Leuven, 2 -6 June 2003, FANTOM Study Week on

Trapping and Manipulating Atomic and Subatomic Particles

Principles of (Ion) Storage Rings

Fritz Bosch, GSI Darmstadt, Germany

Outline

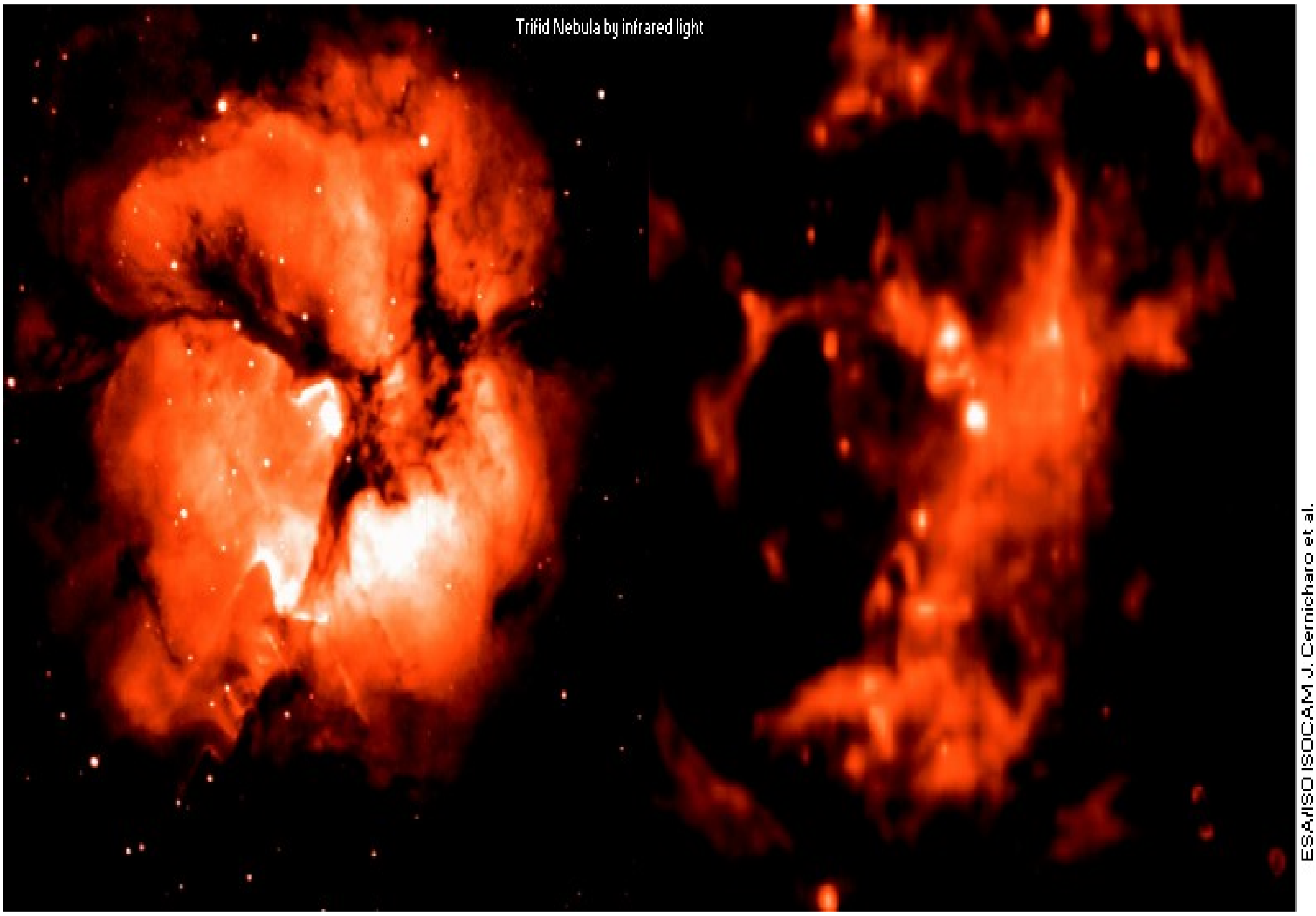
1. **Why do we need ion storage-cooler rings or ion traps?**
   Traps and Rings - complementary devices

2. **Basic concepts of rings: ion optics, storage equation of motion**

3. **Beam-cooling techniques**

4. **Tools for the diagnosis of stored and cooled beams**

1. Why do we need storage-cooler rings or traps?

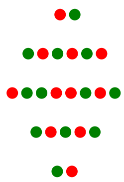


Trifodi nebula, glowing in the infrared light of a nascent star

The major part of matter in the universe exists as a plasma, in a well-balanced equilibrium of ions and electrons

Ion storage rings (traps): doing atomic physics, nuclear physics and astrophysics with ions in well-preserved atomic charge states

Highly charged ions **can be** ***stored*** **for hours and** ***'cooled'*** **in** ***Storage-Cooler Rings*** **where their properties are investigated by** ***sophisticated methods***



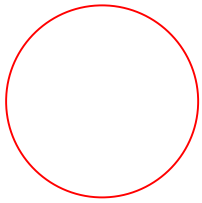
Stars

dense plasma *of* ***ions***
and e^- **(10^{26}/cm^3)**

high temperature
kT ≈ 1...10 keV

excited atomic and nuclear ***states***

equilibrium of charge states



Storage Rings

highly charged ions
low density (10^4/cm^3)

low temperature
kT ≈ 0.1 eV ($T = 10^3$K)

ions in **ground-state**

non-equilibrium of charge states

Ion Traps	Ion Storage Rings
localized	extended
fixed (low) velocity	tunable high velocity
medium charge states	high charge states
few...one ion	many...one ion

cooling techniques

restricted lifetime

photonic excitation

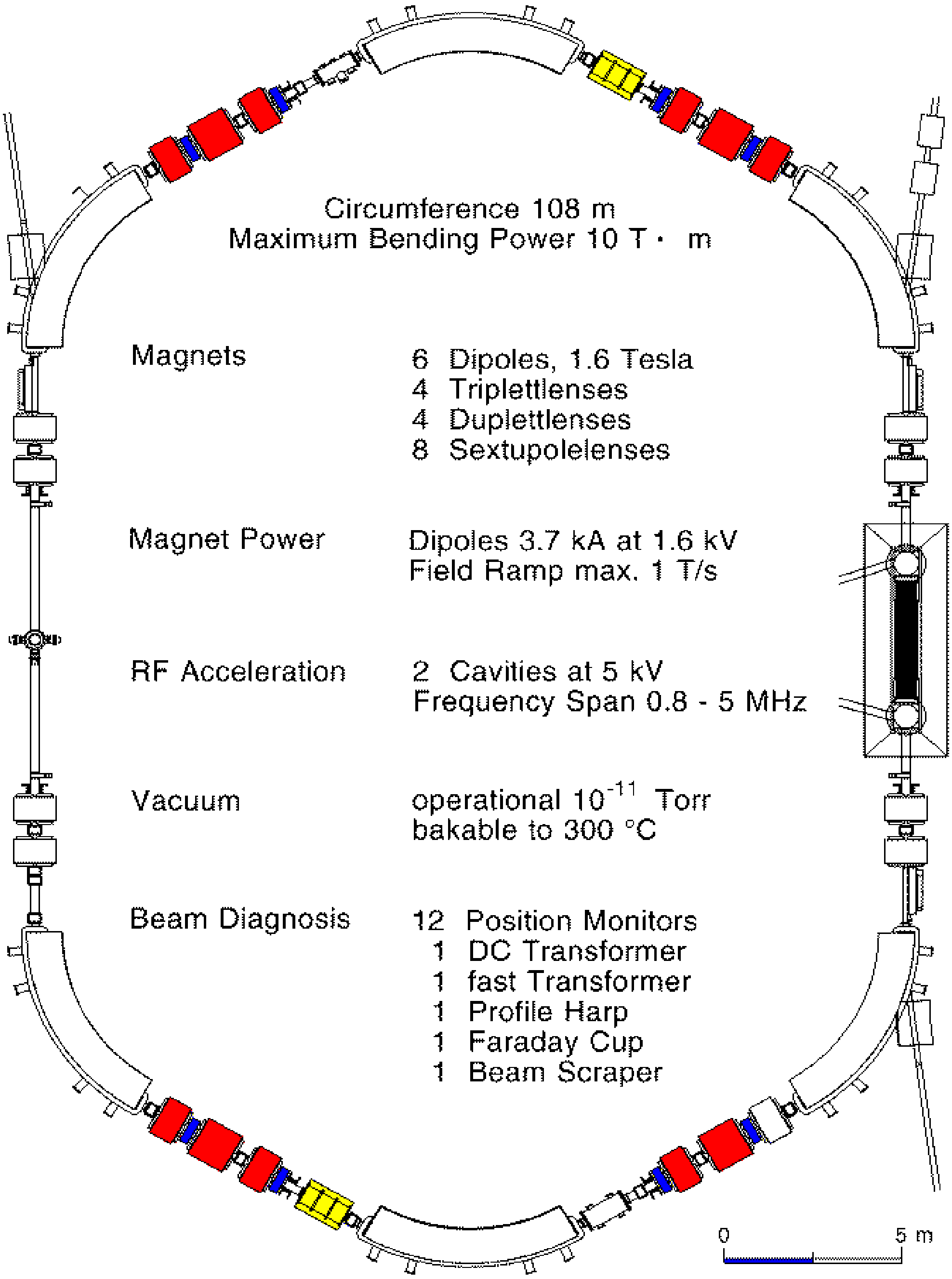
radioactive decay

mass determination

lifetime measurement

2. Basic concepts of storage rings: ion-optics, storage, equation of motion

To store ions one needs a set of bending and focusing magnetic multipoles, a 'lattice'.



Experimental Storage Ring ESR at GSI

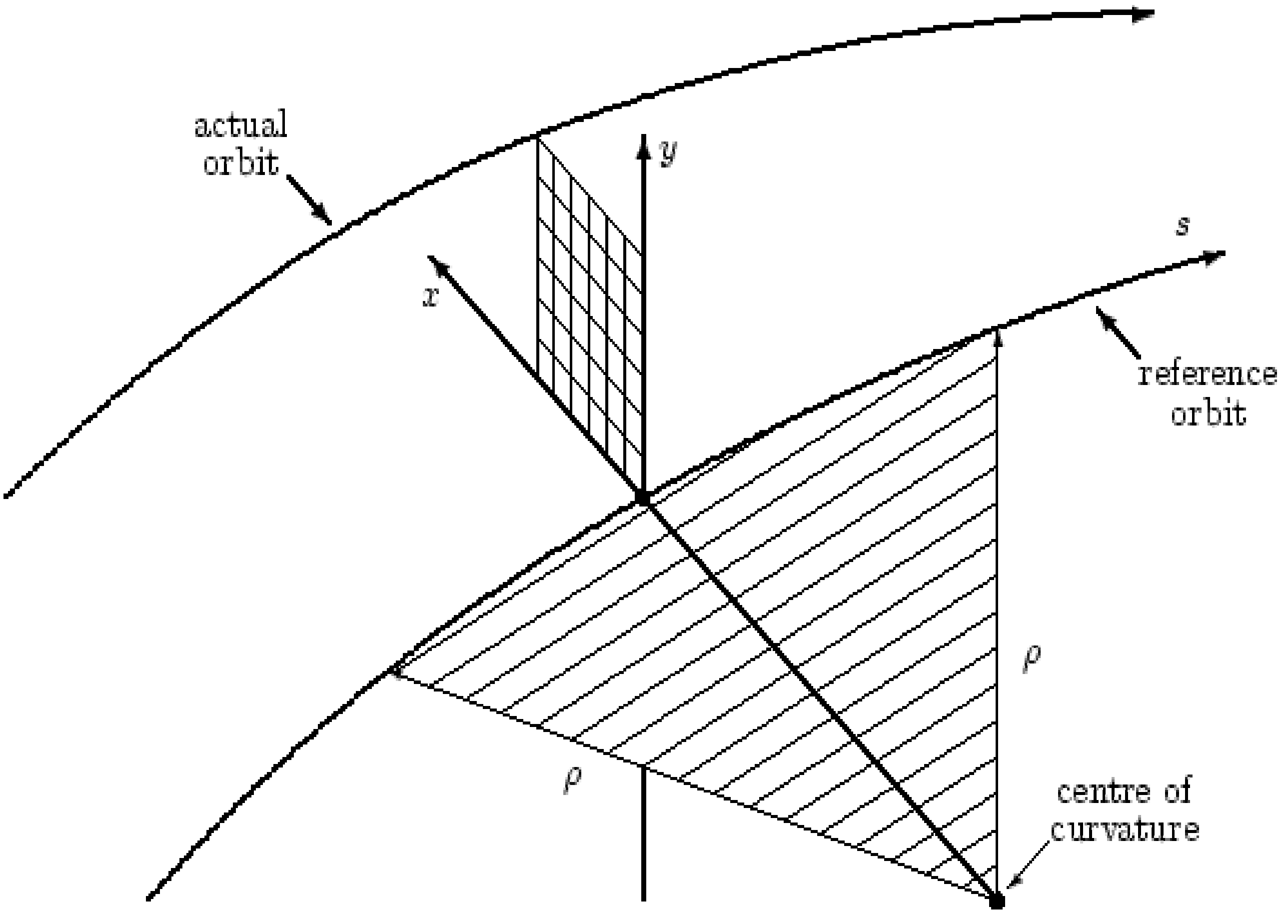
Due to the **finite emittance ε (= size x divergence)**

ions move on ***quasi-periodic orbits*** performing

horizontal and vertical **'betatron oscillations'**

around the **'reference orbit'**

with a '**betatron wavelength' $[\lambda_\beta]_{h,v}$**



[orbit length **C**] / $[\lambda_\beta]_{h,v}$ = **'tune $Q_{h,v}$'**

The orbits in terms of deviations from the 'Sollbahn' (including 'orbit dispersion' due to $\Delta p \neq 0$) are solutions of 'Hill's differential equation', first proposed by G.W.Hill in 1886 to describe the motion of planets disturbed by 3-body forces (for a Paul trap it's the Mathieu equation):

$$u''(s) + k(s)u - 1/\rho\ \Delta p/p = 0$$

u(s) = deviation from reference orbit; s = ion path; **k(s) = k(s + C) periodic force**, determined by the 'lattice'; **C** = circumference

'cos-like' solutions **without** 'dispersion' (**Δp = 0**):

$$u(s)_{h,v} = \{\varepsilon_{h,v}\ \beta_{h,v}(s)\}^{1/2} \cos\{\ \psi(s) + \delta\ \}$$

'phase' $[\psi(s)]_{h,v} = \int_0^s ds'/\beta(s')_{h,v}$

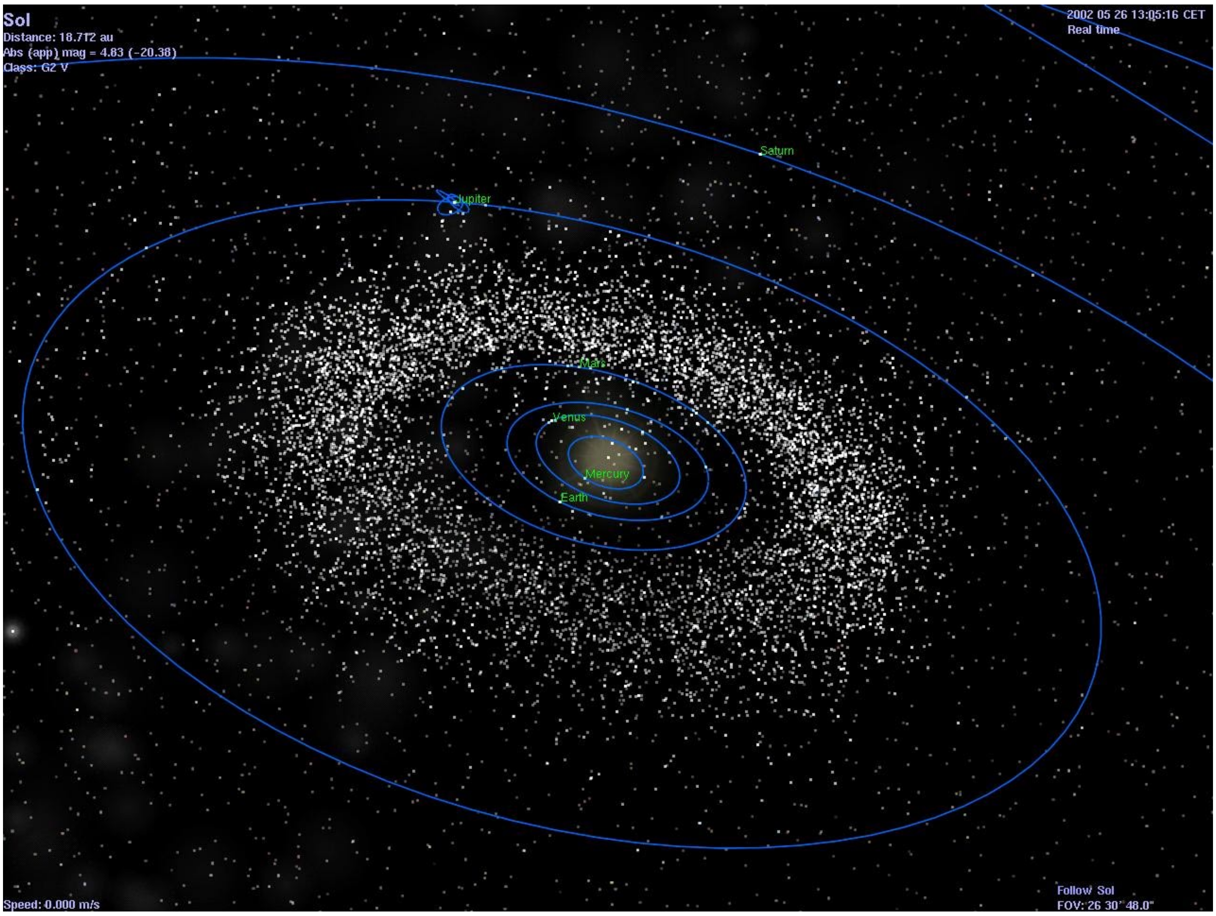
then the 'betatron amplitudes' β(s) depend only on k(s)
'Strong focusing' gets small β, large ψ

with **'betatron wavelength'** $[\lambda_\beta]_{h,v} \equiv 2\pi\ C/\ \psi(s = C)_{h,v}$

→ **'tune'** $Q_{h,v} \equiv C/\ [\lambda_\beta]_{h,v} = \psi(s = C)_{h,v}\ /2\pi$

Avoid integer (n) or 'algebraic' (m/n) $Q_{h,v}$

It generates periodic, resonance-like enhancement of small perturbations and immediate loss of beam



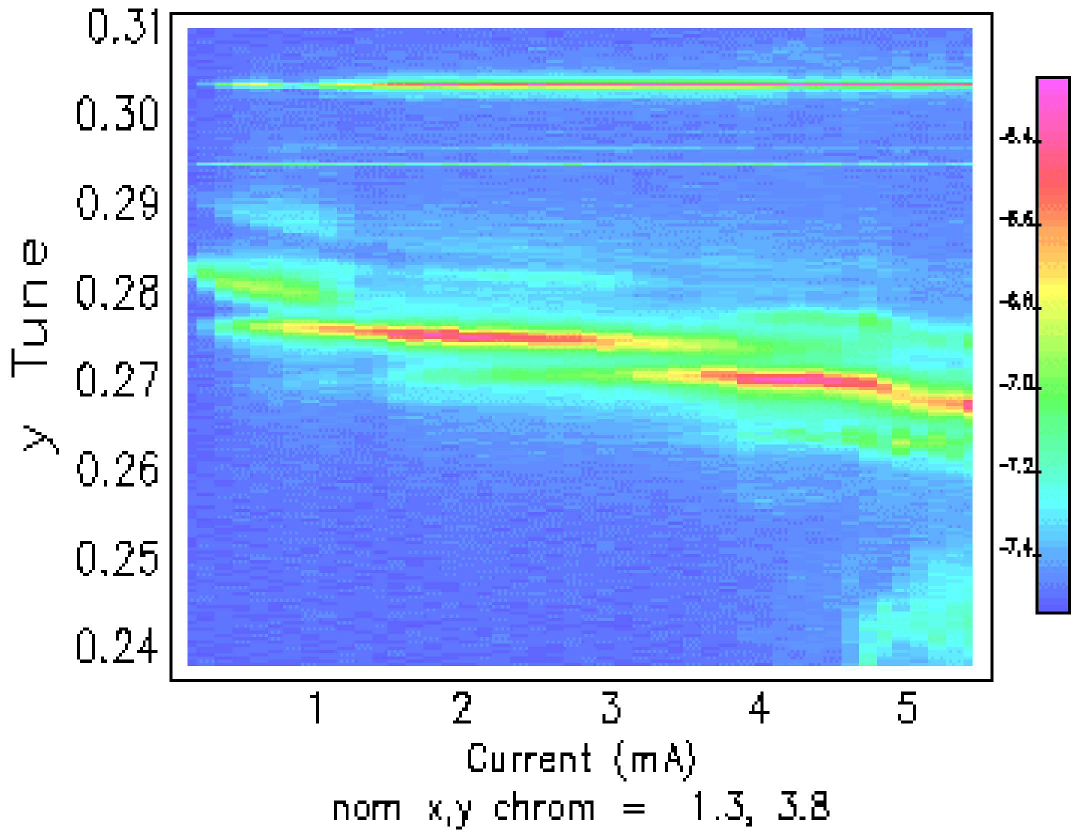
Such a 'Q- resonance' -due mainly to Jupiter's periodic force- forced the destruction of a former planet orbiting between Jupiter and Mars. Today still 'gaps' (e.g. Hecuba) exist.

Ion storage rings have a restricted acceptance given by ε_h, ε_v, (typically 10...30 π mm mrad) or $\Delta p/p \approx 1...5$ %.

These values and the set of magnets (the 'lattice') determine the solution of Hill's equation, i.e. the actual betatron wavelengths, the betatron amplitudes $\beta(s)_{h,v}$ and $Q_{h,v}$.

Q depends on momentum spread Δp and beam current:

ΔQ large → crossing resonances → beam loss



Q changes too, when **accelerating/decelerating** ions

→ **fast crossing of resonances needed**

Coulomb repulsion of ions with charge q effects a

Space-charge limit of number N of ions ($\Delta p = 0$):

$$N_{max} < \pi/r \;\; A/q^2 \;\; \beta^2\gamma^3 \, \varepsilon_- \left[1 + \{\varepsilon_+ Q_- / \varepsilon_- Q_+\}^{1/2} \right] \Delta Q$$

{ r = classical proton radius, 1.5 *10^{-18} m; $\varepsilon_{+/-}$, $Q_{+/-}$ = larger/smaller of emittances (tunes); **ΔQ = 'tune shift'** (< **0.05...0.2**)}

Examples: (emittances ε in [**π mm x mrad**])

1. **U^{92+}** ($Q_+ = Q_- = 2{,}43$; **$\Delta Q = 0.05$**) :

not cooled, $\varepsilon_{+/-} = 1$	**cooled**, $\varepsilon_{+/-} =$ **0.1**
E = **500** A MeV → **$N_{max} \approx 4 \times 10^{12}$**	**$N_{max} \approx 4 \times 10^{11}$**
E = **50** A MeV → **$N_{max} \approx 2.2 \times 10^{11}$**	**$N_{max} \approx 2.2 \times 10^{10}$**

2. Ne^{10+}

E = **500** A MeV → **$N_{max} \approx 3.4 \times 10^{14}$**	**$N_{max} \approx 3.4 \times 10^{13}$**
E = **50** A MeV → **$N_{max} \approx 1.9 \times 10^{13}$**	**$N_{max} \approx 1.9 \times 10^{12}$**

in addition: **'chromaticity'** (momentum dependence).....

3. Beam-cooling techniques

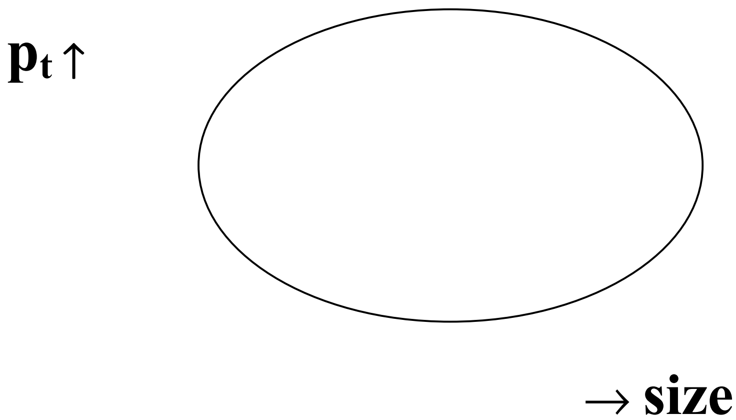
'Cooling' :

Enhancing the phase-space density

i.e. Reducing size, Δp, → emittance ε

but:

for **fixed velocity v, ε is constant (Liouville)**



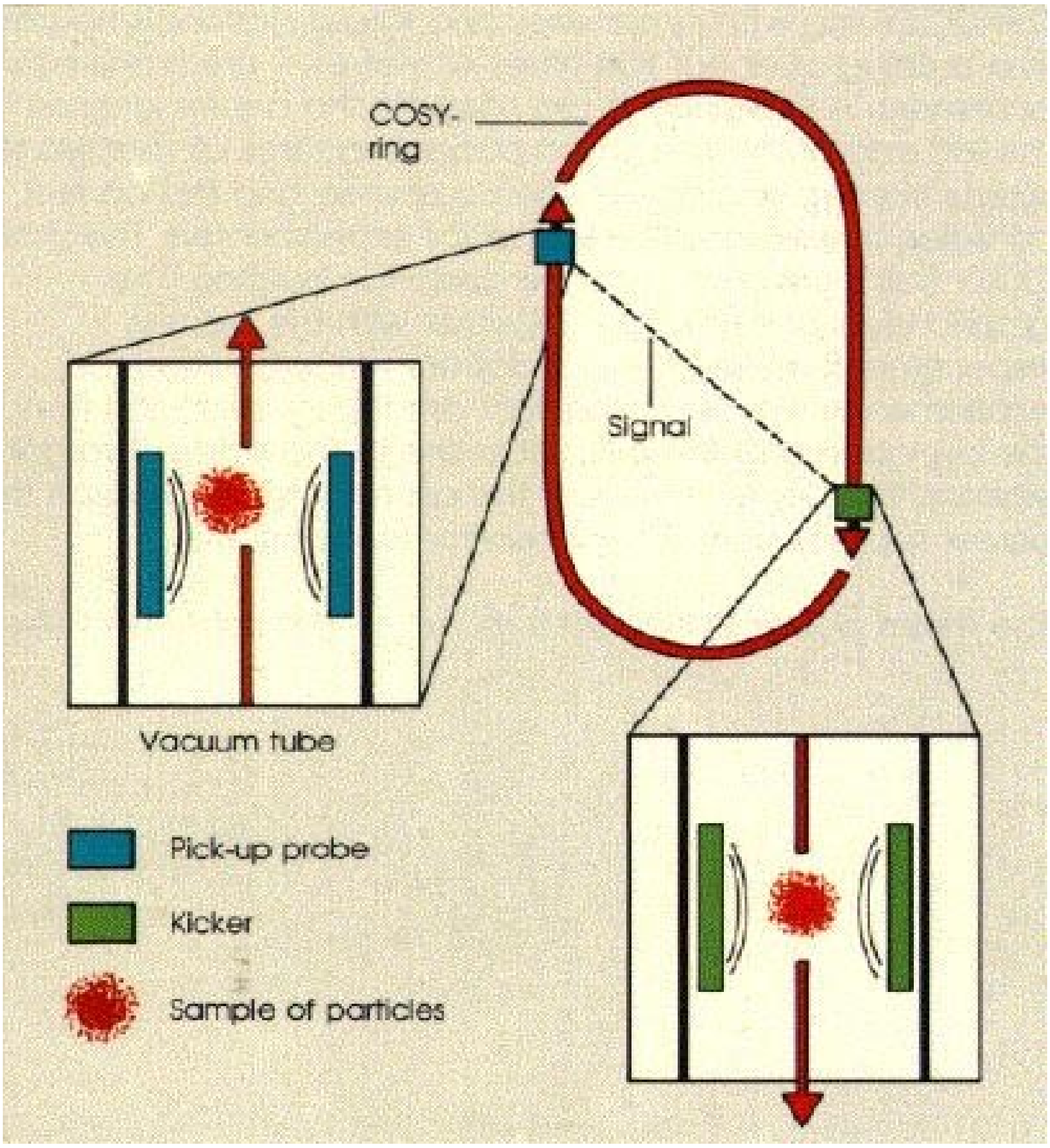
We can never change the area = π ε of the ellipse

→ apply external interactions → cooling

for ion storage rings three cooling methods:

'stochastic'-, 'electron'- and 'laser'-cooling

Simon van der Meer 1925*, CERN, Nobel award 1984
invented 1983 'stochastic cooling' to get a cooled antiproton beam in the CERN SPS collider for detection of the W Boson the 'mediator' of weak interaction



Principle of 'stochastic' cooling

[www.fz-juelich.de/ikp/ikp-general/images/stochast]

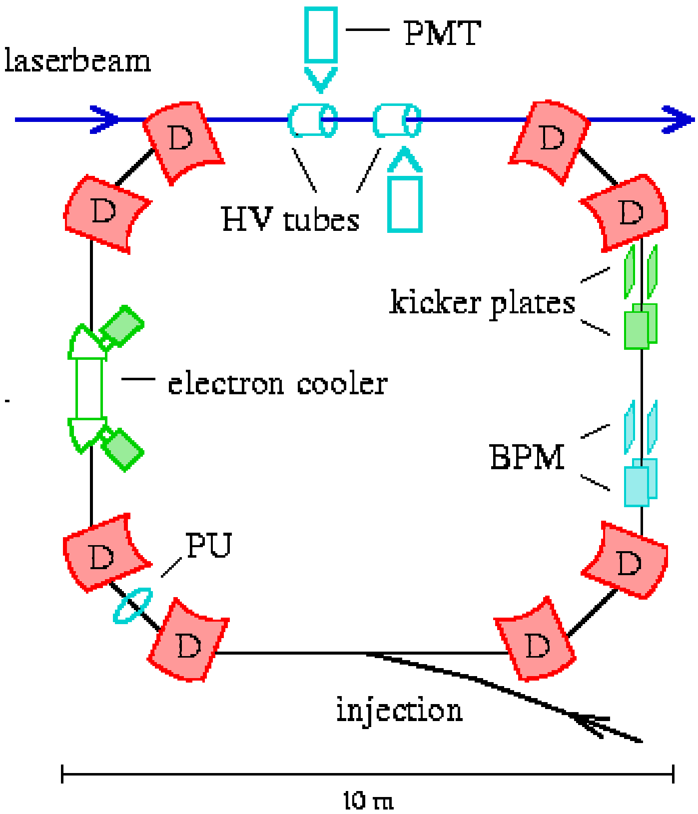
pick-up: $\rightarrow$ beam position, deviations from reference orbit

difference signal (left/right) $\rightarrow$ amplifier

$\rightarrow$ kicker at $(n + 1/4)\ \lambda_\beta$

cooling time $\tau_{sto} \propto N_{ion}$ /Bandwith; $\Delta p/p \approx 10^{-3}$

laser cooling proposed first by Ted Haensch realized in ion storage rings first at TSR and ASTRID



Test Storage Ring TSR Heidelberg

1. **resonant absorption** of a photon E_γ

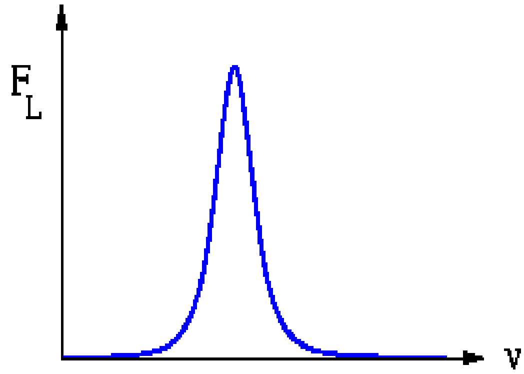
2. **directed momentum transfer** on ion, $\Delta p = E_\gamma/c$

3. **isotropic re-emission** of E_γ → **net momentum transfer**

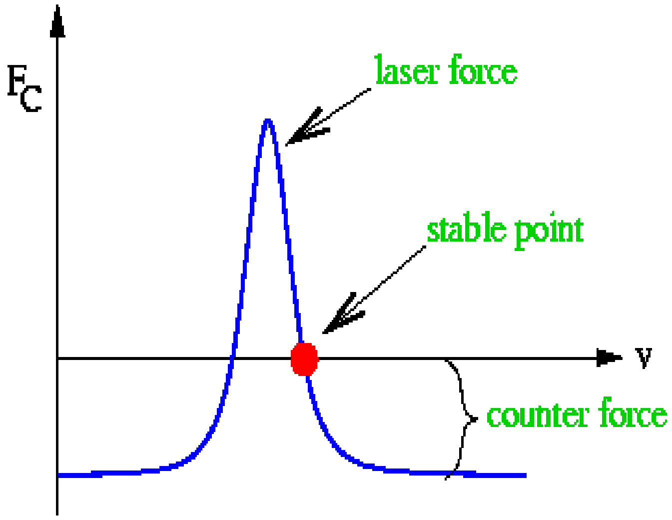
→ **shifting** the **velocity profile** Δv of the stored ions

→ **second** counteracting device **to narrow** Δv

→ **interaction** of **longitudinal and transverse** d.o.f.



Laser force



Cooling force

The counteracting force to narrow Δp may be a second laser or -as at the TSR- a high voltage tube

laser cooling realized for Be^+, Li^+....

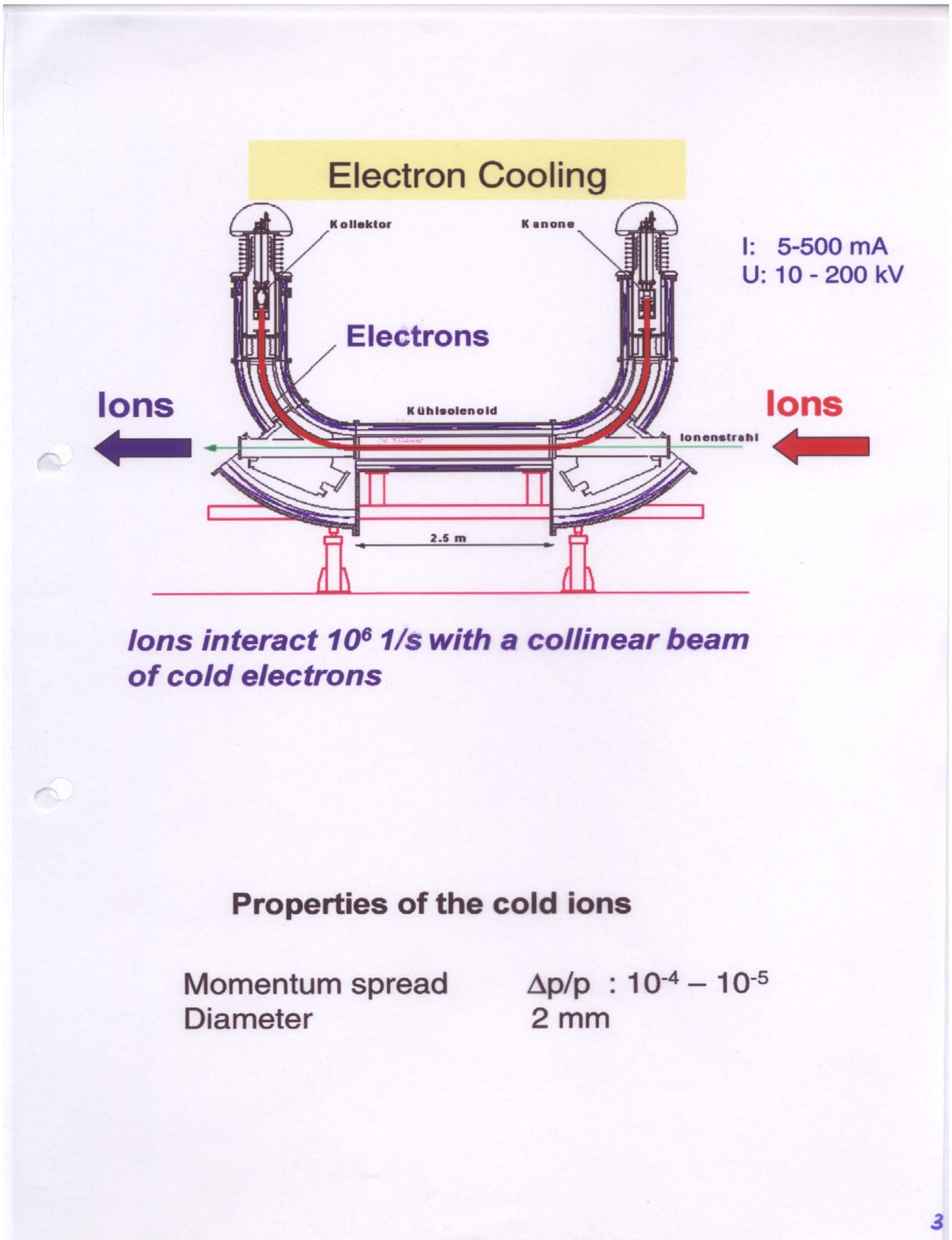
for highly charged ions (H-like, He-like)
only chance to use the 1s hyperfine splitting

advantage of storage rings:

resonance Lorentz-boosted

$$\lambda_{rf} = \lambda_0 \{ (1 - \beta)/(1 + \beta)\}^{1/2} \text{ (laser } 180^0)$$

electron cooling invented in the sixties by G. Budker



collinear, 'cold' (sharp velocity) electrons, guided by a magnetic field, exchange longitudinal and transverse momenta with the ions by Coulomb collisions

electrons removed after one turn

ions come back after $\approx 1\mu s$

ions get the electron temperatures T_l , T_t after equilibrium has been reached:

$$kT_l = A\,\beta^2 c^2 (\Delta p/p)_e^2$$

$$kT_t = 1/2\ A\,\gamma^2 \beta^2 c^2 \{(\varepsilon/\beta)_h + (\varepsilon/\beta)_v\}_e$$

Time τ_C needed for cooling:

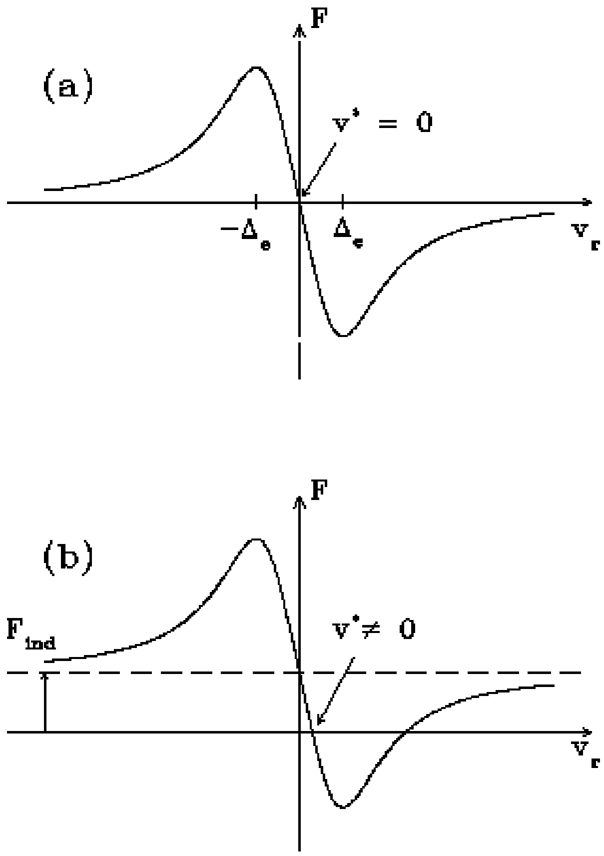
$$\tau_C \propto A/Z^2\ \ 1/j_{e-}\ \ |\Delta v|^3$$

[**0.1s...30s**; A = 200, Z=80; je- = 200 mA)

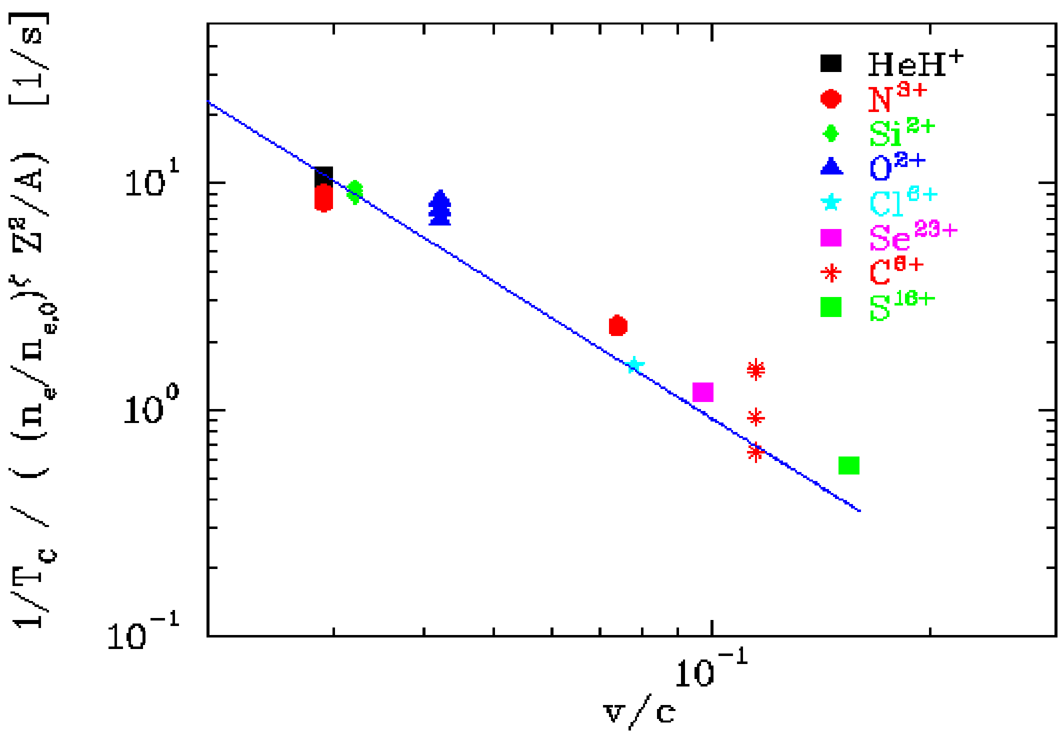
$[\Delta v/v]_{inj} = 10^{-3}.....10^{-1}$ **(hot fragments)**; **j_{e-}= 200 mA**

Electron Cooling provides:

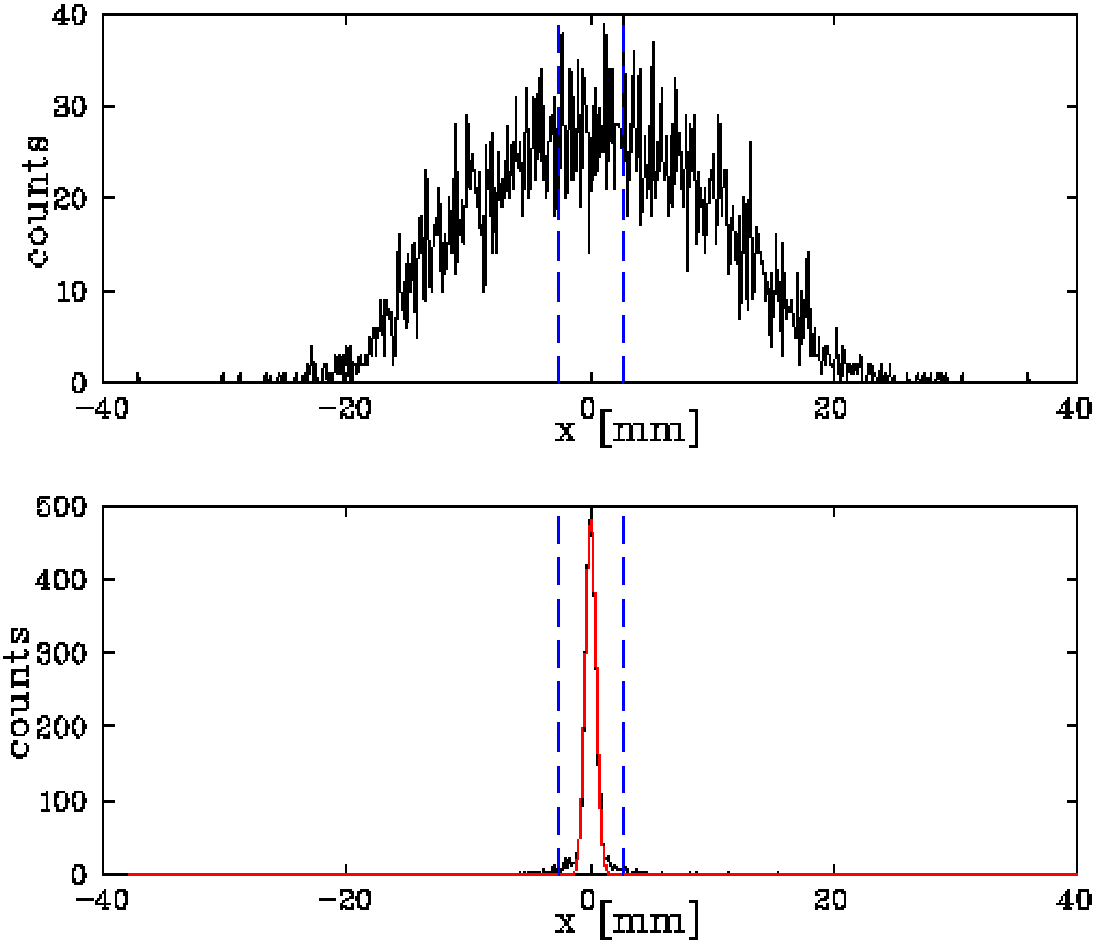
- **brillant beams (ε = 0.1 π mm mrad; $\Delta p/p = 10^{-6}$)**
- **constant energy**
- **long storage times (hours for few-e^- ions)**
- **same velocity for all ions**



Theoretical cooling force: $\propto 1/\Delta v^3$



Experimental cooling force (TSR)

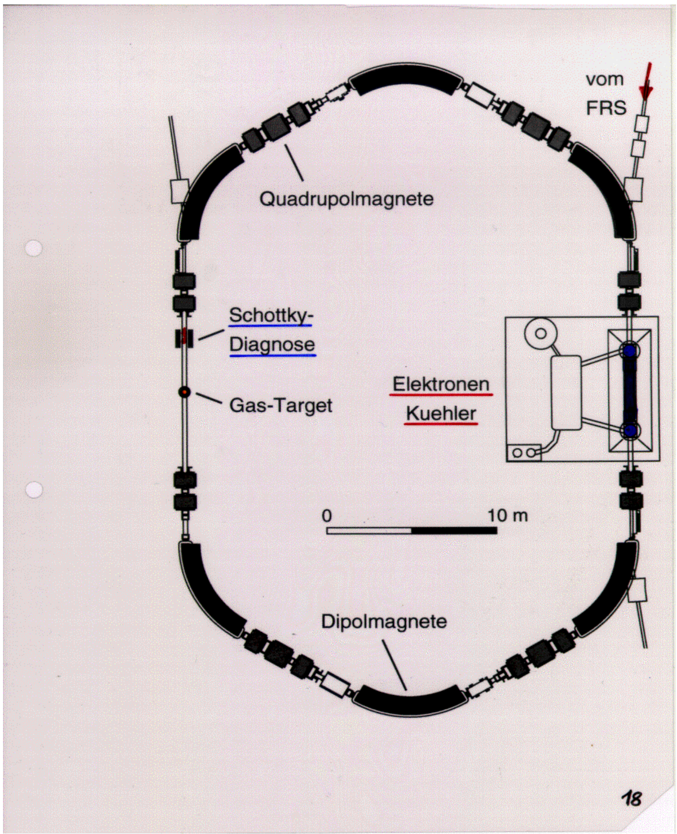


Horizontal beam size before and after electron cooling (TSR)

Since cooled ions all have (almost) the same velocity

a one-to-one correspondence between circulation frequency f and m/q- ratio exists

4. Diagnostic tools: 'Schottky noise'



$$f \;=\; \beta c / 2\pi\rho$$

$$\rightarrow \quad df/f \;=\; d\beta/\beta \;-\; d\rho/\rho$$

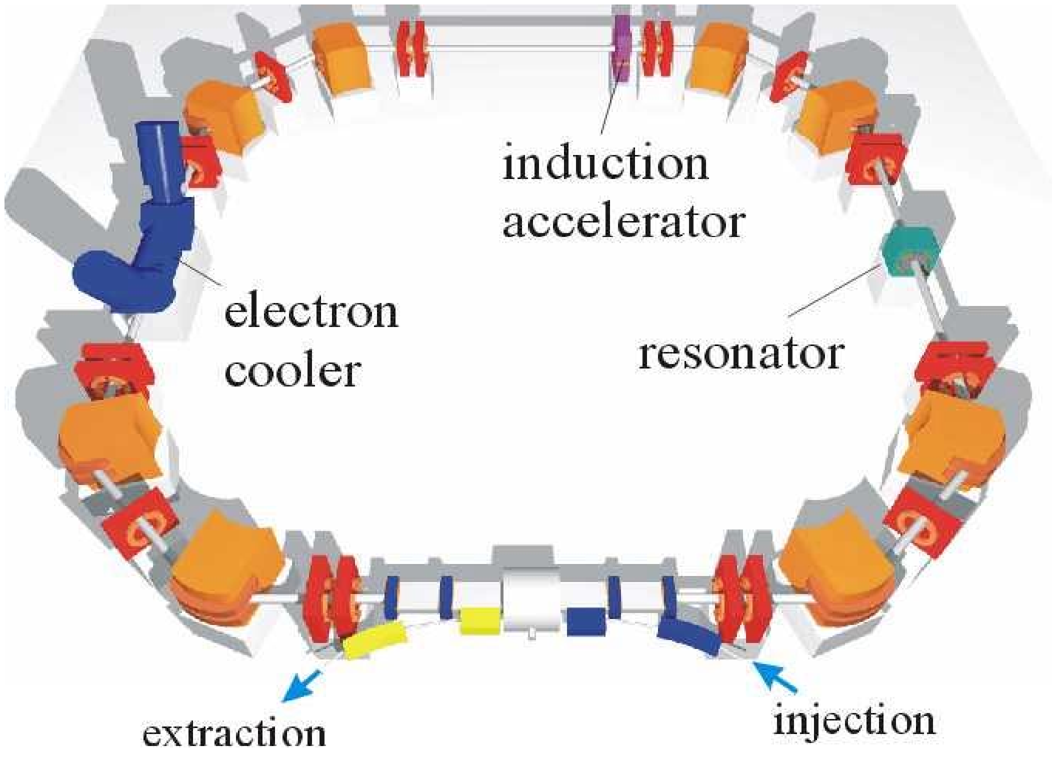
$$\rightarrow \quad df/f \;=\; \{\, 1/\gamma^2 - \alpha_p \,\}\; dp/p$$

$df/dp = 0$ for $\gamma_t^2 = 1/\alpha_p$, γ_t = 'transition energy'

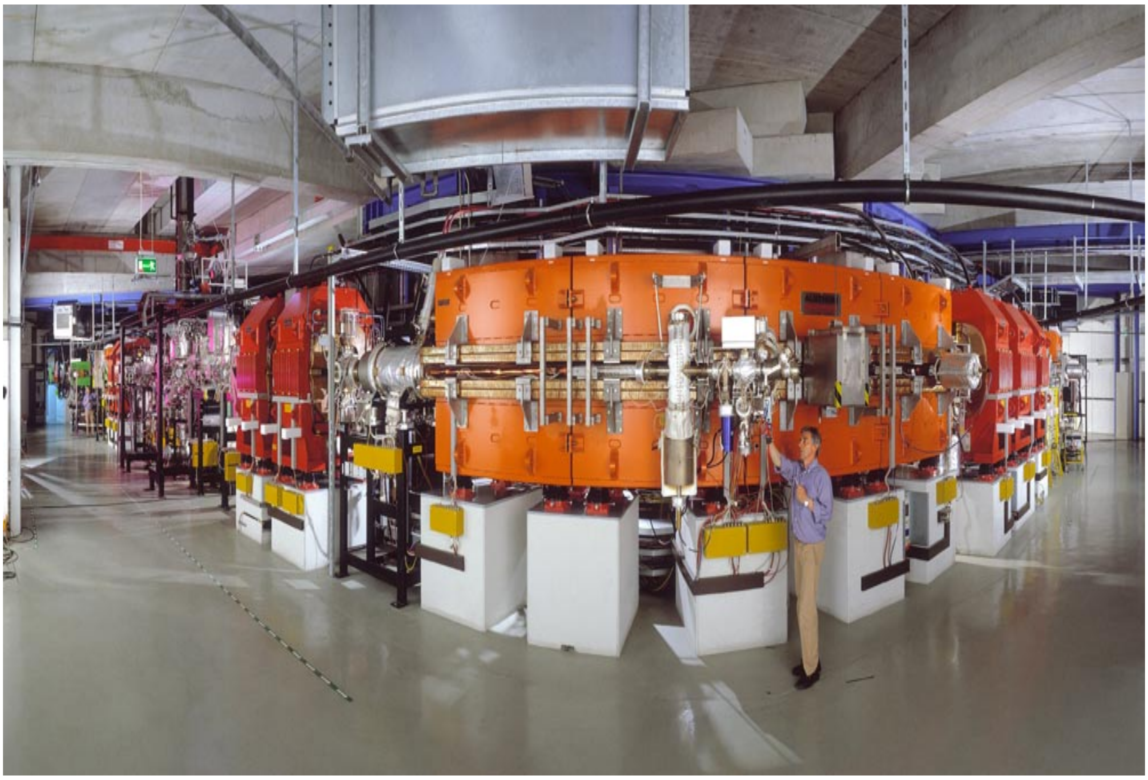
α_p = 'momentum compaction'(property of lattice)
= *$(d\rho/\rho)/(dp/p) \approx 1/7$* (ESR)

for v, B = const. $\rightarrow$ $\rho \propto m/q$

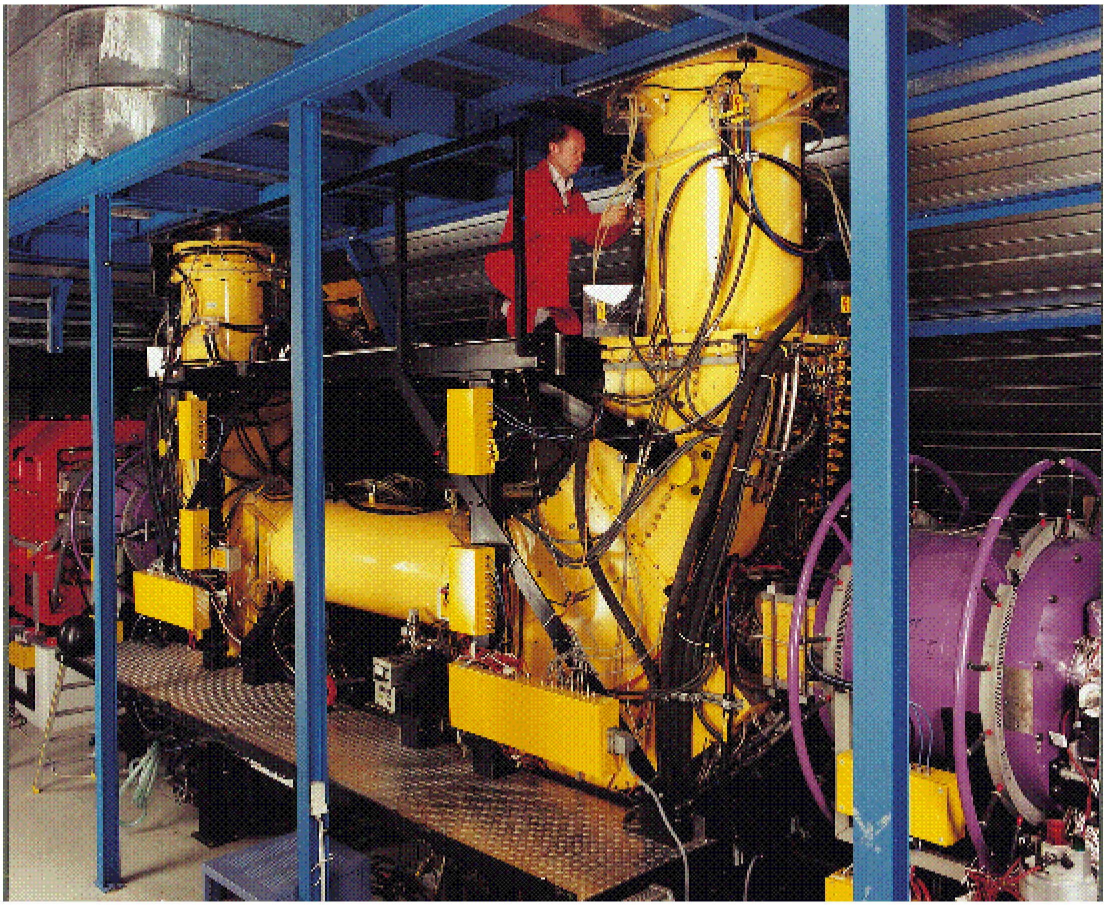
$$\{f_1 - f_2\}/f_1 = -\alpha_p \,\{[(m/q)_1 - (m/q)_2] \,/\, [(m/q)_1]\}$$



Test Storage Ring TSR at the MPI Heidelberg
www.mpi-hd.mpg.de/be/tsr/tsrindex



Experimental Storage Ring ESR at GSI Darmstadt
www.gsi.de/accelerator/esr



Electron cooler at the ESR
www.gsi.de/accelerator/esr