Outline: Experimental storage ring

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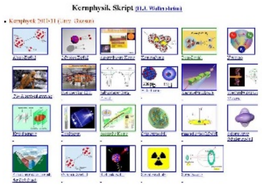
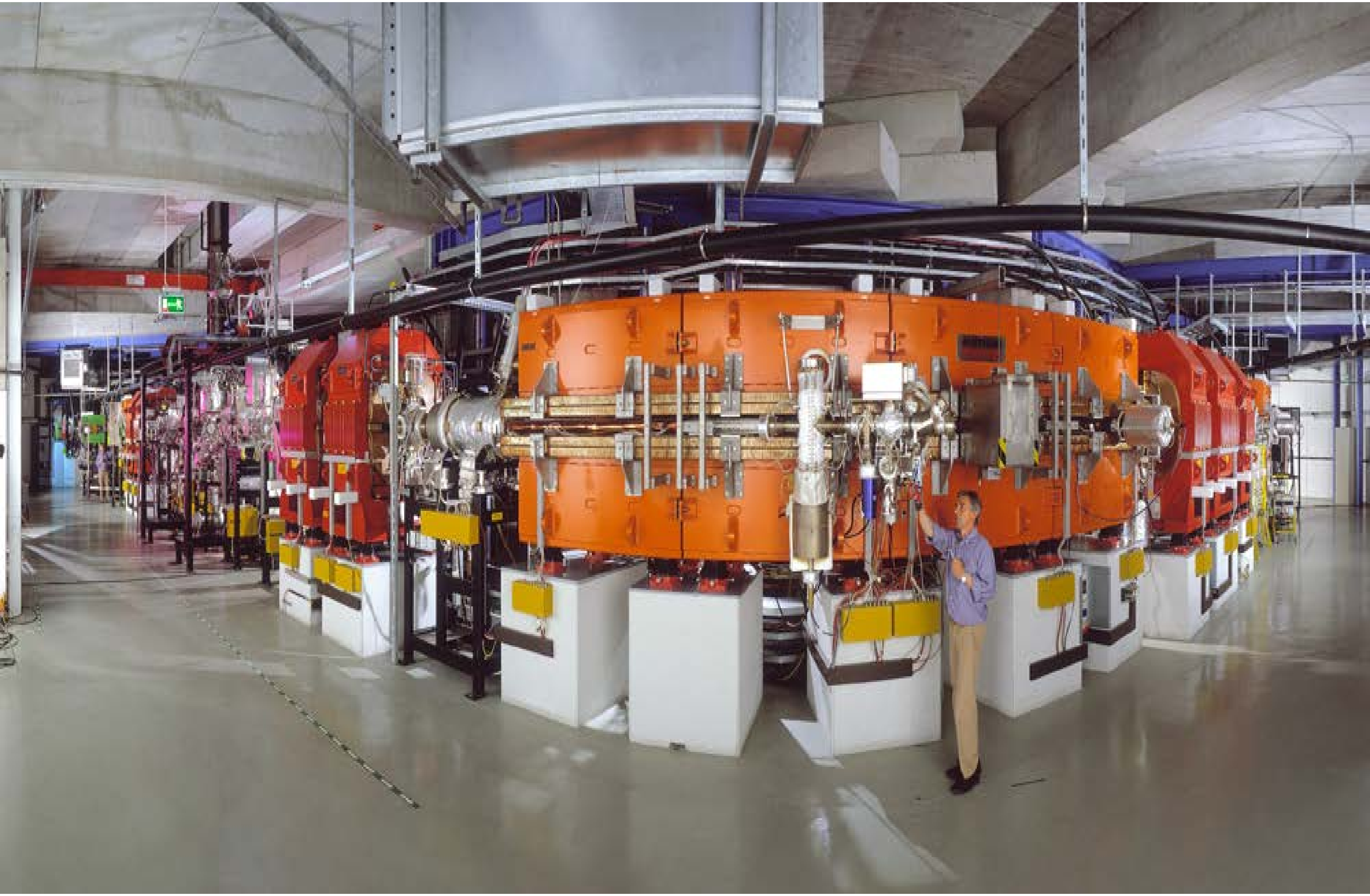
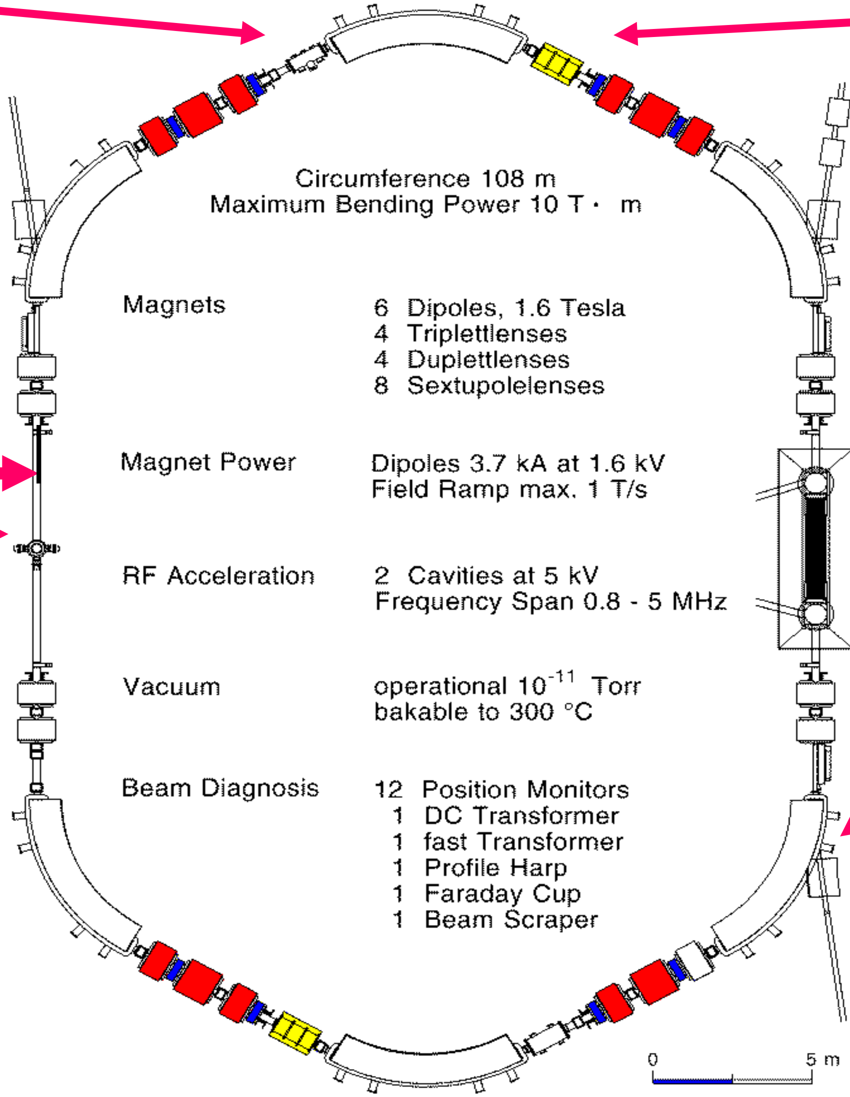


1. phase space - emittance
2. beam cooling at the ESR
3. electron, stochastic and laser cooling
4. mass spectroscopy
5. atomic physics experiments

Experimental Storage Ring – ESR E_{max} = 420 MeV/u, 10 Tm



Specification of the ESR



Particle detectors

Two 5 kV rf-cavities

Re-injection to SIS

Fast Injection

Schottky pick-ups

Gas jet

e^- cooler

I = 10...500 mA

Six 60^0 dipoles

$B\rho \leq 10$ T· m

Extraction

$L = 108$ m $=1/2\, L_{SIS}$

$p = 2 \cdot 10^{-11}$ mbar

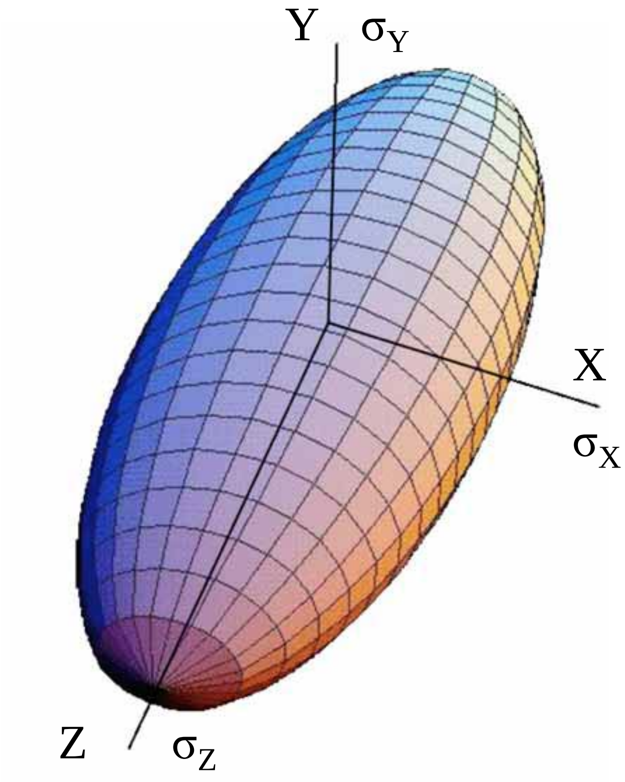
$E = 3...420$ MeV/u

$f \approx 1...2$ MHz

$\beta = 0.08...0.73$

$Q_{h,v} \approx 2.65$

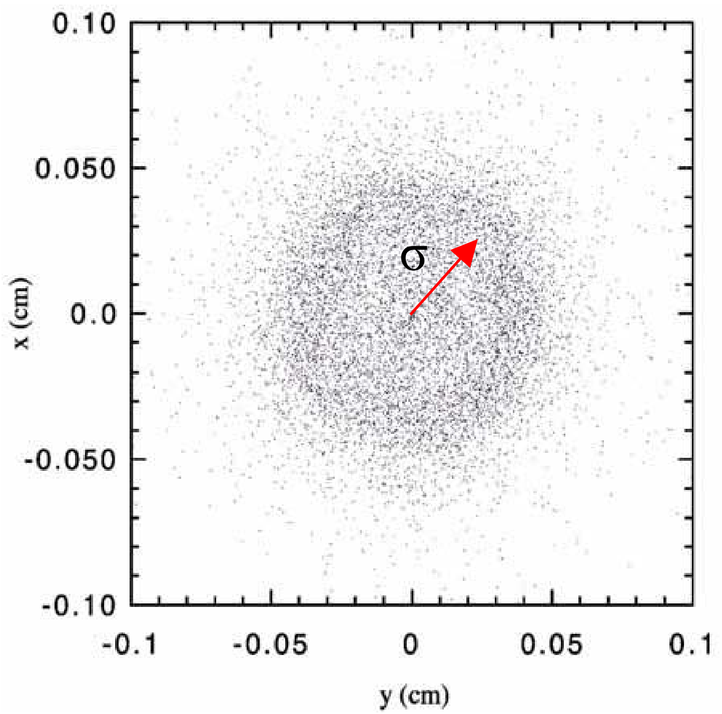
Bunch dimensions



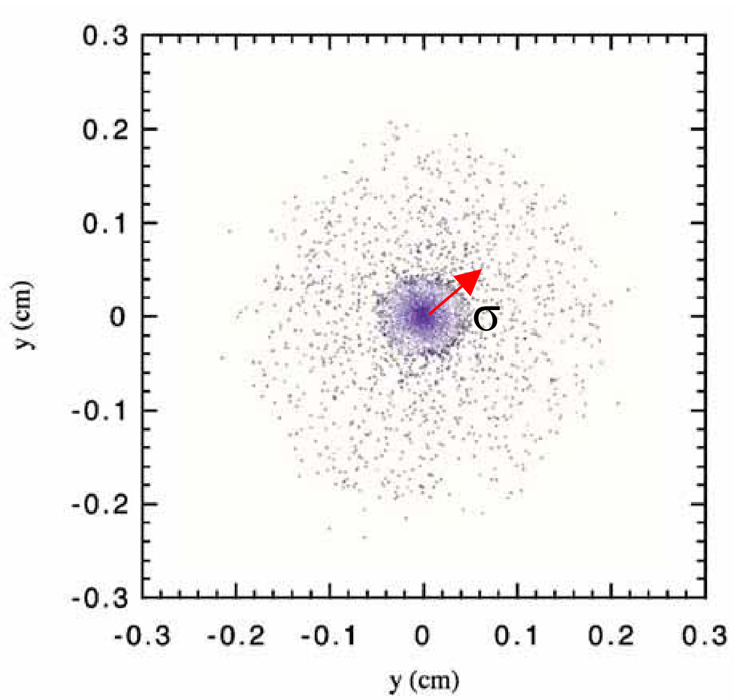
- For uniform charge distributions
  we may use "hard edge values"
- For Gaussian charge distributions
  use rms values σ_x, σ_y, σ_z

We will discuss measurements of bunch size and charge distribution later

But rms values can be misleading



Gaussian beam

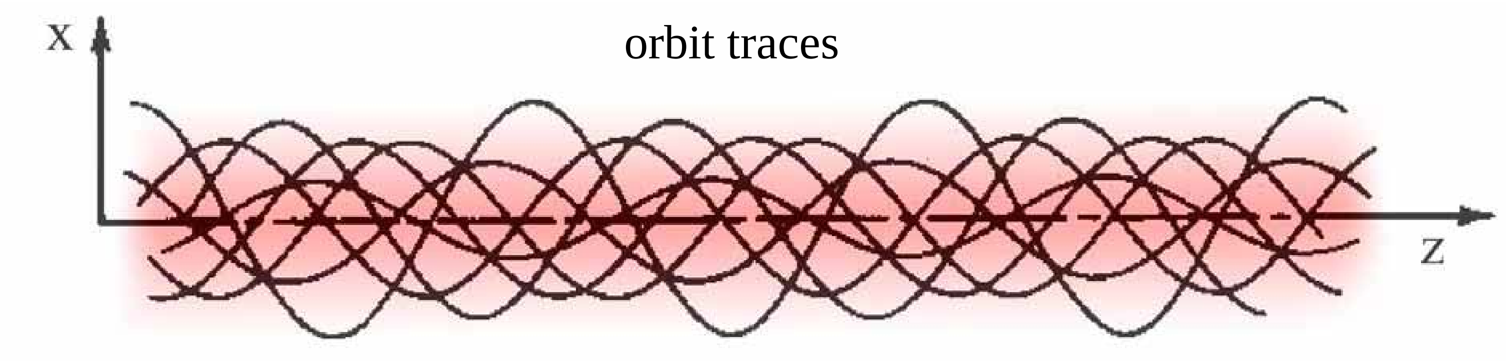


Beam with halo

We need to measure the particle distribution!

Coordinate space

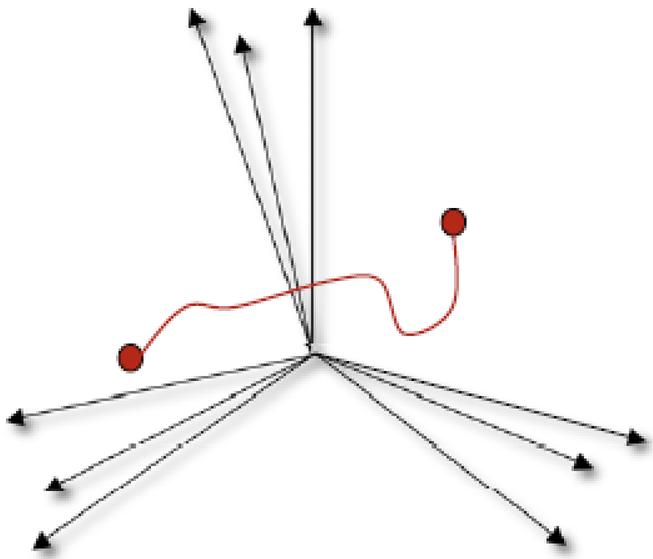
Each of N_b particles is tracked in ordinary 3D-space



Not too helpful!

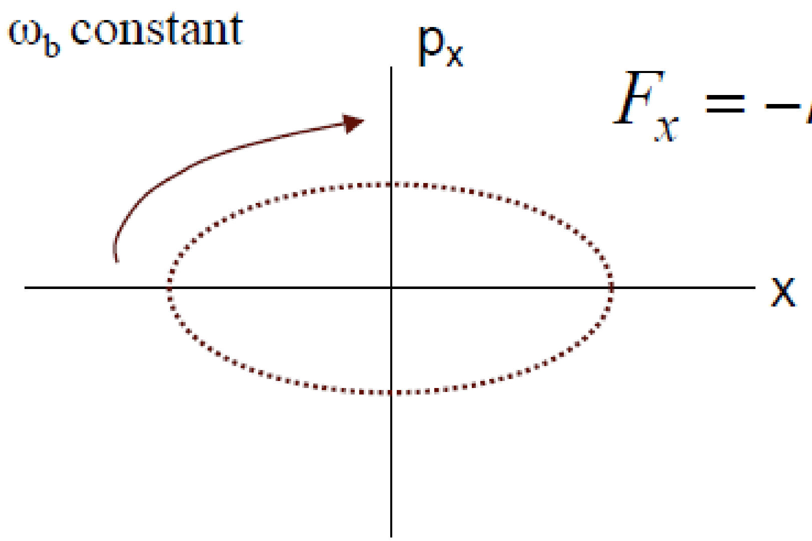
Configuration space

6 N_b-dimensional space for N_b particles; coordinates (x_i, p_i), i = 1, …, N_b
The bunch is represented by a single point that moves in time



Useful for Hamiltonian dynamics

Configuration space example:
1 particle in an harmonic potential



$$F_x = -kx = m\ddot{x}$$

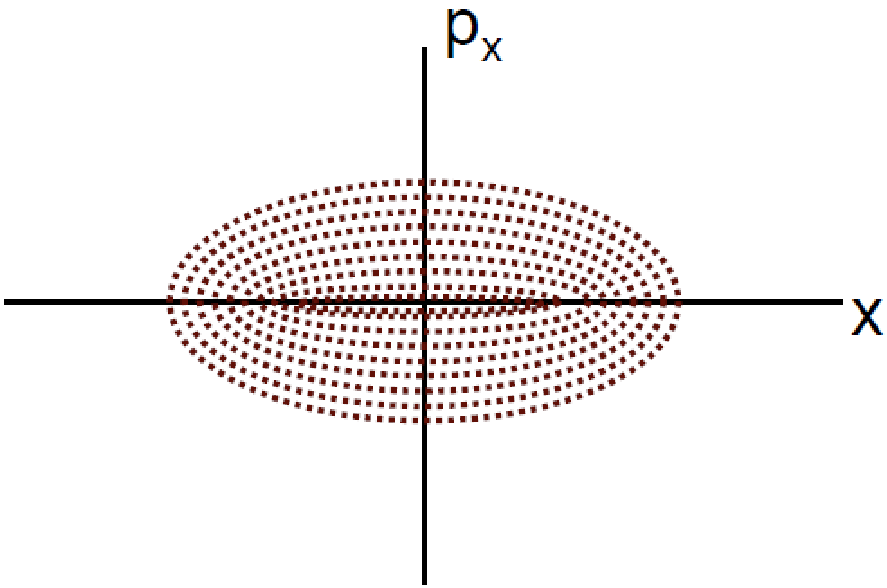
But for many problems this description carries much more information than needed:

We don't care about each of 10^{10} individual particles

*But seeing both **x** & **p**$_x$ looks useful*

Phase space (gas space in statistical mechanics)

6-dimensional space for N_b particles
The i^{th} particle has coordinates (x_i, p_i), i = x, y, z
The bunch is represented by N_b points that move in time



In most cases, the three planes are to very good approximation decoupled
⟹ *One can study the particle evolution independently in each planes*

Particle Systems & Ensembles

- The set of possible states for a system of ***N*** particles is referred as an ***ensemble*** in statistical mechanics.
- In the statistical approach, particles lose their individuality.
- Properties of the whole system are fully represented by ***particle density functions*** f_{6D} and f_{2D}:

$$f_{6D}\left(x, p_x, y, p_y, z, p_z\right)\, dx\, dp_x\, dy\, dp_y\, dz\, dp_z \qquad f_{2D}(x_i, p_i)\, dx_i\, dp_i \quad i = 1,2,3$$

where $$\int f_{6D}\, dx\, dp_x\, dy\, dp_y\, dz\, dp_z = N$$

Longitudinal phase space

- In most accelerators the phase space planes are only weakly coupled.
  → Treat the longitudinal plane independently from the transverse one
  → Effects of weak coupling can be treated as a perturbation of the uncoupled solution

- In the longitudinal plane, electric fields accelerate the particles
  → Use ***energy*** as longitudinal variable together with its canonical conjugated ***time***

- Frequently, we use relative energy variation δ and relative time τ with respect to a reference particle

$$\delta = \frac{E - E_0}{E_0} \qquad\qquad \tau = t - t_0$$

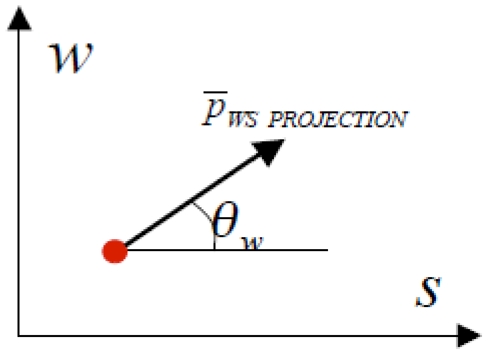
- According to Liouville, in the presence of Hamiltonian forces, the area occupied by the beam in the longitudinal phase space is conserved

Transverse phase space

❖ For transverse planes $\{x, p_x\}$ and $\{y, p_y\}$, use a modified phase space, where the momentum components are replaced by:

$$p_{x_i} \rightarrow x' = \frac{dx}{ds} \qquad\qquad p_{y_i} \rightarrow y' = \frac{dy}{ds}$$

where ***s*** is in the direction of motion



❖ We can relate the old and new variables (for $B_z \neq 0$)

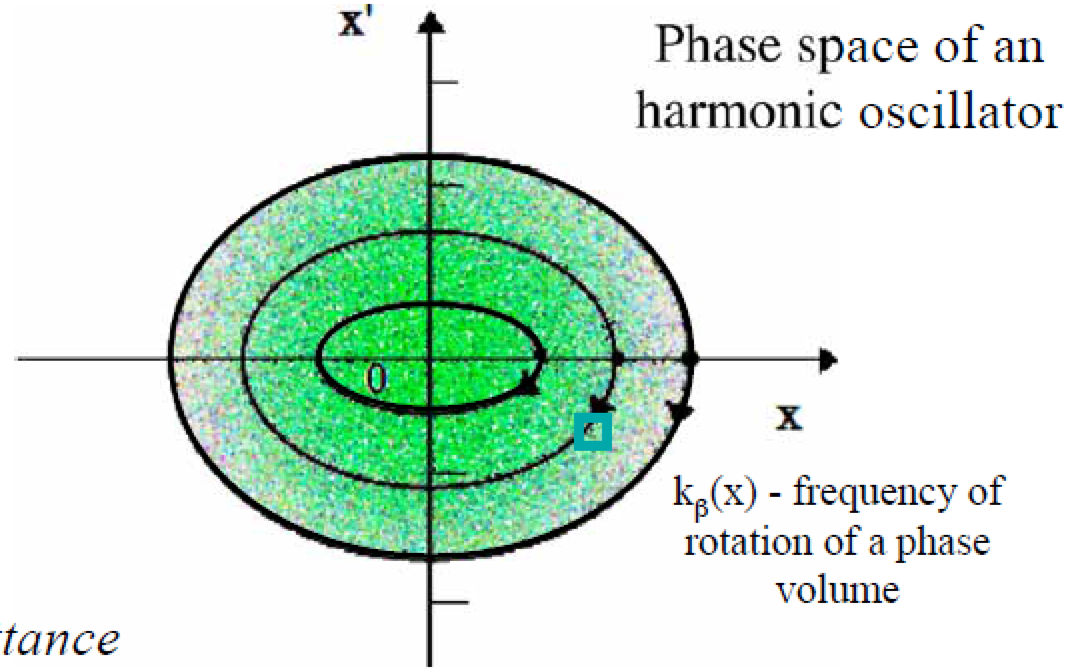
$$p_i = \gamma \cdot m_0 \frac{dx_i}{dt} = \gamma \cdot m_0 v_s \frac{dx_i}{ds} = \gamma \cdot \beta \cdot m_o c x_i' \qquad i = x, y$$

where $\beta = \frac{v_s}{c}$ and $\gamma = (1 - \beta^2)^{-1/2}$

Note: $\mathbf{x_i}$ and $\mathbf{p_i}$ are canonical conjugate variables while **x** and **x'** are not, unless there is no acceleration (γ and β constant)

Emittance describes the area in phase space of the ensemble of beam particles

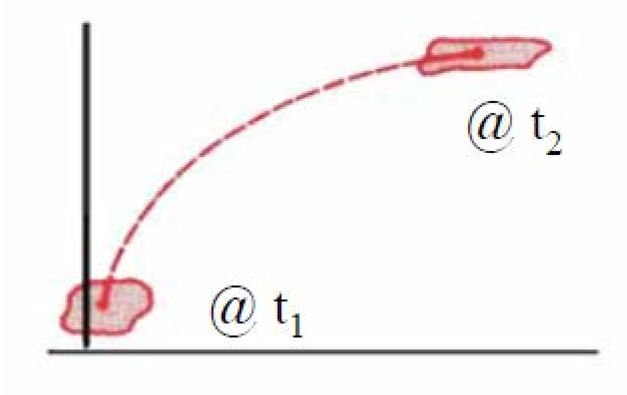
Emittance - Phase space volume of beam



RMS emittance

$$\varepsilon^2 \equiv R^2\left(V^2 - (R')^2\right)/c^2$$

Why is emittance an important concept



1) Liouville: Under conservative forces phase space evolves like an incompressible fluid $\Longrightarrow$

2) Under linear forces macroscopic (such as focusing magnets) & $\gamma = constant$ emittanceis an invariant of motion

3) Under acceleration $\gamma\varepsilon = \varepsilon_n$ is an adiabatic invariant

Is there any way to decrease the emittance?

This means taking away mean transverse momentum
but
keeping mean longitudinal momentum

What is beam cooling?

Beam cooling is synonymous for a reduction of beam temperature

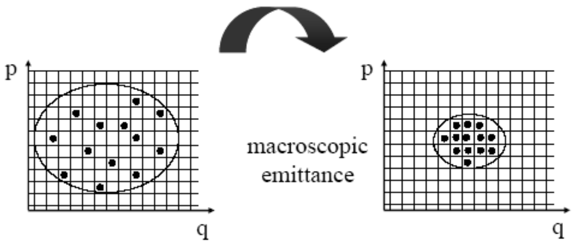
Temperature is equivalent to terms as

phase space volume, emittance and momentum spread

Beam cooling processes are not following Liouville's Theorem:
(which neglects interactions between beam particles)
"In a system where the particle motion is controlled by external conservative forces the phase density is conserved"

Beam cooling techniques are non-Liouvillean processes
e.g. interaction of beam particles with other particles (electrons, photons)

❖ **Benefit of beam cooling:**
- Improved beam quality (precision experiments, luminosity increase)



What is cooling? What is temperature?

$$\left(\frac{3}{2}\cdot k\right)\cdot T_{\perp\,||} = \frac{1}{2}\cdot m\cdot\left\langle \vec{v}_{\perp\,||}^{\,2}\right\rangle$$

v is the velocity relative to a reference particle, which moves with an average ion-velocity.
The temperature is a measure of the random movement.

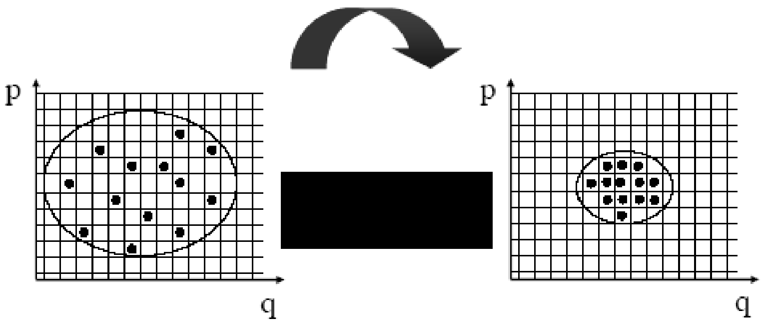
In an accelerator

$$T_{||} = M\cdot c^2\cdot\beta^2\cdot\left\langle \Delta p/p\right\rangle^2$$

$$T_{\perp} = M\cdot c^2\cdot\beta^2\cdot\gamma^2\cdot\varepsilon\left(\frac{1}{\langle\beta_H\rangle}+\frac{1}{\langle\beta_V\rangle}\right)$$

Why beam cooling?

Improve of the beam quality
- smaller beam size and reduction of the emittance
- broadening of the energy
- better beam intensity, accumulation
- lifetime of the beam

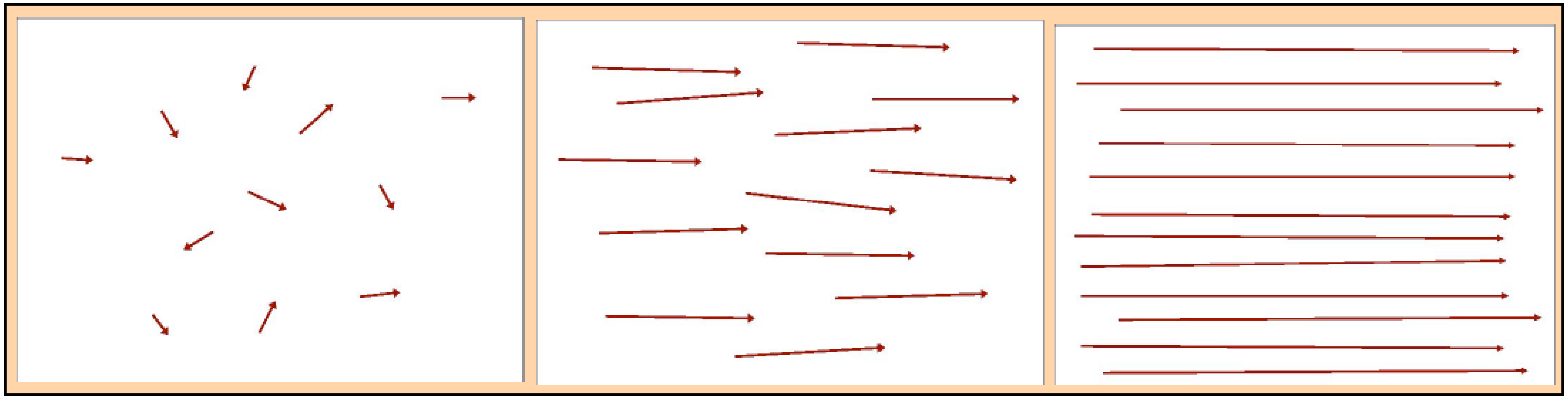


Beam temperature

Where does the beam temperature originate from?

The beam particles are generated in a 'hot' source

Thermal particle motion (temperature is conserved)



at rest (source) low energy high energy

temperature

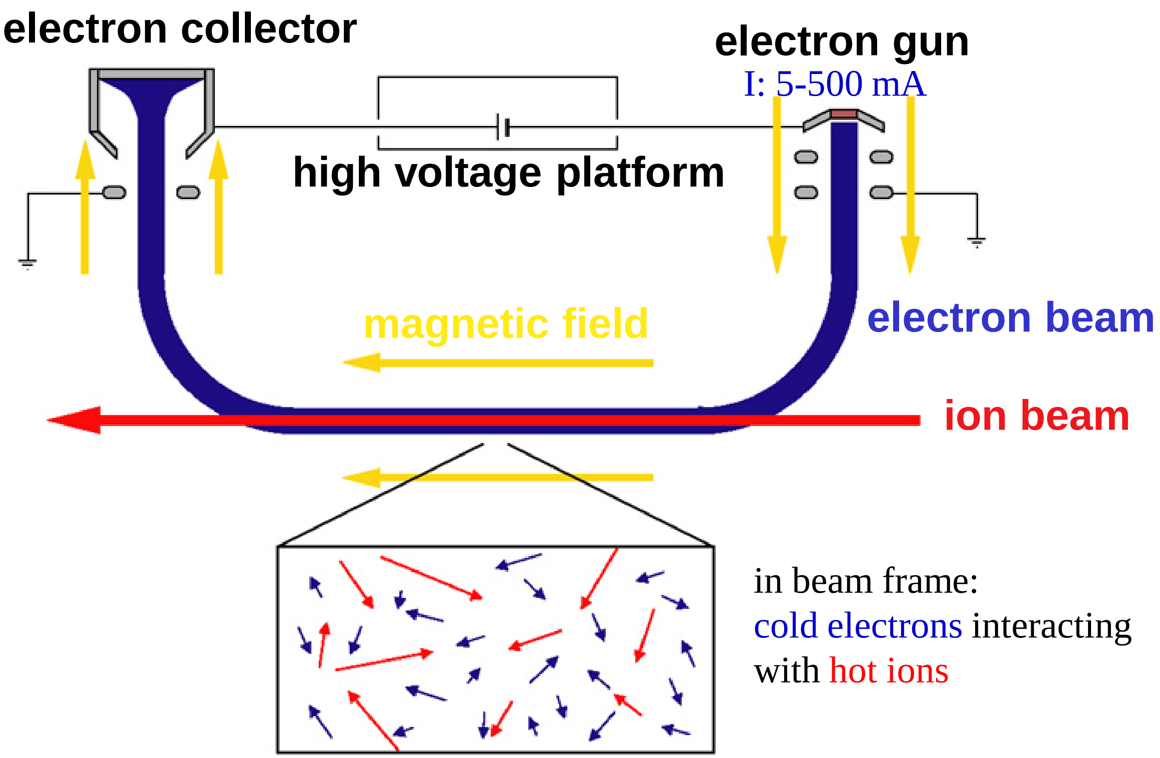
$$\text{longitudinal} \quad \frac{1}{2}k_B T_{\parallel} = \frac{1}{2}m v_{\parallel}{}^2 = \frac{1}{2}mc^2\beta^2\left(\frac{\delta p_{\parallel}}{p}\right)^2$$

$$\text{transverse} \quad \frac{1}{2}k_B T_{\perp} = \frac{1}{2}m v_{\perp}{}^2 = \frac{1}{2}mc^2\beta^2\gamma^2\theta_{\perp}{}^2$$

Benefits of beam cooling

- Improve beam quality
  - Precision experiments
  - Luminosity increase
- Compensation of heating
  - Experiments with internal target
  - Colliding beams
- Intensity increase by accumulation
  - Weak beams from source can be increased
  - Secondary beams (antiprotons, rare isotopes)

Electron cooling



in beam frame:
cold electrons interacting
with hot ions

superposition of a cold
intense electron beam
with the same velocity

$v_{e\parallel} = v_{ion\parallel}$

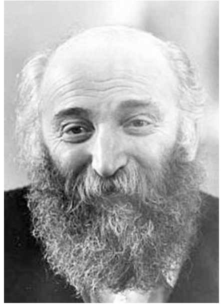
$E_e = m_e/M_{ion} \cdot E_{ion}$

e.g.: 200 keV electrons
cool 400 MeV/u ions

electron temperature:

$k_B T_\perp \approx 0.1\ eV$

$k_B T_\parallel \approx 0.1 - 1\ meV$



G. Budker

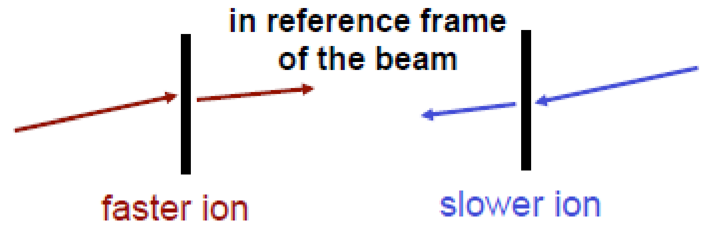
momentum transfer by Coulomb collisions

cooling force results from energy loss
in the co-moving gas of free electrons

G.I. Budker, At. En. 22 (1967) 346
G.I. Budker, A.N. Skrinsky et al., IEEE NS-22 (1975) 2093

Characteristics of electron cooling force

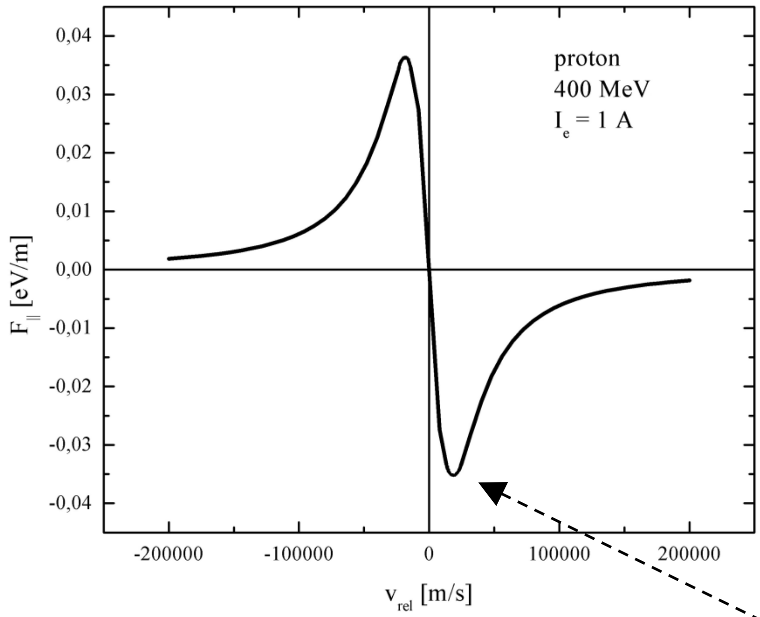
Analogy: energy loss in matter
(electrons in the shell)

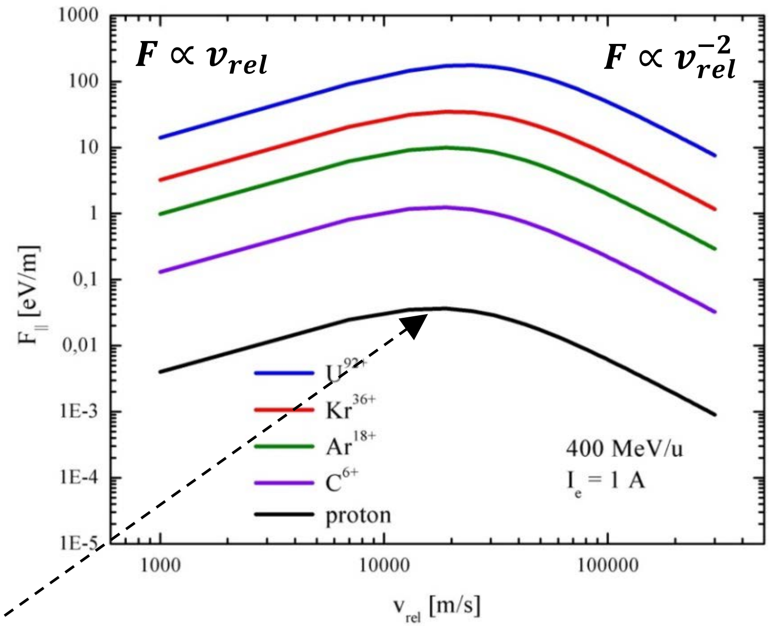


$$\vec{F}(\overrightarrow{v_{ion}}) = -\frac{4\pi \cdot Q^2 e^4 \cdot n_e}{(4\pi\varepsilon_0)^2 \cdot m_e} \int L_C(\overrightarrow{v_{rel}}) \cdot f(\overrightarrow{v_e}) \frac{\overrightarrow{v_{rel}}}{v_{rel}^3} d^3\overrightarrow{v_e}$$

$$\overrightarrow{v_{rel}} = \overrightarrow{v_{ion}} - \overrightarrow{v_e}$$

cooling force F
for small relative velocity: $\propto v_{rel}$
for large relative velocity: $\propto v_{rel}^{-2}$
increase with charge: $\propto Q^2$

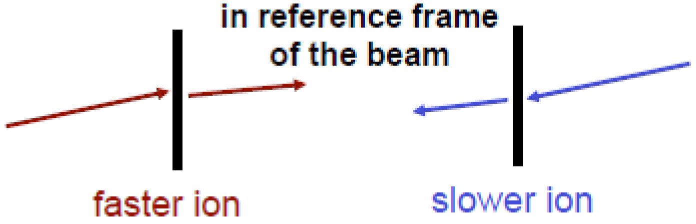




maximum cooling force at effective electron temperature

Simple derivation of electron cooling force

Analogy: energy loss in matter
(electrons in the shell)



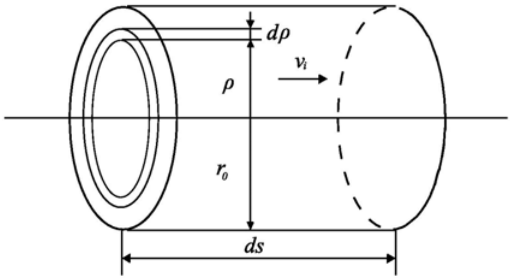
Rutherford scattering: $2 \cdot tan\left(\frac{\theta}{2}\right) = \frac{2Z_1Z_2e^2}{4\pi\varepsilon_0 \Delta p \cdot v \cdot b}$ $\quad Z_1 = Q\ (ion),\ \ Z_2 = -1\ (electron)$

Energy transfer: $\Delta E(b) = \frac{(\Delta p)^2}{2m_e} \cong \frac{2 \cdot Q^2 e^4}{(4\pi\varepsilon_0)^2 m_e v^2} \frac{1}{b^2} \quad (for\ b \gg b_{min})$

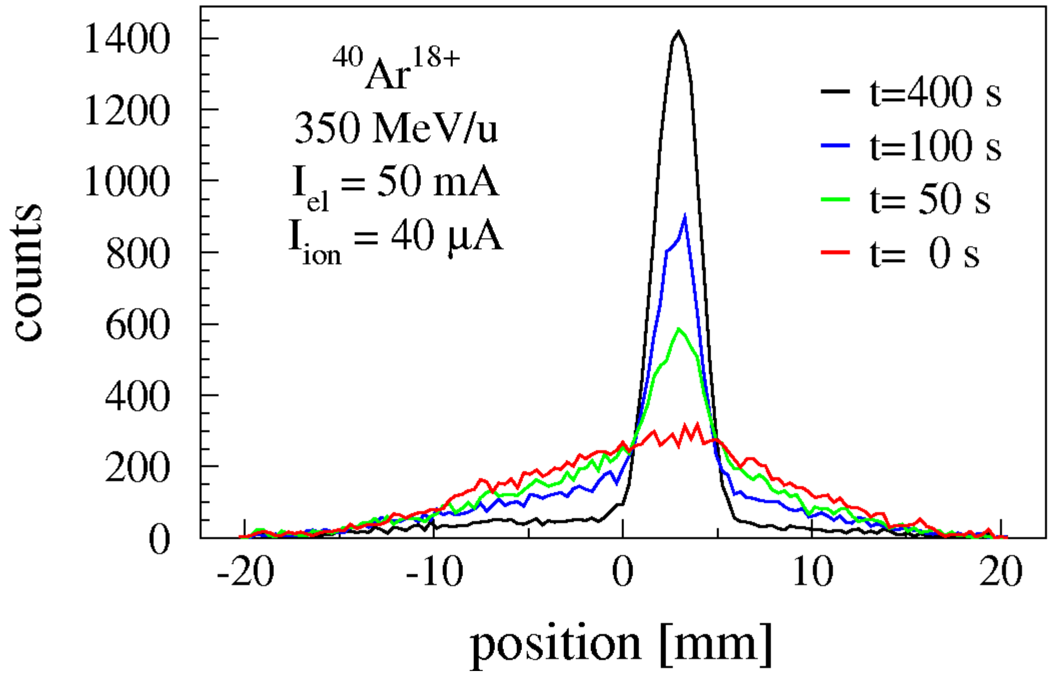
Minimum impact parameter: $b_{min} = \frac{Qe^2}{(4\pi\varepsilon_0)^2 m_e v^2}$ $\quad from: \ \ \Delta E(b_{min}) = \Delta E_{max} \cong m_e v^2$

Energy loss: $-\frac{dE}{dx} = 2\pi \int_{b_{min}}^{b_{max}} b \cdot n_e \cdot \Delta E\ db = \frac{4\pi Q^2 e^4}{(4\pi\varepsilon_0)^2 m_e v^2} n_e \cdot ln \frac{b_{max}}{b_{min}}$

Coulomb logarithm $\quad L_C = ln(b_{max}/b_{min}) \approx 10 \quad (typical\ value)$



Example of electron cooling

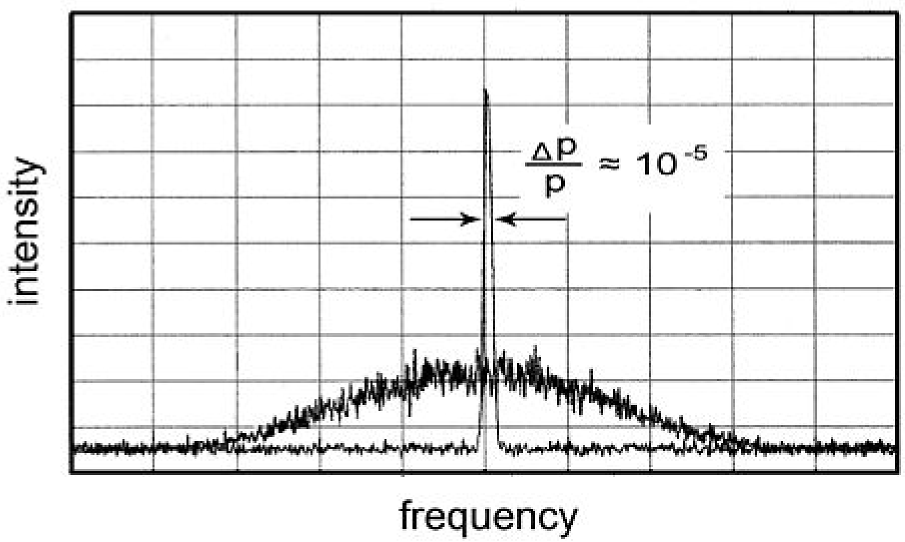


transverse cooling at ESR

measured with residual gas ionization beam profile monitor

cooling of 350 MeV/u Ar^{18+} ions 0.05 A, 192 keV electron beam $n_e = 0.8 \cdot 10^6$ cm^{-3}

Electron cooling



momentum spread $\Delta p/p = 10^{-5}$
diameter 2 mm

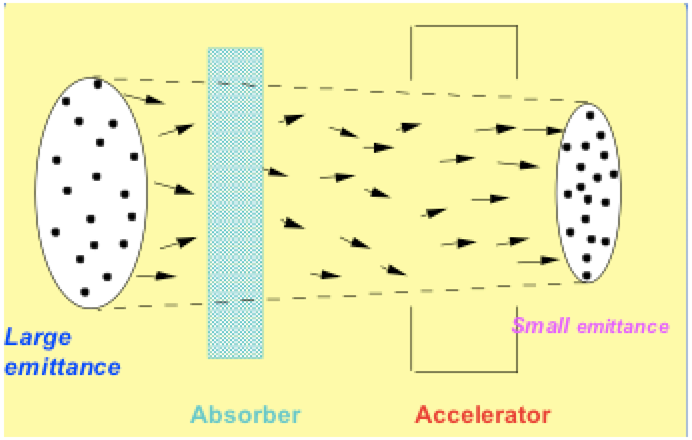
- The ions get the sharp velocity of electrons, small size and divergence

G.I. Budker, At. En. 22 (1967) 346
G.I. Budker, A.N. Skrinsky et al., IEEE NS-22 (1975) 2093

Ionization cooling

❖ Hot muon beam:

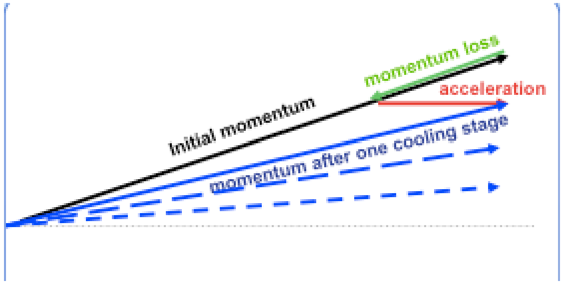
- large transverse momentum
- cannot fit in the beam pipe in muon accelerator

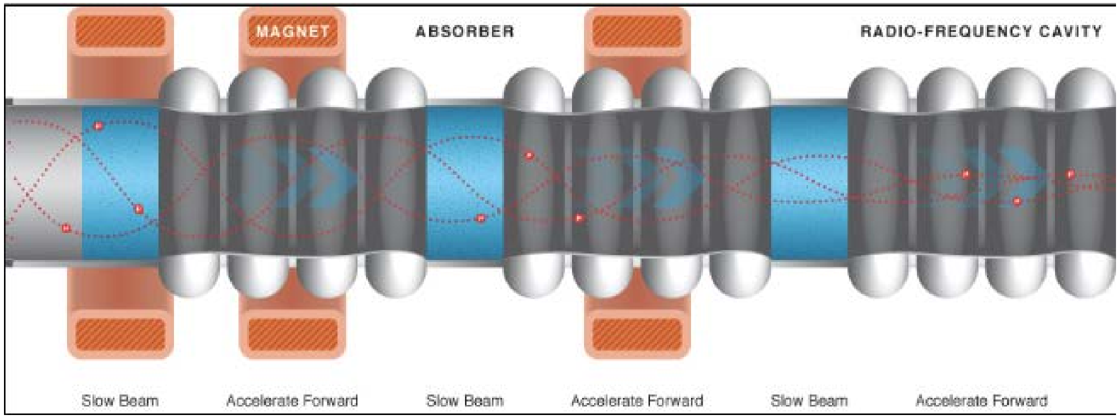


Ionization cooling:

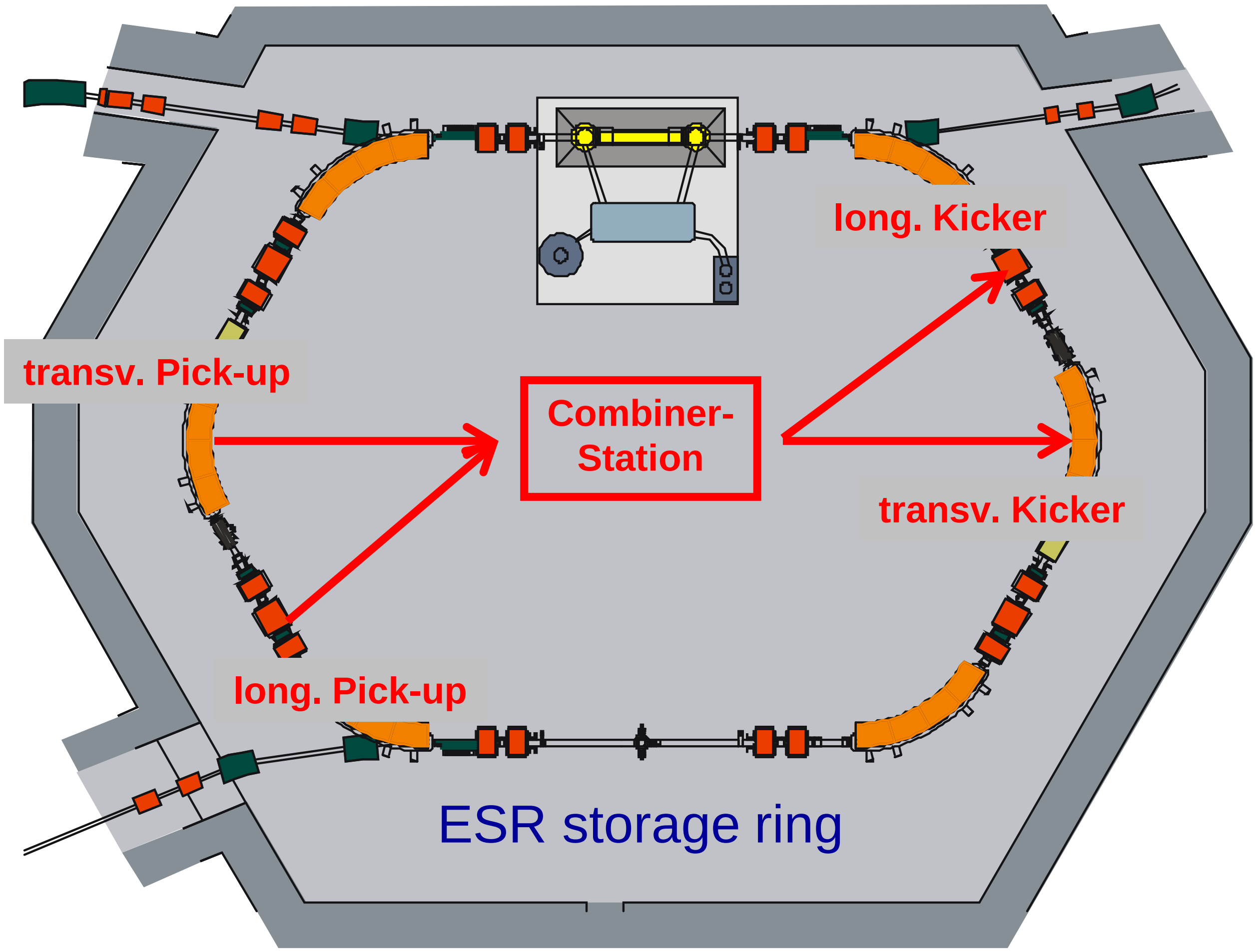
Based on use of ionization energy loss of accelerated charged particles

Reduce the transfers motion and accelerate them in forward direction





Stochastic cooling: Implementation at the ESR



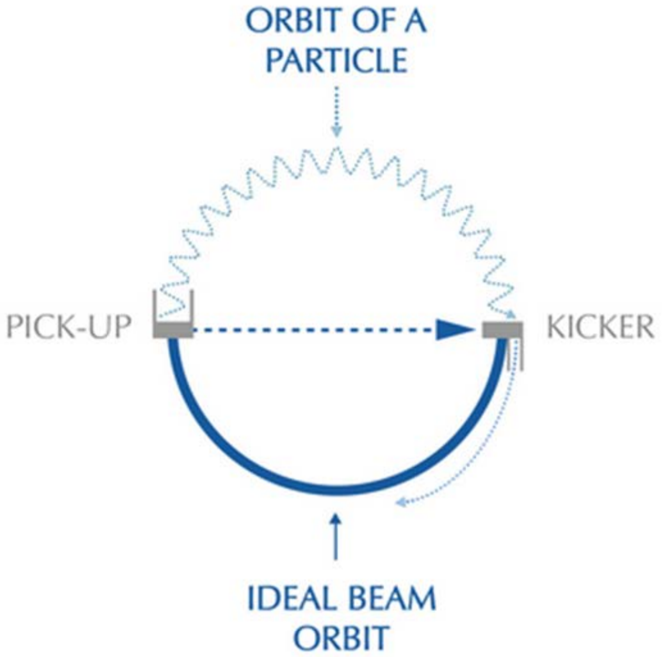
Simon van der Meer

Stochastic cooling is in particular efficient for hot ion beams

Principle of ‘stochastic’ cooling

A Feedback System: A detector or pick-up which measures the motion of the particle and a corrector, the kicker, which adjusts their angles.

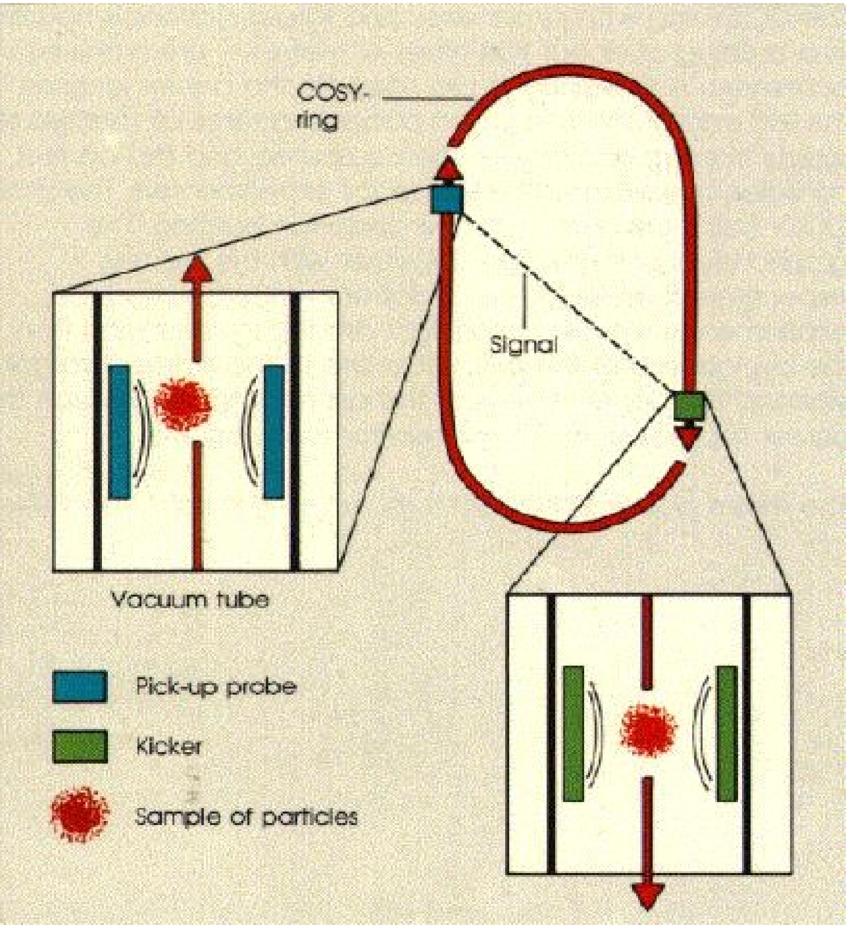
Measures the deviation of the center of gravity of a sample of particles with respect to the requisite orbit and sends an error signal to the kicker.



The kicker applies an electric field to the same sample to correct the deviation measured.

Principle of ‘stochastic’ cooling

Self correction of ion trajectory



Using a pick-up probe, the position of the ion beam is measured at a fixed position via the induced signal. A deviation of the beam from the ideal orbit can be corrected by amplification of this signal**.**

The amplified signal is now used as a correction signal which acts on the beam at a second position (zero crossing of the betatron function) via a "kicker“.

This method was invented for the cooling of hot p(bar) by van der Meer. He showed that after a cooling time of $\boldsymbol{\tau \propto N/C}$ (N: particle number, C = Bandwidth of the amplifier) a momentum width of the beam of about $\boldsymbol{\Delta p/p \approx 10^{-3}}$ can be achieved by stochastic cooling.

Detection of the **W boson** from p ↔ p(bar)

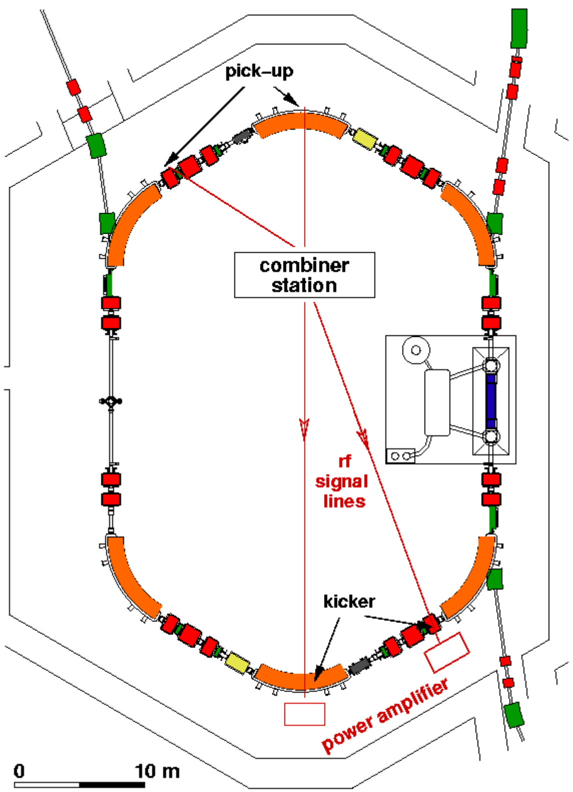
Stochastic cooling at GSI

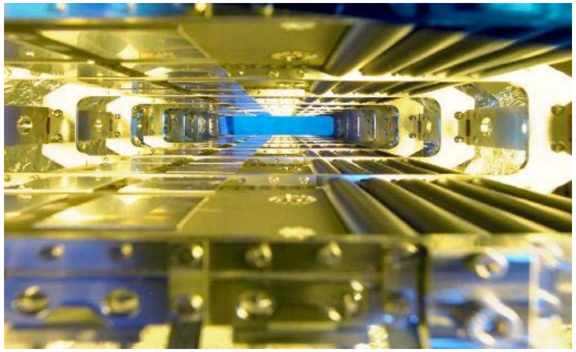
fast pre-cooling of hot fragment beams

energy 400 (-550) MeV/u
bandwidth 0.8 GHz (range 0.9-1.7 GHz)

$\delta p/p = \pm 0.35\% \rightarrow \delta p/p = \pm 0.01\%$

$\varepsilon = 10 \cdot 10^{-6} m \rightarrow \varepsilon = 2 \cdot 10^{-6} m$





electrodes installed inside magnets

combination of signals from electrodes

power amplifiers for generation of correction kicks

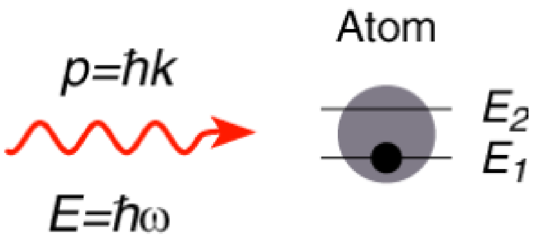
Comparison of Cooling Methods

	Stochastic Cooling	Electron Cooling
Useful for:	low intensity beams	low energy
		all intensities
	hot (secondary) beams	warm beams (pre-cooled)
	high charge	high charge
	full 3-D control	bunched beams
Limitations:	high intensity beams	space charge effects
/problems	beam quality limited	recombination losses
	bunched beams	high energy

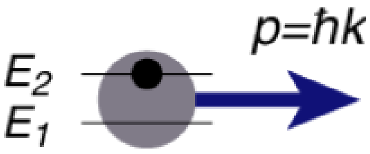
Principle of laser cooling (snowplow)

only longitudinal cooling

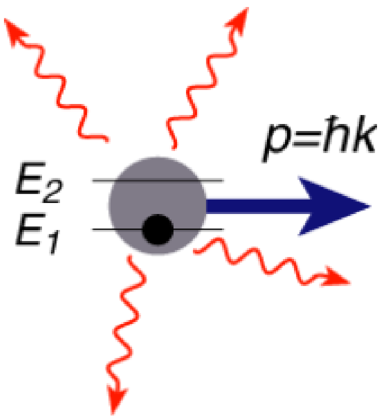
1. Absorption of photons from a laser beam:
   Energy and momentum must be conserved.



2. Absorption of photons:
   Momentum transfer in a defined direction
   (directed momentum transfer).



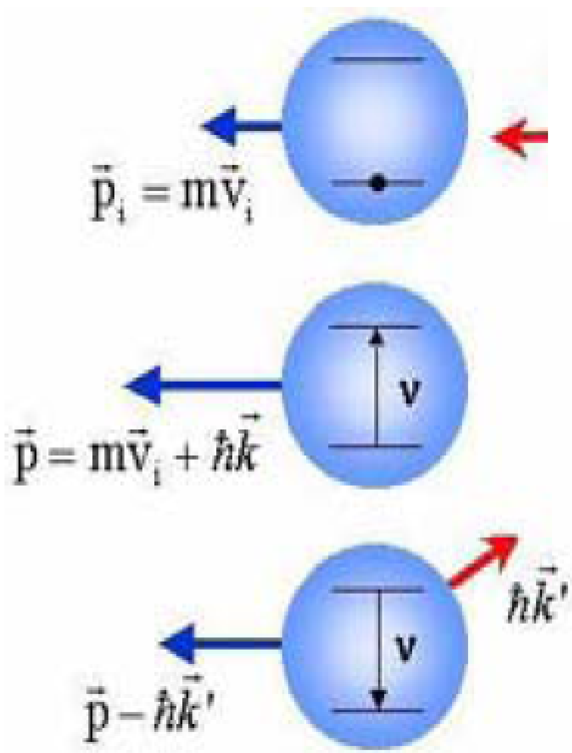
3. No defined direction for the spontaneous emission (isotropic re-emission):
   Momentum transfer cancels out over many absorption-emission-cycles.



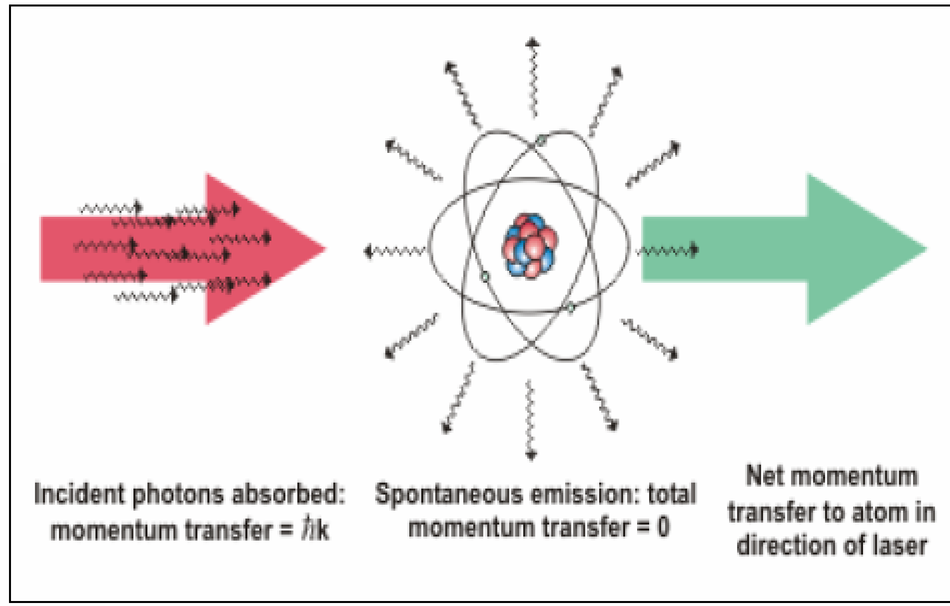
typical cooling times ~ 10 μs

Principle of laser cooling

2-step process



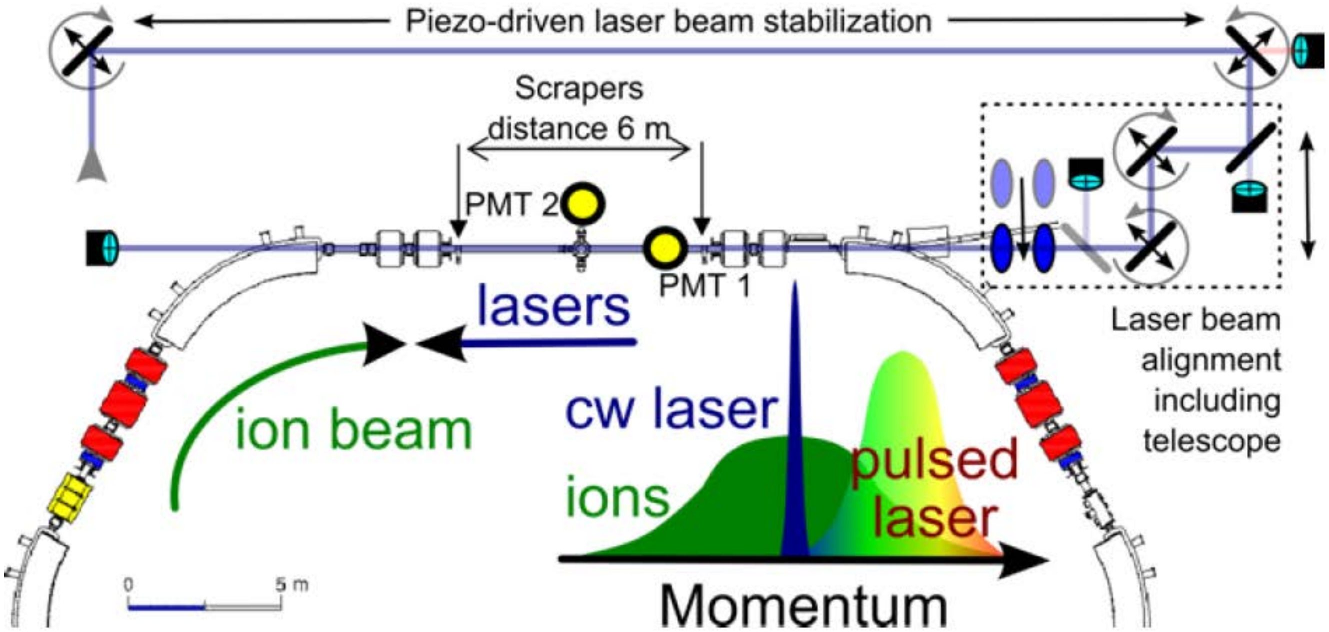
$\hbar k$

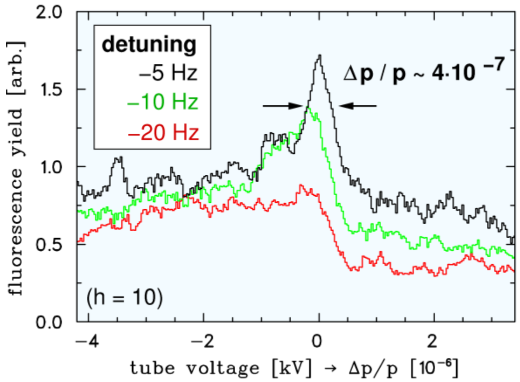


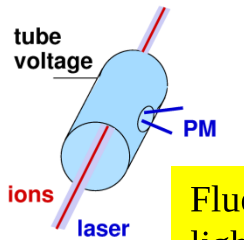
users.york.ac.uk

http://inms-ienm.nrc-cnrc.gc.ca/research/cesium_clock_e.html

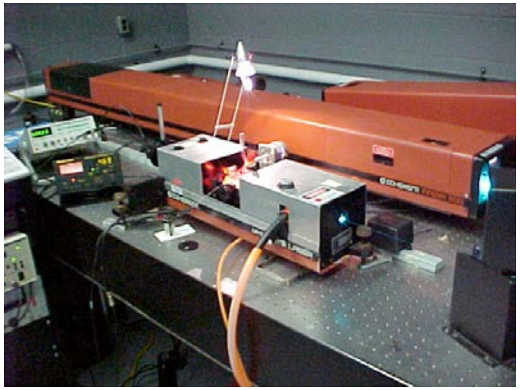
Laser cooling at ESR





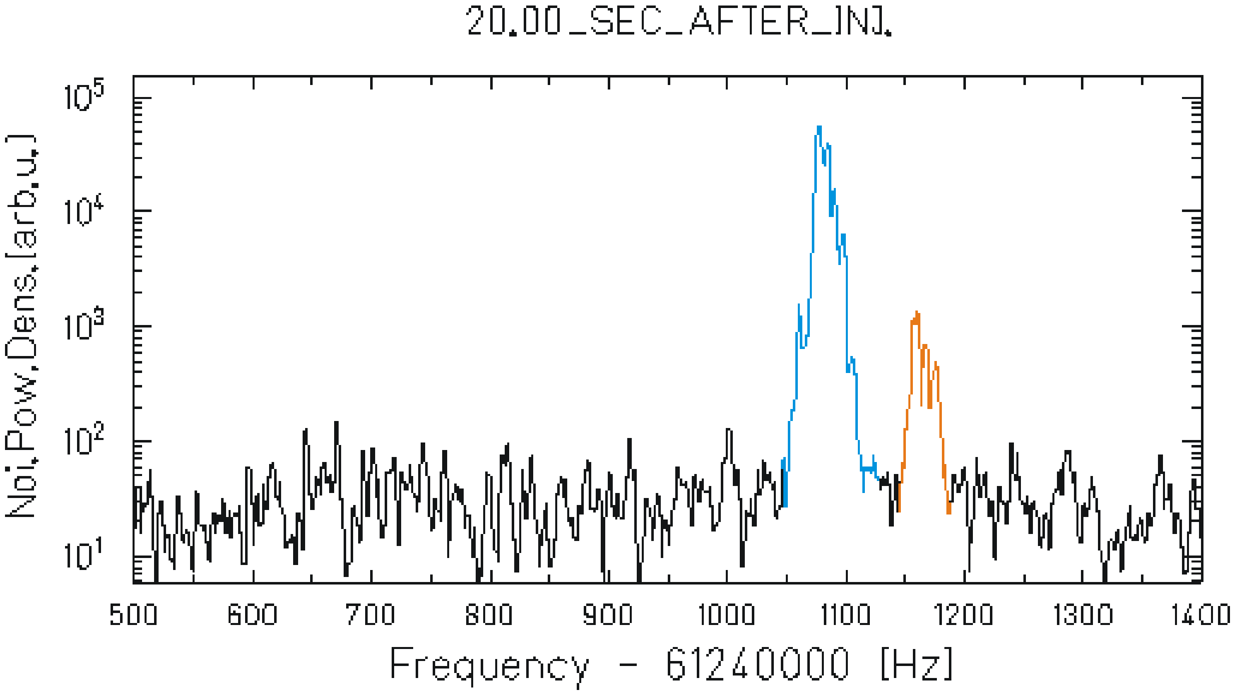


Fluorescence light detection



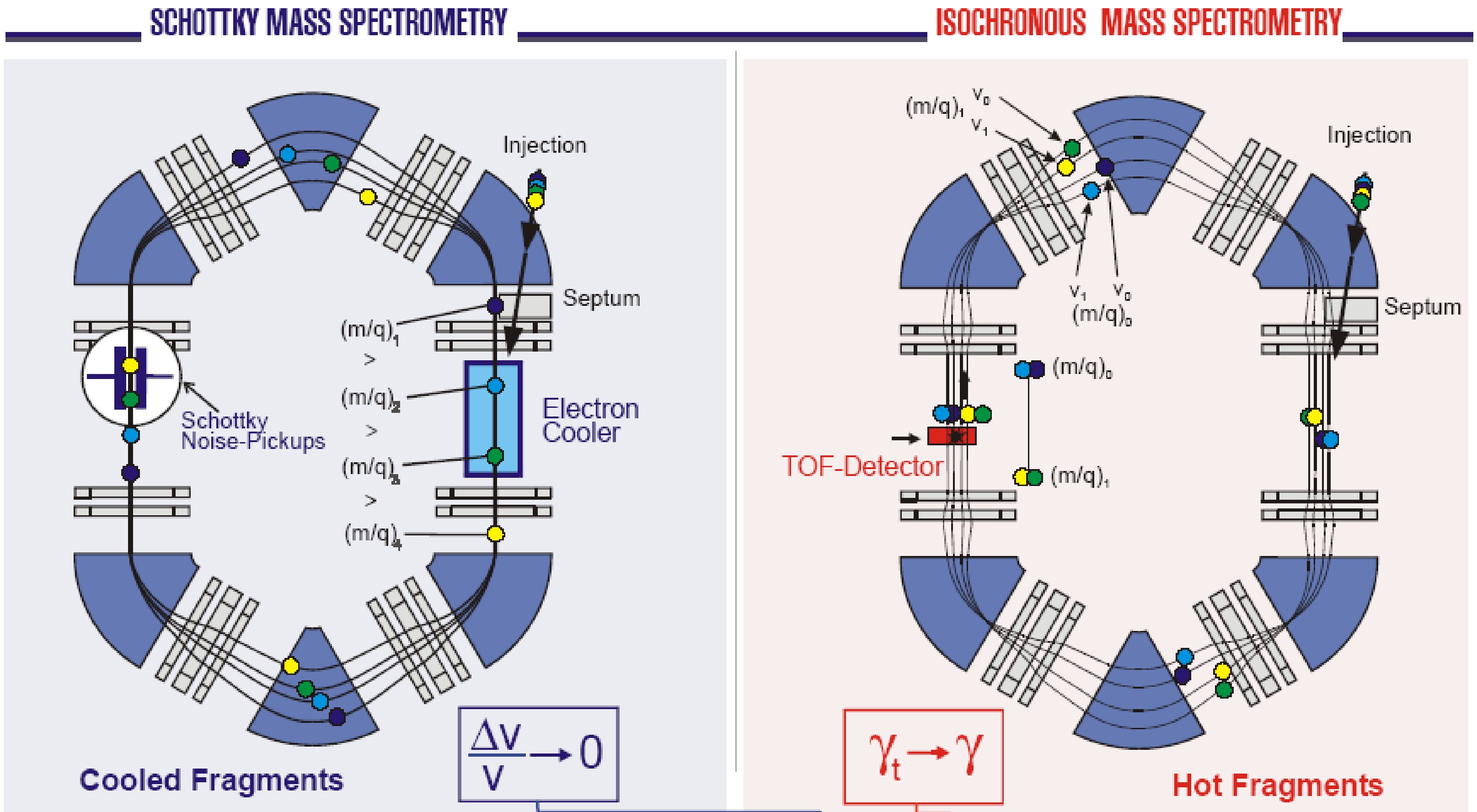
Argon ion laser (257.3 nm) frequency doubled

Cooling



D. Boutin

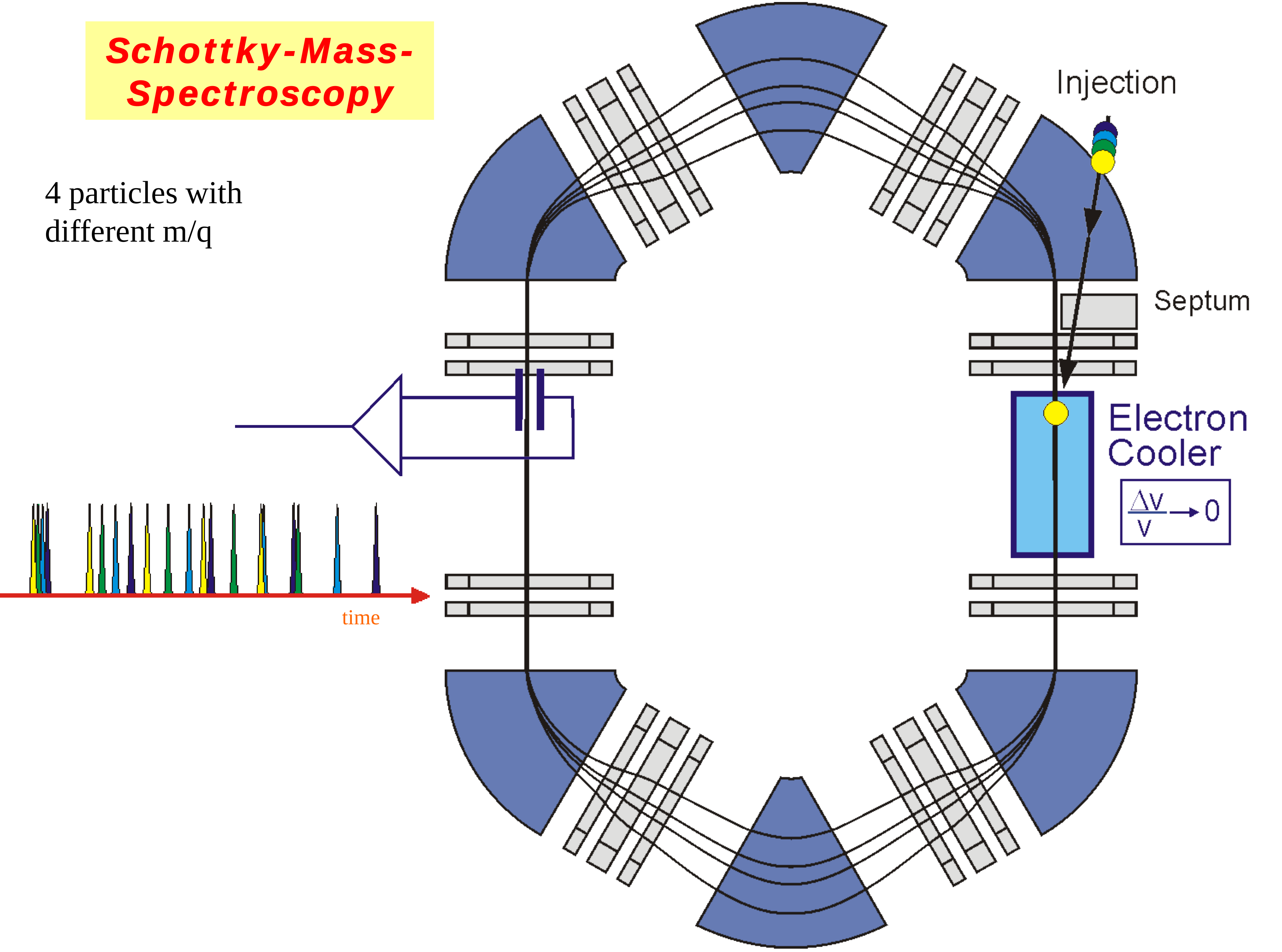
Cooling with the ESR



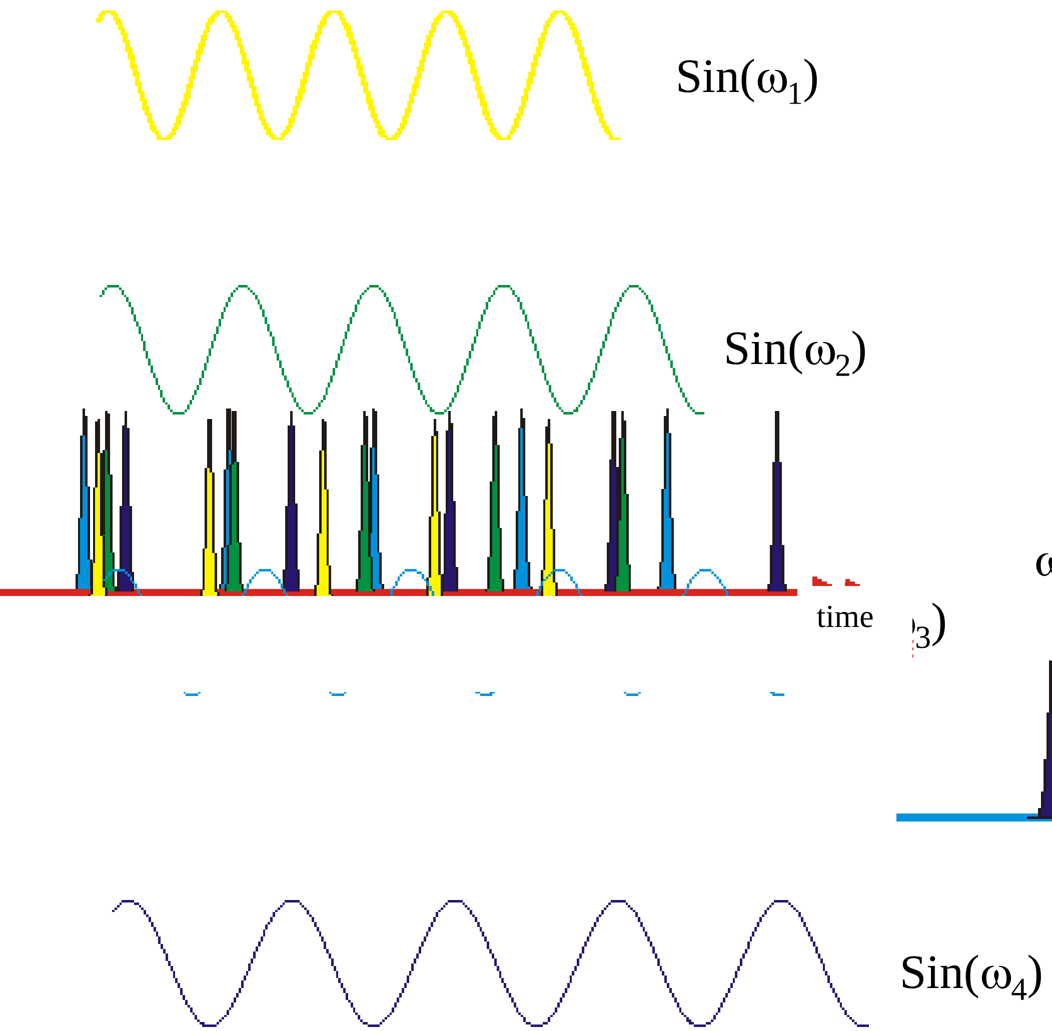
$$\frac{\Delta f}{f} = -\frac{1}{\gamma_t^2}\frac{\Delta(m/q)}{m/q} + \frac{\Delta v}{v}\left(1-\frac{\gamma^2}{\gamma_t^2}\right)$$

Schottky-Mass-Spectroscopy

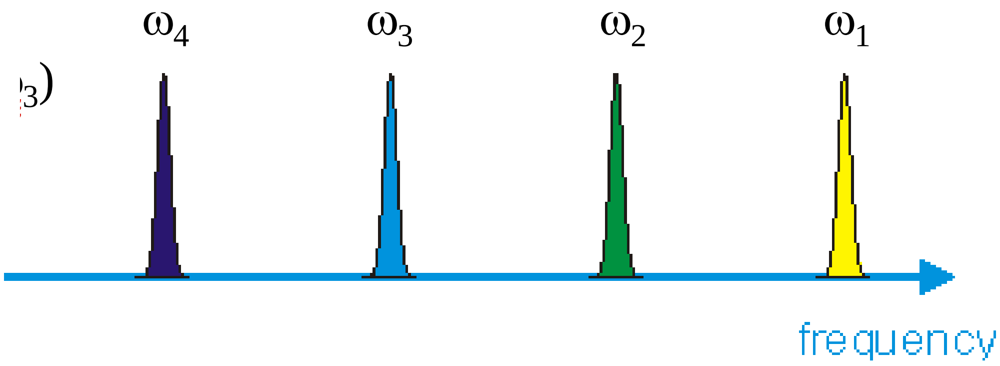
4 particles with different m/q



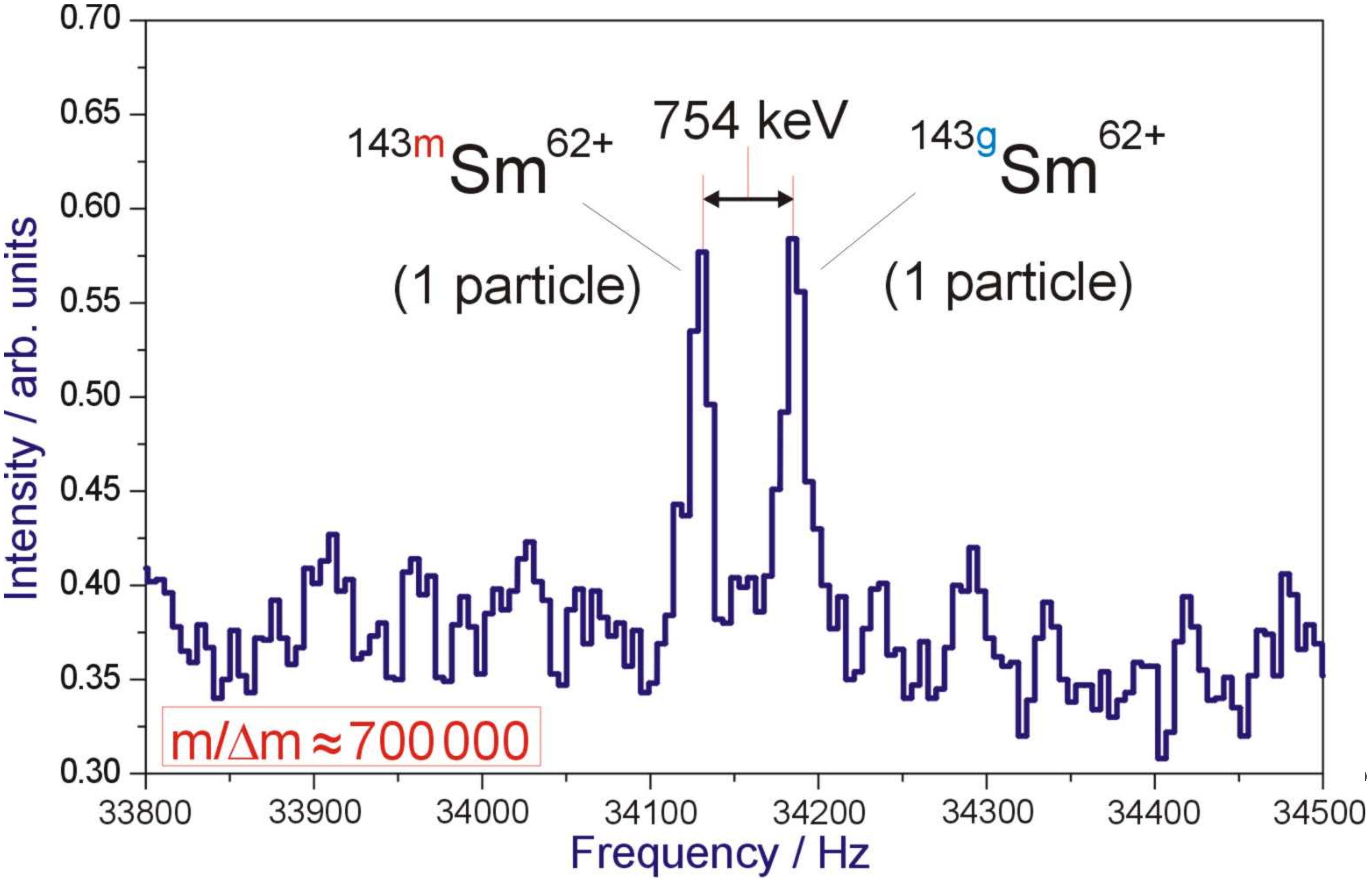
Schottky mass spectroscopy



Fast Fourier Transform

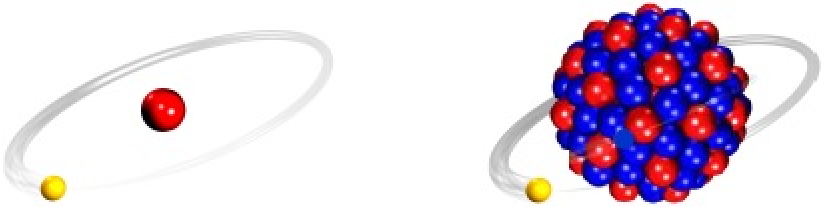


Small-band Schottky frequency spectra

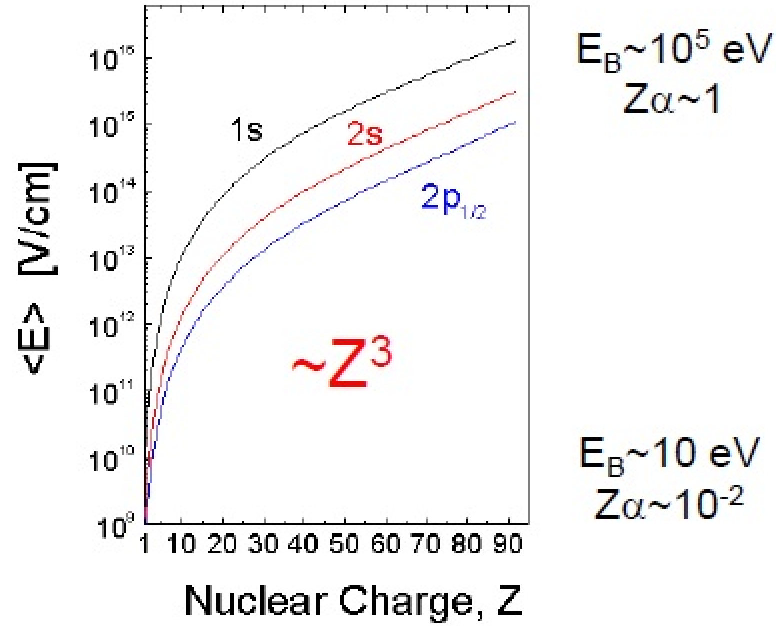


The interest in highly-charged ions

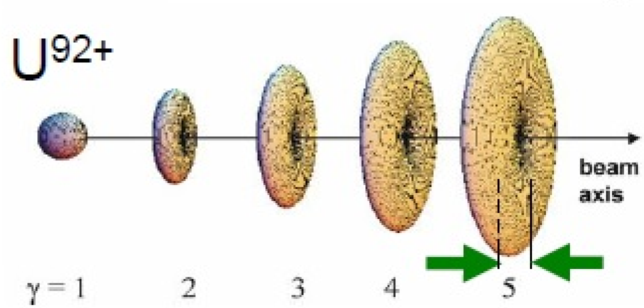
Simple (few electron) systems:
from hydrogen to H-like uranium



Tests of QED in extreme electromagnetic fields. New access to fundamental constants and to nuclear ground state properties



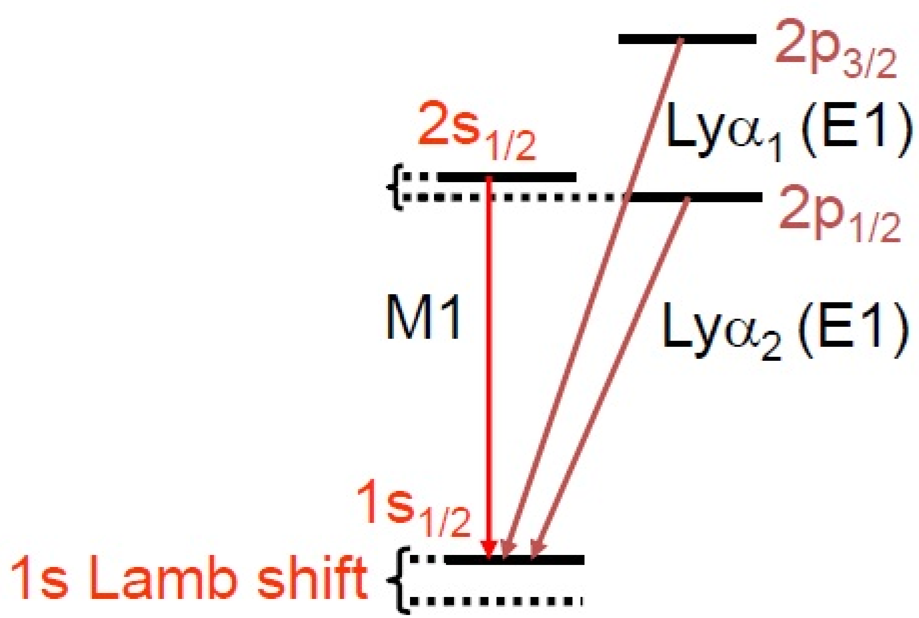
Extremely short and extremely intensive electromagnetic pulses at relativistic energies of highly-charged ions.



$t \leq 0.1$ as
$I \approx 10^{21}$ W/cm²

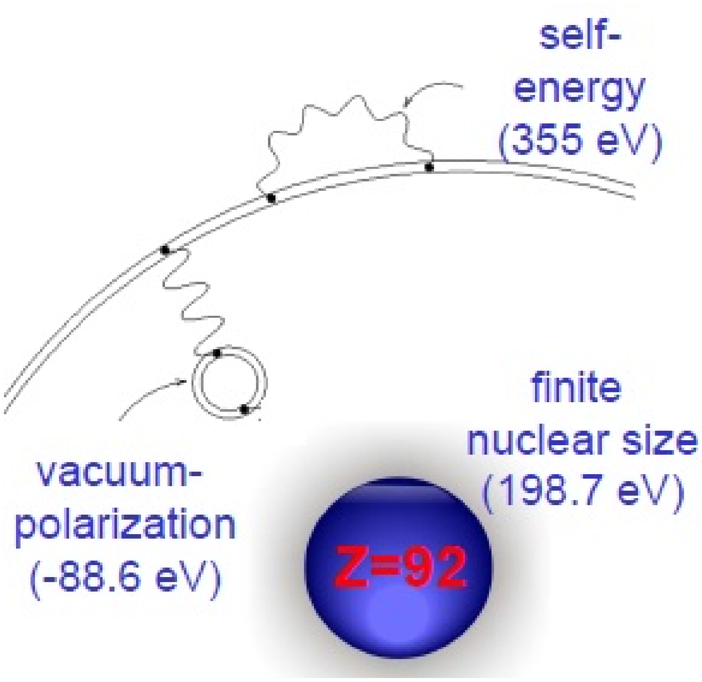
Lamb shift in hydrogen-like ions

Strong Coulomb Fields: 1s-Lamb shift in H-like ions



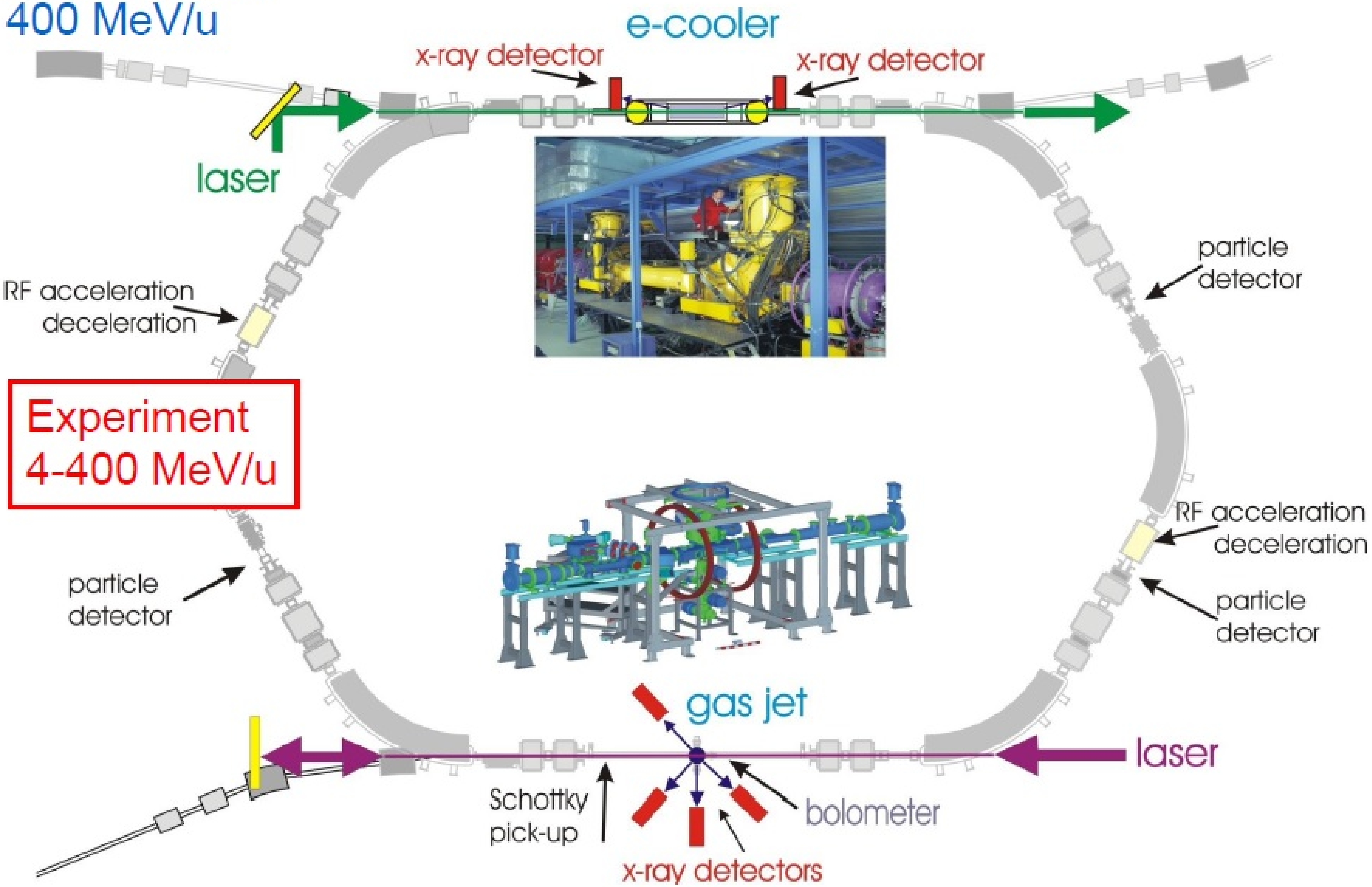
$2s_{1/2}$ (ℓ=0) and $2p_{1/2}$ (ℓ=1) have not the same energy as predicted by Dirac

- self energy (s-electrons are closer to the nucleus than p-electrons → different binding
- vacuum polarization (virtual pairs of electrons and positrons are created and annihilated → screening effect
- finite nuclear size

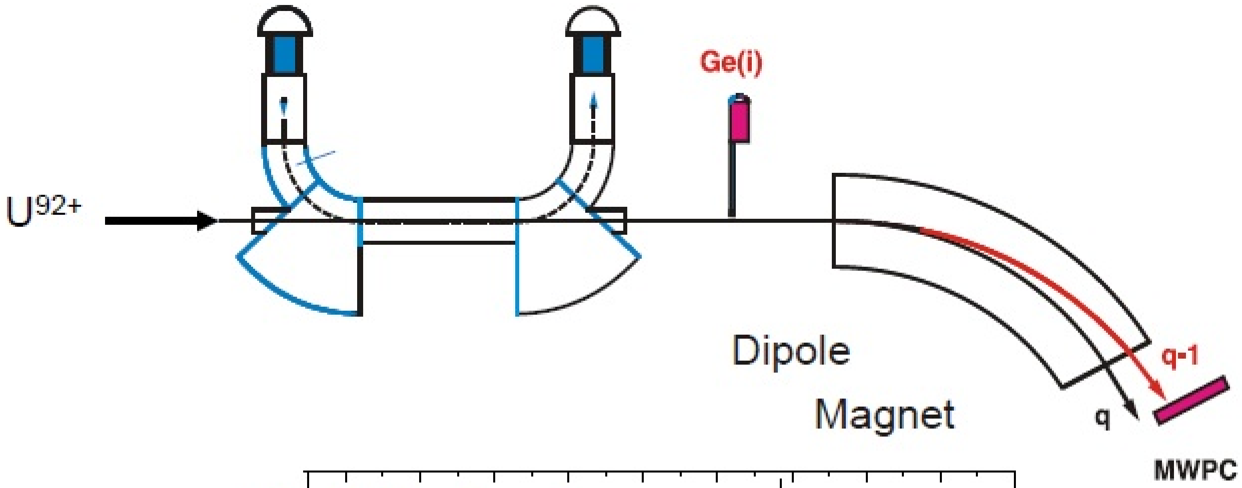


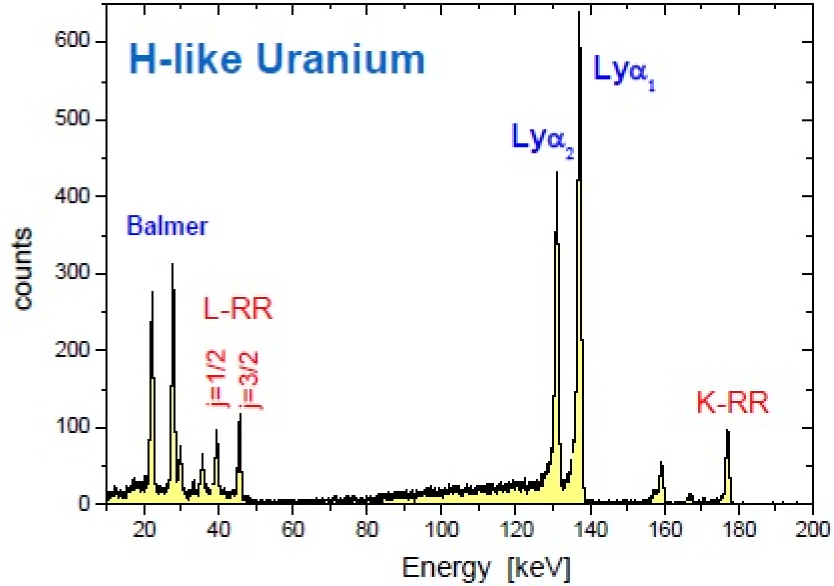
Spectroscopy at the ESR

Injection Energy
400 MeV/u



Spectroscopy at the ESR





1s-Lamb Shift

Experiment: 459.8 eV ± 4.6 eV

Theory: 463.95 eV