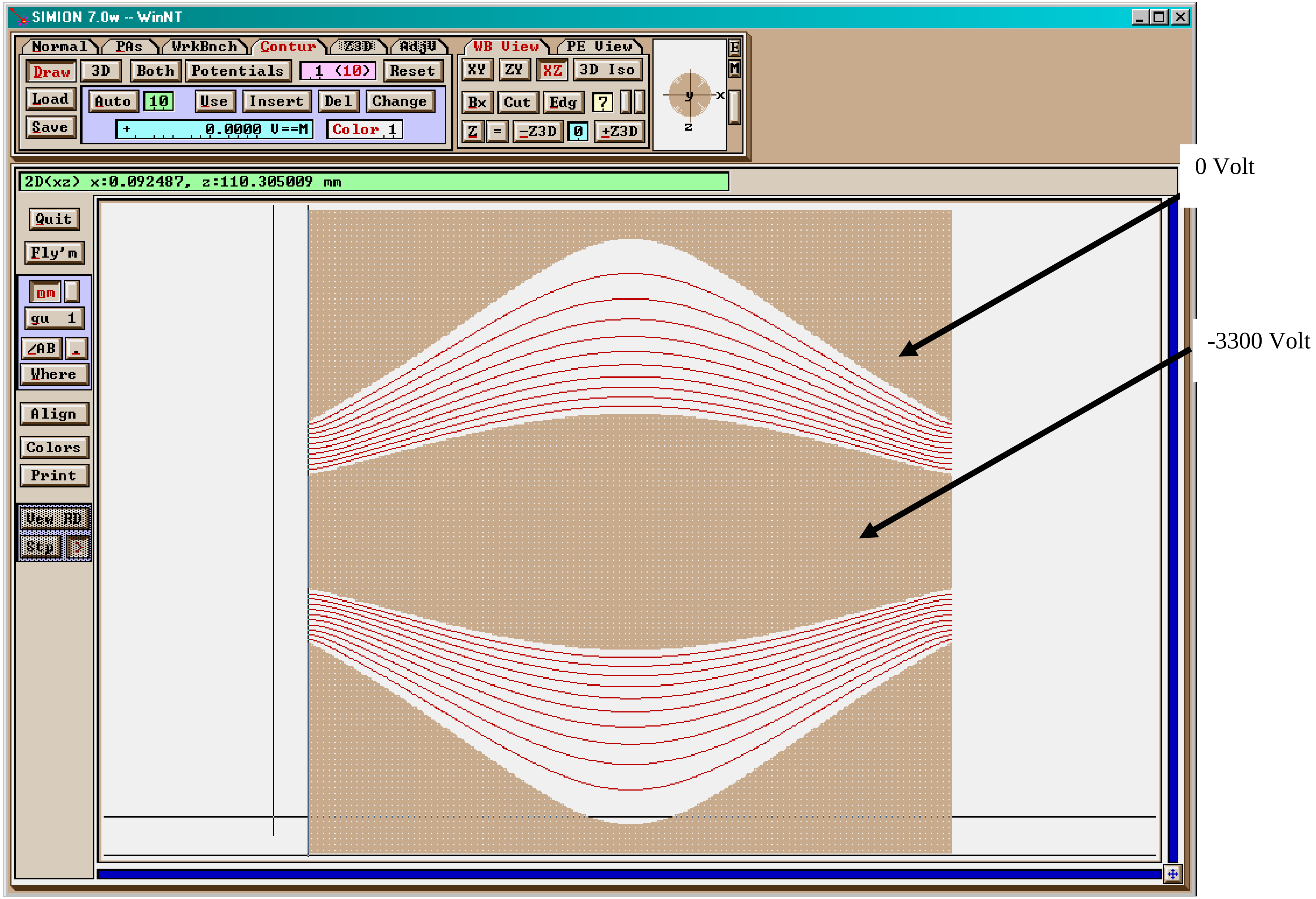
Shape the 2 electrodes according to the law: $$z_{1,2}(r)=\sqrt{\frac{r^2}{2}-\frac{(R_{1,2})^2}{2}+(R_m)^2\ln\left[\frac{R_{1,2}}{r}\right]}$$







2D(xy) x:1.284973, y:110.305009 mm



2D(xz) x:0.092487, z:110.305009 mm

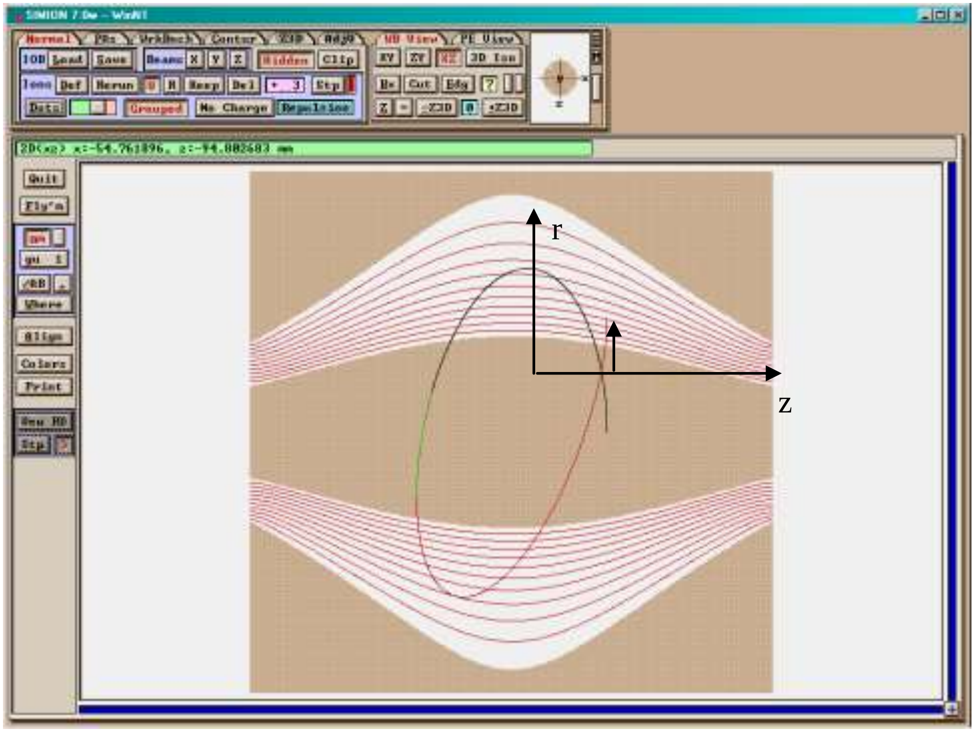
0 Volt

-3300 Volt

We launch 3 cations:

masse/charge 100, 400 et 600
energy: 1730 eV
initial z > 0
initial r median between the 2 electrodes
tangent to local field lines

All ions have exactly similar trajectory, the only difference is in the velocity at which ions of different masses travel in the Orbitrap



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2D(xz) x:-54.761896, z:-94.882683 mm
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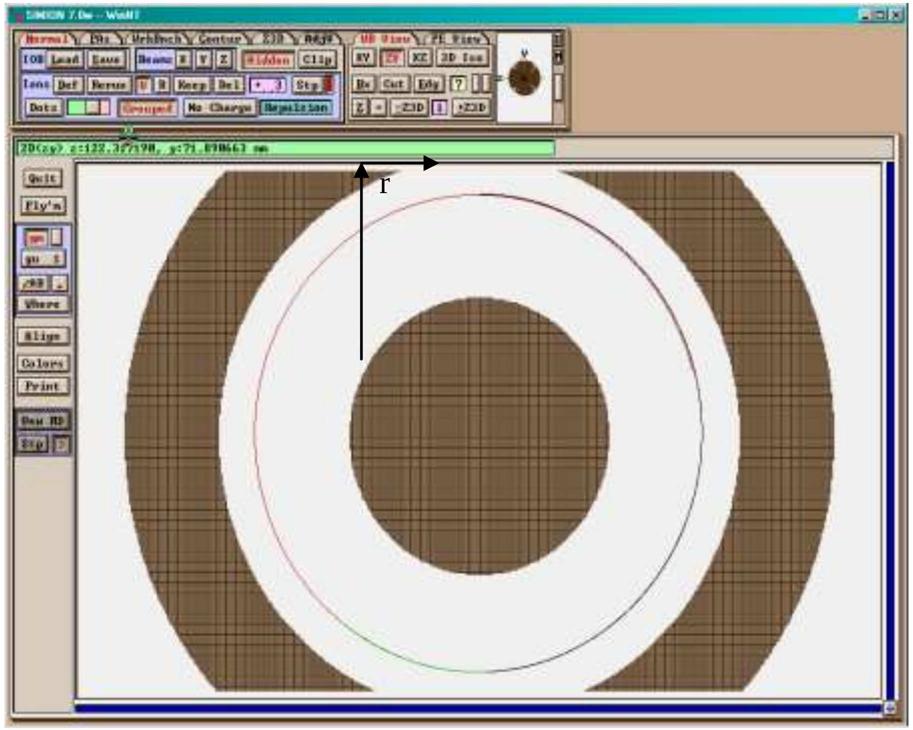

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2D(zy) z:122.377190, y:71.898663 mm
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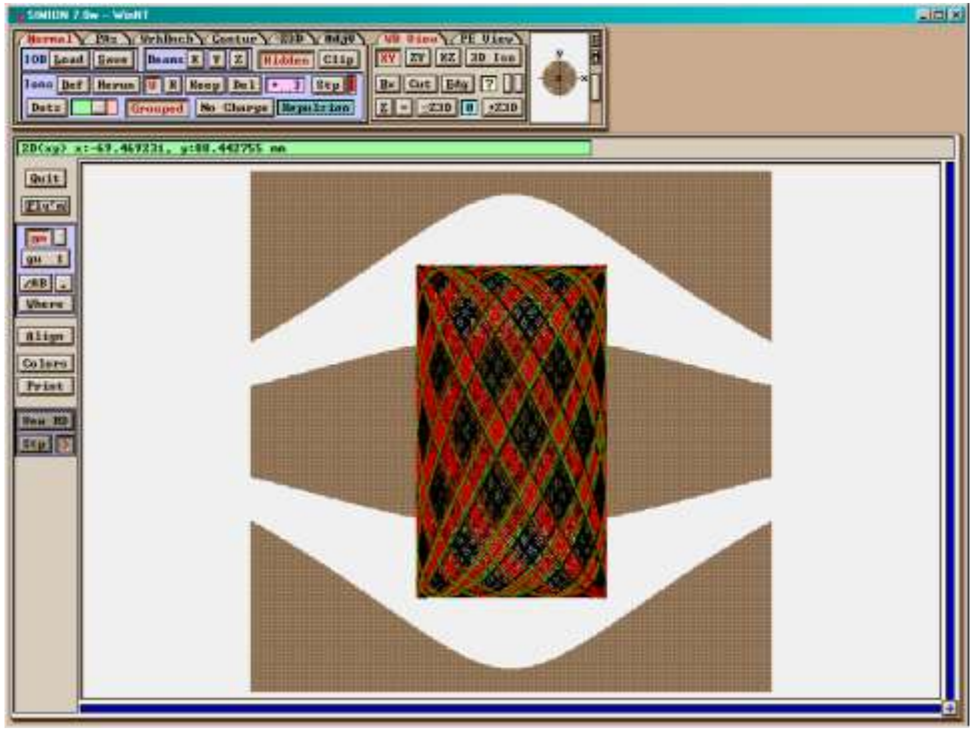
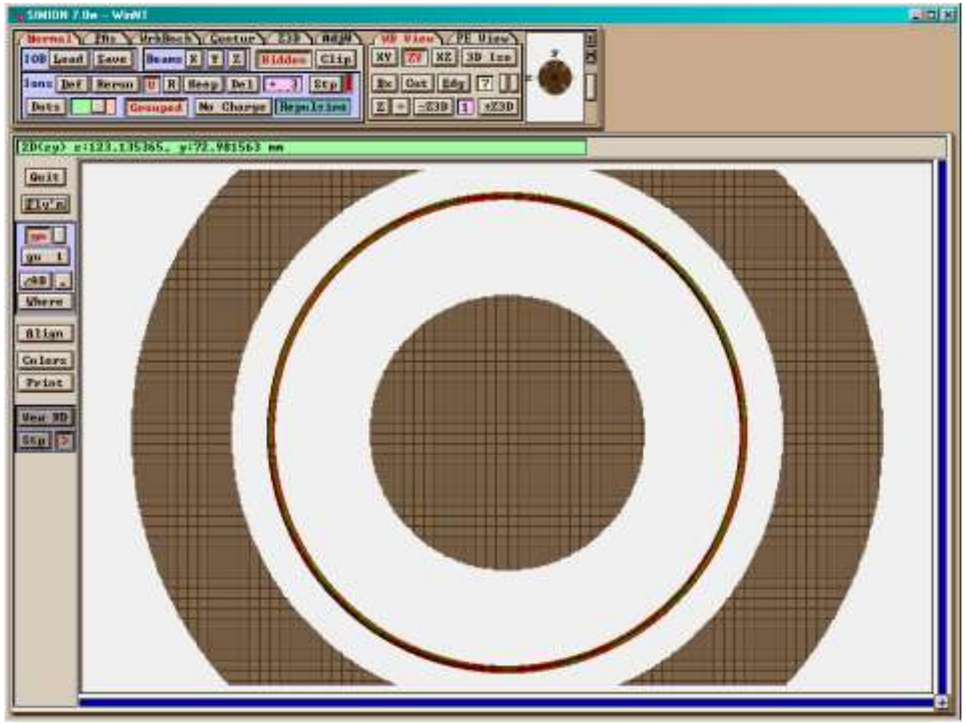
Let’s wait longer :

Trajectories build up in a kind of cylinder with constant diameter, ions bounce between the two extremities, the frequency of this oscillation is inversely proportional to the ionic m/z



2D(xy) x:-69.469231, y:88.442755 mm



2D(zy) z:123.135365, y:72.981563 mm

IIa. Other Electrostatic analyzers

2a) other types of electrostatic ion de traps

A) Linear electrostatic ion trap:

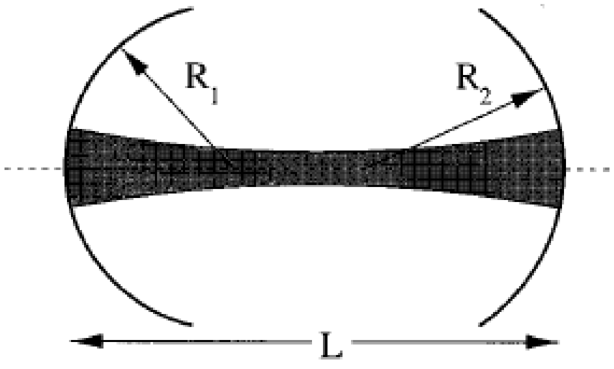
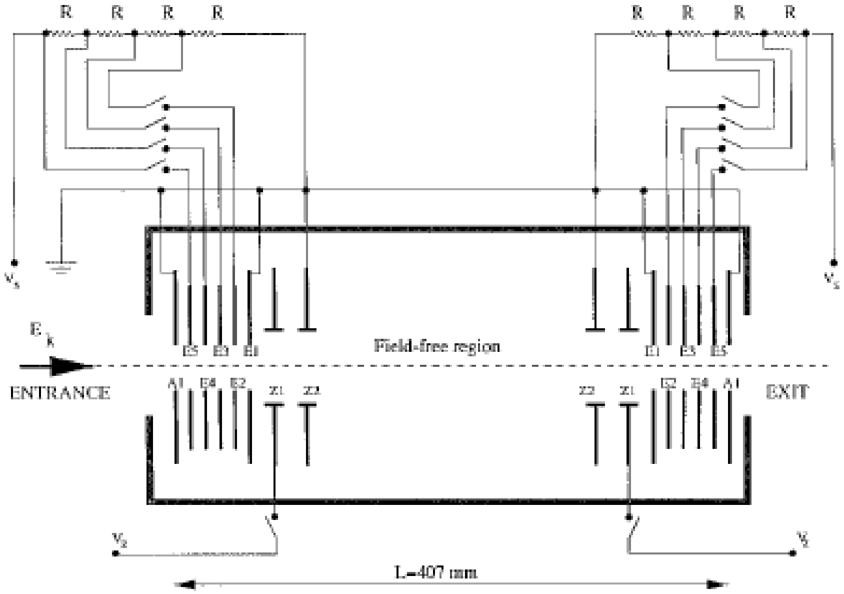


FIG. 1. Optical resonator with mirror curvatures R_1 and R_2.

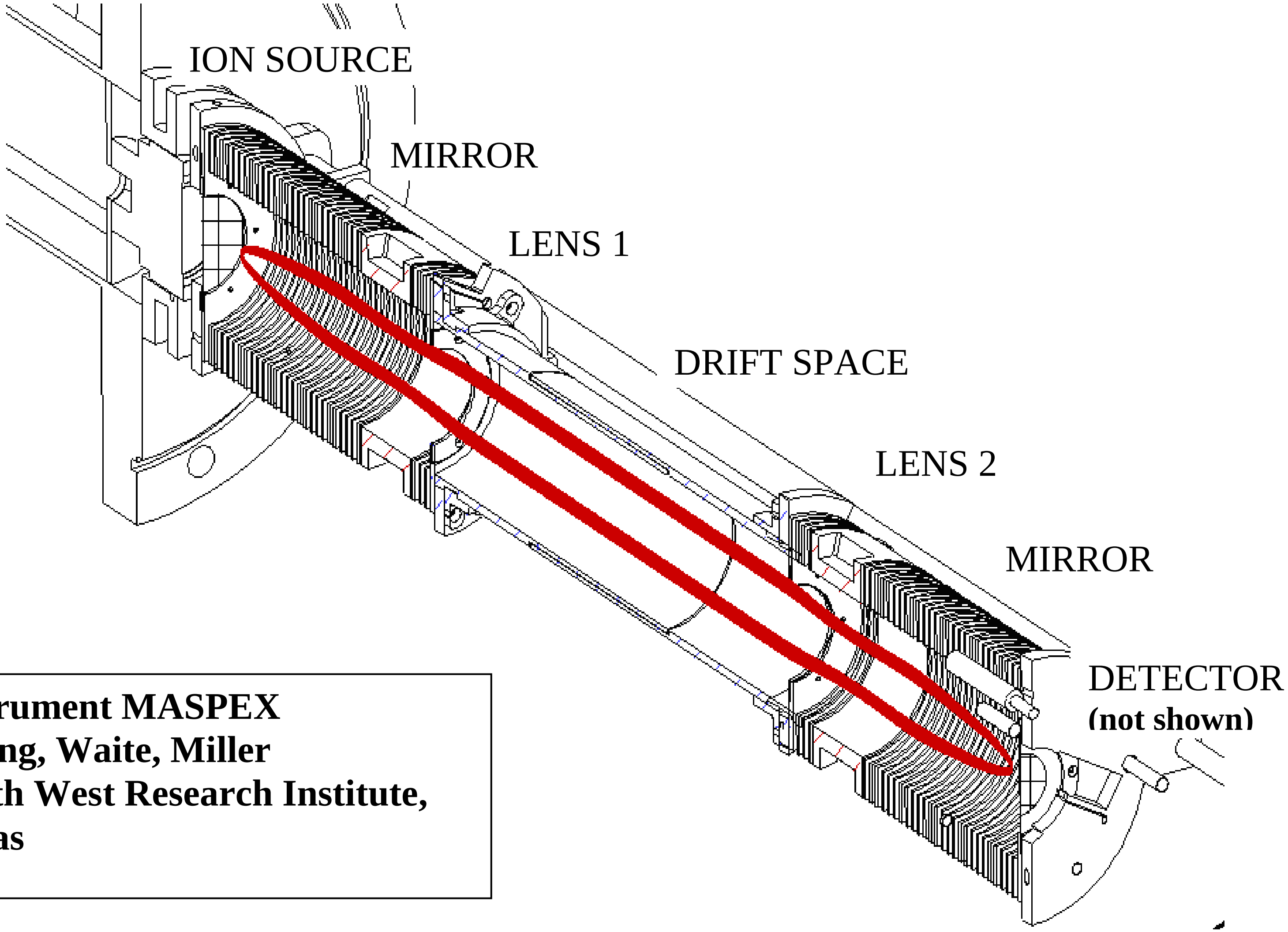
$$0 \leqslant \left(1-\frac{L}{R_1}\right)\left(1-\frac{L}{R_2}\right) \leqslant 1. \qquad (1)$$



1) able to store de ions with energies > KeV.
2) main use: storage of ions & measurement of cross sections for production of neutral products (which exit the set-up on axis)
3) possible mass analysis, but with limited mass range (see after)

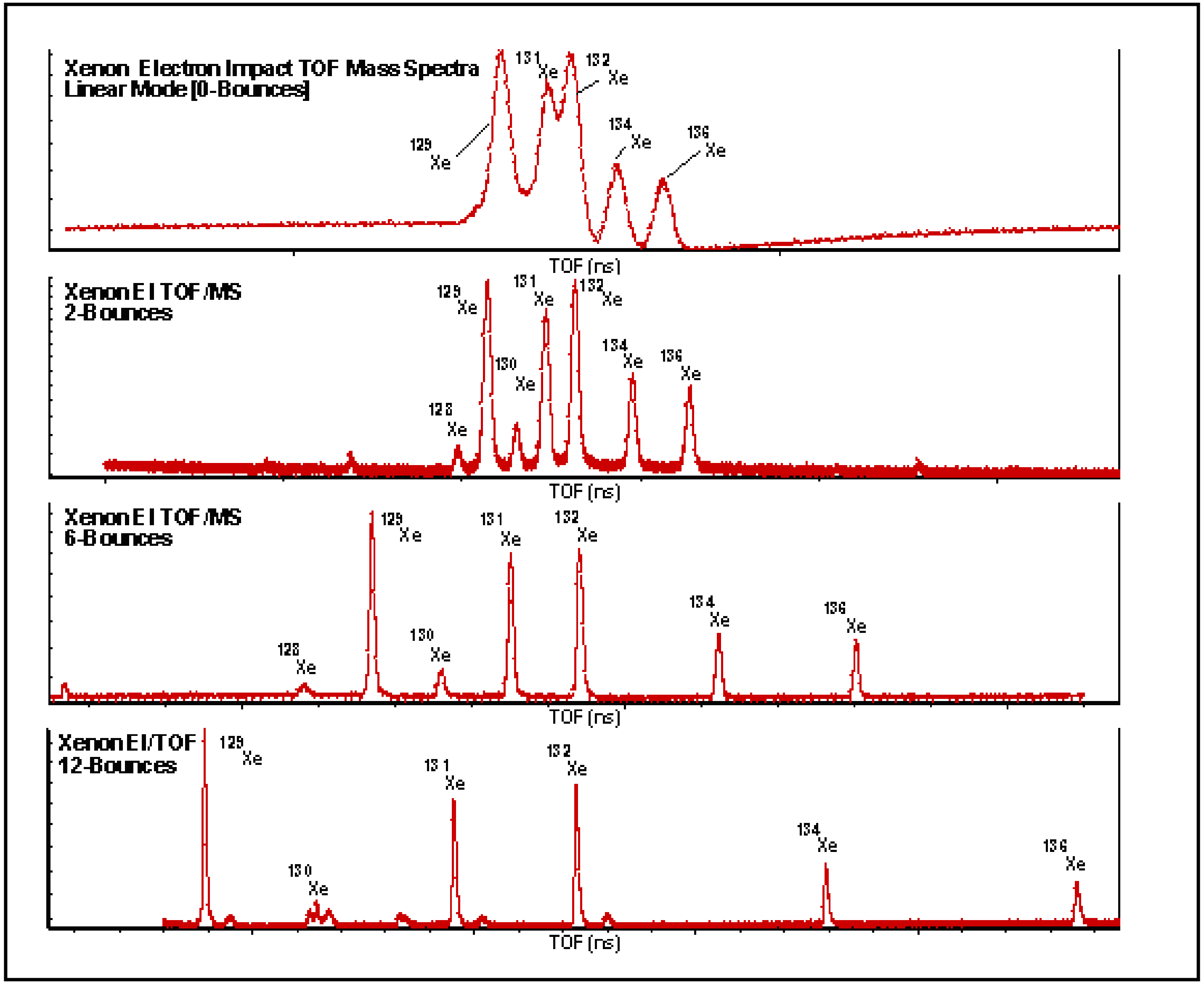
International Journal of Mass Spectrometry and Ion Processes, 131 (1994), 387-407 H. Wollnik

Example for space exploration



Instrument MASPEX
Young, Waite, Miller
South West Research Institute,
Texas

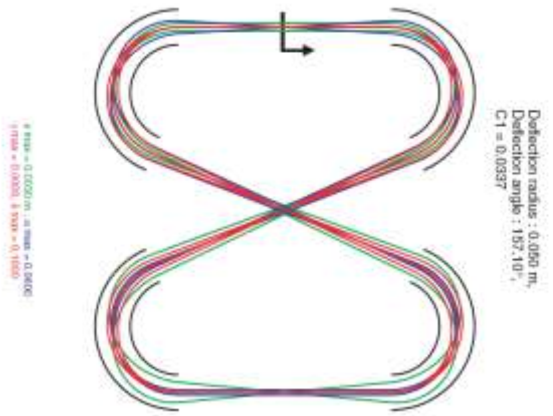
Illustration of the effect of bounce number on the resolving power

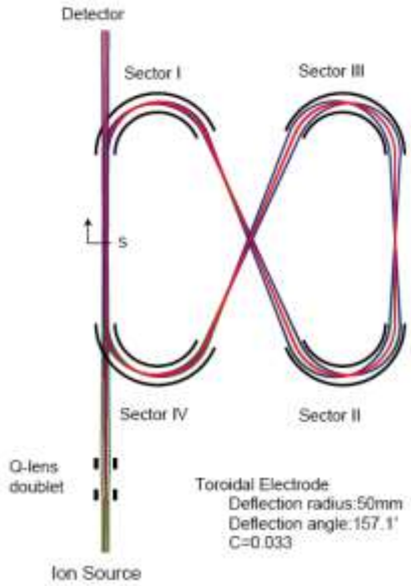


B) trap by electrostatic sectors: MULTUM

Nuclear Instruments and Methods in Physics Research Section A: 427 (1999), 182-186
T. Sakurai, H. Nakabushi, T. Hiasa, K. Okanishi

Design similar to nuclear physic storage rings.



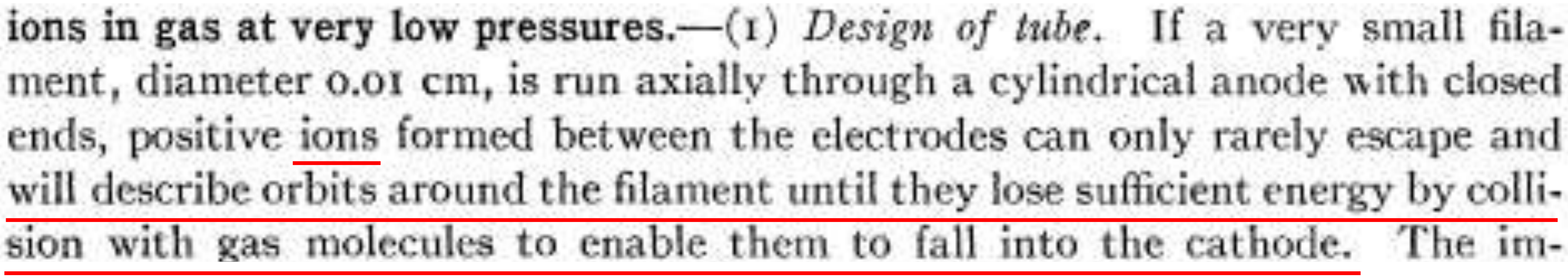


Few examples of real usage

IIb. Historical steps

2b) 1923 : the Kingdon trap

K.H. Kingdon, Phys. Rev. 21, 408 - 418 (1923)



ions in gas at very low pressures.—(1) *Design of tube.* If a very small filament, diameter 0.01 cm, is run axially through a cylindrical anode with closed ends, positive ions formed between the electrodes can only rarely escape and will describe orbits around the filament until they lose sufficient energy by collision with gas molecules to enable them to fall into the cathode. The im-

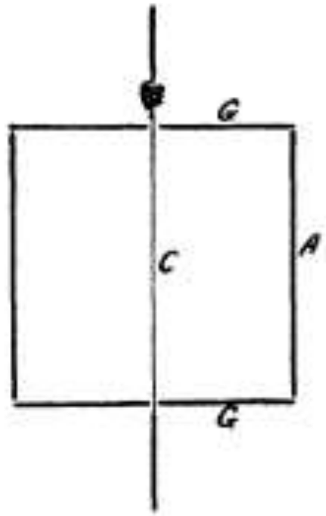


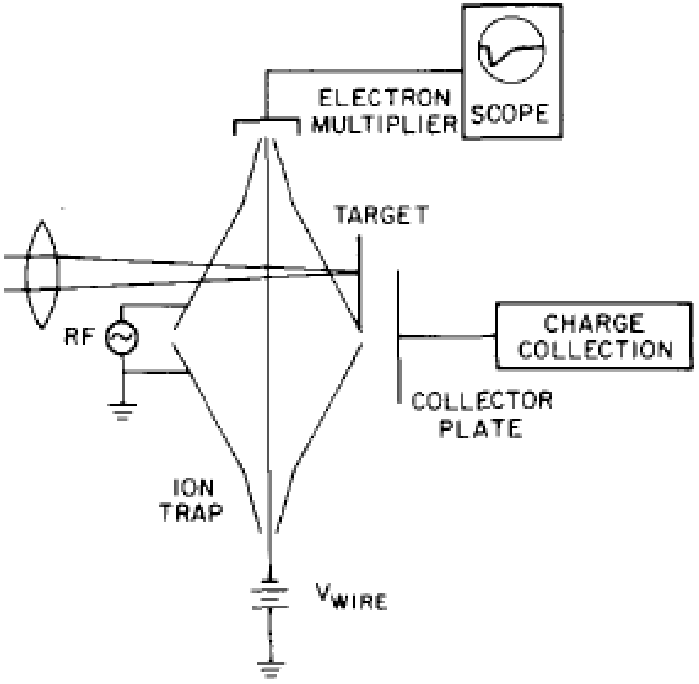
Fig. 1. Design of experimental tube.

2c) 1981 : the Knight trap

R.D. Knight Appl. Phys. Lett. 38, 221 (1981)

This work has been performed with an electrostatic ion trap based on the cylindrically symmetric potential

$$\phi = A\,(z^2 - r^2/2 + B\ \ln r). \qquad (1)$$



but:
central electrode is still a wire
external electrode is very simple design with grids

the potential is far from the ideal formula, and therefore the performances are limited

However, demonstration of mass analysis,

2d) 1996 : The Gillig ideal trap (SIMULATION by SIMION)

the formalism of the Kingdon "ideal trap" – discovery of the benefit of "quadro log" field

International Journal of Mass Spectrometry and Ion Processes 157 (1996) 129-147
Ion motion in a Fourier transform ion cyclotron resonance wire ion guide cell
K.J.Gillig, B.K. Bluhm, D.H. Russell

$$V(r,z) = A\left(z^2 - r^2/2 + B\ln r\right)$$

$$\omega_z = \sqrt{\frac{kq}{m}}$$

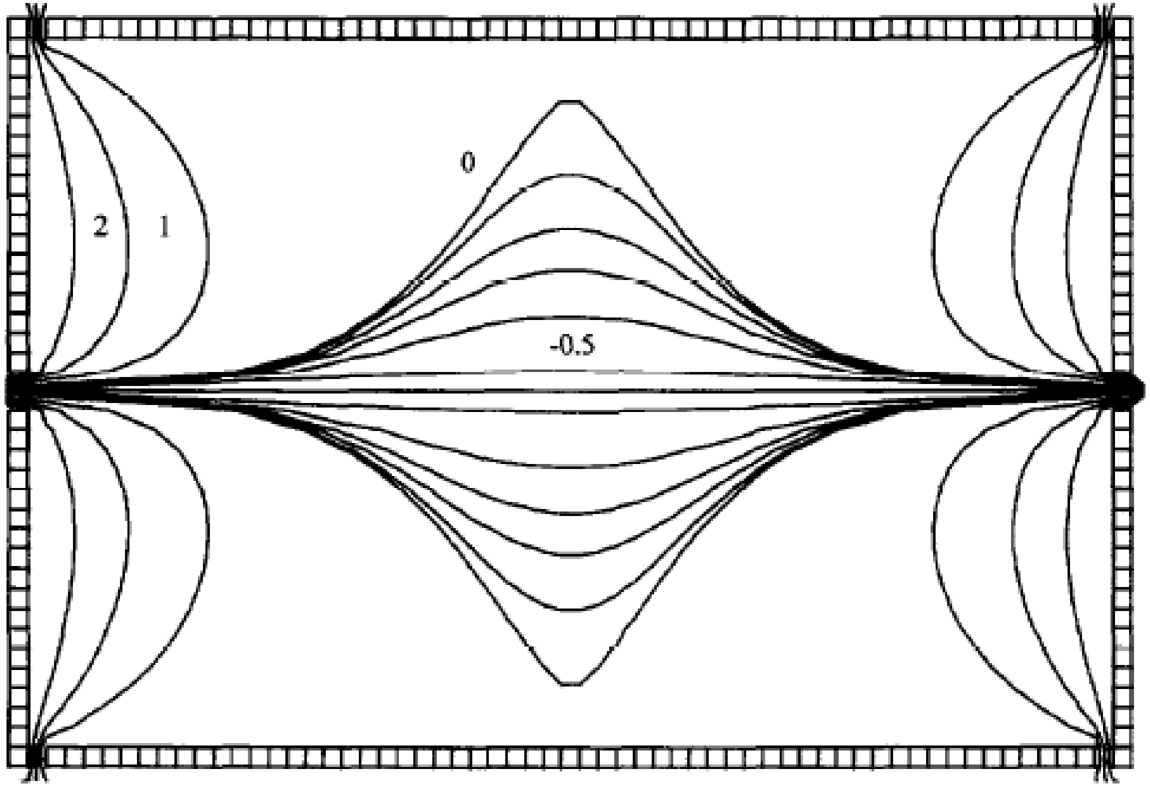


Fig. 6. (a) SIMION plot of equipotential lines for ideal Kingdon trap parameters, end plates at 14 V and wire at −1 V.

2d) 2000: Orbitrap of Makarov

Anal. Chem. 2000, 72, 1156-1162 Alexander Makarov
Electrostatic Axially Harmonic Orbital Trapping: A High-Performance Technique of Mass Analysis

$$U(r,z) = \frac{k}{2}\left(z^2 - \frac{r^2}{2}\right) + \frac{k}{2}(R_m)^2 \ln\left[\frac{r}{R_m}\right] + C$$

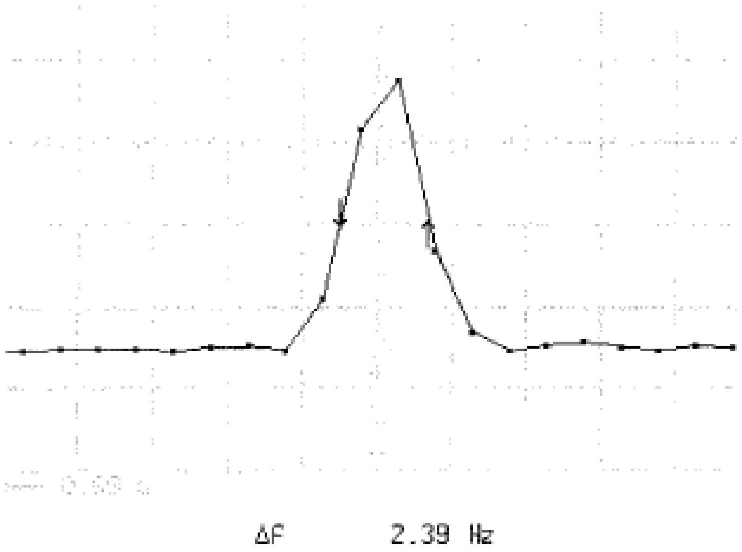
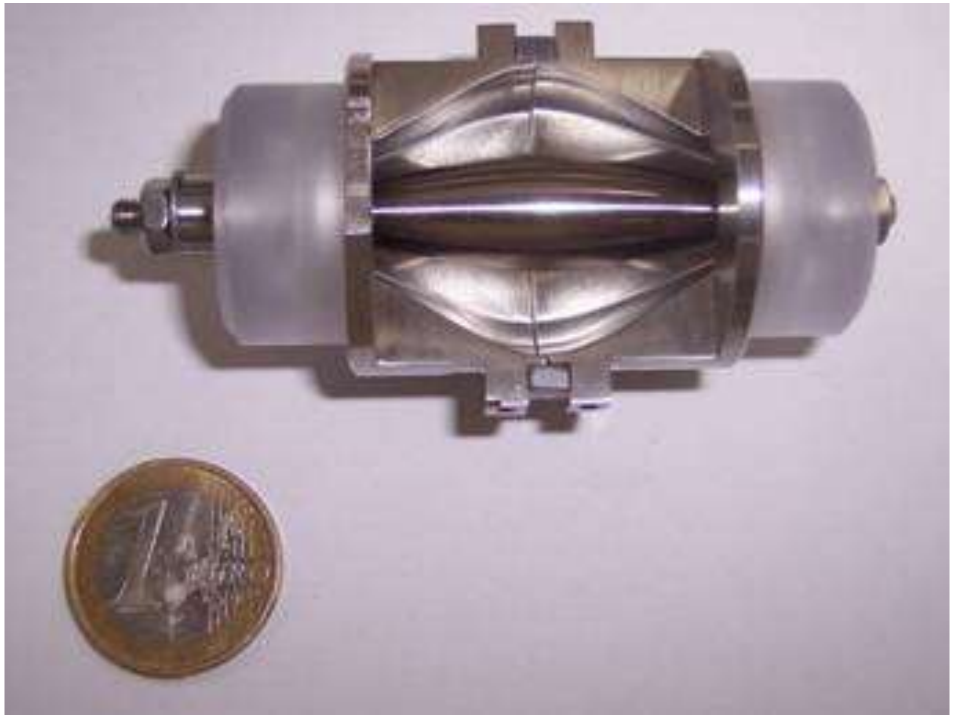


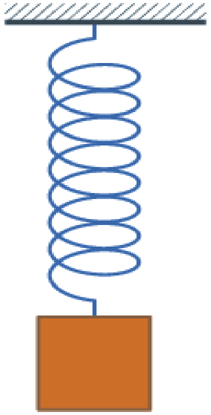
Figure 7. Mass peak of $^{56}Fe^+$ in the frequency domain (peak centroid is at 711 kHz).

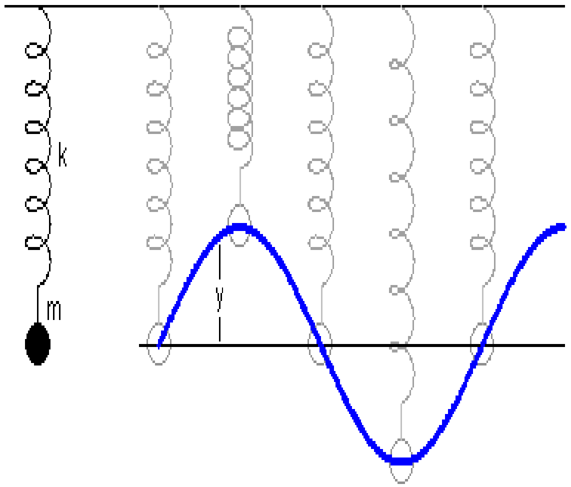


FWHM = 2.39 Hz à 711 000 Hz,
f/Δf= 300 000
M/ΔM= 150 000

III. Physical principles behind the measurement concept

3a) harmonic oscillator, example of the spring





$F = -kx$ k = constant, x = position

According to the second Newton law:

$F = ma = -kx$ “***a force accelerates mass***”

therefore $m\frac{\mathrm{d}^2x}{\mathrm{d}t^2} = -kx$

considering $\omega_0{}^2$ = k/m, the equation rearranges into:

$$\frac{\mathrm{d}^2x}{\mathrm{d}t^2} + \omega_0{}^2x = 0$$

Considering $\dot{x} = \frac{\mathrm{d}x}{\mathrm{d}t}$ then $\frac{\mathrm{d}^2x}{\mathrm{d}t^2} = \ddot{x} = \frac{\mathrm{d}\dot{x}}{\mathrm{d}t}\frac{\mathrm{d}x}{\mathrm{d}x} = \frac{\mathrm{d}\dot{x}}{\mathrm{d}x}\frac{\mathrm{d}x}{\mathrm{d}t} = \frac{\mathrm{d}\dot{x}}{\mathrm{d}x}\dot{x}$ replacing :

$$\mathrm{d}\dot{x}\cdot\dot{x} + \omega_0{}^2x\cdot\mathrm{d}x = 0$$

If we integrate this function :

$\dot{x}^2 + \omega_0{}^2x^2 = K$ we consider K= $(A.\omega_0)^2$ $\dot{x}^2 = A^2\omega_0{}^2 - \omega_0{}^2x^2$

Or $\dot{x} = \pm\omega_0\sqrt{A^2 - x^2}$

This integrate as $\begin{cases} \arcsin\frac{x}{A} = \omega_0 t + \phi \\ \arccos\frac{x}{A} = \omega_0 t + \phi \end{cases}$ the generic form of which is $x = A\sin(\omega_0 t + \phi)$

Therefore the frequency of oscillation is $f = \frac{\omega_0}{2\pi} = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$

Frequency depends only on mass and a (geometric) constant.

Orbitrap, in its axial dimension, is a harmonic oscillator.

$$U(r,z) = \underset{\text{quadro}}{\boxed{\frac{k}{2}\left(z^2 - \frac{r^2}{2}\right)}} + \underset{\text{logarithmic}}{\boxed{\frac{k}{2}(R_m)^2 \ln\left[\frac{r}{R_m}\right]}} + C$$

$$\left.\begin{aligned}
&\ddot{r} - r\dot{\varphi}^2 = -\frac{q}{m}\frac{k}{2}\left[\frac{(R_m)^2}{r} - r\right] && \text{(a)}\\
&\frac{\mathrm{d}}{\mathrm{d}t}(r^2\dot{\varphi}) = 0 && \text{(b)}\\
&\boxed{\ddot{z} = -\frac{q}{m}kz} && \text{(c)}
\end{aligned}\right\}$$

No transfer of movement between r and z

$$qE_z = (m/2)(\dot{z}_0)^2$$

$$z(t) = z_0 \cos(\omega t) + \sqrt{(2E_z/k)}\,\sin(\omega t)$$

The movement along Z is purely harmonic

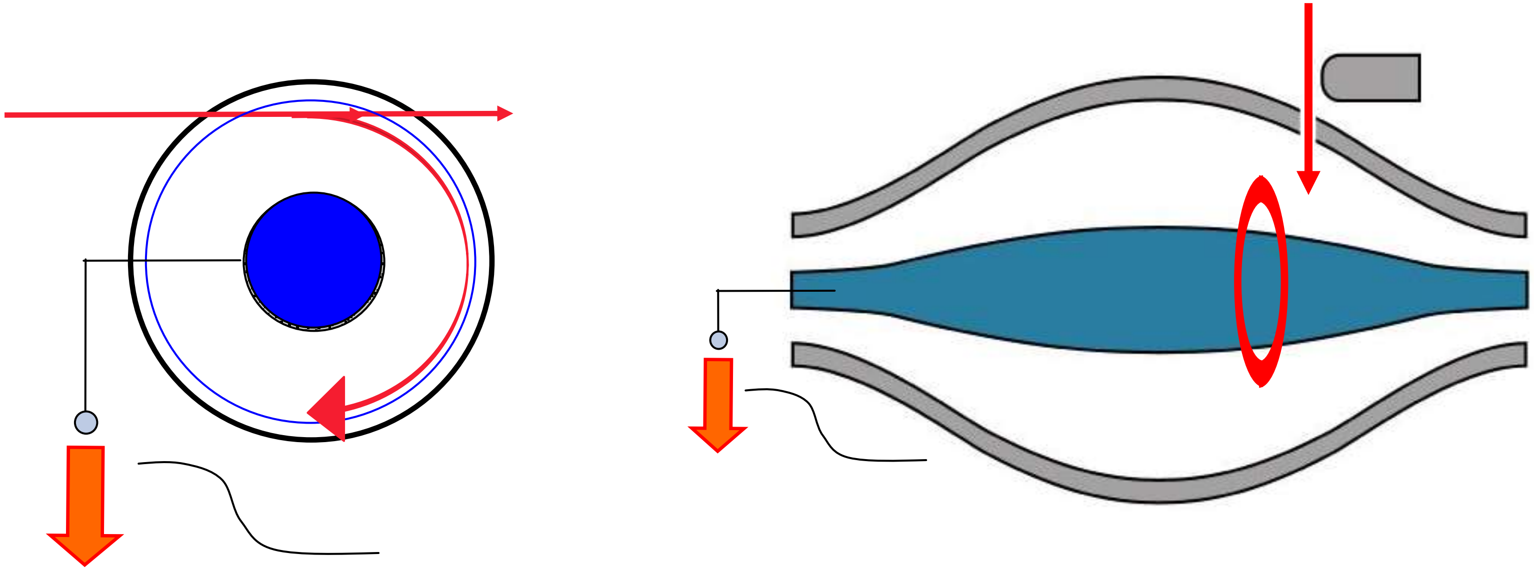
Its frequency is : $\omega = \sqrt{(q/m)k}$

3b) the process of injection

Trajectories are stable when inside Orbitrap, but how to bring ions into the « perfect field » ?

- **One has to inject ions as a well-defined bunch in time,**
- **One has to change the potential in the trap at the same time of injection**

This is “Electrodynamic Squeezing”



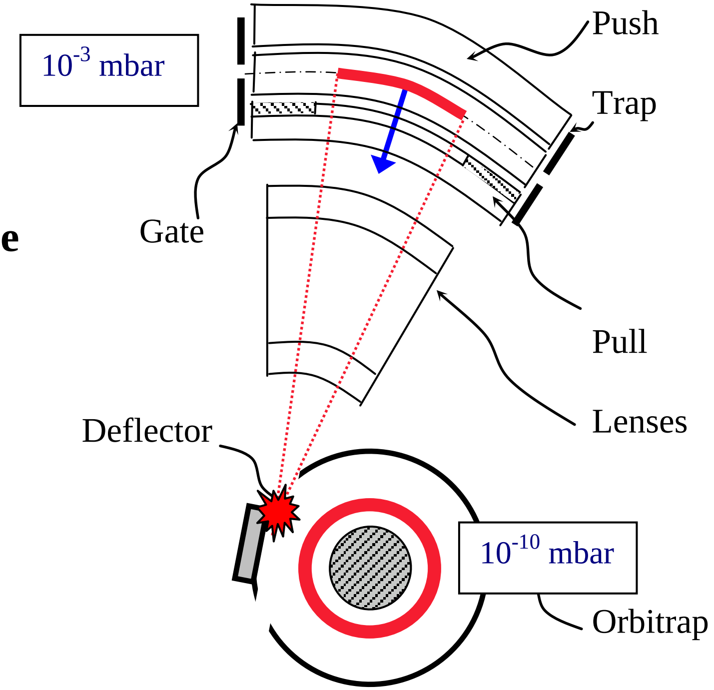
3c) Pulsed injection:

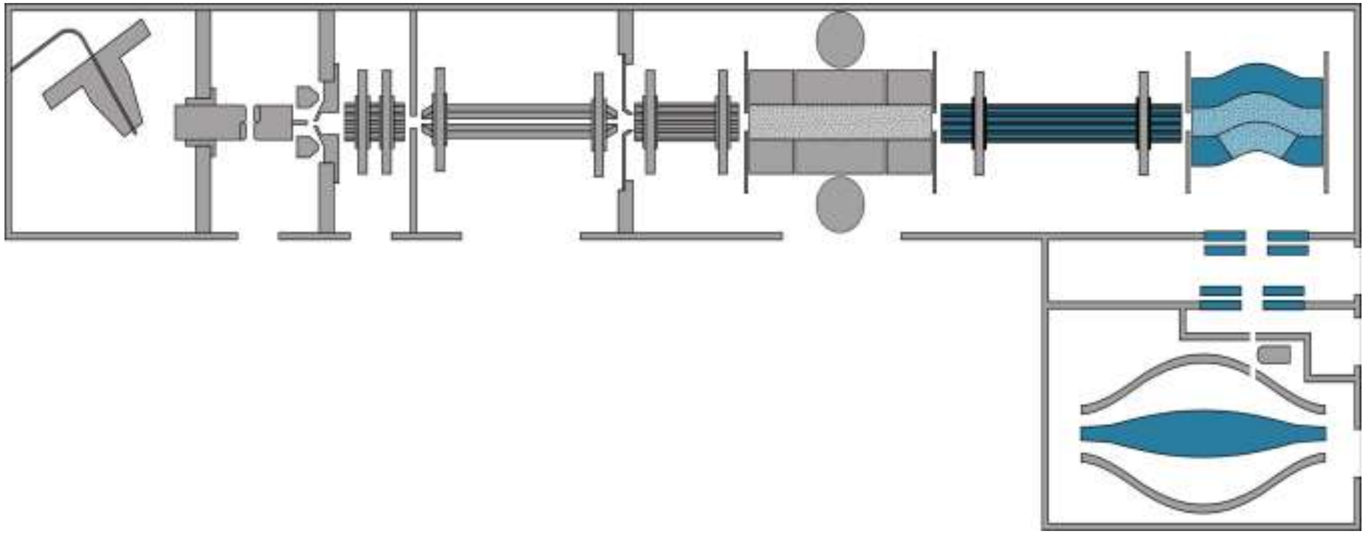
Explains the systematic usage of “C-trap”

One thermalises ions in “C-trap”
One pulses ions out of C-trap

Shape of C-trap induces natural focalisation of ions in the Entrance hole of orbitrap (1mm)

TOF effect, light ions are first to enter orbitrap





Vacuum inside Orbitrap, why 10^{-10} mbar

Exercise to be done during the lesson.

You have to answer 3 questions

1) How many molecules per cubic meter at such pressure ?
2) What is the mean free path of an ion at such pressure ?
3) What is the distance that an ion of m/z 400 with 1000eV kinetic energy travels in1 second?

Usefull information :

Avogadro number Na : 6.10^{23} molecules/mol
Gas constant : 0,08 litre.atm/K.mol

Molecular radius to consider : 10 Angstrom
1 Mass unit : $1, 66.10^{-27}$ kg
1eV : $1,6.10^{-19}$ Joule

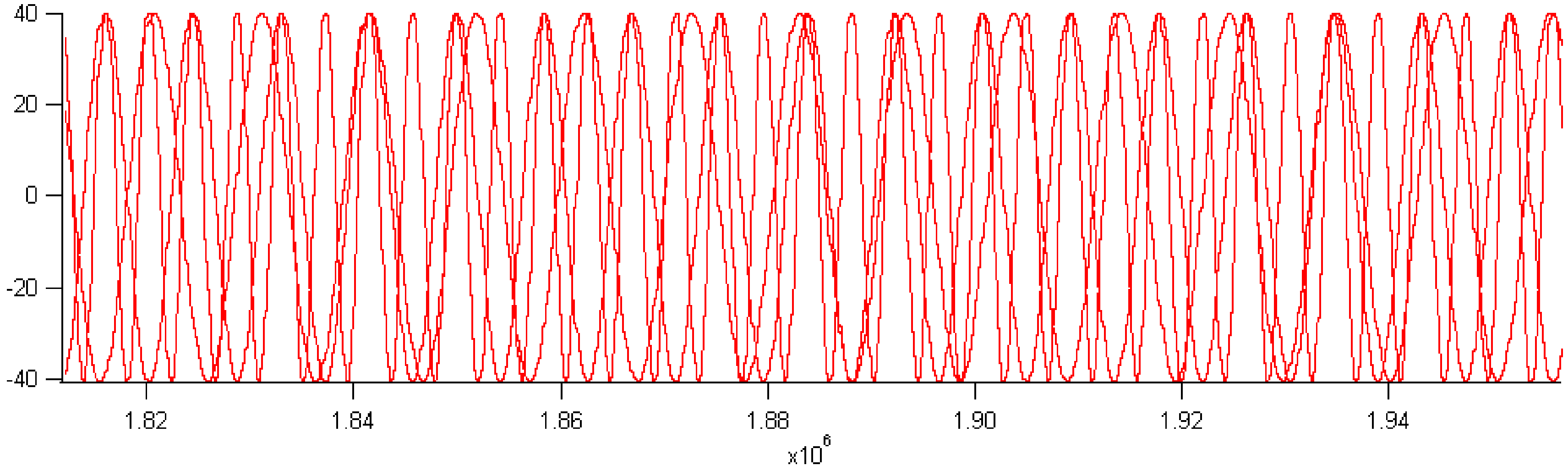
IV. Simulations of Orbitrap performances with SIMION

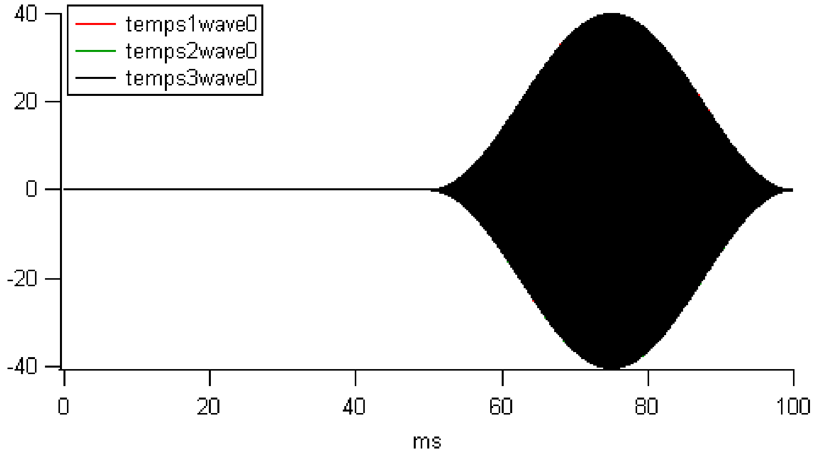
4) illustrations with SIMION

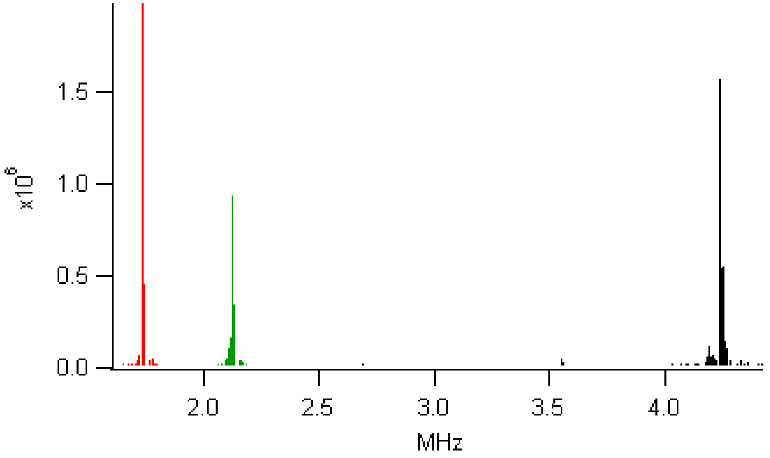
a) Illustration of FFT

a. Extraction of trajectoires

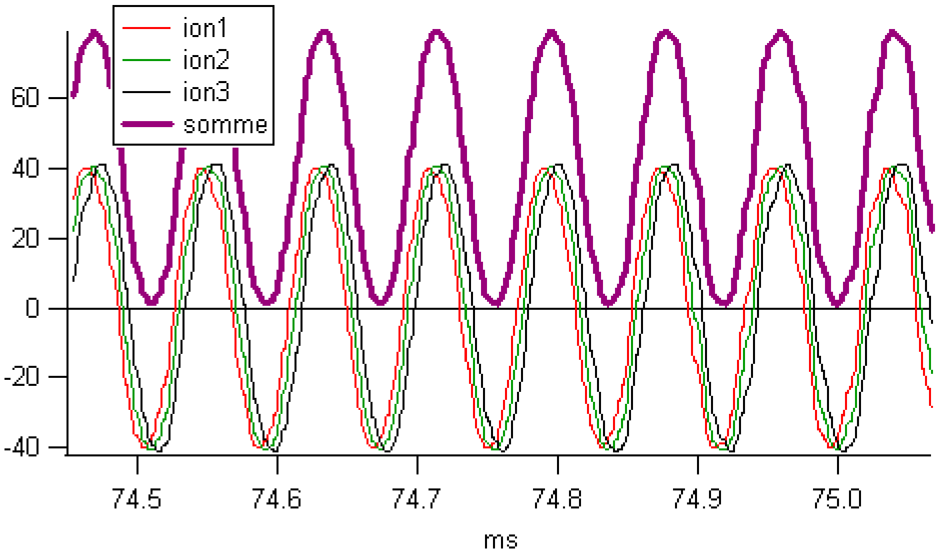
b. Data treatment by Fourier Transform



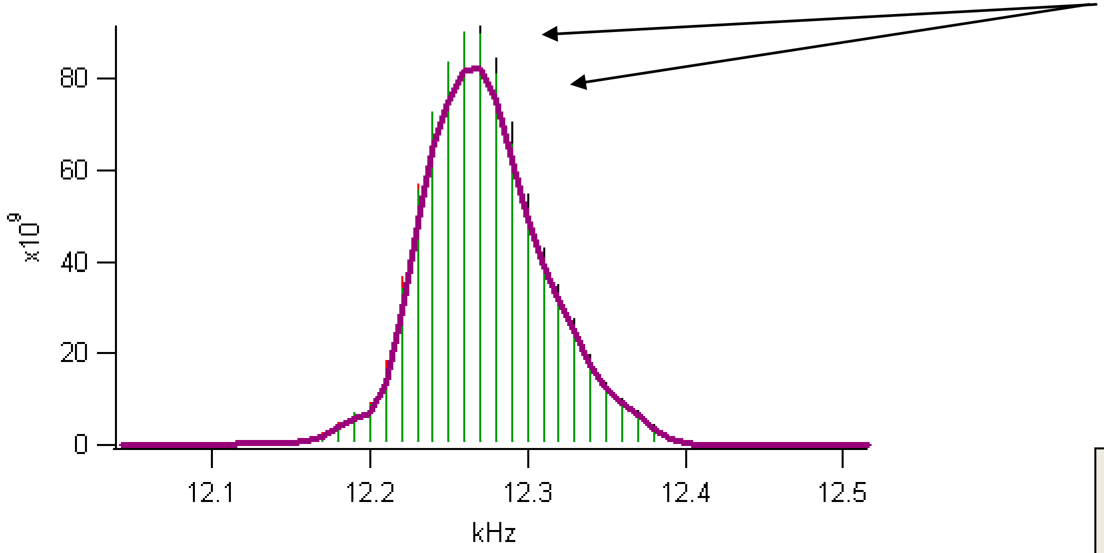




b) Dephasing at injection (ΔT)



for FT, 3 sinus with Δt,
this will produce a signal at similar frequency,



BUT !

Intensity loss

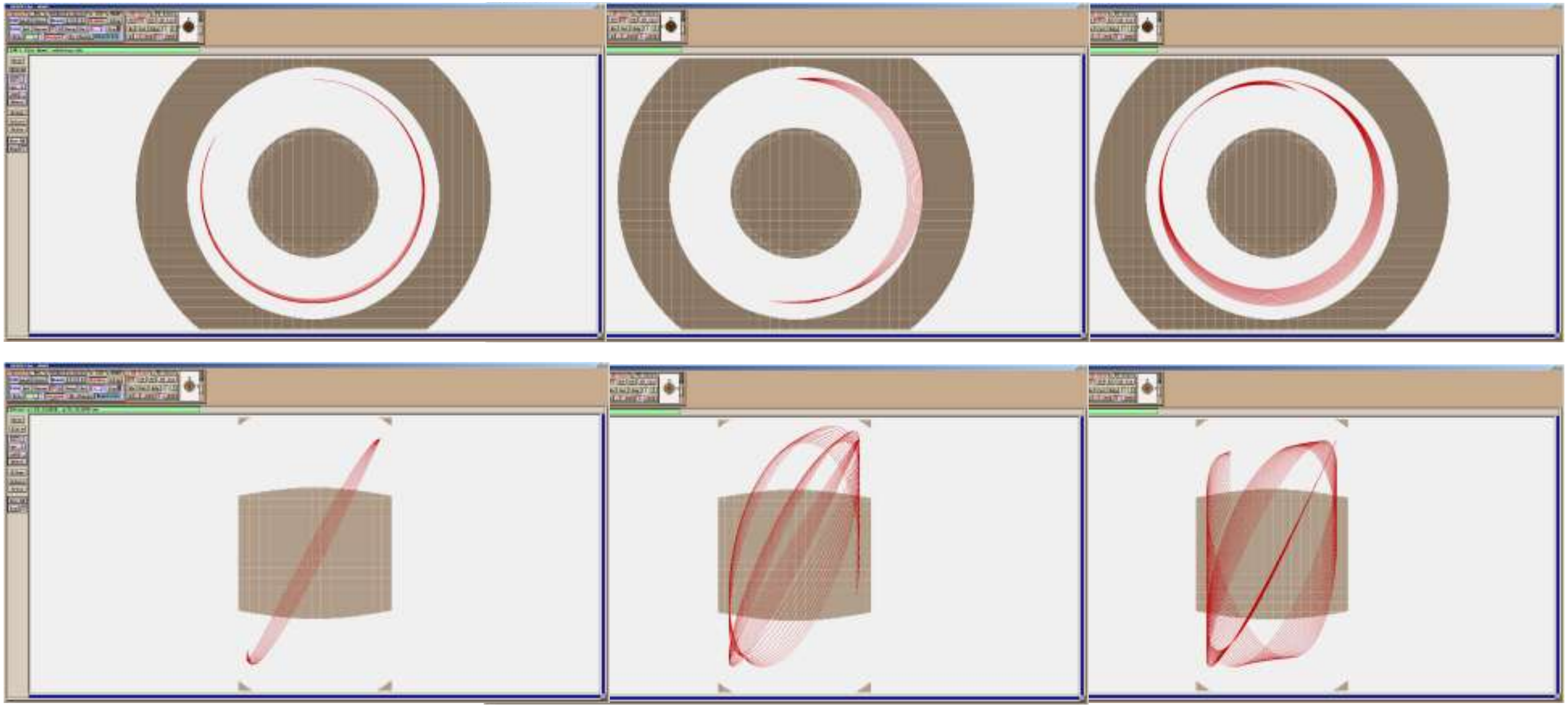
In worst case, if ions of same mass fill the trap for a long ime, (> $\omega_0/2$), no signal will be observed at all…

Ions have to be squeezed in time,
➔ C-TRAP gas for ion thermalisation

Ions of a given mass must enter the oribtrap within a time corresponding to 1/10th of their oscillation period.

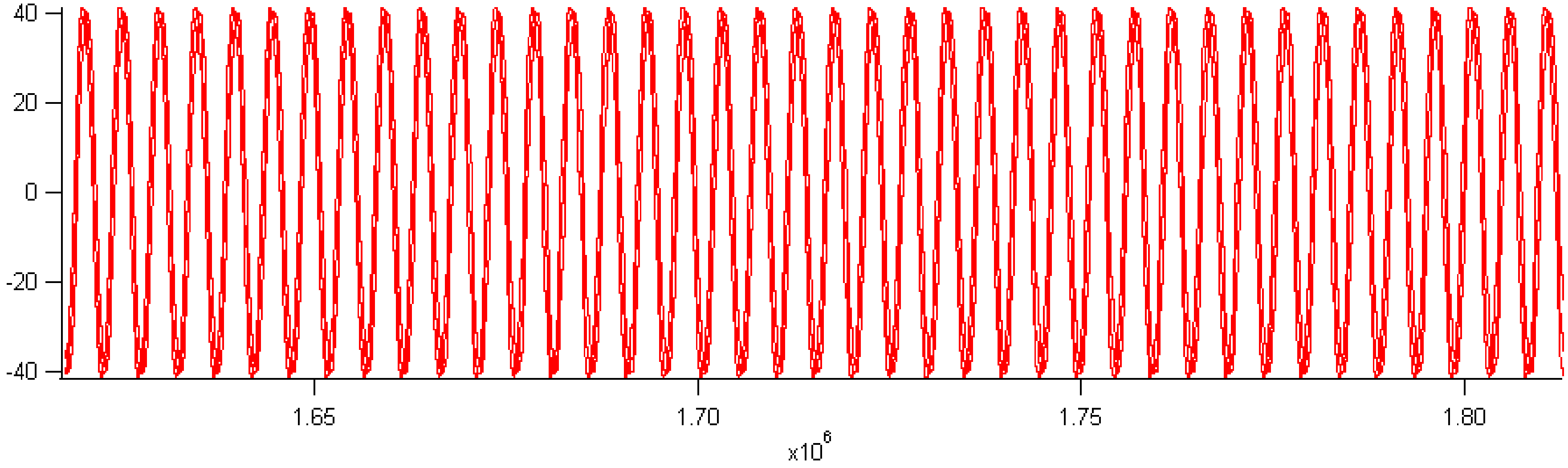
C) (In)sensitivity to source effects

Azimuth angle (90-100°) Elevation angle (0-10°) Ion energy (1560-1760eV)



$$\left.\begin{array}{ll}\ddot{r} - r\dot{\varphi}^2 = -\dfrac{q}{m}\dfrac{k}{2}\left[\dfrac{(R_m)^2}{r} - r\right] & \text{(a)}\\[2ex] \dfrac{\mathrm{d}}{\mathrm{d}t}(r^2\dot{\varphi}) = 0 & \text{(b)}\\[2ex] \boxed{\ddot{z} = -\dfrac{q}{m}kz} & \text{(c)}\end{array}\right\}$$

Azimut


40
20
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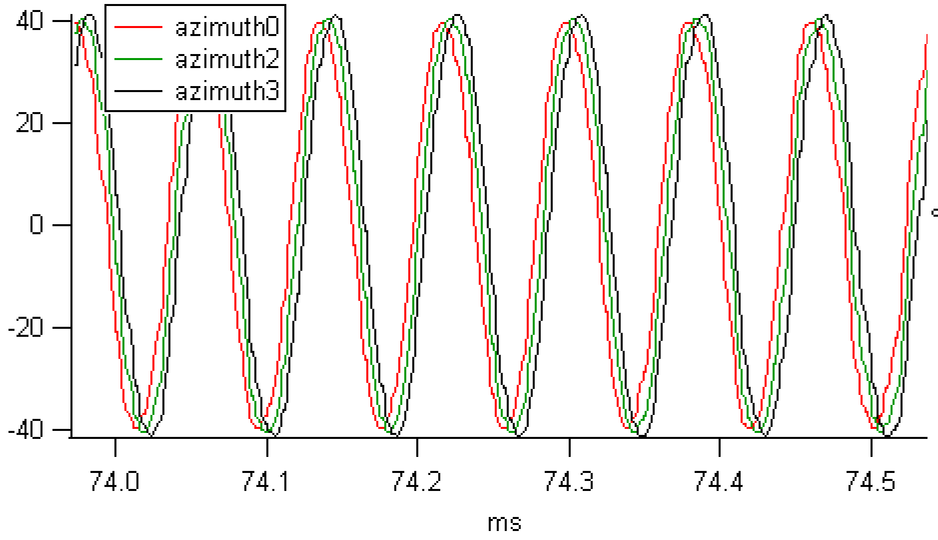
-20
-40
1.65
1.70
1.75
1.80
x10⁶


azimuth0
azimuth2
azimuth3
40
20
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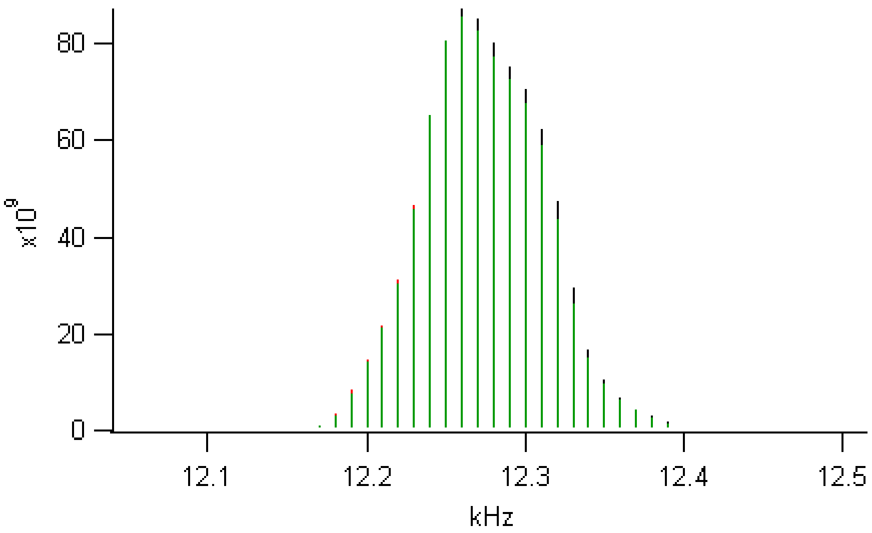
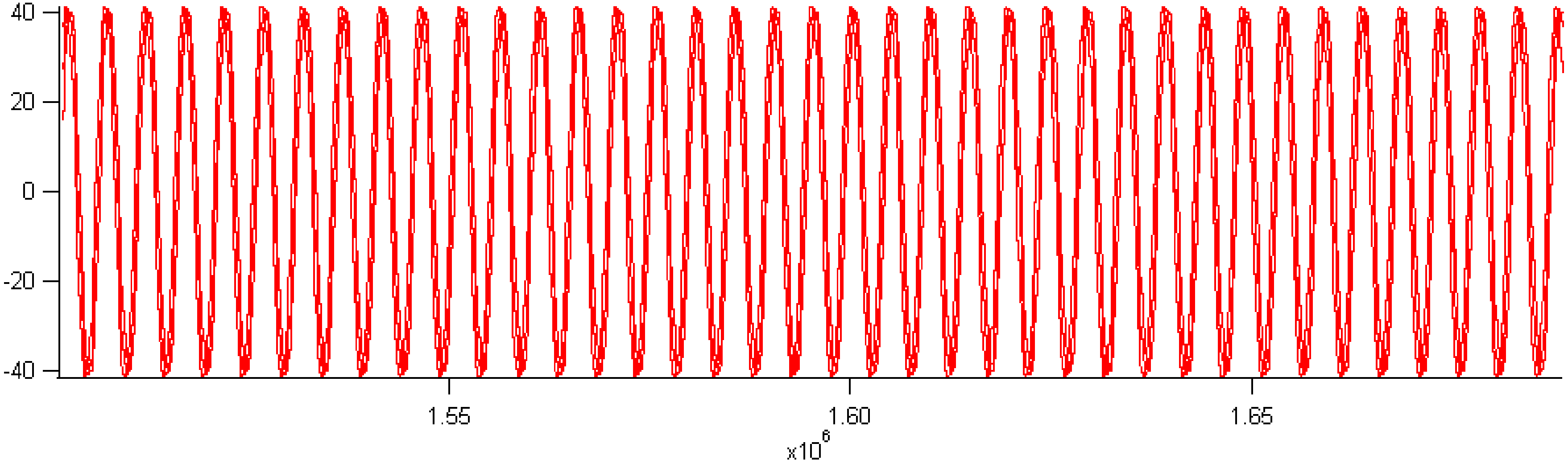
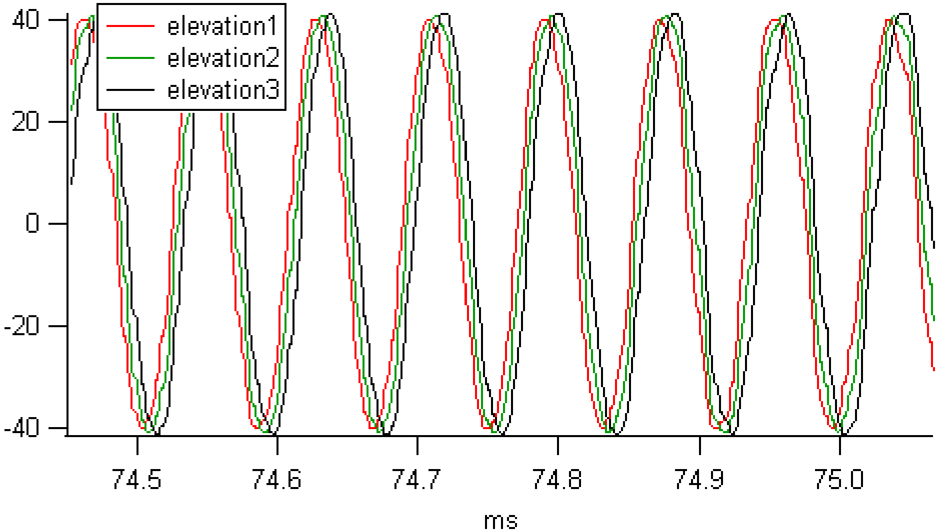
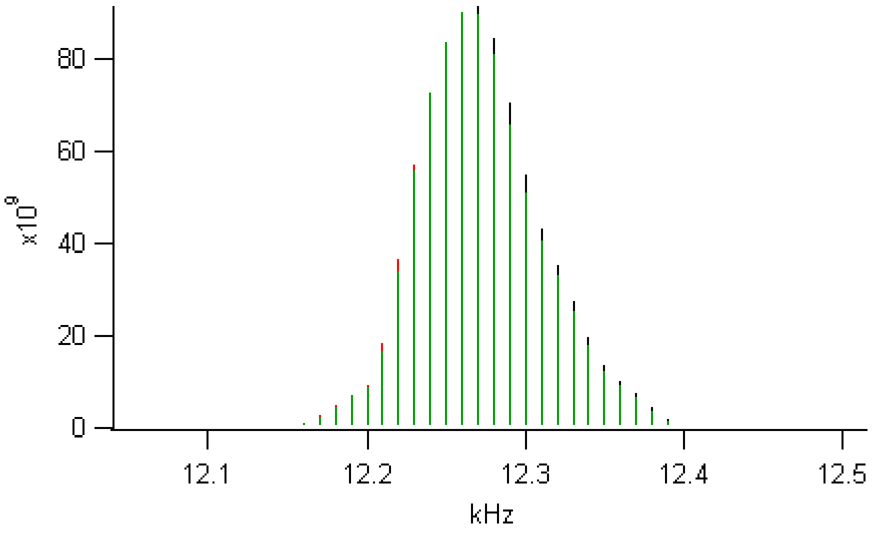
-20
-40
74.0
74.1
74.2
74.3
74.4
74.5
ms


x10⁹
80
60
40
20
0
12.1
12.2
12.3
12.4
12.5
kHz

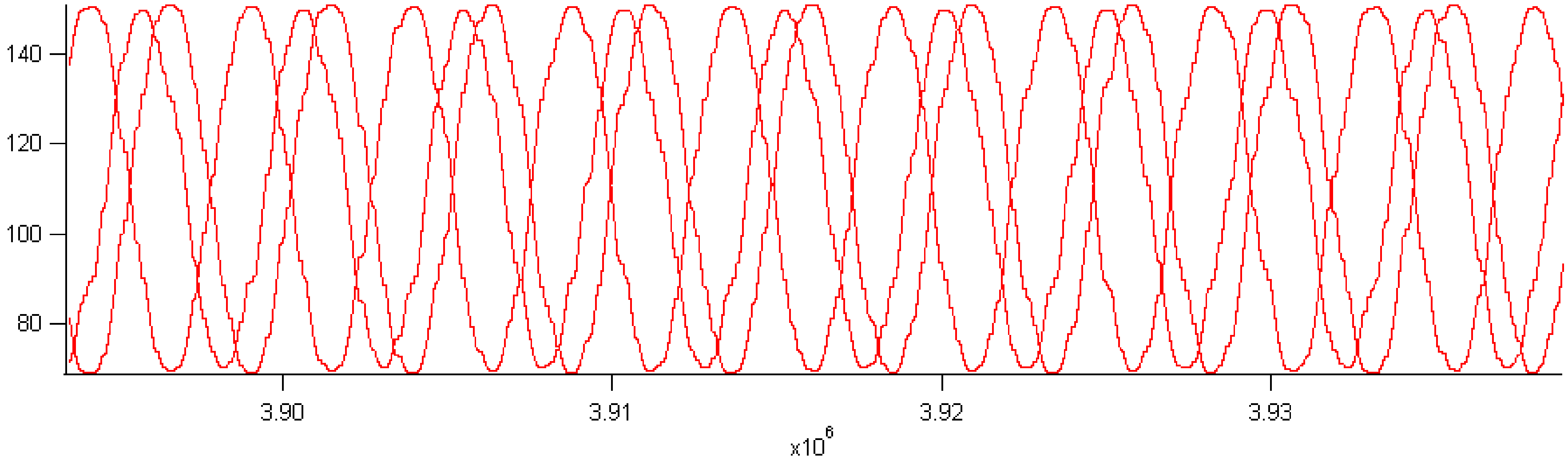
Elevations

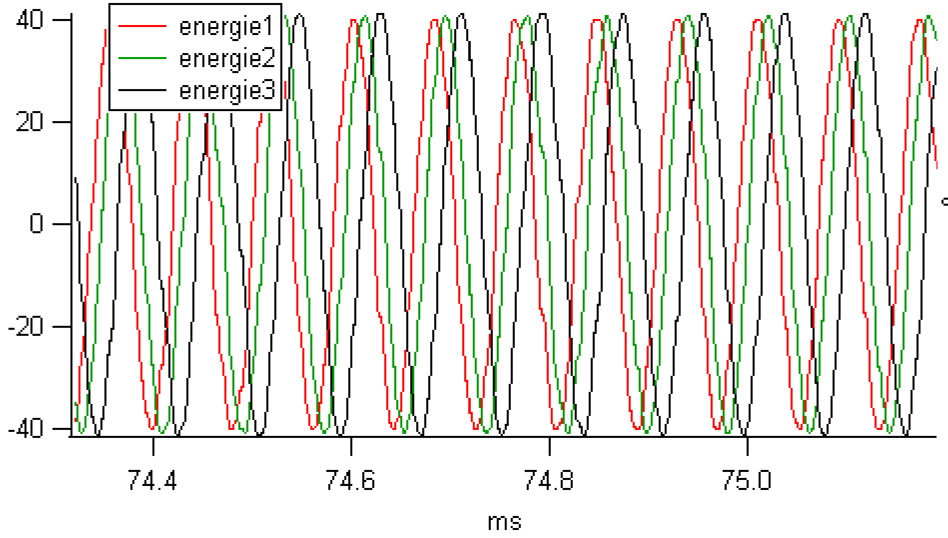

40
20
0
-20
-40
1.55
1.60
1.65
x10^6

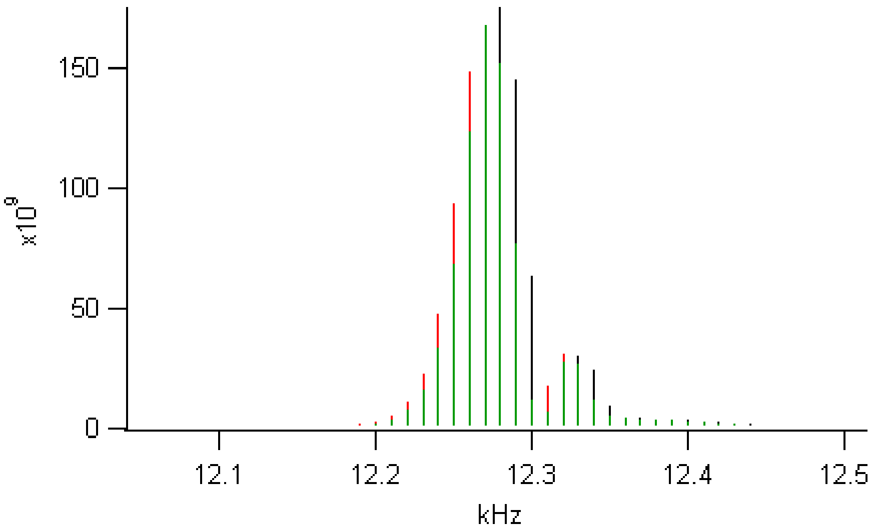

elevation1
elevation2
elevation3
40
20
0
-20
-40
74.5
74.6
74.7
74.8
74.9
75.0
ms


80
60
40
20
0
x10^9
12.1
12.2
12.3
12.4
12.5
kHz

Energy


140
120
100
80
3.90
3.91
3.92
3.93
x10^6

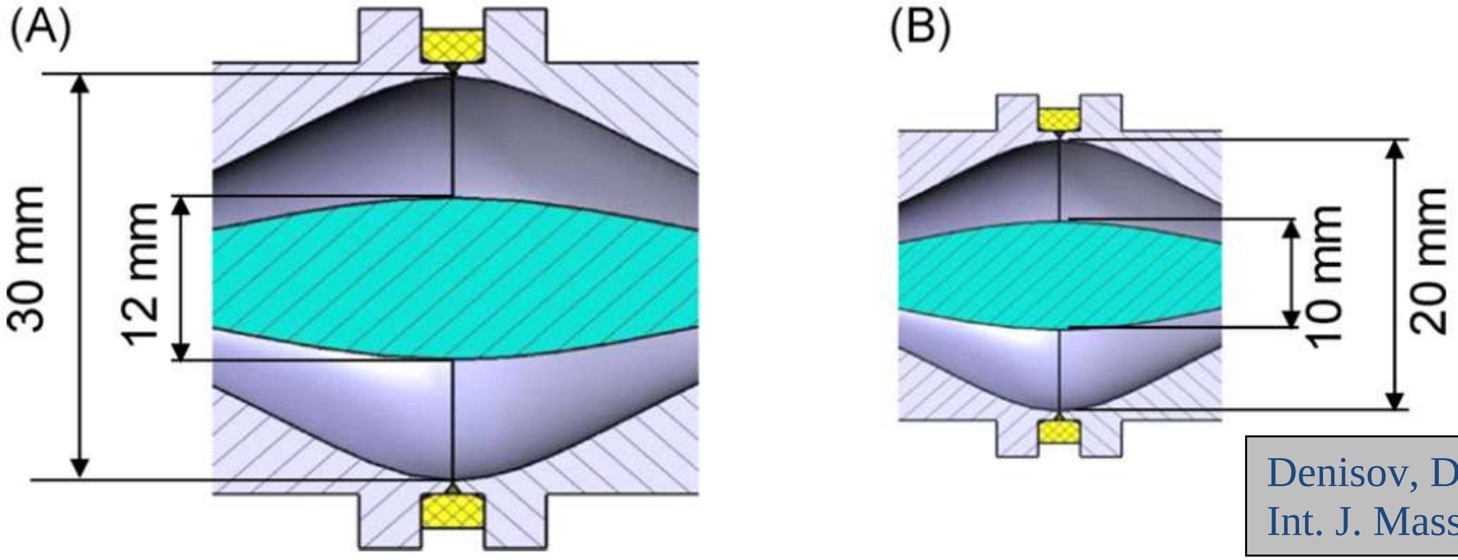

energie1
energie2
energie3
40
20
0
-20
-40
74.4
74.6
74.8
75.0
ms


150
100
50
0
x10^9
12.1
12.2
12.3
12.4
12.5
kHz

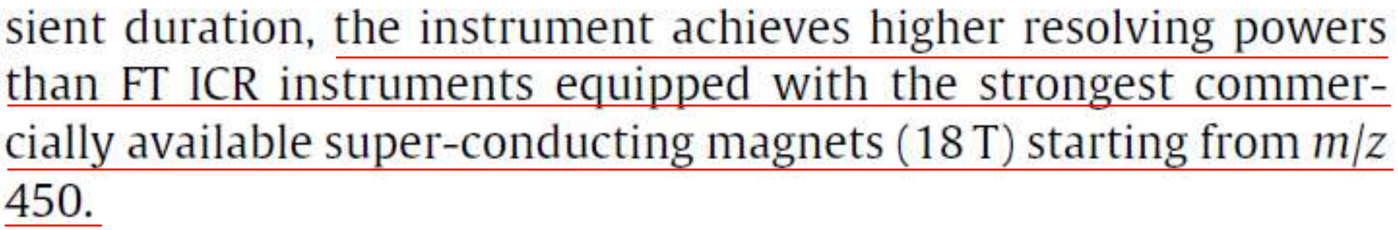
V. Evolutions of Orbitrap

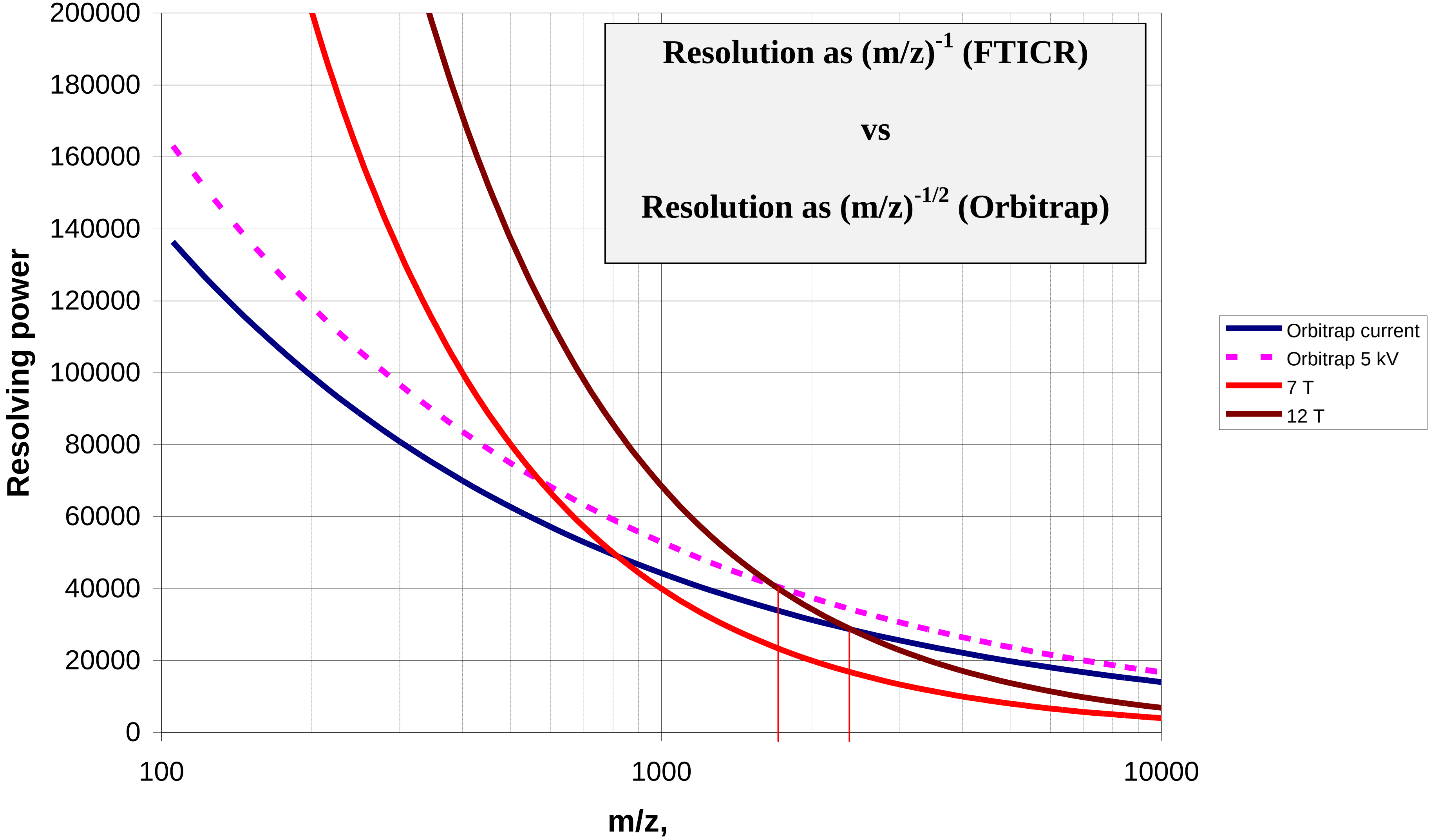
5a) improvement of performances

- Increase the field
  - Geometrical
  - Electrical
- Improve the FFT (correction of injection dephasing)
- Increase of transient signal (3 seconds)



Denisov, Damoc, Lange and Makarov
Int. J. Mass Spec. 325-327 (2012) 80-85


sient duration, the instrument achieves higher resolving powers than FT ICR instruments equipped with the strongest commercially available super-conducting magnets (18 T) starting from *m*/*z* 450.



Resolution as $(m/z)^{-1}$ (FTICR)

vs

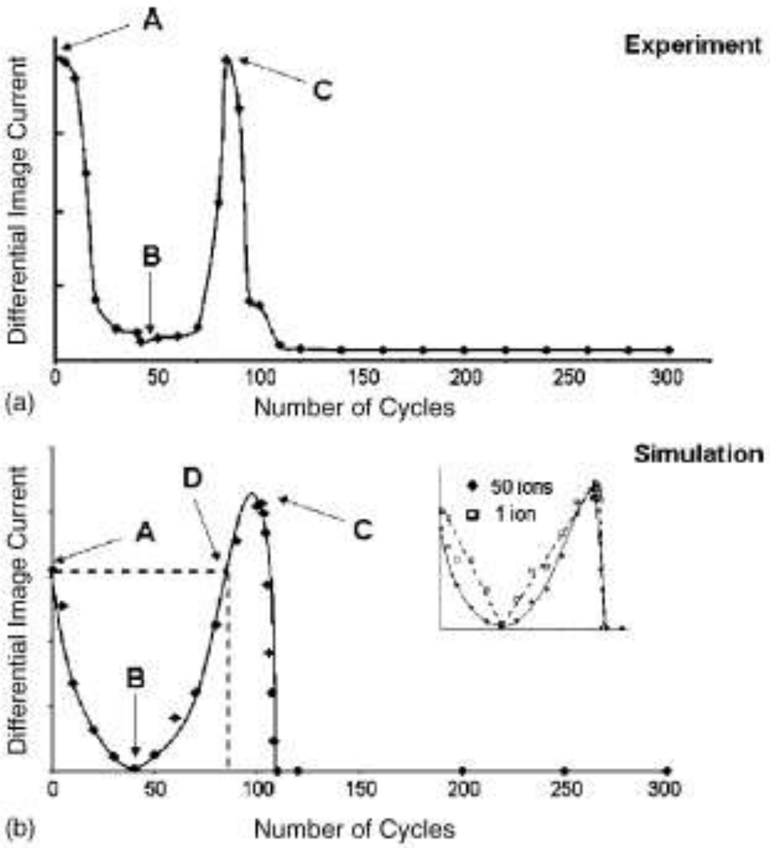
Resolution as $(m/z)^{-1/2}$ (Orbitrap)

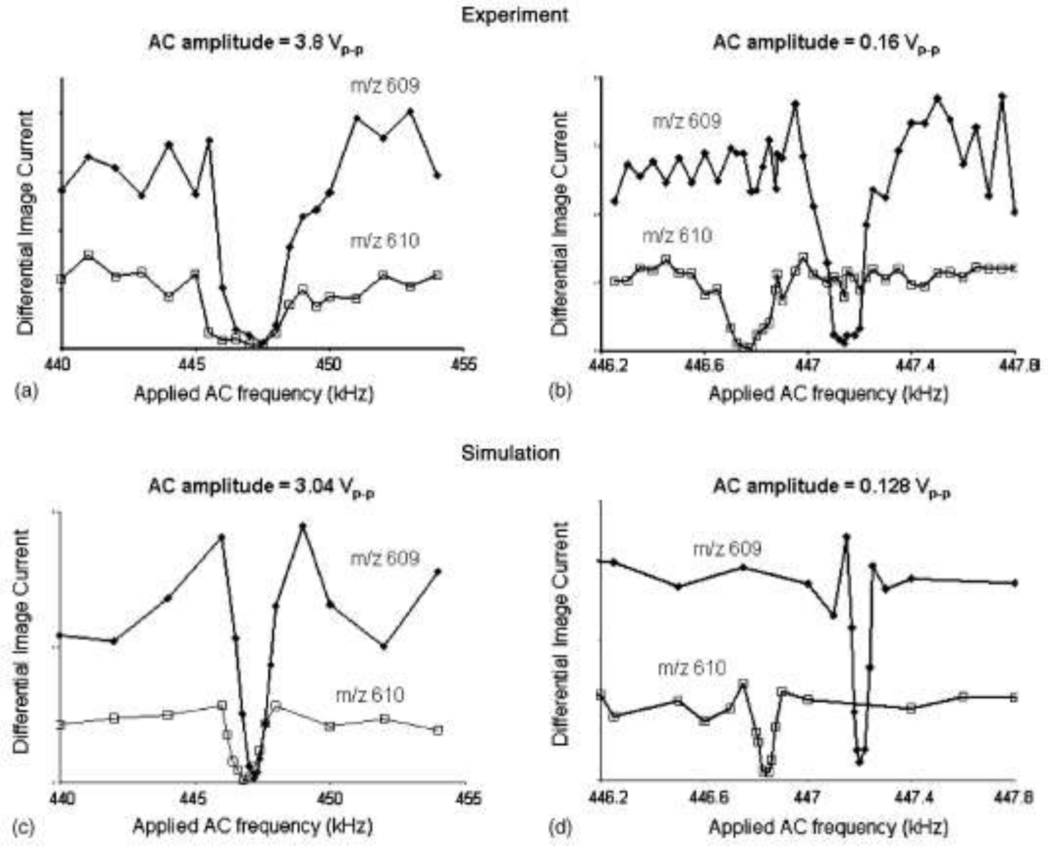
5b) Manipulation of ions inside the Orbitrap, impossible?

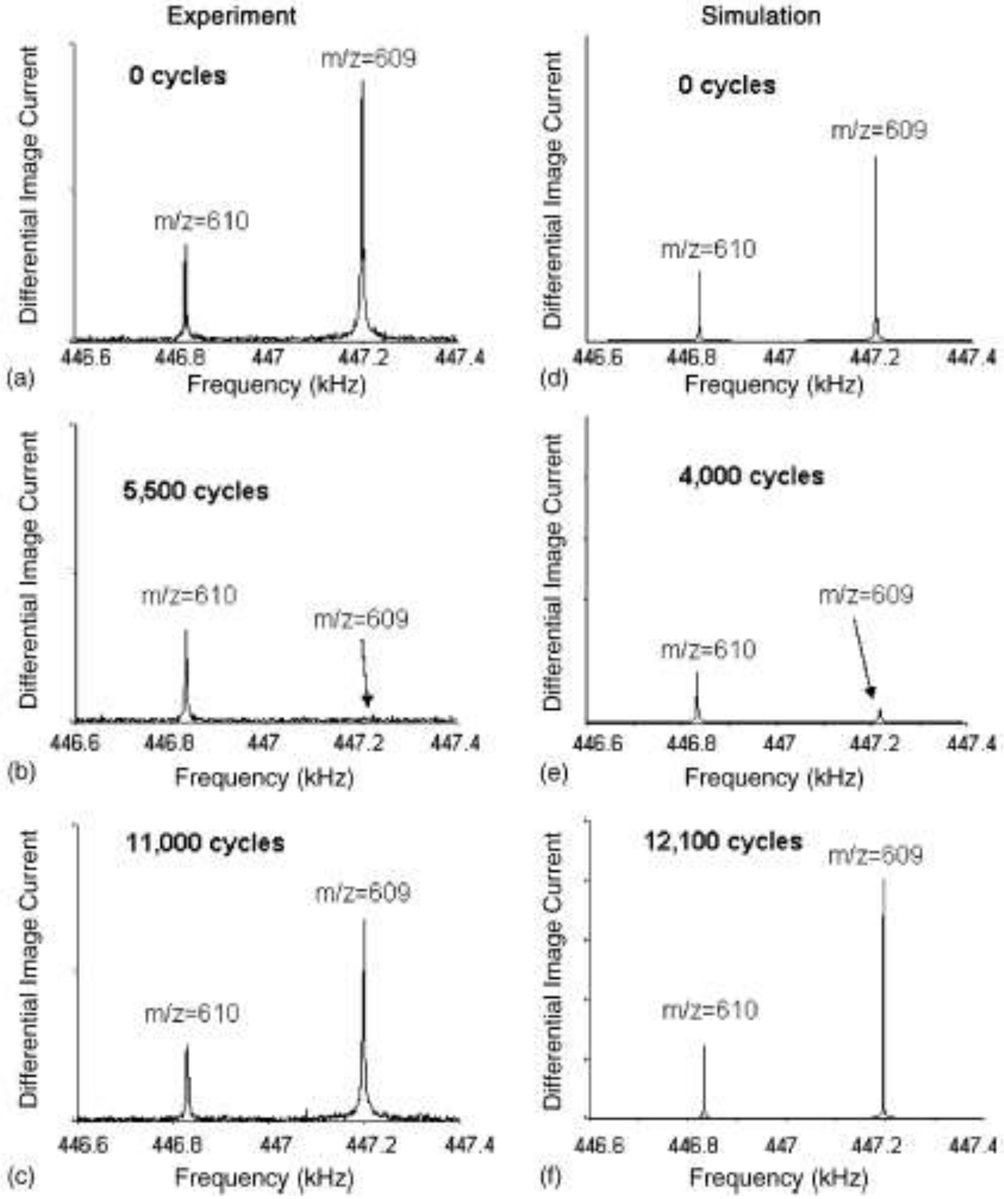
International Journal of Mass Spectrometry 254 (2006) 53–62
“Ion trajectory simulations of axial ac dipolar excitation in the Orbitrap”
G. Wu, R.J. Noll, W.R. Plass, Q. Hu, R.H. Perry, R.G. Cooks

Idea: add some RF (resonant with some ions) on external electrode in order to :

- **Change the ion energy, along z**
- **decrease Ez and bring ions at position z=0 in the trap**
- **increase Ez and eject ions from the trap**



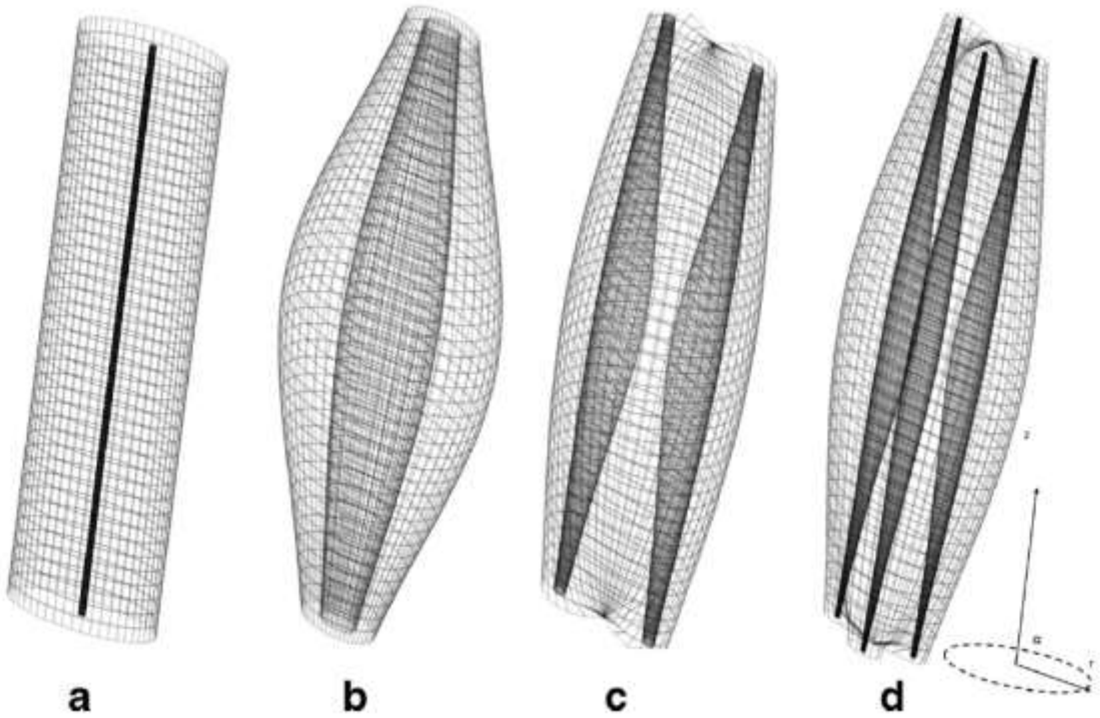



Experiment
Simulation
0 cycles
m/z=609
m/z=610
Differential Image Current
446.6
446.8
447
447.2
447.4
Frequency (kHz)
(a)
0 cycles
m/z=609
m/z=610
(d)
5,500 cycles
m/z=610
m/z=609
(b)
4,000 cycles
m/z=609
m/z=610
(e)
11,000 cycles
m/z=609
m/z=610
(c)
12,100 cycles
m/z=609
m/z=610
(f)

5C) Orbitrap is a single member in a family of analyzers with CASSINIAN potential

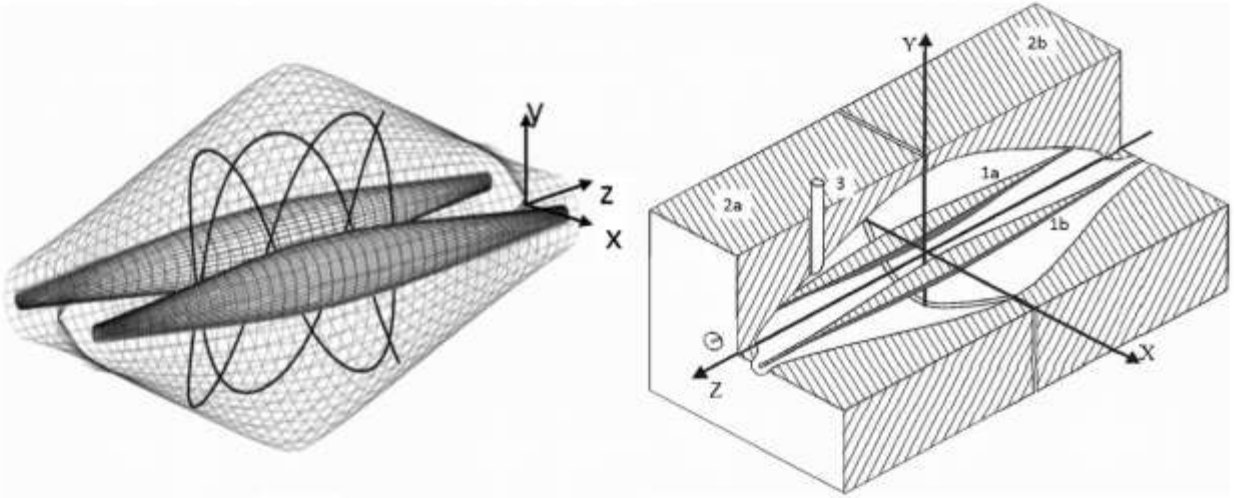
Köster, C. J. Am. Soc. Mass Spectrom. (2015) 26: 390

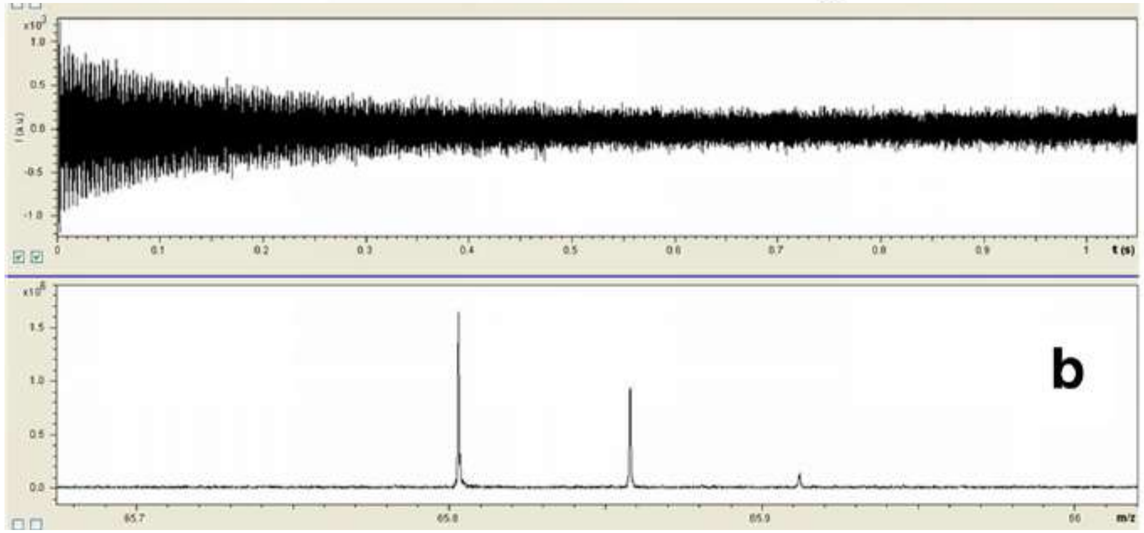
$$\Psi(r,\alpha,z)=\left[\frac{\ln\left(\frac{r^{2n}-2\cdot r^{n}\cdot b^{n}\cdot\cos(n\,\alpha)+b^{2n}}{a^{2n}}\right)}{\mathrm{Aln}}+\frac{z^{2}-r^{2}\cdot\left((1-c)\cdot\cos(\alpha)^{2}+c\cdot\sin(\alpha)^{2}\right)}{Aquad}+d\right]\cdot U_{\mathrm{Cassini}}$$



n=1 n=2 n=3

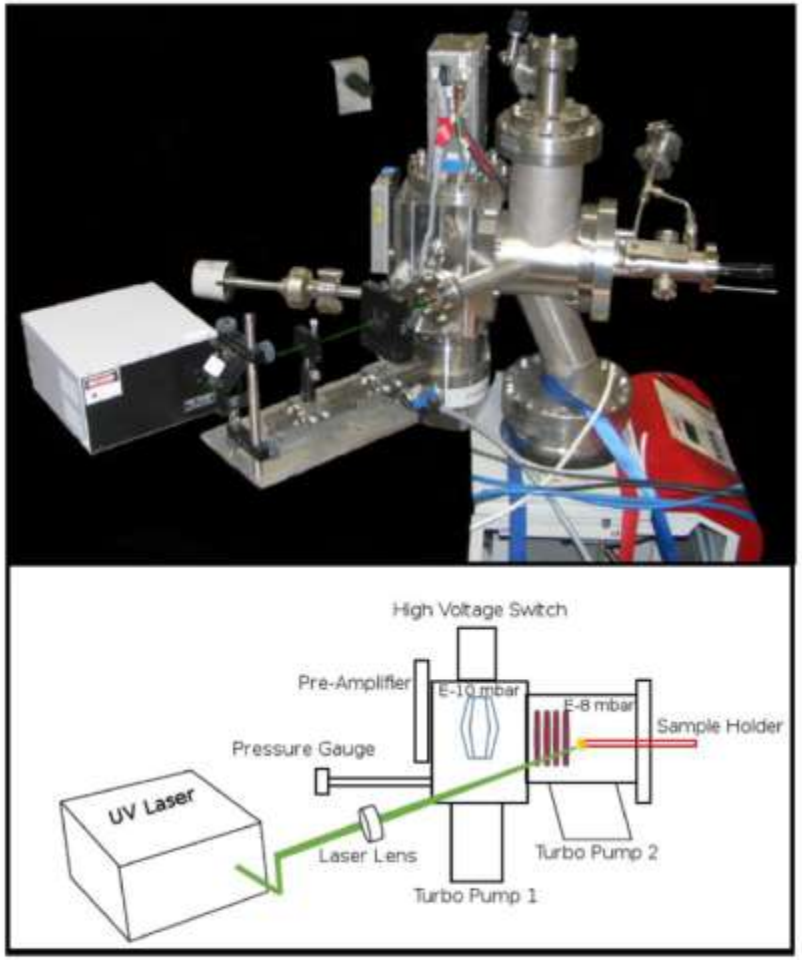
Ultimate R= 140 000 at m/z = 600

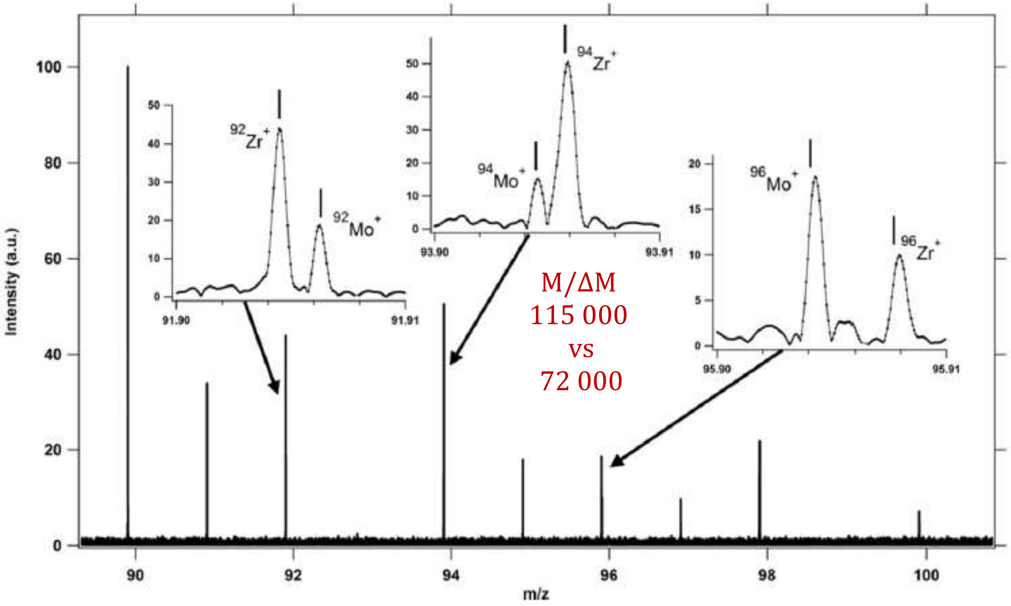




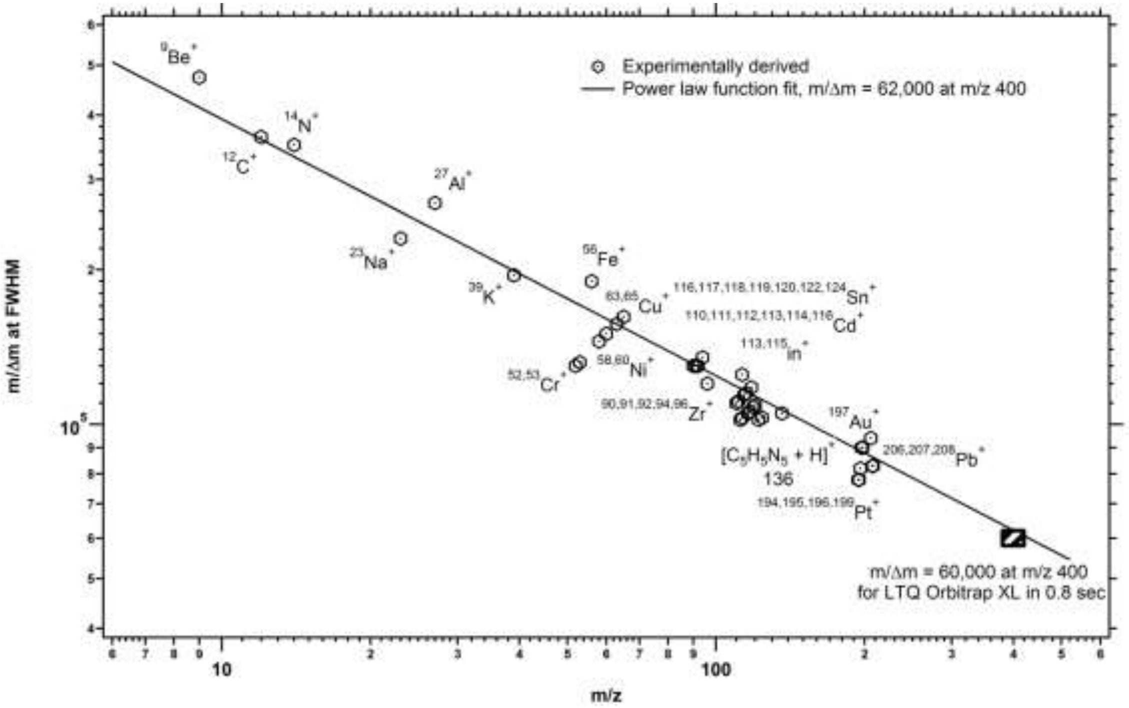
5d) Space portage of the concept: Cosmorbitrap

“Orbitrap mass analyser for in situ characterisation of planetary environments: Performance evaluation of a laboratory prototype”
Briois, et al. Planetary and Space Science, In Press, online 6 July 2016

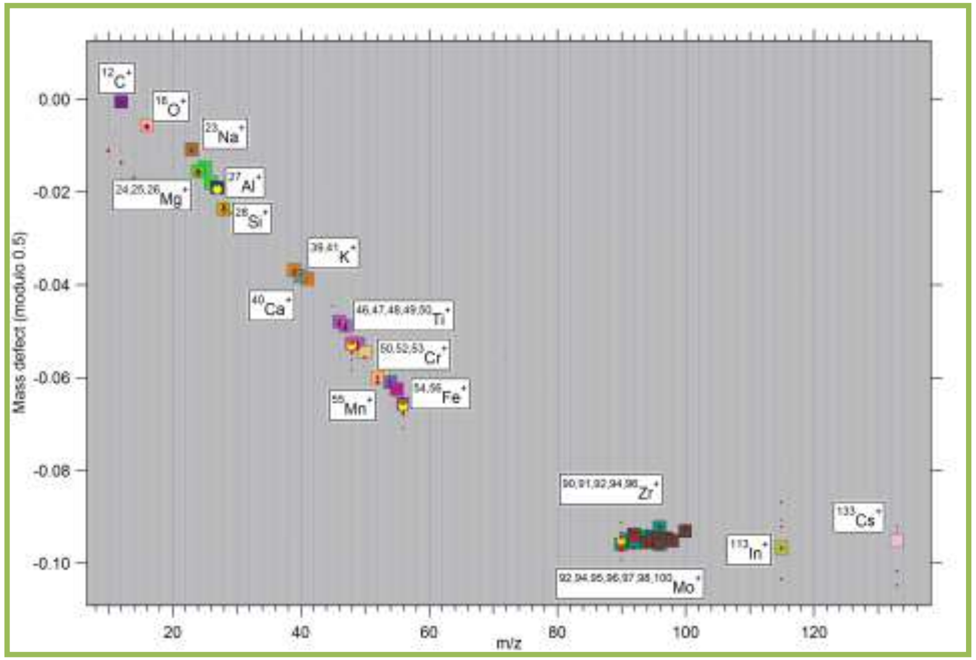




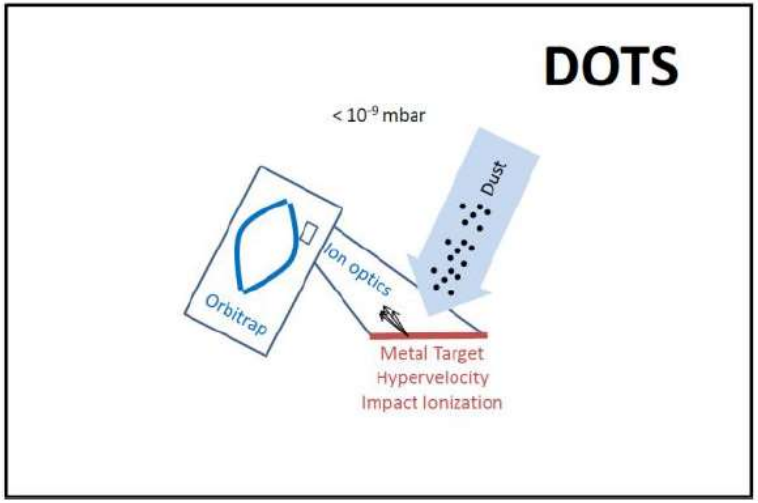
M/ΔM
115 000
vs
72 000

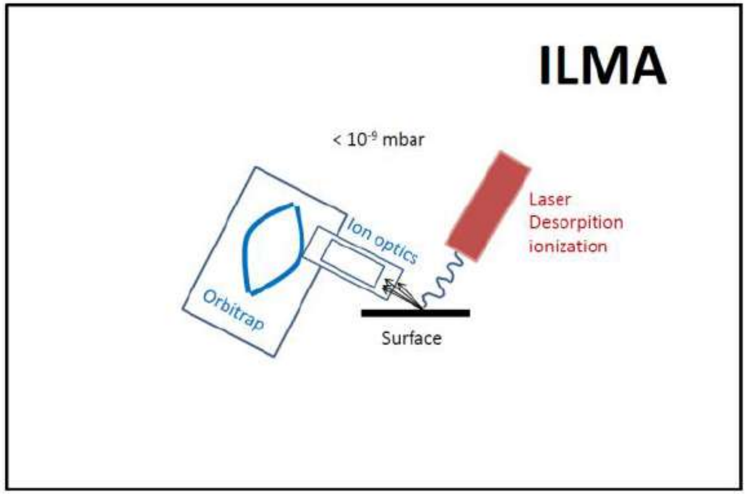


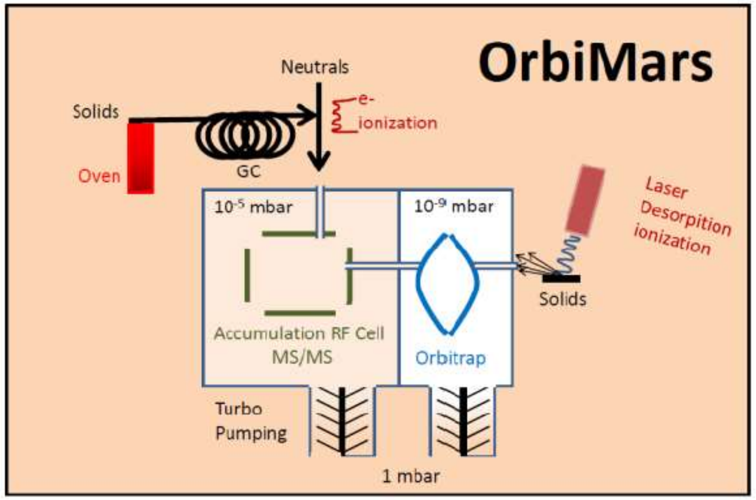
Resolution

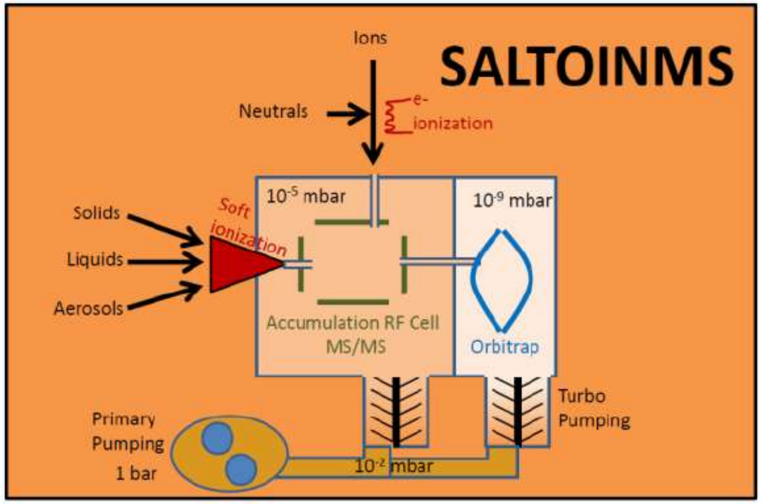


Precision


DOTS
< 10^{-9} mbar
Dust
Orbitrap
Ion optics
Metal Target
Hypervelocity
Impact Ionization


ILMA
< 10^{-9} mbar
Laser
Desorption
ionization
Ion optics
Orbitrap
Surface


OrbiMars
Neutrals
Solids
e-
ionization
Oven
GC
10^{-5} mbar
10^{-9} mbar
Laser
Desorption
ionization
Solids
Accumulation RF Cell
MS/MS
Orbitrap
Turbo
Pumping
1 mbar

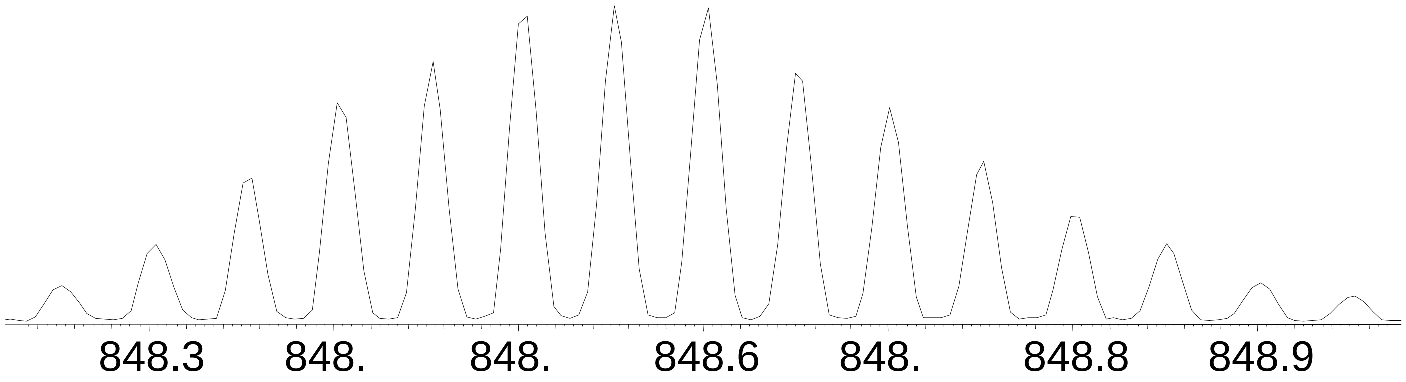

Ions
SALTOINMS
Neutrals
e-
ionization
10^{-5} mbar
10^{-9} mbar
Solids
Liquids
Aerosols
Soft
ionization
Accumulation RF Cell
MS/MS
Orbitrap
Turbo
Pumping
Primary
Pumping
1 bar
10^{-2} mbar

5e) Isotopic measurements with Orbitrap ? !!

i.e. what about quantitative measurements?

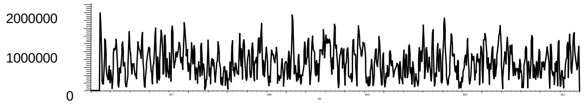
Signal of only 1 ion in Orbitrap !

(Myoglobin+20H)$^+$



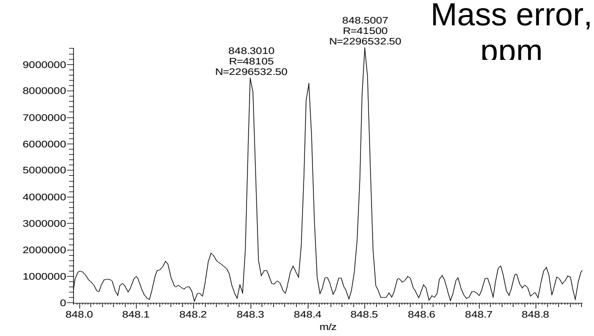
Strong reduction of signal… (dilution, agc, etc)

No ion



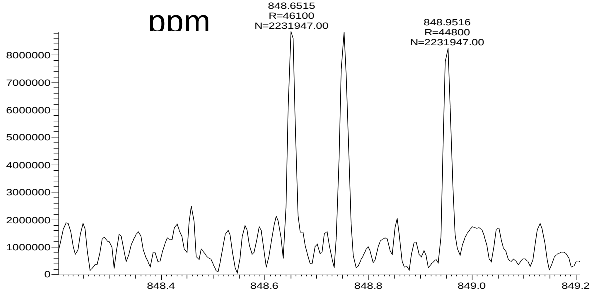
3 x 1 ion

Mass error, ppm

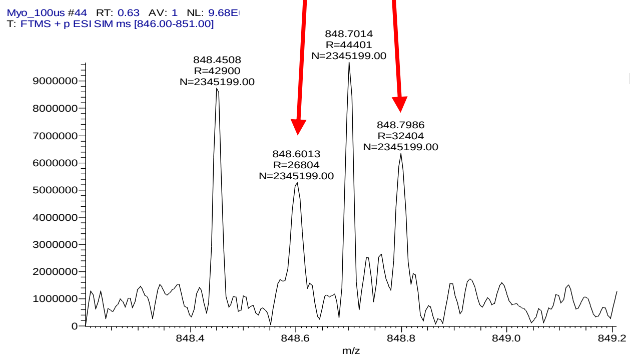


3 x 1 ion

Mass error, ppm

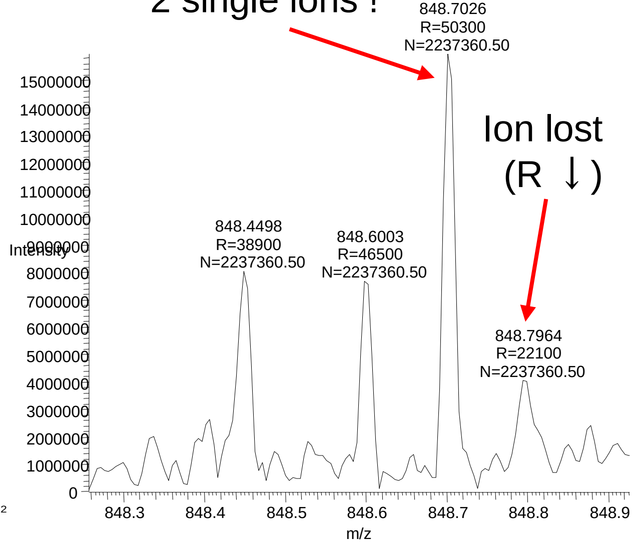


Ion lost during measure
(R ↓)

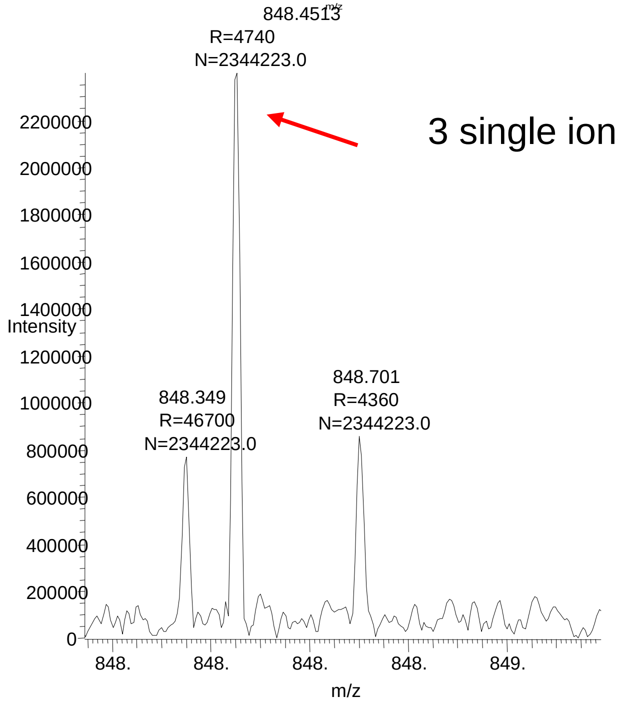


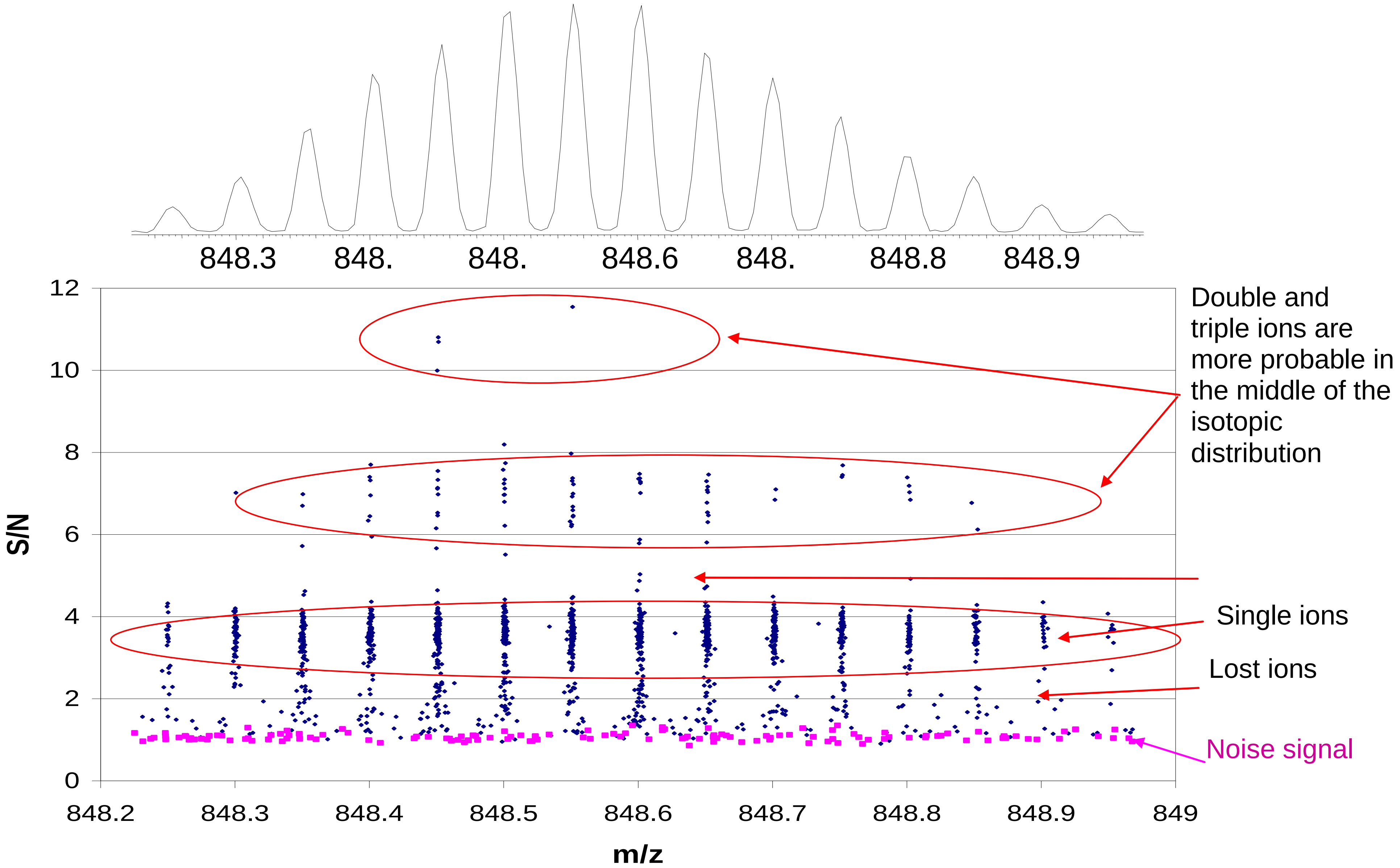
2 single ions !

Ion lost
(R ↓)



3 single ions !





Double and triple ions are more probable in the middle of the isotopic distribution

Single ions

Lost ions

Noise signal

1 ion with +20 charges, S/N=3.7 on average (0.76 sec acquisition). This would correspond to a detection limit of 5.5 charges in Orbitrap

How old is earth ?
What is the link between CO_2 and global warming?
Is the water on earth of cometary origin?
Is the chemistry of Titan same as the early earth?
Where is the heroine found in Marseille coming from?

…..

ISOTOPICAL signatures !!

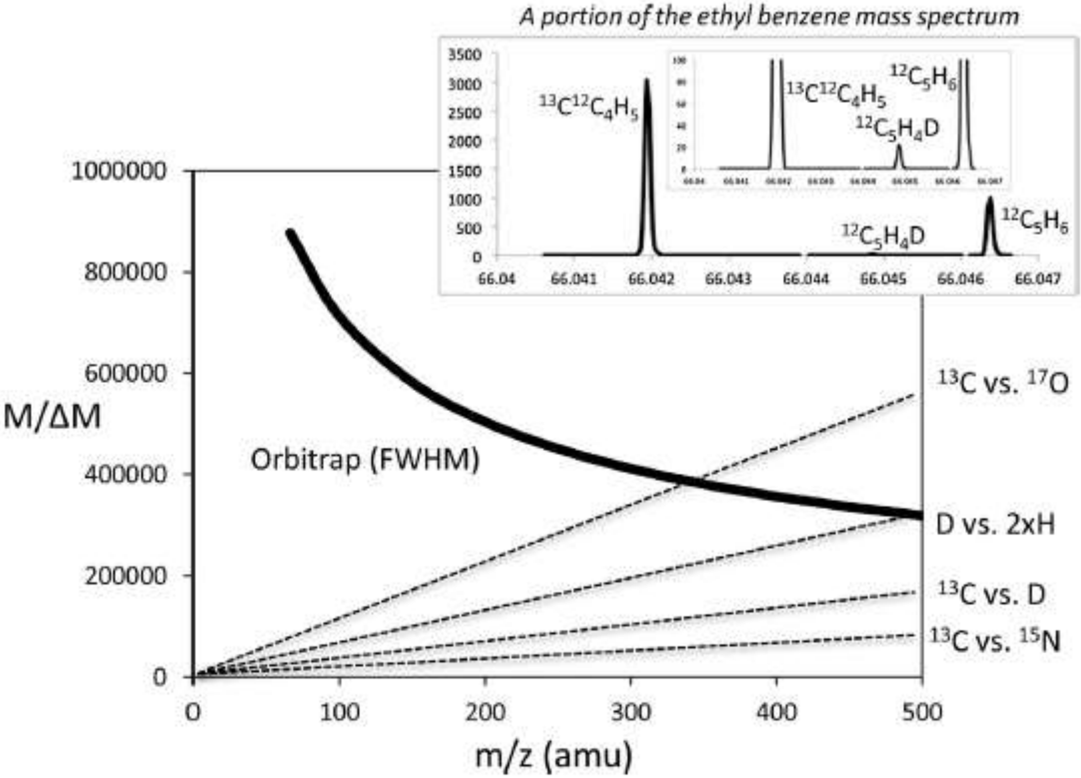
HOWEVER :

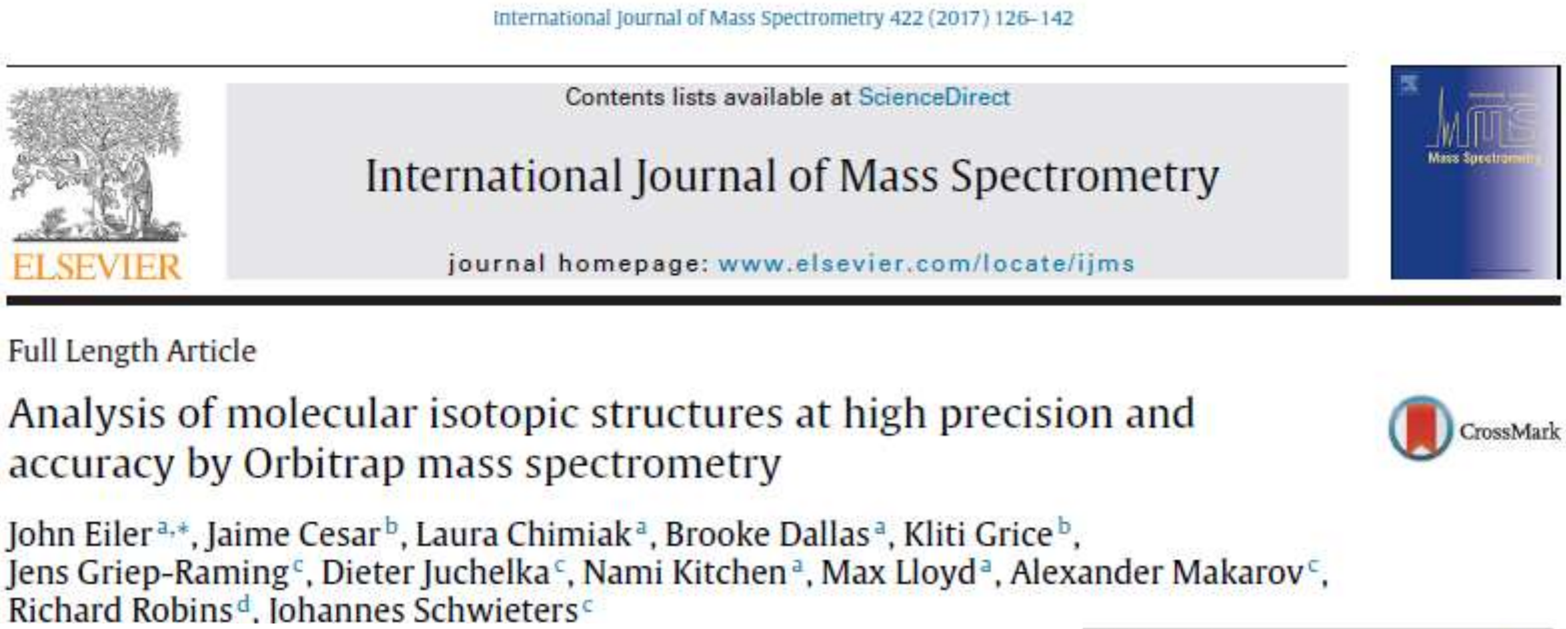
Bulk measurements (all material is burnt and very accurate measurements are performed on the elements present in the sample

DREAM :

Isotope ratios at the <u>molecular scale</u> (measure for each molecule)

Isotope ratios at the <u>sub molecular scale</u> (isotope ratios in fragments of molecules)





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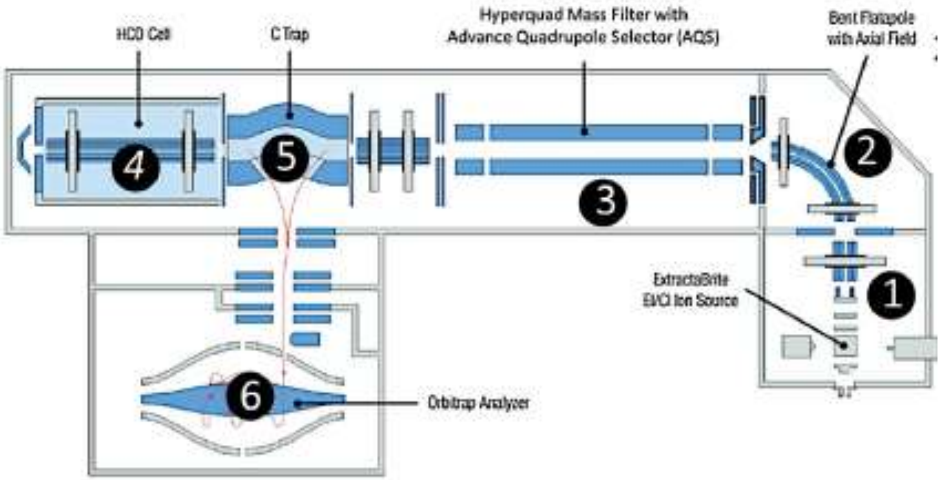
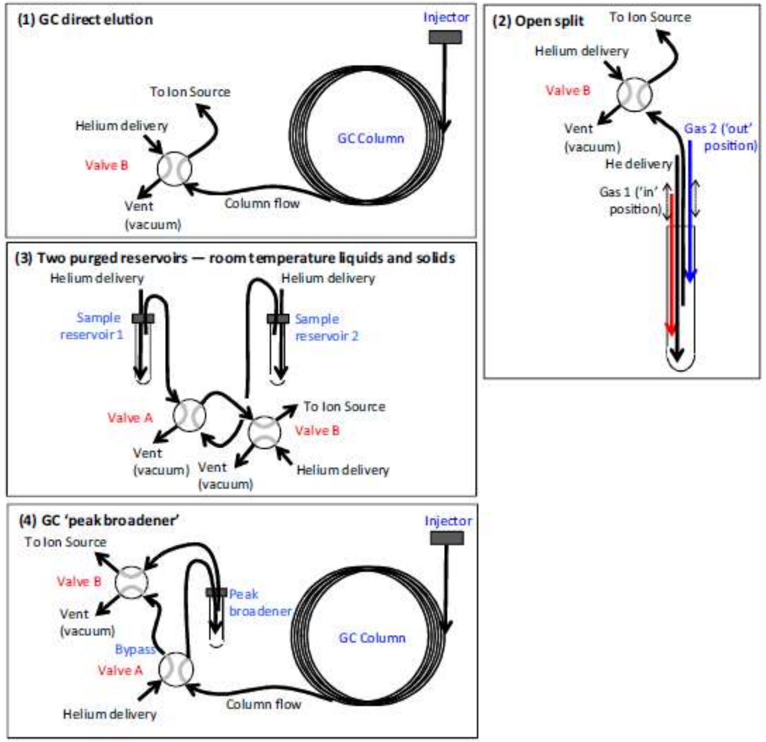
journal homepage: www.elsevier.com/locate/ijms

Full Length Article

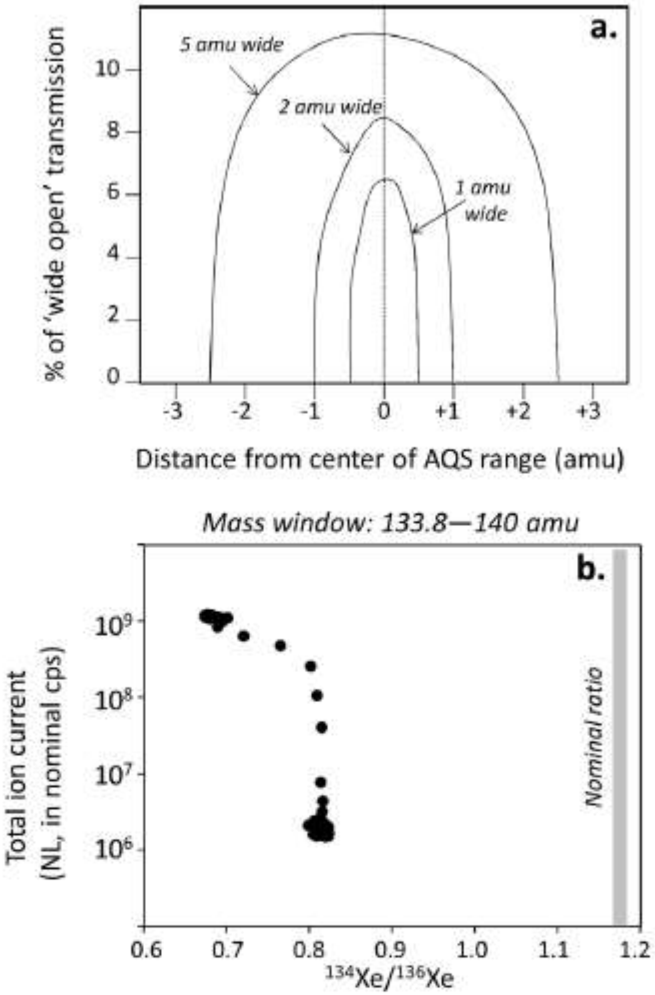
Analysis of molecular isotopic structures at high precision and accuracy by Orbitrap mass spectrometry

John Eiler[a,*], Jaime Cesar[b], Laura Chimiak[a], Brooke Dallas[a], Kliti Grice[b],
Jens Griep-Raming[c], Dieter Juchelka[c], Nami Kitchen[a], Max Lloyd[a], Alexander Makarov[c],
Richard Robins[d], Johannes Schwieters[c]

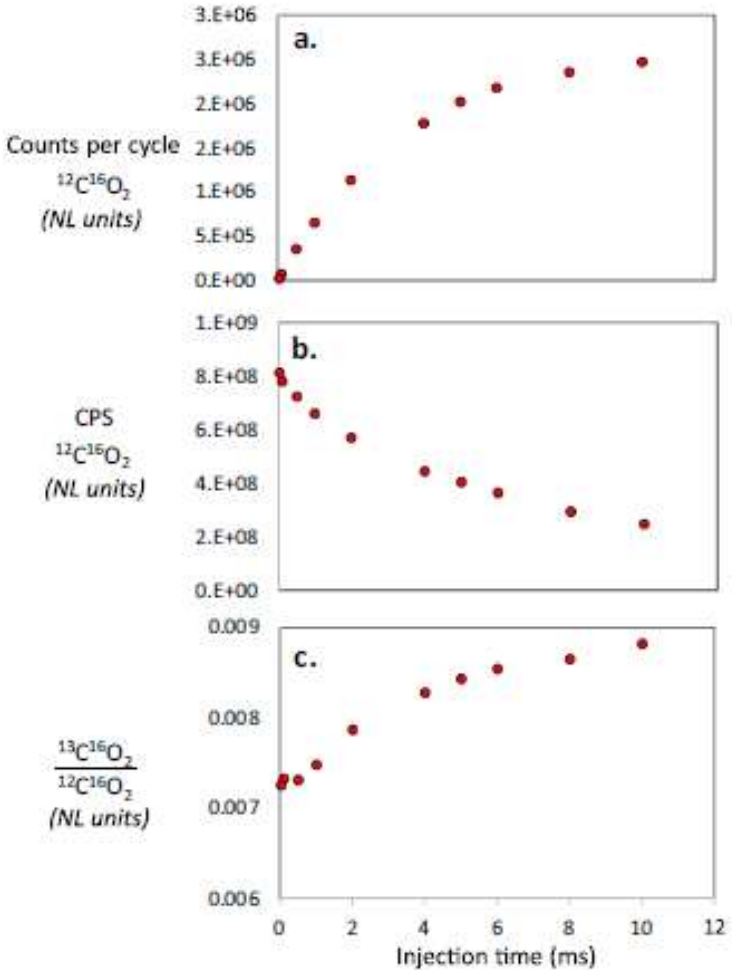




1) Stability and reproducibility: there are biases in Quad filtering and C-trap to Orbitrap transfer, and orbitrap itself
But they are not affecting measurements when the number of ions transferred into the trap is stable and reduced



Quad filtering



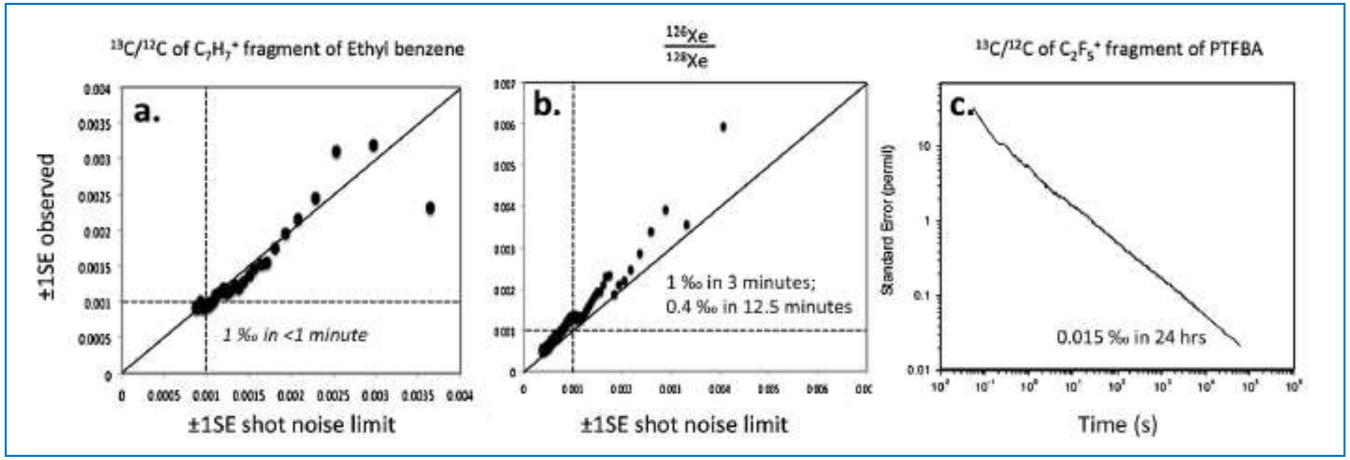
Charge repulsion

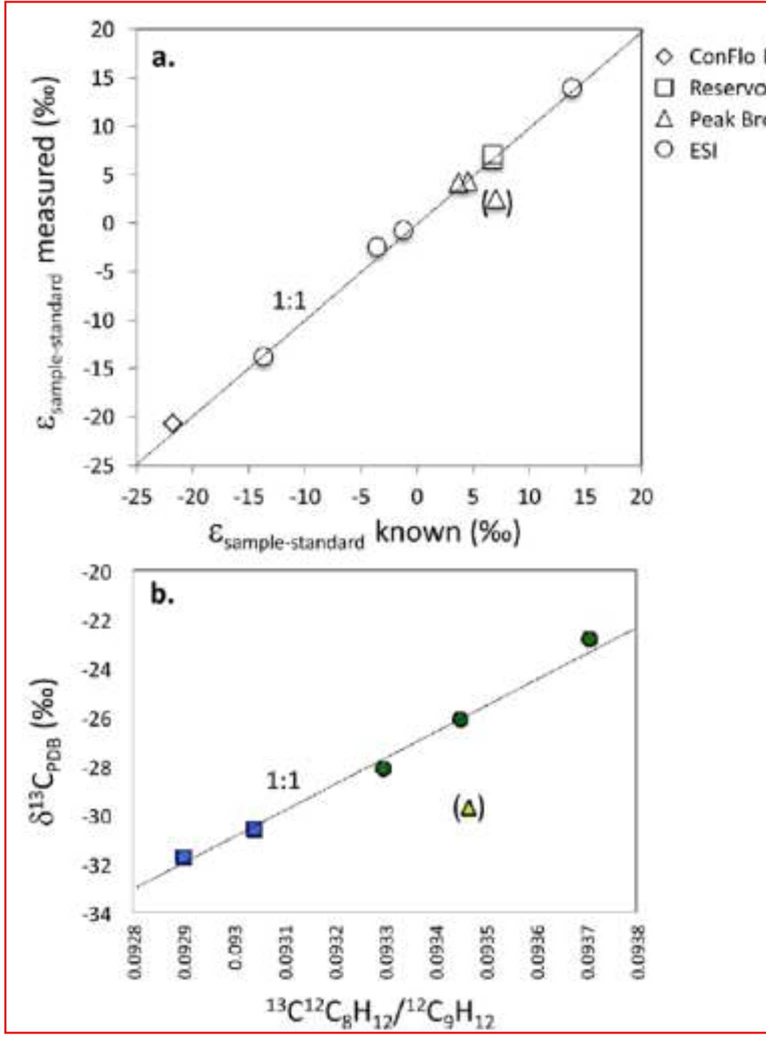
Coalescence

Ion depletion due to transmission window of quad

C-trap to Orbitrap extraction

Provided sufficient time is used for measurement, signal averaging brings very stable information, which keeps improving with acquisition time,





Tests of accuracy when switching with standard and Renormalizing brings very encouraging results

THANK YOU !

TIME FOR QUESTIONS