Intrappolamento di atomi di Francio per test di simmetrie fondamentali

R.Calabrese

Università e INFN - Ferrara

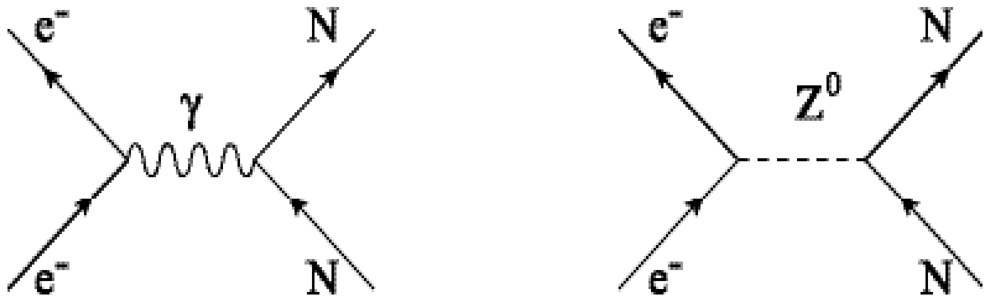
VI Seminario sul Software per la Fisica Nucleare, Subnucleare e Applicata

Porto Conte, 1-5 Giugno 2009

Outline

- General Overview
  - Atomic Parity Violation (APV)
  - Why Francium
  - Magneto-Optical Traps (MOT)
- The experiment
  - Francium production and beam line
  - Francium neutralization and trapping
  - Detection
  - Some results on frequency transition measurements
- Outlook

General Overview – APV



- Dominant force in atoms is the electromagnetic interaction
- The valence electron and the nucleons also exchange virtual Z^0 bosons
  - **The total Hamiltonian of the atomic system has an even and an odd part under spatial reflection**

$$H = H^{even} + H^{odd} \quad \Rightarrow \quad P^{-1}HP = H^{even} - H^{odd} \neq H$$

General Overview – APV

- The dominant PV interaction is given by:

$$H_{PV}^{Q_W} = -\frac{G_F}{2\sqrt{2}} Q_W \gamma^5 \rho_N(\mathbf{r})$$

which in the non relativistic limit becomes:

$$H_{PV}^{Q_W} = \frac{G_F}{4\sqrt{2}} Q_W \frac{\vec{\sigma}_e \cdot \vec{p}_e}{m_e c} \rho_N(\mathbf{r}) + h.c.$$

- Q_W is the coherent sum of contributions to the weak interaction from the 2Z+N up quarks and 2N+Z down quarks:

$$Q_W = 2\left[(2Z+N)C_V^u + (2N+Z)C_V^d\right]$$

General Overview – APV

- The vector coupling constants C_V^u and C_V^d are given in the Standard Model at the tree-level by:

$$\begin{cases} C_V^u = \frac{1}{2} - \frac{4}{3}\sin^2\vartheta_W(M_Z) \\ C_V^d = -\frac{1}{2} + \frac{2}{3}\sin^2\vartheta_W(M_Z) \end{cases}$$

- Substituting the numerical values of the vector coupling constants into the expression for Q_W:

$$Q_W \approx Z(0.07) - N$$

The weak nuclear charge has a much stronger dependence on the number of neutrons than on the number of protons in the nucleus

General Overview – APV

- The weak interaction mixes the parity eigenstates of the atom
  - **The small size of the mixing allows the mixed parity states to be calculated with a perturbation theory:**

$$\overline{|nS\rangle} = |nS\rangle + \sum_{n''} \frac{|n''P\rangle\langle n''P|H_{PNC}|nS\rangle}{E_{nS} - E_{n''P}}$$

  - **An electric dipole (E1) transition can occur between the mixed parity states that is forbidden in the absence of the weak force**

$$\begin{aligned} A_{PV} &= \langle \overline{n'SF'm'} | \mathbf{D} | \overline{nSFm} \rangle \\ &= \sum_{n''P} \left[\frac{\langle n'SF'm'|\mathbf{D}|n''P\rangle\langle n''P|H_{PV}|nSFm\rangle}{E_{nS} - E_{n''P}} + \frac{\langle n'SF'm'|H_{PV}^{\dagger}|n''P\rangle\langle n''P|\mathbf{D}|nSFm\rangle}{E_{n'S} - E_{n''P}} \right] \\ &= i\,\mathrm{Im}(E1_{PV})\vec{\varepsilon} \cdot \langle F'm'|\vec{\sigma}|Fm\rangle \end{aligned}$$

General Overview – APV

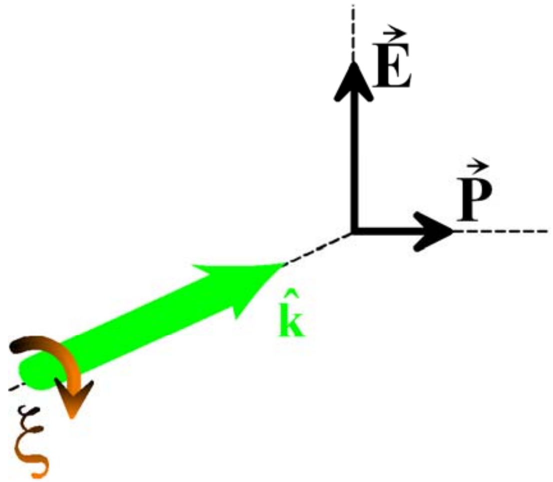
- How to search for APV effects ?
  - **Measurement of the transition rate for the forbidden transition**
  - **Stark interference method:**
    - It uses an electric field to allow a parity conserving transition amplitude A_{Stark}, that interferes with the parity nonconserving amplitude E_1^{PV}, giving the transition rate:

$$\boxed{\begin{aligned} R &\propto \left| A_{Stark} + e^{i\vartheta} E_1^{PV} \right|^2 \\ R &\propto A_{Stark}^2 + k A_{Stark} \cdot \Im m(E_1^{PV}) \end{aligned}}$$

    - Modulation of direction of polarization of laser beam $\Rightarrow$ measurement of transition rate $\Rightarrow$ measurement of $\Im m(E_1^{PV})$ $\Rightarrow$ measurement of Q_W

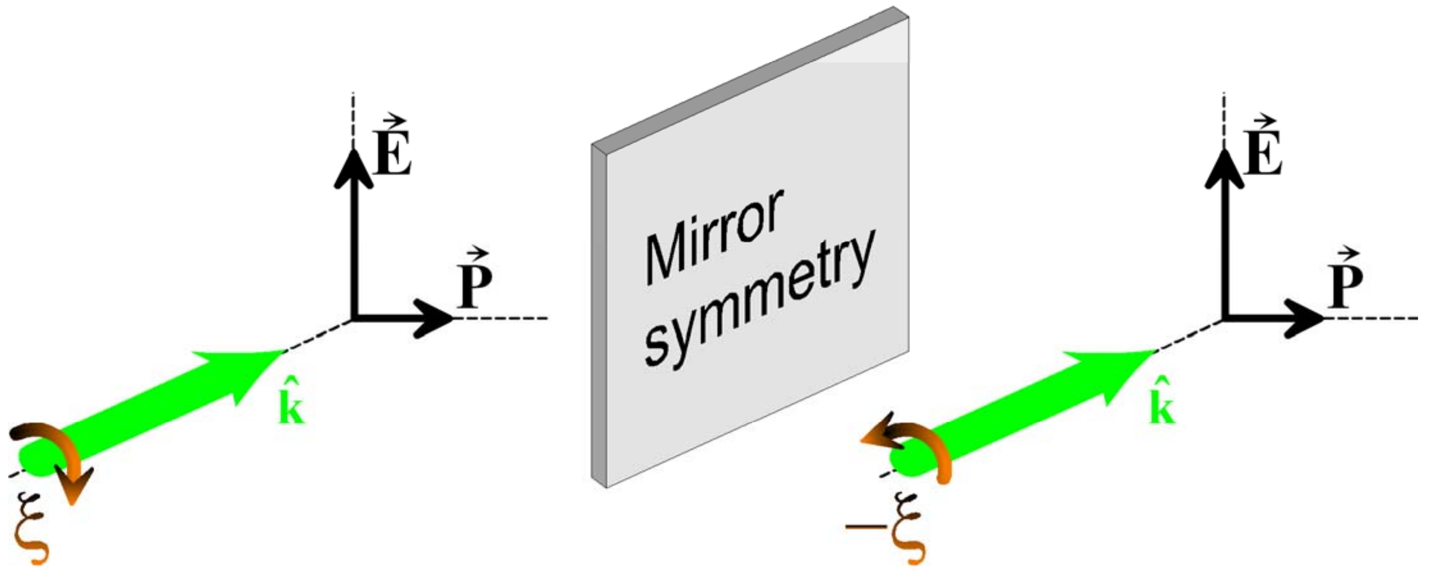
$$\boxed{\Im m(E_1^{PV}) = K_{PV} \frac{Q_W}{N}}$$

Circular dichroism for 7S-8S transition



- ☞ $7S-8S$ transition assisted by a static electric field $\sim$ 1000 V/cm
- ☞ Polarized ($\vec{P}$) atoms in an optical dipole trap

Circular dichroism for 7S-8S transition



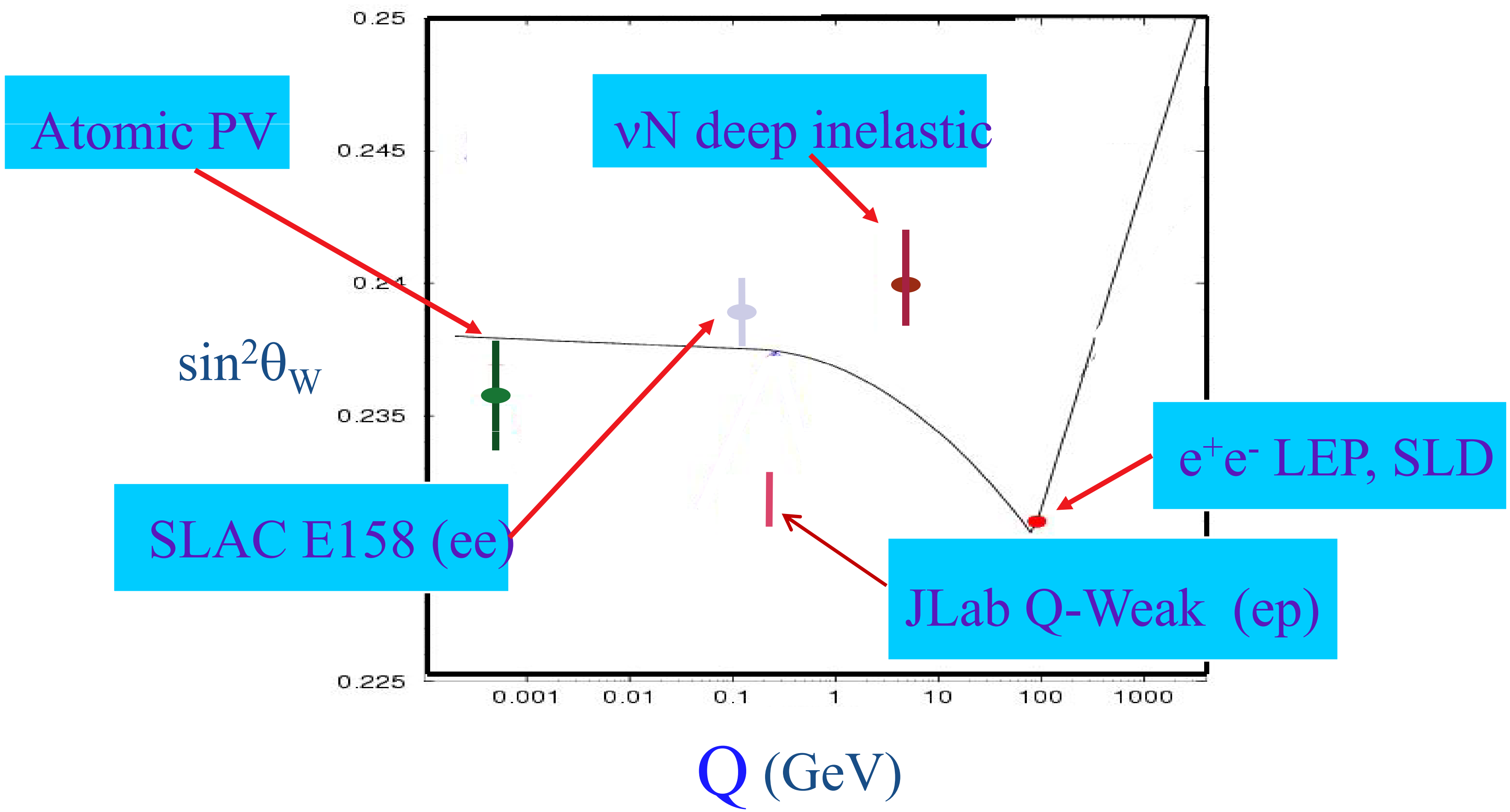
- ☞ $7S-8S$ transition assisted by a static electric field $\sim$ 1000 V/cm
- ☞ Polarized ($\overrightarrow{P}$) atoms in an optical dipole trap
- ☞ The transition rate changes when the helicity ξ is reversed
  $\Rightarrow$ Discrimination of the PV effect

General Overview – APV

- Last results on Cs (1999):
  - **Experiment of C. Wieman group**
  - **$Q_W = -72.62 \pm 0.46_{th+ex}$** **Exp. Result (PDG 2008)**
  - **$Q_W = -73.16 \pm 0.03$** **Standard Model (PDG 2008)**
  - **Discrepancy ~1.0 σ**

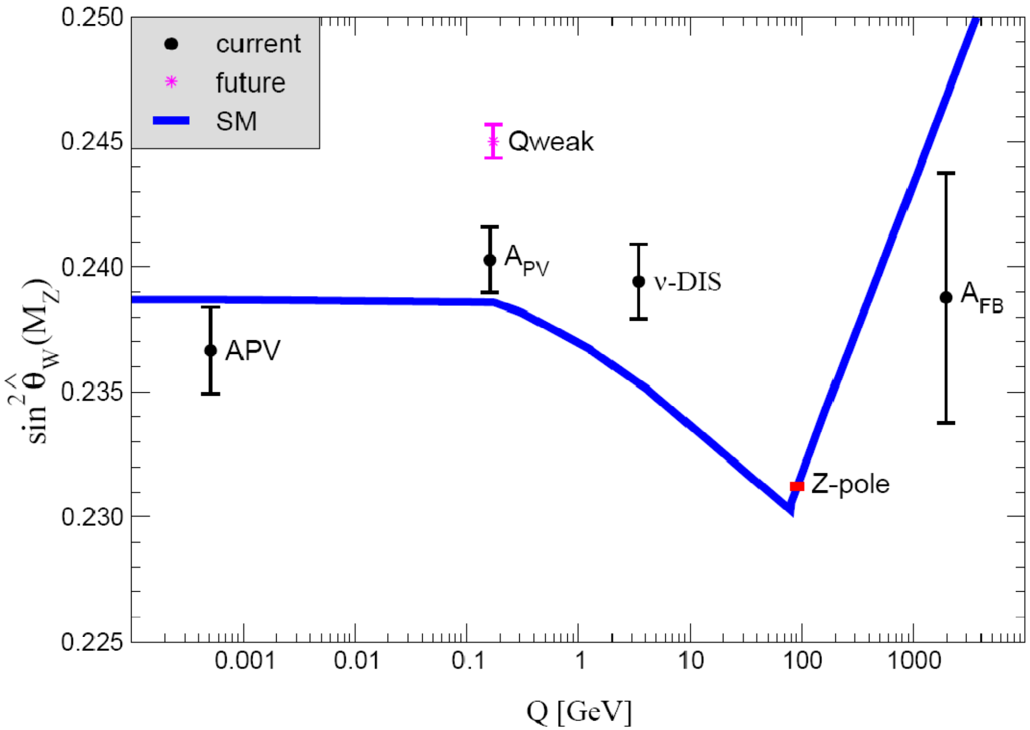
General Overview - APV

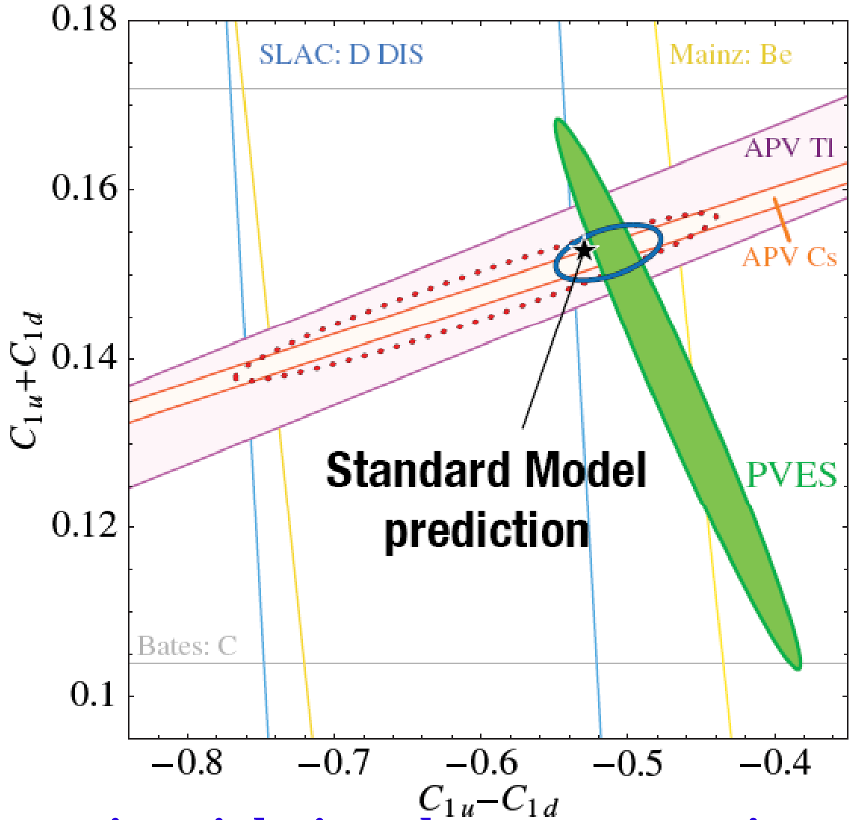
Experimental results on running weak mixing angle



General Overview - APV

Experimental results on running weak mixing angle

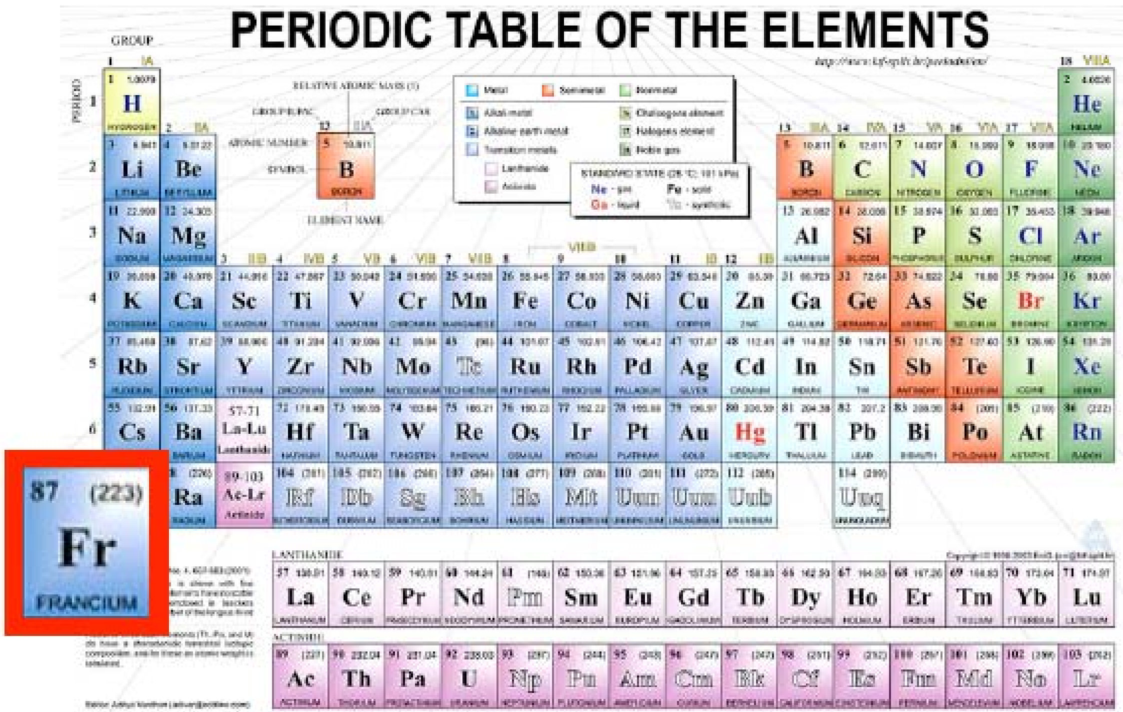




Atomic parity violation is complementary to parity-violating electron scattering (PVES) in determining the effective weak couplings of the quarks, to probe fundamental interactions and put constraints on New Physics beyond SM

General Overview – Francium

- Fr is the heaviest alkali (Z=87)
- Discovered by Marguerite Perey on 1939
- During the 1970s and 1980s the group of S. Lieberman studied at ISOLDE/CERN its atomic structure.
- Fr is a radioactive element with short-lived isotopes
  - **Fr^{209} – 50 s**
  - **Fr^{210} – 3.2 m**
  - **Fr^{211} – 3.1 m**
  - **Fr^{212} – 20 m**
  - **Fr^{223} – 22 m**



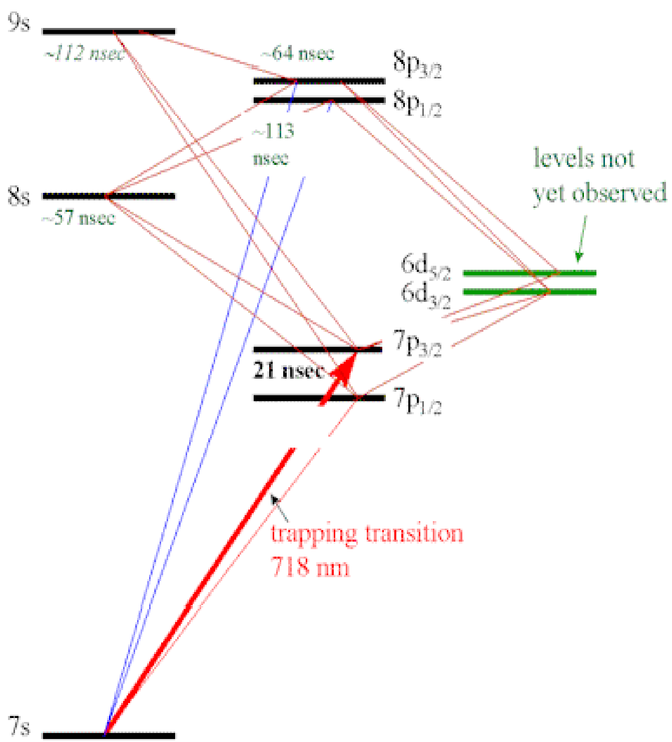
Francium-223 is the result of the alpha decay of actinium-227 and can be found in trace amounts in uranium and thorium minerals. It is also calculated that there is at most 30 g of francium in the earth's crust at any time.

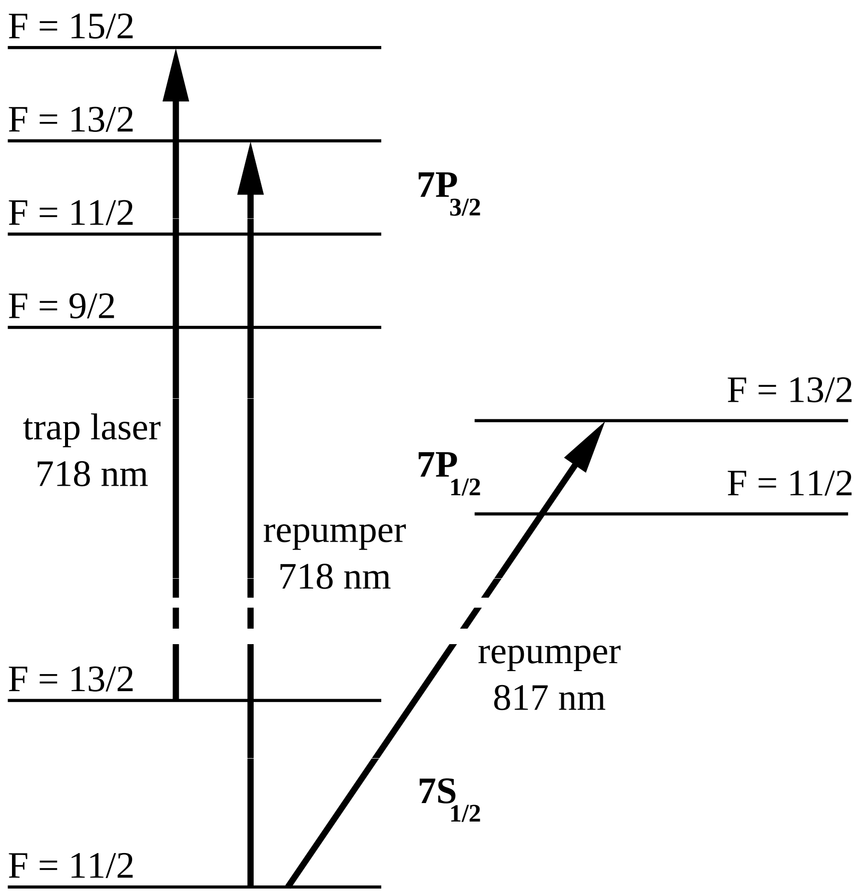
General Overview – Francium

- Fr is a good candidate to perform APV experiments:
  - **Simple electronic structure**
  - **APV has a strong Z dependence**
    - Fr is the heaviest alkali atom
    - There is a factor of 18 larger APV effect for Fr over Cs
  - **Fr exists in many isotopes**
    - Isotopic APV ratio comparison is available
- There are also some disadvantages:
  - **Fr has to be produced by nuclear reaction**
  - **No stable isotopes for Fr**
    - Short lifetime and production rate can limit APV measurements
    - No reference cell for spectroscopy/calibration

General Overview – Francium

Francium Atomic Level Scheme





Electronic Configuration:

$1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 3d^{10}\ 4s^2\ 4p^6\ 4d^{10}\ 4f^{14}\ 5s^2\ 5p^6\ 5d^{10}\ 6s^2\ 6p^6\ 7s^1$

General Overview – Magneto-Optical Traps

- Optical trapping can be useful to collect large samples of cold and dense atoms:
  - **low temperature (~ 1 mK)**
  - **high density (~ 10^{10} atoms/cm^3)**

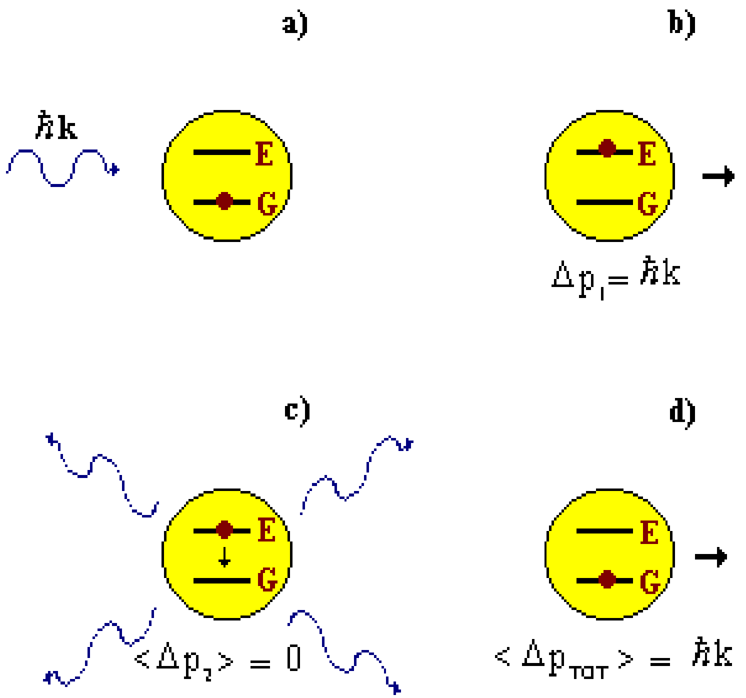
- Such samples are useful for:
  - **Studying rare radioactive isotopes in**
    - Atomic Parity Violation experiments
    - β decay experiments

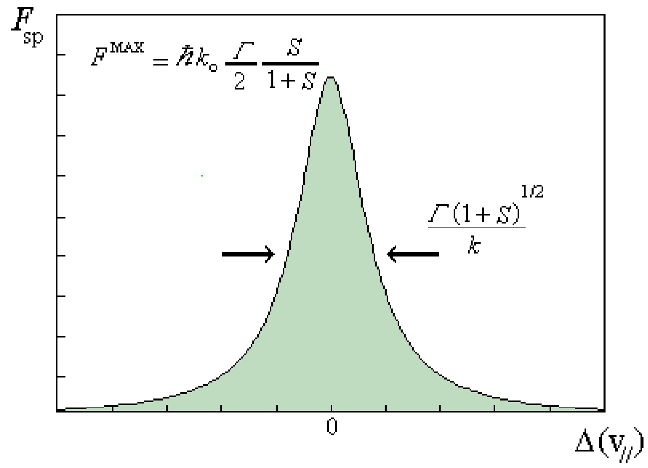
General Overview – Magneto-Optical Traps

- From kinetic theory of gas we know the proportionality between absolute temperature and medium kinetic energy of gas atoms.

Cooling of gas atoms means slowing down atoms

General Overview – Magneto-Optical Traps



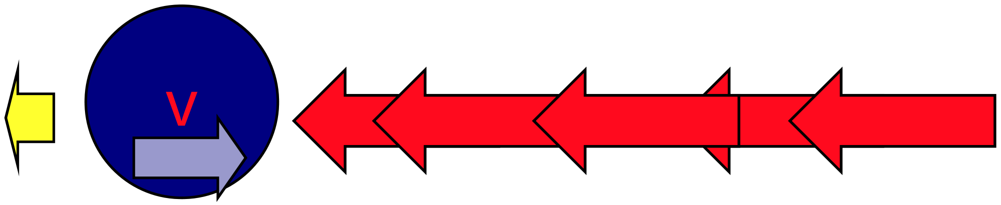


But this force is not sufficient...

General Overview – Magneto-Optical Traps

We have to consider the Doppler effect → Optical molasses

$$\nu \approx \nu_0 \left(1 \pm \frac{u}{c} \right)$$

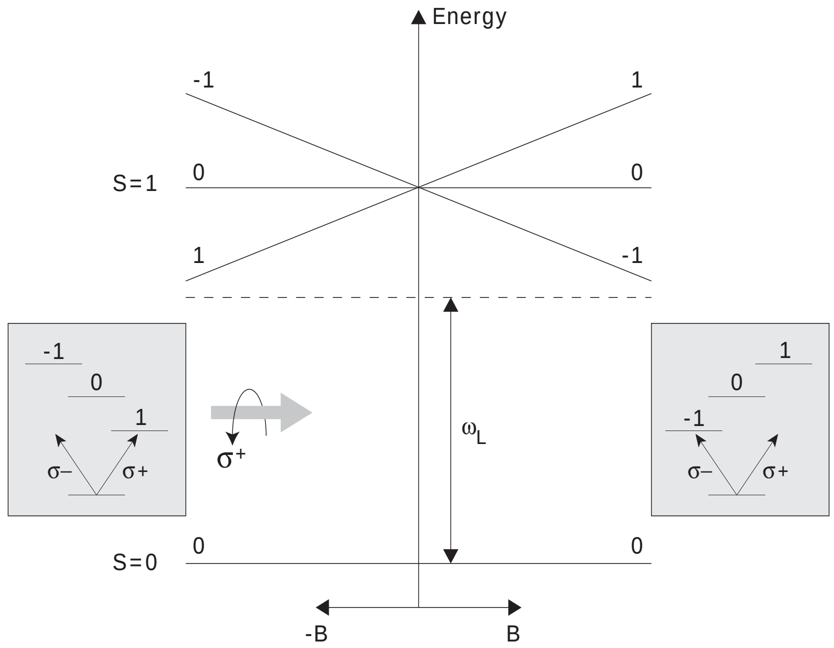


molassa ottica

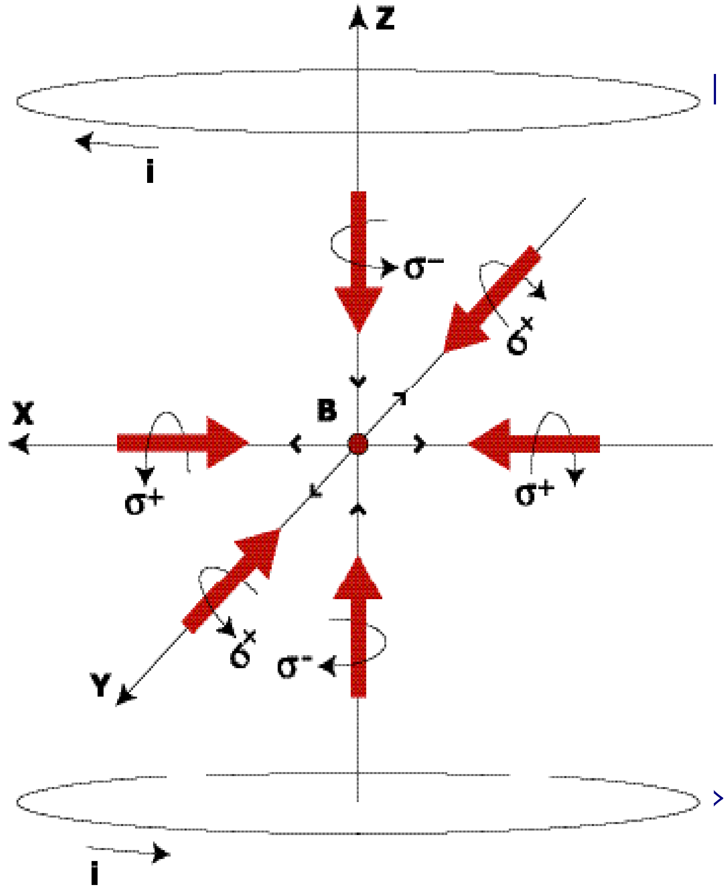
General Overview – Magneto-Optical Traps

- 1-D model:
  - **Spatially varying magnetic field**
    - Quadrupolar magnetic field induces a position dependent Zeeman shift in atomic levels
  - **Counterpropagating laser beams**
    - Laser absorption induces a light pressure that slows down atoms

⇒ **Light pressure is position dependent**

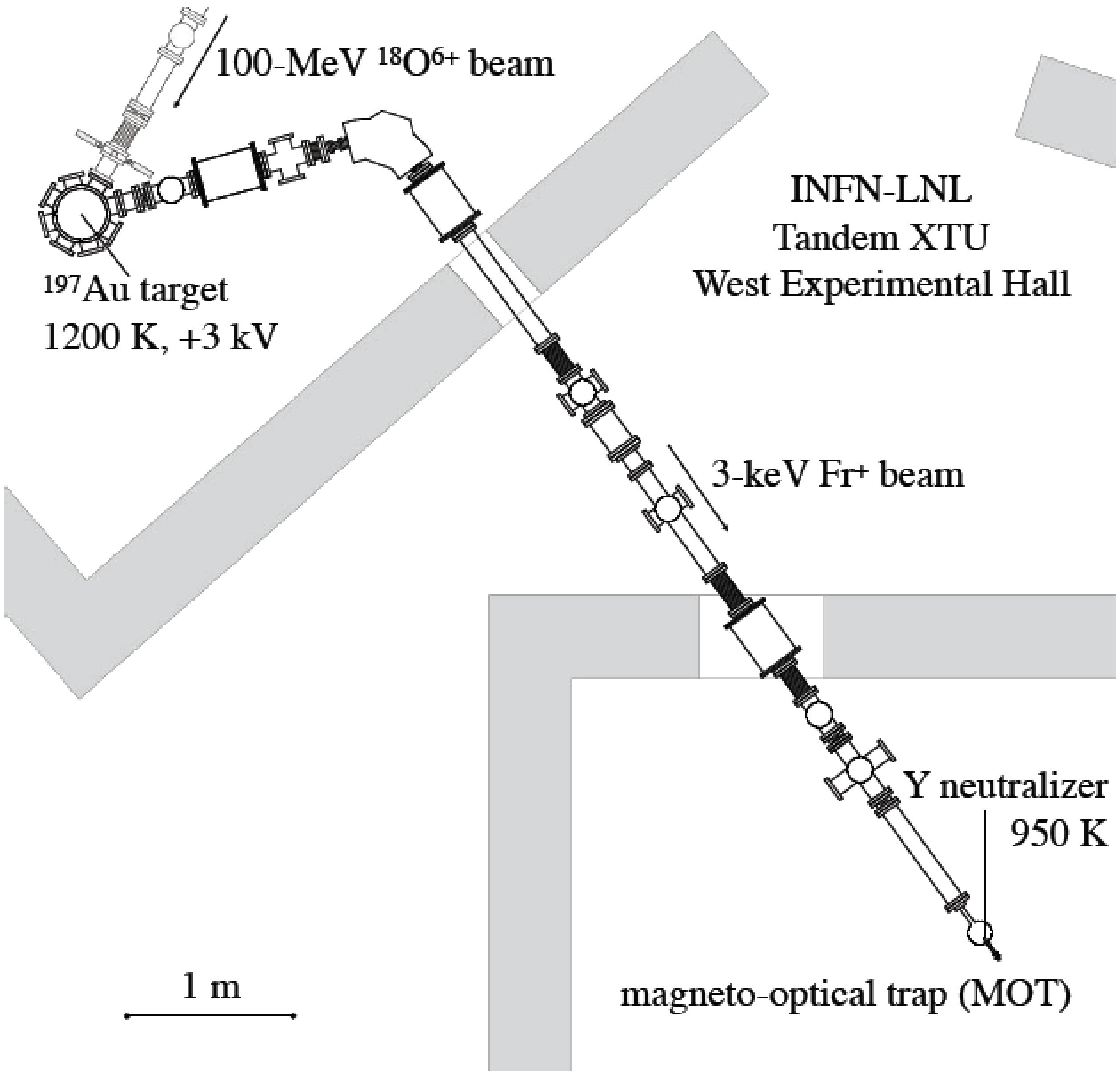


General Overview – Magneto-Optical Traps



- 3-D scheme
  - **Quadrupolar magnetic field can be achieved using two coils in Anti-Helmholz configuration**
  - **Three orthogonal pairs of counterpropagating laser beams**
  - **Red detuning of laser beams to achieve cooling conditions**
- Resulting force towards B=0

The experiment

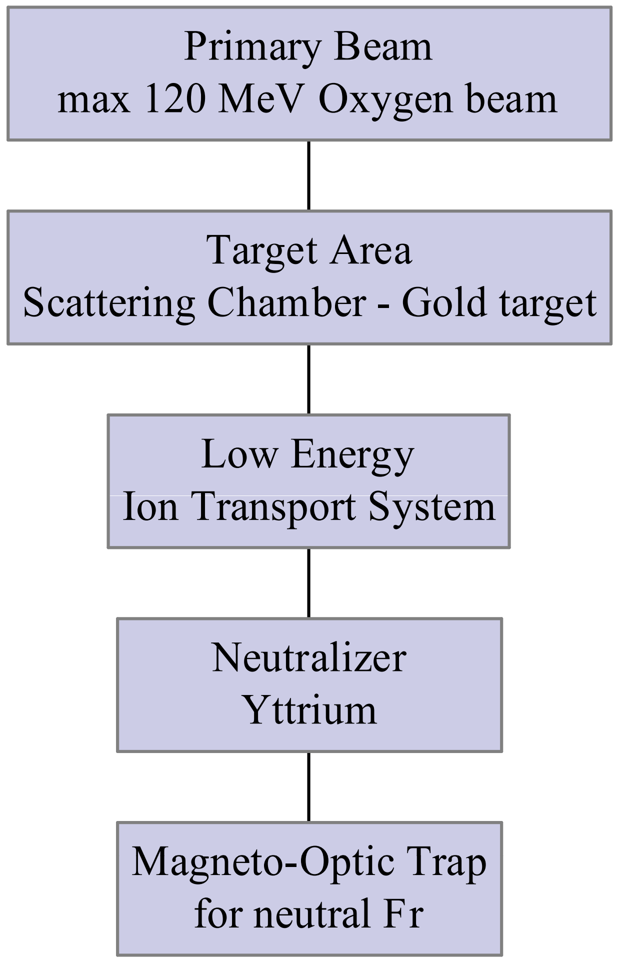


The experiment

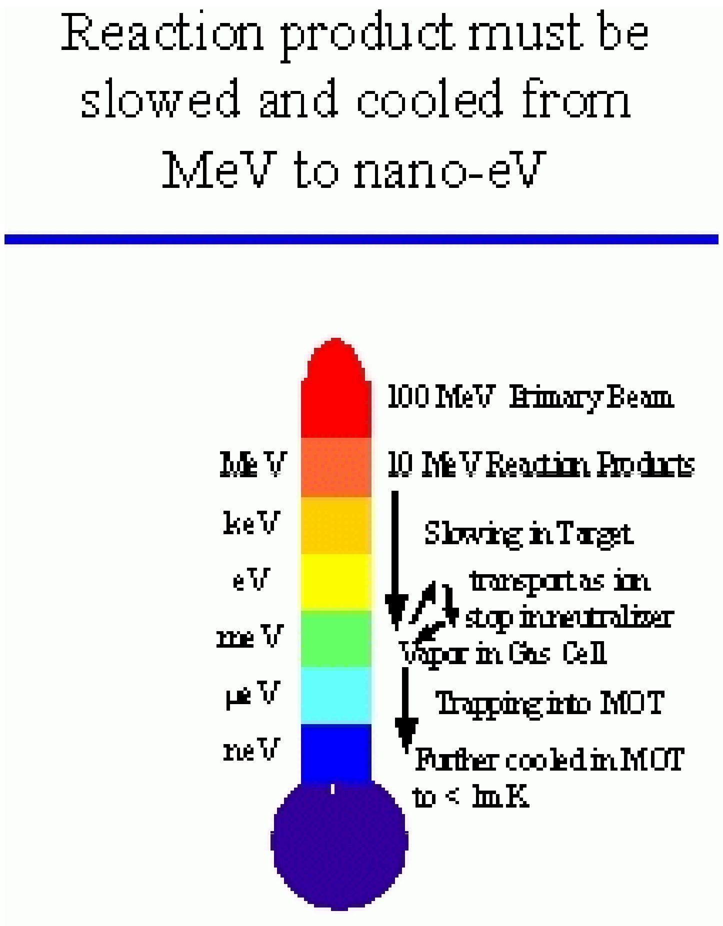
- Francium is produced via a fusion–evaporation nuclear reaction:

$$^{197}Au(^{18}O, xn)^{215-x}Fr$$

- Francium is delivered to the trapping region through an ion transport system
- Then francium is neutralized and trapped



The experiment: cooling to T < 1mK

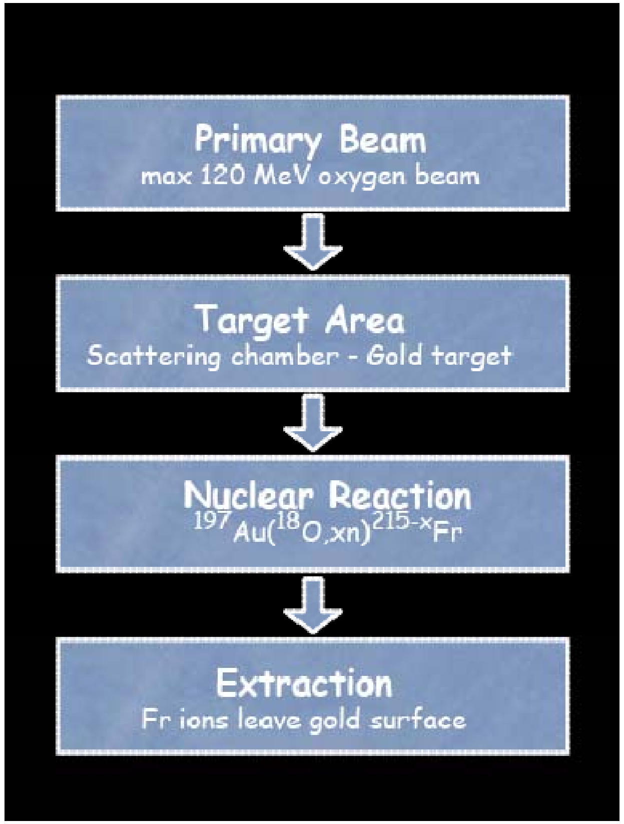


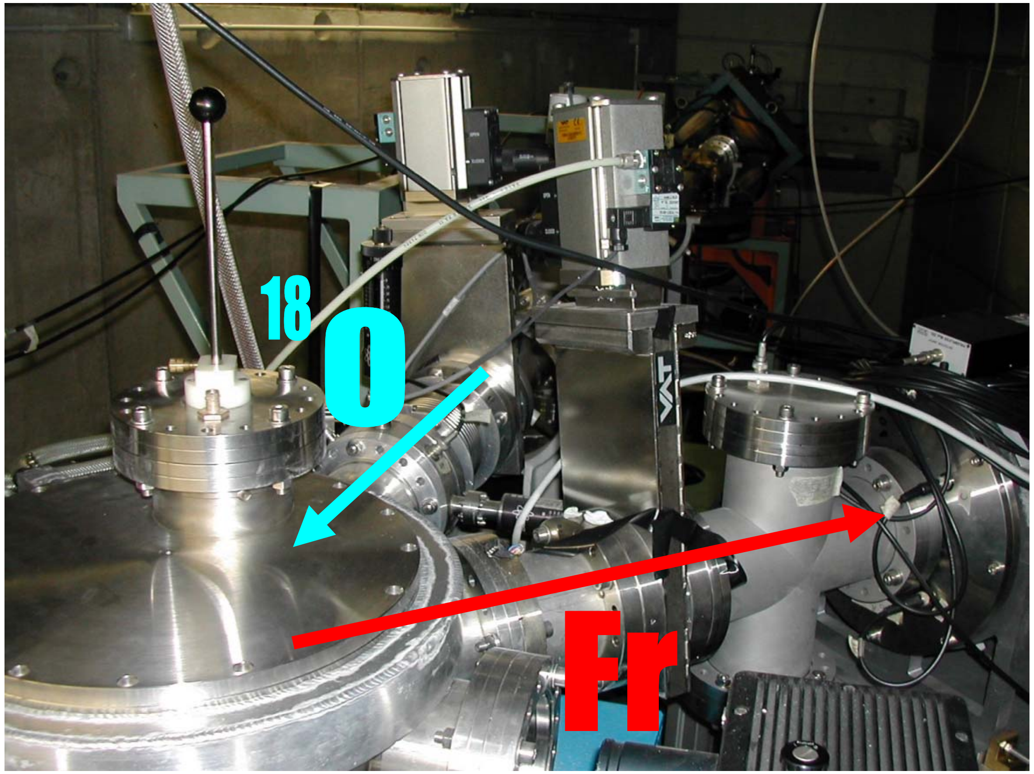
The experiment

The primary $^{18}O^{6+}$ beam is provided by Tandem-XTU accelerator at 95-115 MeV

Maximum intensity 2 x 10^{12} particles/s (~2μA)

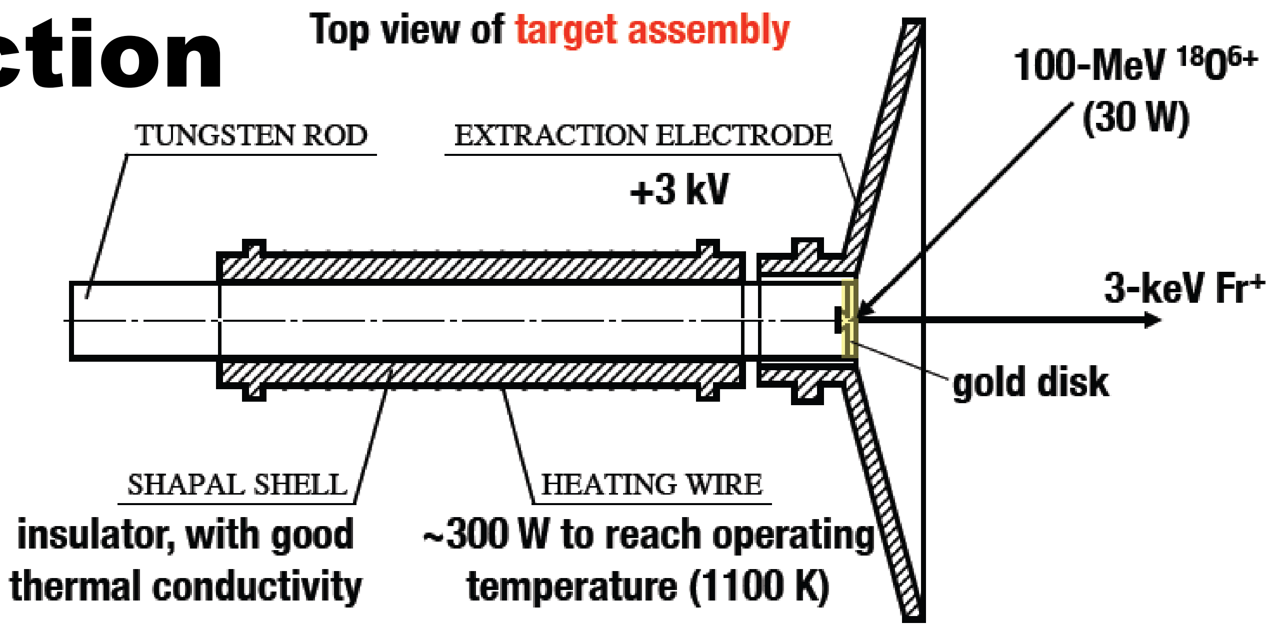
Francium production





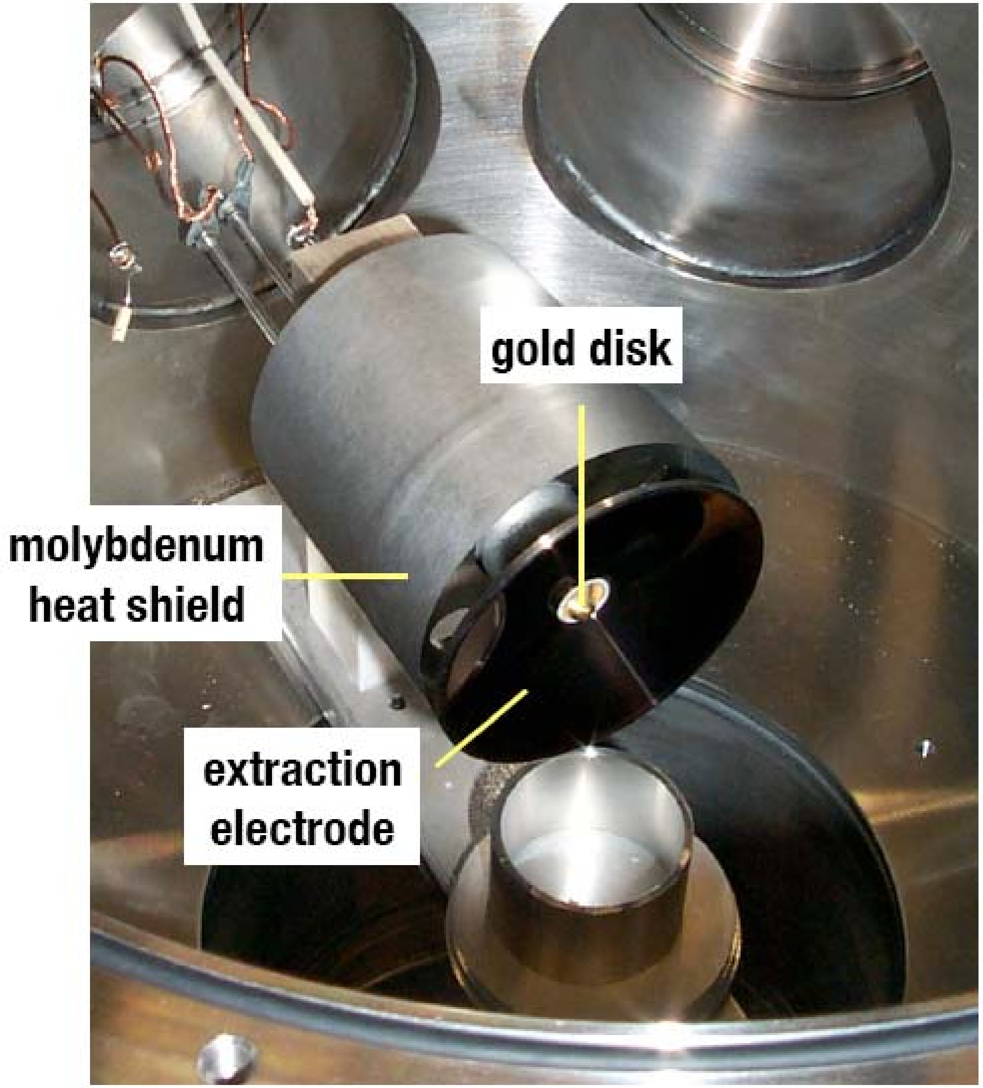
- Fr atoms are produced inside a gold target by a fusion-evaporation nuclear reaction
- Fr ions are extracted from the target and delivered to the trapping laboratory

Fr production

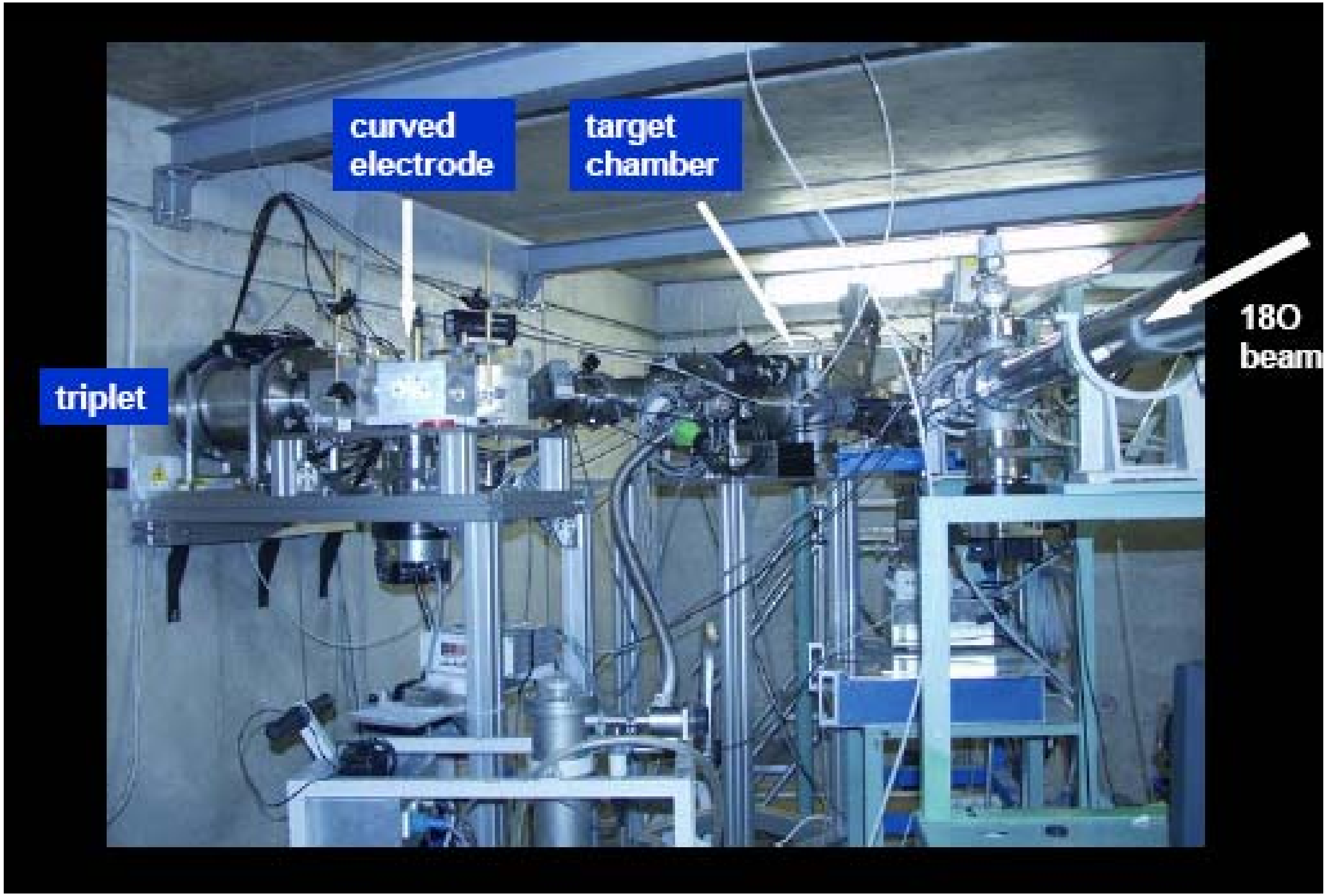


- Au target:
  - **The gold is placed on a Tungsten rod.**
  - **Thermical and electrical isolation is provided by ceramic material**
  - **Temperature T~1270 K close to fusion (gold melting point 1337 K) to enhance the Fr diffusion**
  - **The target is kept at a positive potential of +3 KV**
- ^{210}Fr production:
  - **Fr ionizes as it escapes from the gold because the work function of gold (5eV) is larger than the ionization potential of Fr (4.1 eV)**
  - **Rate ≈ 10^6 ions/s**

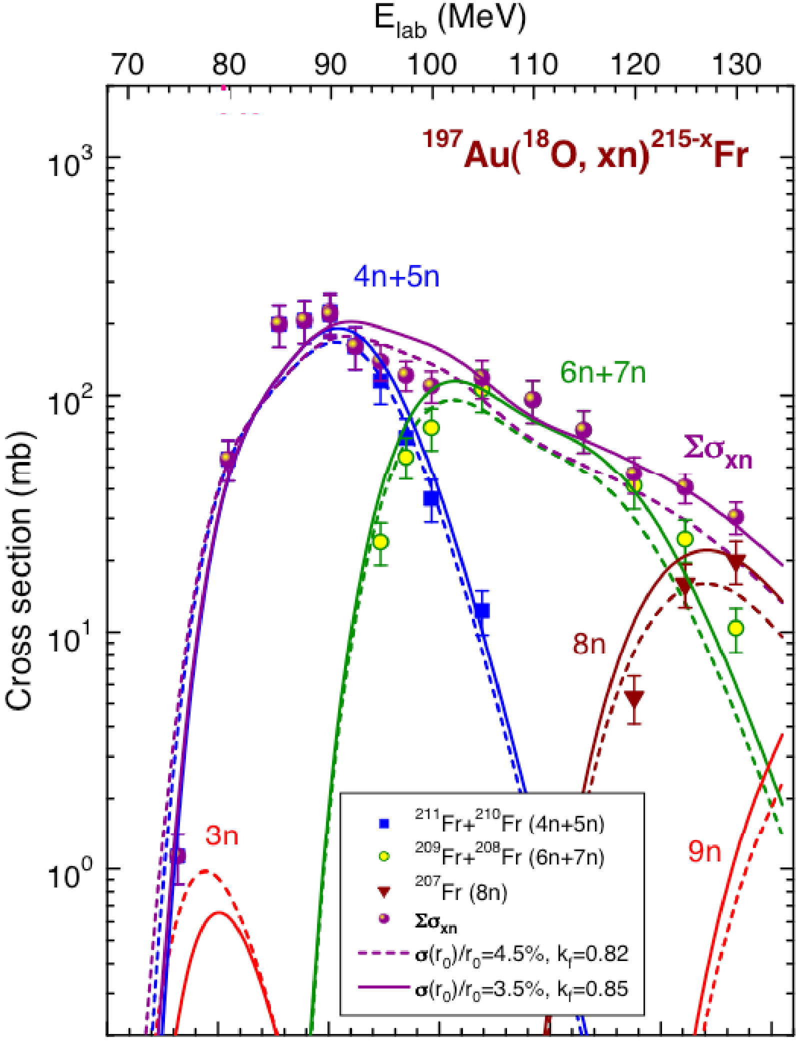
Fr production - The target



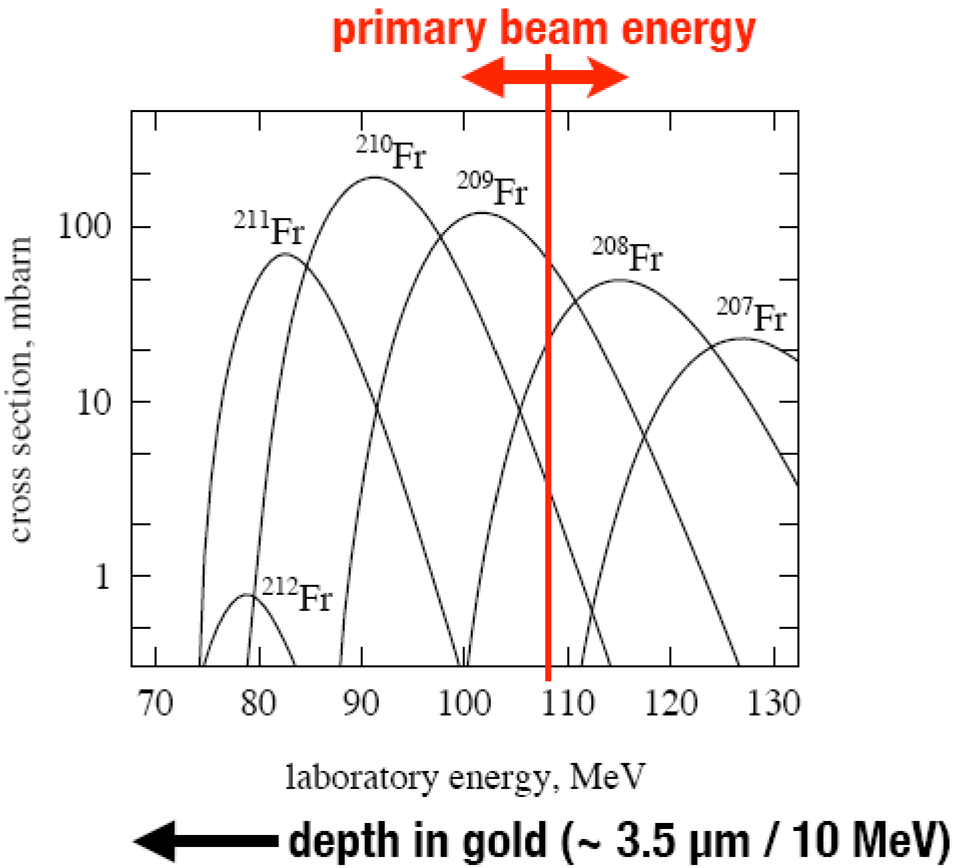
The target region



TANDEM "tuning":
fusion-evaporation cross sections

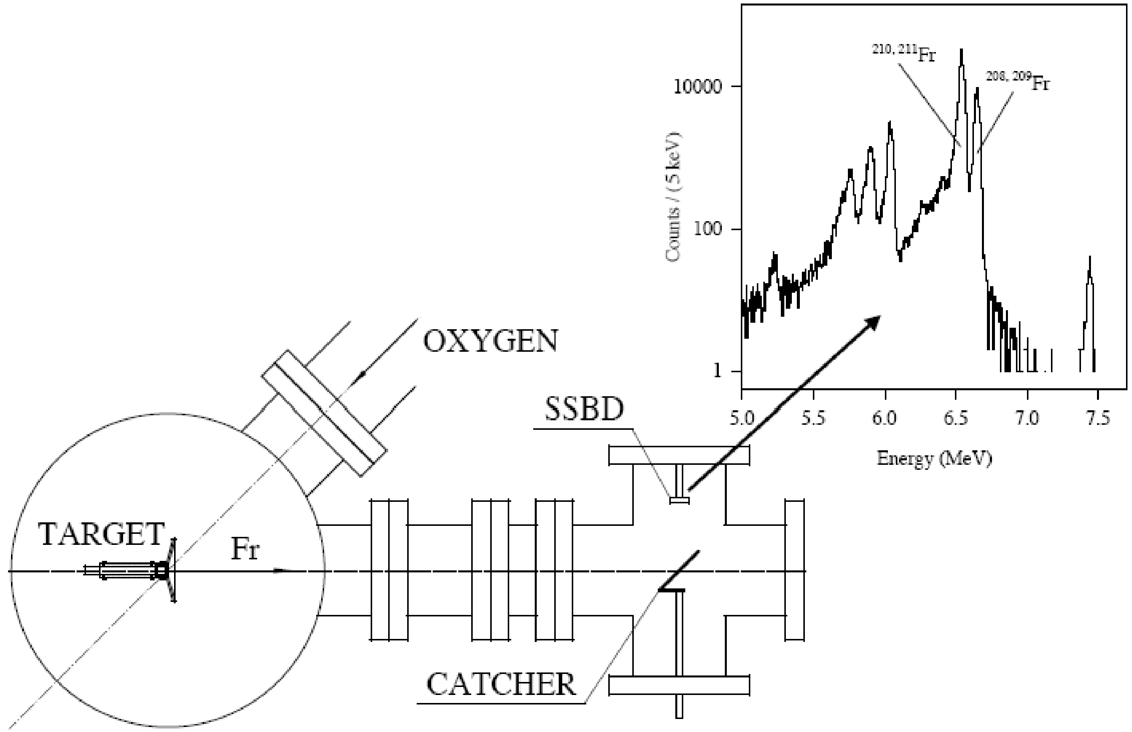


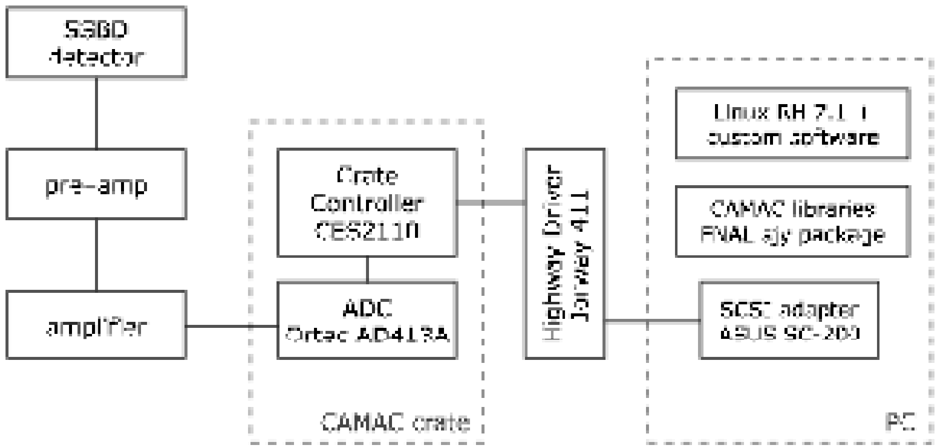
TANDEM “tuning”:
choice of the primary beam energy



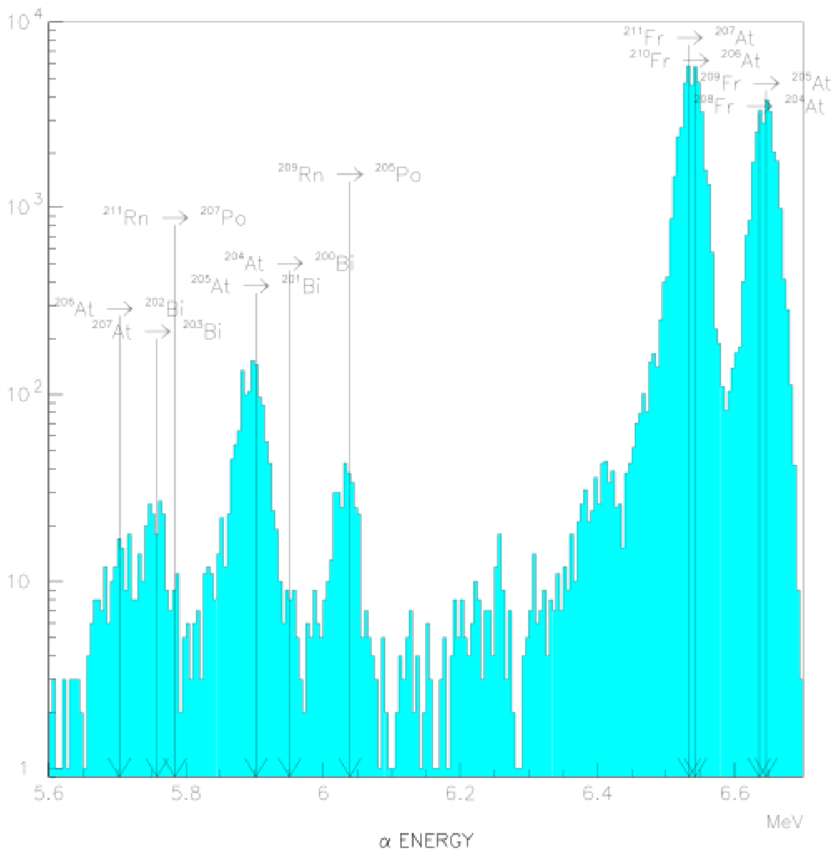
Fr production

- Fr is detected by counting the α particles emitted during its decay
  - **DAQ System acquires the signal of a silicon detector**
  - **Spectra are recorded**





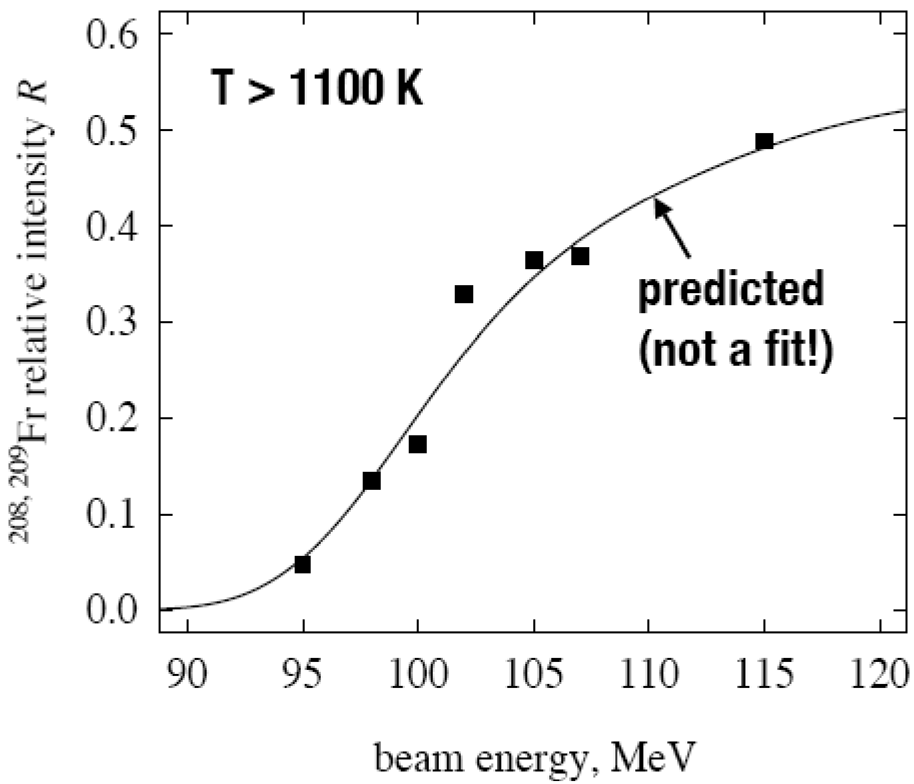
Fr production



isotope	half life (s)	α fraction (%)	α energy (keV)
^{208}Fr	59.1(3)	90(4)	6641(3)
^{209}Fr	50.0(3)	89(3)	6646(5)
^{210}Fr	191(4)	60(30)	6543(5)
^{211}Fr	186(1)	> 80	6534(5)

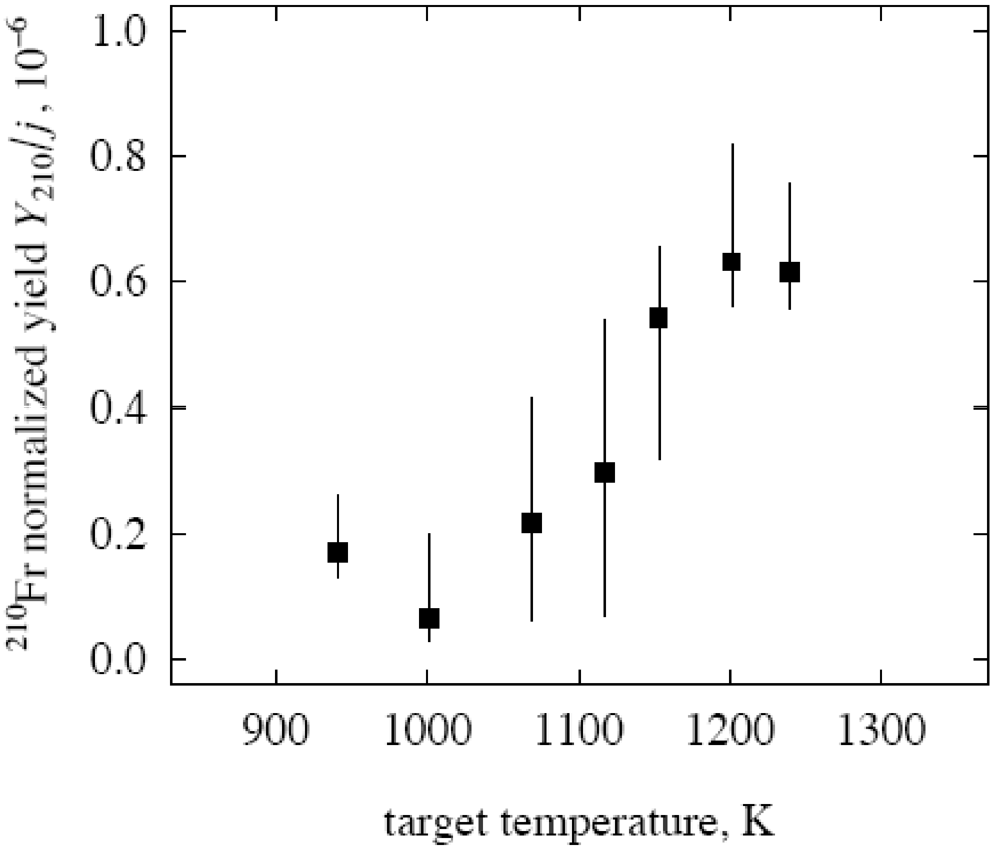
Fr production

Yield ratio (208+209)/total measured vs beam energy



Fr production

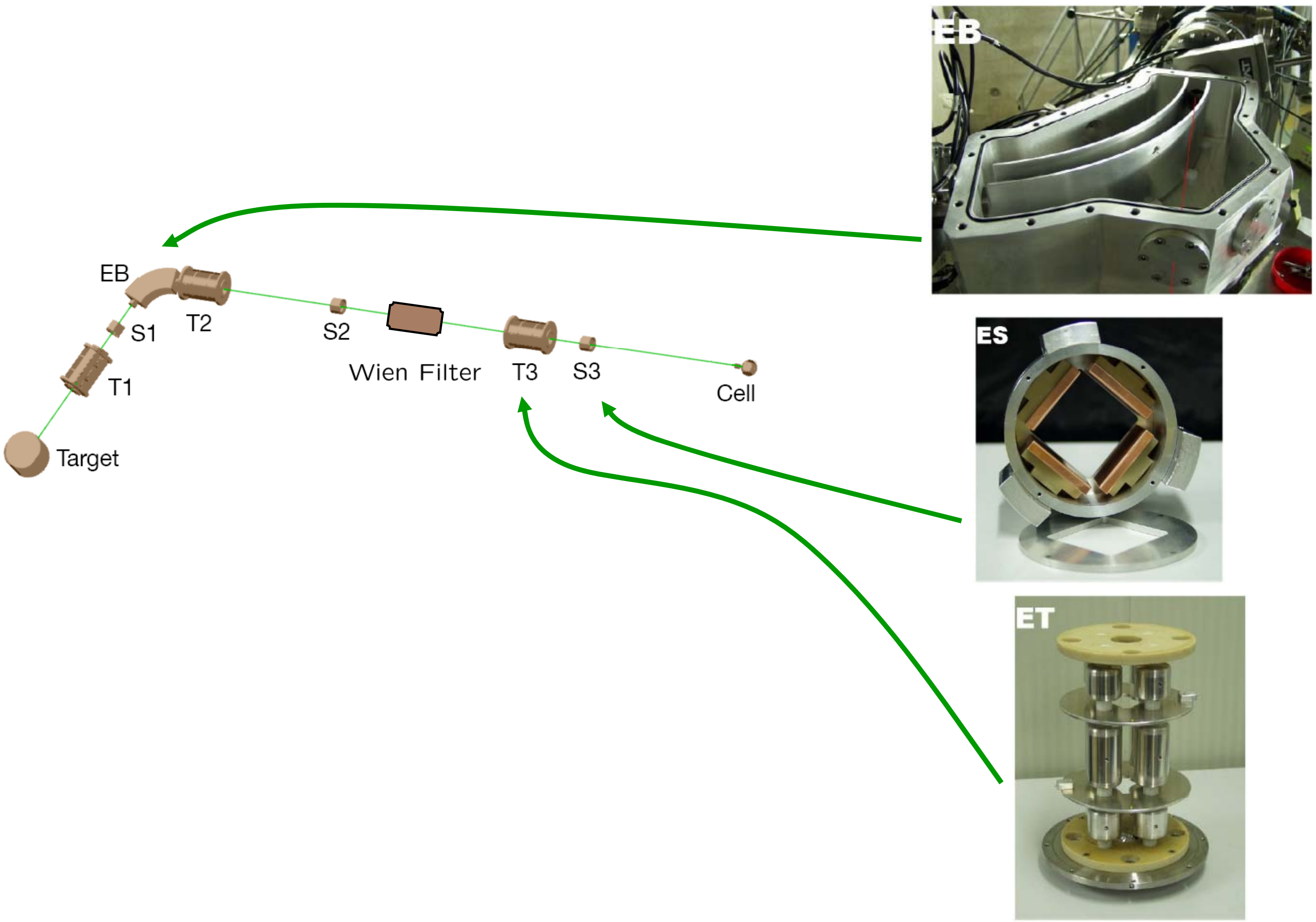
Measured yield vs temperature



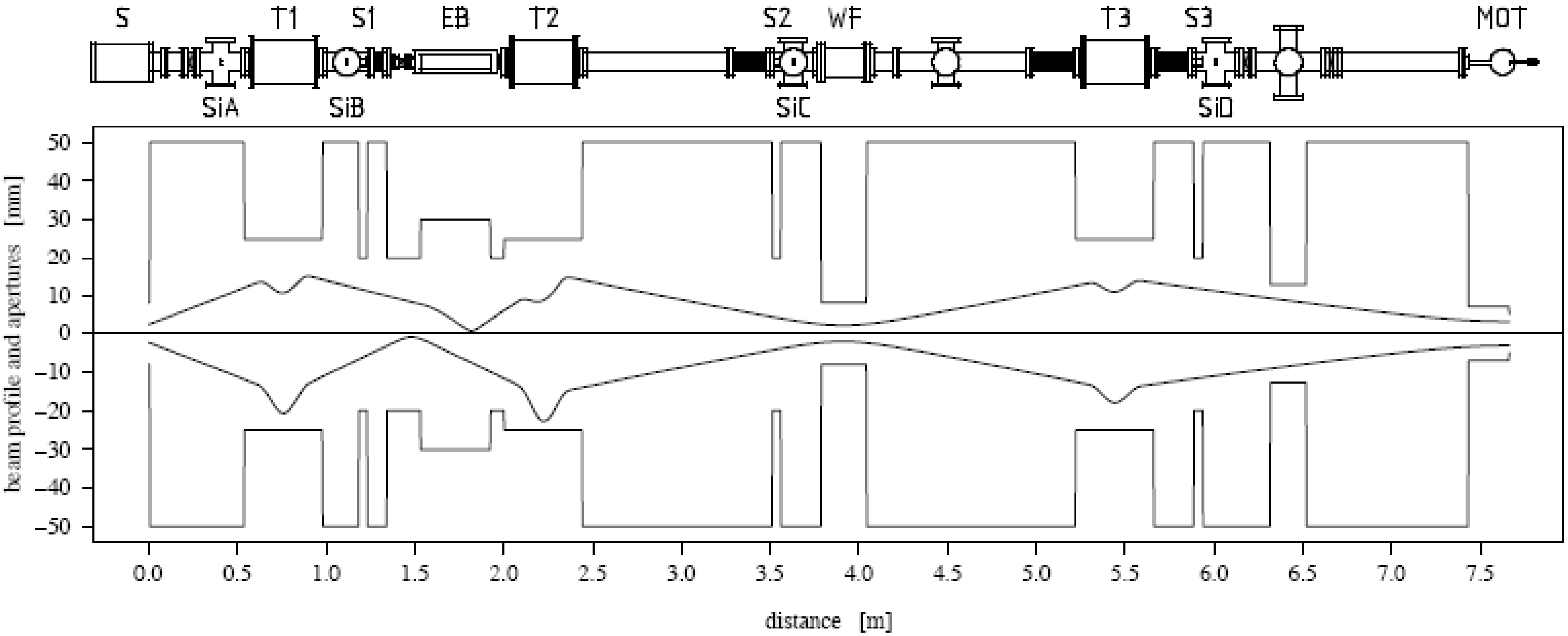
Fr production

- Transport line to send Fr ions to the trap region
  - **A conical electrode placed near the target gives the necessary electrical field to accelerate the Fr ion beam**
  - **Distructive detectors can be put on the beam in order to check isotopes production and beam-line parameters**
  - **Electrostatic deflector to curve the beam**
  - **A set of electrostatic lenses keep the beam focused during the path to the trap region**

Francium beam line elements



Francium beam line optics



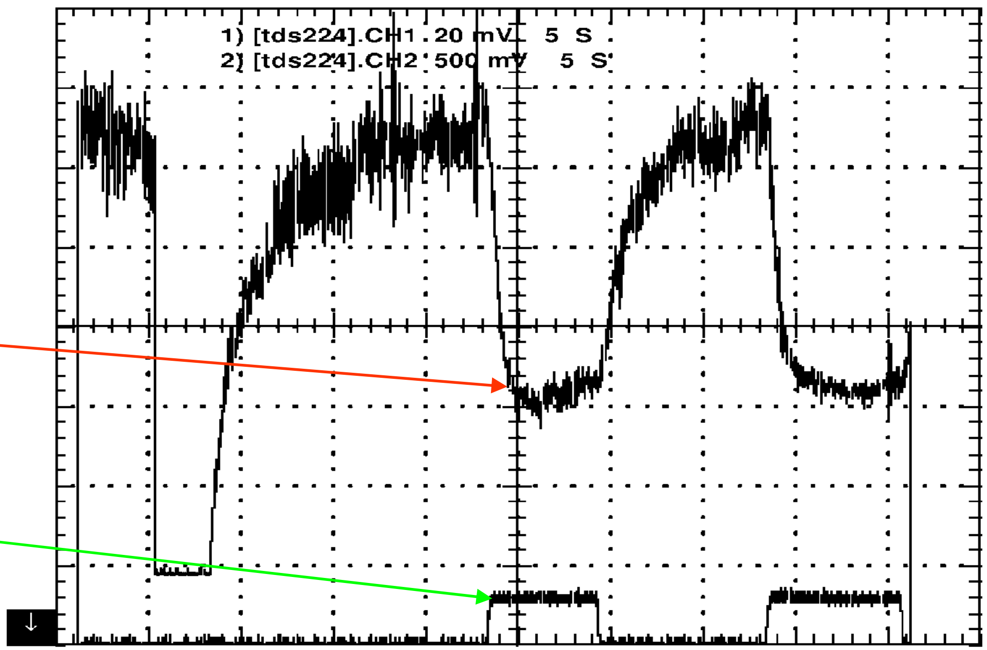
Electrostatic beamline:

all kind of ions are transported towards the MOT cell

The thermoionic current limits trapping efficiency and contaminates cell and neutralizer

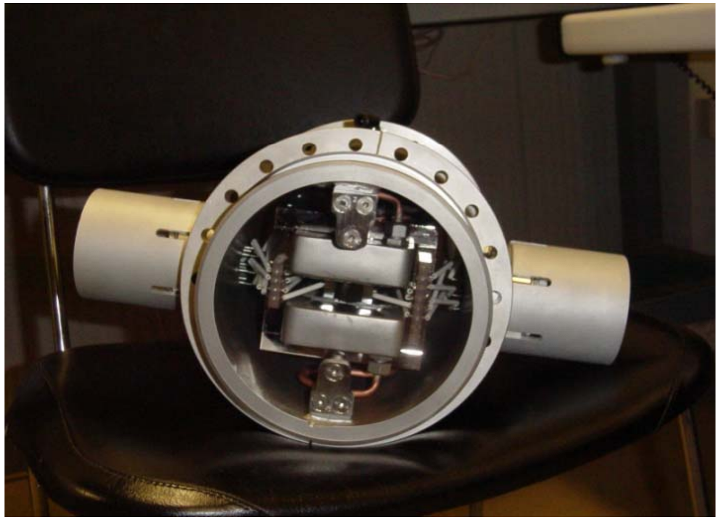
Trap population decreases

Thermoionic current on

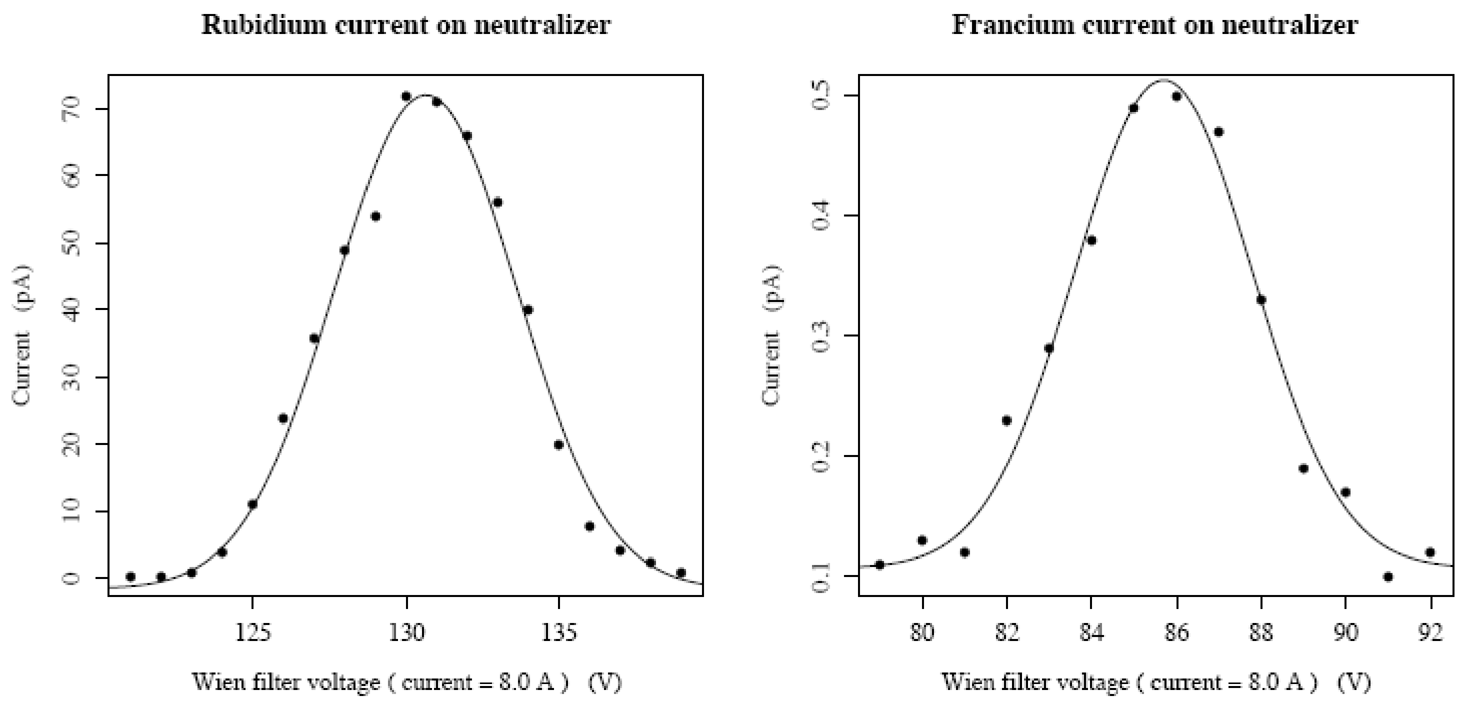


Velocity filter

- Mass selection is performed with a Wien filter (E x B velocity selector)
- Mass/Charge ratio can be selected by tuning Wien's filter voltages
- Filter has been placed along the beamline where the ionic beam has the smallest size
- Electromagnet to be able to switch it off



Wien filter: transmission



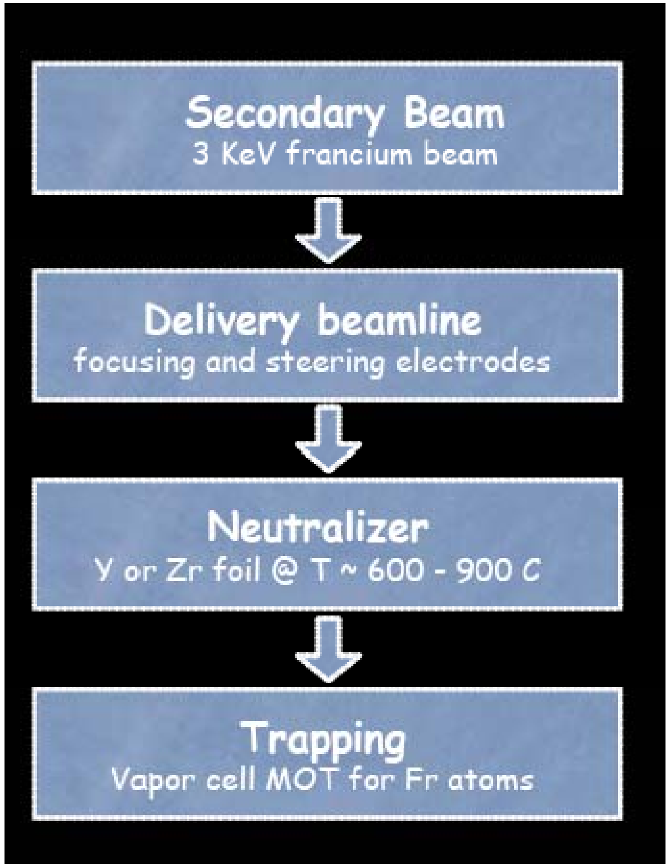
$$B = I\left[\frac{0.29\ \mathrm{T}}{14\ \mathrm{A}}\right]$$

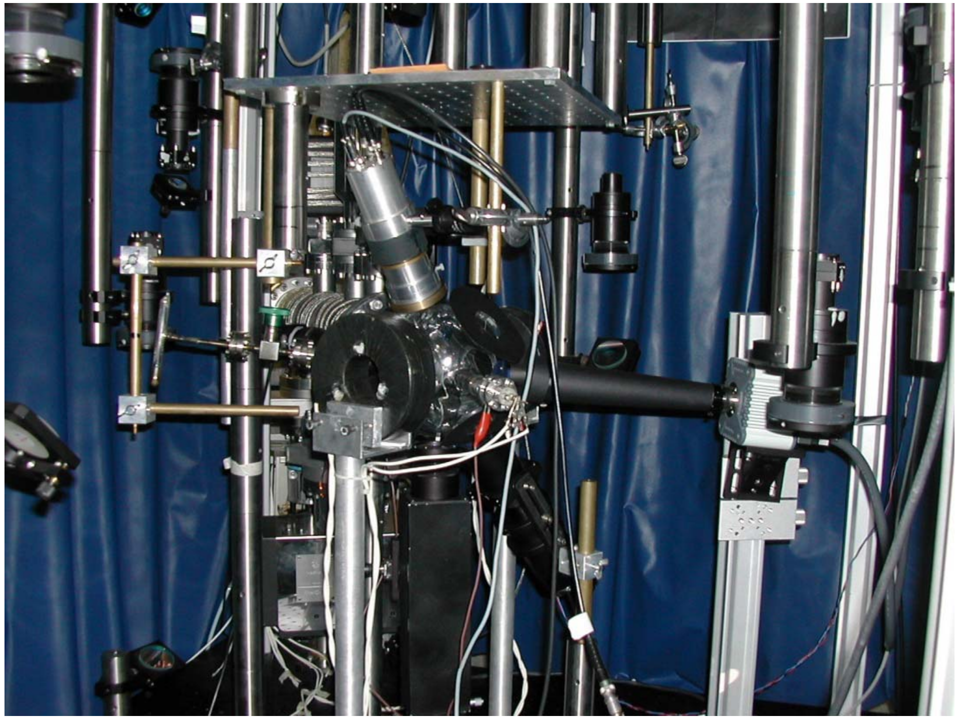
Wien-filter resolution set to $\Delta m/m \sim 20/210$ to accept all Fr isotopes

Fr neutralization

- Collisions with a low work function material are sufficient for a neutralization close to the surface
- Yttrium neutralizer
  - **Work Function W = 3.1 eV (ionization potential of Fr 4.1 eV)**
  - **Temperature in the range 600-900 °C to enhance diffusion (deterioration of the cell coating must be minimized)**
  - **Y foil is placed inside the trap cell, Fr ions are stopped and neutralized on it and Fr atoms are released directly in the cell.**

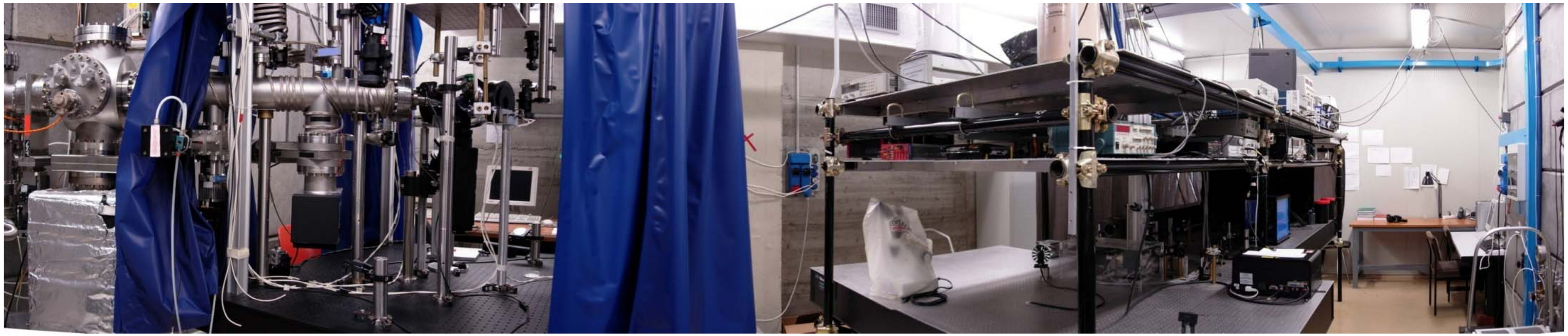
Francium neutralization and trapping



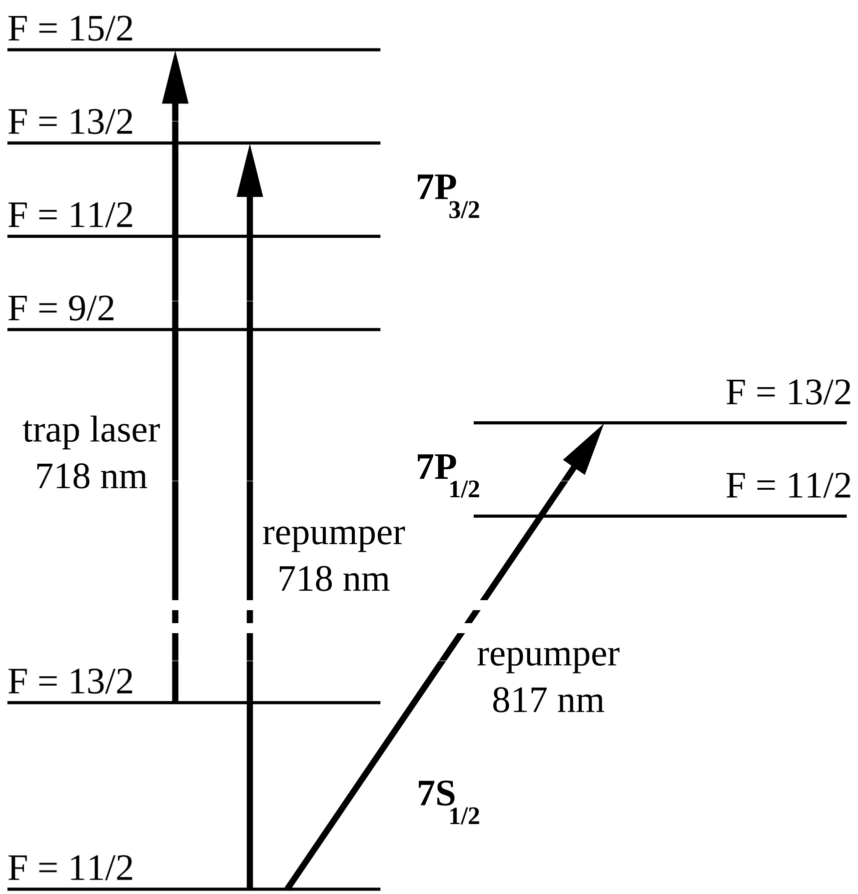


- Fr ions are focused into the cell where they are neutralized
- Y foil at high temperture serves as neutralizer
- PDMS or Dryfilm coated cell for trapping

MOT and laser setup



On–Line Trap for Fr



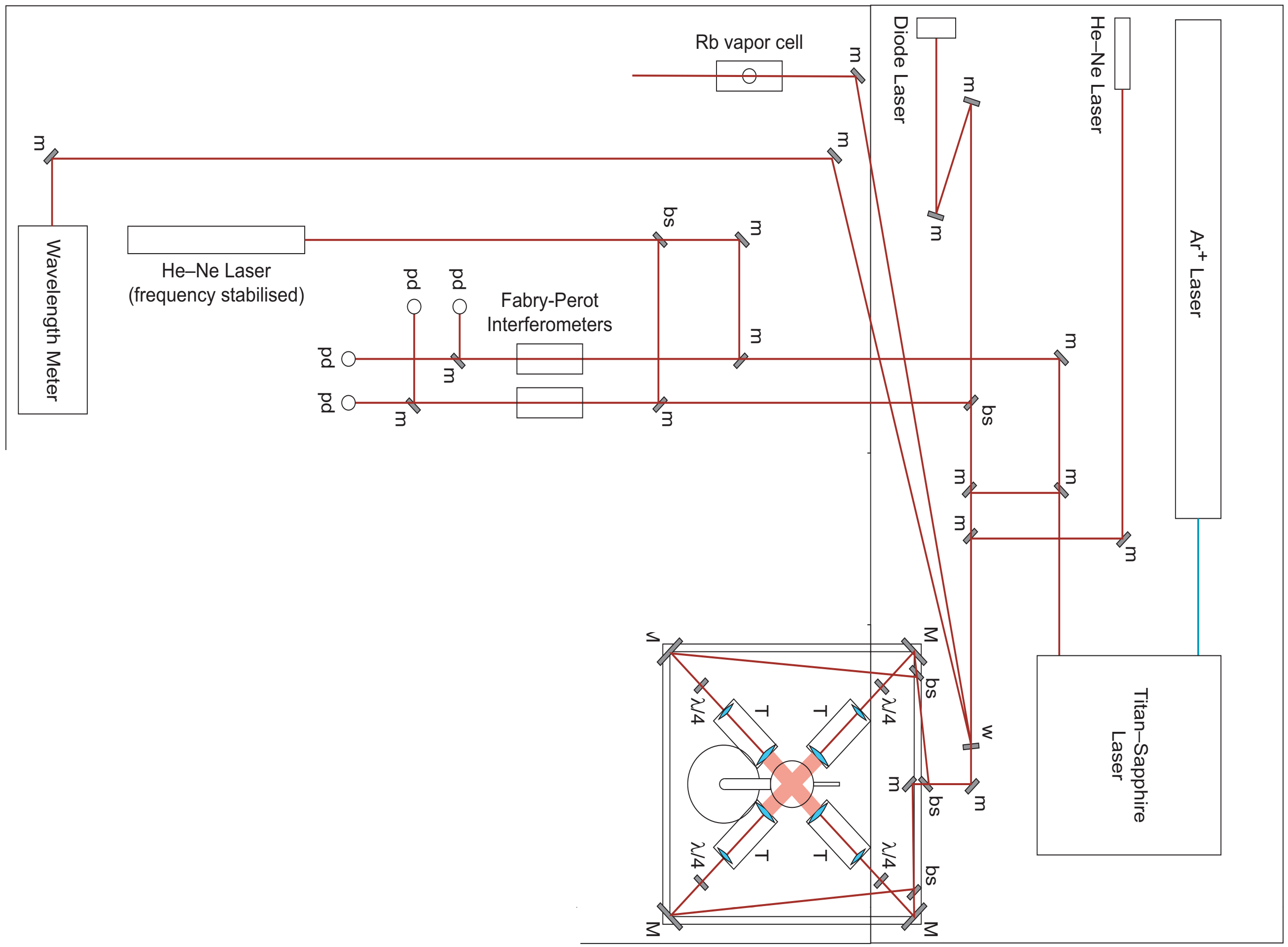
- Hyperfine Structure of Fr atomic levels
  - **Cooling laser at 718nm**
    Titan:Sapph laser
  - **Repump laser at 718nm or at 817nm**
    Titan:Sapph or diode laser

The MOT

- Optical system
  - **12 laser beams:**
    Three orthogonal pairs of counterpropagating laser beams
    - Cooling Laser
      - **Ti:Sapphire Laser**
        - Ar^+ pumping laser
      - **Frequency stability:** $\Delta\nu$**<10MHz**
    - Repumping Laser
      - **Diode Laser**
    - Cell with special coating
- Frequency stabilization
  - **Instability due to temperature variation and acoustic noise**
    - Active stabilization for both lasers
    - Special technique to lock the laser line to a stabilized Fabry-Perot resonator.
  - **Wavelength meter**

  - **Six telescopes are used to expand beam diameters (Enlargement = 5)**
  - **Six $\lambda/4$ plates are used to circular polarize the beams**
- Magnetic Field
  - **Two coils in Anti-Helmholtz configuration**
  - d = 8.5 cm, f = 16 cm, I_{MAX} = 4 A, B_{MAX} = 125 Gauss, gradient ~ 10 gauss/cm

The Experiment – MOT



Problem: frequency stability of lasers

- Laser must have a frequency stability of the order of 10 MHz during the measurement time
- "Fast" stability provided by laser drivers (jitter, etc…) ≤ 1 MHz
- "Slow" frequency drift needs another approach to compensate for

- Necessity of long term (slow) stability of the trapping and repumping laser frequencies
- Frequency drift due to:
  - **Termic effects on laser cavity**
  - **Variations on diode I e T**
  - **Atmosferic pressure variation**
  - **Noise in the lab (pumps, people, etc…)**

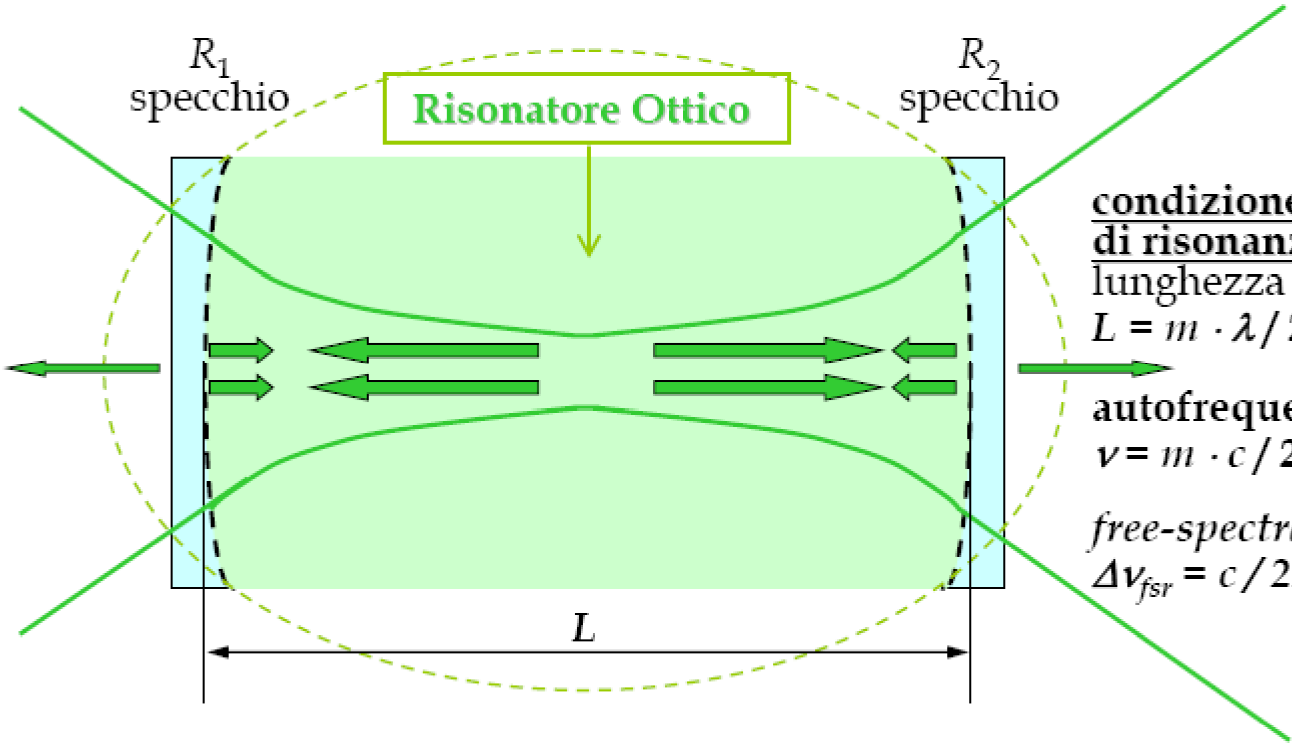
Solution

- Laser frequency monitor
  - **Fabry-Perot cavity**
- Identification of the lasers frequency drift
  - **Position of the peak of trasmission**
- Generation of feedback signal

Working principle

- Fabry-Perot cavity locked to a stabilized (2 MHz) He-Ne laser
- Ti:Sa laser and diode laser locked to the Fabry-Perot cavity

Fabry-Perot cavity



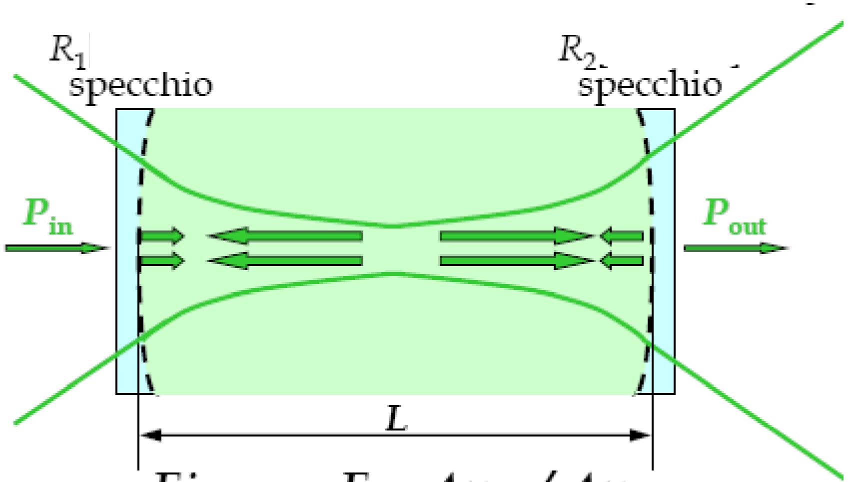
condizione di risonanza
lunghezza
$L = m \cdot \lambda / 2$

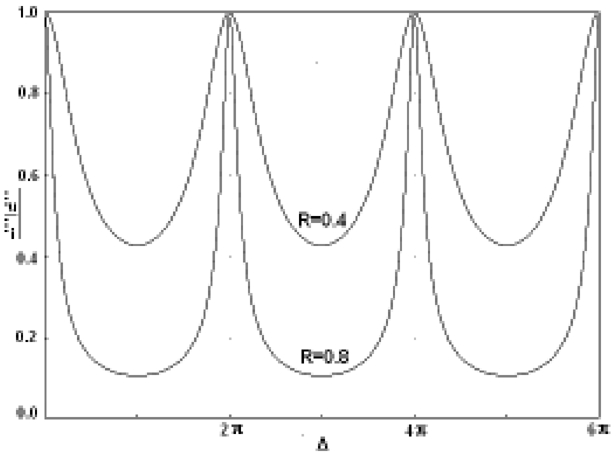
autofrequenze
$\nu = m \cdot c / 2L$

free-spectral range
$\Delta\nu_{fsr} = c / 2L$

m, intero, è l'ordine del modo di risonanza
ci dice quante λ ci sono in un *round-trip* ($2L$)

Fabry-Perot cavity



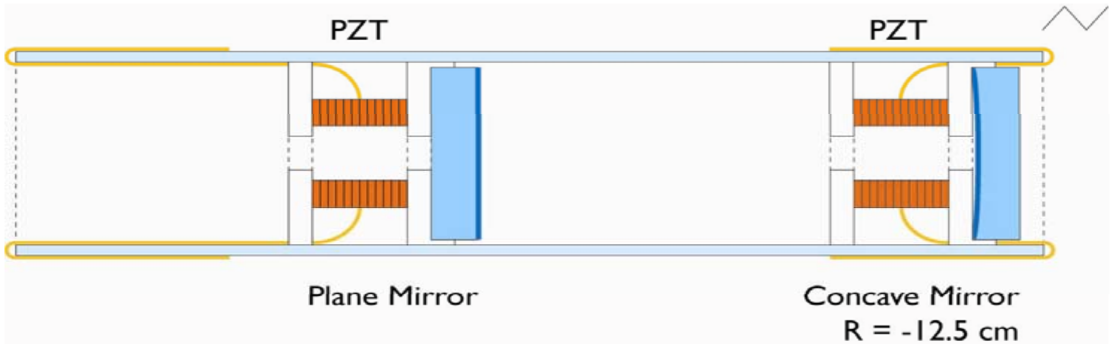


Finesse $F = \Delta\nu_{fsr} / \Delta\nu_c$

$F = \pi(R_1R_2)^{1/4} / \{1- (R_1R_2)^{1/2}\}$

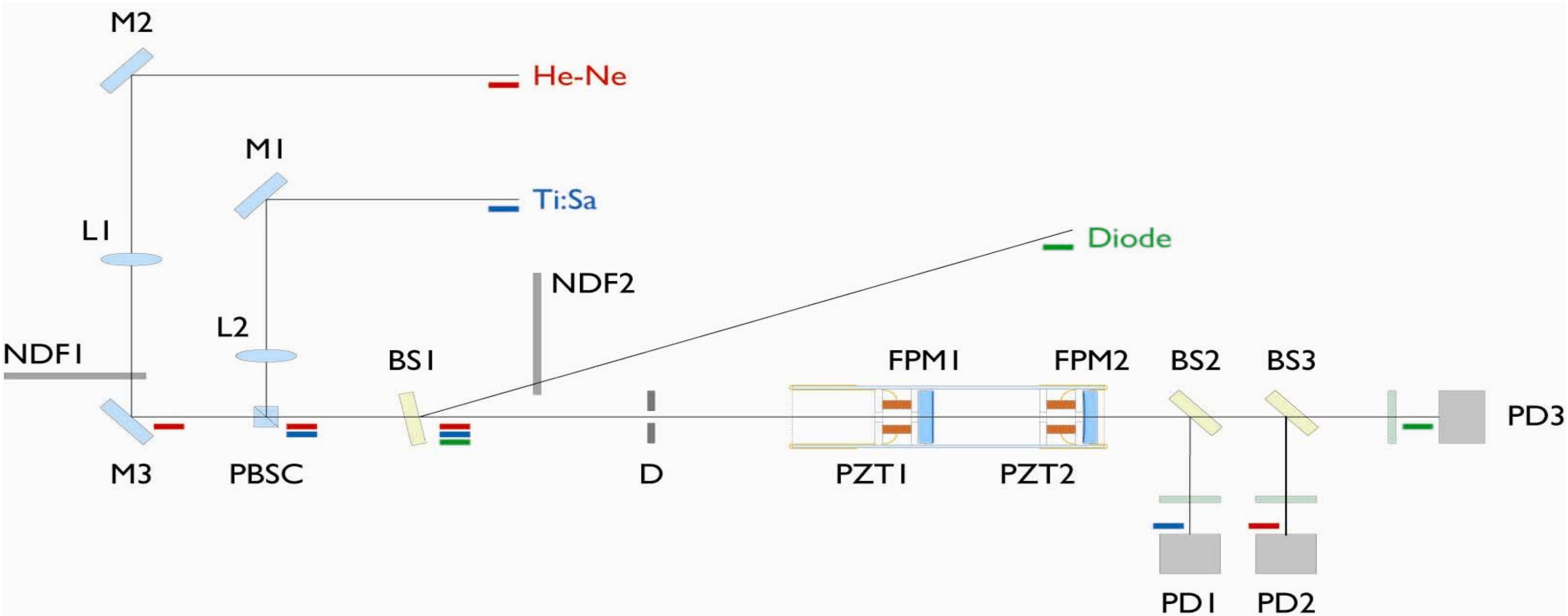
$\boxed{F = \pi R^{1/2}/ (1- R)}$ con $R=R_1=R_2$

Fabry-Perot cavity

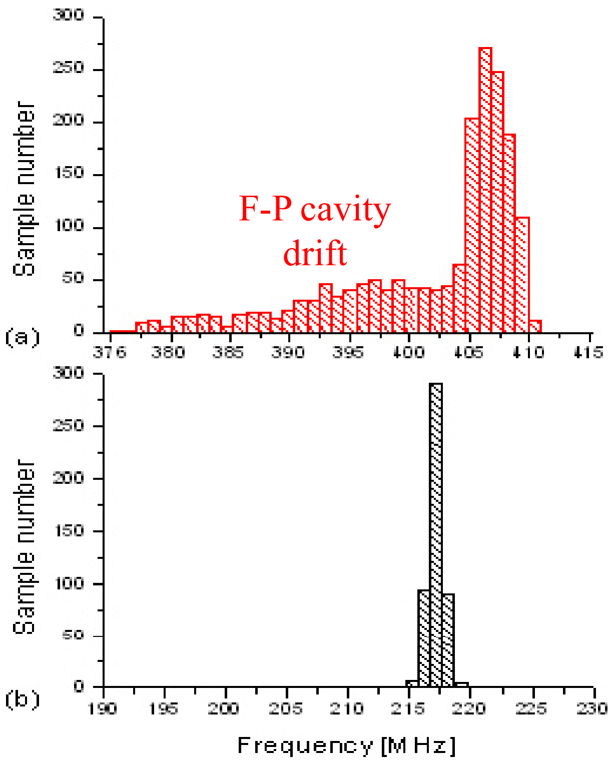


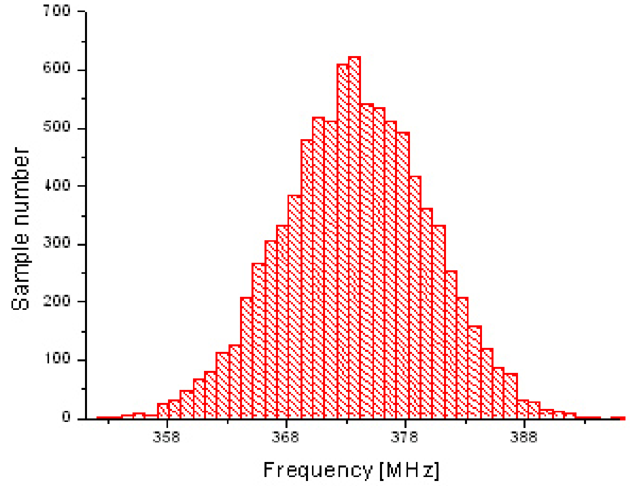
- Mirrors for λ = 633, 718, 780 nm
- FSR = 600 MHz
- Finesse = 209
- PZT: 10 μm @ -1000 V

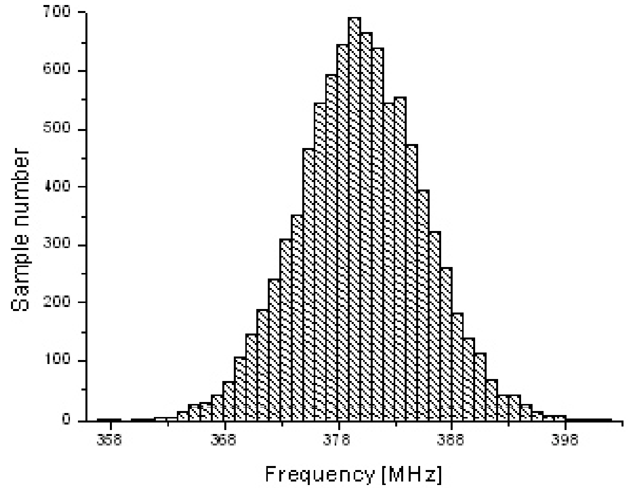
Laser frequency stabilization layout



Stabilization results

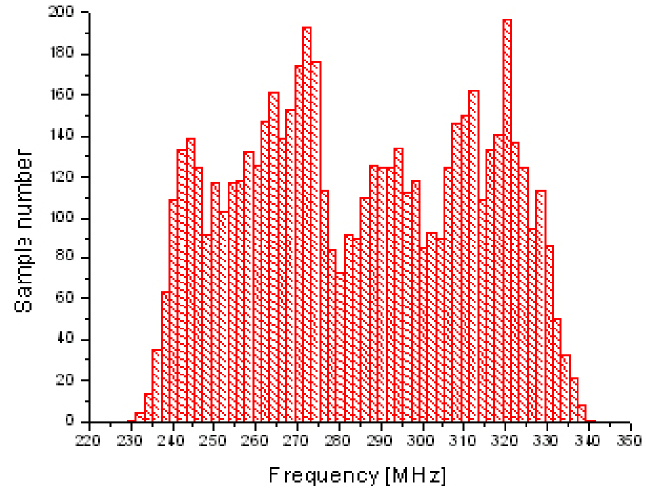


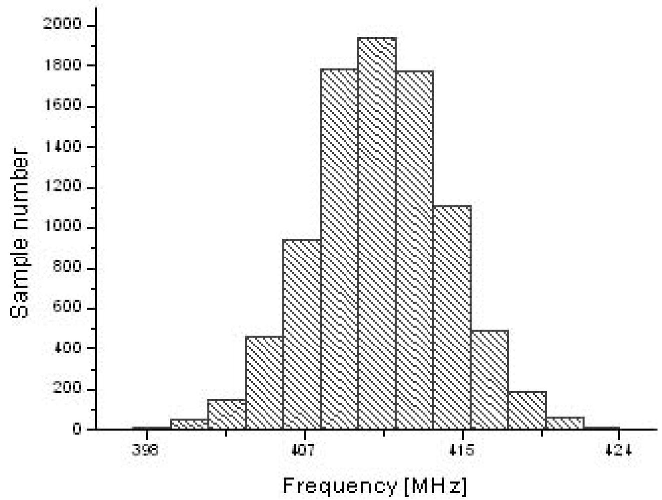




Stabilization results

- 3 MHz F-P cavity stability for 1 hour
- 10 MHz Ti:Sa stability (20 MHz OFF)
- 20 MHz diode stability (100 MHz OFF)

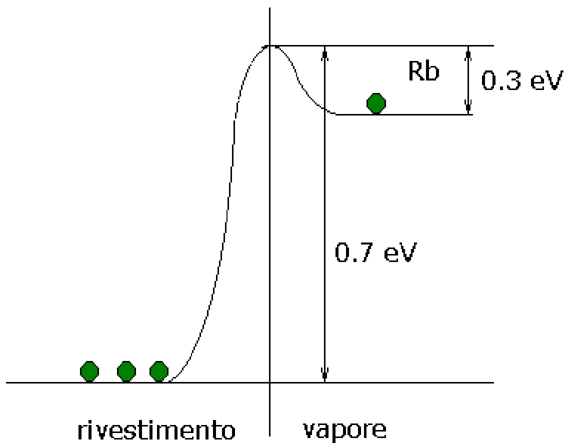




Cell coating: LIAD effect

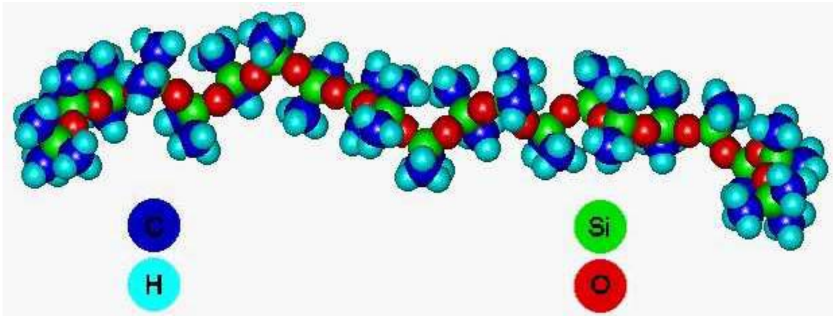
- The LIAD effect consists in atom desorption produced by incoherent light
  - **Using special siloxane composites as trap cell coating, it has been discovered that the atoms are absorbed and then, when flashed by weak light, they are released.**
  - **This effect has been studied on alkali (Na, Rb, Cs) in polymers solution (PMDS, OCT)**

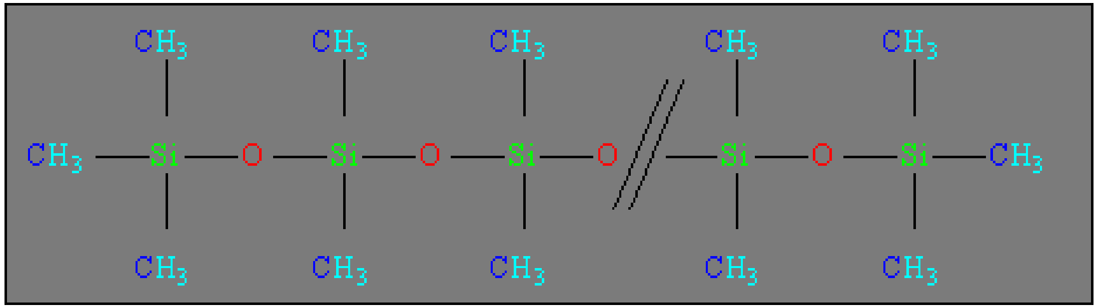
  - **Simple model**
    - Atoms meet ~1 eV potential barrier
    - Photons from flash light give them energy to overcome the barrier
    - Desorption is enhanced



LIAD: Siloxane Composites

- Siloxane composites are organic materials with the twofold property:
  - **Low surface adsorption coefficient**
  - **Atom desorption from the surfaces triggered by non resonant light**
  - **Polydimethilsiloxane:**





LIAD: Technique

- These properties give the possibility to increase the maximum density in MOT through:
  - **Continuously trapping atoms in the cell minimizing the losses due to adsorption**
  - **Accumulating atoms, previously adsorbed on the surfaces, via "triggered desorption"**

- This technique has been applied to our MOT for Rb

LIAD on Rb

- Time evolution of trapped atoms number N_t and atoms in the vapor number N_v

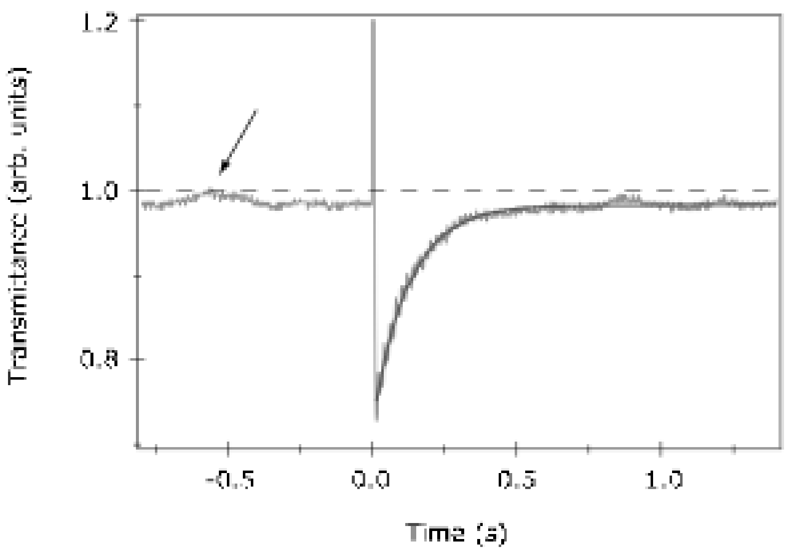
$$\frac{dN_t}{dt} = LN_v - CN_t - \alpha N_t N_v - \beta N_t^2$$

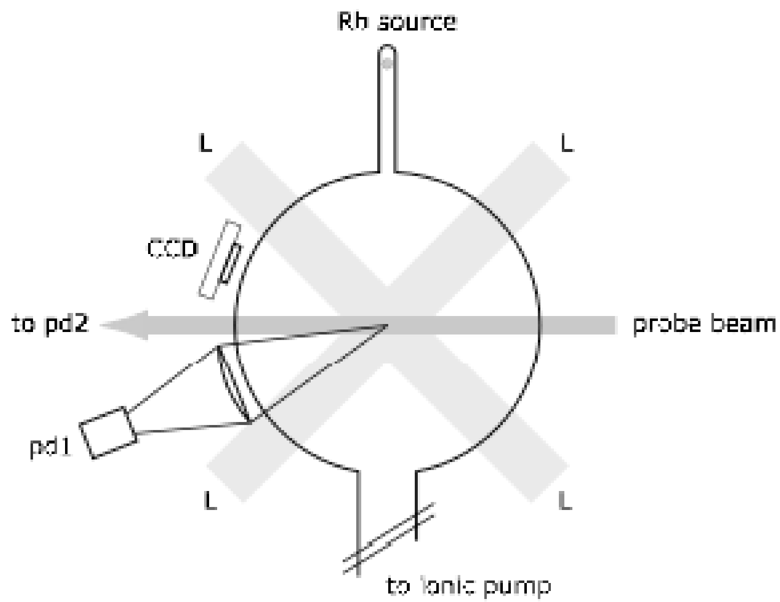
$$\frac{dN_v}{dt} = -LN_v + CN_t - WN_v + \alpha N_t N_v + \beta N_t^2 + I(t)$$

- Efficiency: $\eta = \dfrac{N_t^{\max}}{\int_0^{\tau} I(t)dt}$

LIAD on Rb

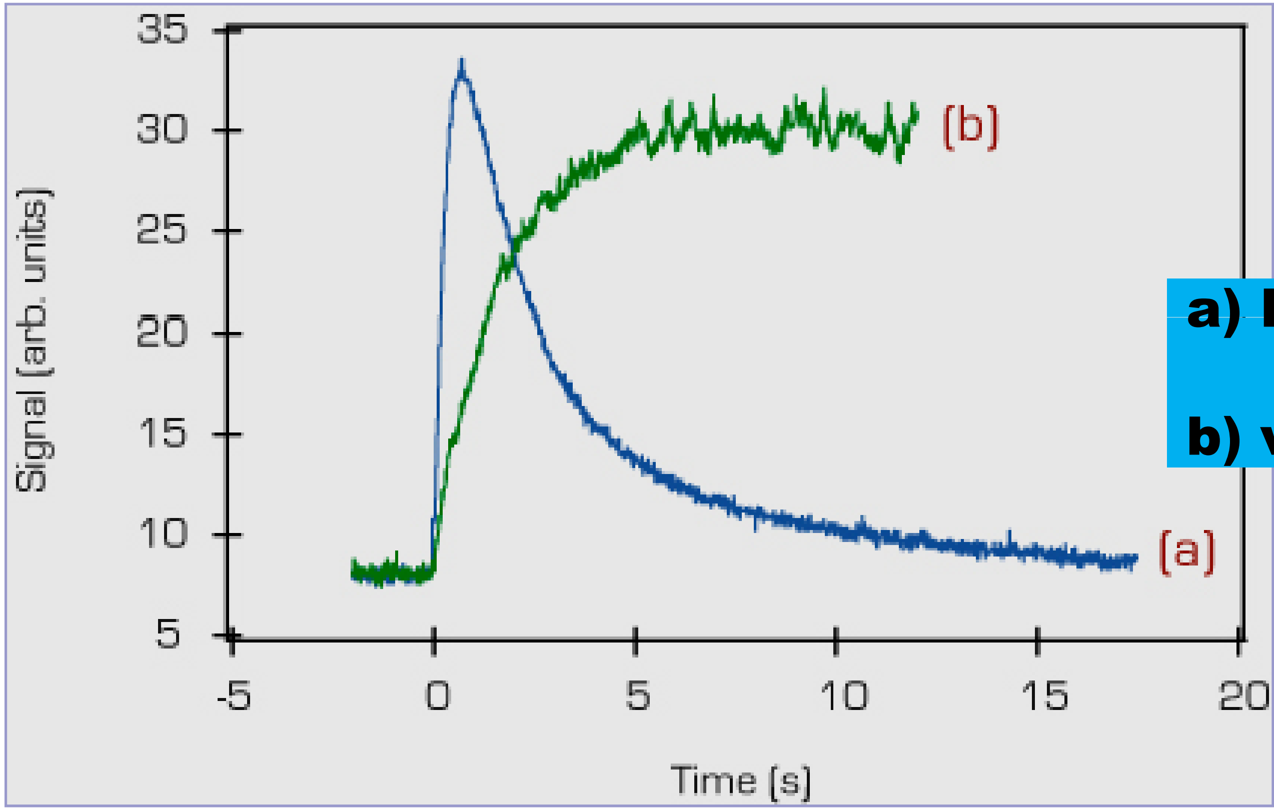
- LIAD measurements on the Rb MOT
  - **Probe beam transmittance**
  - **Loss rate: 1/W = 125 ± 5 ms**





LIAD on Rb: results

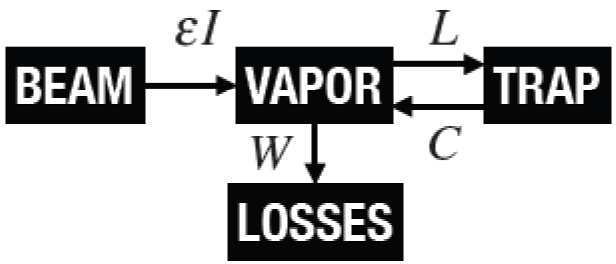
- Loading of the Rb MOT through the LIAD
  - **Loading time: $1/L = (65 \pm 5)$ ms**
  - **Trap Efficiency: $\eta = L/(L+W) \approx 65\%$**



a) LIAD loading

b) vapor loading

Francium trapping efficiency



trap loading rate

neutralization efficiency

number of trapped atoms

$$N_t = \frac{L\varepsilon}{CW} I$$

incoming ion flux

trap loss rate

vapor cell loss rate

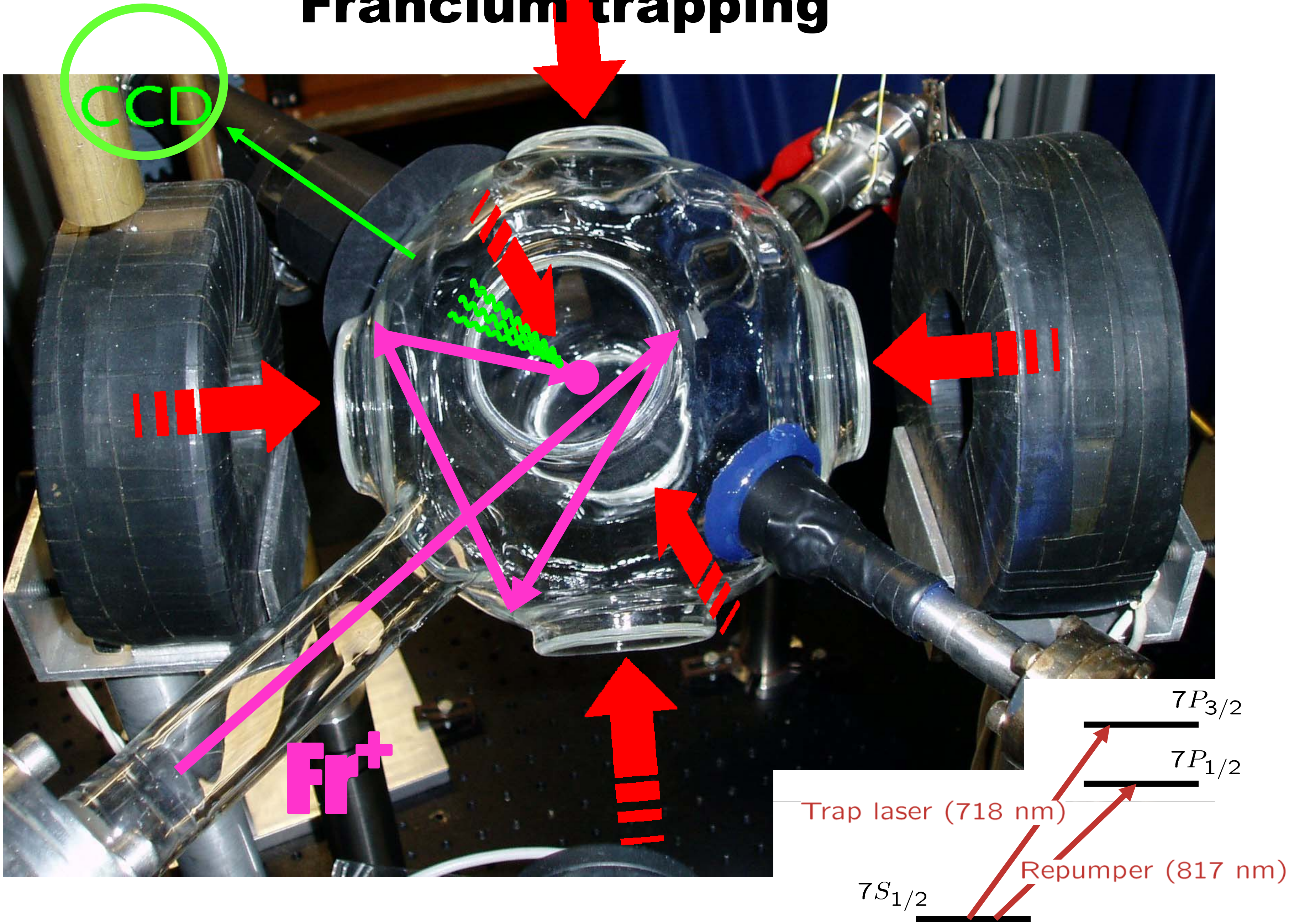
$\sim 2 \times 10^{-3}$ s

- Trapping efficiency depends on several factors, including cell coating and geometry (through W), vacuum (C), laser power (L), neutralizer temperature (ε)

Optimization of the Fr MOT to maximize the number of trapped atoms.

- **Possibility of various improvements**
  - Close the cell with valve coated with dryfilm (improves W)
  - Increase the laser beam intensity or retroreflected configuration (improves L)
  - Vacuum (improves C)

Francium trapping



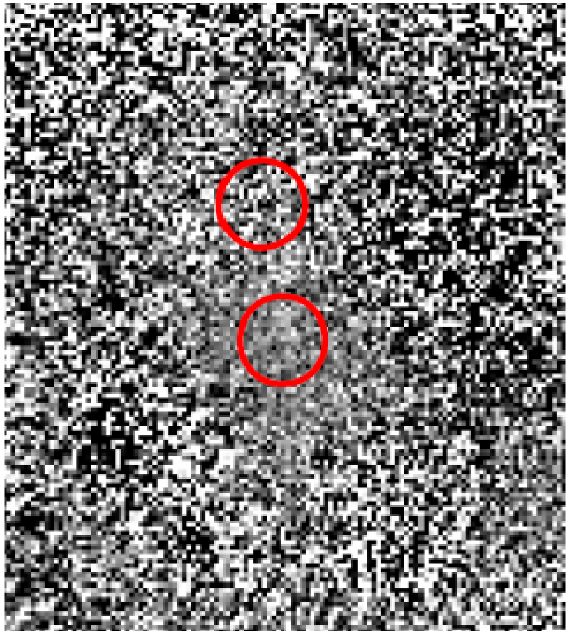
Data acquisition to find trap

Repumping laser: 100 mW Diode, 817 nm. Spectrum enlarged to 100 MHz by current modulation at a rate of 4 kHz. $\nu_{\text{repump}} = 366898751(90)$ MHz.

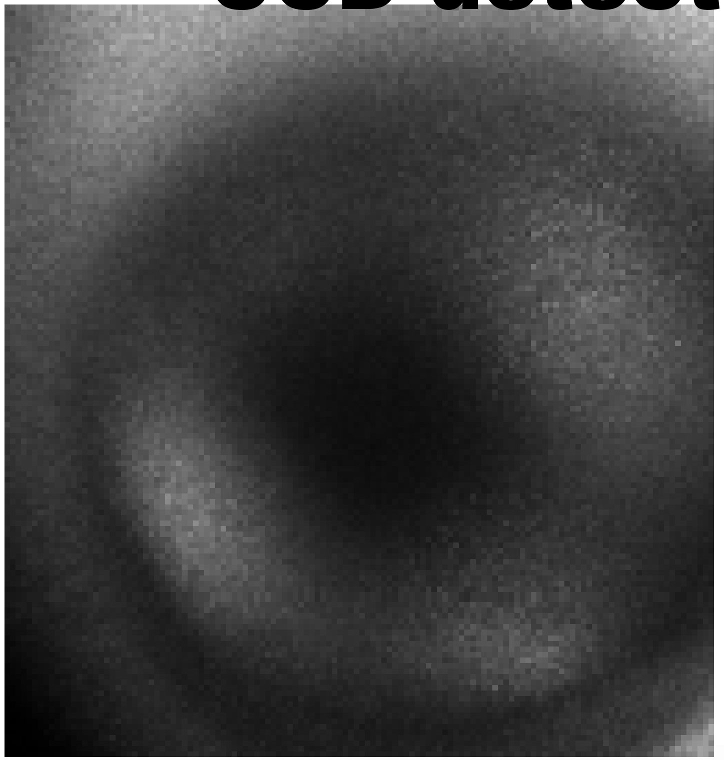
Trapping laser: 200 mW Ti:sa, 718 nm. Slow scan to find Fr trap. $\nu_{\text{trap}} = 417412461(90)$ MHz.

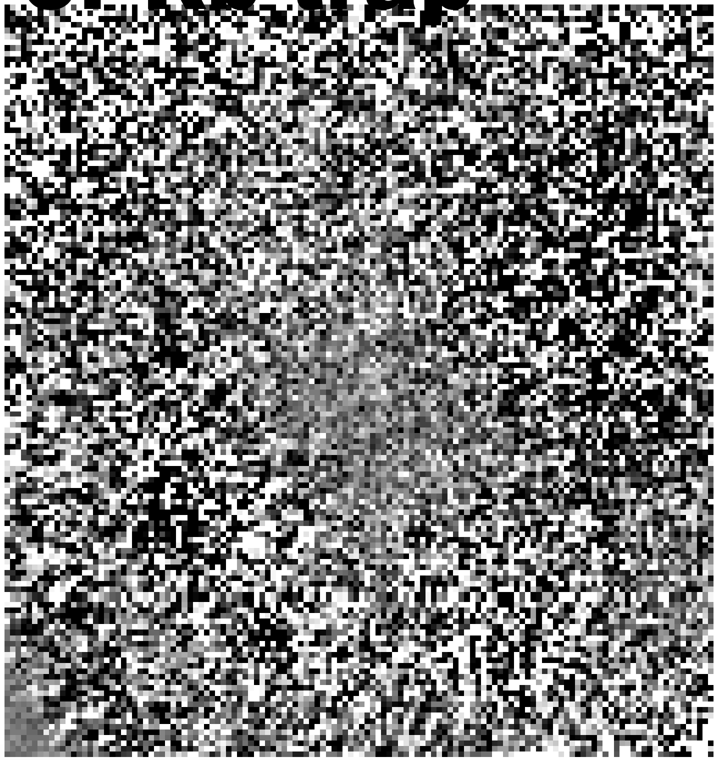
CCD detection

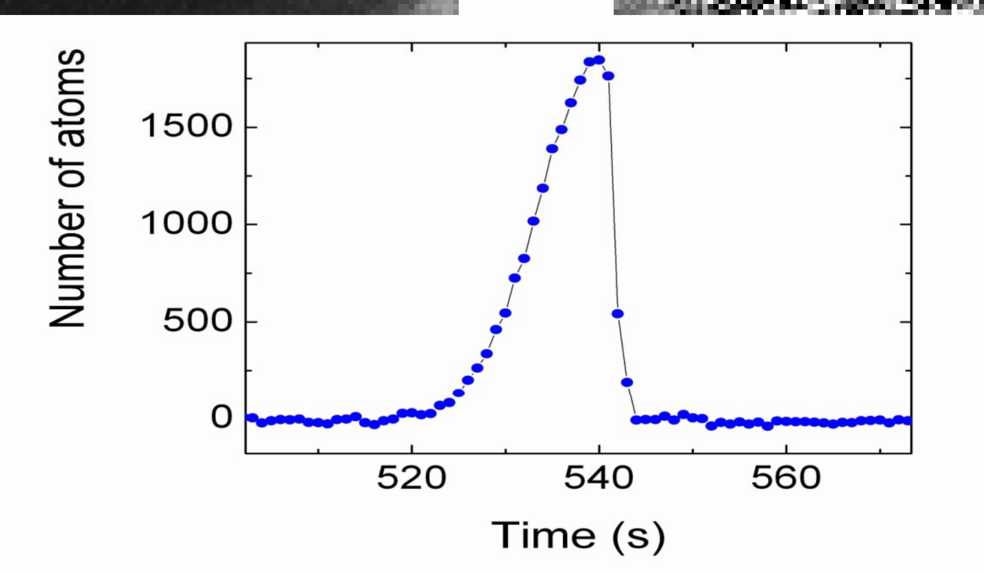
- Hamamatsu ORCA II CCD camera (IEEE1394)
- Short focal length (21mm) objective
- Background subtraction (uniform images)
- Weighted background subtraction (to compensate for laser intensity fluctuations)
- Calibration (number of atoms in the trap)
- Noise < 0.005 pW (50 atoms)
- Labview® based control system for image acquisition and online analysis

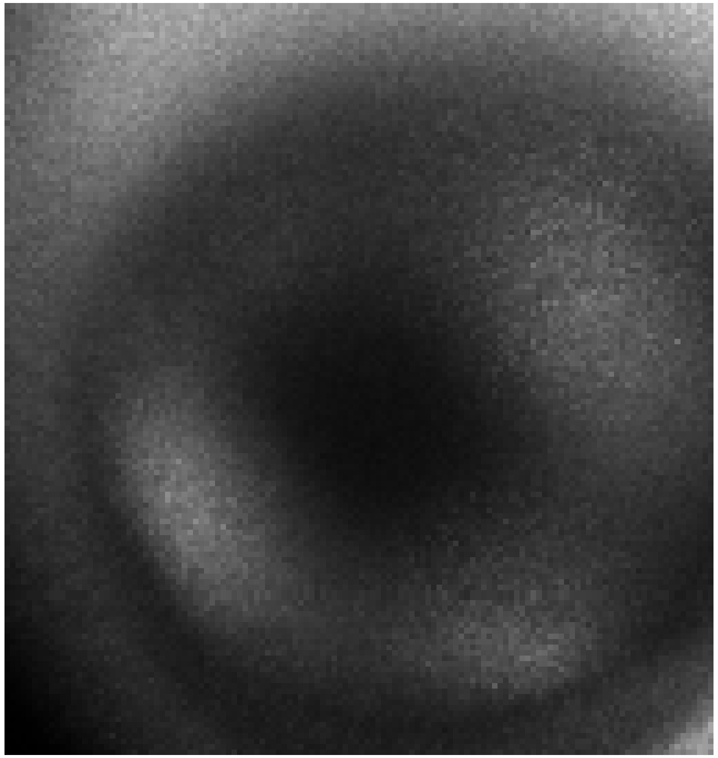


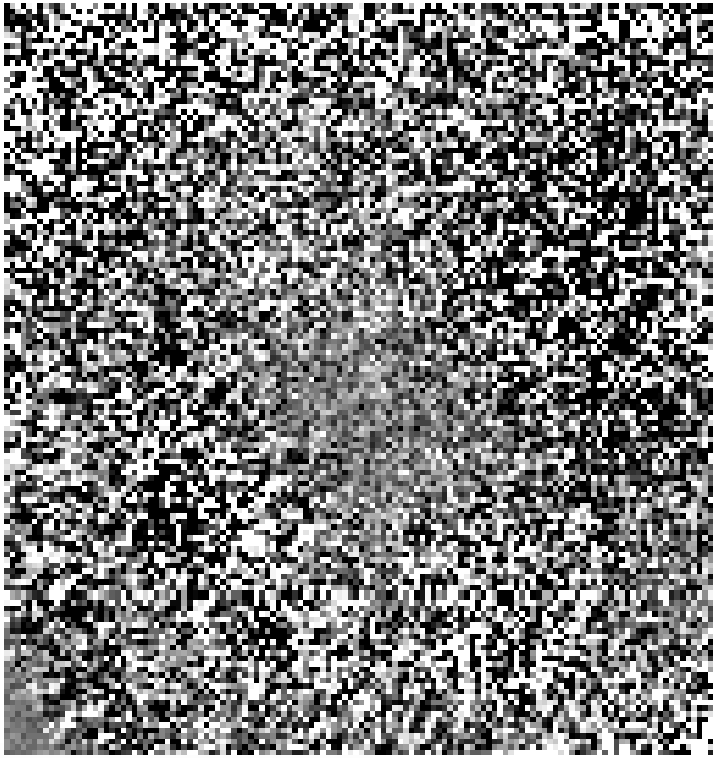
CCD detection of Rb trap

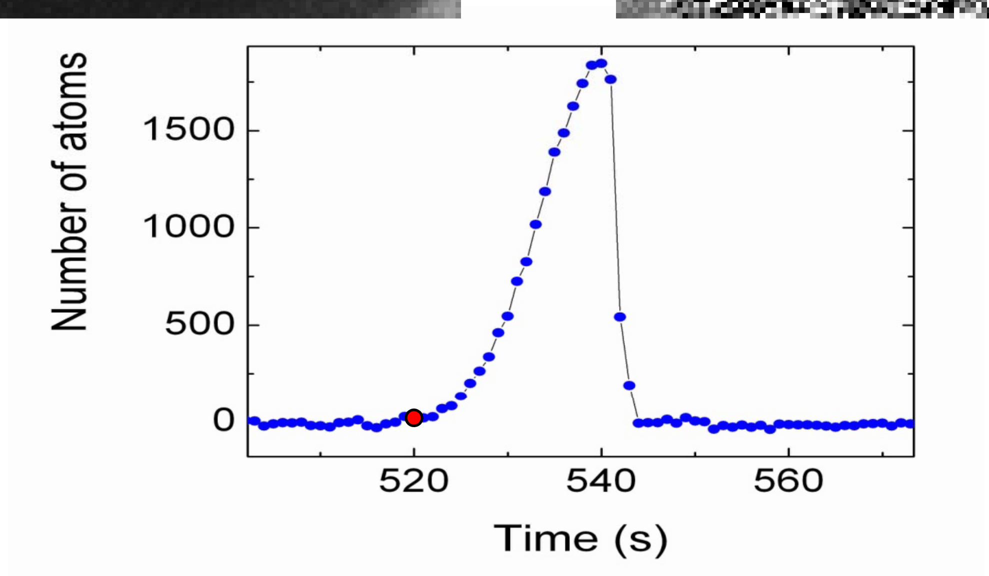


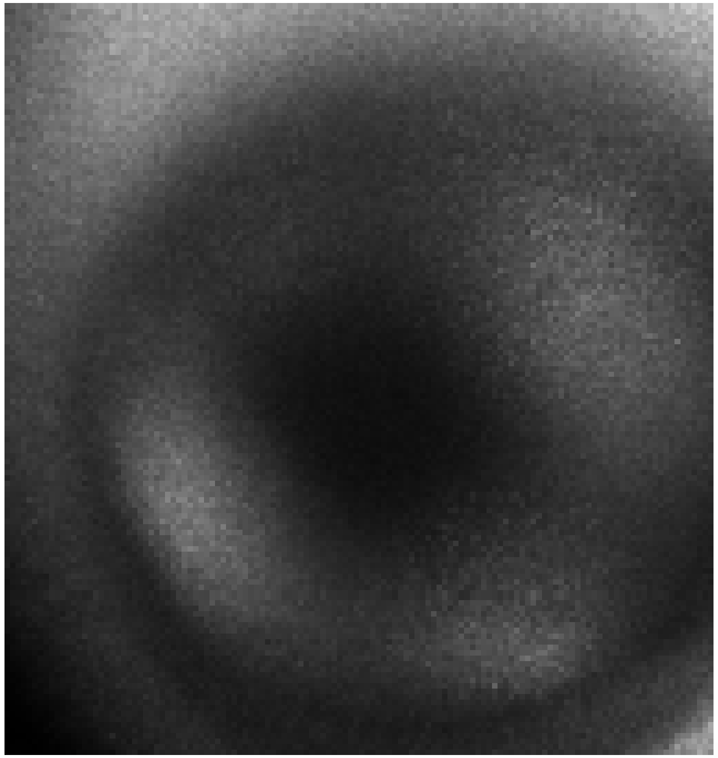


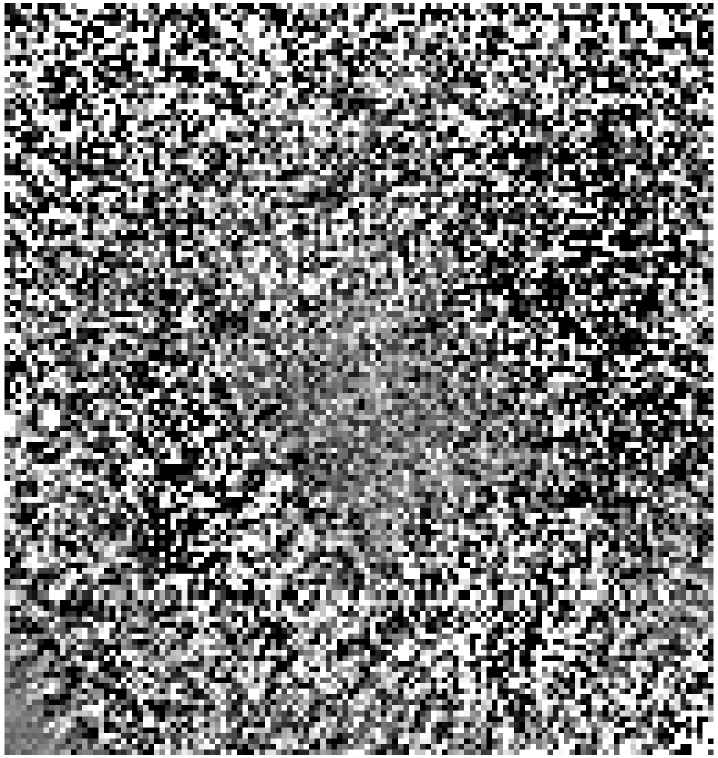


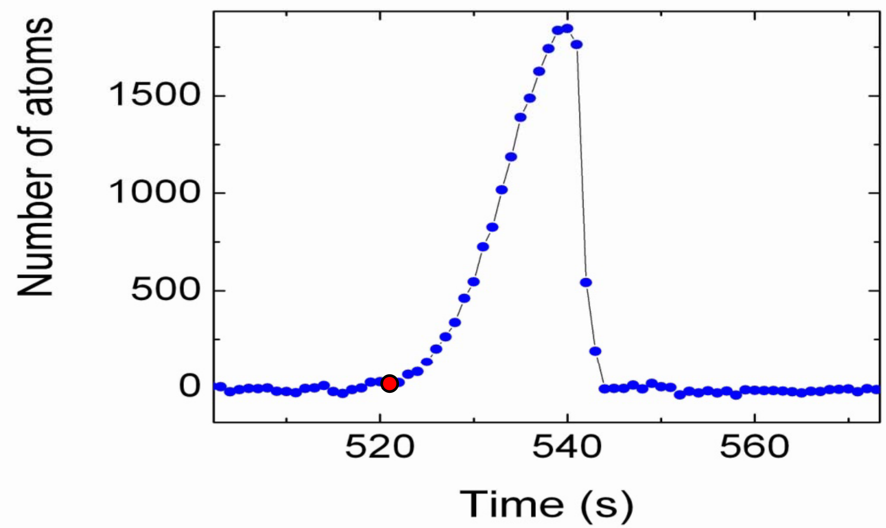


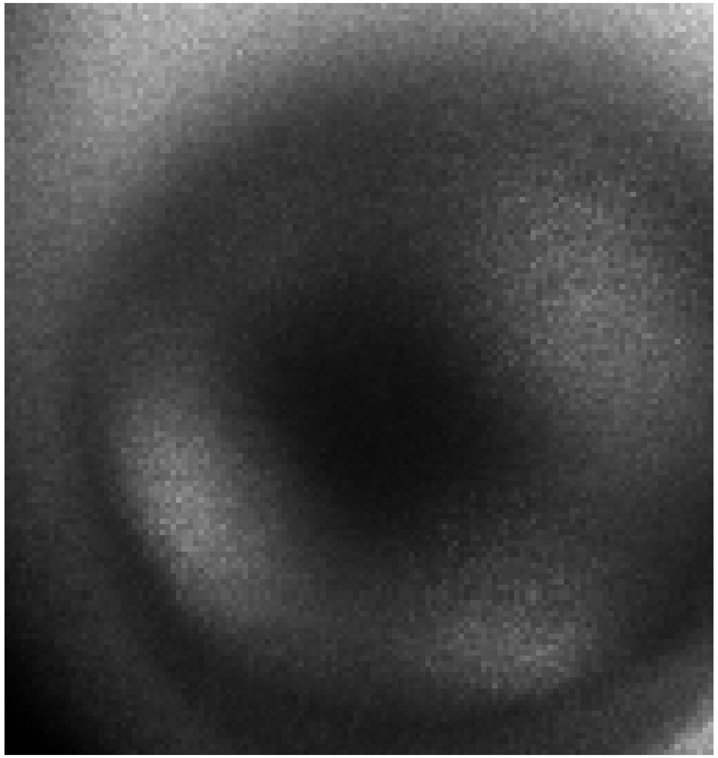


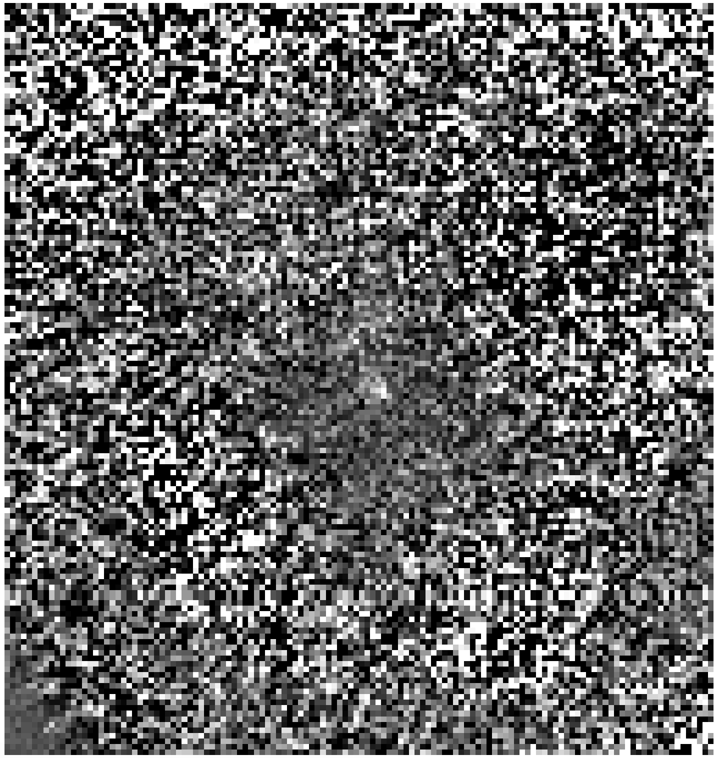

Number of atoms
0
500
1000
1500
520
540
560
Time (s)

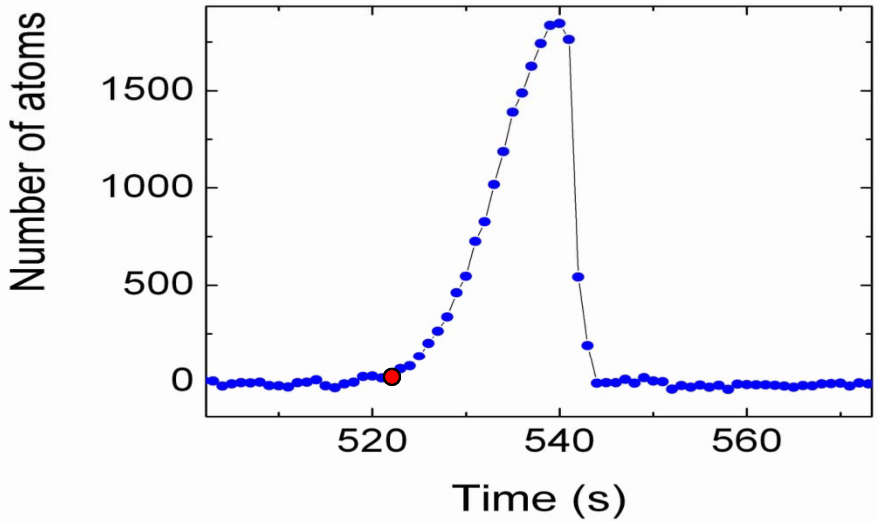


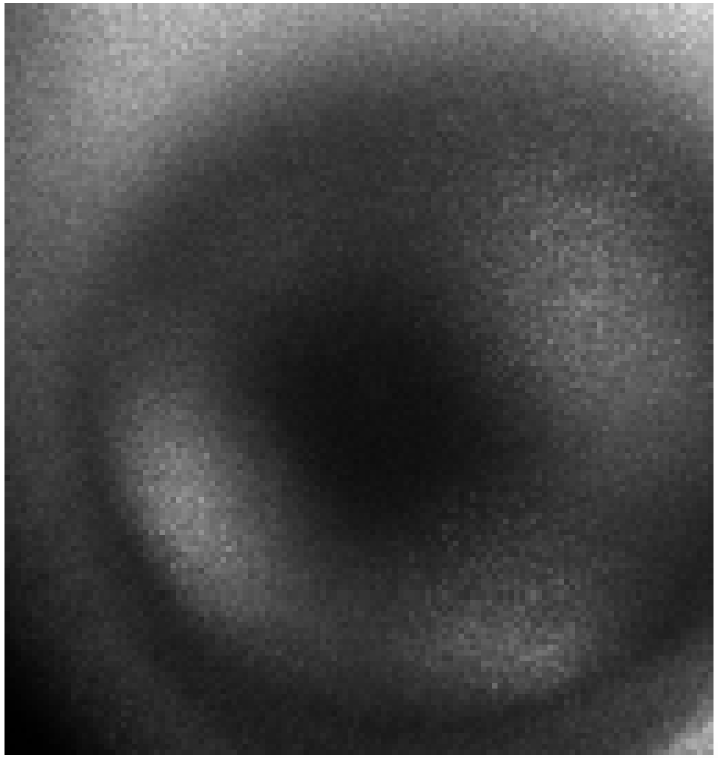


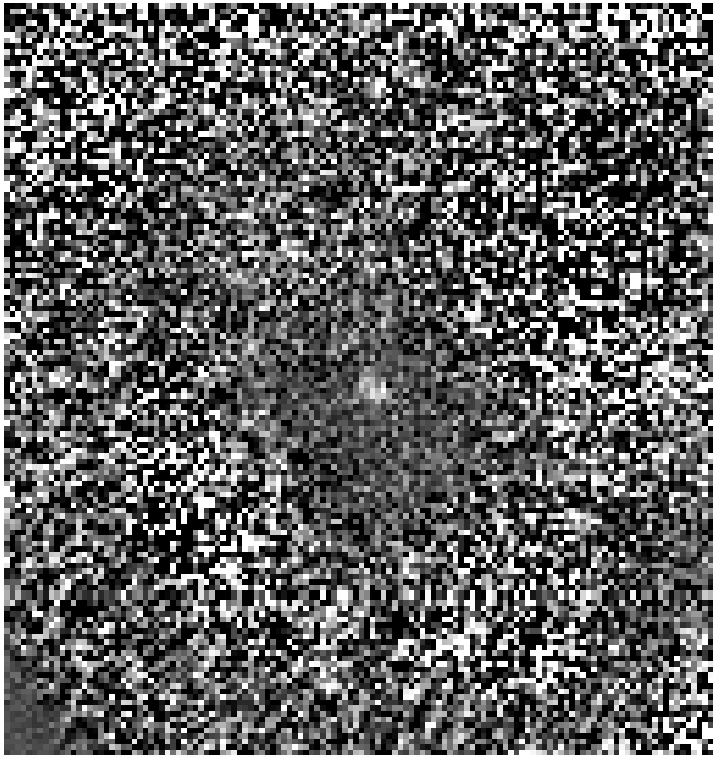

Number of atoms
1500
1000
500
0
520
540
560
Time (s)

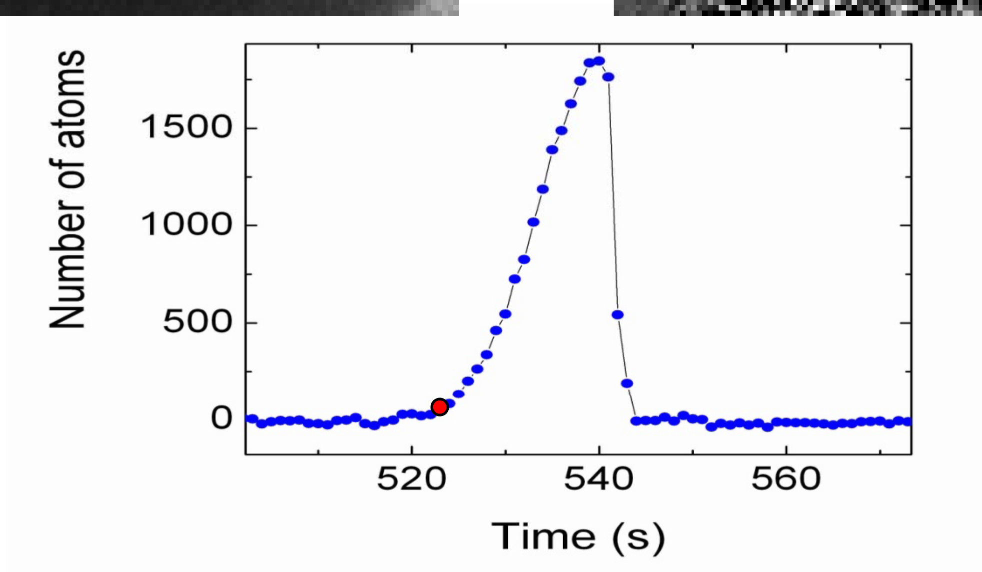


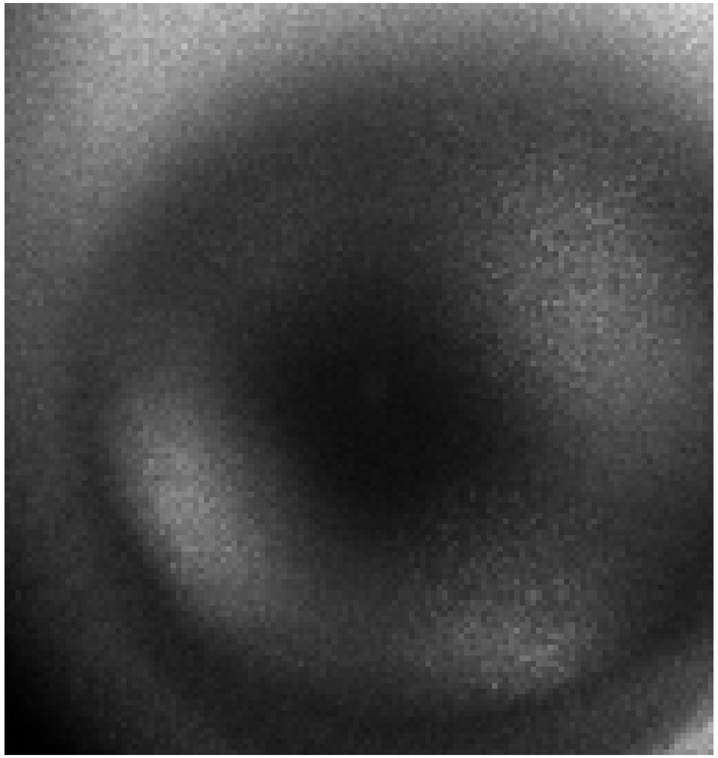


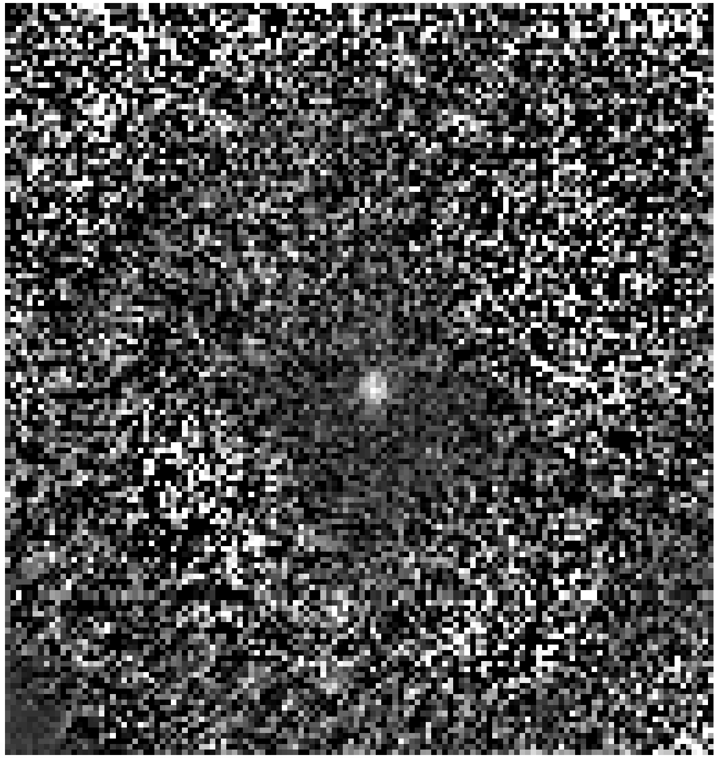

Number of atoms
1500
1000
500
0
520
540
560
Time (s)

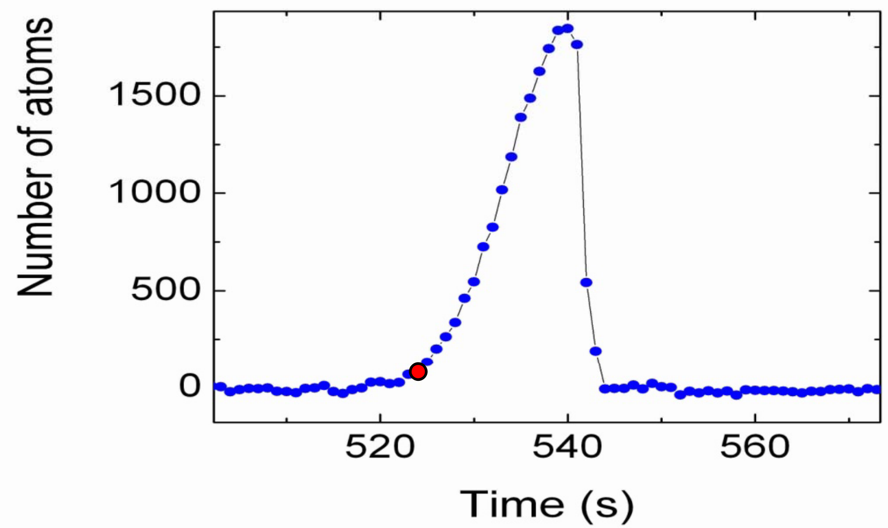




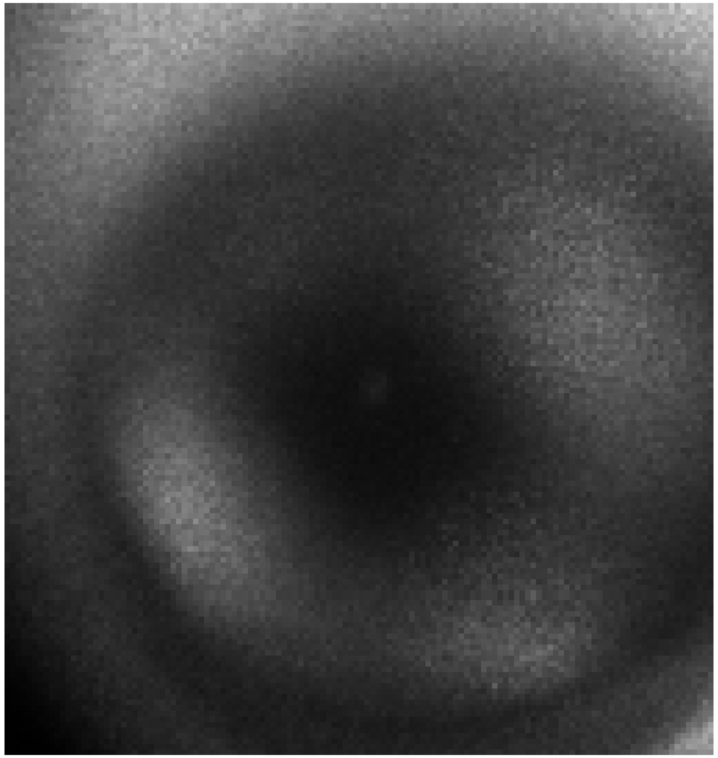

Number of atoms
1500
1000
500
0
520
540
560
Time (s)

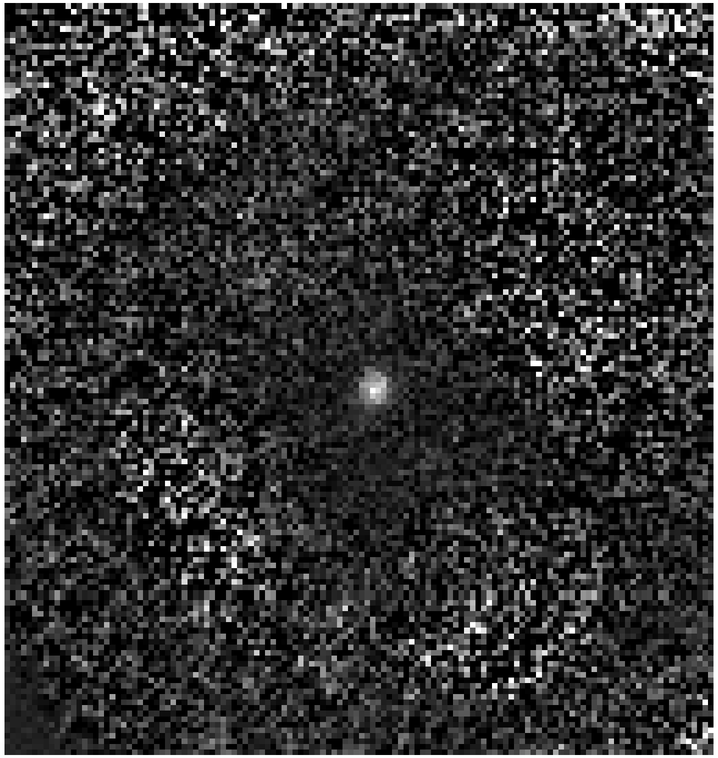


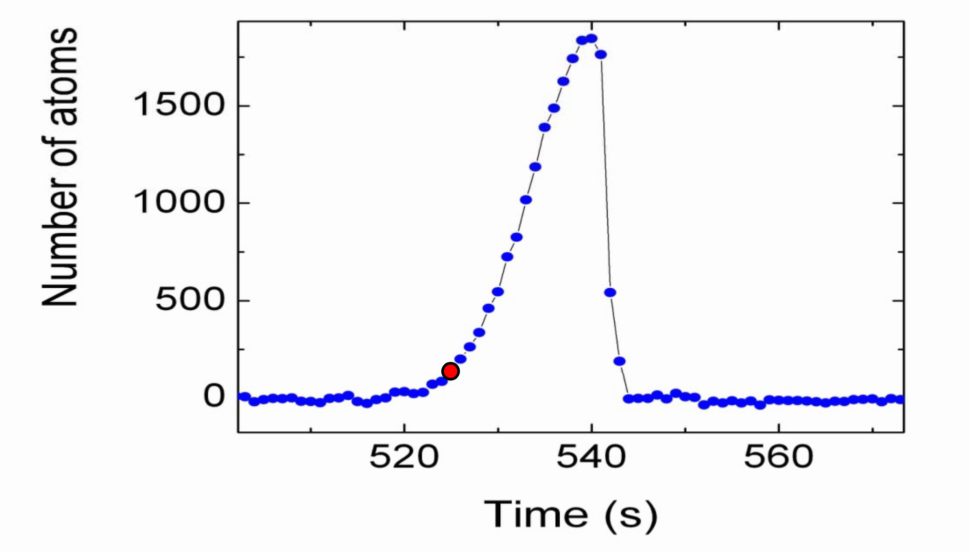




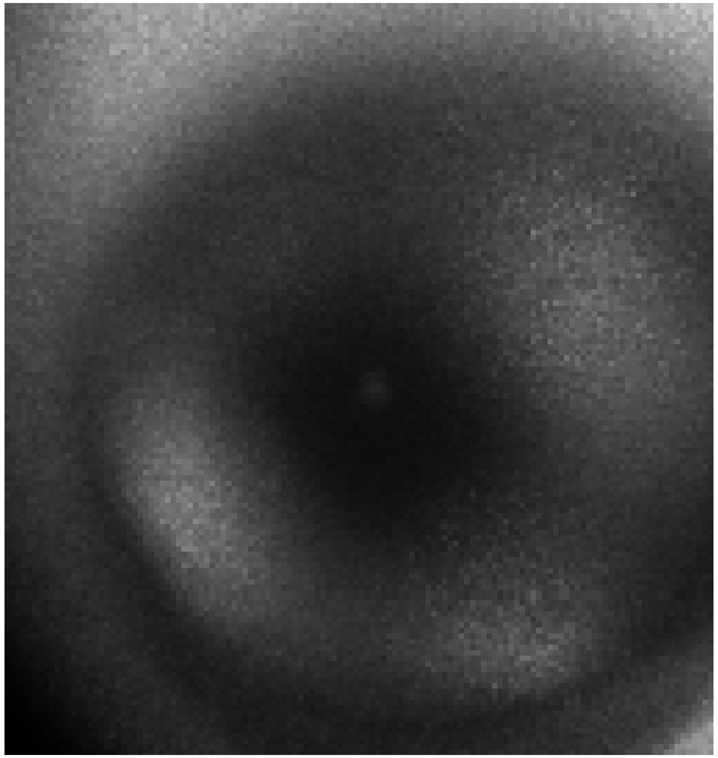
Number of atoms
1500
1000
500
0
520
540
560
Time (s)

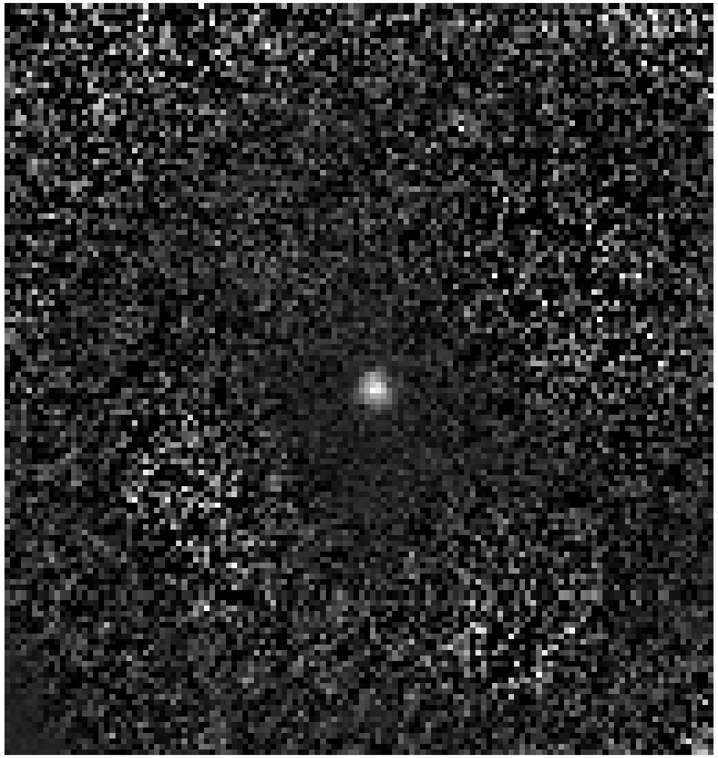


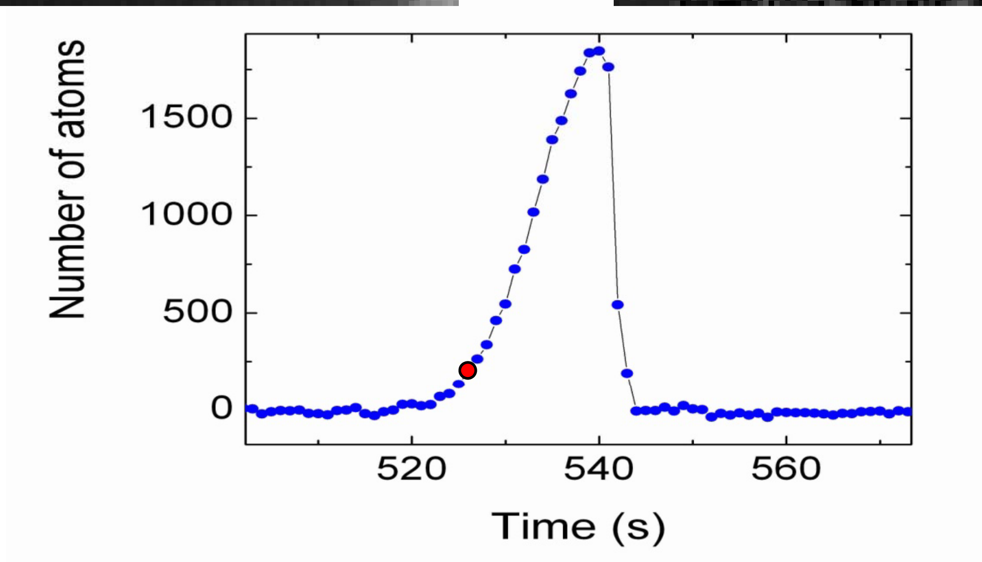




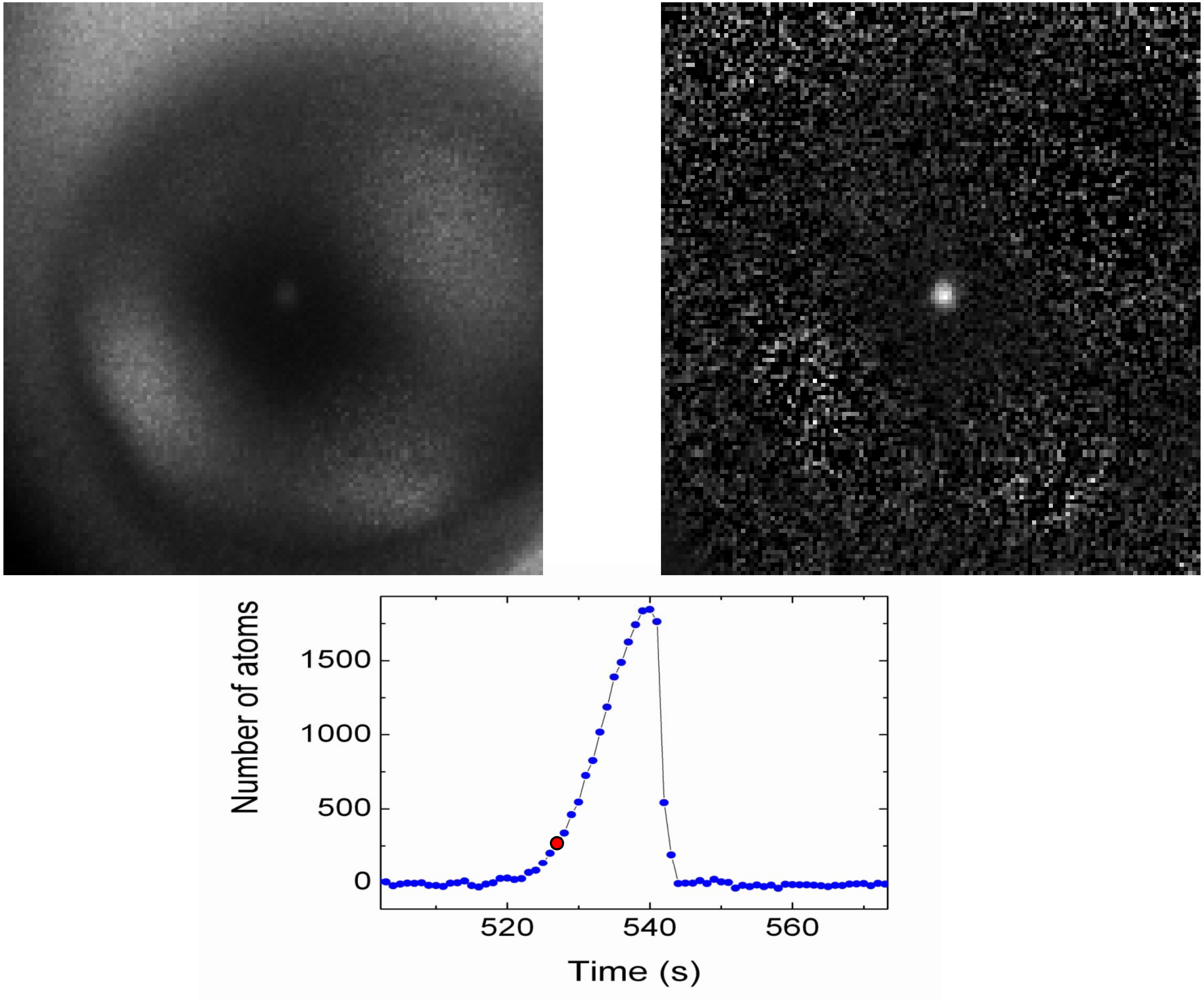
Number of atoms
1500
1000
500
0
520
540
560
Time (s)

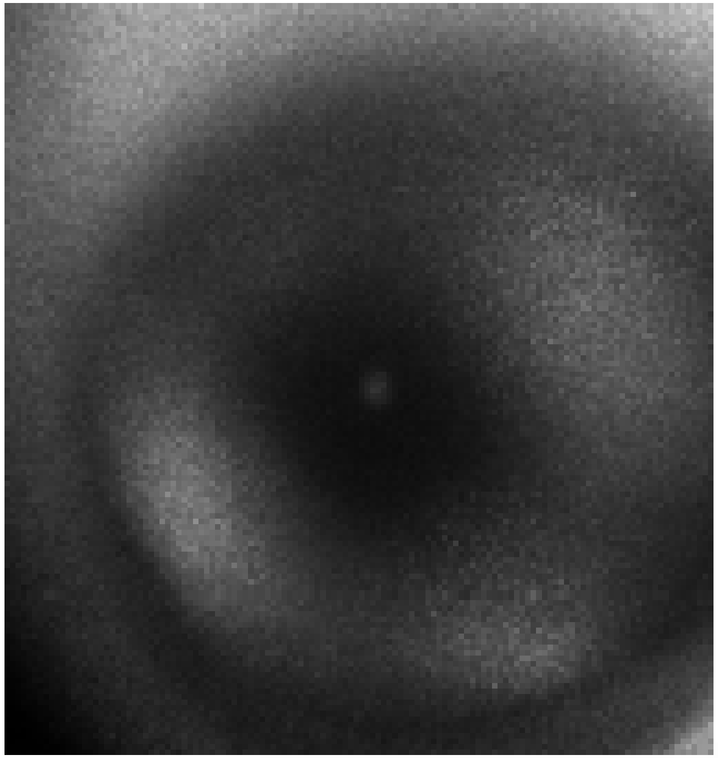


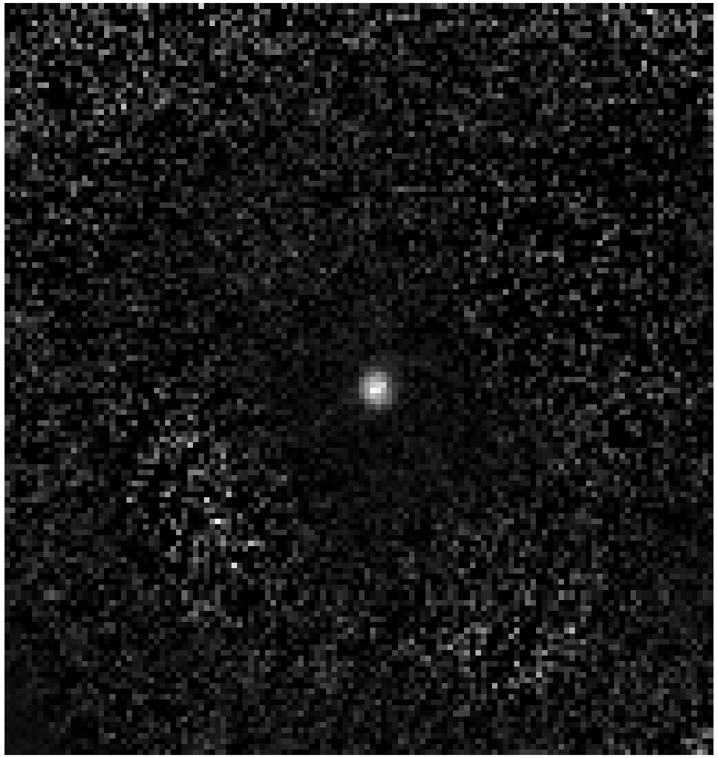


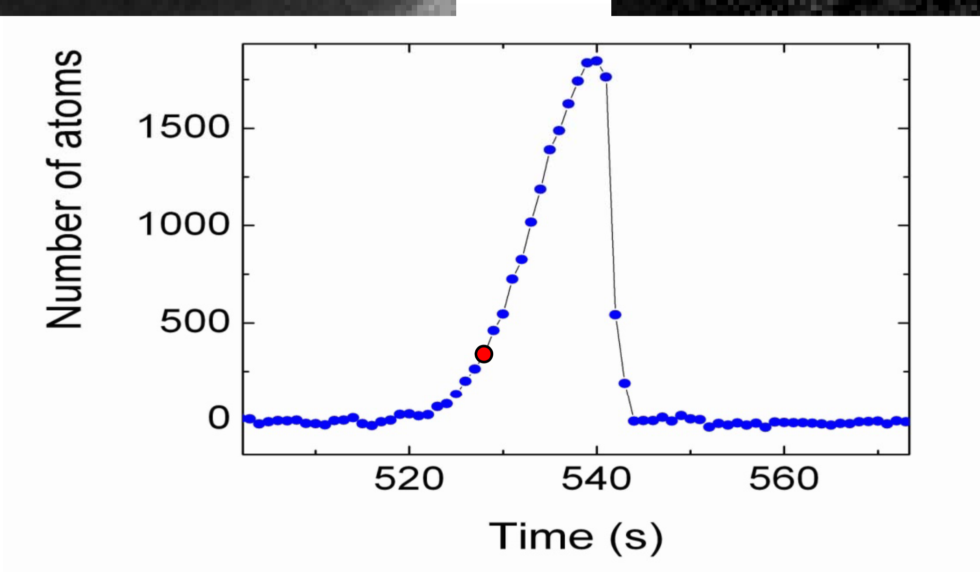


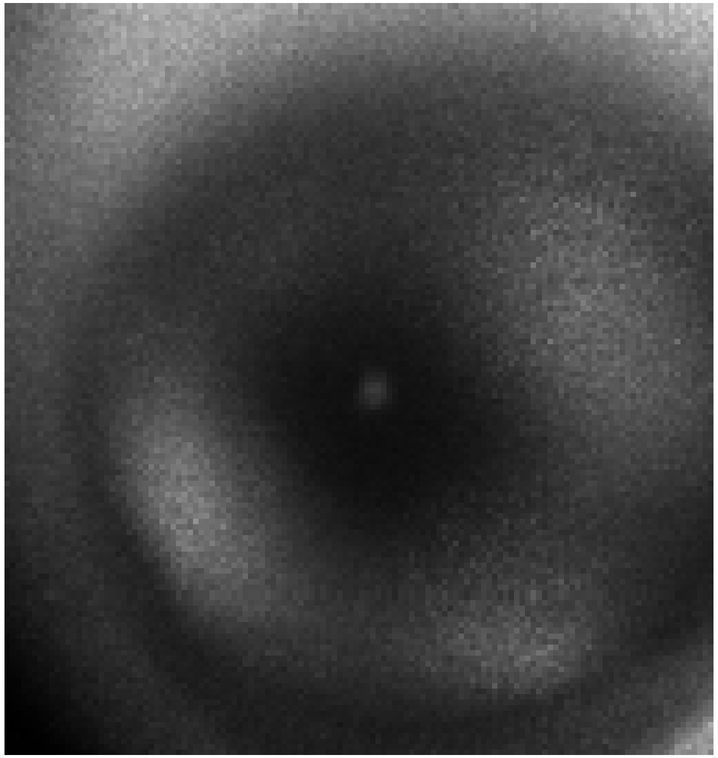
Number of atoms
1500
1000
500
0
520
540
560
Time (s)

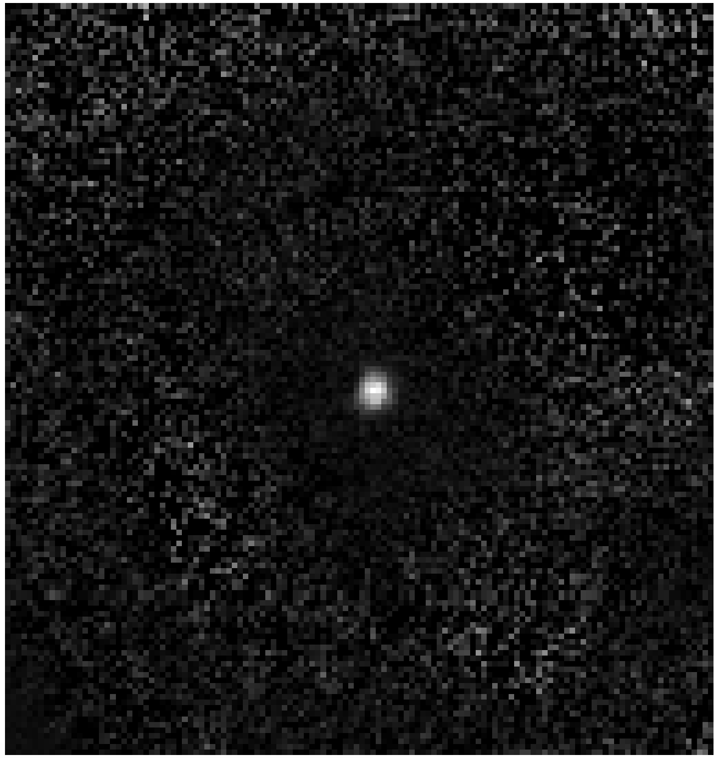

Number of atoms
1500
1000
500
0
520
540
560
Time (s)

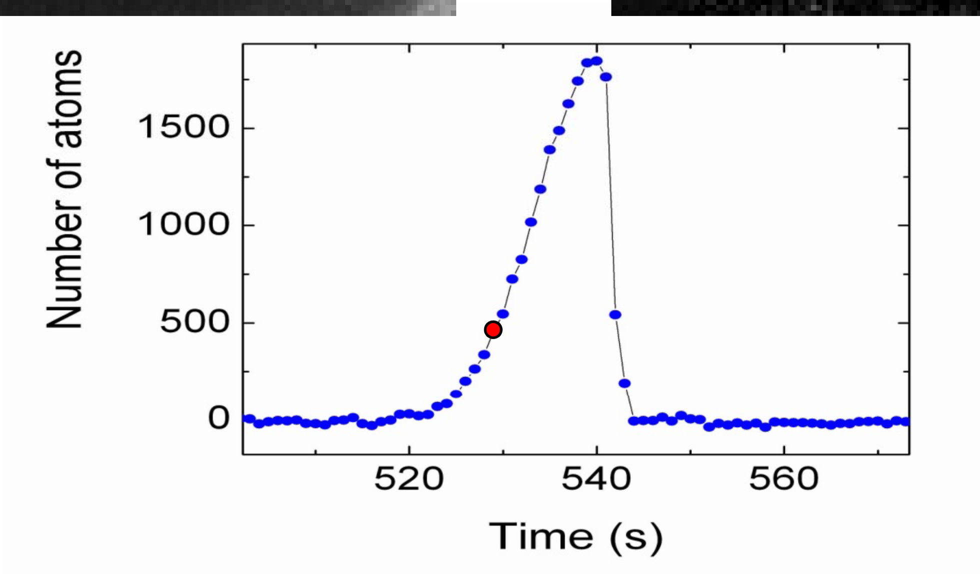


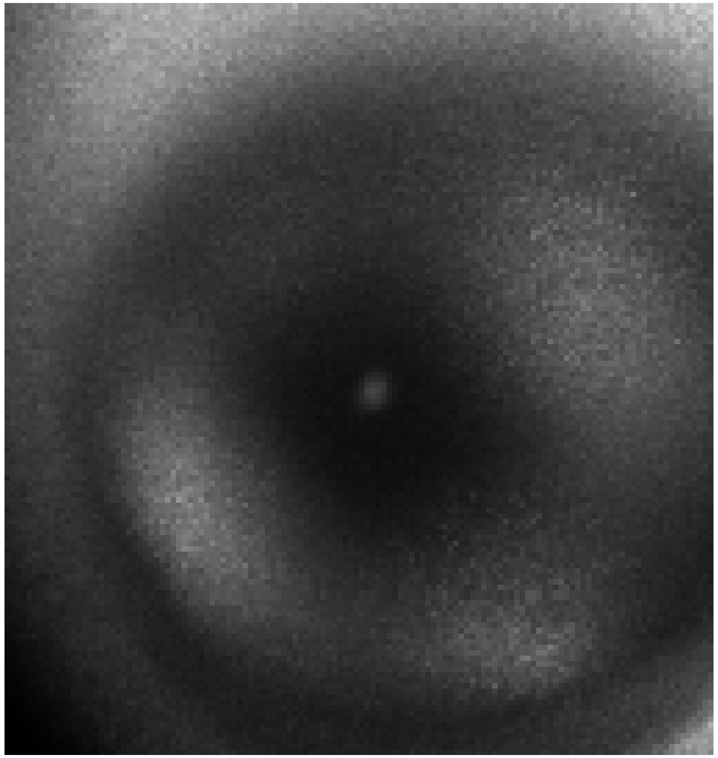


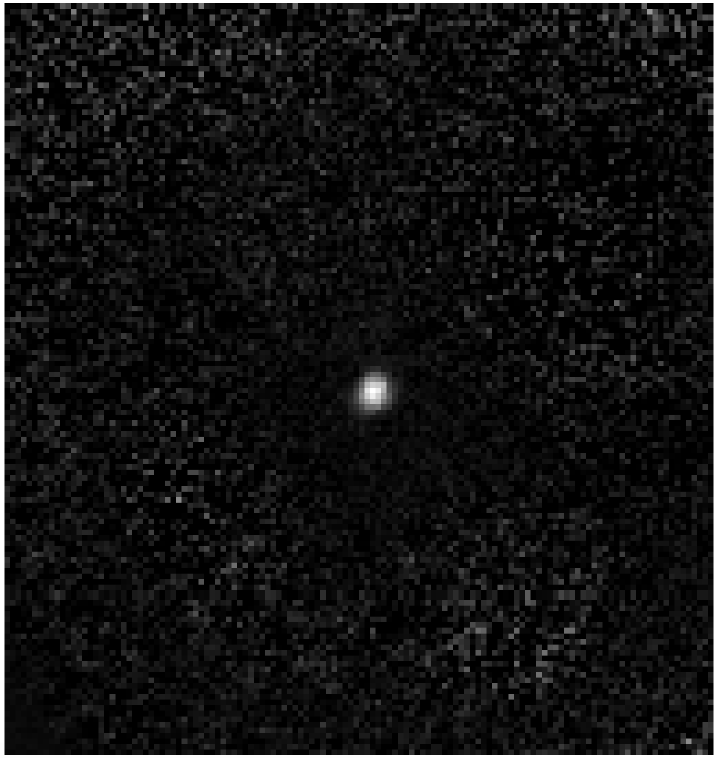

Number of atoms
1500
1000
500
0
520
540
560
Time (s)

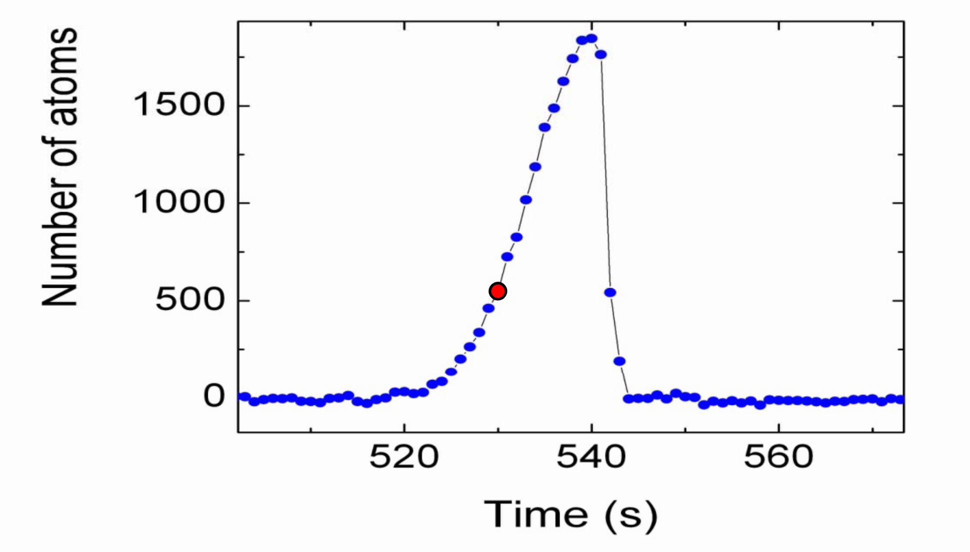




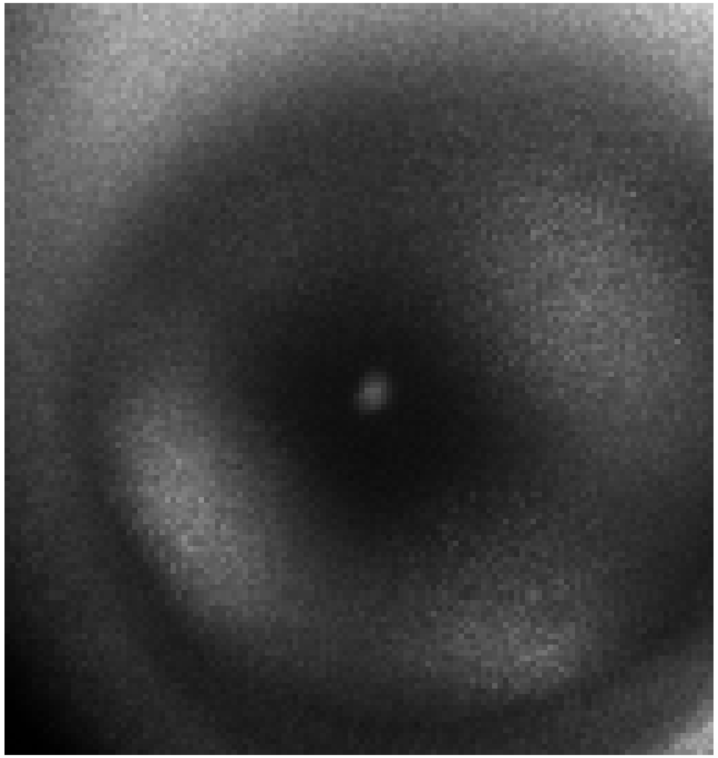

Number of atoms
0
500
1000
1500
520
540
560
Time (s)

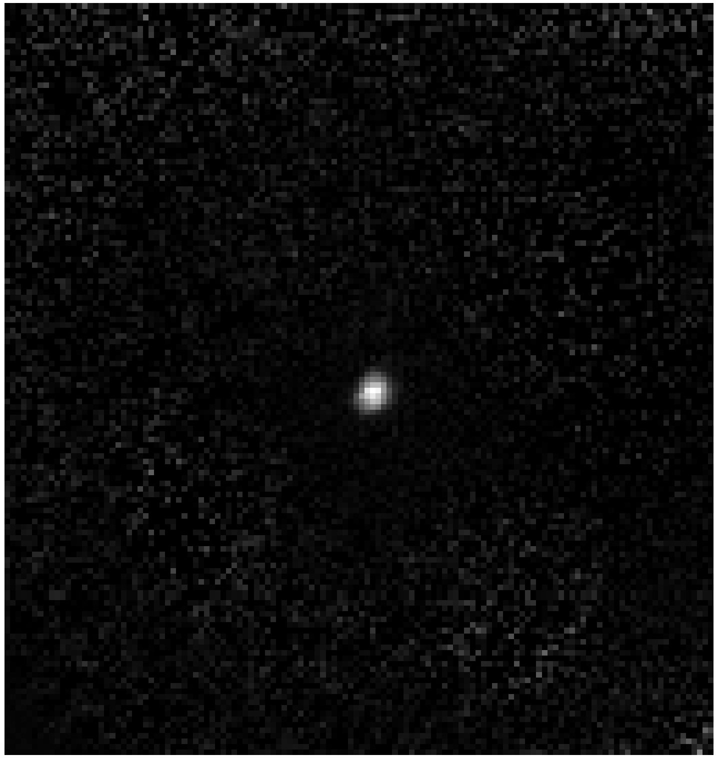


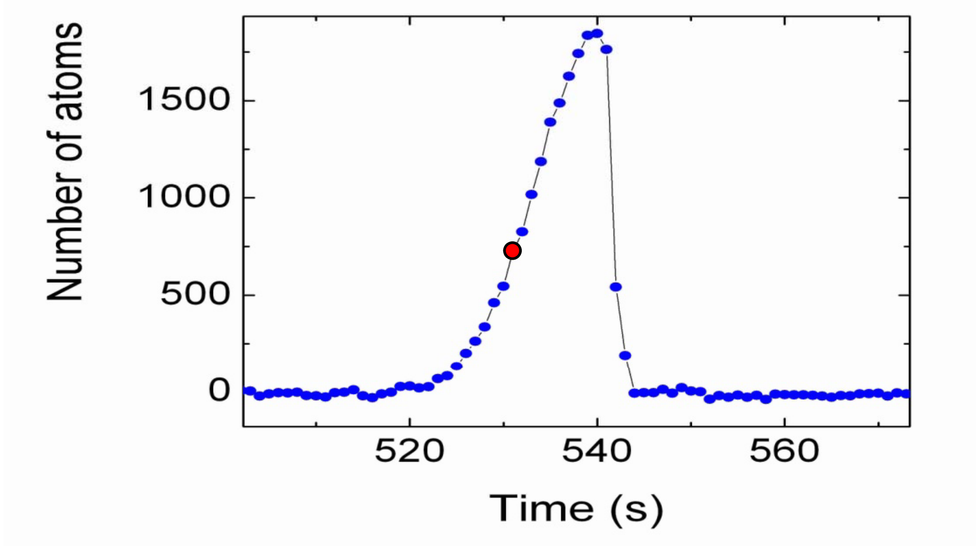




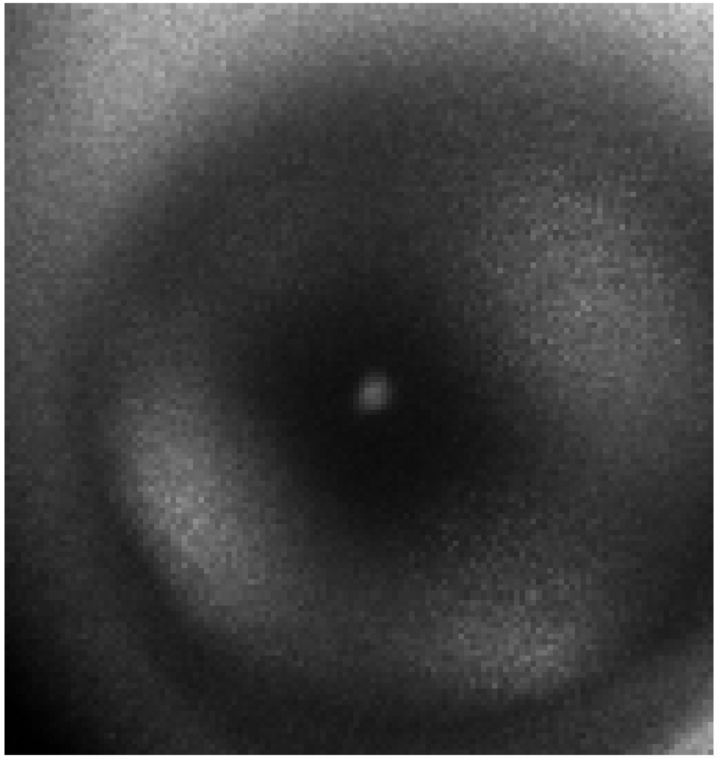
Number of atoms
1500
1000
500
0
520
540
560
Time (s)

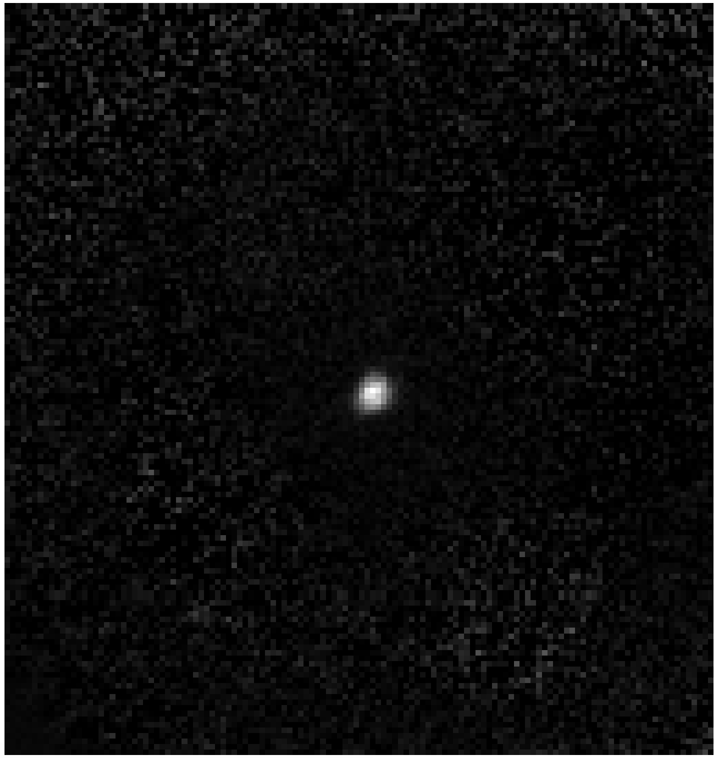


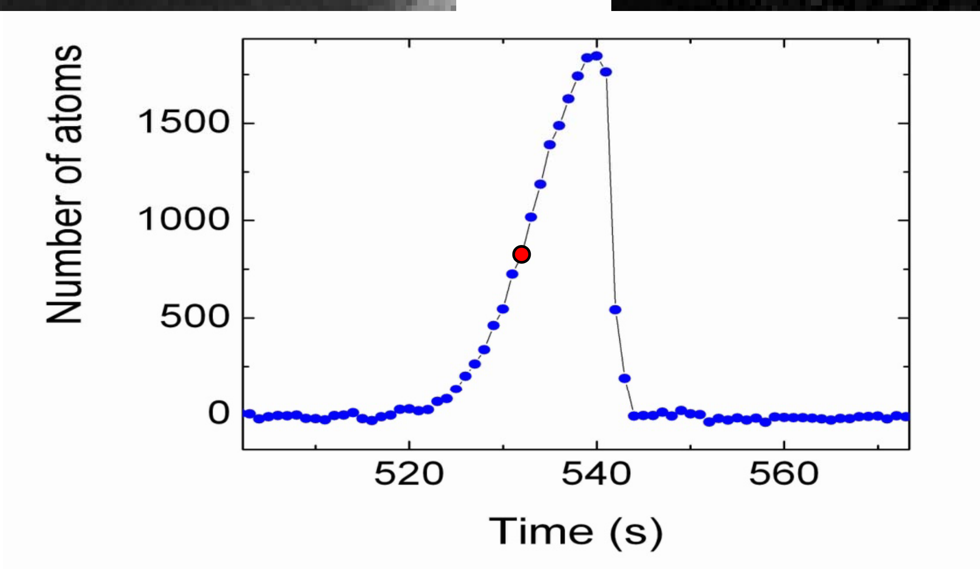


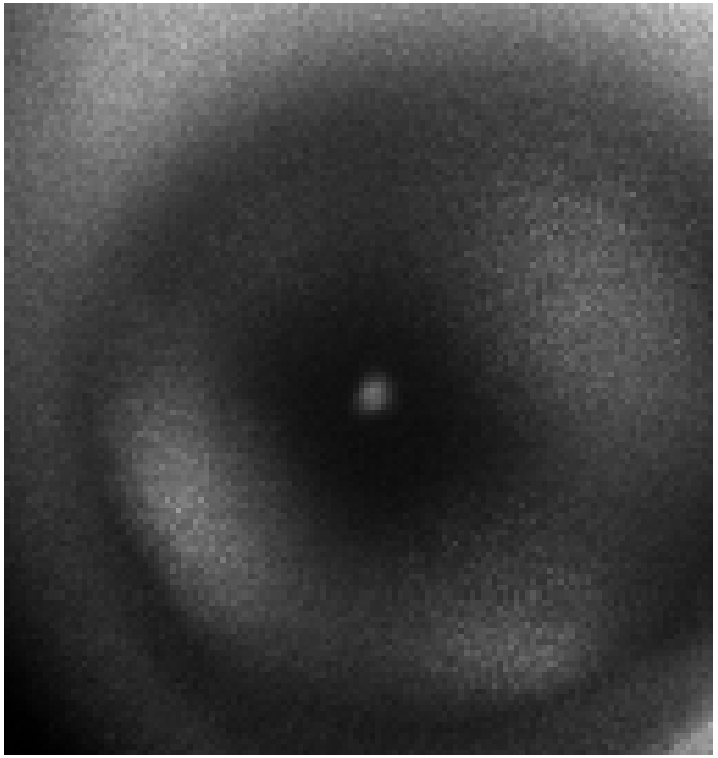


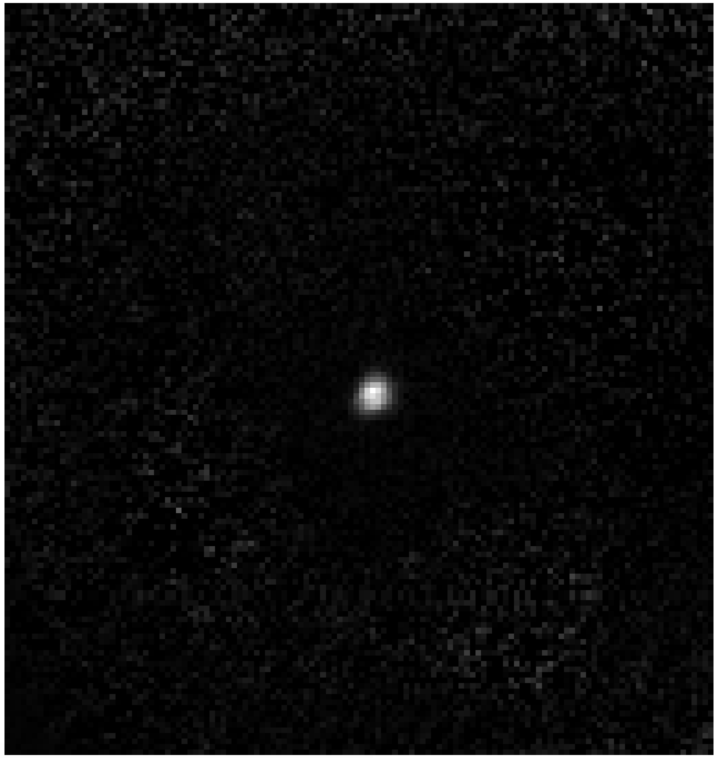
Number of atoms
1500
1000
500
0
520
540
560
Time (s)

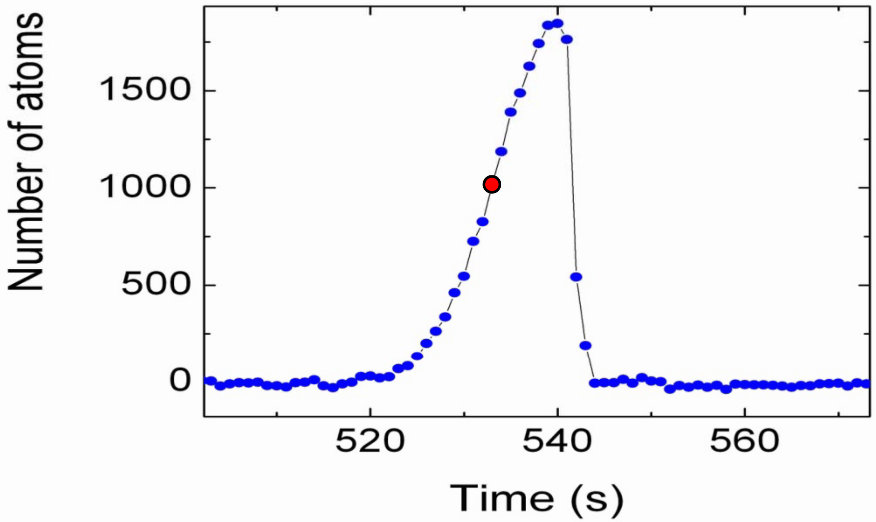


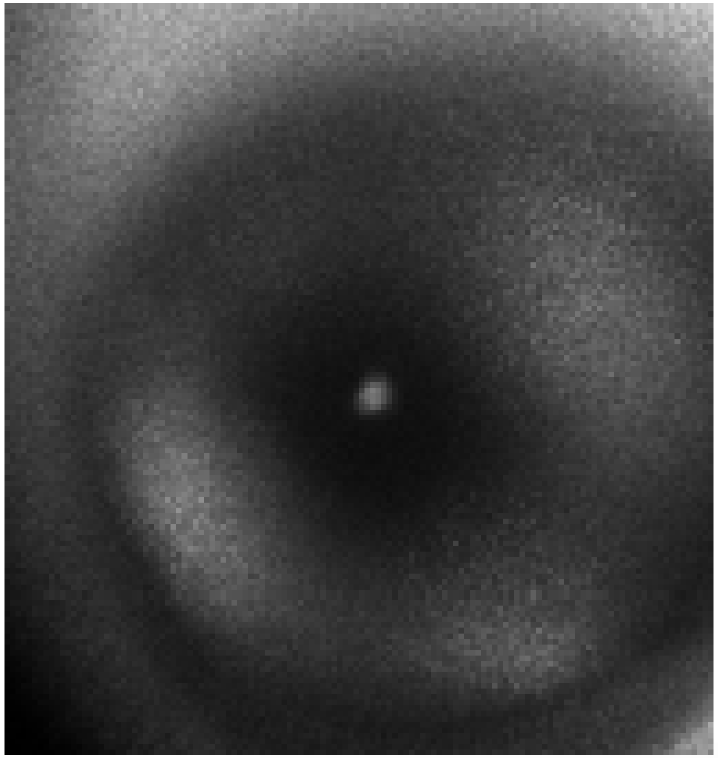


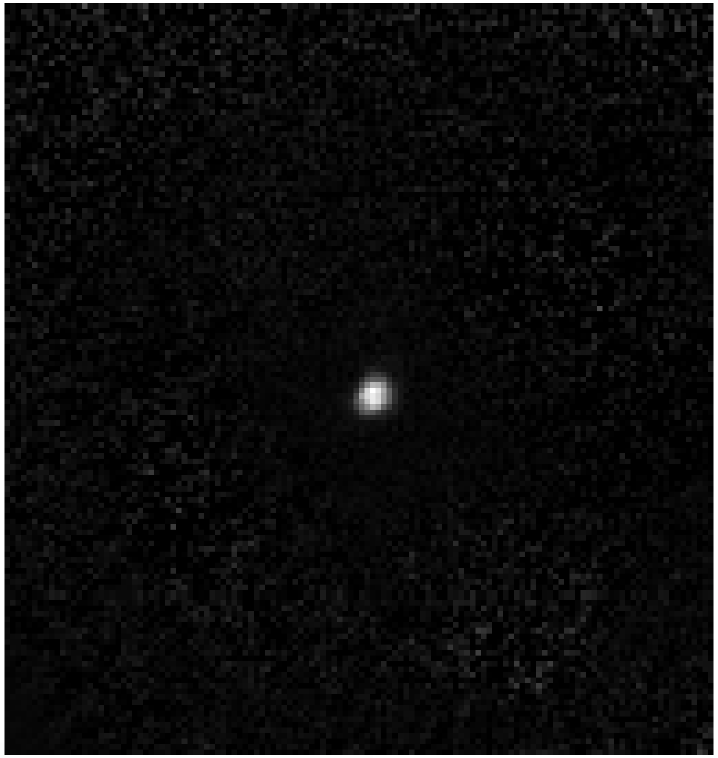

Number of atoms
1500
1000
500
0
520
540
560
Time (s)

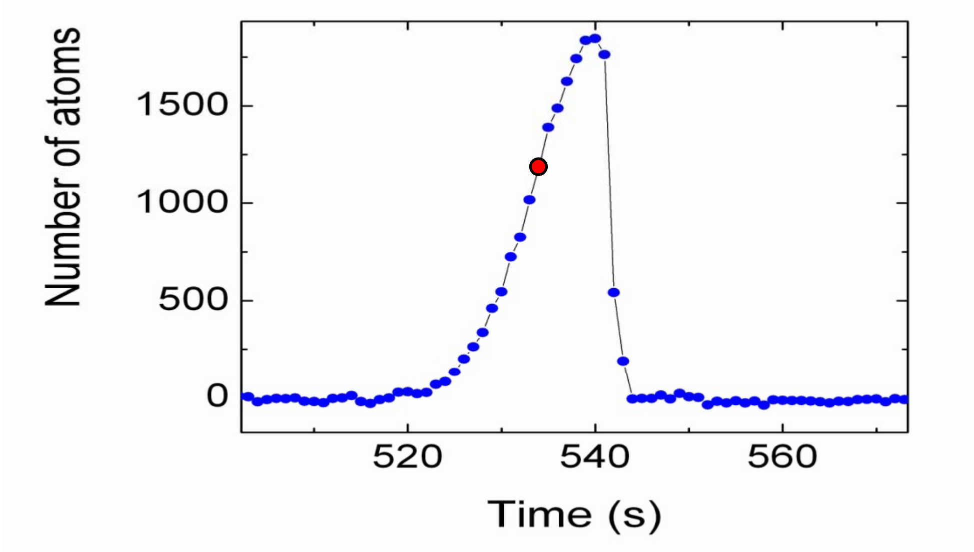


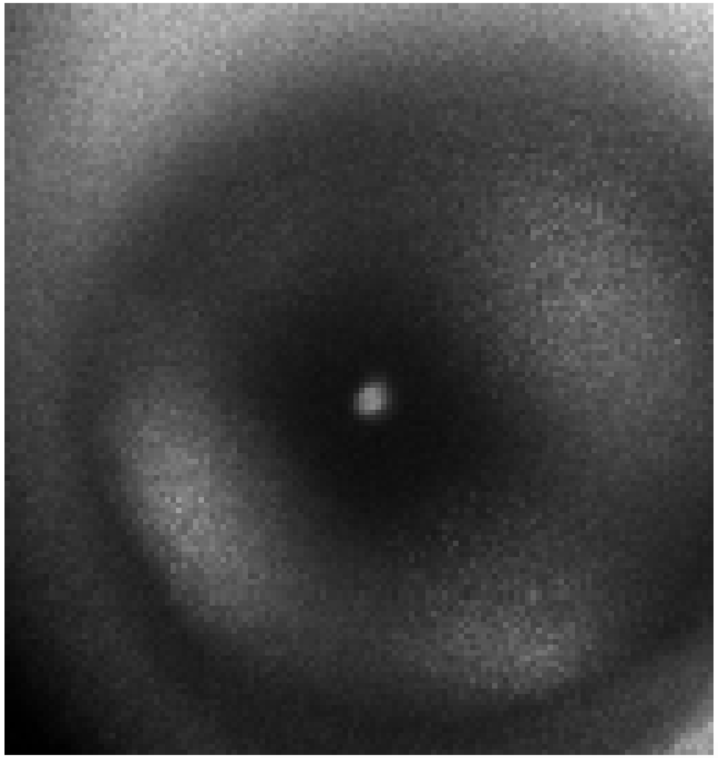


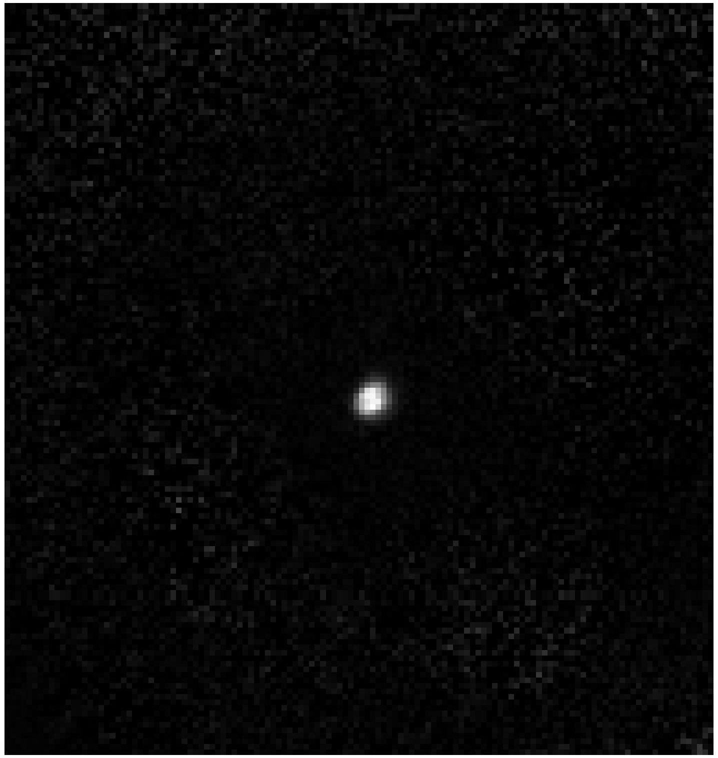

Number of atoms
1500
1000
500
0
520
540
560
Time (s)

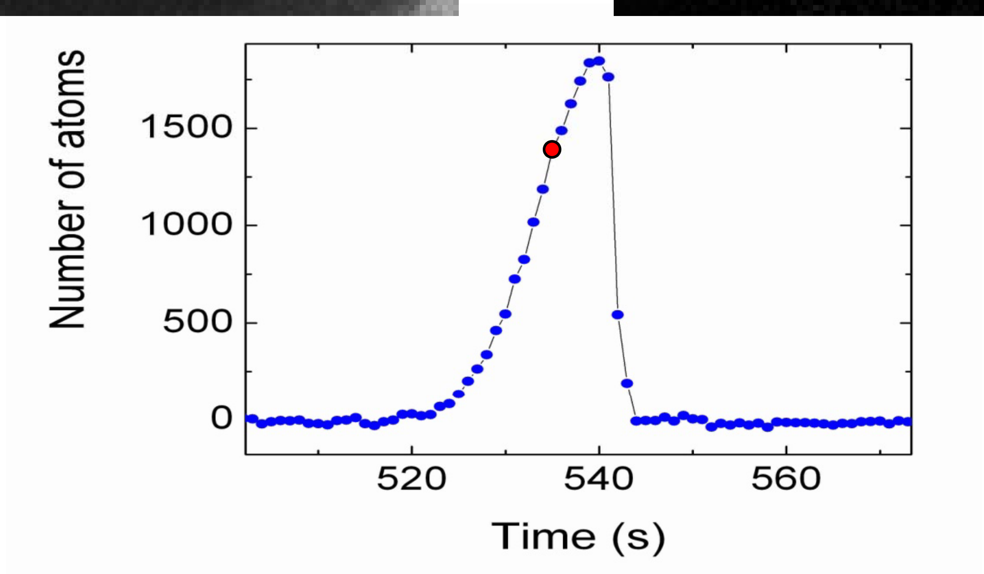




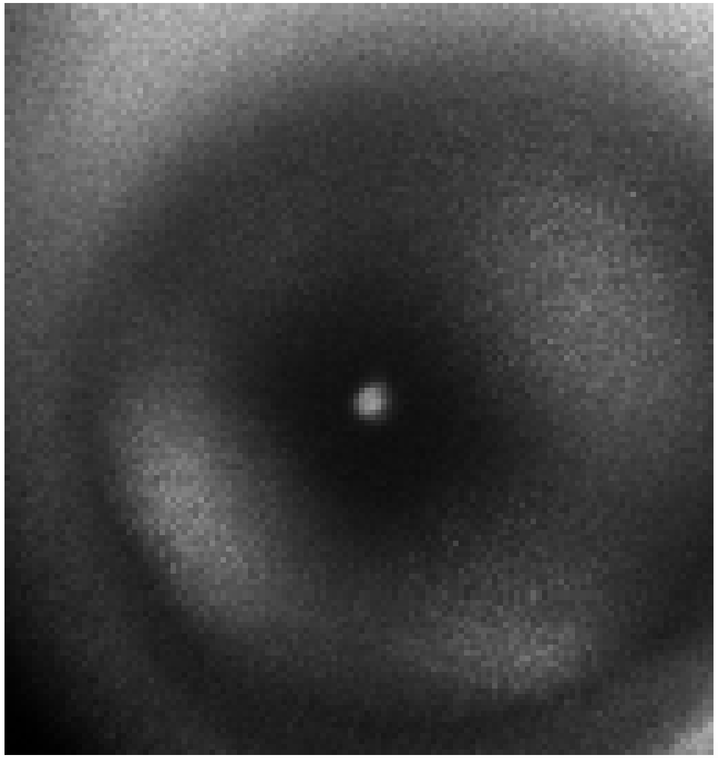

Number of atoms
0
500
1000
1500
520
540
560
Time (s)

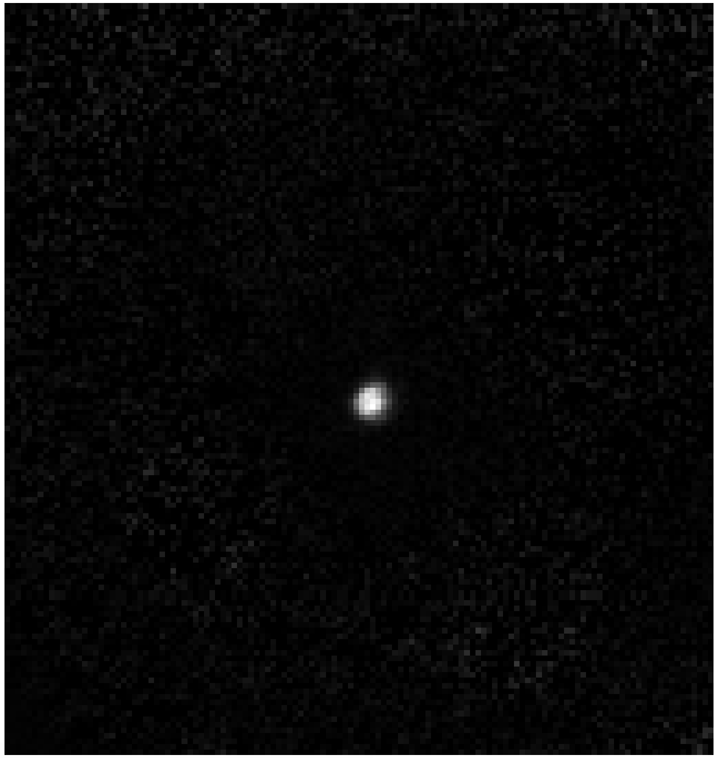


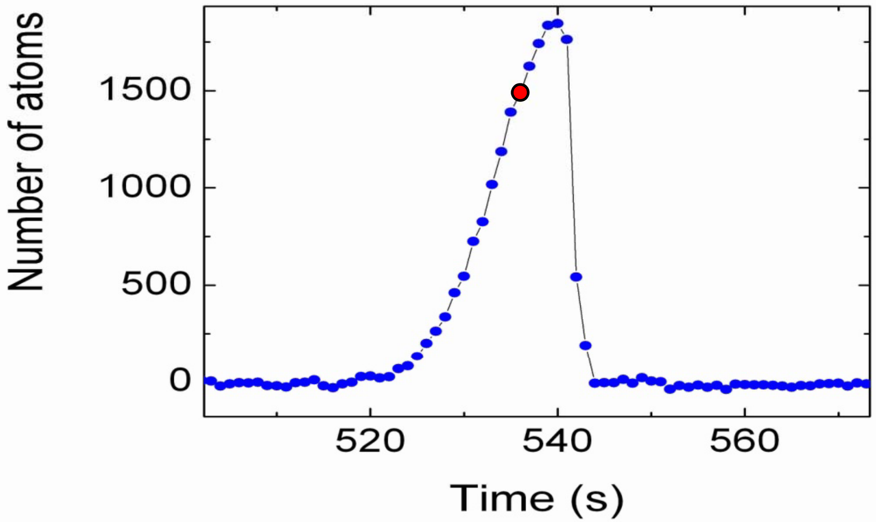




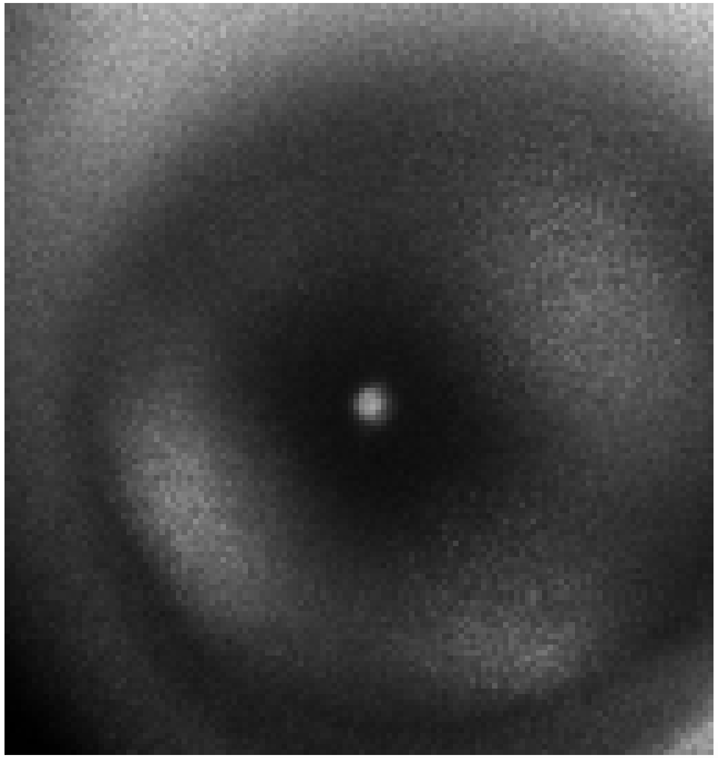
Number of atoms
1500
1000
500
0
520
540
560
Time (s)

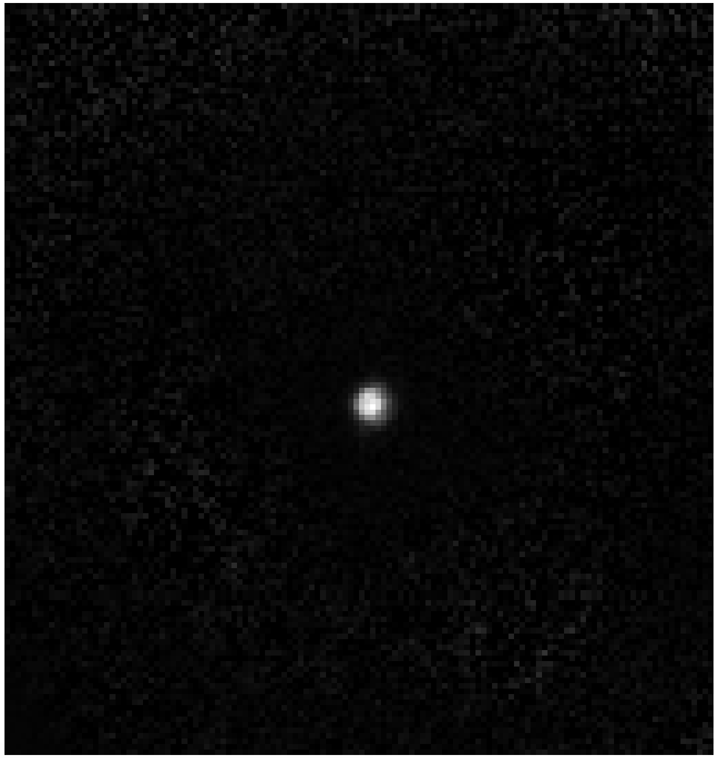


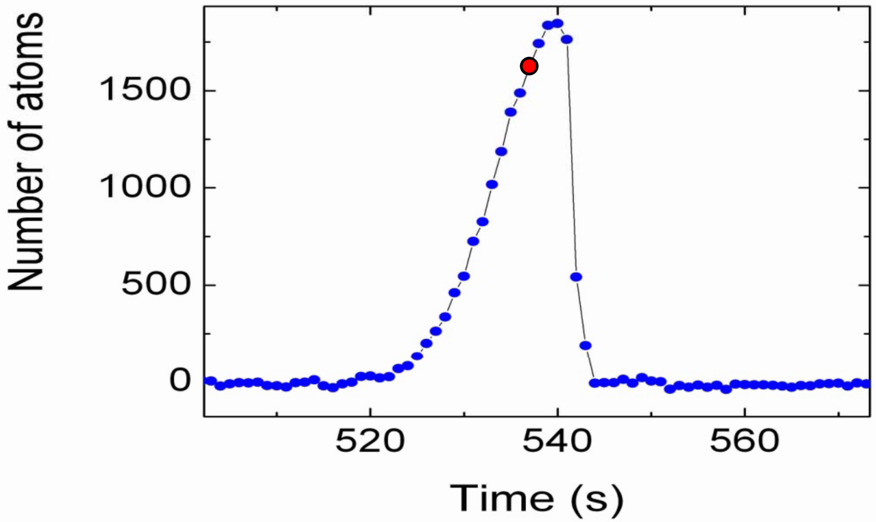




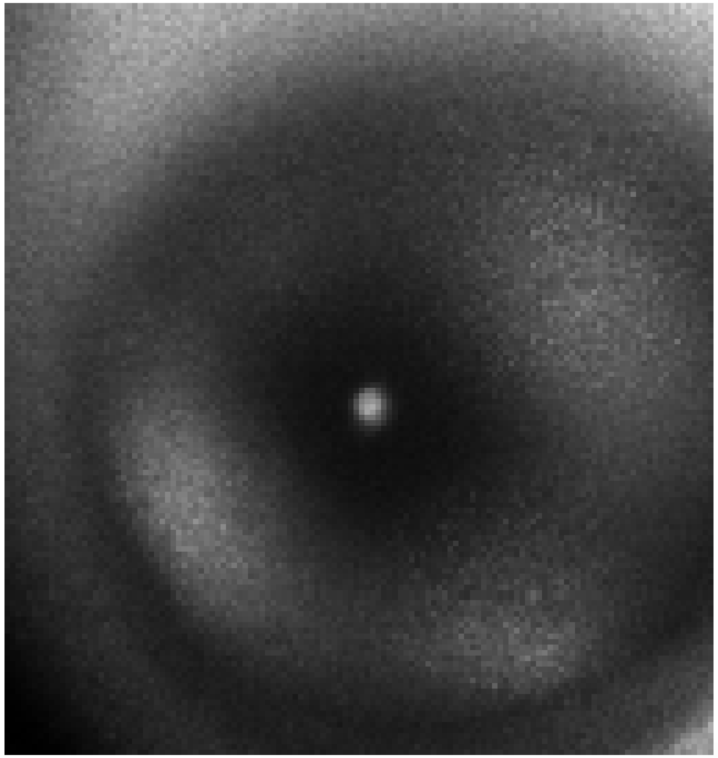
Number of atoms
0
500
1000
1500
520
540
560
Time (s)

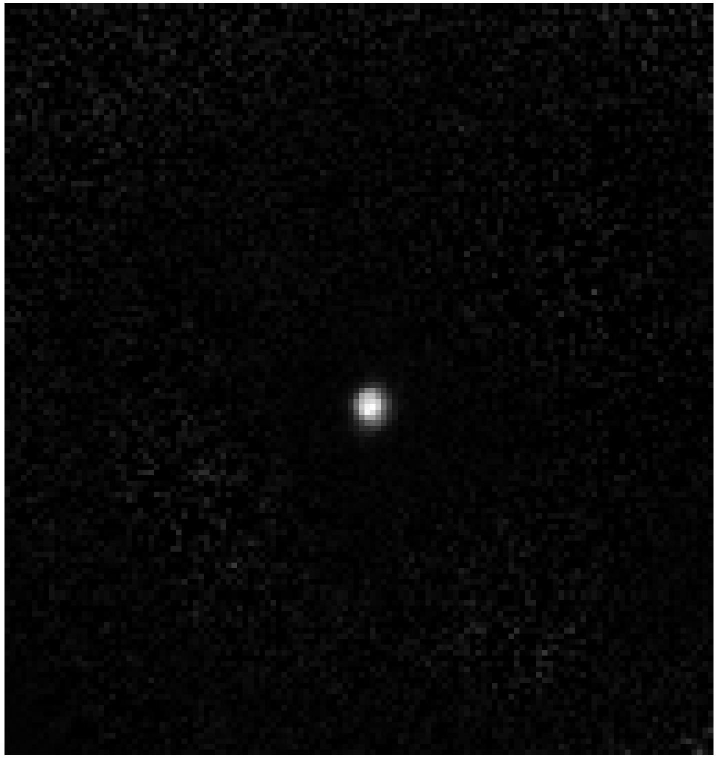


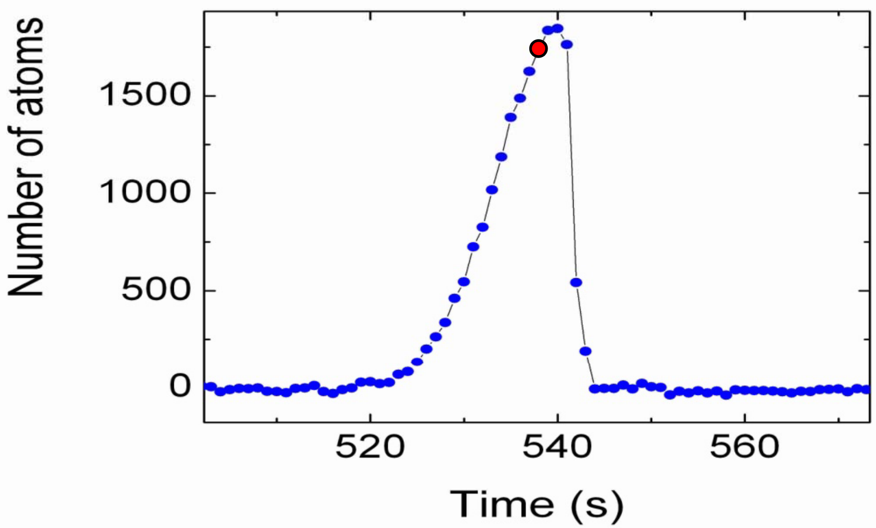




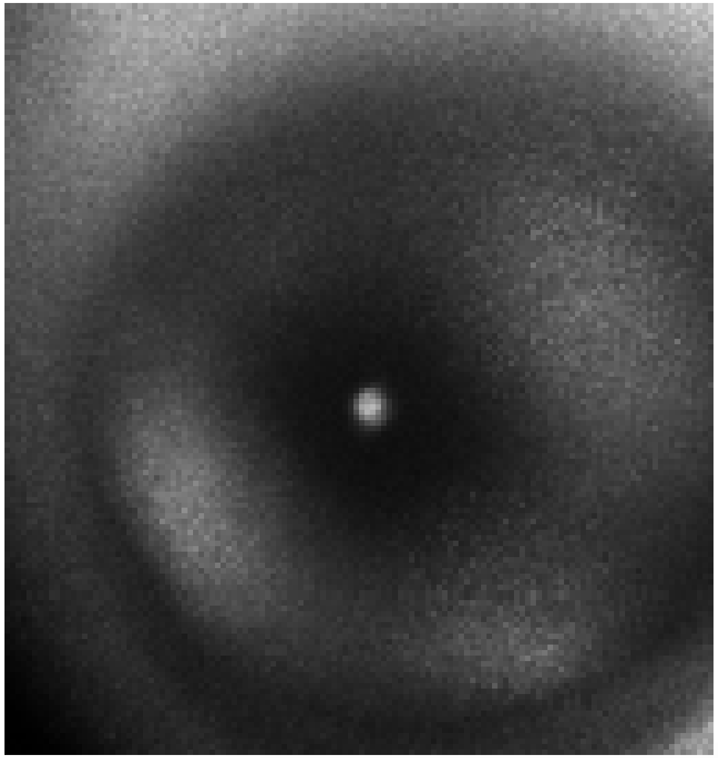
Number of atoms
1500
1000
500
0
520
540
560
Time (s)

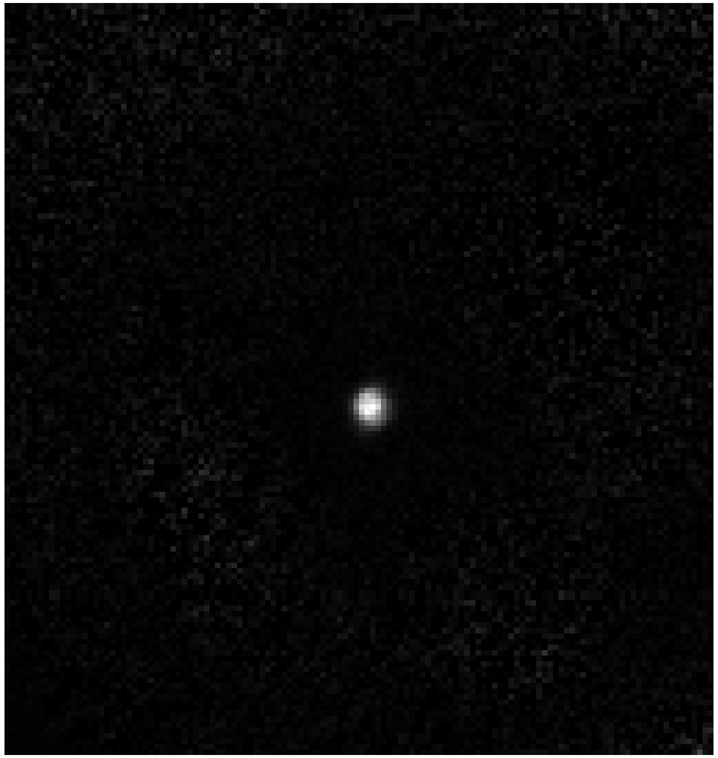


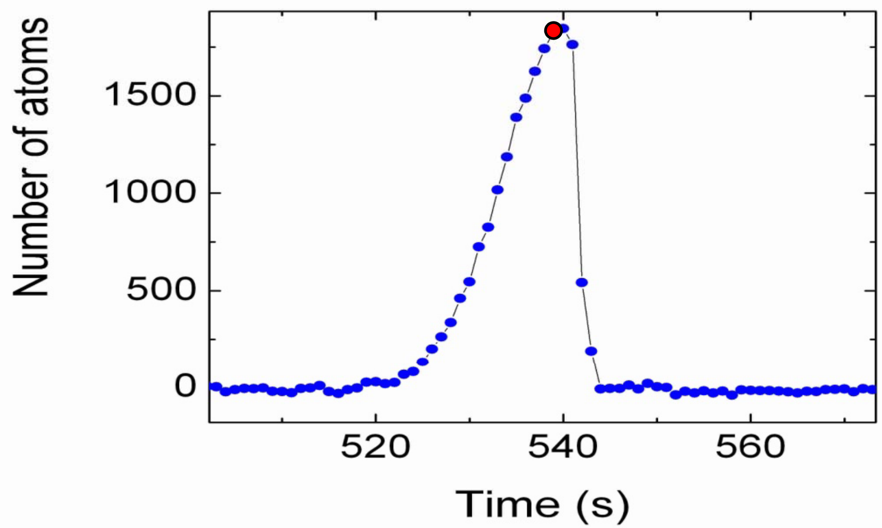


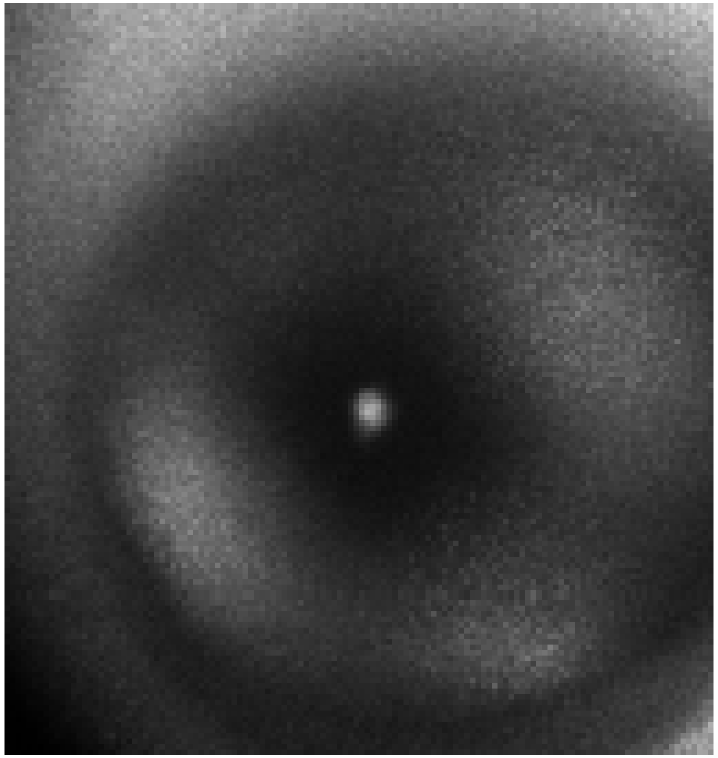


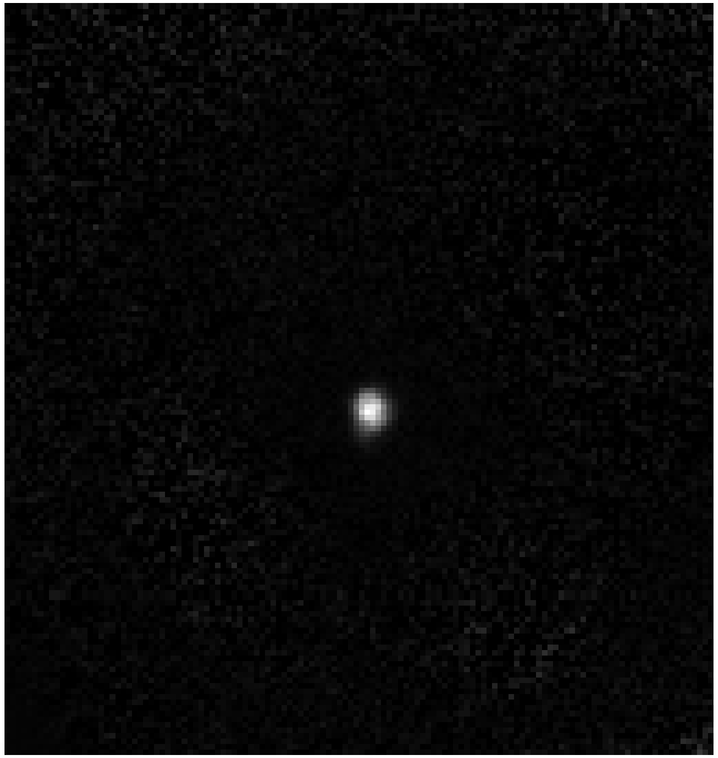
Number of atoms
1500
1000
500
0
520
540
560
Time (s)

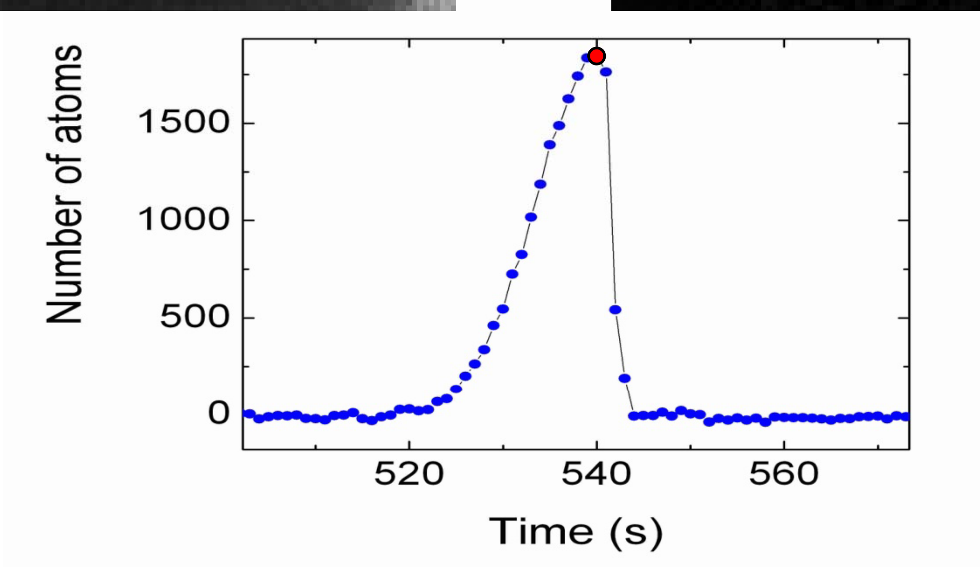


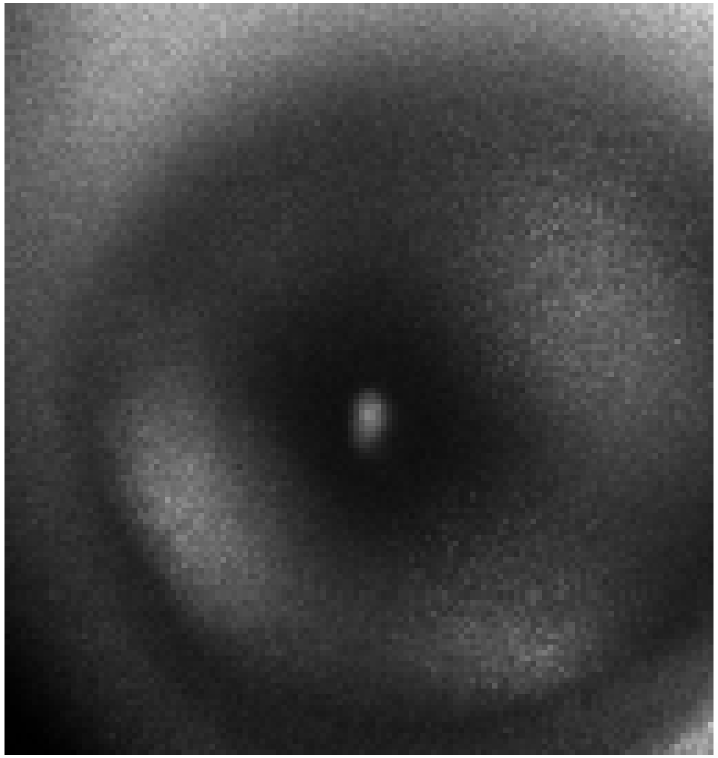


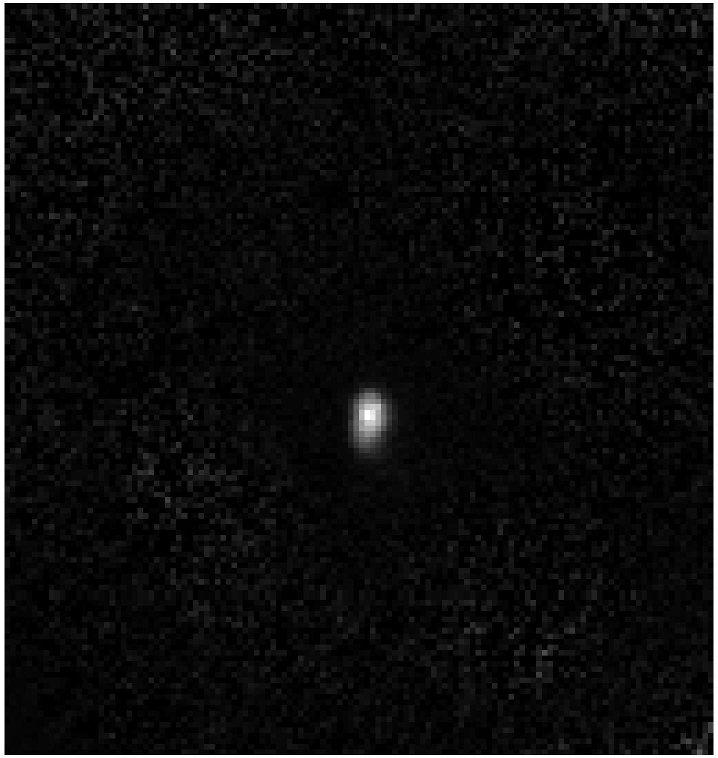

Number of atoms
0
500
1000
1500
520
540
560
Time (s)

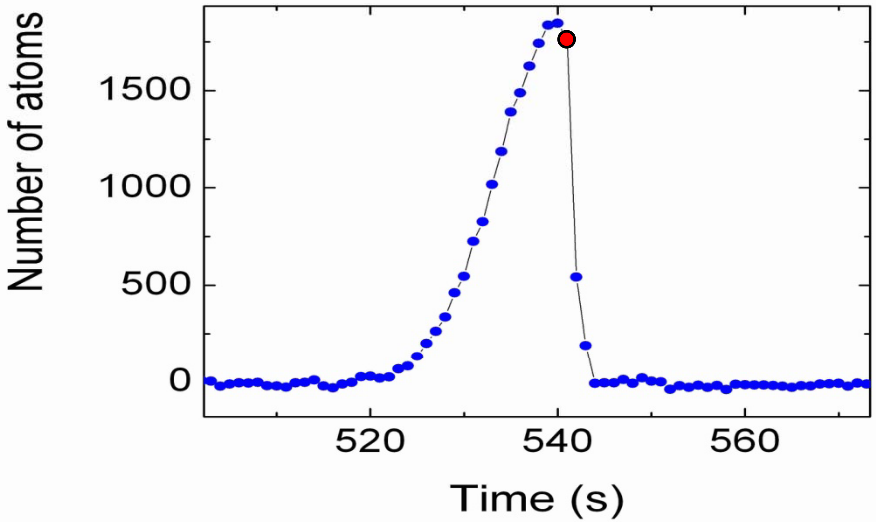




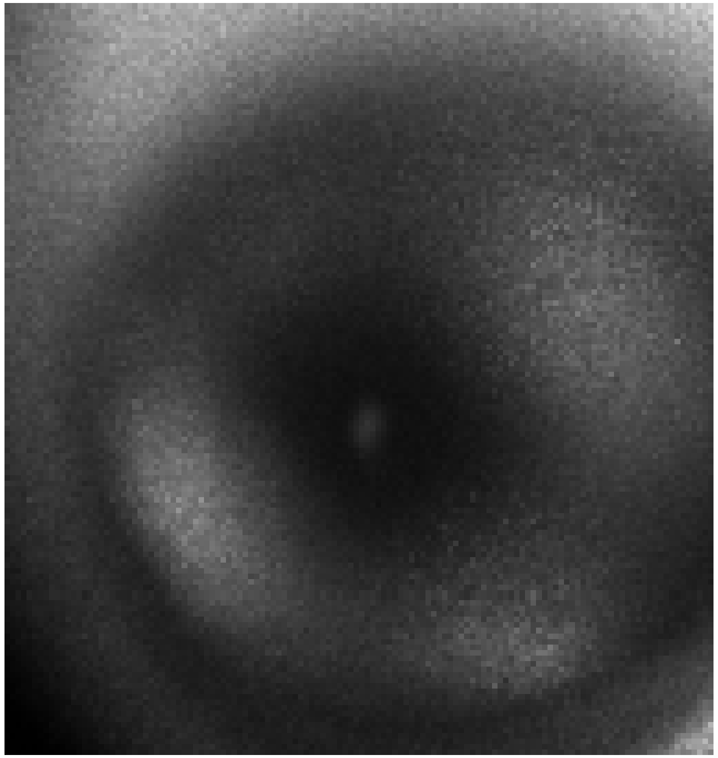

Number of atoms
1500
1000
500
0
520
540
560
Time (s)

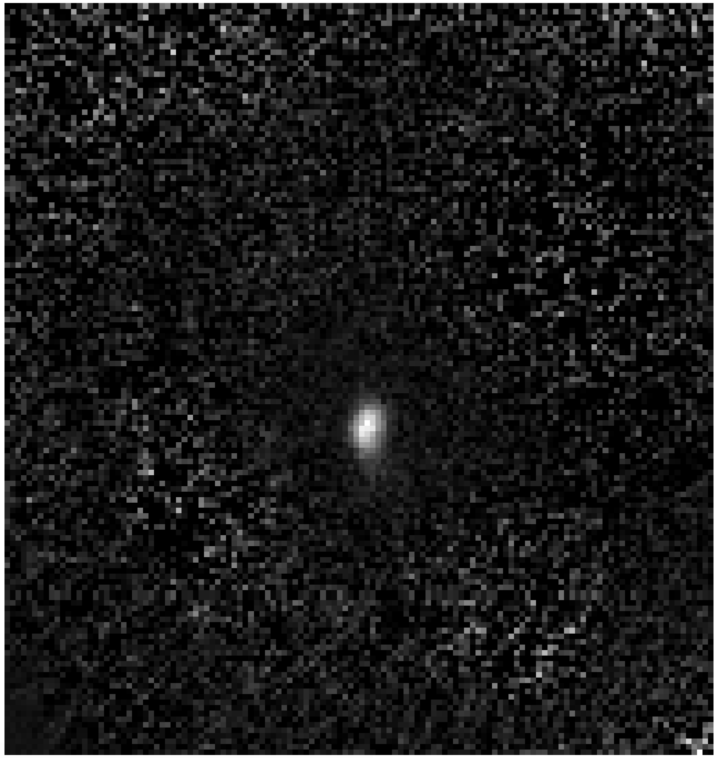


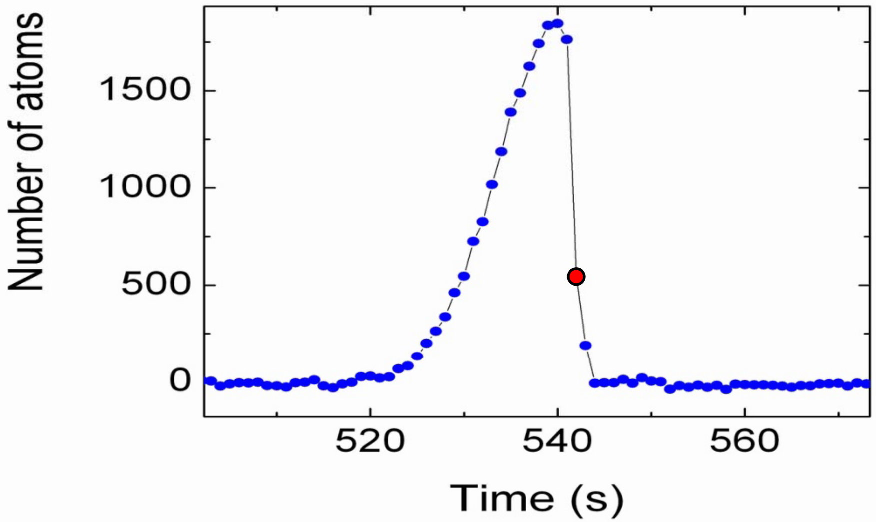




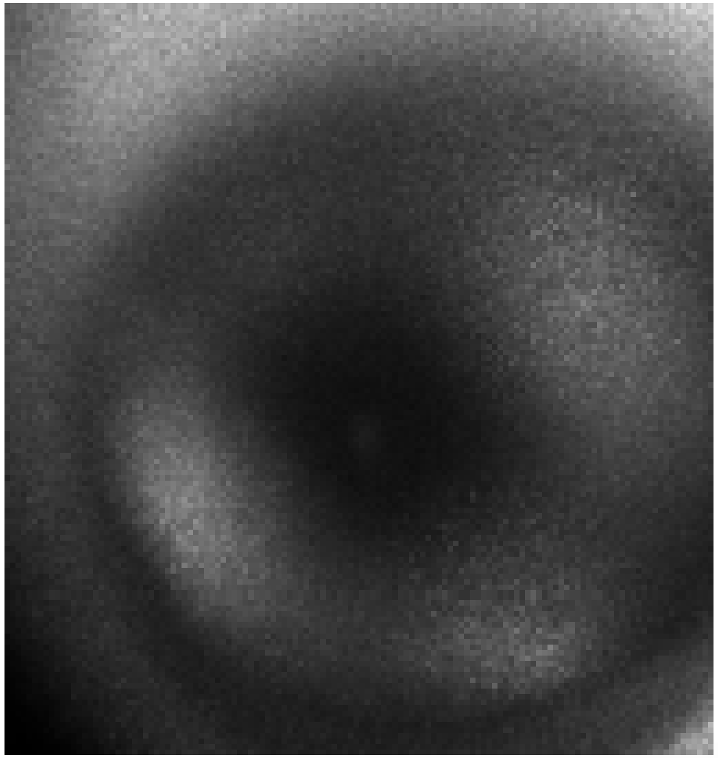
Number of atoms
1500
1000
500
0
520
540
560
Time (s)

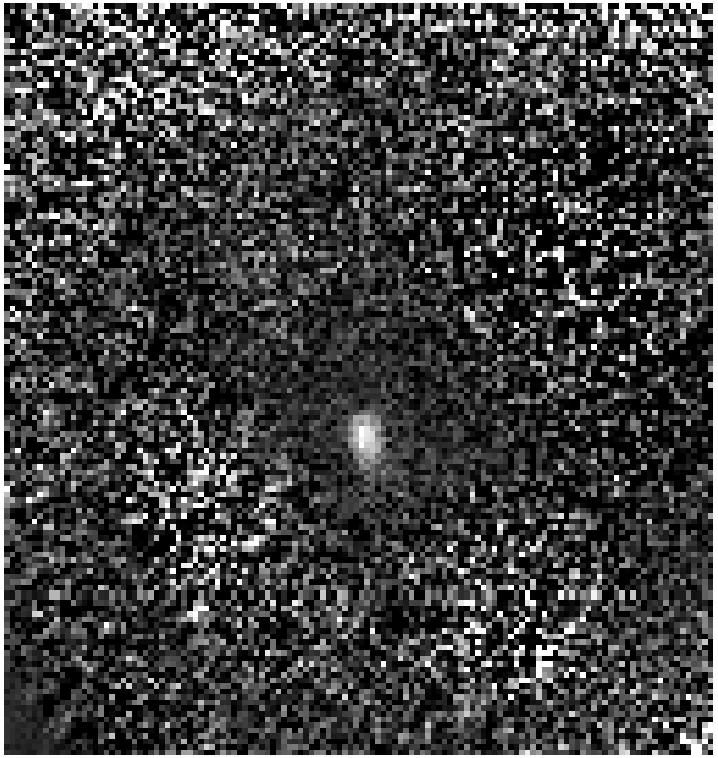


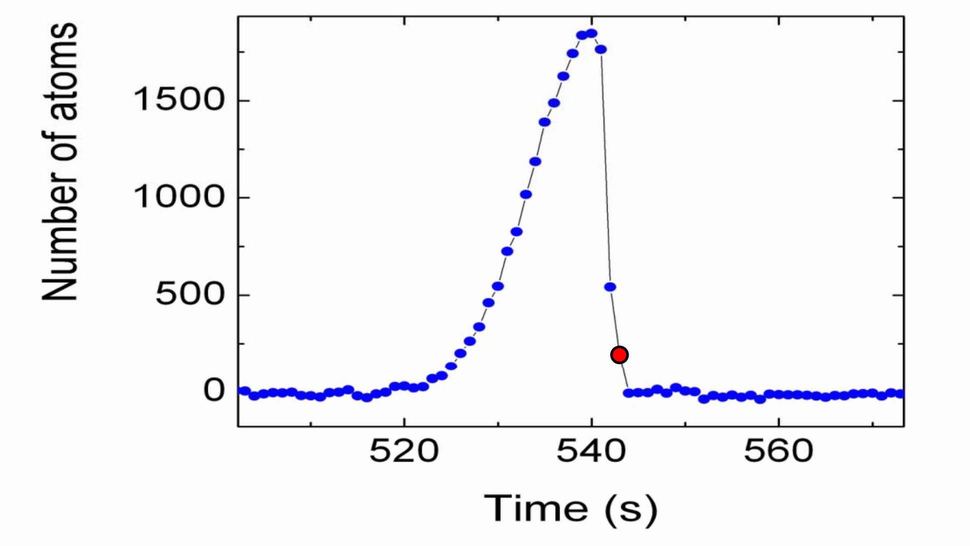


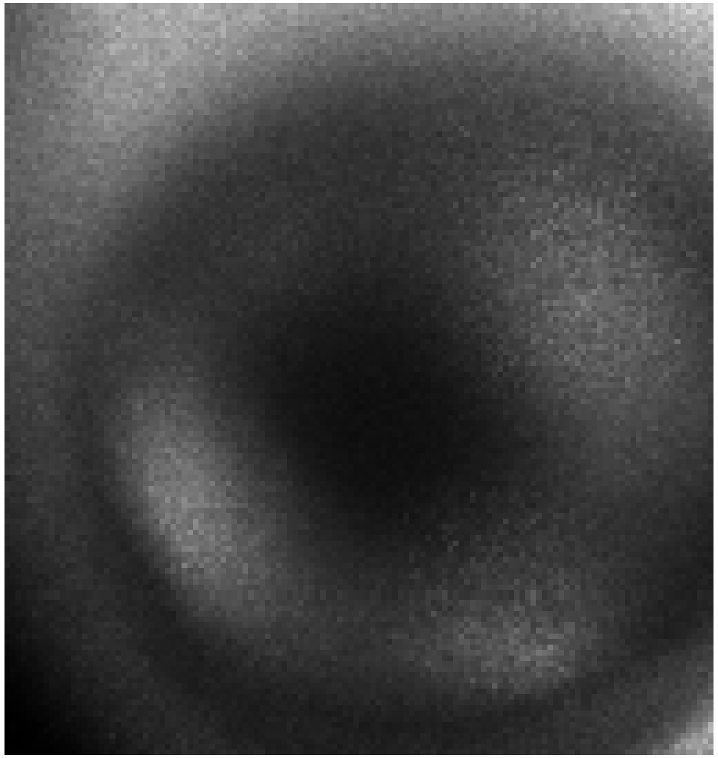


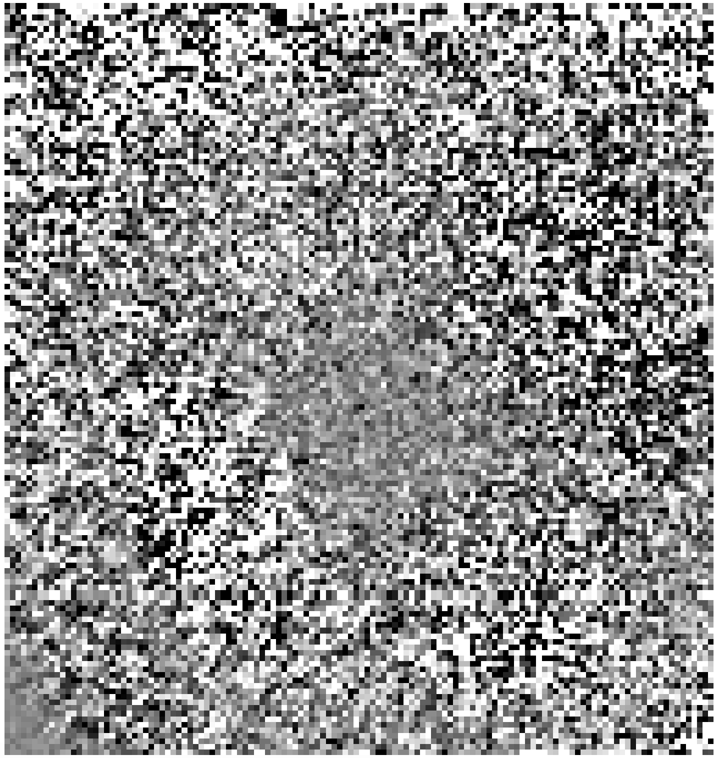
Number of atoms
1500
1000
500
0
520
540
560
Time (s)

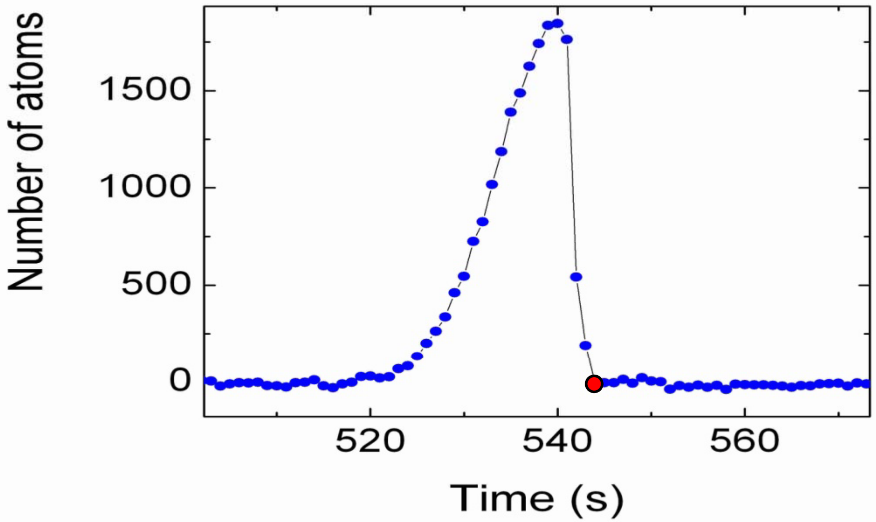




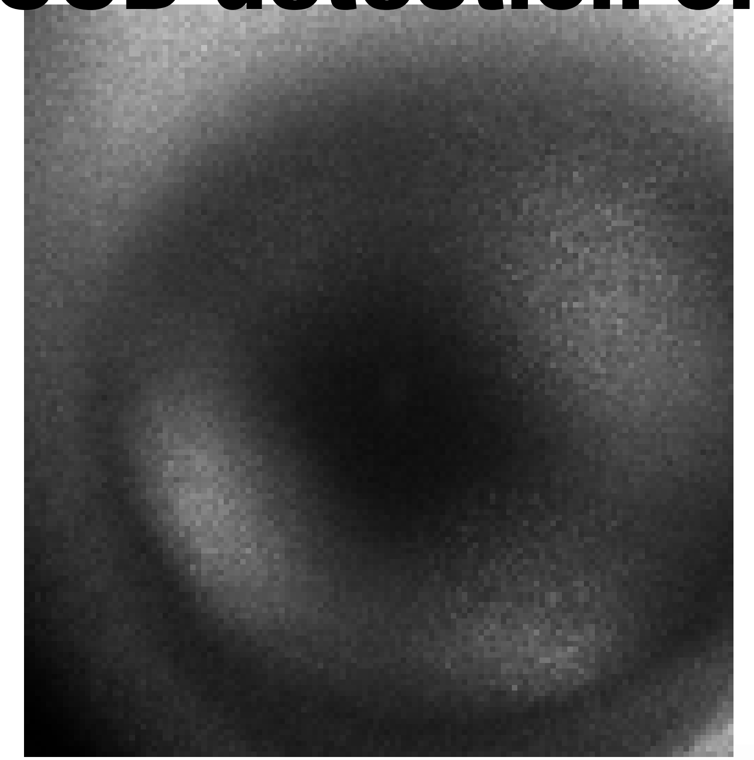

Number of atoms
0
500
1000
1500
520
540
560
Time (s)

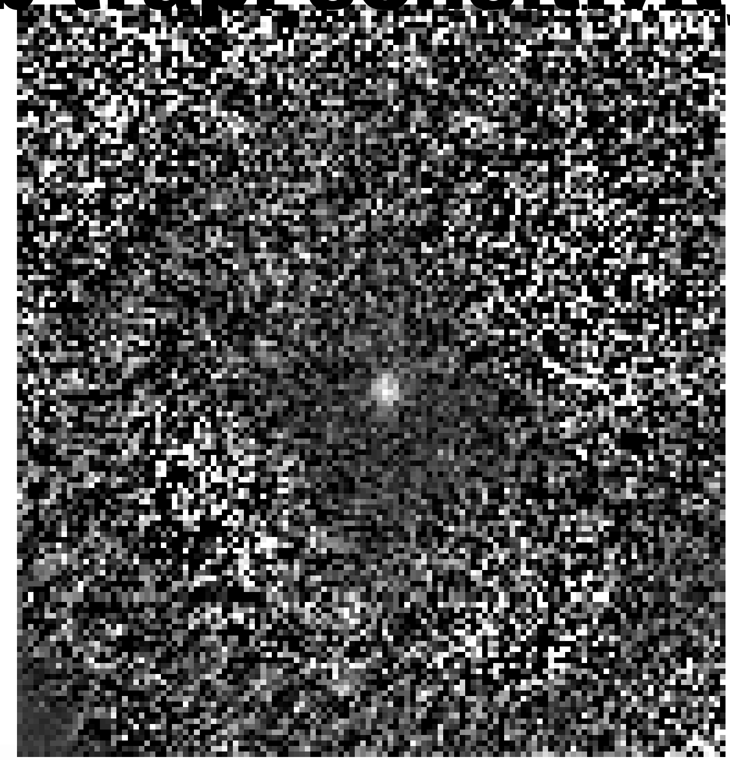


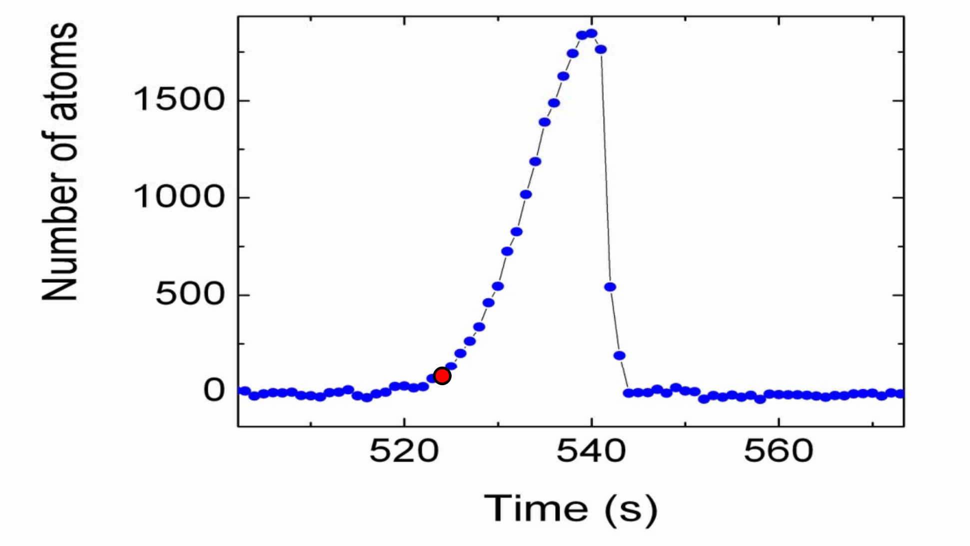



Number of atoms
1500
1000
500
0
520
540
560
Time (s)

CCD detection of Rb trap: sensitivity

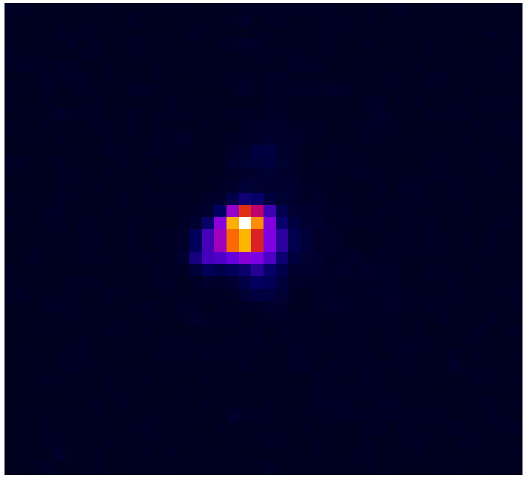






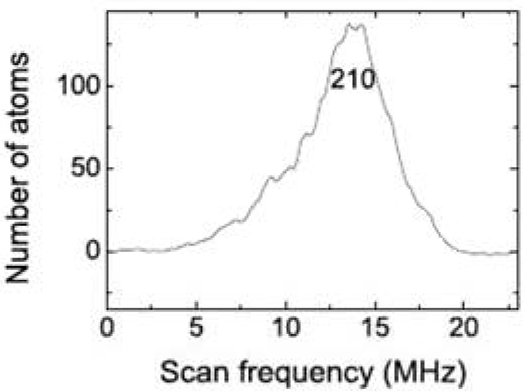
~50 atoms

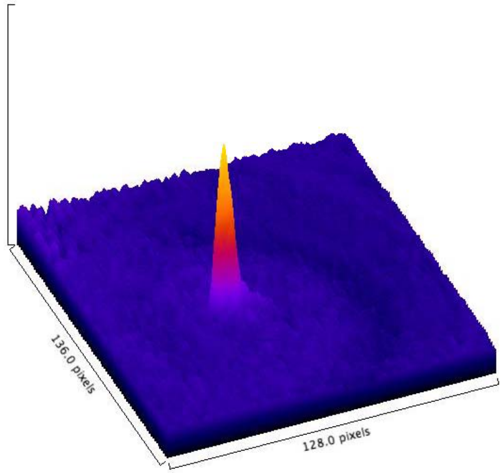
Present results



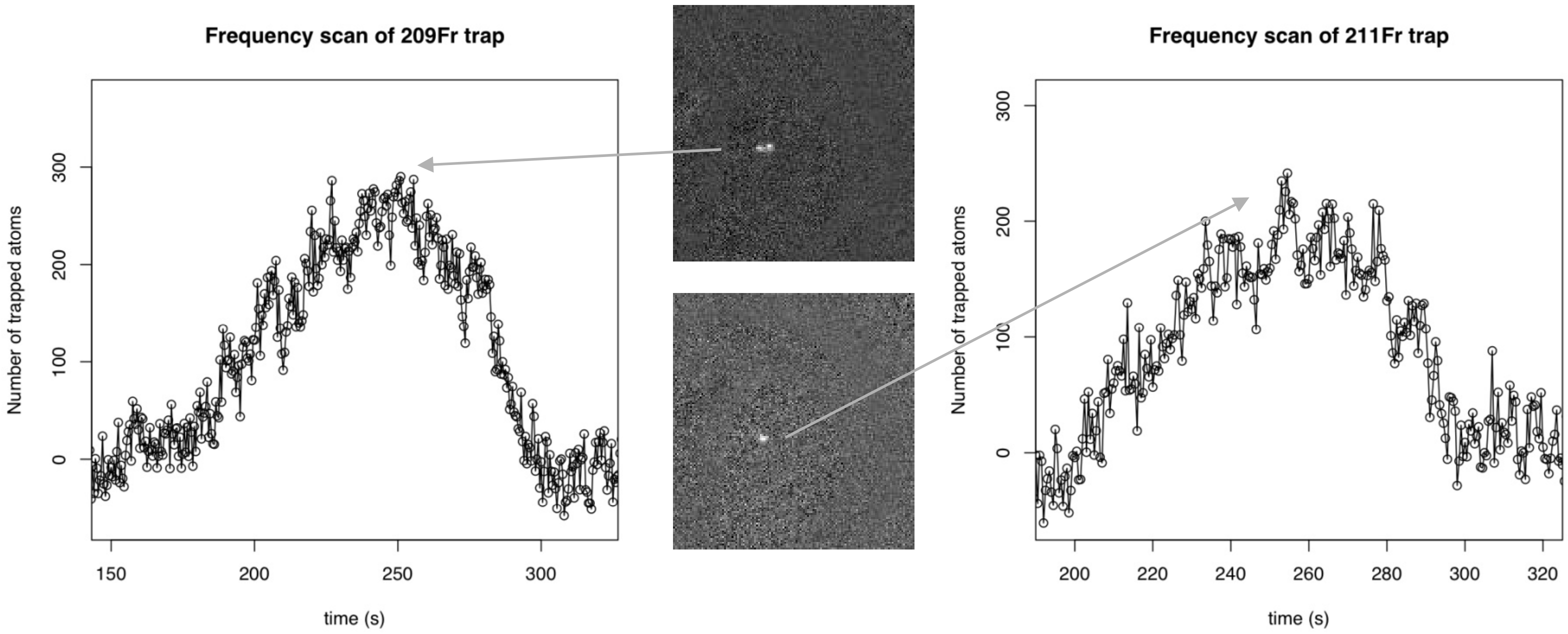
- **Trapped Fr isotopes:**

^{210}Fr 1100 atoms
^{209}Fr 270 atoms
^{211}Fr 180 atoms
Efficiency: 200 ^{210}Fr trapped atoms for 10^5 Fr^+/s



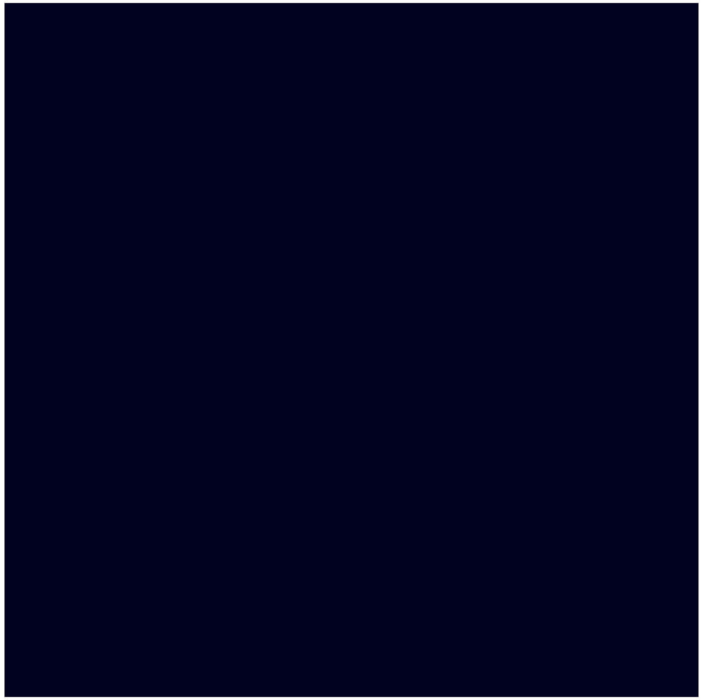


209 and 211 isotopes



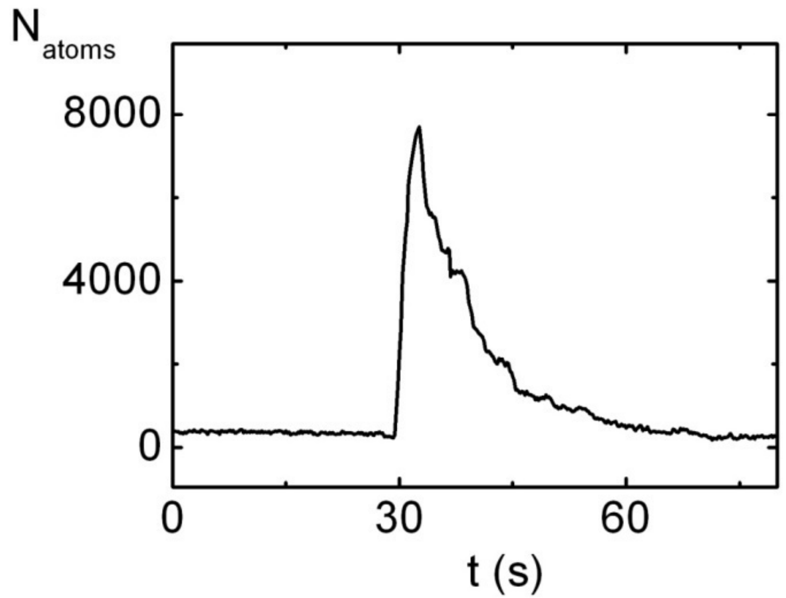
- Frequency scans of francium trap for 209 and 211 isotopes

Francium trap



Pulsed mode

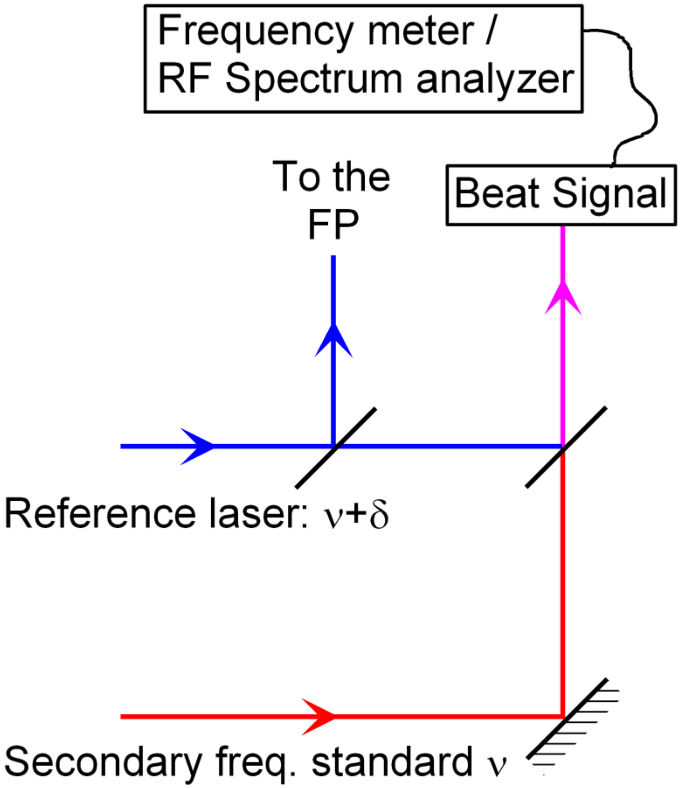
- Temporal evolution of the fluorescence signal of ^{210}Fr trap
- Accumulation for 600s on the cold neutralizer
- Beam stopped and neutralizer heated at t = 30



- **Pulsed mode: 8000 atoms**

Frequency measurement: methodology

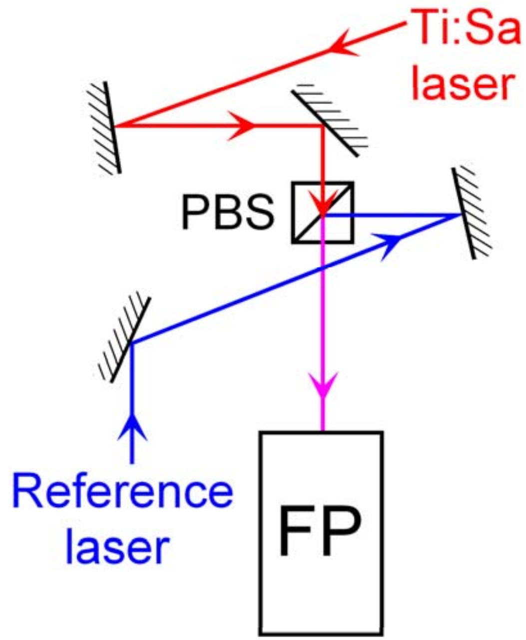
The Ti:Sa and the frequency standard frequencies are fixed $\Rightarrow$
In general, no FP transmission peak corresponding to both frequencies
$\Rightarrow$ Use a tunable reference laser, detuned from the secondary standard.



- Ti:Sa frequency: fixed.
- FP cavity length: stabilized on the Ti:Sa transmission peak.
- Reference laser: tuned to a transmission peak of the FP $\Rightarrow$ Frequency $\nu + \delta$.

– ν is the frequency of the secondary standard
– δ is measured from the beat signal (Reference laser – Secondary standard)

Trapping Frequencies



- **Measurements of the trapping frequencies for the three Fr isotopes**
  - confocal Fabry-Perot
  - reference laser tuned to FP transmission peak and its frequency (ν_1) measured by laser beat with respect to the secondary frequency standard
  - secondary frequency standard : diode laser locked to the accurate Rb two-photon transition $5S - 5D_{5/2}$ (778 nm, 8 KHz accuracy!)

- **Accuracy 9 MHz:** improvement by a factor 10 wrt Stony Brook 90 MHz accuracy

Already some new and unexpected results…

April 1, 2009 / Vol. 34, No. 7 / OPTICS LETTERS 893

Accurate measurements of transition frequencies and isotope shifts of laser-trapped francium

S. Sanguinetti,[1,*] R. Calabrese,[2] L. Corradi,[3] A. Dainelli,[3] A. Khanbekyan,[4] E. Mariotti,[4] C. de Mauro,[4] P. Minguzzi,[1] L. Moi,[4] G. Stancari,[2] L. Tomassetti,[2] and S. Veronesi[4]

An interferometric method is used to improve the accuracy of the $7S-7P$ transition frequencies of three francium isotopes by 1 order of magnitude. The deduced isotope shifts for $^{209-211}$Fr confirm the ISOLDE data. The frequency of the D_2 transition of ^{212}Fr—the accepted reference for all Fr isotope shifts—is revised, and a significant difference with the ISOLDE value is found. Our results will be a benchmark for the accuracy of the theory of Fr energy levels, a necessary step to investigate fundamental symmetries.

- Whole set of old D_2 wavelengths of different Fr isotopes **shifted by 0.007 cm^{-1}**

Frequency value for the D_2 reference centroid for ^{212}Fr

13923.9910(6) cm $^{-1}$ LNL (2009)

13923.998(2) cm $^{-1}$ ISOLDE (1986)

Precise measurements of transition frequencies and isotope shifts: benchmark for theoretical models.

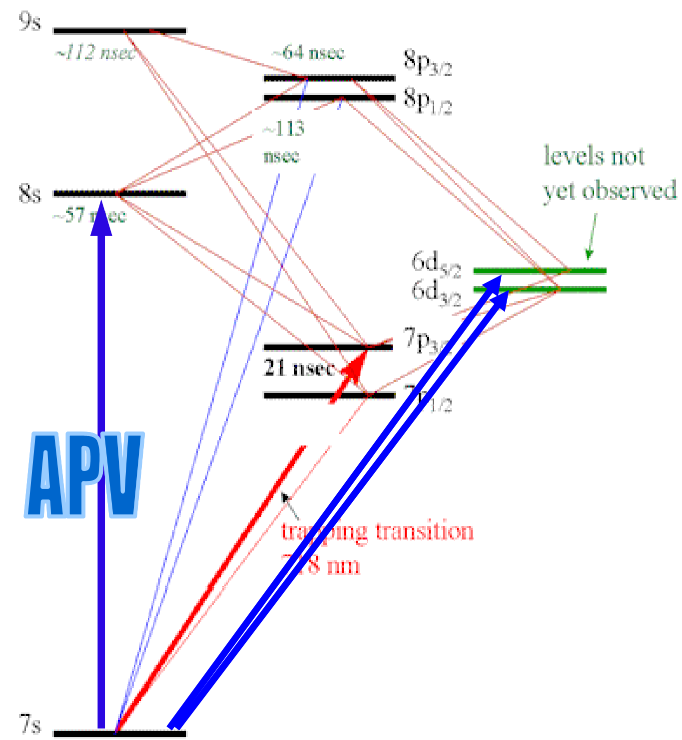
Continue with search of unobserved transitions

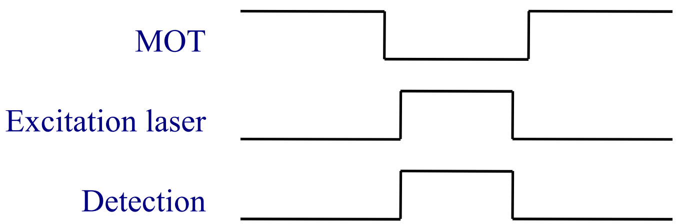
GHz

Isotope	Trapping laser	Trapping transition	D_2 Centroid
209	417 415.087(8)	417 415.125(17)	417 433.876(18)
210	417 412.448(7)	417 412.486(17)	417 433.357(17)
211	417 412.627(9)	417 412.665(18)	417 431.643(19)
212			417 430.748(17)

Quadrupole transitions

- **Quadrupole transitions 7S – 6D$_{3/2}$, 7S – 6D$_{5/2}$ not yet measured**
  - theory predicts 616 nm and 608 nm respectively
  - the transition probability is larger than the forbidden transition but frequency is unknown: tunable laser to scan this region
  - atoms in 6D levels should be ionized by the laser and leave the MOT (detection of Fr ions leaving the MOT)
  - detection by monitoring the fluorescence signal of the MOT (SNR limited by trap fluctuations and stray light)
  - alternative detection method: measurement of the fluorescence of 7P – 7S decay as signature of quadrupole transition: same frequency as trapping laser (measurement to be done in pulsed regime to reduce noise)





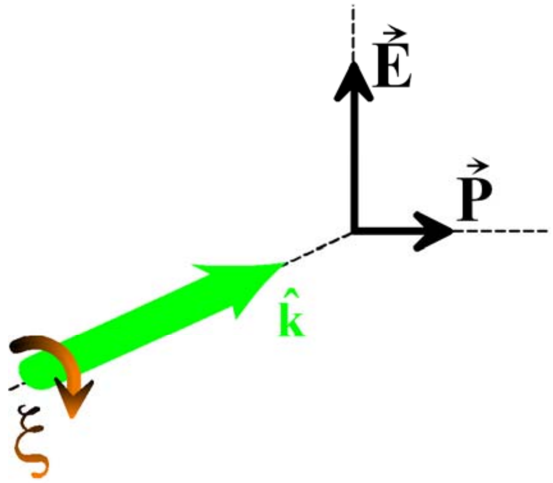
Two possible detection schemes for APV measurement in Fr

- Measure an absorption rate which is different for two mirror configurations ⇒ **CIRCULAR DICHROISM**

- Measure an electric dipole moment which is different for two mirror configurations ⇒ **LINEAR STARK SHIFT**

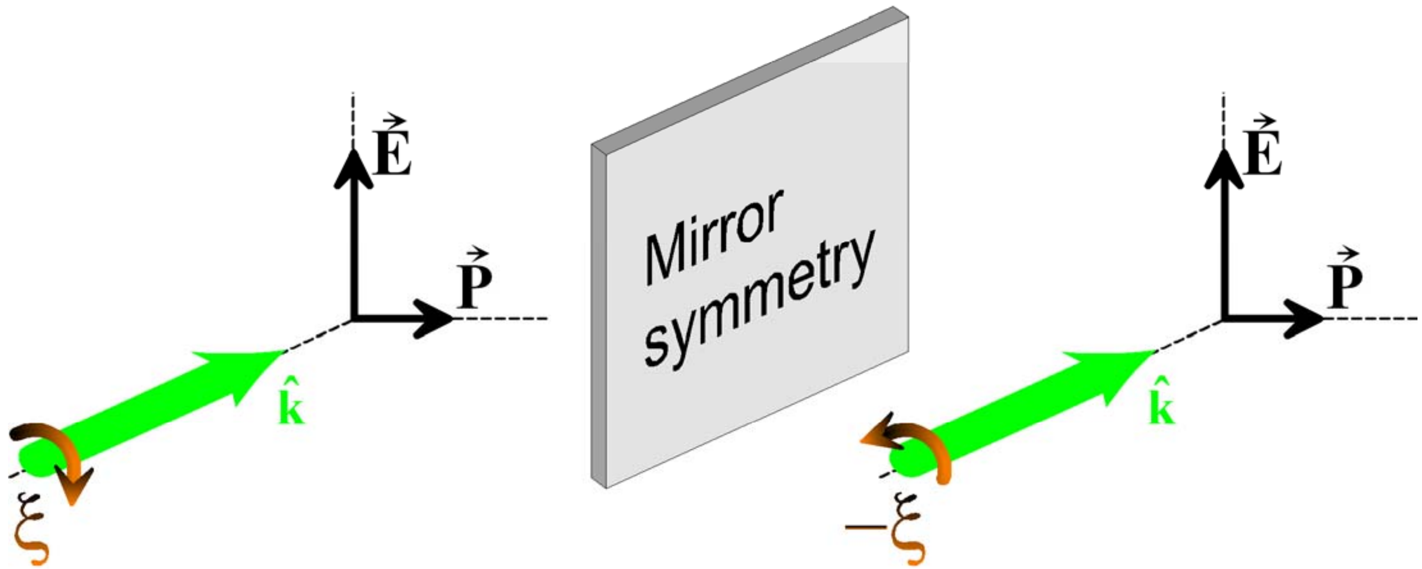
  M.-A. Bouchiat
  "Measuring the Fr Weak Nuclear Charge by Observing a Linear Stark Shift with Small Atomic Samples"
  Phys. Rev. Lett. **100**, 123003 (2008).

Circular dichroism for 7S-8S transition



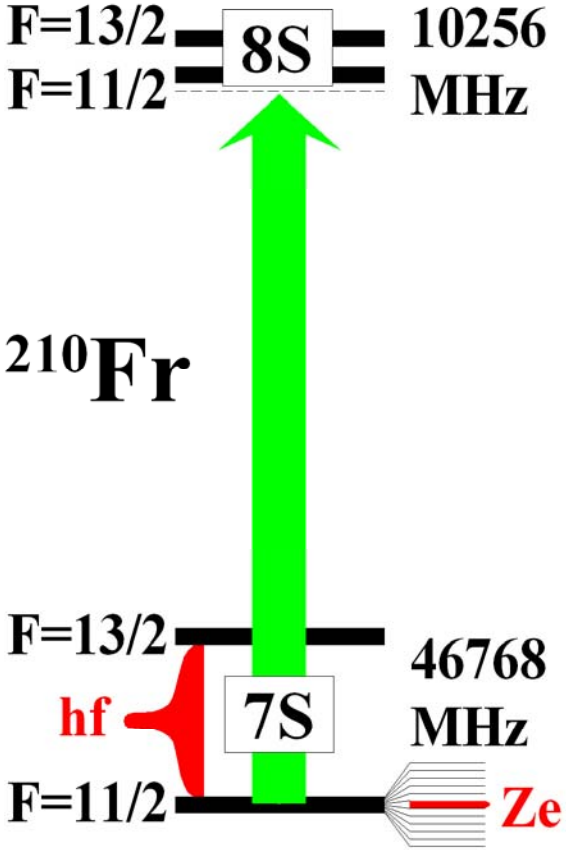
- ☞ $7S-8S$ transition assisted by a static electric field $\sim$ 1000 V/cm
- ☞ Polarized ($\overrightarrow{P}$) atoms in an optical dipole trap

Circular dichroism for 7S-8S transition



- $7S-8S$ transition assisted by a static electric field $\sim$ 1000 V/cm
- Polarized ($\vec{P}$) atoms in an optical dipole trap
- The transition rate changes when the helicity ξ is reversed
  $\Rightarrow$ Discrimination of the PV effect

PV Linear Stark shift



Detuning δ, laser electric field ϵ

$\Rightarrow$ Shift $\delta\mathcal{E} = |\langle 7S \mid \mathbf{d}^{\text{eff}} \cdot \boldsymbol{\epsilon} \mid 8S\rangle|^2 / h\delta$

Circular dichroism: $N_{8S} \sim \beta^2 E^2 - \chi\ (M_1' + \xi\, \Im m E_1^{PV})\ \beta \mathbf{E} \wedge \hat{\mathbf{k}} \cdot \mathbf{P}$

Linear Stark shift: $\Delta\nu \sim (M_1 + \xi\, \Im m E_1^{PV})\ \beta \mathbf{E} \wedge \hat{\mathbf{k}} \cdot \mathbf{P}$

Possibility to measure the weak charge even with small atomic sample ($\geq 10^4$ trapped atoms)

International situation

- Francium trapping:
  - **Triumf (in 2010-2015 planning), Osaka (in preparation)**
- Traps for radioactive atoms:
  - **Los Alamos, Berkeley, KVI (in preparation), GANIL (Spiral2, in preparation), Michigan State University (proposed)**

Outlook

- The first European facility for on-line trapping of radioactive atoms has been built and commissioned at LNL (at present is the only working)
- First results on high-precision laser spectroscopy were achieved
- Next challenging phase of atomic parity-violation measurements in francium: study of techniques and measurements of atomic parameters