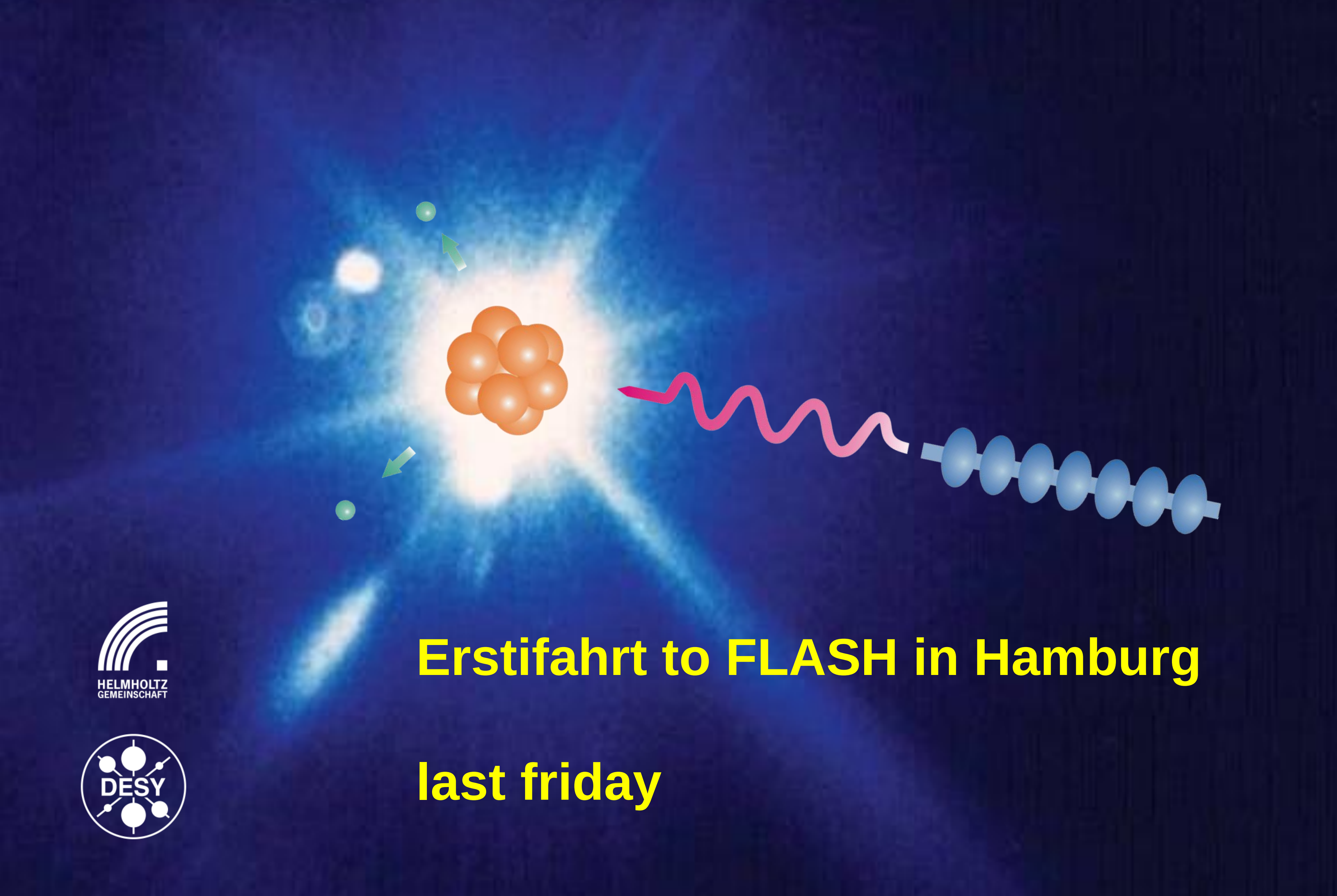
The free electron laser FLASH



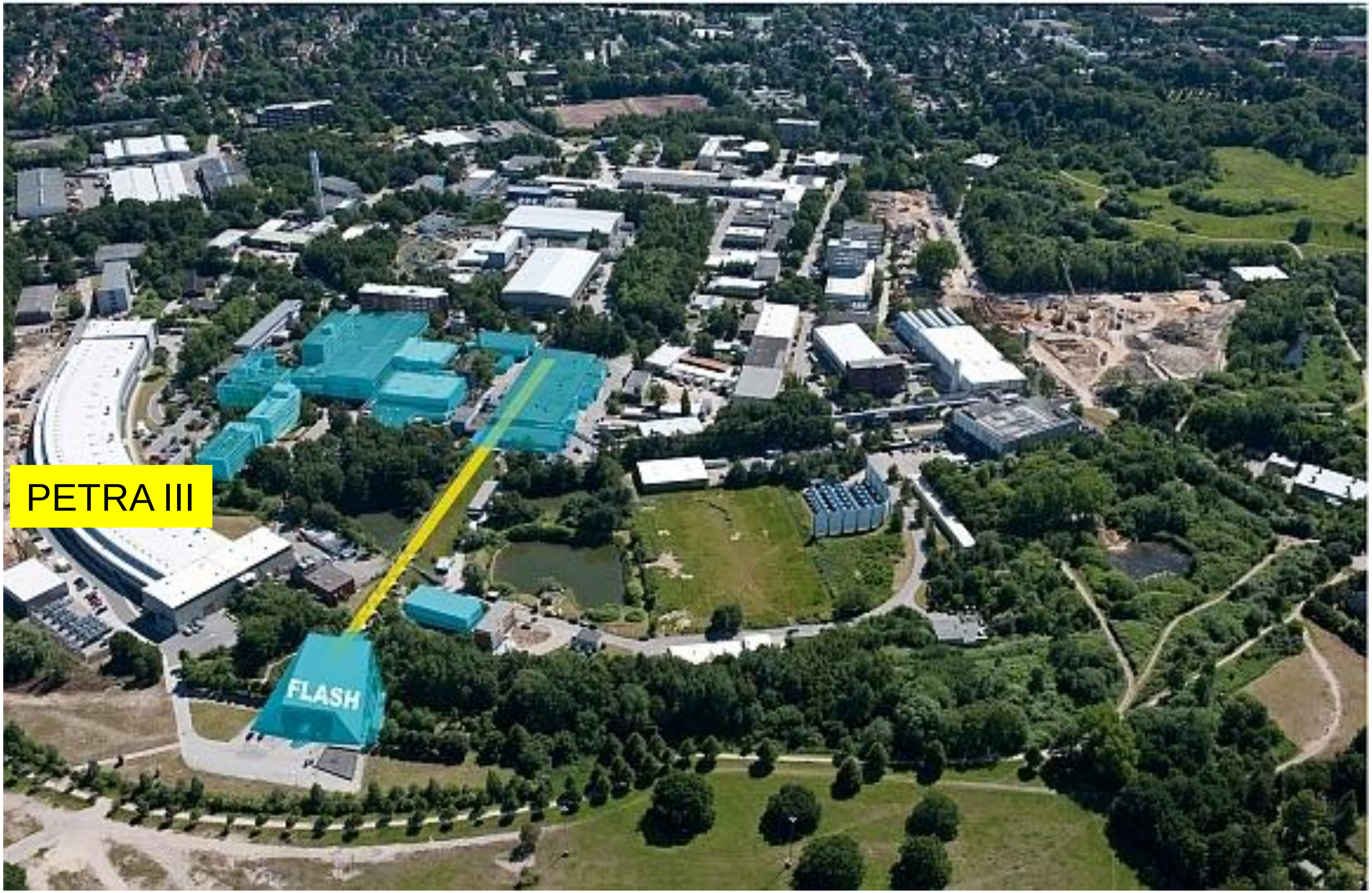
Erstifahrt to FLASH in Hamburg

last friday

HELMHOLTZ GEMEINSCHAFT

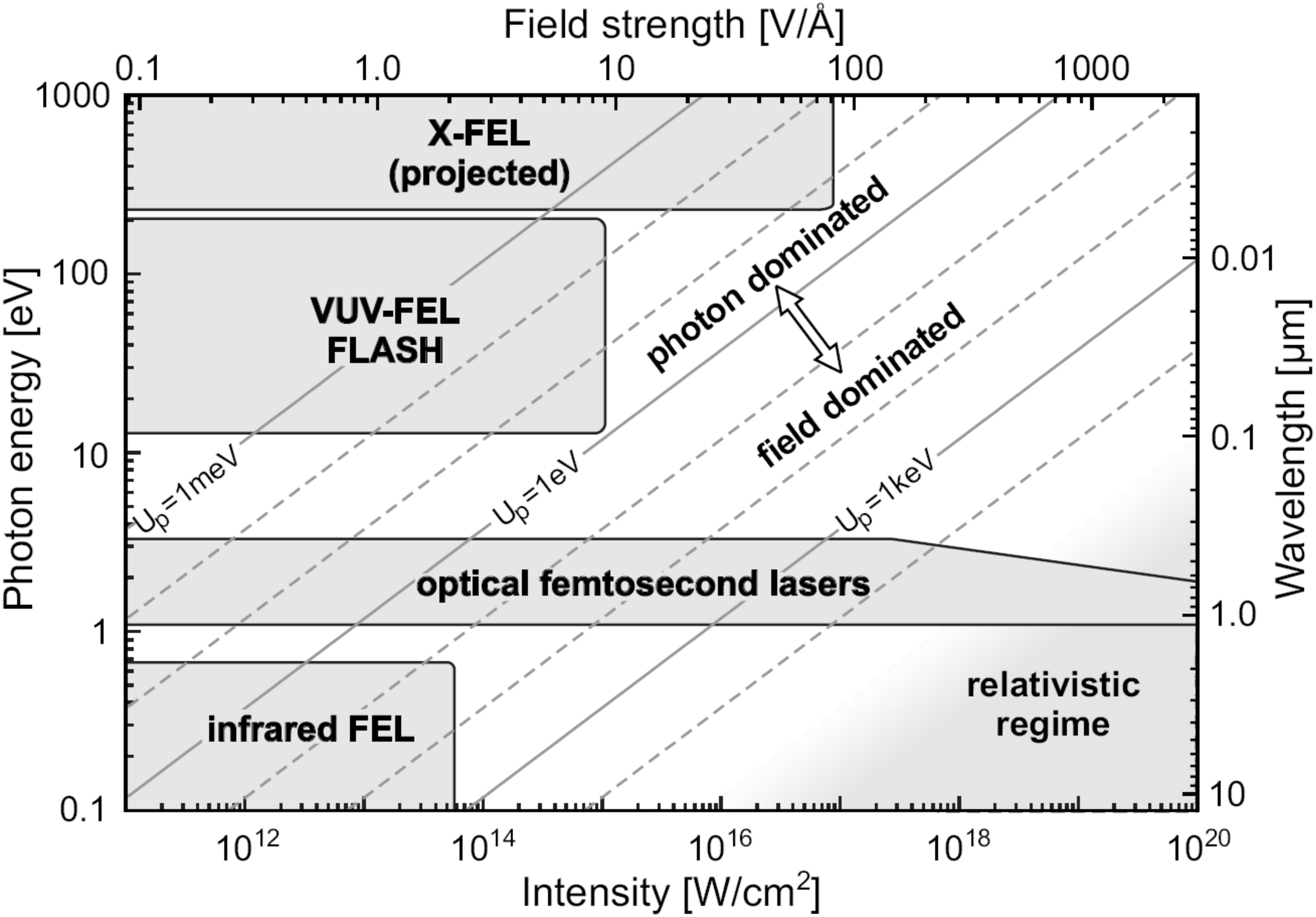
DESY

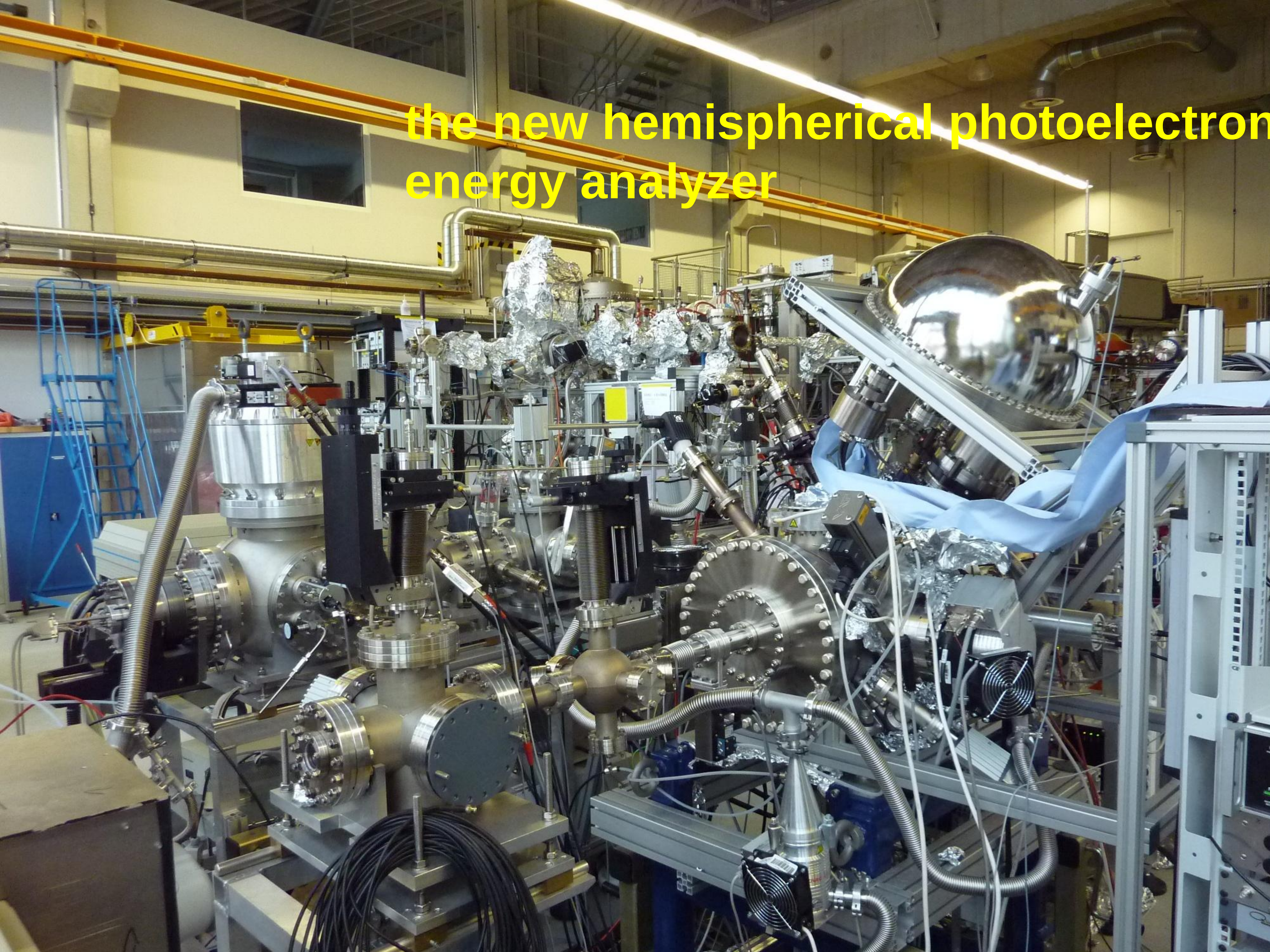
FLASH and PETRA III



free electron laser FLASH up to 260 eV or down to 4.8 nm

Laser intensity regimes





the new hemispherical photoelectron energy analyzer

our team in Hamburg

lecture 24.11.2011

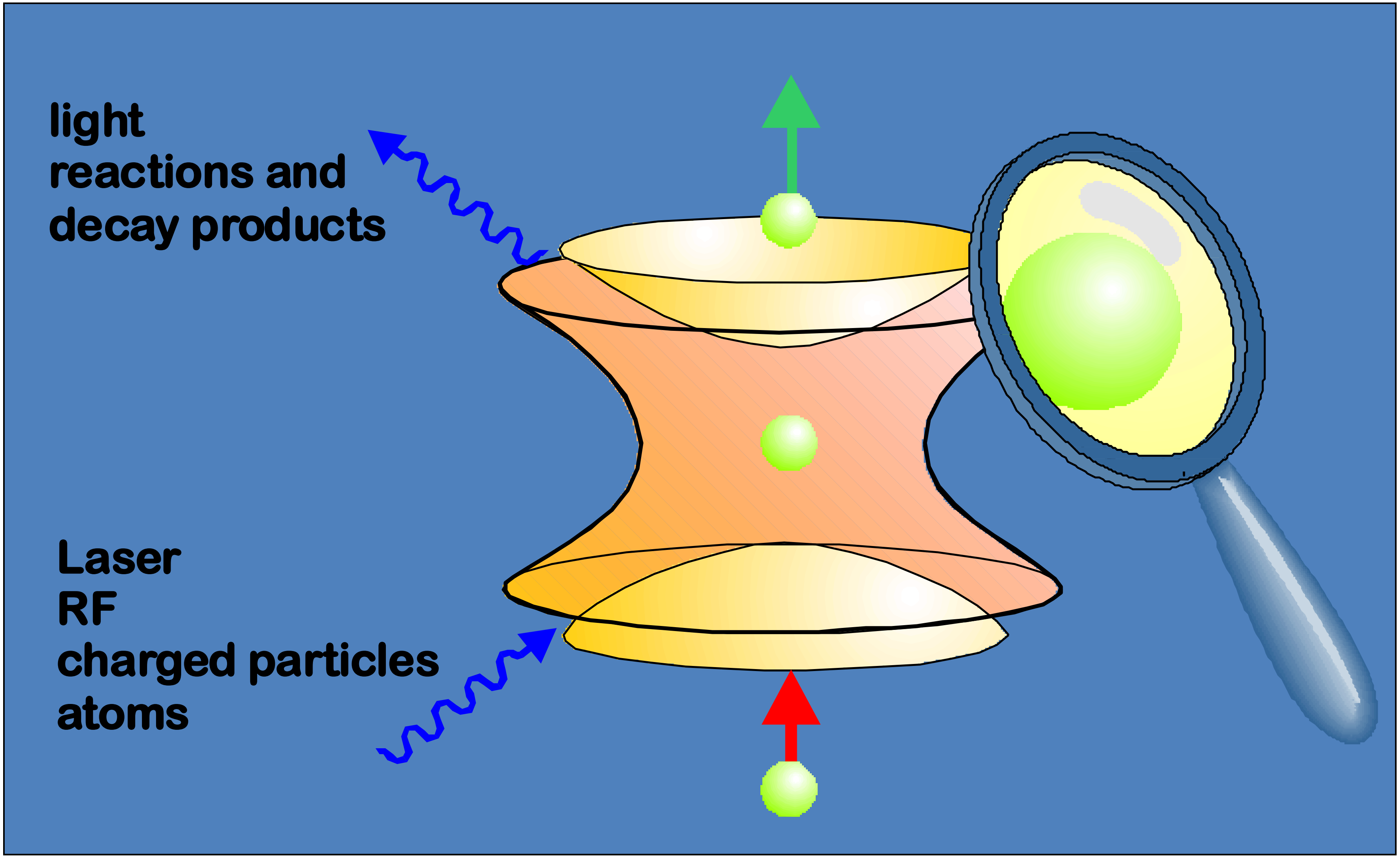
we had so far:

- cooling and trapping of atoms, Bose Einstein condensation
- trapping and cooling of ions

now:

- continuation with trapping and cooling of ions
- ion crystals

Ion traps: store, select and investigate particles in ‘free’ space

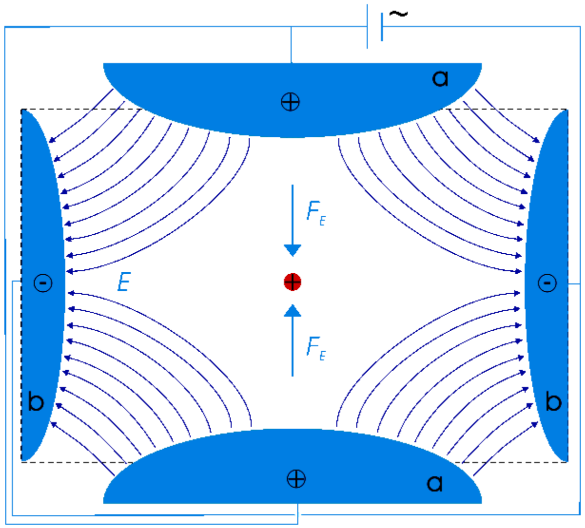


light
reactions and
decay products

Laser
RF
charged particles
atoms

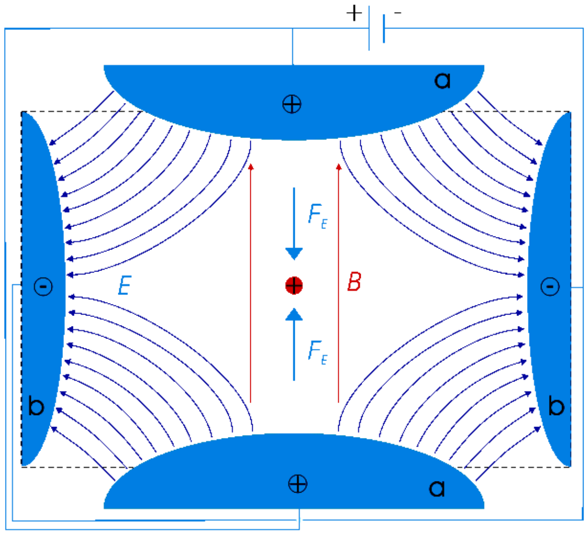
Paul trap

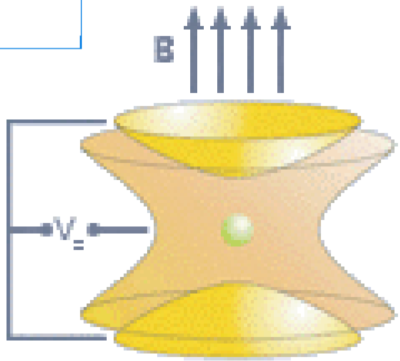
principle: electric alternating field



Penning trap

principle: superposition of a magnetic field



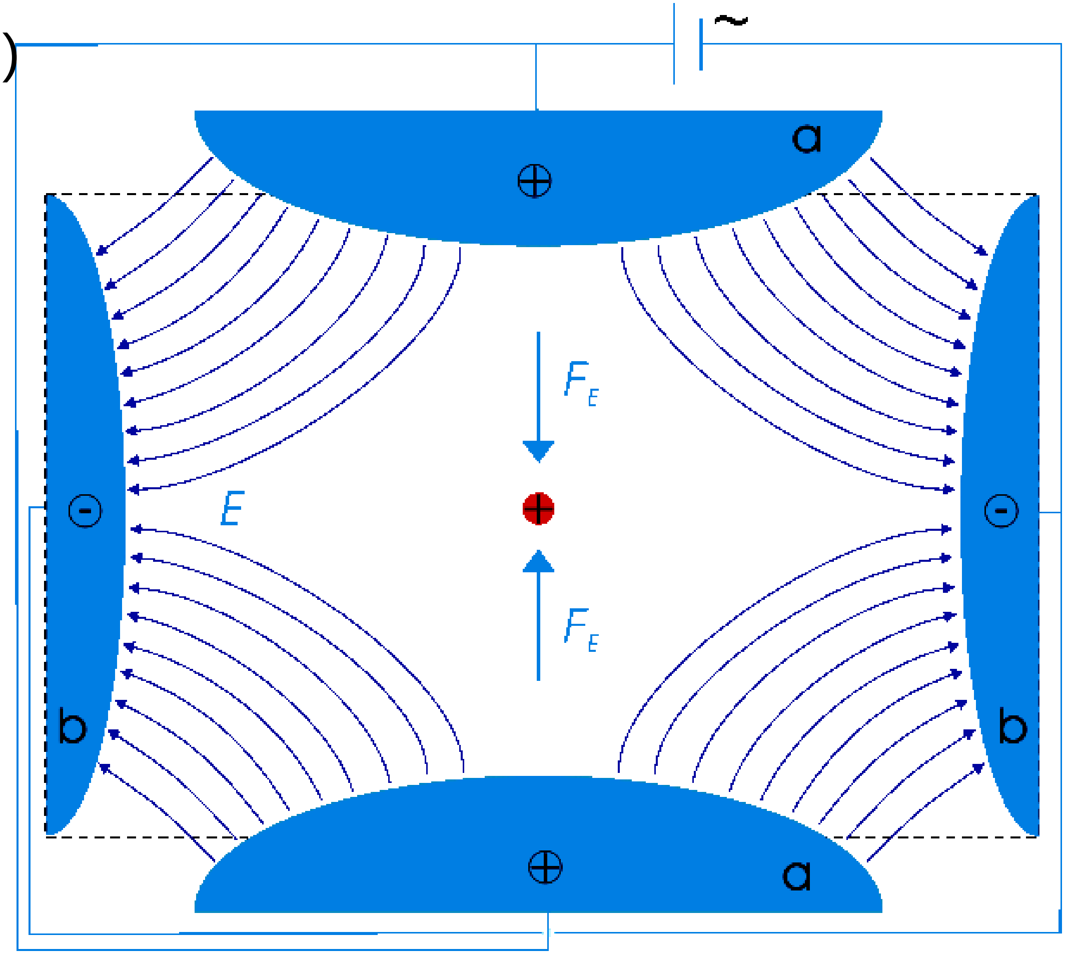


[K. Blaum, Phys. Rep. 425, 1-78 (2006)]

the Paul trap

developed by
Wolfgang Paul (1913-1993)
in the 1950ies

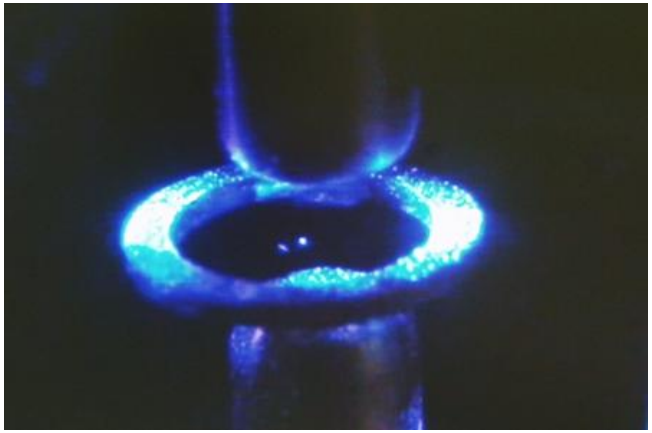
Nobel price
in physics 1989



Electrically alternating field creates a static pseudopotential

operation of a Paul trap with charged dust particles

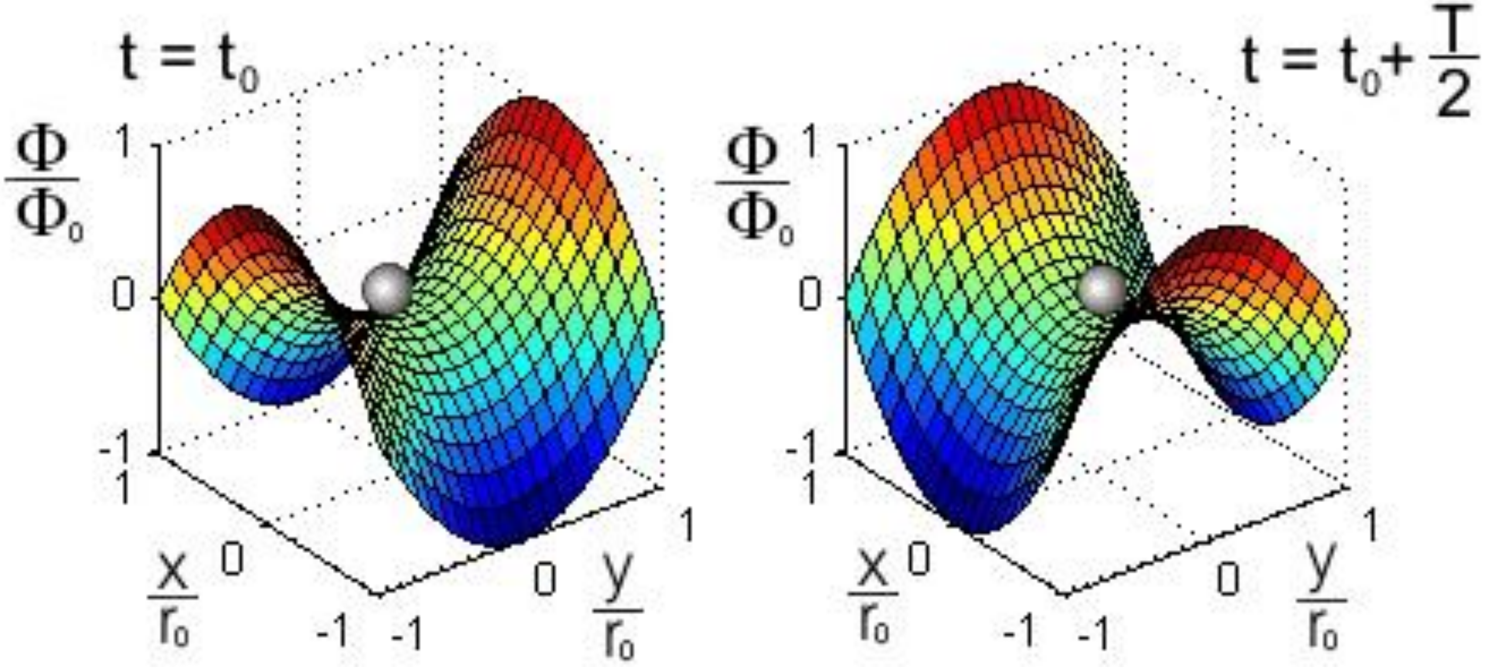
see Youtube http://www.youtube.com/watch?v=bkYXNeJ8IP0



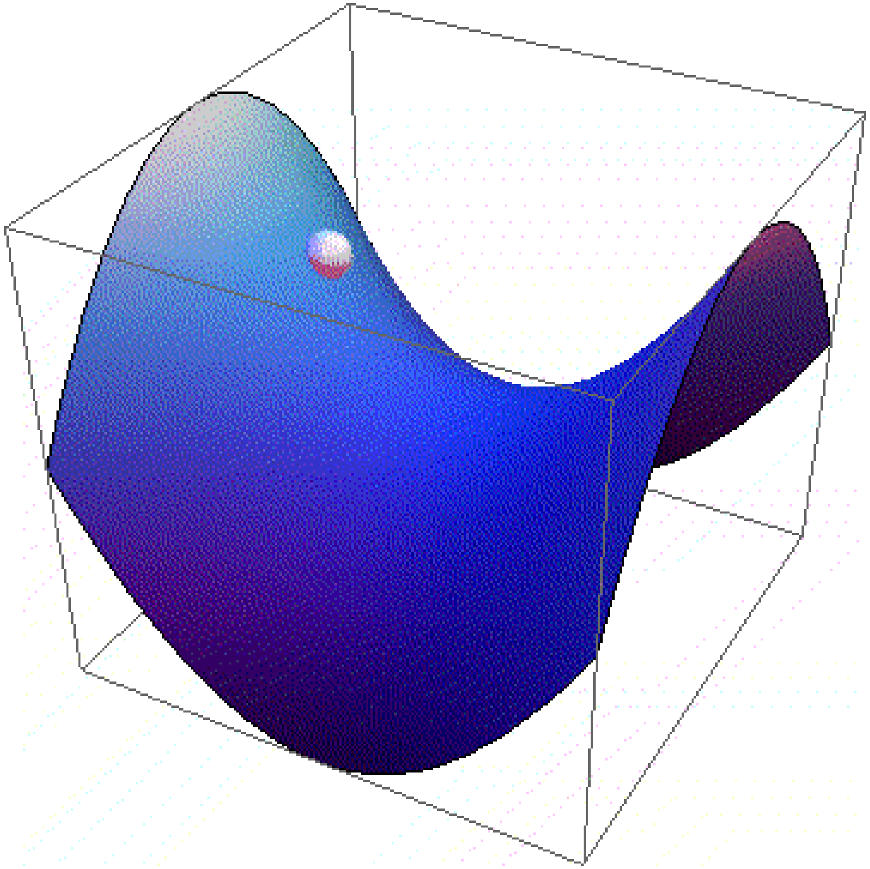
Principle:

Paul traps allow for the trapping of charged particles (normally ions) in a purely electric alternating field. For field oscillations that are fast compared to the motion of the trapped particle, the trajectory can be described by a ponderomotive force that always directs the particle towards regions of low electric field and therefore enables stable trapping at field minima.

time dependent potential of the Paul trap



$$\Phi(x,y,z,t) = \frac{U_0 \cdot sin\omega t}{2r_0^2} \cdot (x^2 + y^2 - 2z^2)$$



c.f.:
the mechanical analogon - rotating saddle will trap a ball

equation of motion

$$\frac{d^2 r}{dt^2} + \frac{e(U_0 + V_0 \cos(\Omega t))}{m r_0^{\,2}} r = 0 \qquad \frac{d^2 z}{dt^2} - \frac{2e(U_0 + V_0 \cos(\Omega t))}{m r_0^{\,2}} z = 0$$

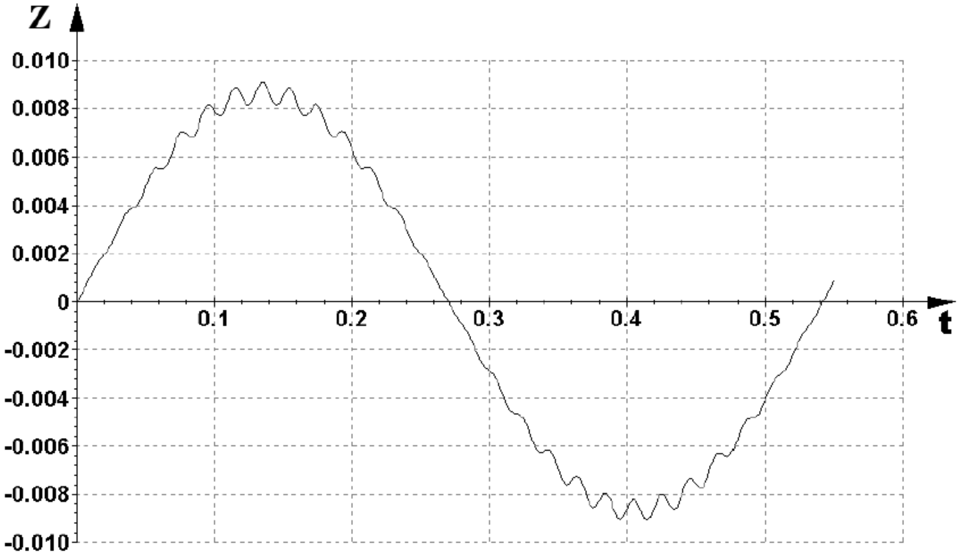
special cases of the Mathieu differential equation

equation of motion derived from the static 'pseudo potential':

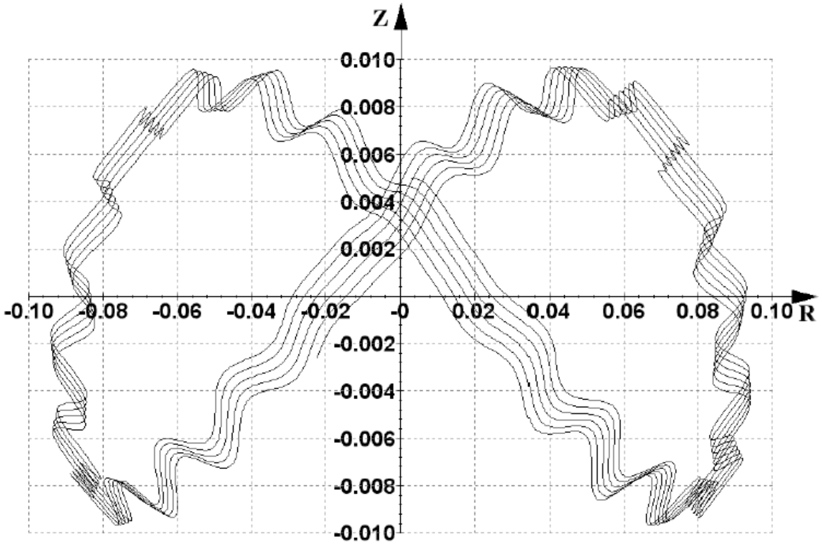
$$u(t) \propto \left[1 - \frac{q_u}{2}\cos(\Omega t)\right]\cos(\omega t - \varphi) \qquad \omega = \frac{\beta_u}{2}\Omega$$

- micro motion: driven oscillation with phase locked to the exciting field
- macro motion: free oscillations of the ions in the pseudopotential

ion motion in time and space

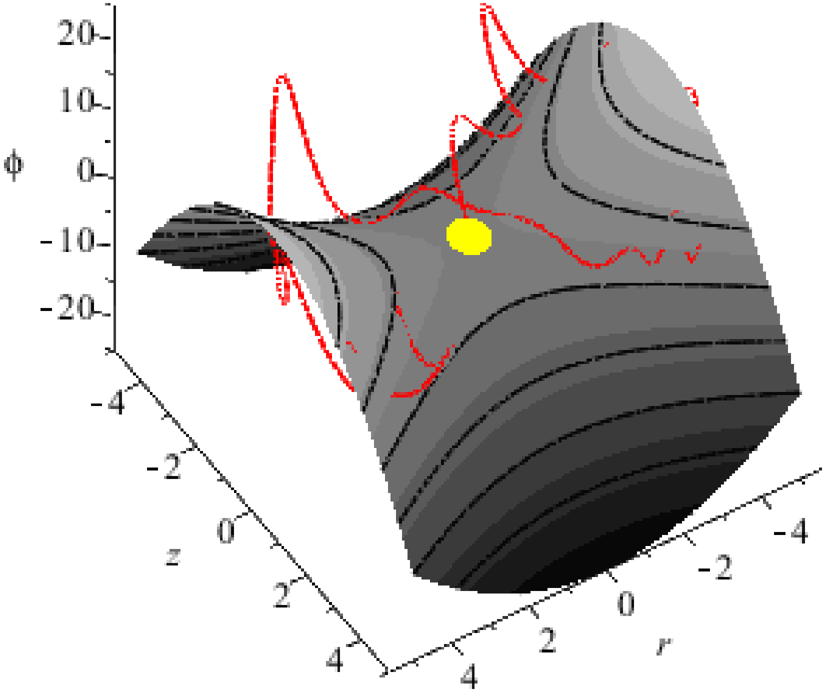


micro and macromotion

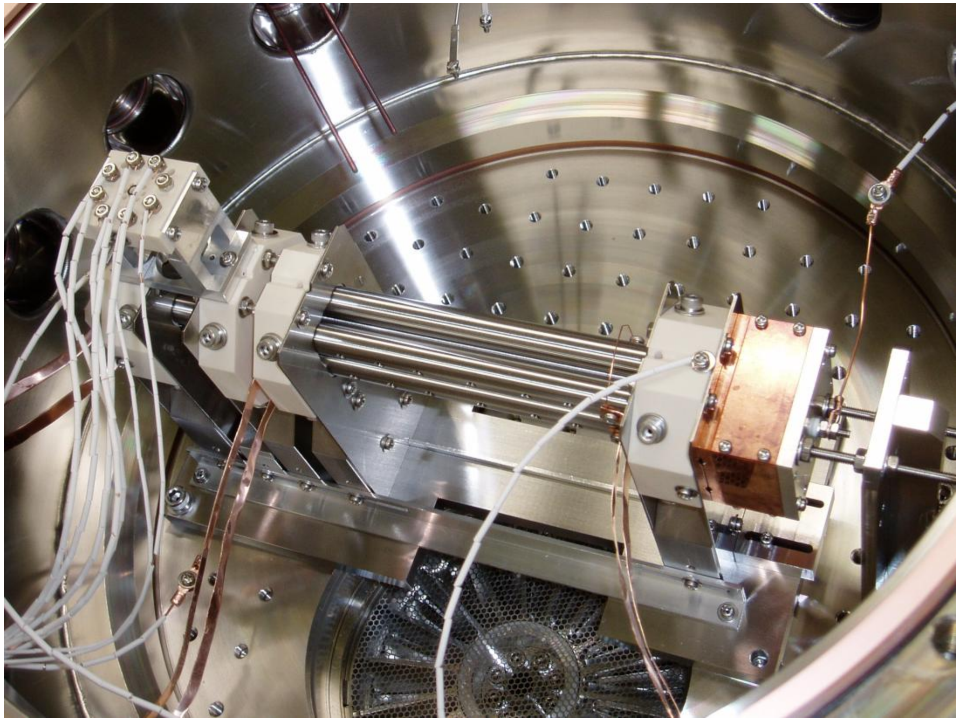


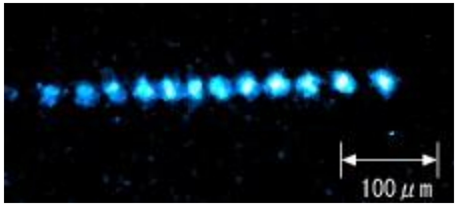
trajectory

hallo paul!



Ca $^+$ ions in a linear Paul trap

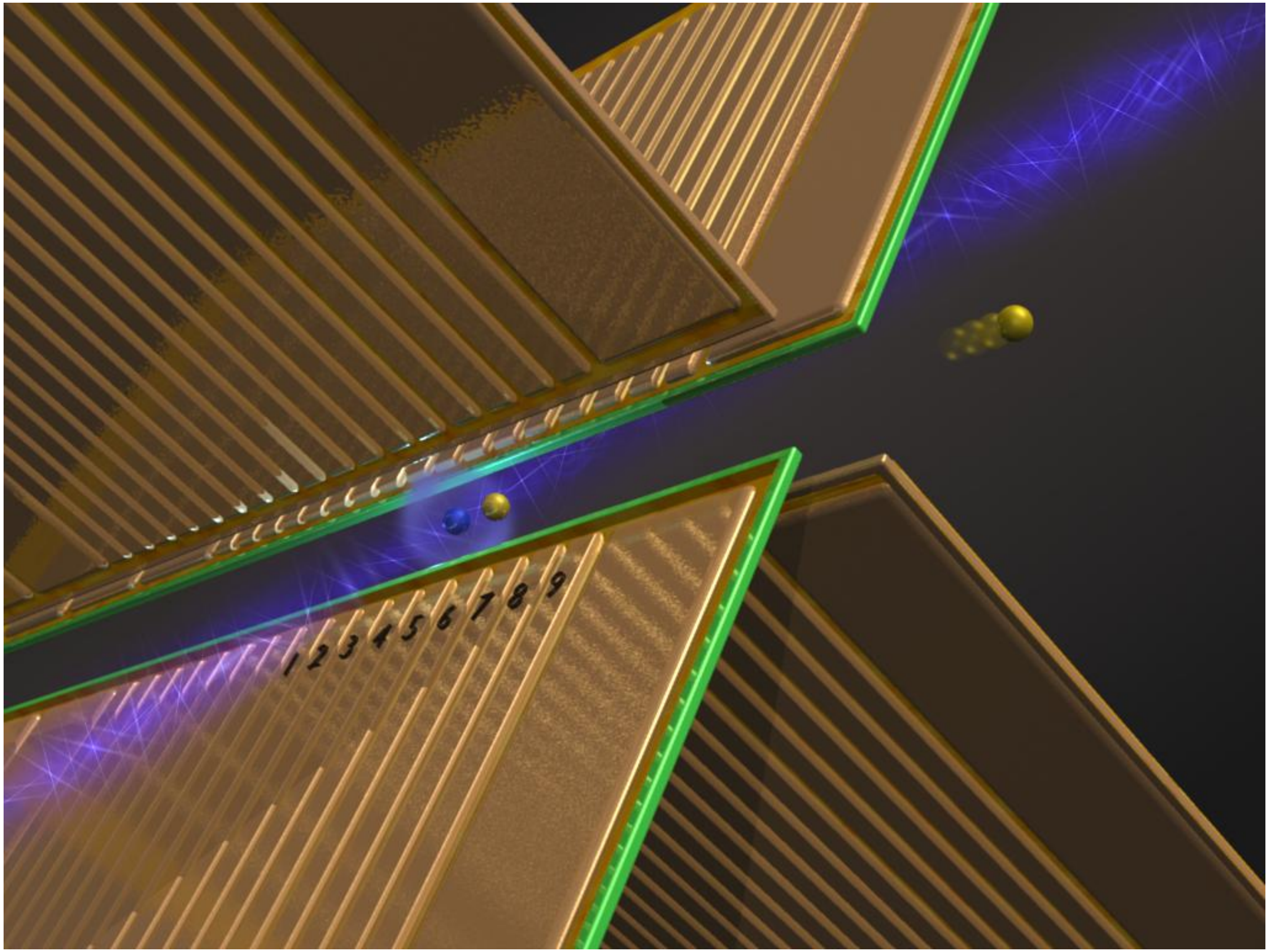




Wolfgang Paul, Bonn
Nobel prize 1989
with Hans Dehmelt and Norman Ramsey

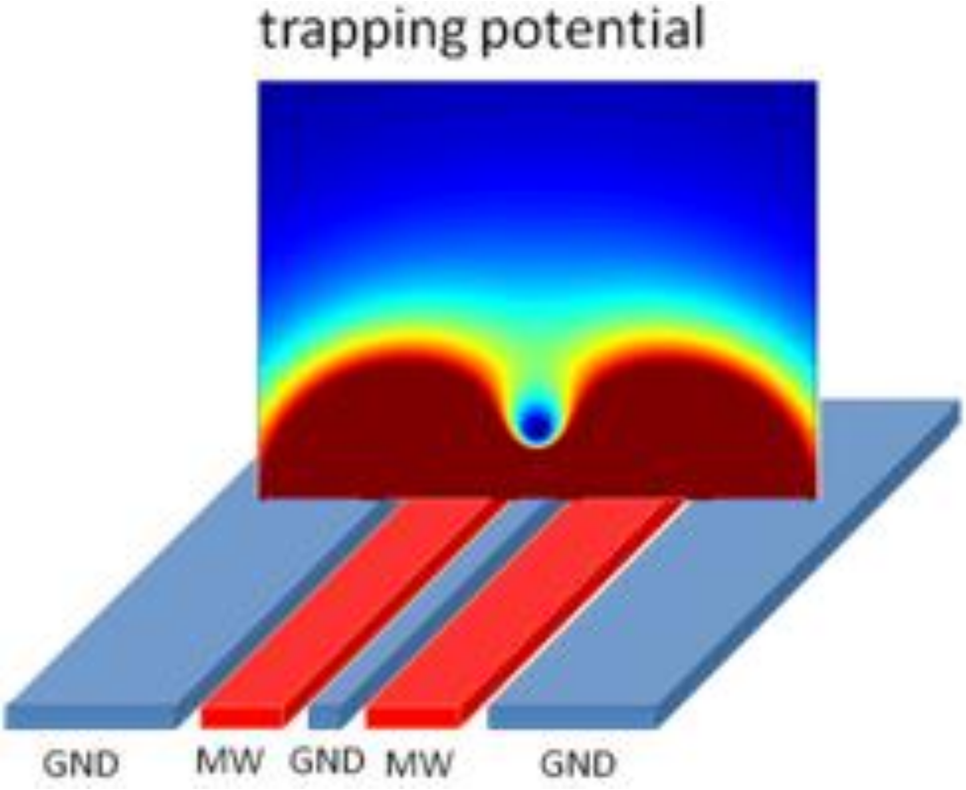
segmented linear Paul trap as single ion source

for quantum information experiments



University of Ulm

planar Paul trap for electrons

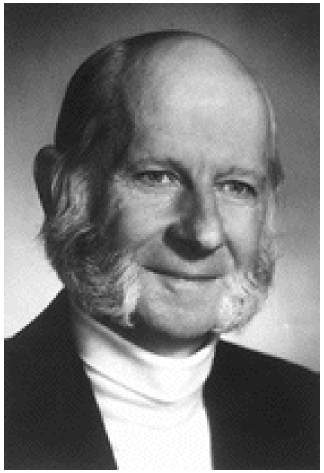


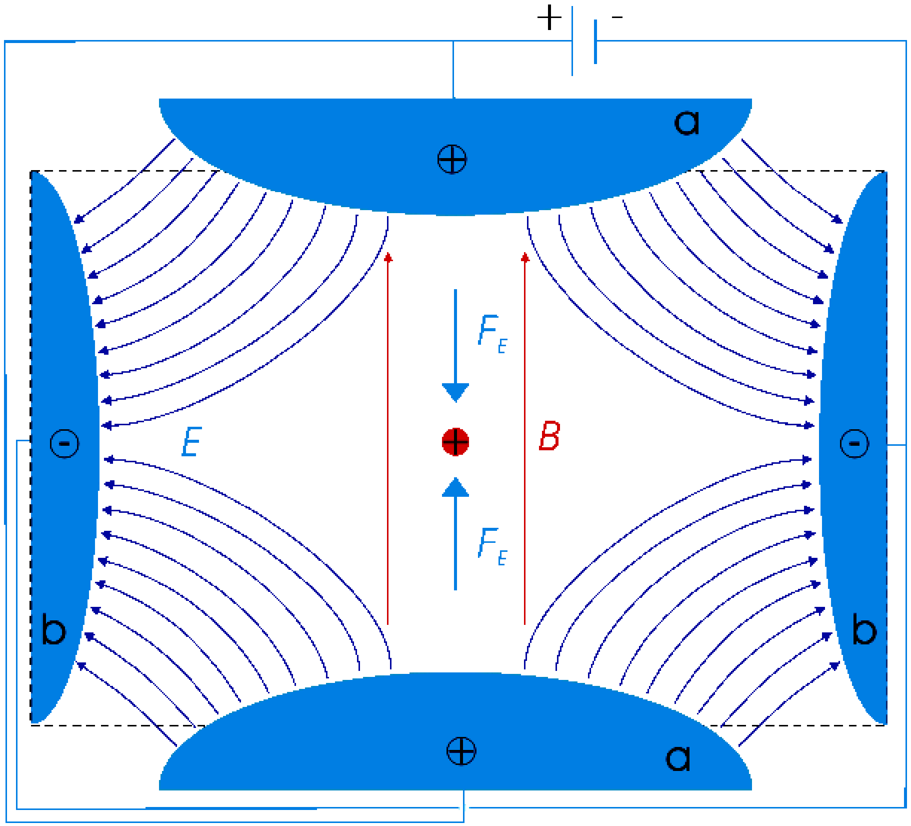
Planar five wire structure with cut through the time averaged potential seen by electrons above the wires. A microwave voltage is applied to the red electrodes (MW), whereas the blue electrodes are held at ground potential (GND). The plot shows regions of high potential energy in red and those of low potential energy in blue. Electrons are guided in the blue minimum in the lower center of the image

Due to their low mass, electrons move fast in electric fields, so that high driving frequencies are necessary: 1GHz and 10GHz.
Ions: 10MHz to 100MHz.

the Penning trap

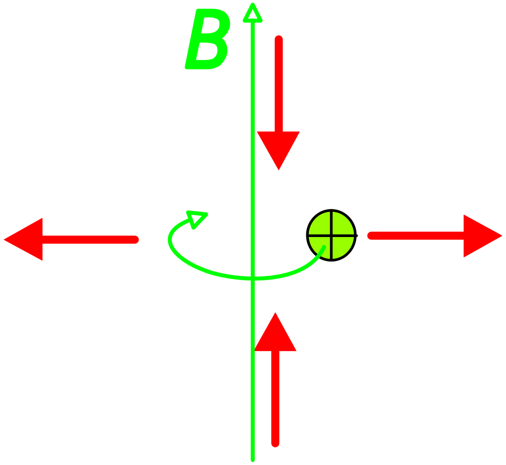
idea of the Dutch Physicist Frans Michel Penning in the 1930ies





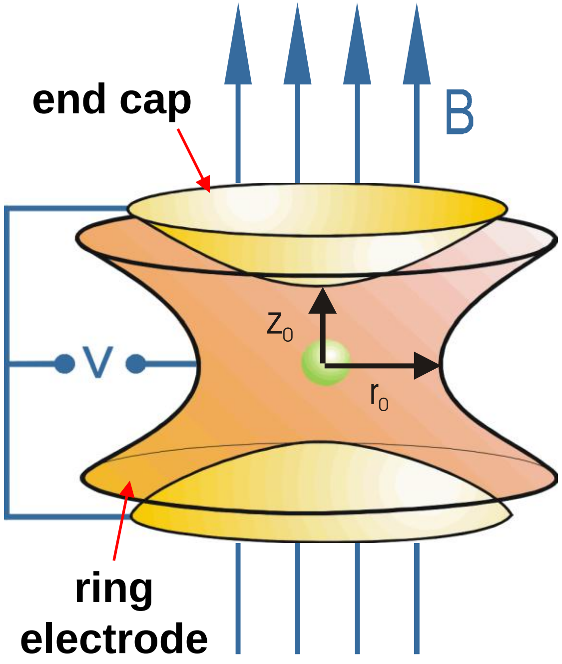
realization: Hans G. Dehmelt
(Nobel prize in physics 1989)

Principle of Penning traps (see exercise)



Cyclotron frequency: $f_c = \frac{1}{2\pi} \cdot \frac{q}{m} \cdot B$

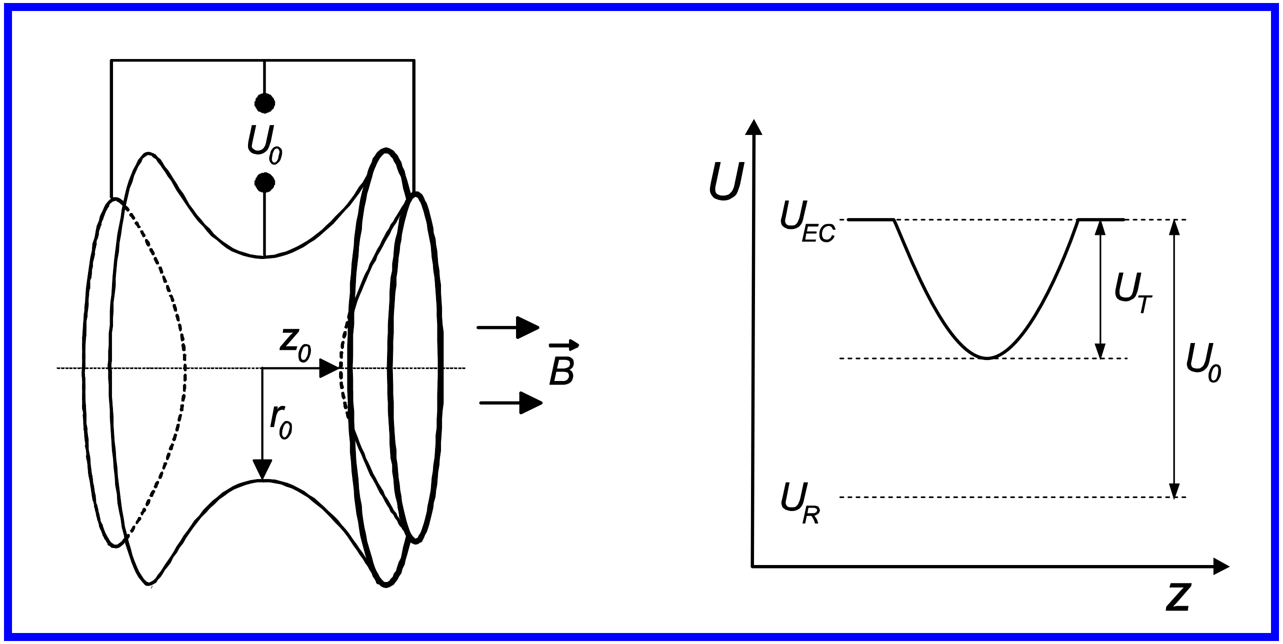
- **Strong homogeneous magnetic field**
- **Weak electric 3D quadrupole field**



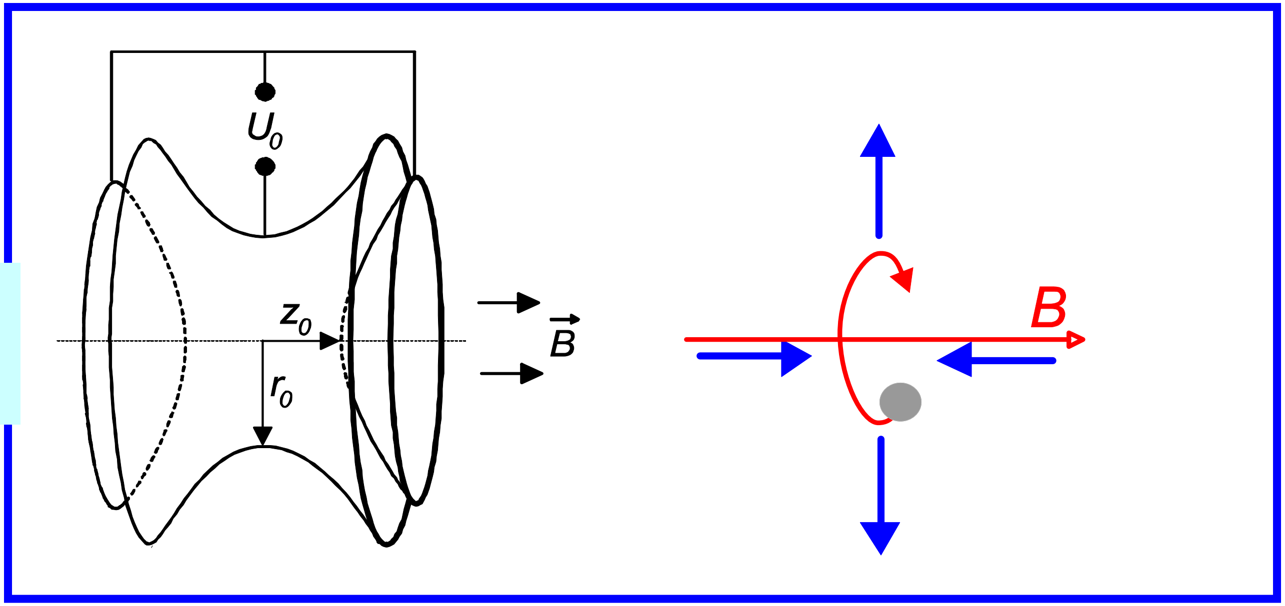
Confinement

in a Penning trap

axial harmonic potential



radial confinement with magnetic field



motion in the Penning trap

plus Lorentz force:

$$\vec{F} = -e_0\vec{\nabla}\phi(r) + e_0\vec{v}\times\vec{B}$$

equation of motion:

$$e_0(\vec{\nabla}\phi(r) + \vec{v}\times\vec{B}) + m\ddot{\vec{r}} = 0$$

axial oscillation

$$\frac{2e_0U_0}{md_0^2}\cdot z + m\ddot{z} = 0$$

$$\omega_z = \sqrt{\frac{2e_0U_0}{md_0^2}}$$

***z* or axial frequency**

radial oscillation

substitution:

$$u = x + iy$$

$$\omega_c = \frac{e_0}{m}B$$

$$u(t) = u_0 e^{-i\omega t}$$

$$i\omega_c\dot{u} - \frac{\omega_z^2}{2}u + \ddot{u} = 0$$

$$\omega_+ = \frac{\omega_c}{2} + \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}}$$

modified or reduced cyclotron frequency

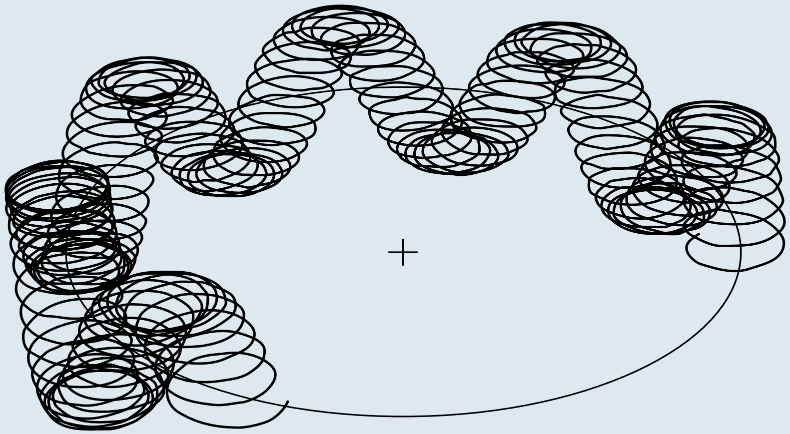
$$\omega_- = \frac{\omega_c}{2} - \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}}$$

magnetron frequency

Ion motion in a Penning trap

Motion of an ion is the superposition of three harmonic eigenmodes:

- axial motion (frequency f_z)
- magnetron motion (frequency f_-)
- modified cyclotron motion (frequency f_+)



$$f_+ + f_- = f_c$$

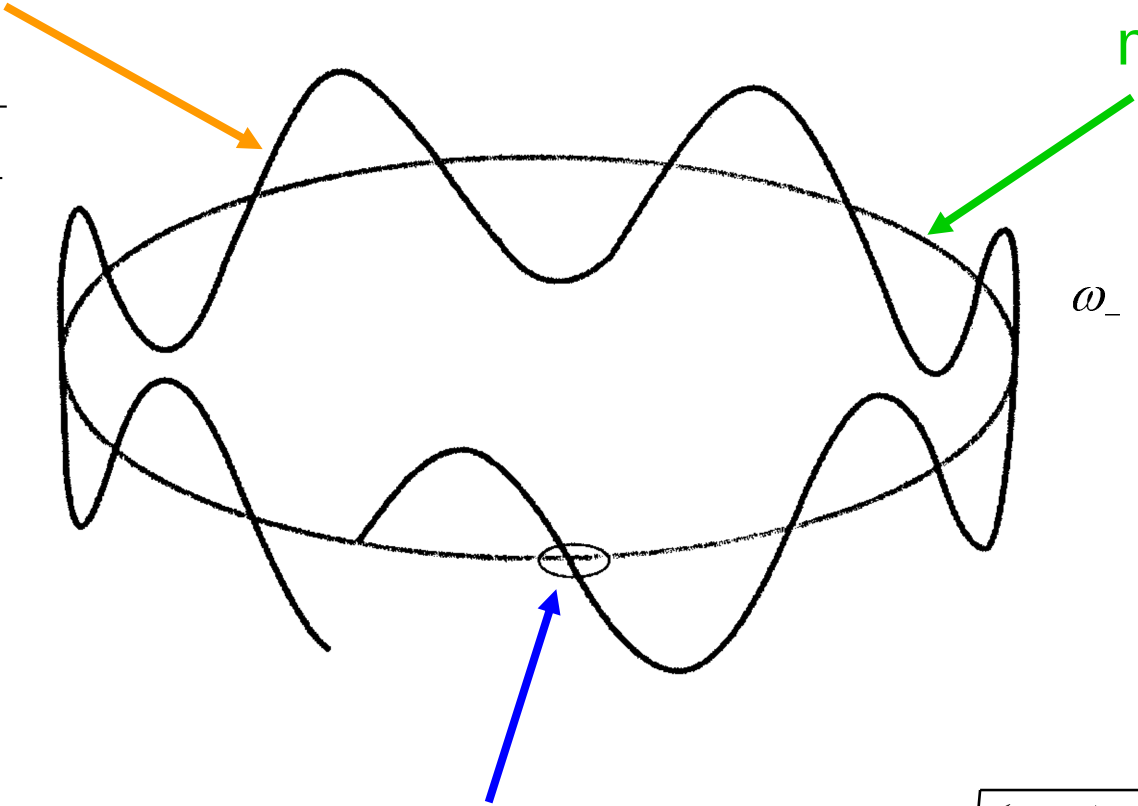
fc:= cyclotron frequency

Typical frequencies
q = e, m = 1000 u,
B = 6 T

$\Rightarrow$ $f_- \approx$ 1 kHz
$f_+ \approx$ 100 kHz

L.S. Brown, G. Gabrielse,
Rev. Mod. Phys. 58, 233 (1986).

another view on the ion motion in Penning trap



trapping
motion

$$\omega_z = \sqrt{\frac{qU}{md^2}}$$

magnetron
motion

$$\omega_- = \frac{\omega_c}{2} - \sqrt{\left(\frac{\omega_c}{2}\right) - \frac{\omega_z^2}{2}}$$

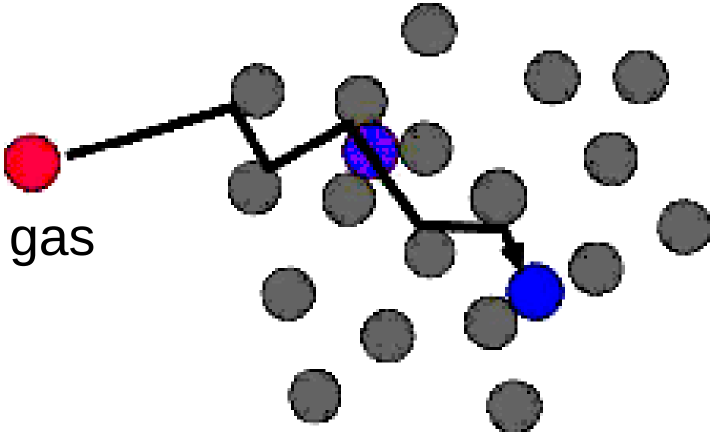
cyclotron
motion

$$\omega_+ = \frac{\omega_c}{2} + \sqrt{\left(\frac{\omega_c}{2}\right) - \frac{\omega_z^2}{2}}$$

cooling methods

- buffer gas collisions
- electron collisions
- evaporation cooling
- Laser cooling
- sympathic cooling

buffer gas cooling:



- collisions with a cold gas

- final temperature is temp. of the cold gas

- good for all particles

electron collisions cooling:

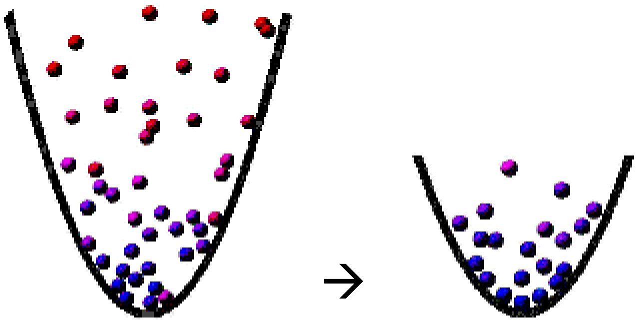
- co-propagating electron beam

- ion velocity ultimately adapts the electron velocity

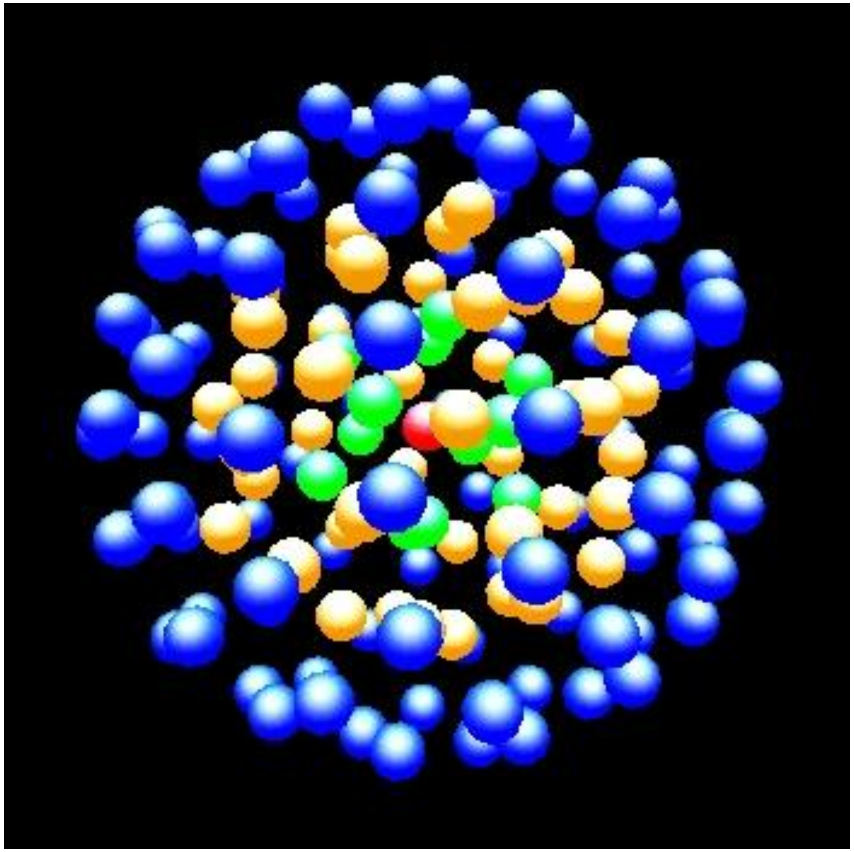
→monoenergetic ion beam with low divergence

evaporation cooling:

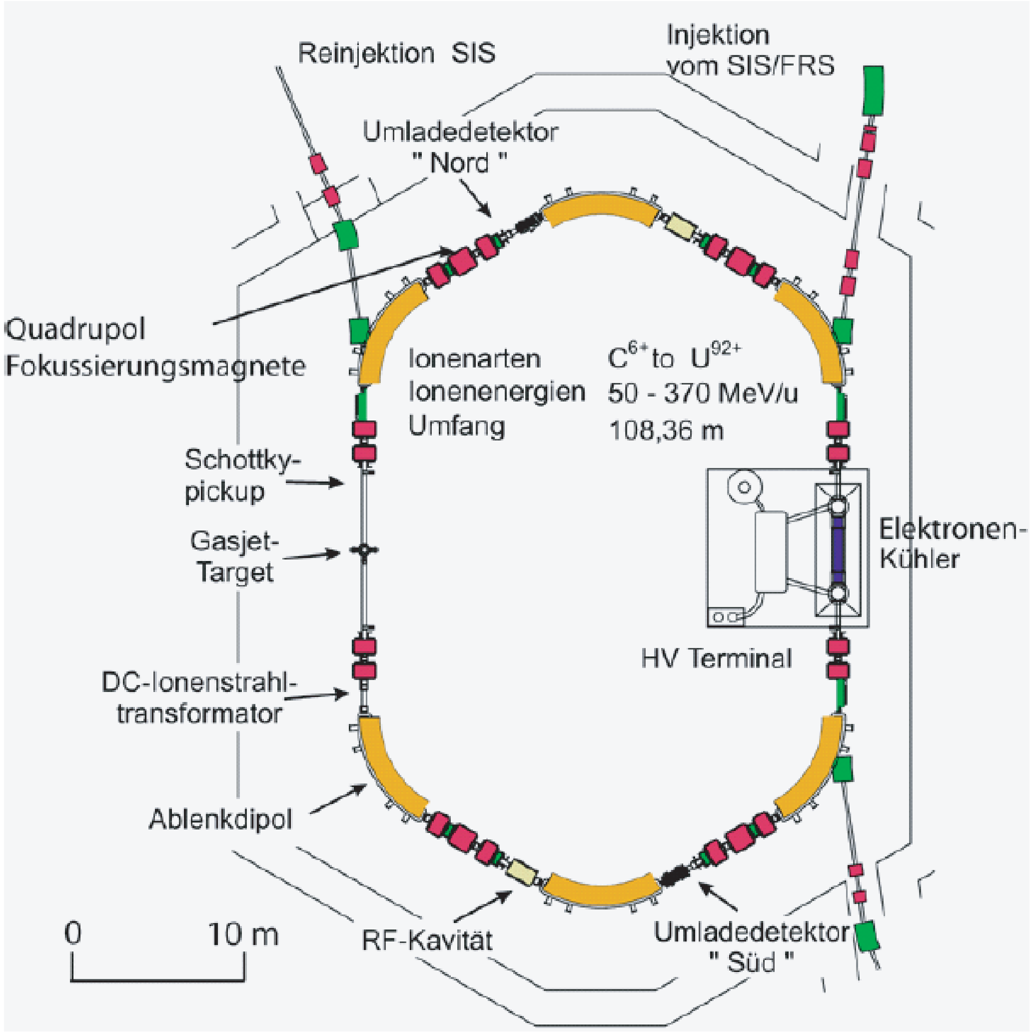
- hot atoms of the **Maxwell-Boltzmann distribution** will be removed



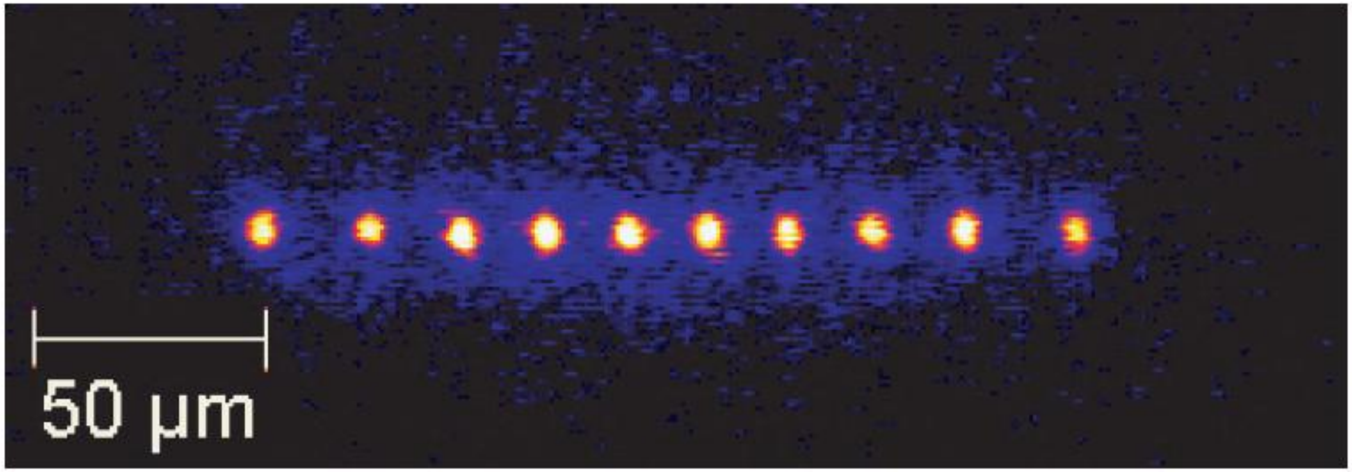
Wigner crystal



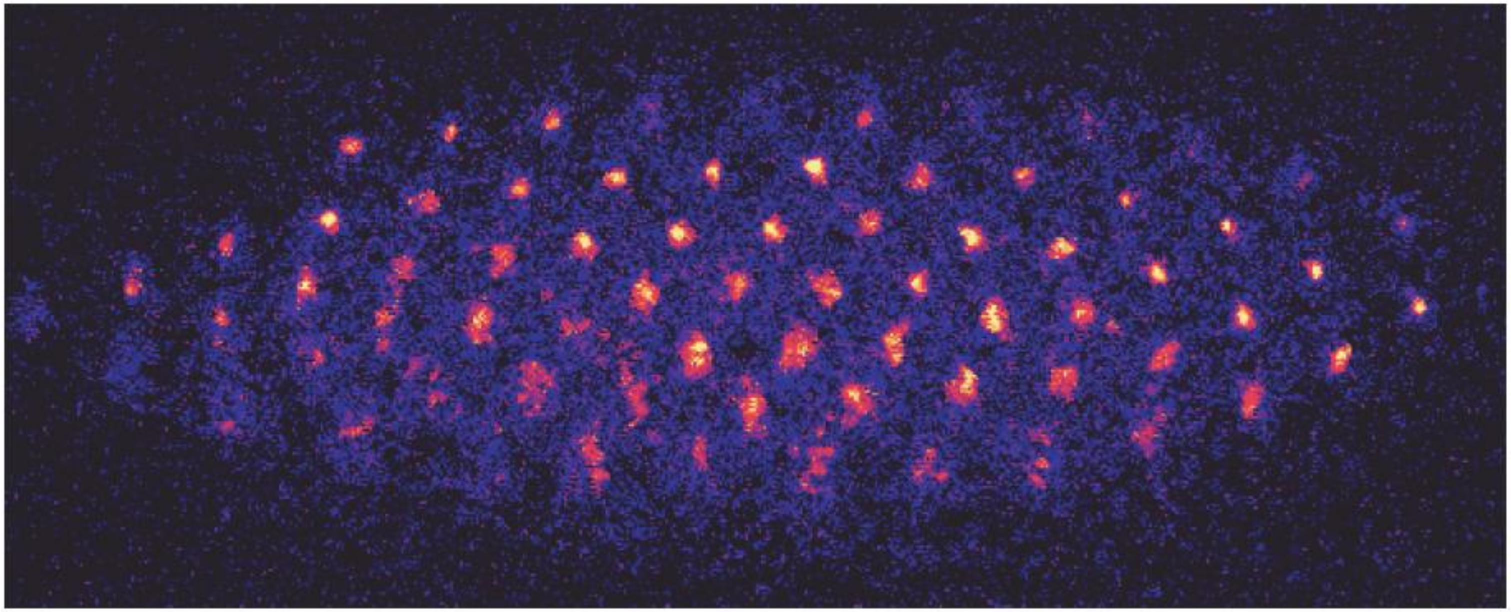
storage ring at the GSI Darmstadt



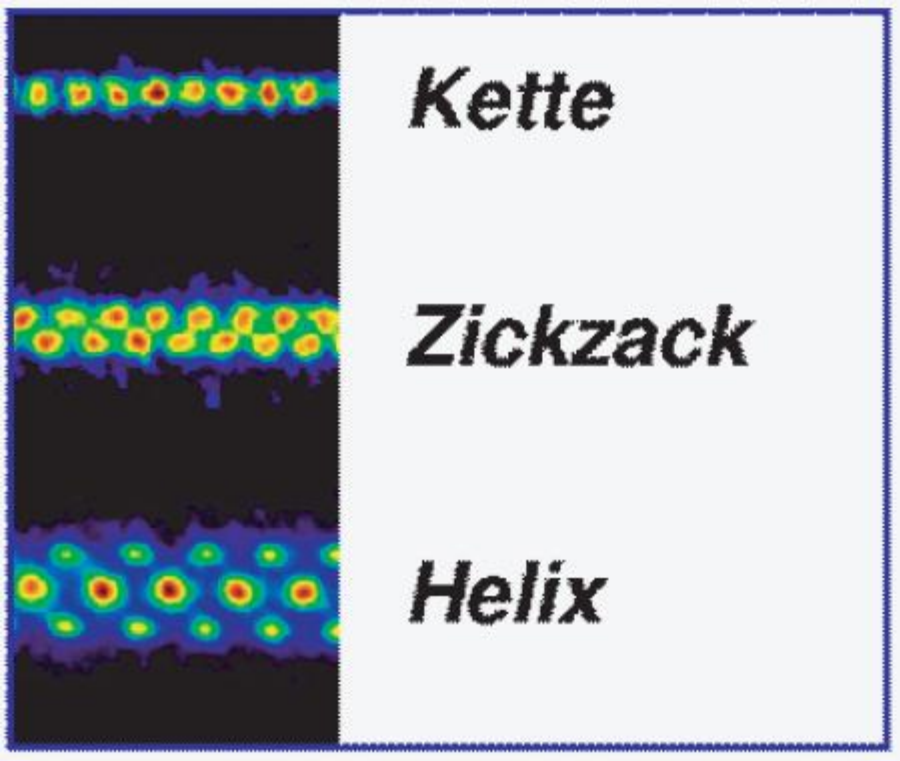
Calcium ions in a linear Paul trap



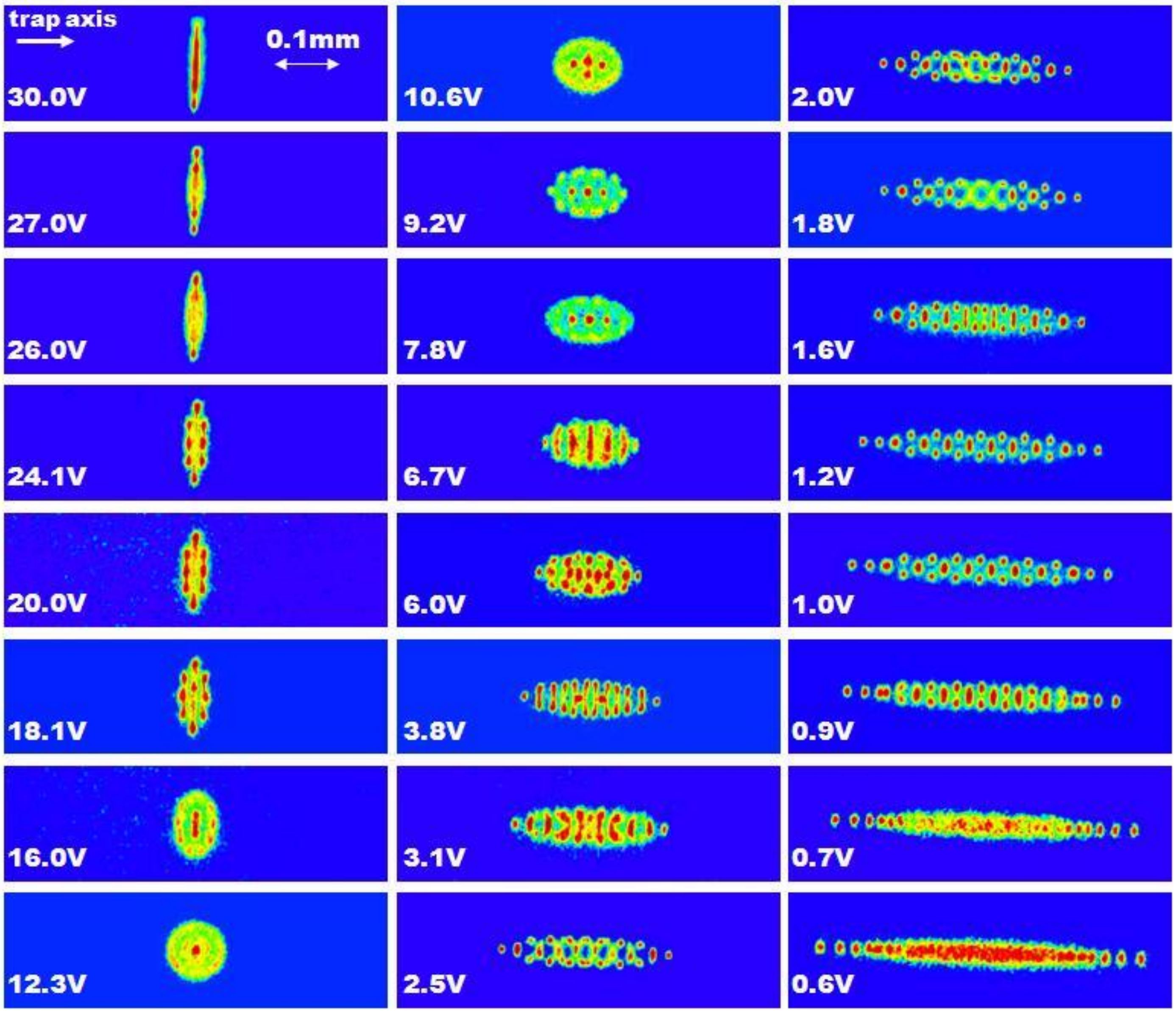
Calcium ions crystal



ion crystals at different linear densities

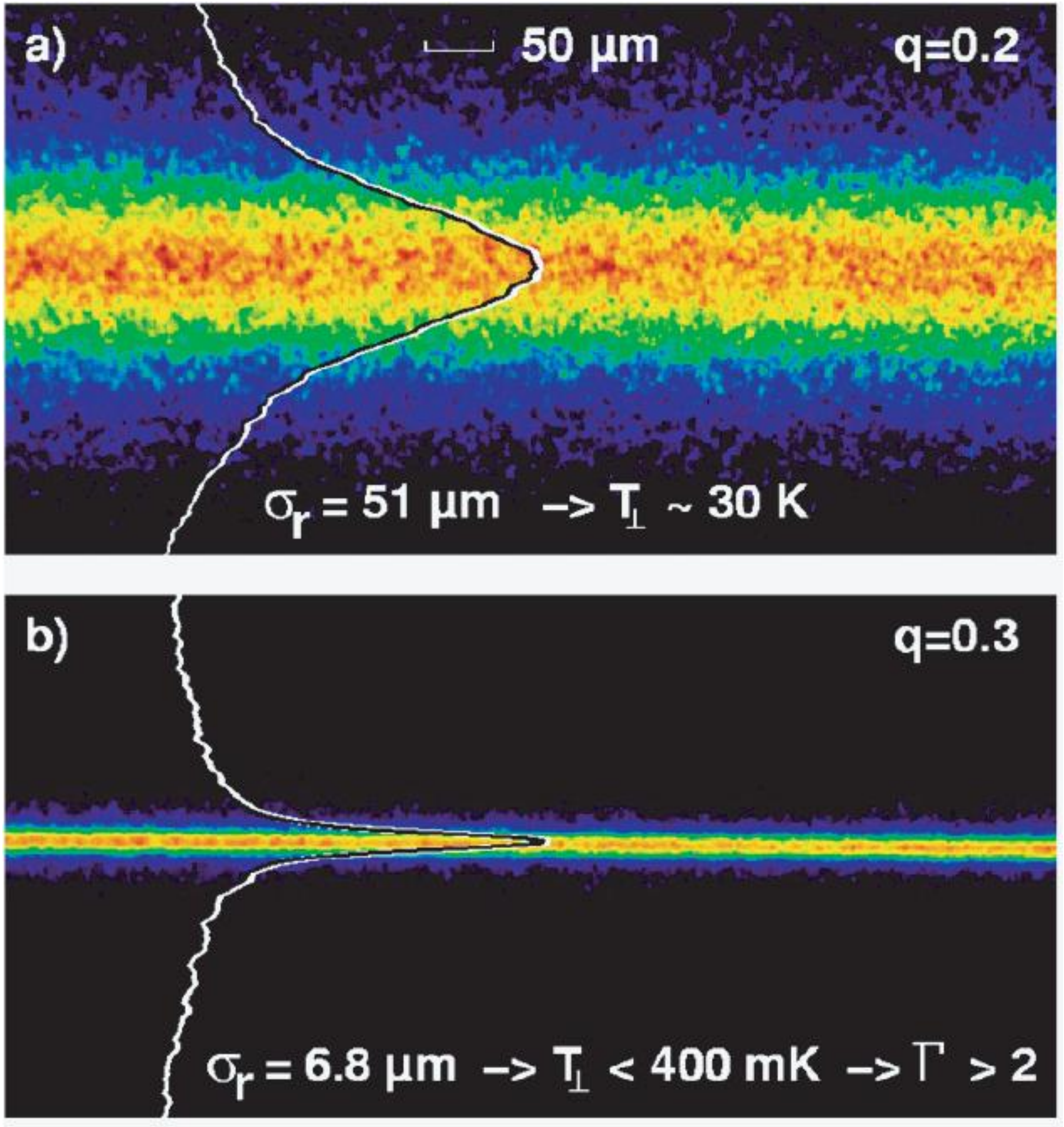


Ca^+ Coulomb crystals in a linear Paul trap, 34 ions

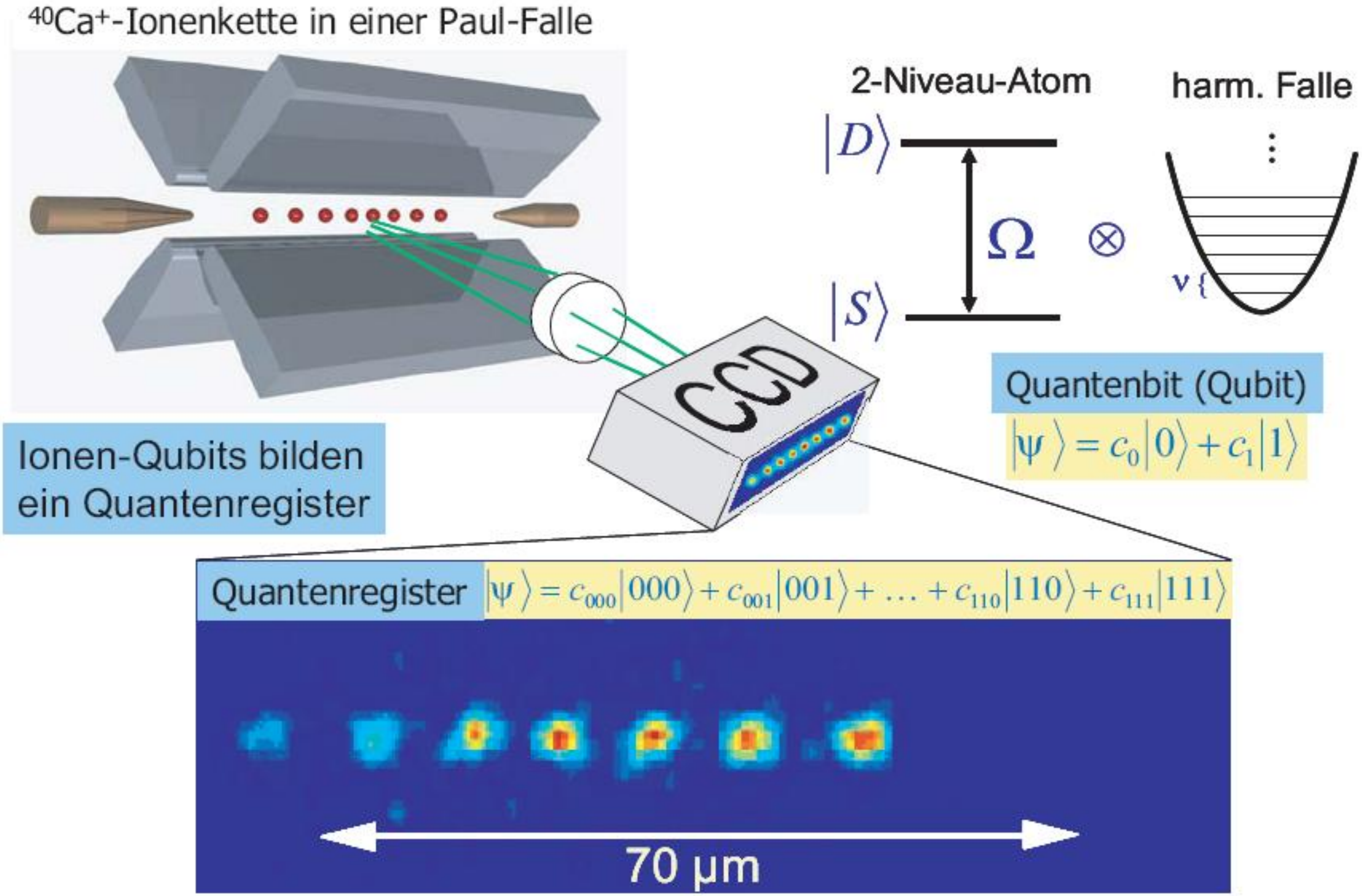


Gallery of Ion Coulomb crystals, Univ. of Sofia

phase transition from liquid to crystalline phase in an ion beam



ions can be crystallized and manipulated for quantum information



$^{40}Ca^{+}$-Ionenkette in einer Paul-Falle

2-Niveau-Atom

harm. Falle

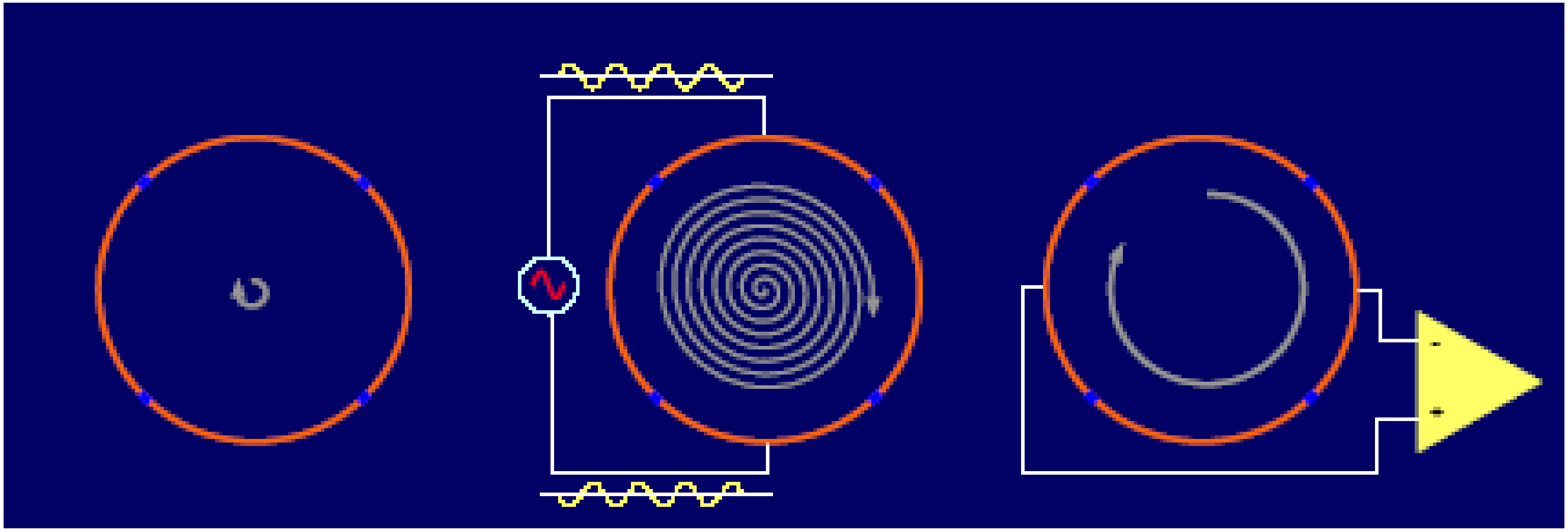
Quantenbit (Qubit)

$|\psi\rangle = c_0|0\rangle + c_1|1\rangle$

Ionen-Qubits bilden ein Quantenregister

Quantenregister $|\psi\rangle = c_{000}|000\rangle + c_{001}|001\rangle + \ldots + c_{110}|110\rangle + c_{111}|111\rangle$

Penning trap: Fourier transform ion cyclotron resonance mass spectroscopy FTICR



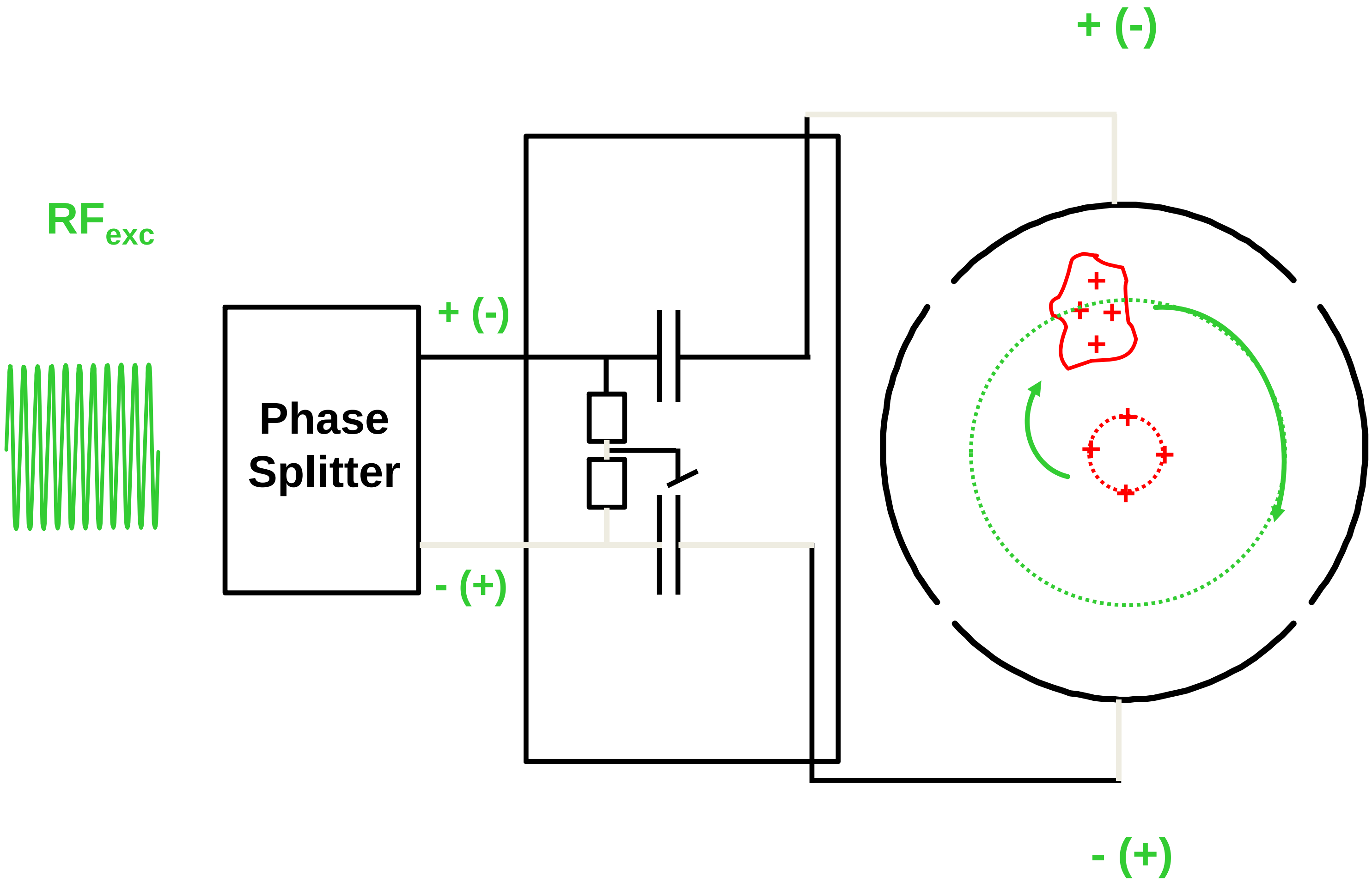
- Ions are trapped and oscillate with low, incoherent, thermal amplitude

- Excitation sweeps resonant ions into a large, coherent cyclotron orbit

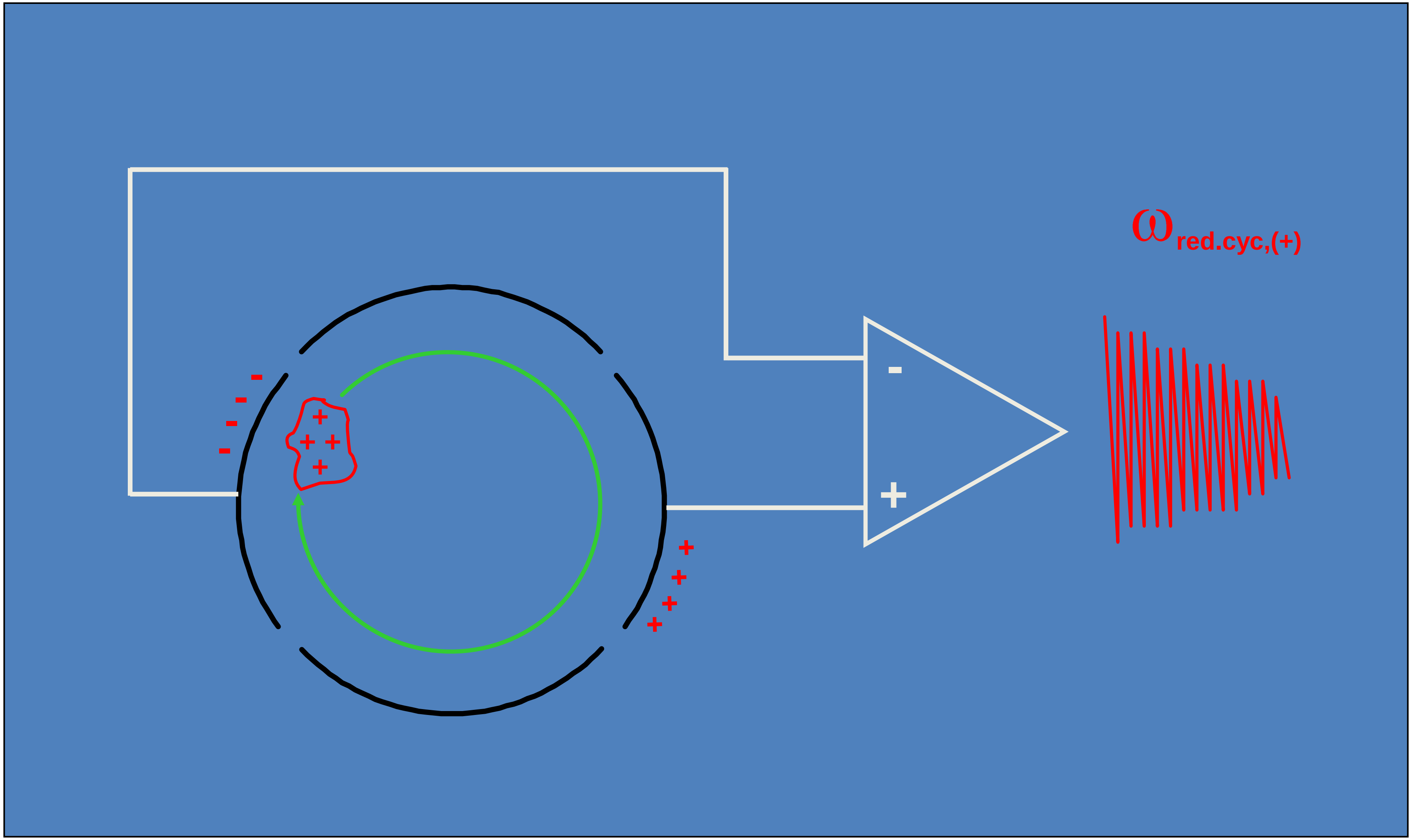
- Preamplifier and digitizer pick up the induced potentials on the cell wall

Fourier transform ion cyclotron resonance mass spectroscopy FTICR

Excitation of Ion Motion

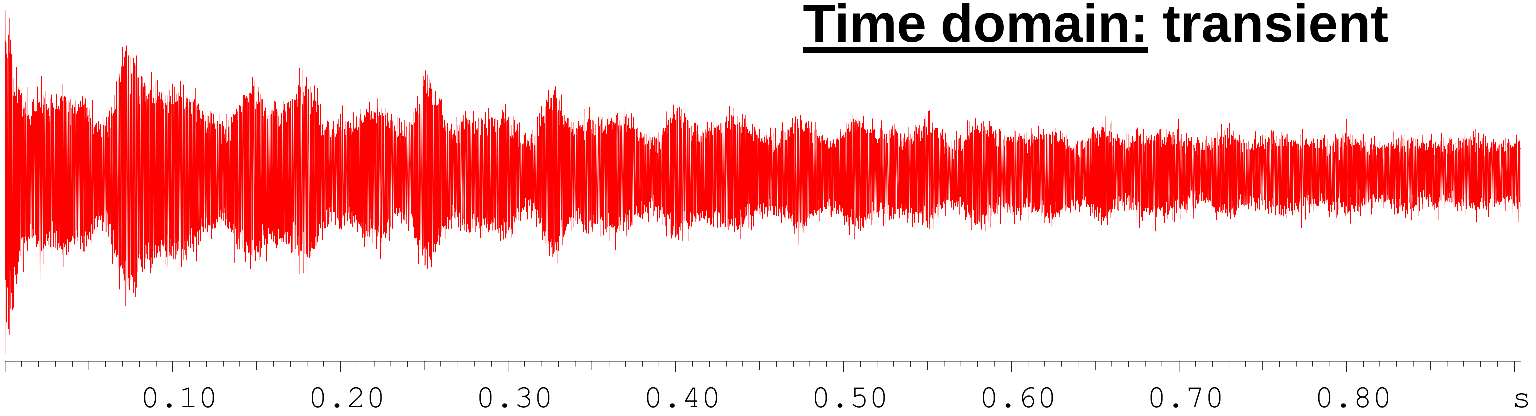


Detection of Ion Motion

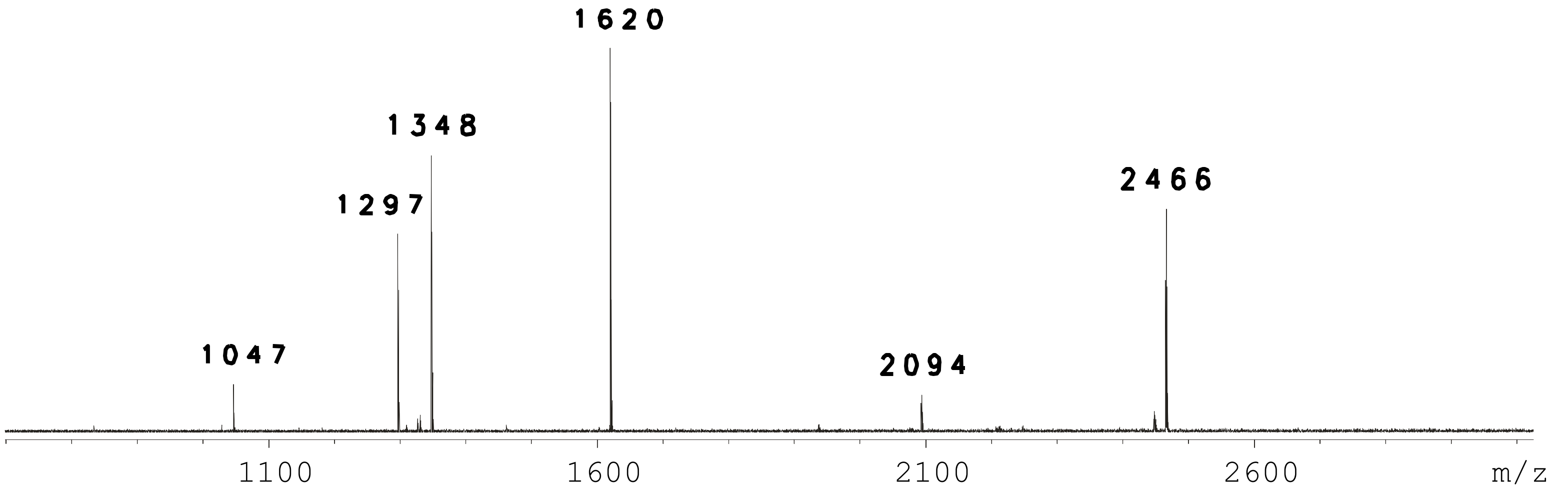


Fourier Transformation

<u>Time domain:</u> transient



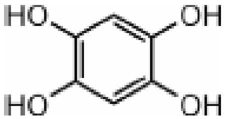
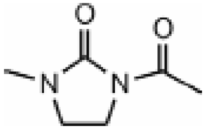
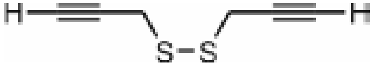
<u>Frequency domain:</u> mass spectrum

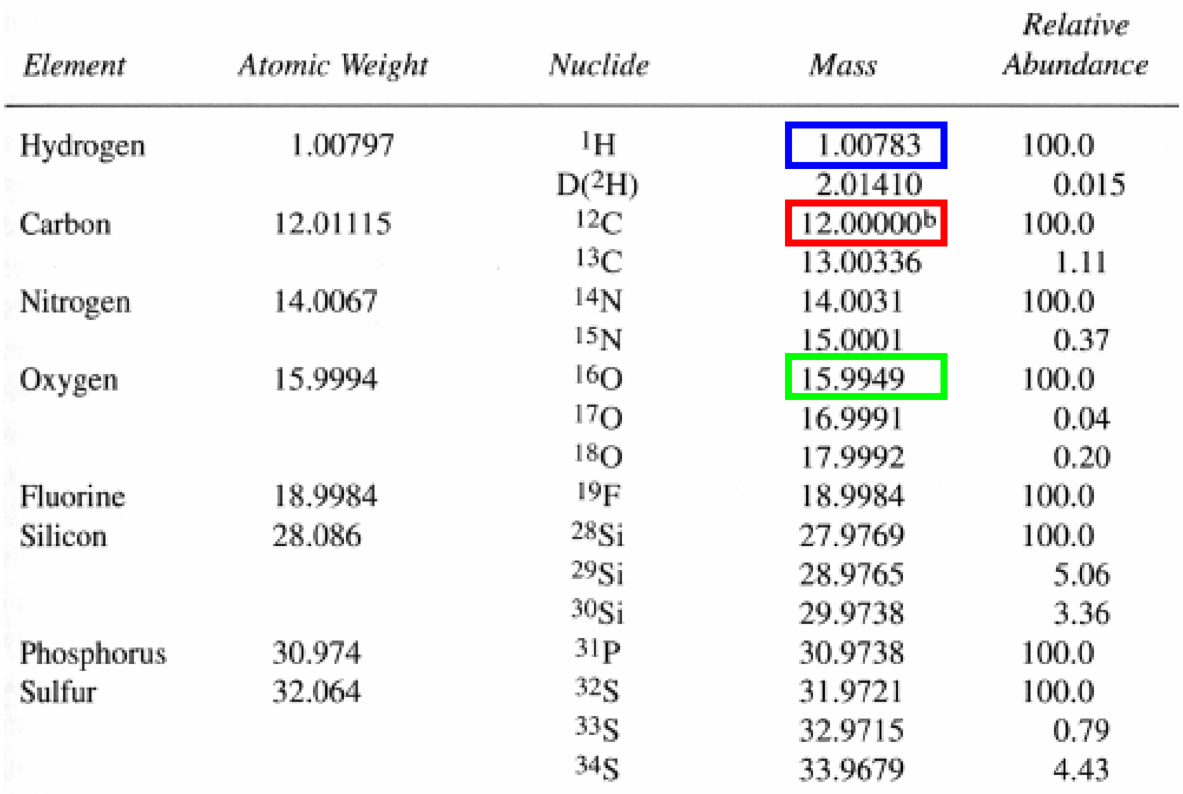


Why do we need such a high mass resolution?

Exact Masses and Molecular Formulae

So, molecules with different molecular formulae have different exact masses.

				
molecular formula	$C_{10}H_{22}$	$C_6H_6O_4$	$C_6H_{10}N_2O_2$	$C_6H_6S_2$
m/z (unit)	142	142	142	142
m/z (exact mass)	142.1723	142.0264	142.0743	141.9911



Element	*Atomic Weight*	*Nuclide*	*Mass*	*Relative Abundance*
Hydrogen	1.00797	^{1}H	1.00783	100.0
		$D(^{2}H)$	2.01410	0.015
Carbon	12.01115	^{12}C	12.00000[b]	100.0
		^{13}C	13.00336	1.11
Nitrogen	14.0067	^{14}N	14.0031	100.0
		^{15}N	15.0001	0.37
Oxygen	15.9994	^{16}O	15.9949	100.0
		^{17}O	16.9991	0.04
		^{18}O	17.9992	0.20
Fluorine	18.9984	^{19}F	18.9984	100.0
Silicon	28.086	^{28}Si	27.9769	100.0
		^{29}Si	28.9765	5.06
		^{30}Si	29.9738	3.36
Phosphorus	30.974	^{31}P	30.9738	100.0
Sulfur	32.064	^{32}S	31.9721	100.0
		^{33}S	32.9715	0.79
		^{34}S	33.9679	4.43

^{12}C mass set to 12 amu, exactly.

As a result, ^{1}H mass is actually higher than 1 amu.

And ^{16}O mass is lower than 16 amu.

Isotopes vary from unit masses by “mass defect”.

^{1}H has positive mass defect; ^{16}O has negative mass defect.

FTMS Extreme Resolution

From
Watson

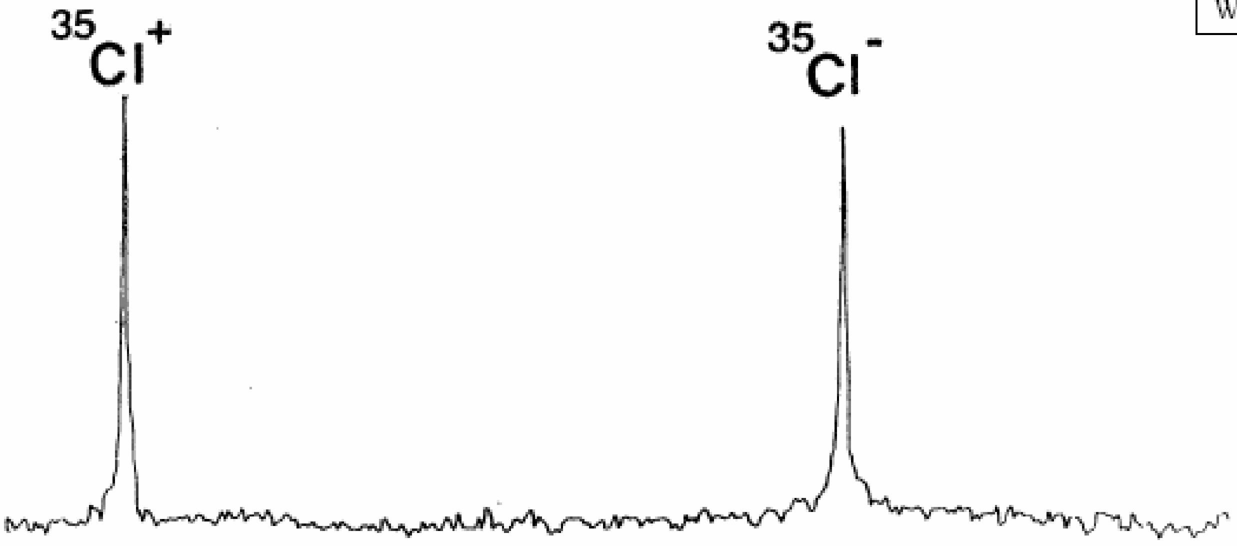
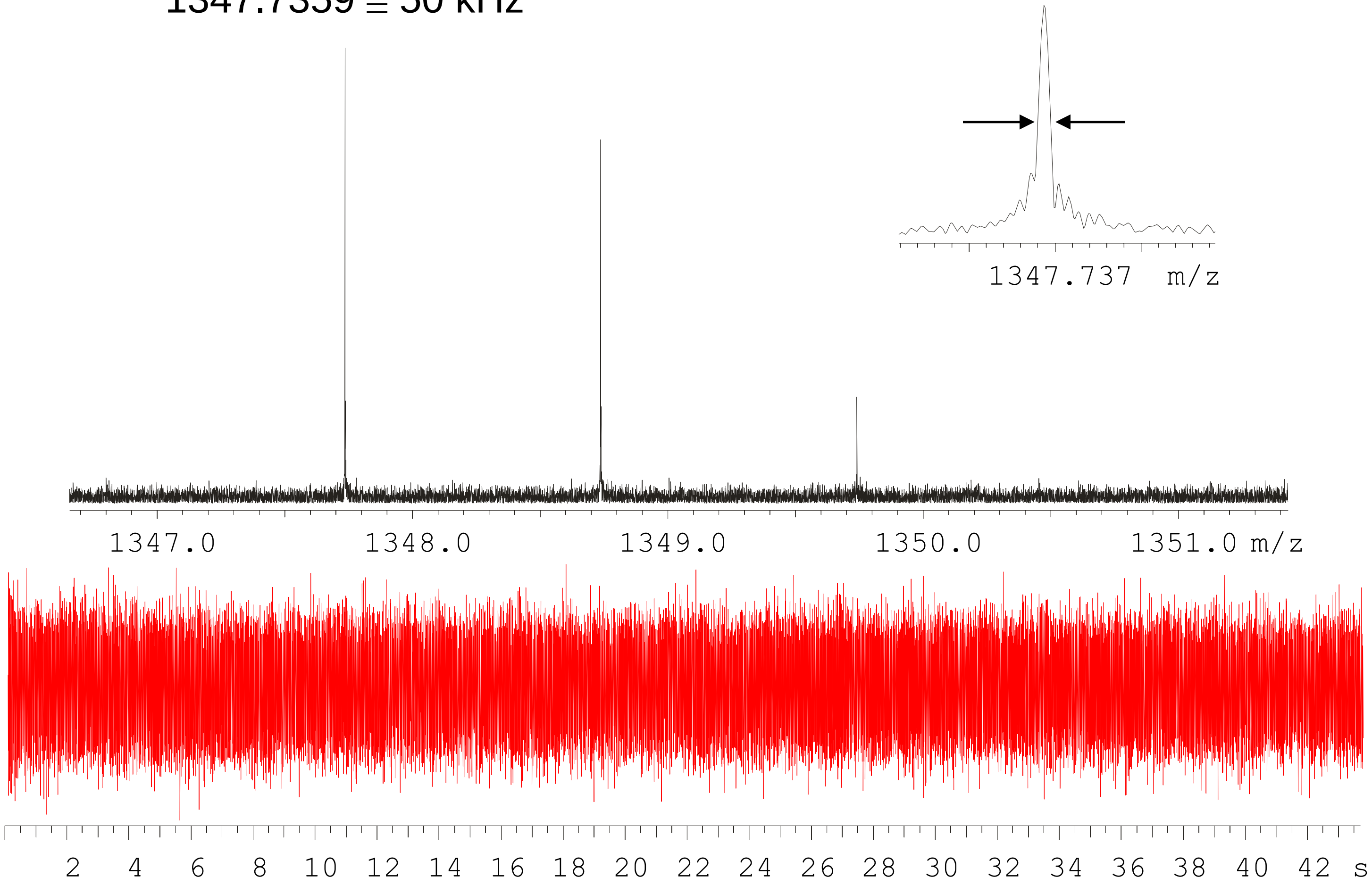


FIG. 4.22. Segment of mass spectrum in region of nominal mass 35 showing a resolution greater than 1,000,000 (FWHM definition) when using FT-MS. The peaks represent the positive and negative ions of ^{35}Cl that have a difference in mass equivalent to the mass of two electrons. The spectrum was obtained using a FT-ICR mass spectrometer with a superconducting magnet (4.7 tesla); the instrument was switched from the positive-ion-detection mode to the negative-ion-detection mode during the scan between the two peaks (Courtesy of Spectrospin AG.)

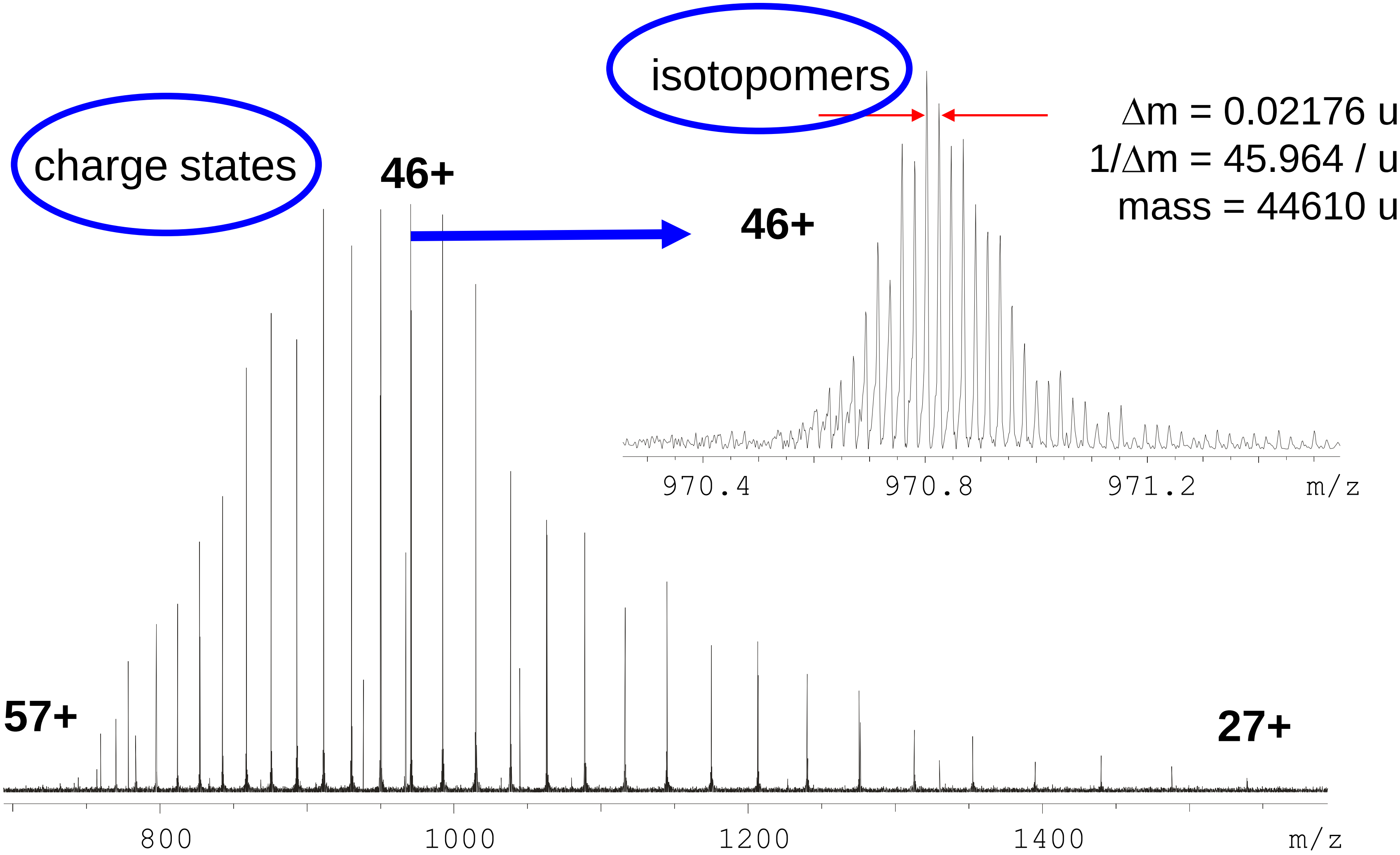
Resolution of Substance P



1347.7359 ≅ 50 kHz

Resolving Power = 1,800,000

Protein A (44kDa) Broadband Spectrum

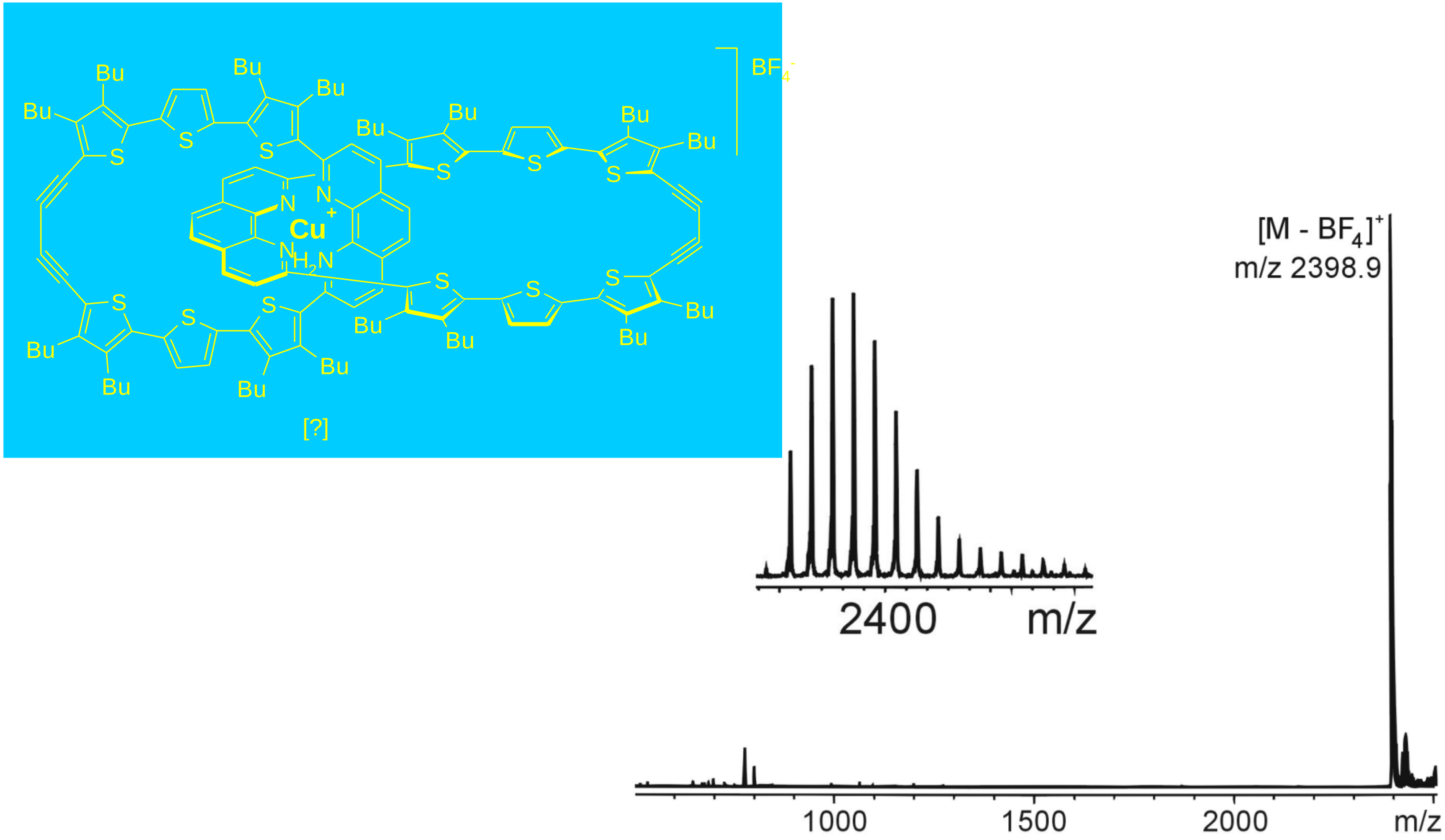


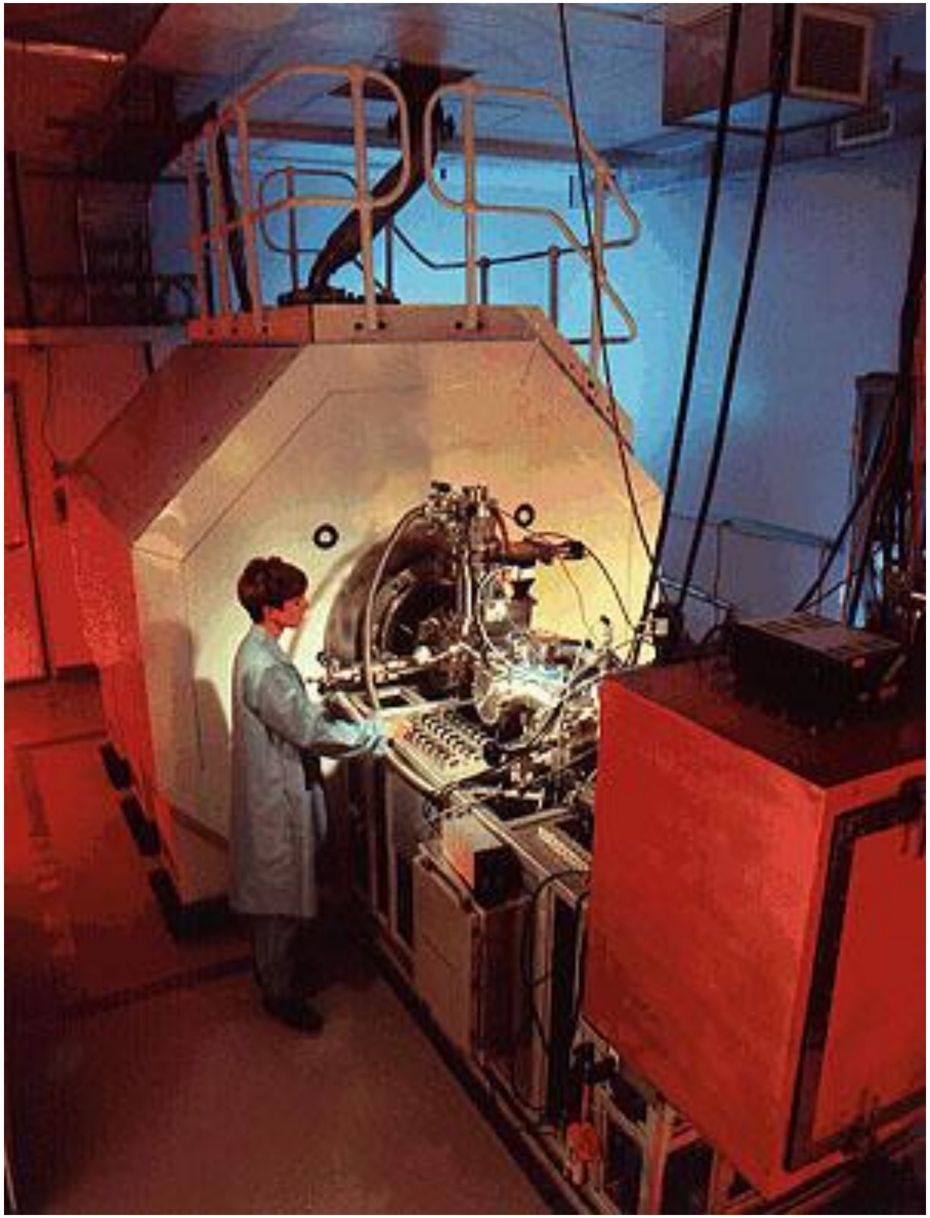
charge states

isotopomers

Δm = 0.02176 u
1/Δm = 45.964 / u
mass = 44610 u

another large molecular complex



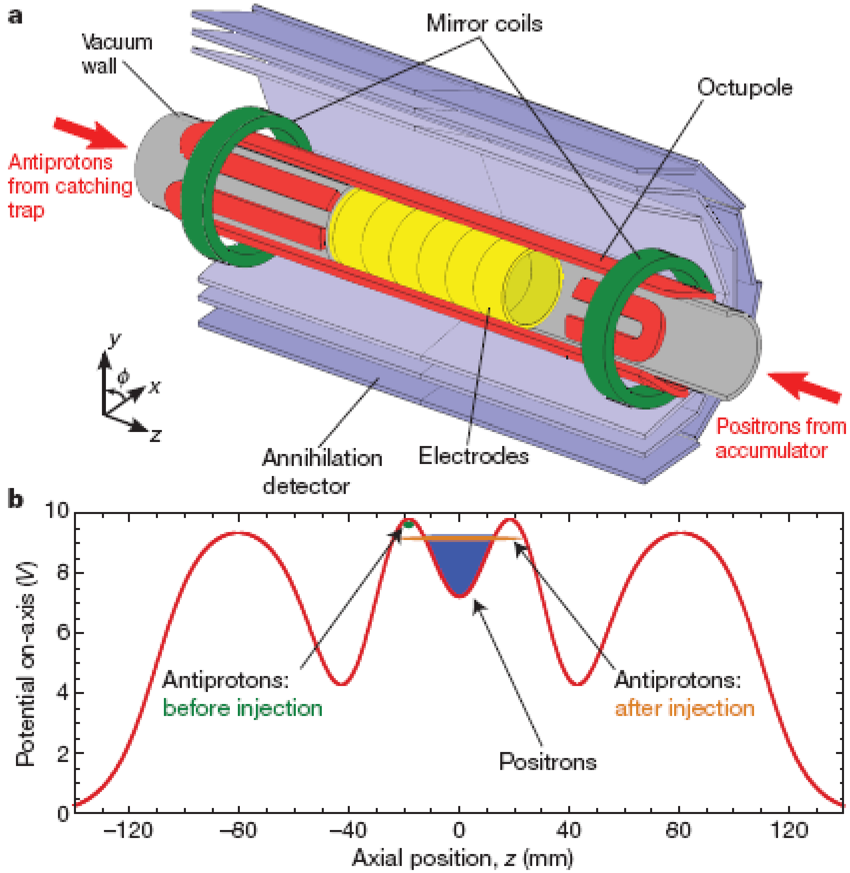


Thermo Finnigan FT ICR
(Ion cyclotron resonance)
Mass spectrometer
11.5 Tesla

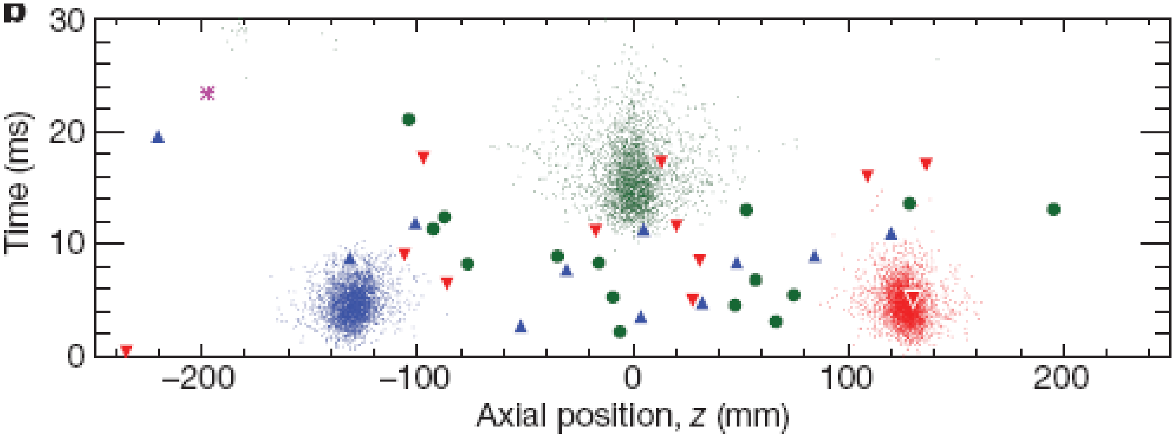
mass resolution
> 3 000 000

sensitivity ca. 50 attomol

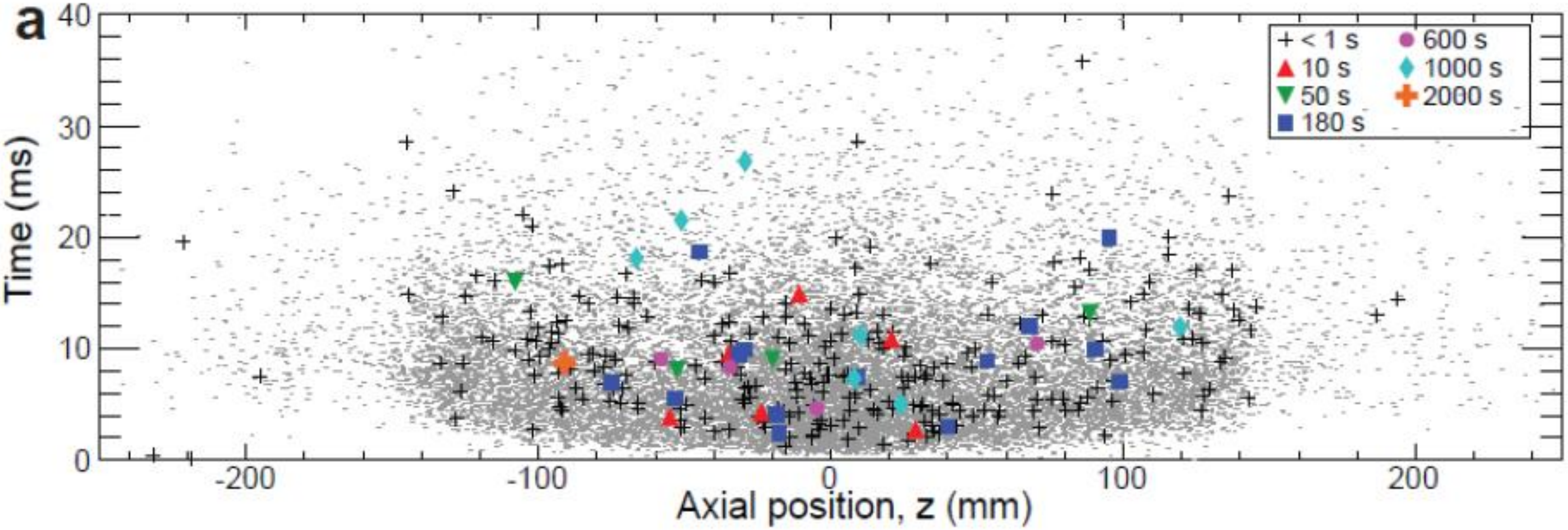
ion traps:
trapped antihydrogen
Nature October 2010



annihilations (colored dots),
and simulations



trapped antihydrogen,
Nature Physics 7, 558 (2011)



Time t- and axial z-distribution of annihilations upon release of antihydrogen from the magnetic trap for different confinement times (see legend), and comparison with simulation (grey dots)