Ultracold atoms as targets

ALBERT-LUDWIGS-
UNIVERSITÄT FREIBURG
Atomic and Molecular Quantum Dynamics

Wenzel Salzmann
Simone Götz
Judith Eng
Roland Wester
Matthias Weidemüller

Physikalisches Institut
Albert-Ludwigs-Universität Freiburg

Atomare und Molekulare
Quantendynamik

Atomare und Molekulare Quantendynamik

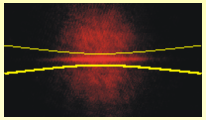
€€€
DFG
Landesstiftung BW
MWK Baden-Württemberg
EU and ESF
DAAD

Matthias Weidemüller

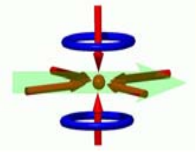
Roland Wester *(Habil)*


http://quantendynamik.physik.uni-freiburg.de

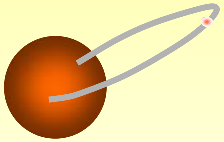
- Mixtures of ultracold atoms and ultracold chemistry
  Stephan Kraft *(PostDoct)*
  Jörg Lange *(Doct)*
  Johannes Deiglmayr *(Doct)*
  Christian Giese *(Dipl)*
  Leif Vogel *(Dipl)*



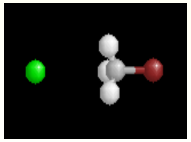
- Cold atom targets / coherent control with femtosecond pulses
  Wenzel Salzmann *(Doct)*
  Terry Mullins *(Doct)*
  Simone Götz *(Doct)*
  Judith Eng *(Dipl)*
  Magnus Albert *(Dipl)*



- Ultracold Rydberg gases and plasmas
  Markus Reetz-Lamour *(Doct)*
  Thomas Amthor *(Doct)*
  Sebastian Westermann *(Dipl)*
  Janne Denskat *(Dipl)*
  Andre de Oliveira *(GuestProf)*



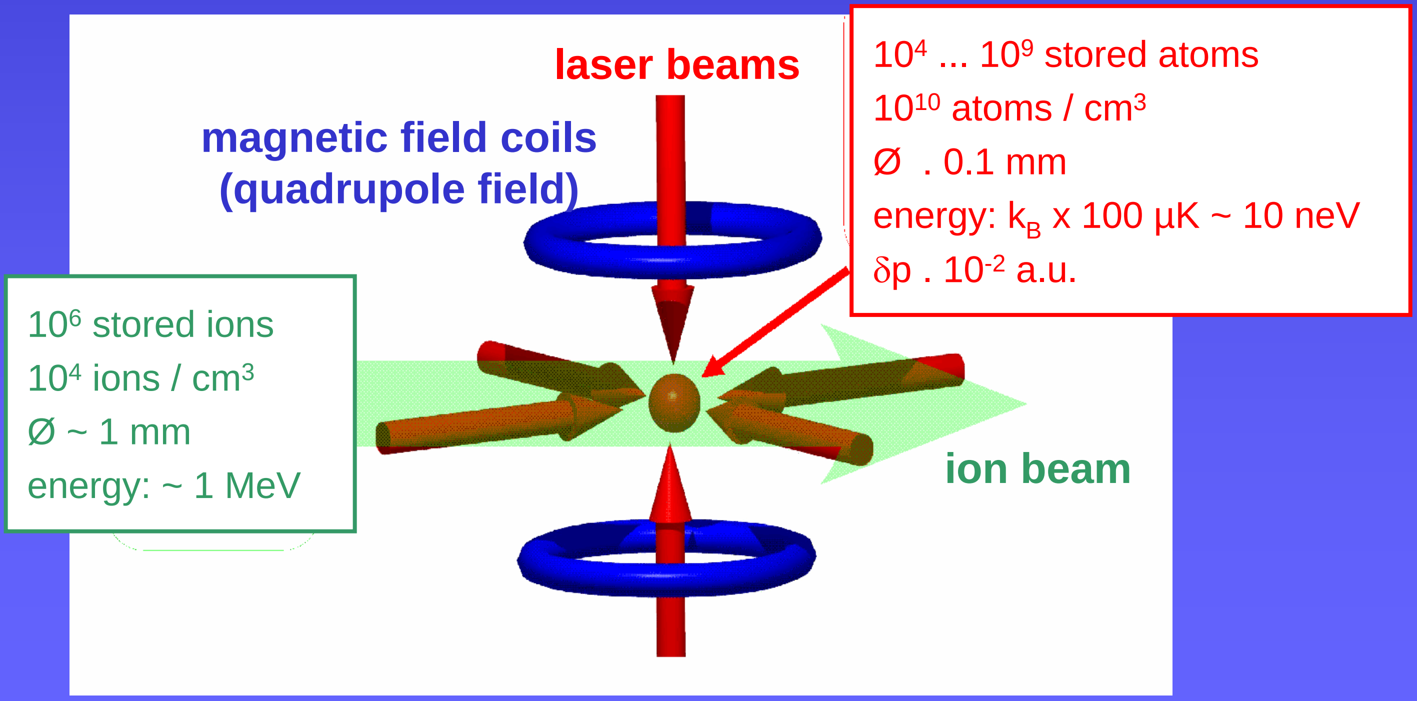
- Quantum dynamics of ion-molecule reactions at low energies
  Jochen Mikosch *(Doct)*
  Sebastian Trippel *(Doct)*
  Rico Otto *(Dipl)*
  Christoph Eichhorn *(Dipl)*
  Markus Debatin *(Dipl)*



Ultracold atoms and a heavy-ion beam

Magneto-optical trap (MOT) in a storage ring

Light-pressure force for confinement (Zeeman effect)
and
cooling (Doppler effect)



laser beams

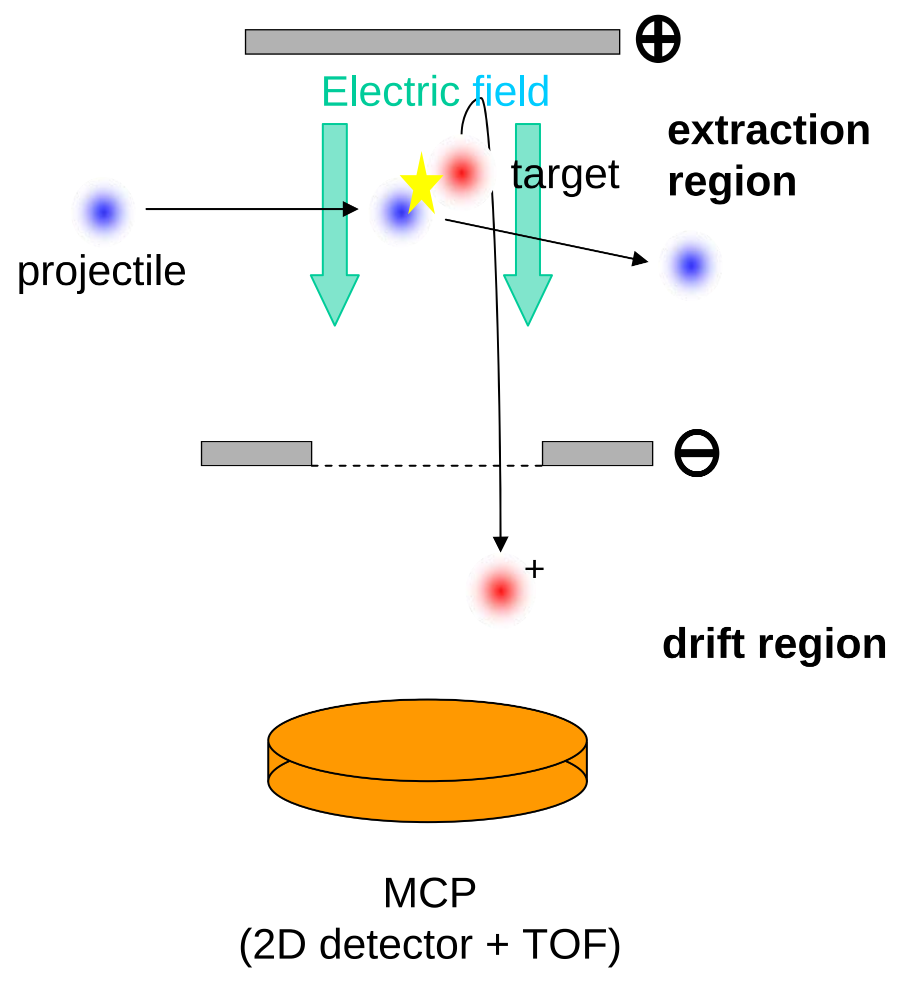
magnetic field coils (quadrupole field)

10^4 ... 10^9 stored atoms
10^{10} atoms / cm^3
Ø . 0.1 mm
energy: k_B x 100 μK ~ 10 neV
δp . 10^{-2} a.u.

10^6 stored ions
10^4 ions / cm^3
Ø ~ 1 mm
energy: ~ 1 MeV

ion beam

Recoil ion momentum spectroscopy



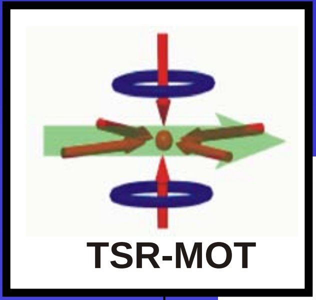
cf. Robert Moshammer / Joachim Ullrich

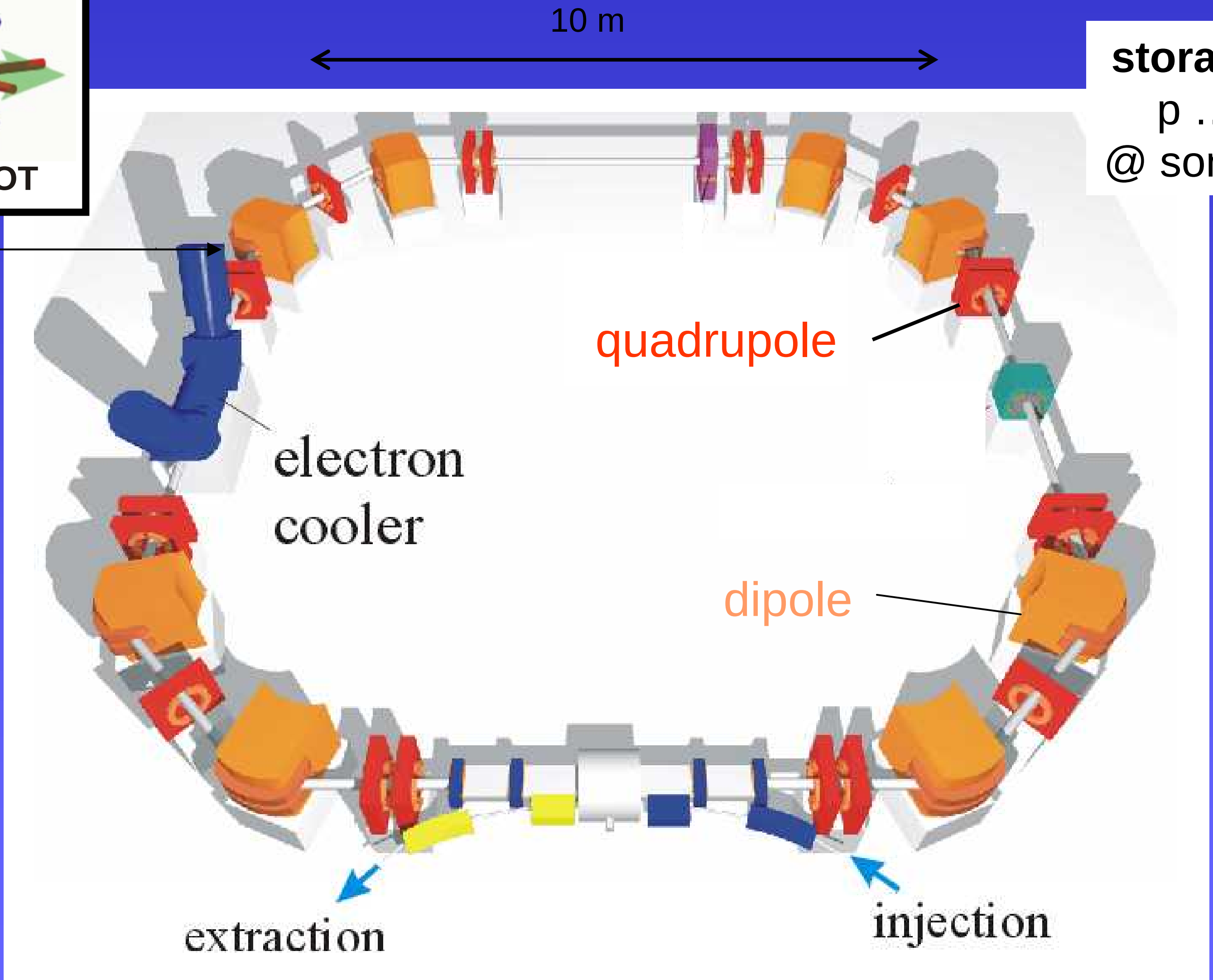
Momentum information from
time-of-flight plus **2D ion image**

Momentum resolution is limited by
temperature and **localiztion**
of target gas

Magneto-optical trap:
T ~ 100 μK → Δp ~ 0.01 a.u.
Δr ~ 100 μm

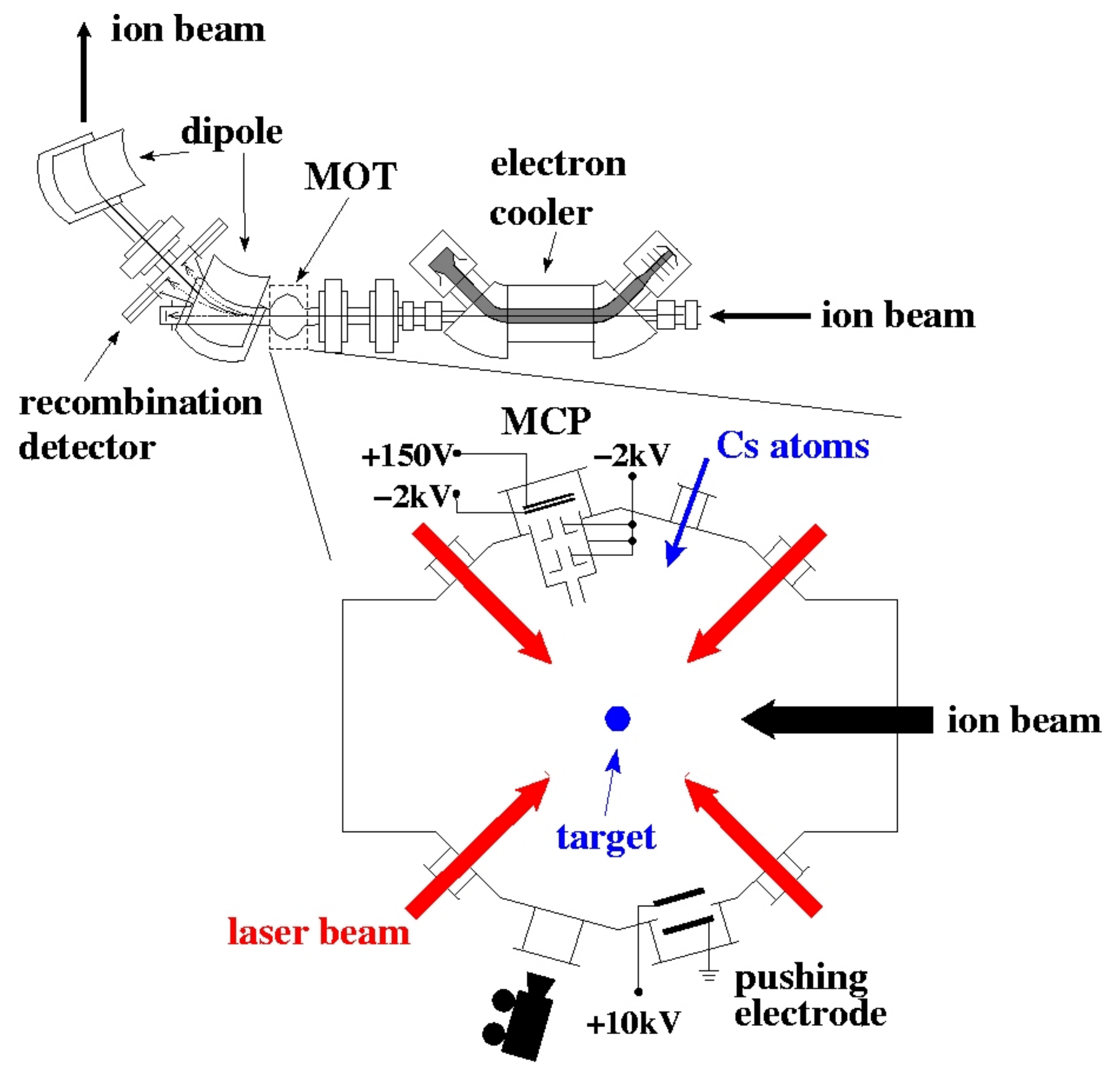
Heidelberg Test Storage Ring



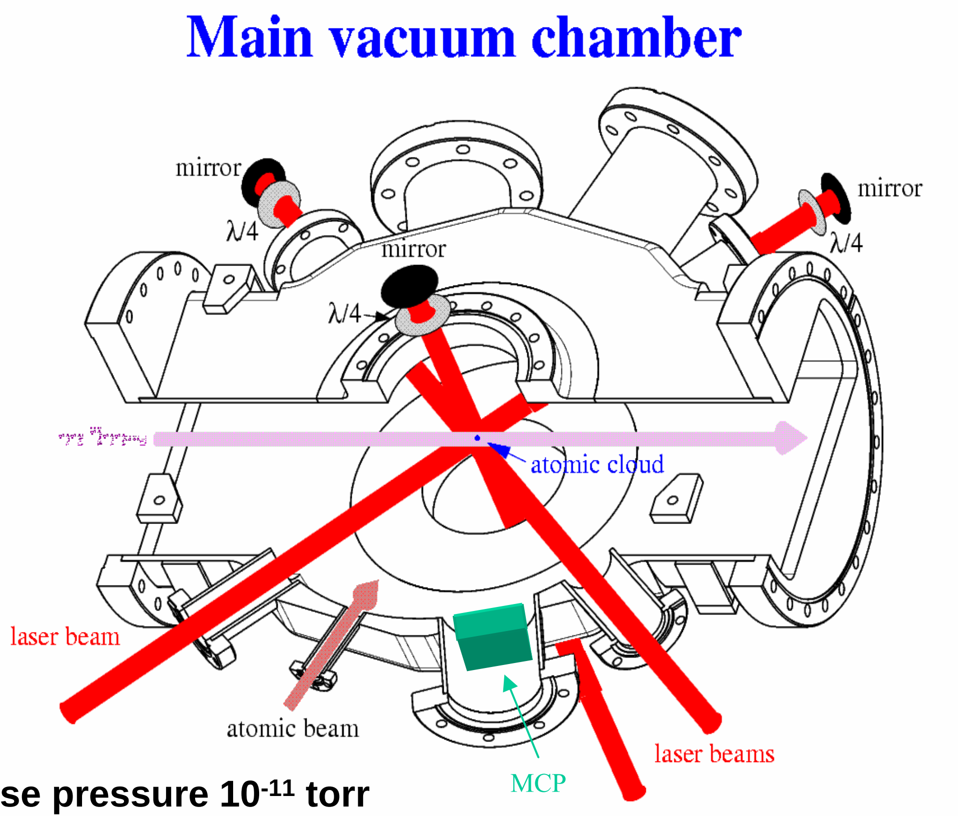


storable ions:
p … Au^{79+}
@ some MeV/u

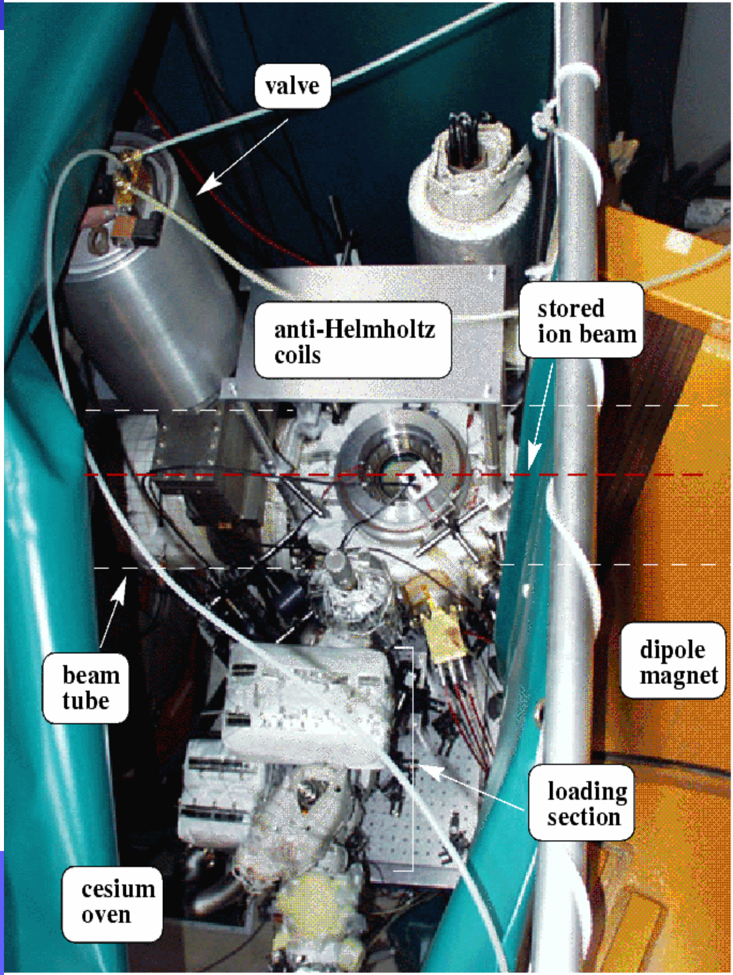
Implementation into the storage ring



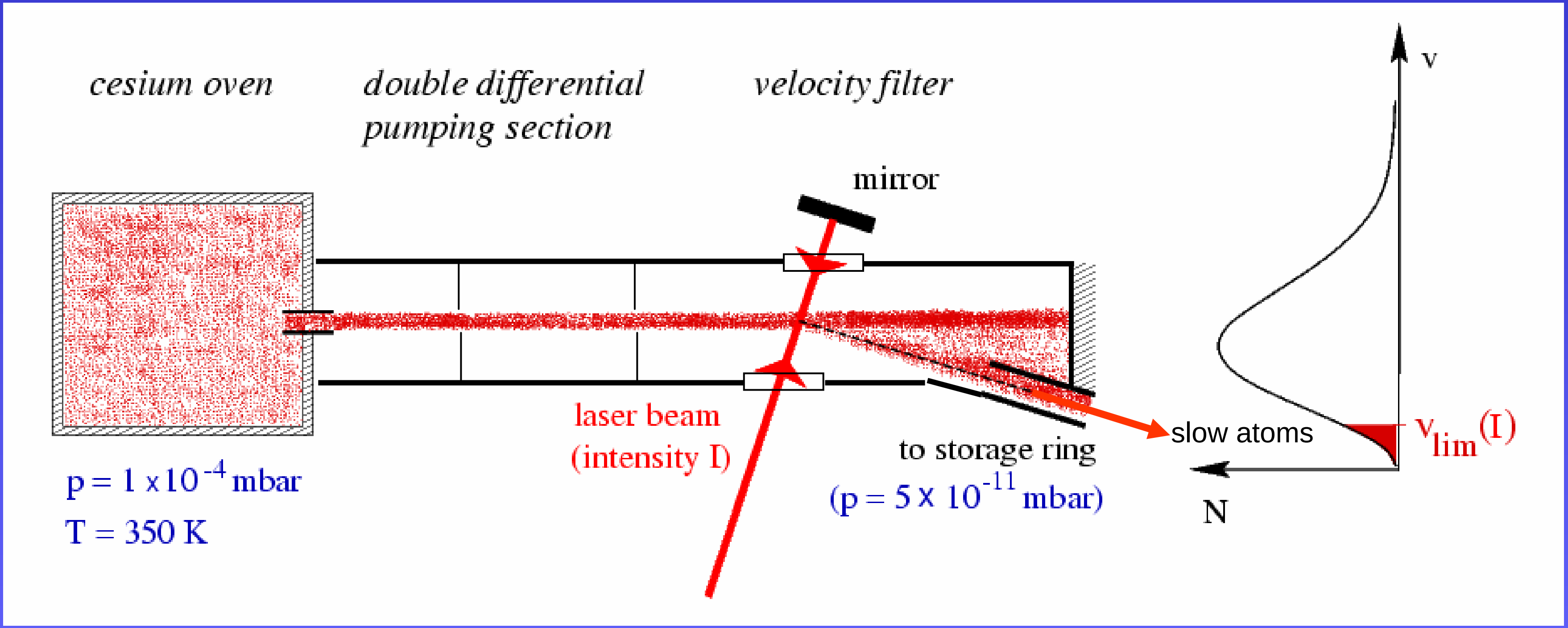
Implementation into the storage ring (cont‘d)



Base pressure 10^{-11} torr

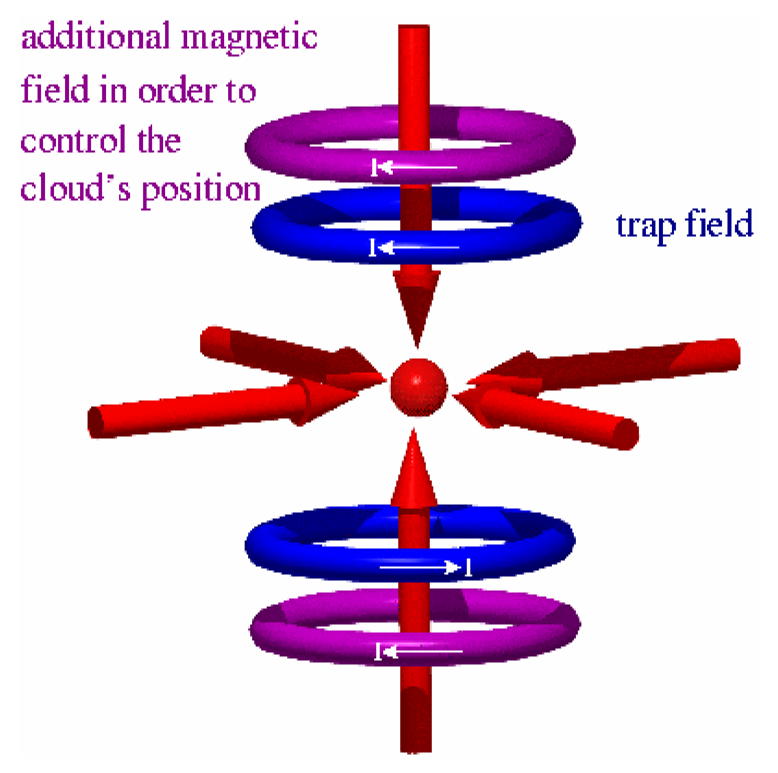


Loading concept

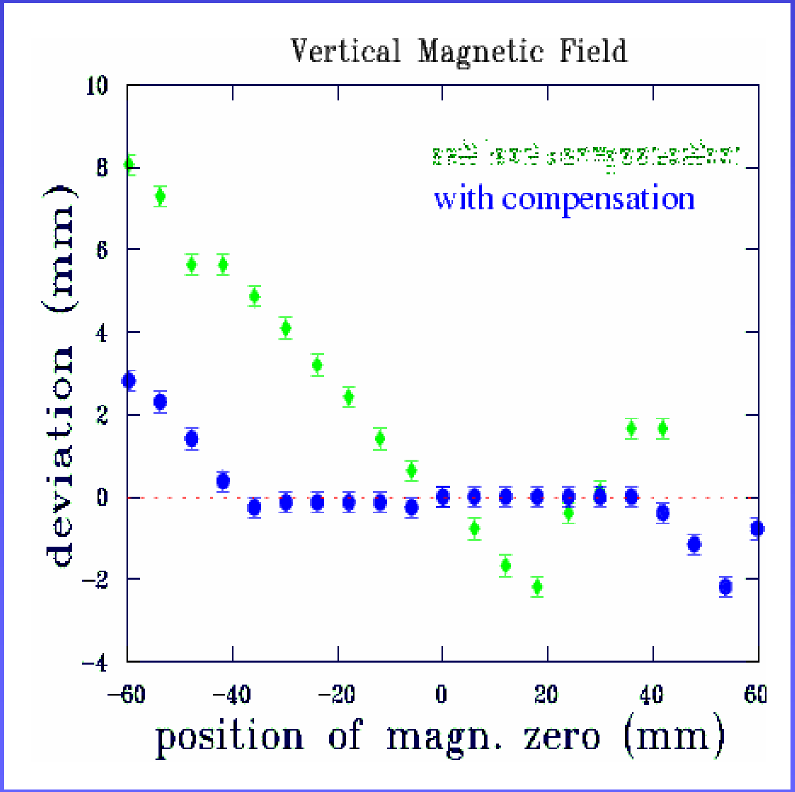


Control of the target position

Shift of the quadrupole magnetic field center by additional homogeneous magnetic field

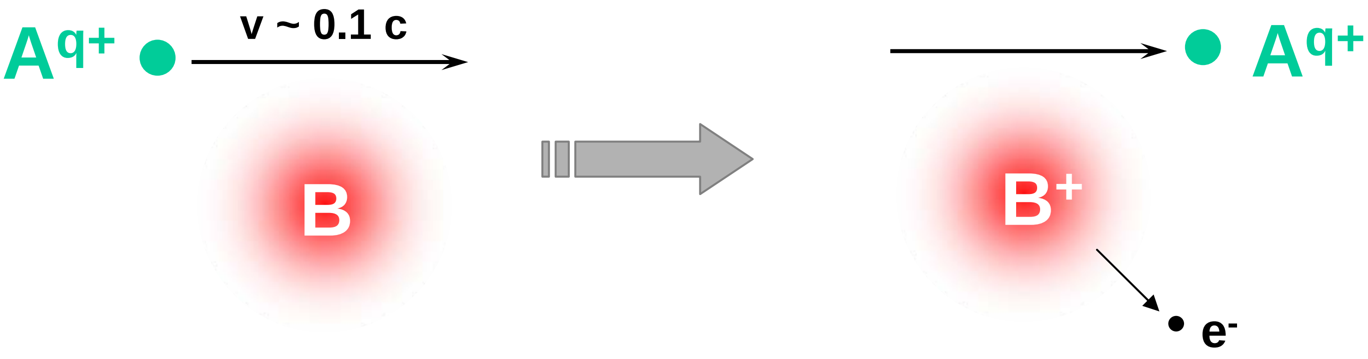


Reaction of the ion beam on the MOT control field:

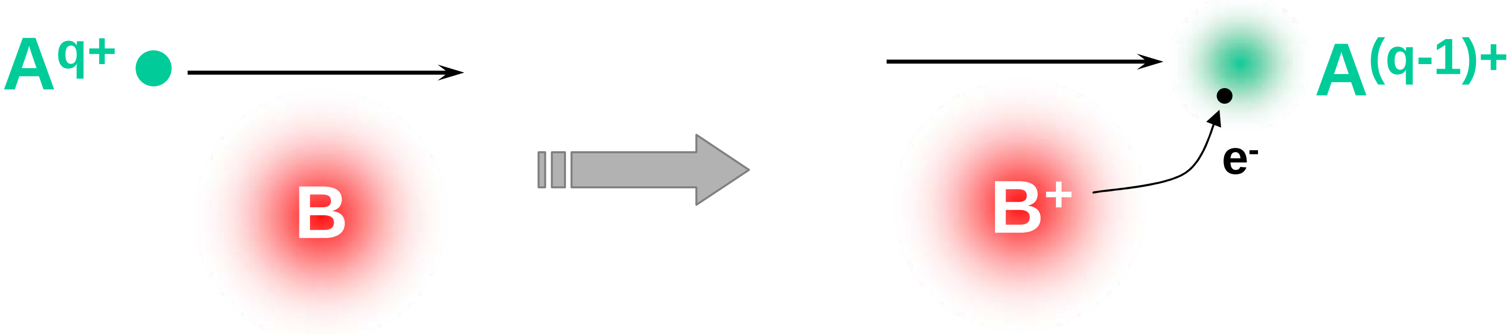


Interaction of fast ions with atoms

Impact ionization:

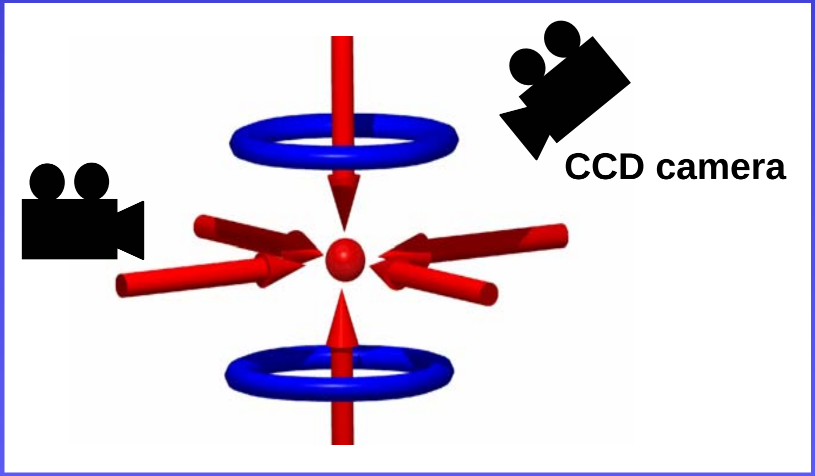


Electron capture:

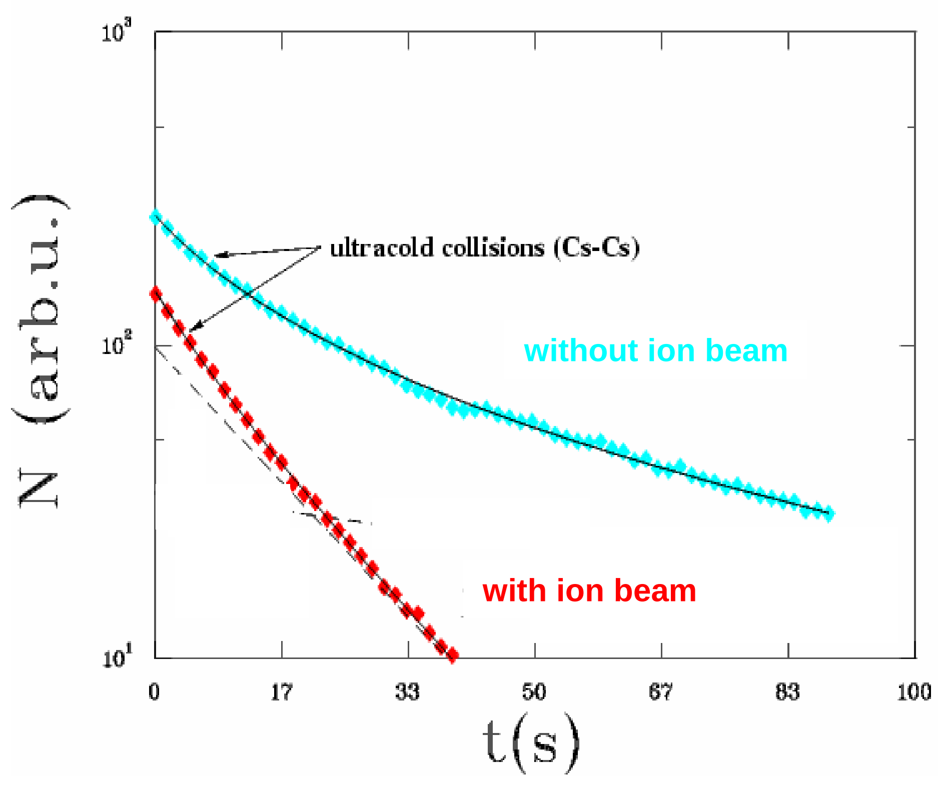


Detection of interactions: Fluorescence

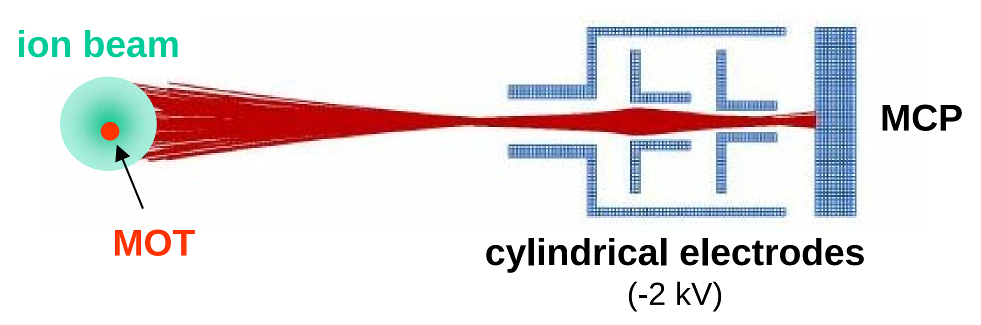
Detection of fluorescence light
$\propto$ number of trapped atoms



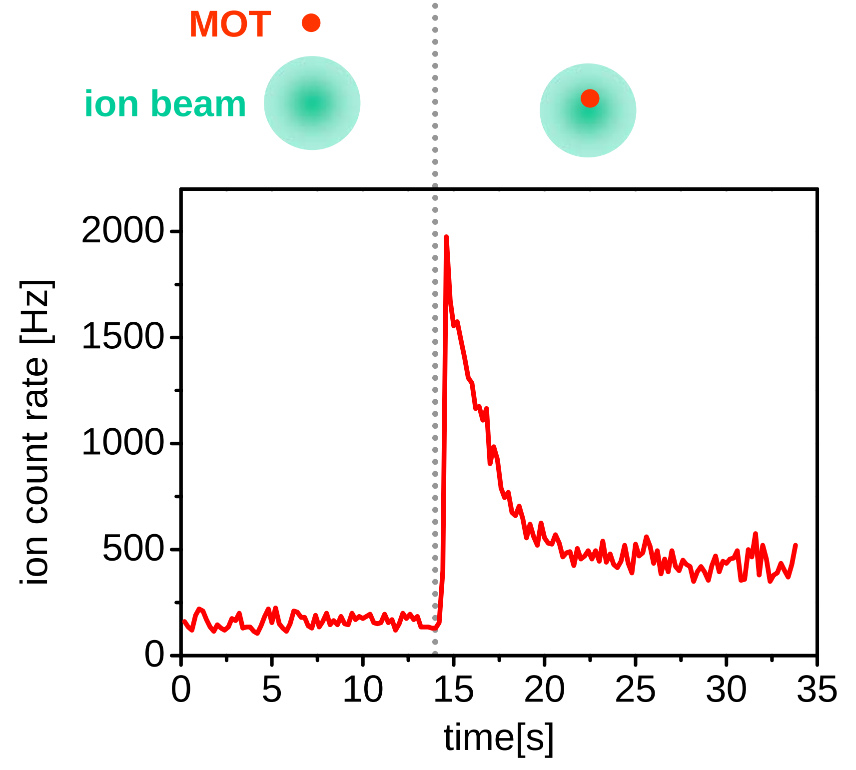
Stereoscopic detection with two cameras
for determination **of atom cloud's position**



Detection of interactions: Ionized atoms



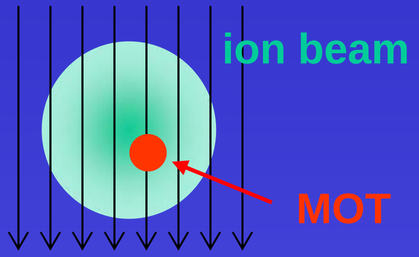
Ion signal:

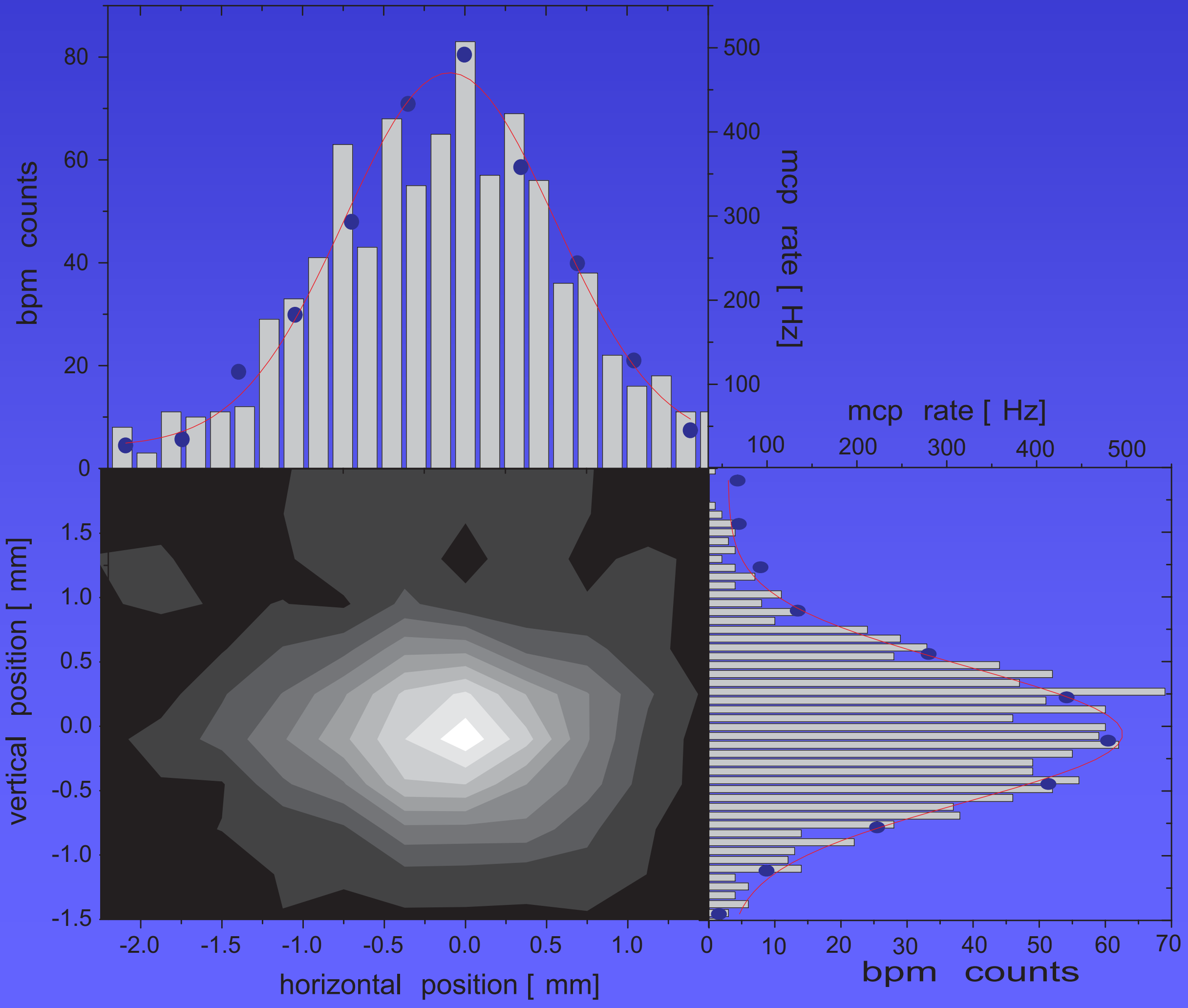


TSR-MOT as a beam profile monitor

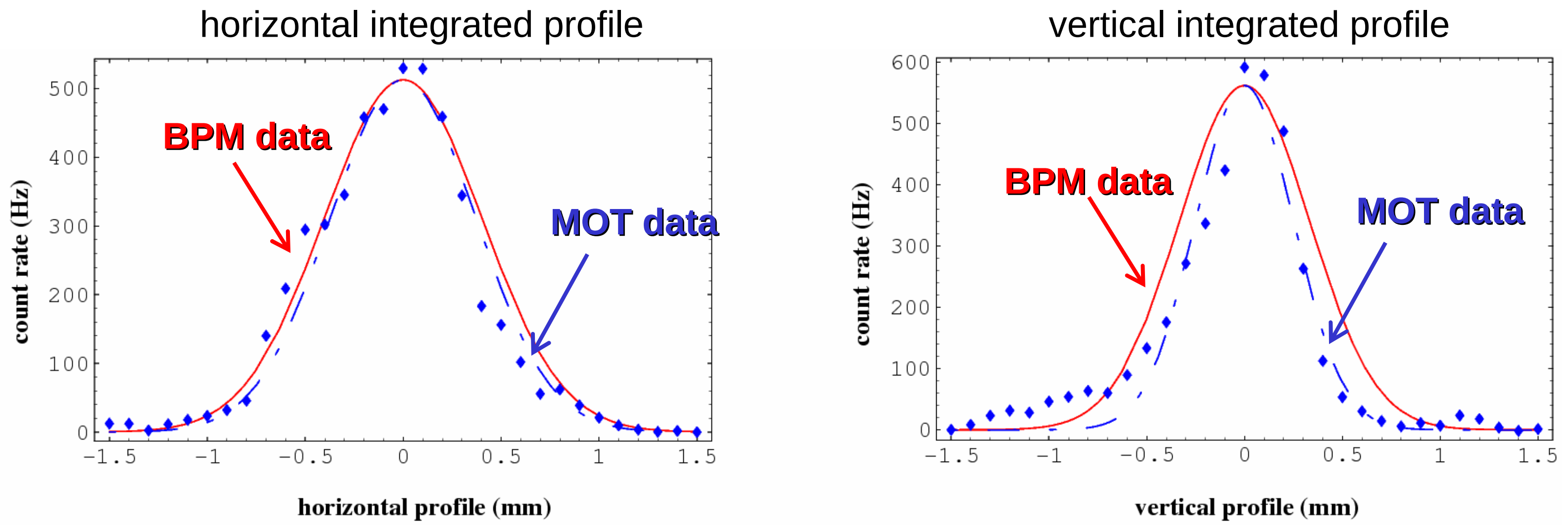
Ion count rate for a 2D scan of atom cloud position

(cloud dia. ~ 100 mm)





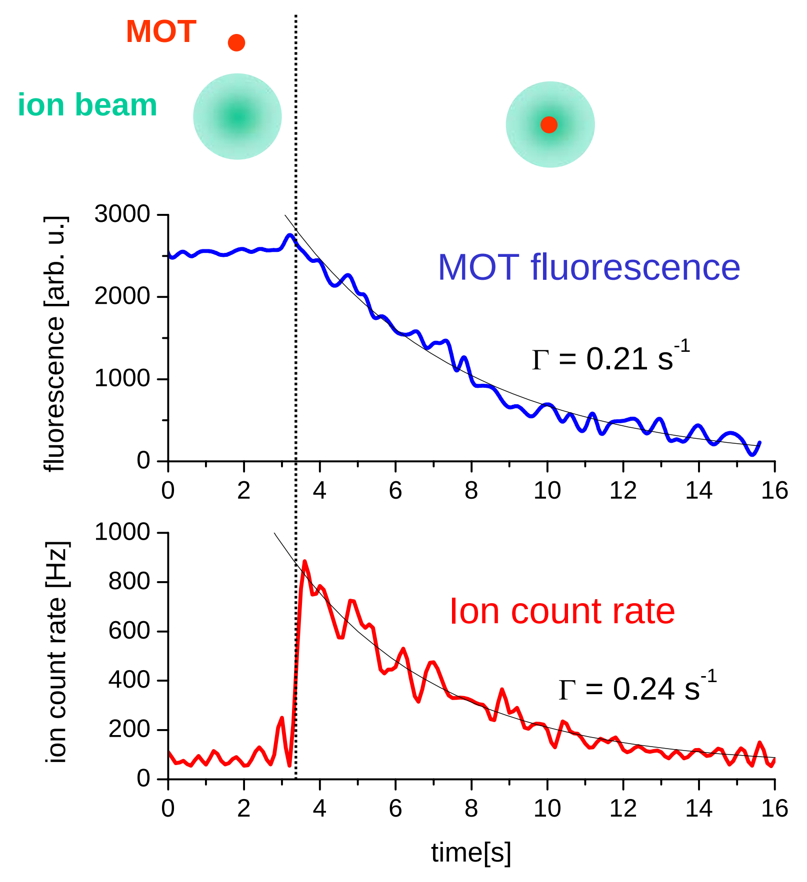
Comparison with rest-gas BPM



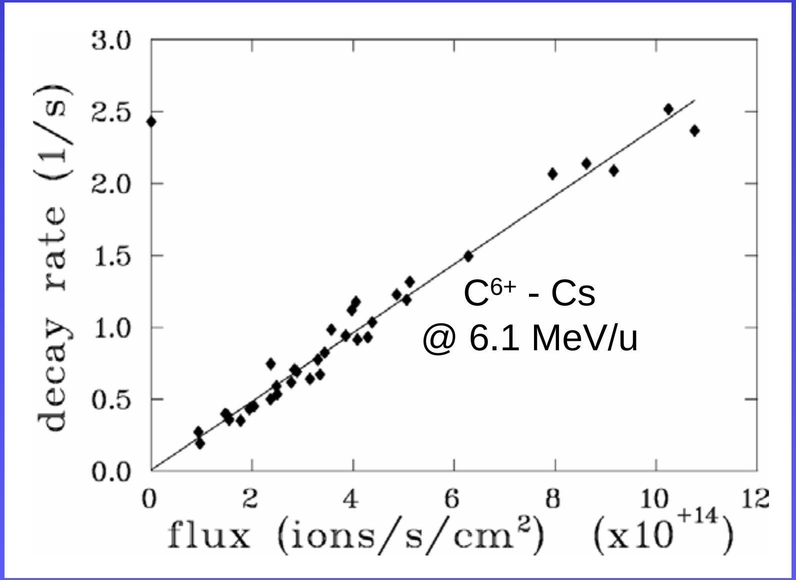
ADVANTAGES of the cold-atom BPM

- Sensitivity down to low ion currents (<10 nA)
- Better resolution than rest-gas BPM
- Direct 2D beam profile

Total collision cross sections



Decay rate versus ion flux

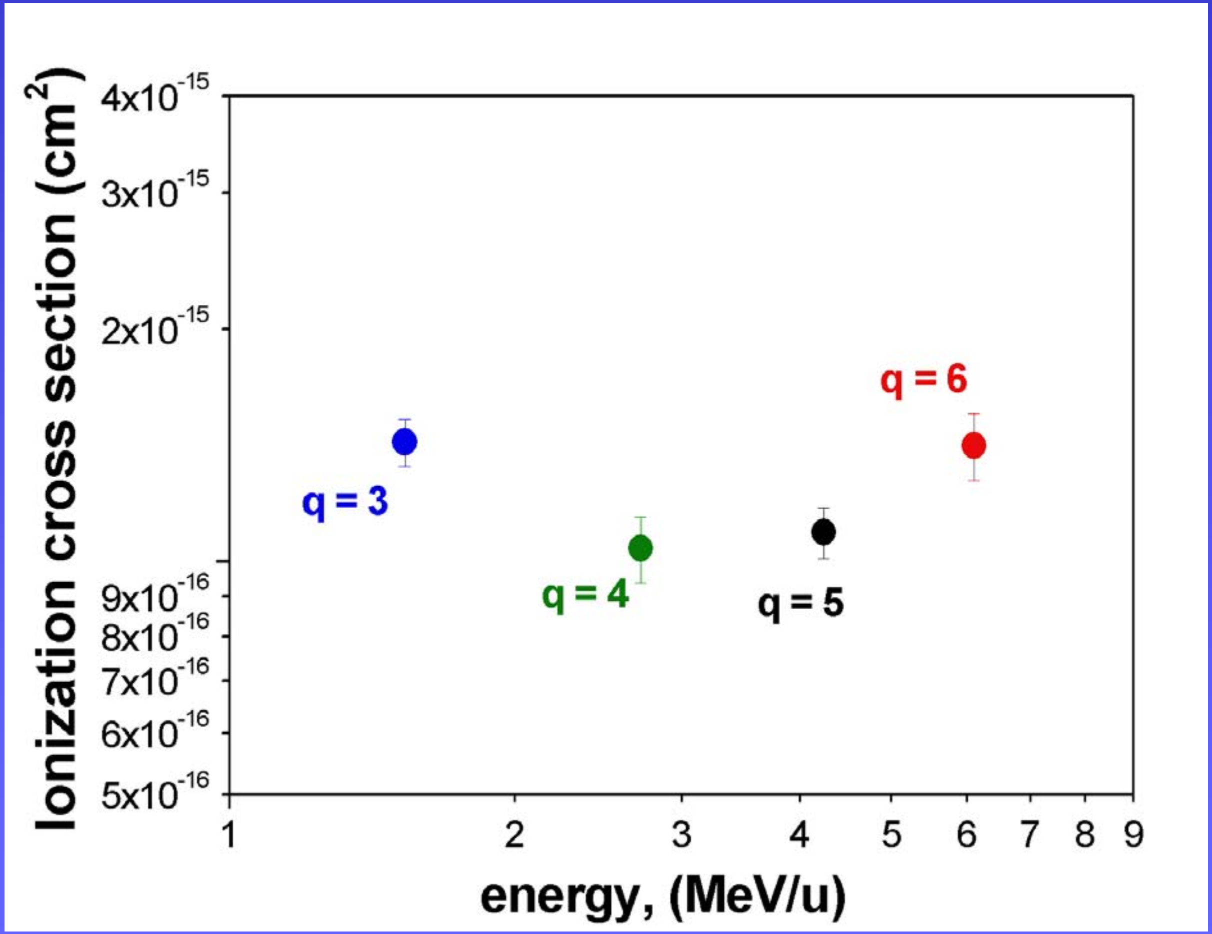


Ion flux determined from calibrated BPM count rate

$$\boxed{\text{cross section } \sigma = \frac{\text{decay rate } \Gamma}{\text{ion flux } \eta}}$$

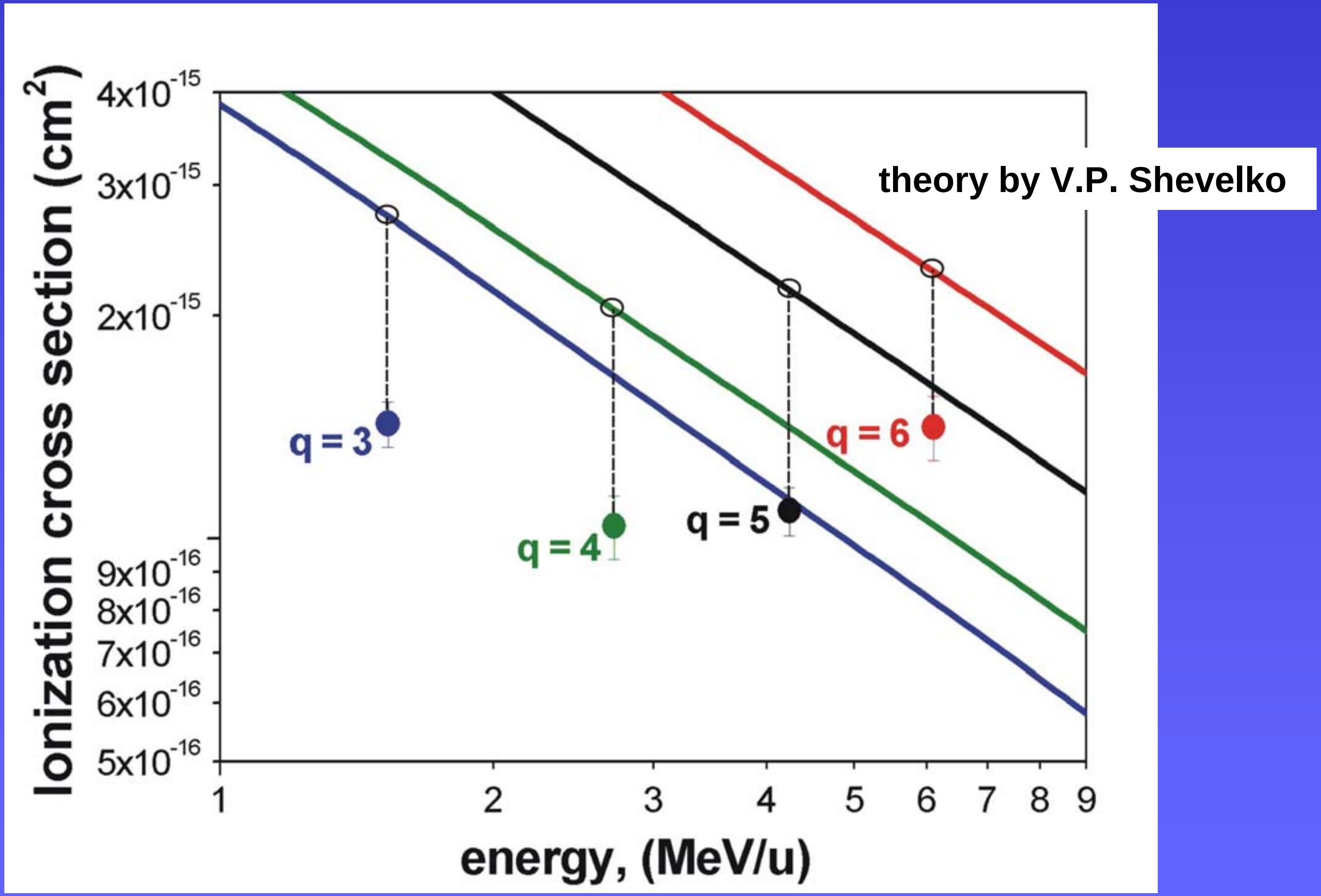
Dependence on charge state

Dependence of the cross section on the charge state
C^{q+} - Cs collisions



Comparison with theory

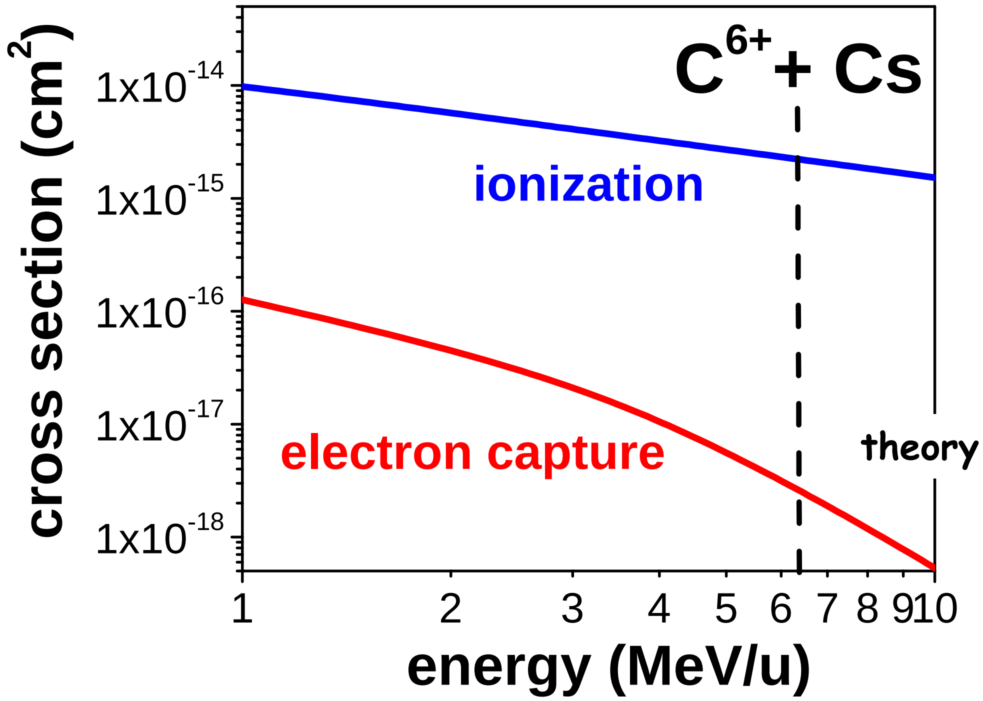
Dependence of the cross section on the charge state
C^{q+} - Cs collisions



Ionization vs. electron capture

main contribution to total cross section:

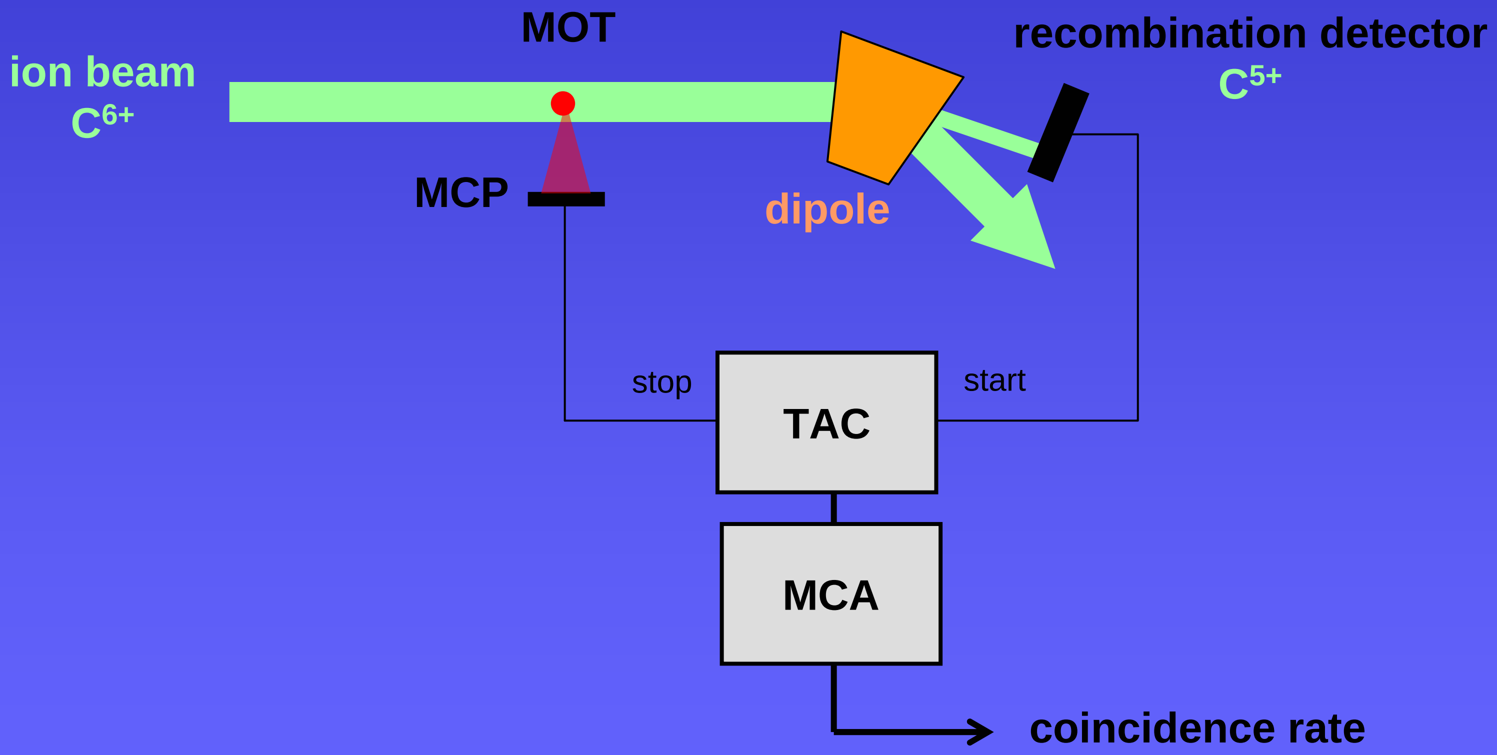
ionization of the cesium target



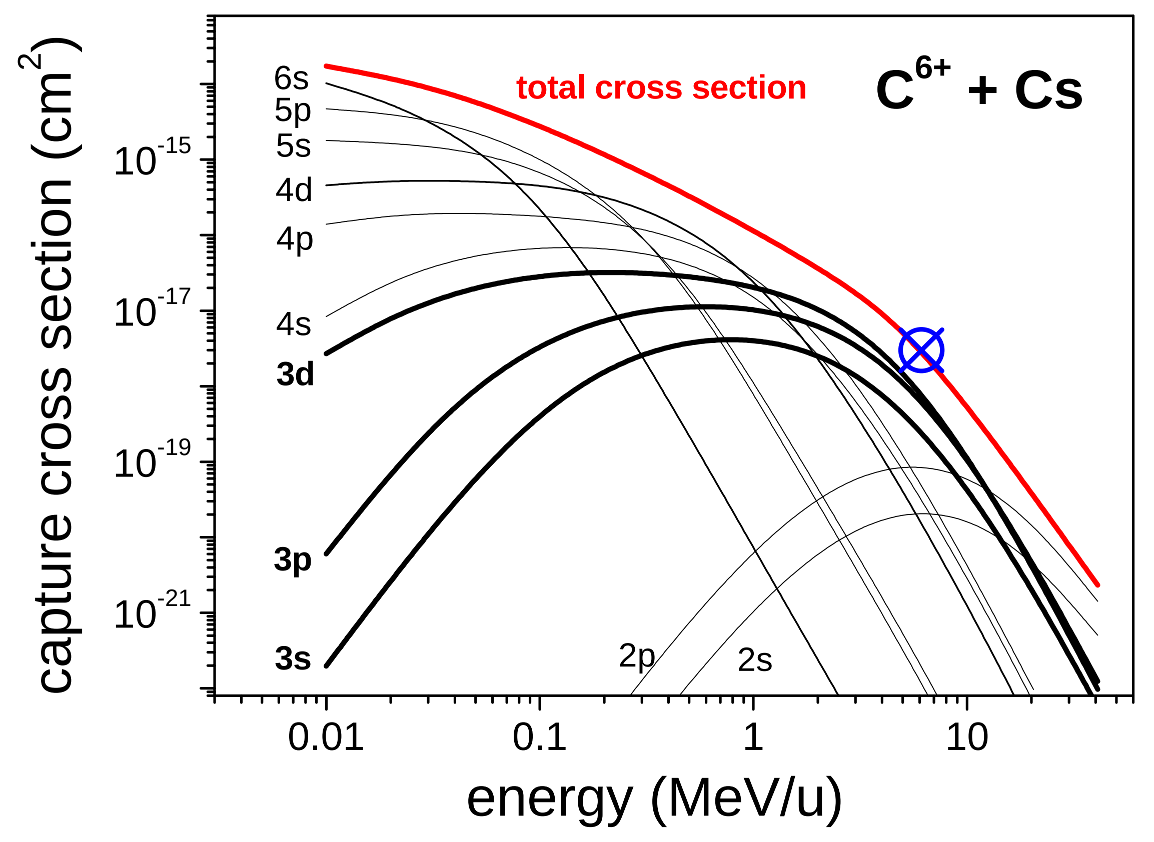
theory by V.P. Shevelko

Detection of electron capture

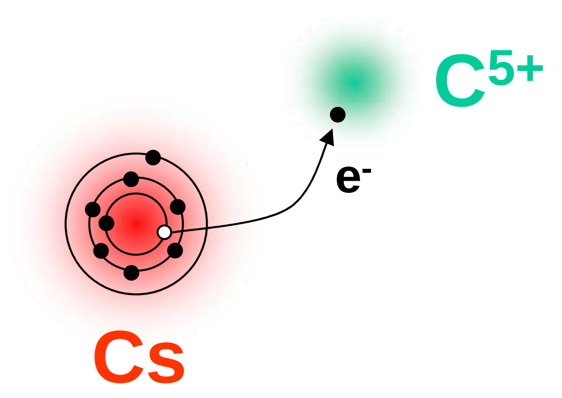
$$C^{6+}(6.1\ \text{MeV/u}) + \mathbf{Cs} \rightarrow C^{5+} + \mathbf{Cs}^{q+}$$



Electron capture cross section

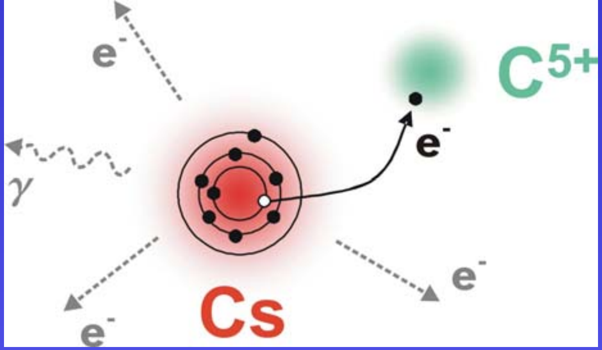


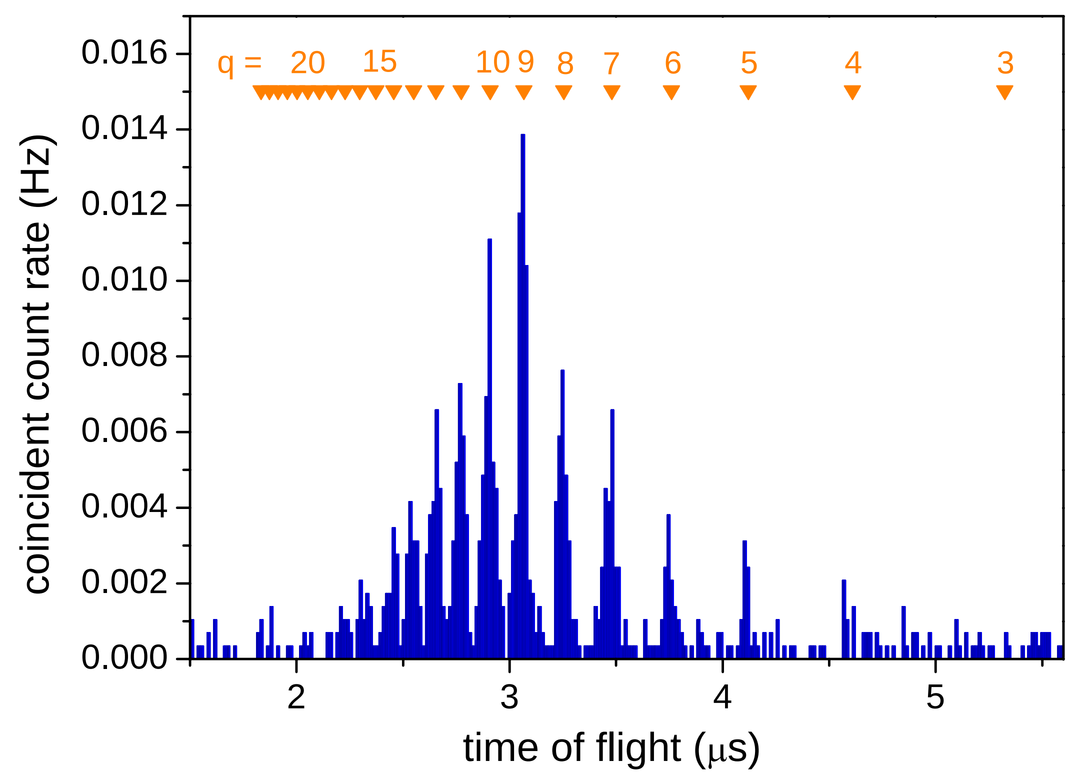
mainly **M-shell** electrons are captured



Distribution of final charge states

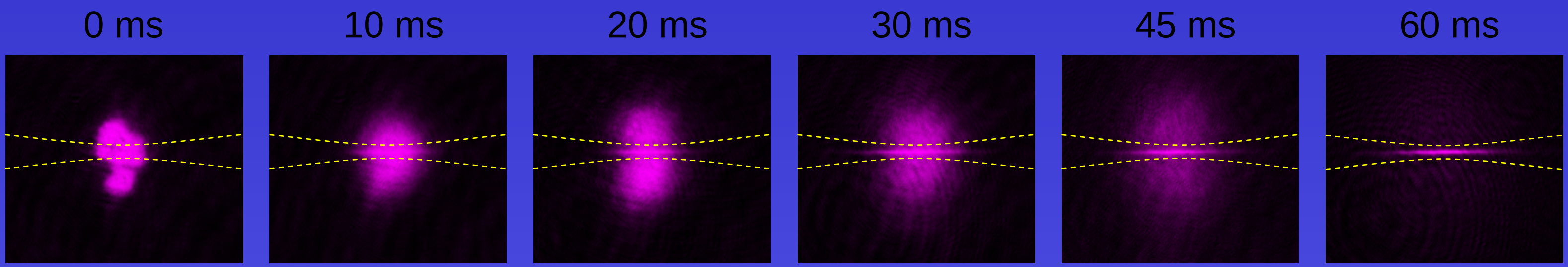
Electron capture: $C^{6+} + Cs \rightarrow C^{5+} + Cs^{q+}$ @ 6.1 MeV/u





Optical dipole traps

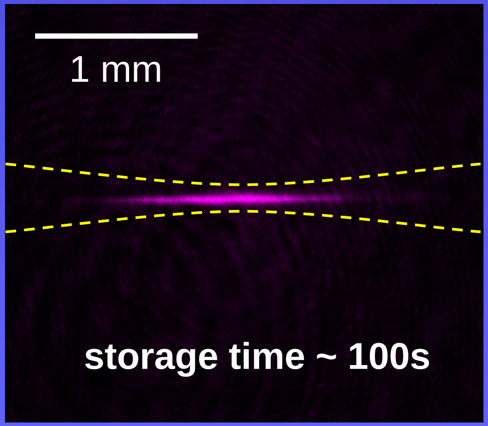
Transfer into the optical dipole trap (absorption images)



Trap parameters

	Cs	**Li**
trap depth	1000 μK	400 μK
eff. temperature	30 μK	~ 100 μK
# of stored atoms	~ 10^6	~ 10^5
transfer efficiency	7%	0.03%
peak density	~ 10^{12} cm^{-3}	~ 10^{10} cm^{-3}

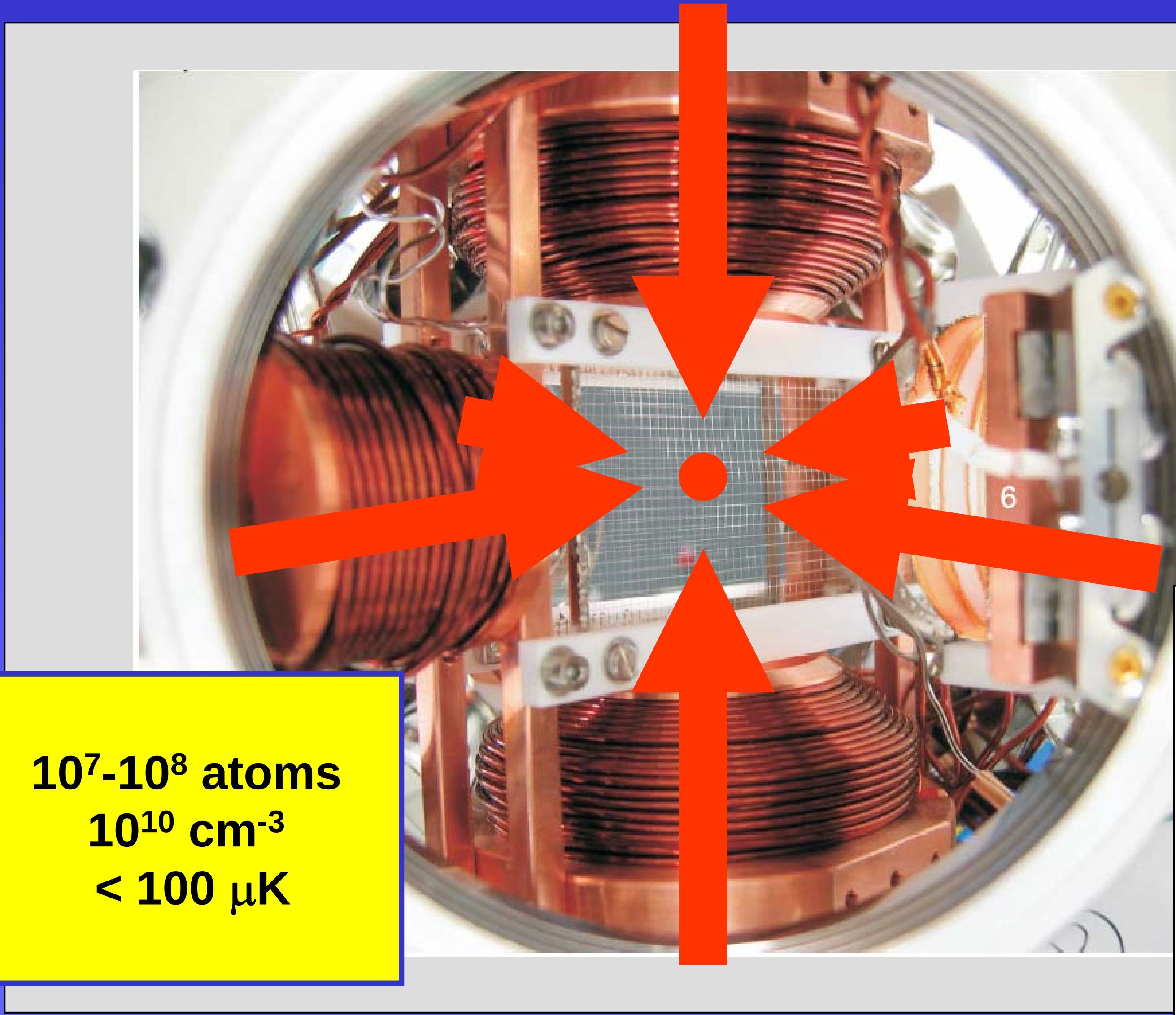
density distribution



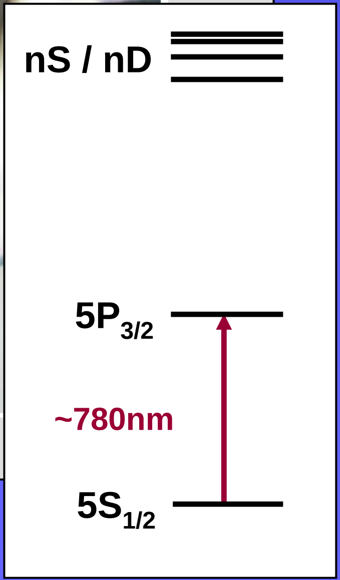
storage time ~ 100s

Atoms can be polarized in any internal state!

Creation of a cold Rydberg gas

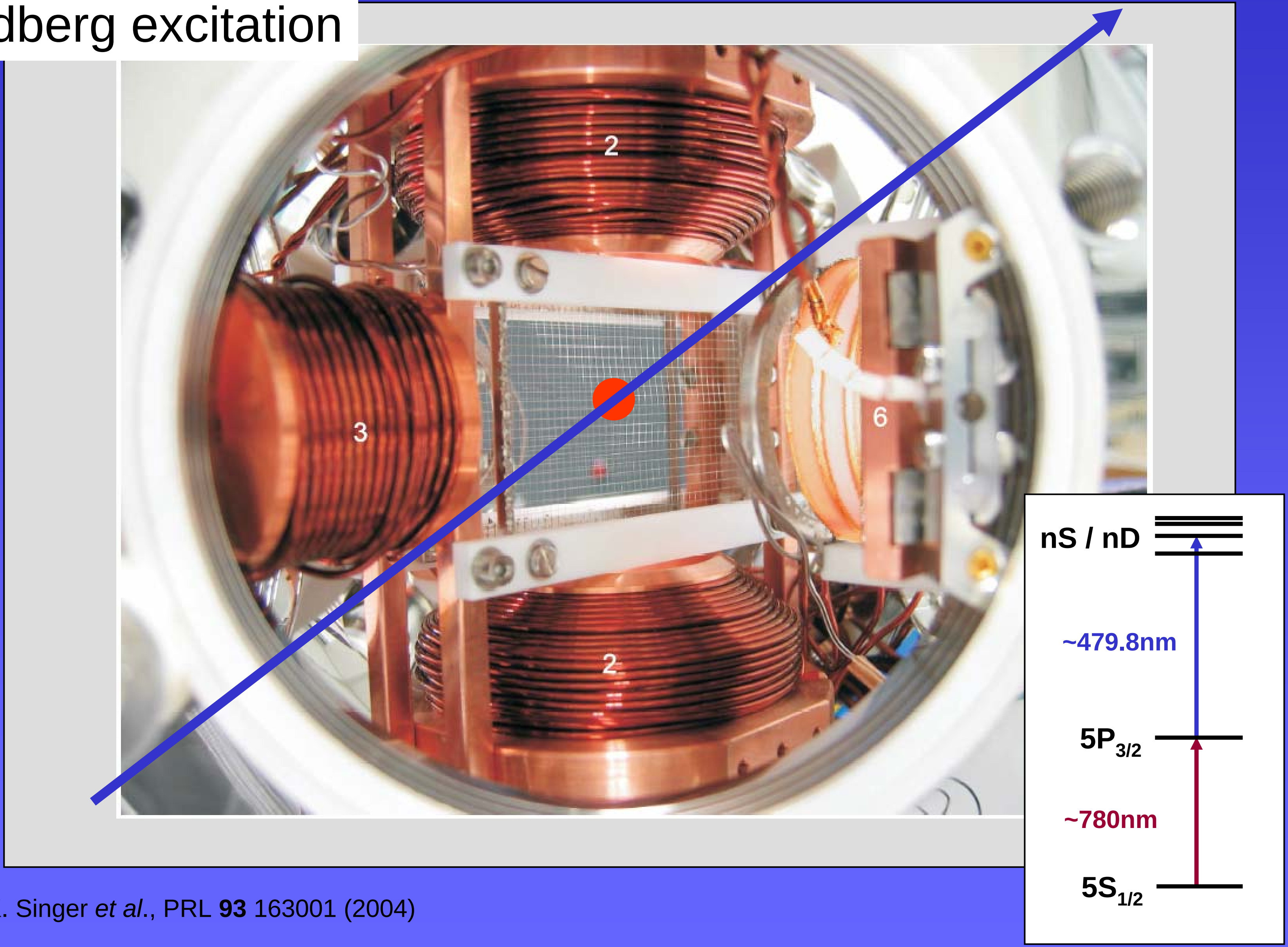


10^7-10^8 atoms
10^{10} cm^{-3}
< 100 μK



Creation of a cold Rydberg gas

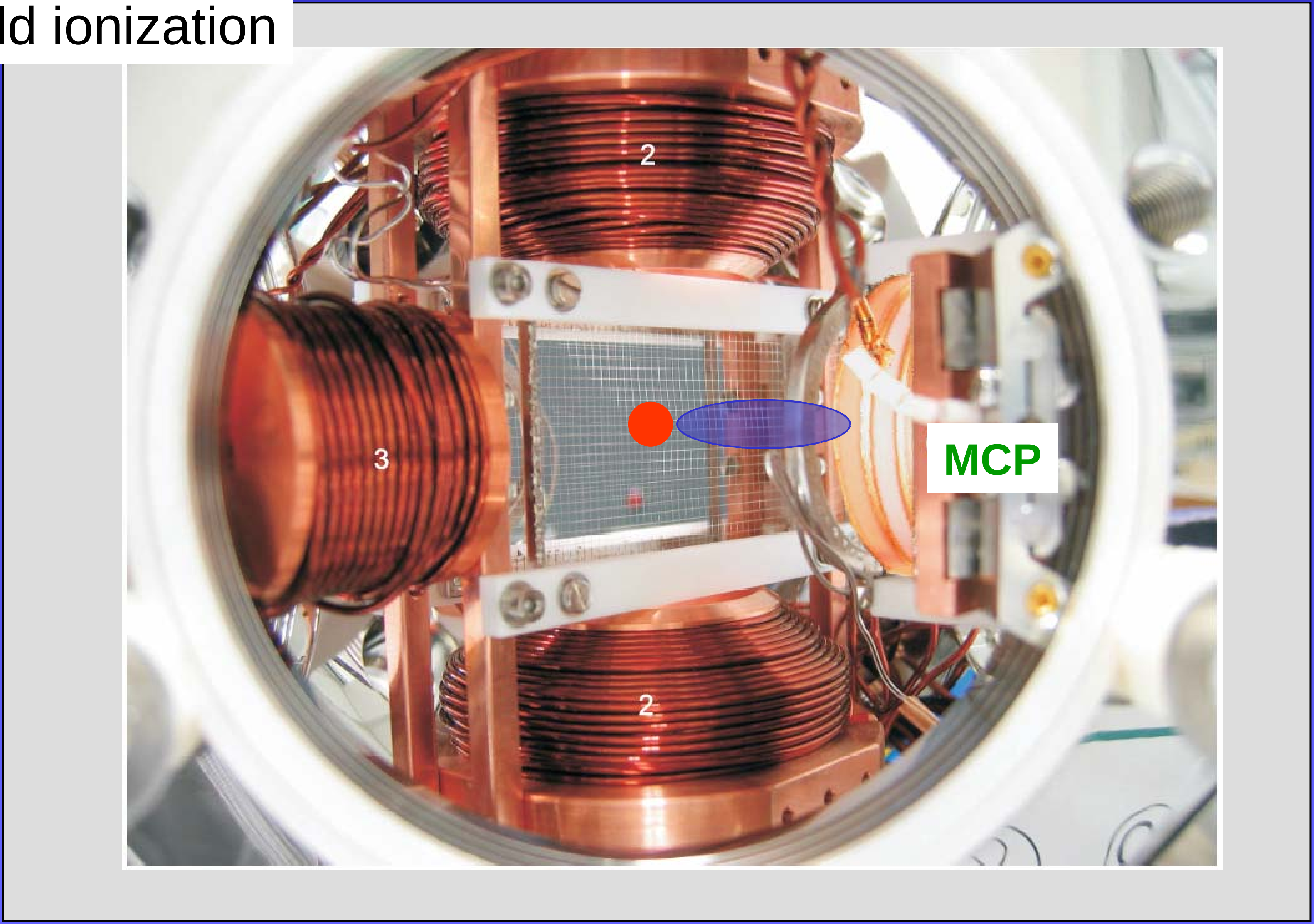
Rydberg excitation



K. Singer *et al.*, PRL **93** 163001 (2004)

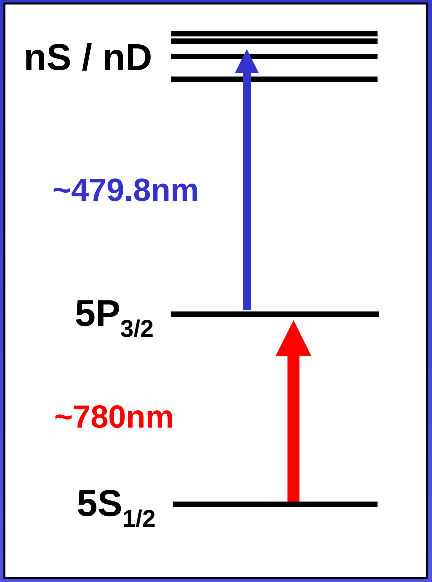
Detection of the Rydberg atoms

Field ionization

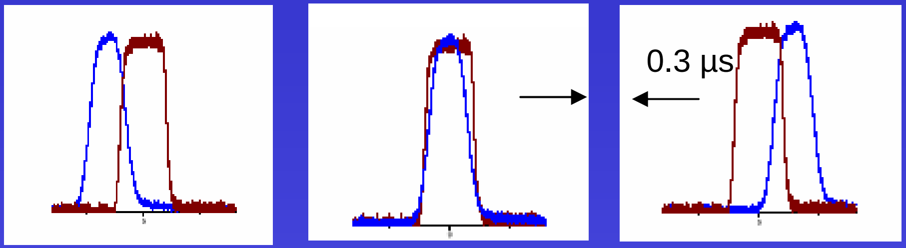


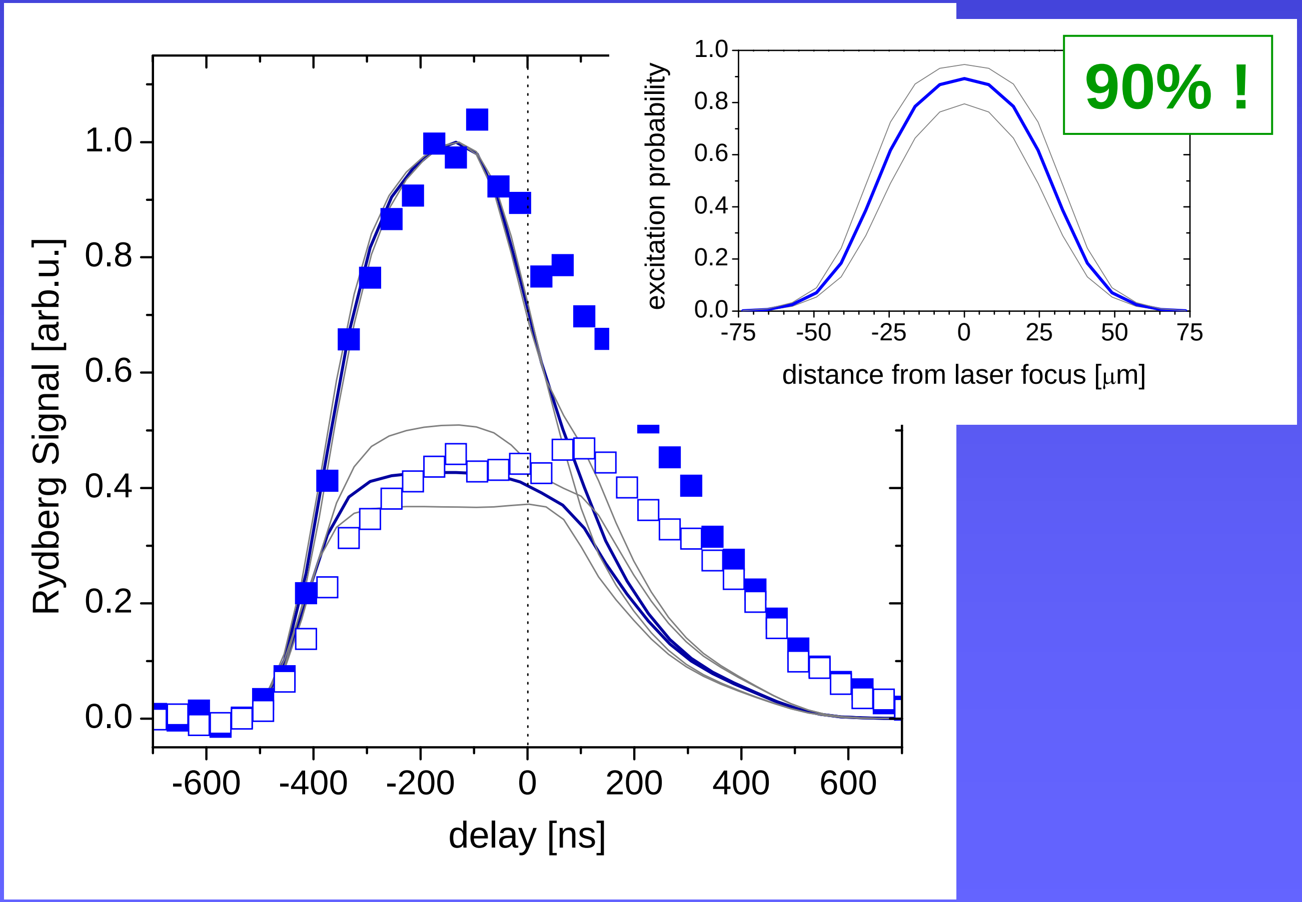
K. Singer *et al.*, PRL **93** 163001 (2004)

High Rydberg excitation efficiency



STIRAP



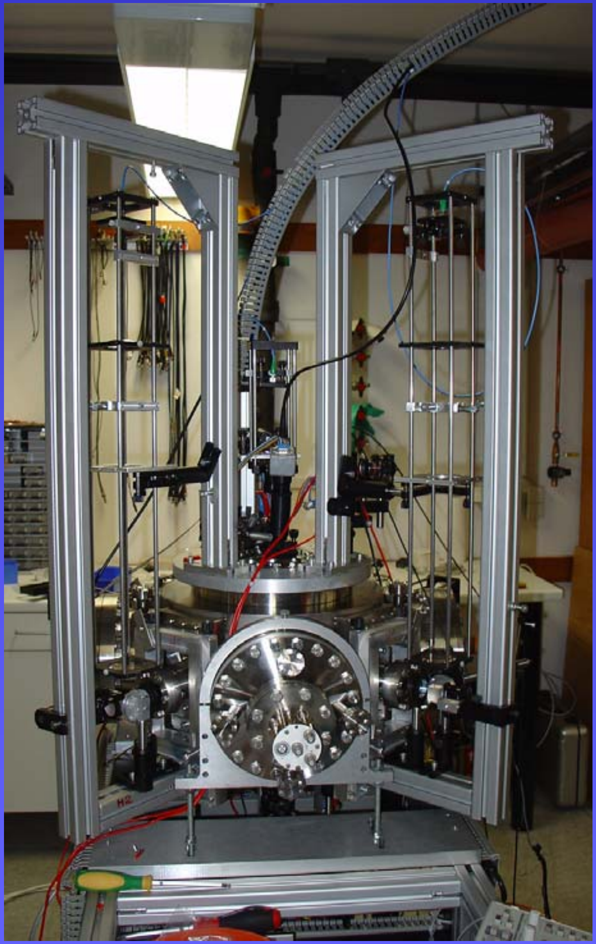


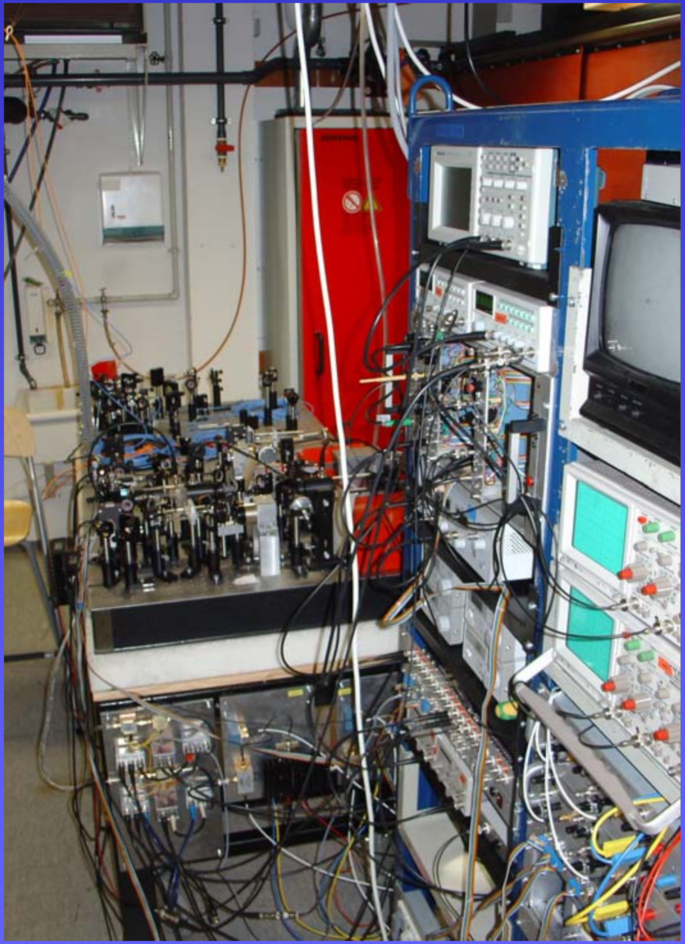
90% !

J. Deiglmayr *et al.*,
Optics Comm. (2006)
see also:
T. Cubel *et al.* (Raithel group),
PRA **72**, 023405 (2005).

Portable cold-atom target

Portable MOT system with recoil-ion momentum spectrometer

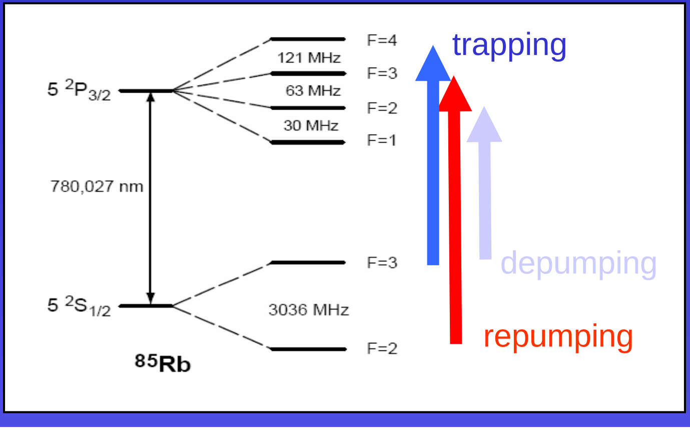




Recoil spectrometer courtesy Niels Andersen (Copenhagen)

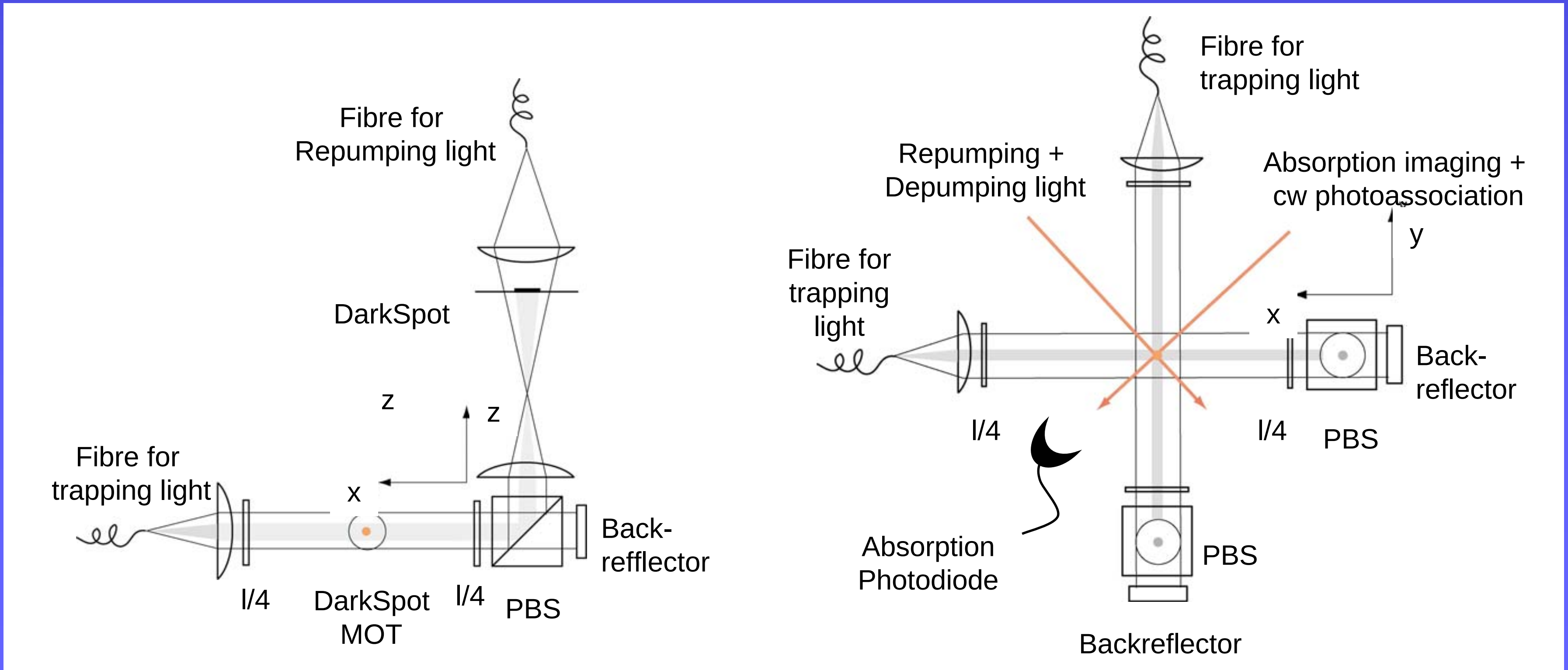
Dark-Spot MOT

Permanently loaded high-density cloud of ultracold atoms



Compact setup for darkspot magneto-optical trap

- **High densities up to 10^{11} 1/cm^3**
- **All trapped atoms in electronic ground state**



Properties of cold-atom targets

✓ **Full control over important target parameters**
(number of target atoms, density, target position and size)

✓ **Full control over internal degrees of freedom**
(spin polarization, ground state vs. Rydberg states)

\- **Limited number of elements**
(Laser-coolable species: alkali, alkali-earth, metastable rare gases
and some exotic elements like chromium)

✓ **High isotope selectivity**

\- **Limited loading flux and densities**

✓ **Large repertoire in cooling, trapping and manipulation techniques**

Prospects at HITRAP

1. **Trapped atoms as a probe**
   for precision experiments with dilute beams

   Improved copy of the TSR concept (enhanced loading flux, improved position control)
   possibly combined with photon detectors

2. **COLTRIMS with an ultracold Rb, Li or other species target**
   for kinematically complete collision experiments

   Combination of COLTRIMS technology with atom manipulation techniques (e.g. high-flux source)

3. **Ultracold molecules as targets**
   for studies of interactions with highly-charged ions

   Combination of COLTRIMS technology with atom manipulation techniques (e.g. high-flux source)

4. **Cold Rydberg atoms as an electron target**
   for studies of ion-electron interactions

   Two- or three-step laser excitation of trapped alkali atoms into highly-excited states