Francium trapping

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CNISM

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The "traprad"/"francium"/"wade" collaboration

Ferrara University and INFN:
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Legnaro National Laboratories:
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Pisa University:
P.Minguzzi, (S.Sanguinetti), M.L.Chiofalo

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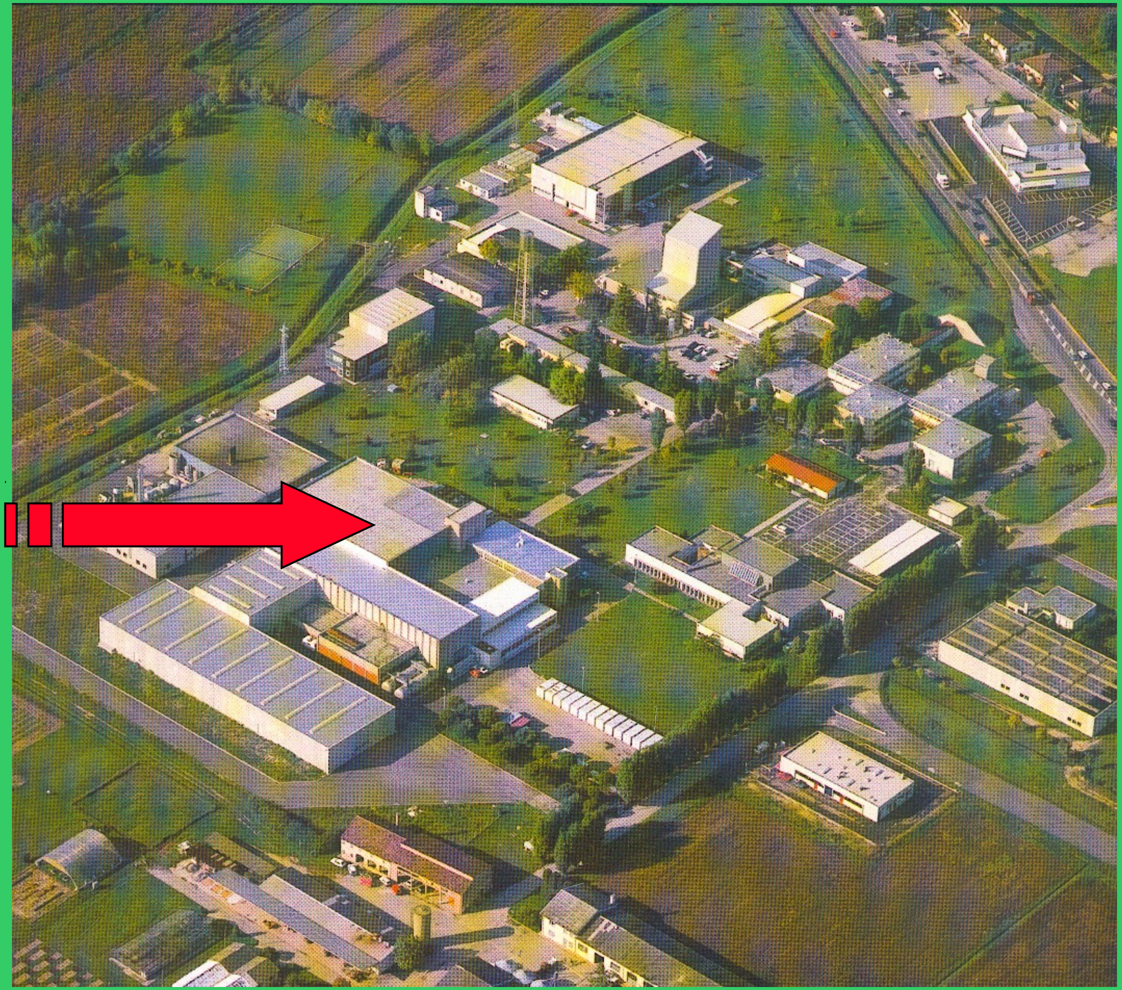
Ferruccio Renzoni (UCL), Leonardo Ricci (UniTrento)

The “traprad”/“francium” location (?)

The “traprad”/“francium” (real) location



Outline

- **Introduction/Motivation (if any...)**
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  Laser spectroscopy diffusion coefficients meas.
  Detection of lines by change in trapped atom number
  Application of Light Induced Atom Desorption
- Perspectives

(Bad) facts about francium

	Mass no. (*A*)	Half-life
Fr	202	0.34 s
	203	0.55 s
	205	3.85 s
	206	15.9 s
	207	14.8 s
	209	50 s
	211	3.1 min
	213	34.6 s
	220	27.4 s
	223	21.8 min
	224	3.3 min
Fr	225	4.0 min
	226	48 s
	227	2.47 min
	228	39 s
	230	19.1 s
	232	5 s

Fr has no stable isotopes

The longest lifetime is 22min

There is at most a tea spoon of francium in the whole Earth at any given time

$\Rightarrow$ **continuos production and trapping for further studies is necessary**

$$^{210}\mathrm{Fr} \rightarrow 3.2\ \mathrm{min}$$

Facts about francium

-First spectroscopy measurements at CERN (ISOLDE):

S. Liberman *et al.*, C. R. Acad. Sci. Ser. B **286**, 253 (1978).
Francium is produced by spallation reactions in Th or U Carbide targets bombarded with protons: 10^9 **Fr/s**.

-Francium Magneto-Optical Trap (MOT):

J.E. Simsarian *et al.*, PRL **76**, 003522 (1996). (STONY-BROOK)
S.N. Atutov *et al.*, JOSA B **20**, 953 (2003). (LEGNARO)
Nuclear fusion-evaporation reactions in a Au target: 10^6 **Fr/s**.

Z.-T. Lu *et al.*, PRL **79**, 994 (1997). (Boulder/Berkeley)
Radioactive source: Francium produced in the decay chain
$^{229}\text{Th}\rightarrow{}^{225}\text{Ra}\rightarrow{}^{225}\text{Ac}\rightarrow{}^{221}\text{Fr} \;\Rightarrow\; 10^4$ **Fr/s**.

(Interesting) facts about francium

spectroscopically poorly known

simple electronic structure

several isotopes suitable for trapping

enhanced relativistic effects

enhanced P and T violations

$\Downarrow$

Parity Violation for the 7S – 8S transition:
test of neutral weak interactions

Parity Violation for the ground state hyperfine atomic transition: measurement of Nuclear Anapole Moment
(TRIUMF/ISAC, production rate 10^{10} Fr/s, trap number 10^{7} Fr)

Search for permanent Electric Dipole Moment:
test of Time reversal violation and SUSY
(RNCP @Sendai, trap number 10^{8} Fr)

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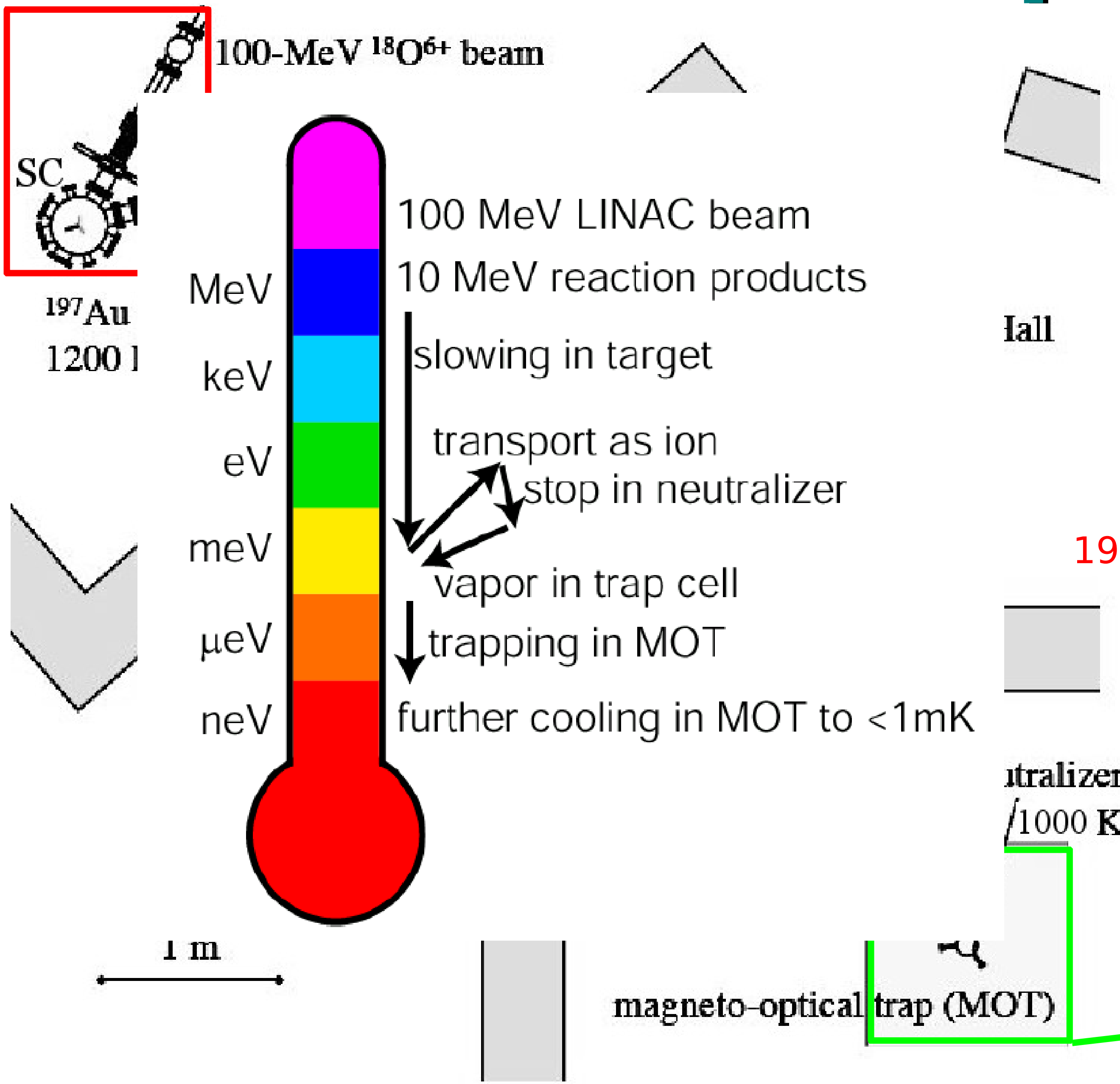
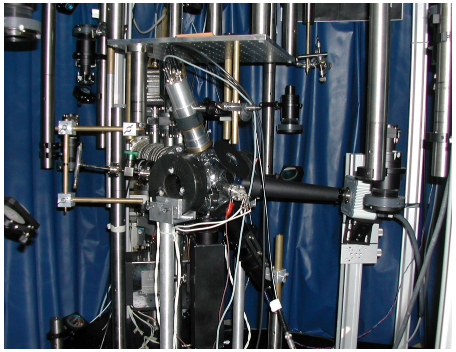
The TRAPRAD experiment



Fr production

$^{197}Au + ^{18}O \rightarrow xn + ^{215-x}Fr$

Fr^{+} (and Rb^{+}) ions transport at 3 keV



Eur Phys J ST 150 389 (2007)

The laser setup

Ti:Sa laser pumped by Ar+ laser

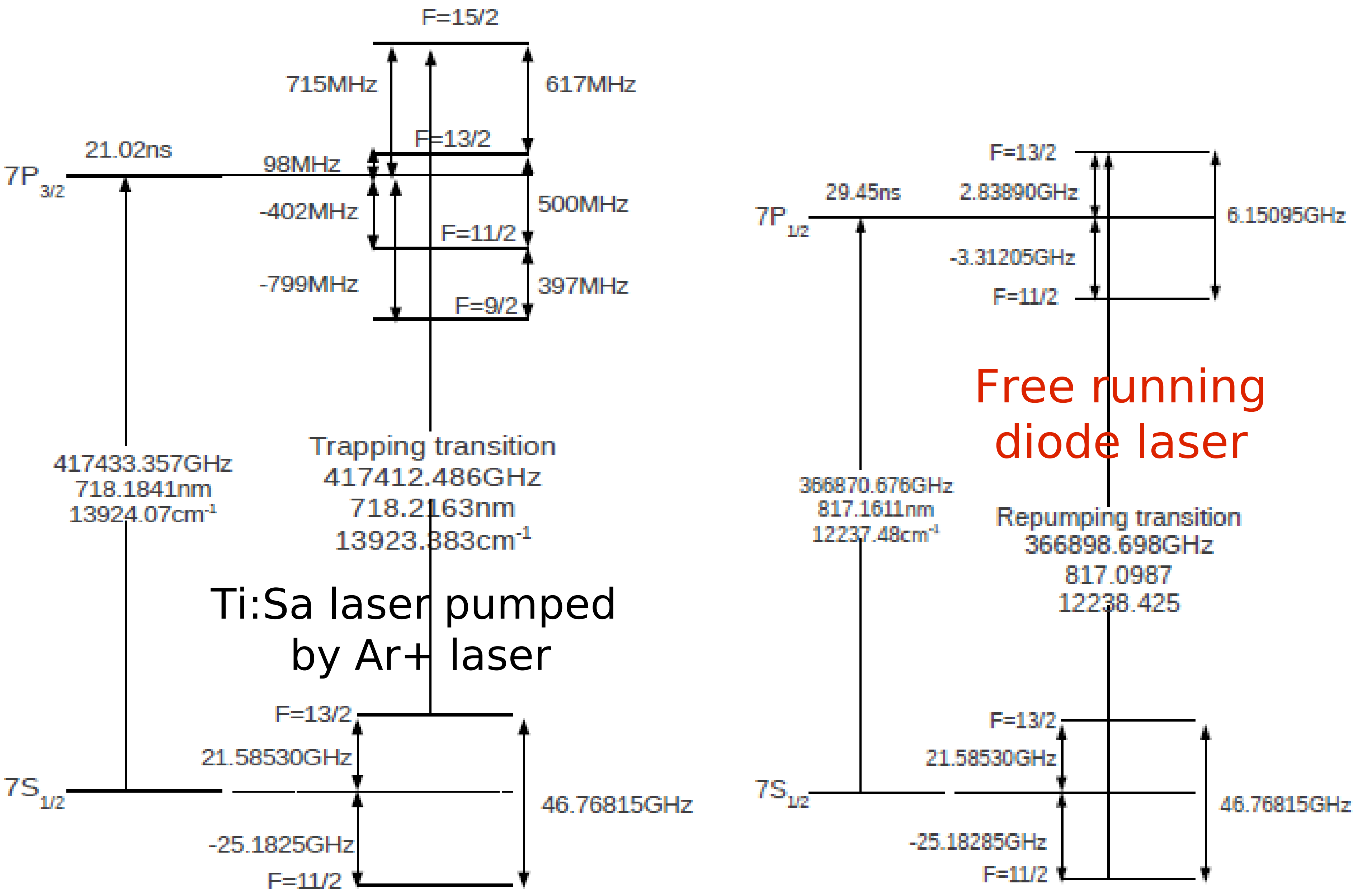
covering of both Fr (718 nm) and Rb (780 nm) D2 line
for trapping transition

diode lasers for repumping

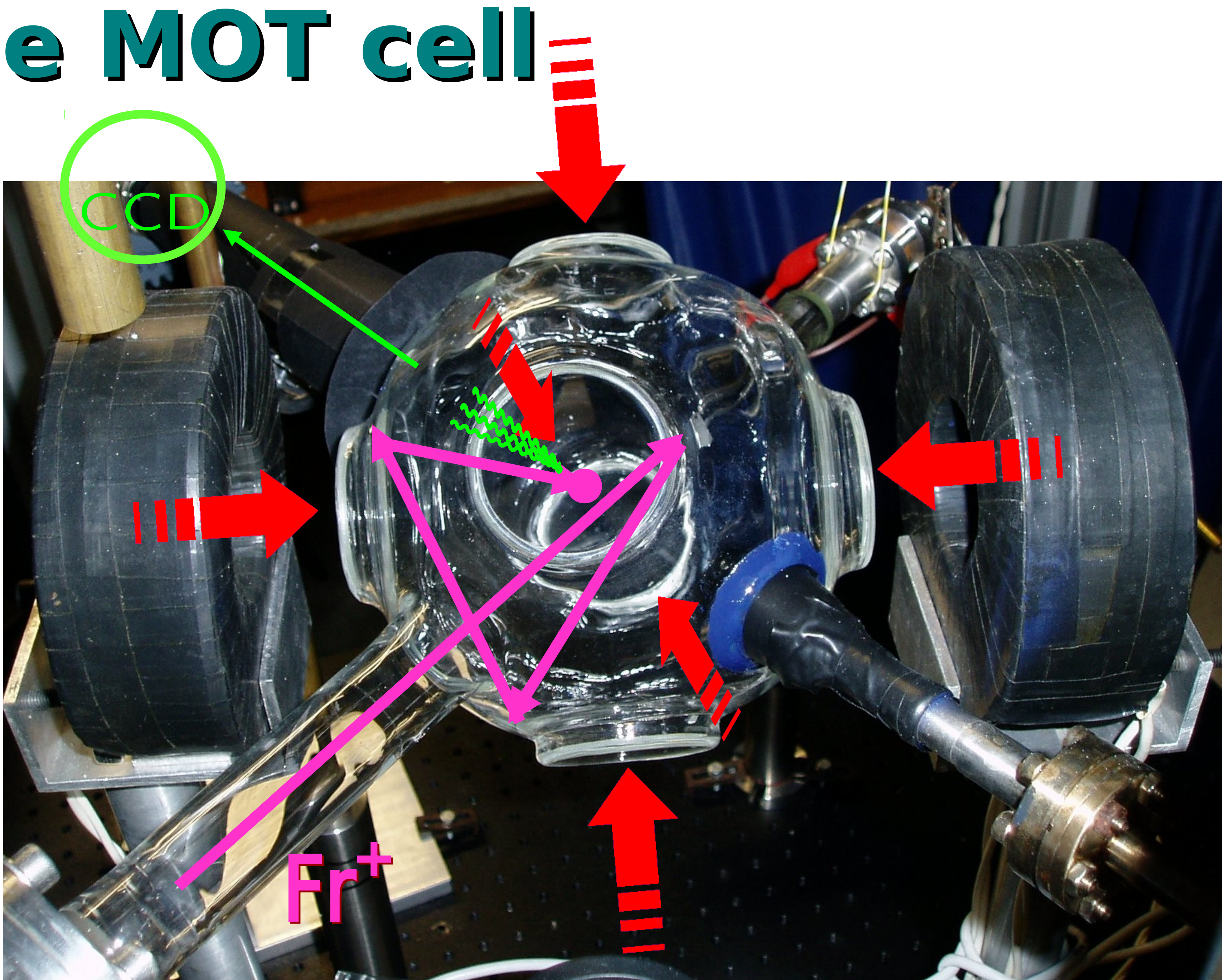
active stabilisation

interferometric
wavelength measurement

The trapping and repumping transitions



The MOT cell



Dryfilm coated pyrex

The MOT cell

$$\frac{n_+}{n_a} = \frac{g_+}{g_a} \exp\left(\frac{\phi - I}{k_B T}\right)$$

ϕ_{Au}=5.1eV
ϕ_Y=3.1eV
I=4.1eV

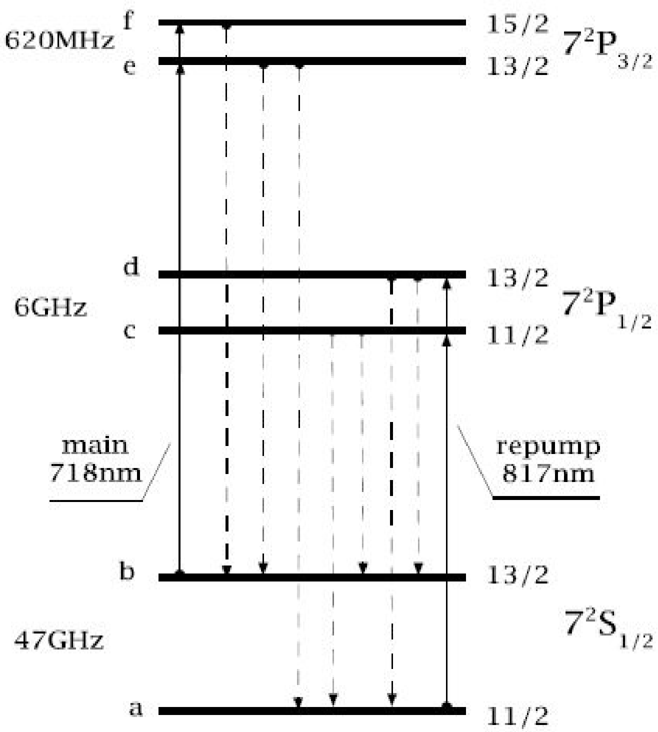
CCD Detection of the MOT

we locate a dark region behind the MOT

background subtraction: uniform image

weighted background subtraction: compensation for laser intensity fluctuations

Calibration power-number of atoms



$$H = \hbar \begin{pmatrix} 0 & 0 & A & A & 0 & 0 \\ 0 & \omega_b & 0 & 0 & C & C \\ A^* & 0 & \omega_c & 0 & 0 & 0 \\ A^* & 0 & 0 & \omega_d & 0 & 0 \\ 0 & C^* & 0 & 0 & \omega_e & 0 \\ 0 & C^* & 0 & 0 & 0 & \omega_f \end{pmatrix}$$

hyp: trap laser detuning $-5\gamma_f$

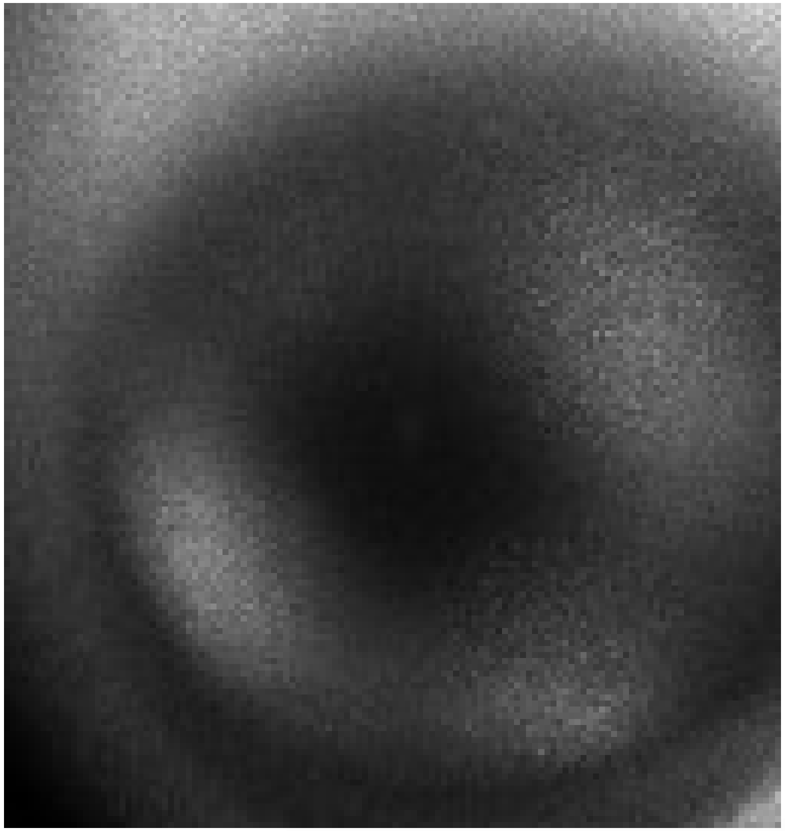
$$\Gamma = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \gamma_c & 0 & 0 & 0 \\ 0 & 0 & 0 & \gamma_c & 0 & 0 \\ 0 & 0 & 0 & 0 & \gamma_f & 0 \\ 0 & 0 & 0 & 0 & 0 & \gamma_f \end{pmatrix}$$

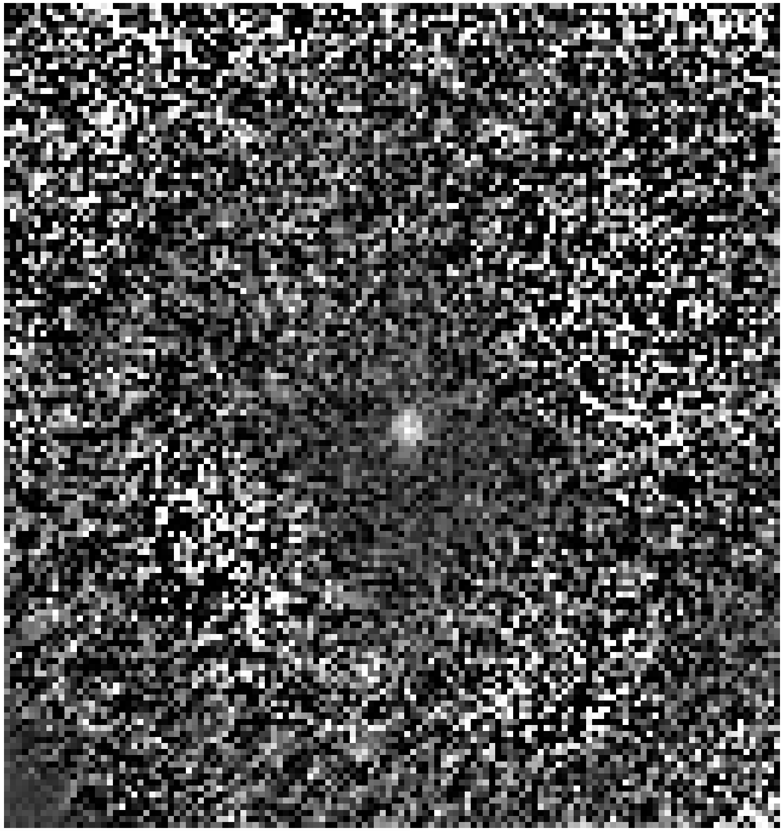
Rb: 1pW 1400 atoms

Fr: 1pW 1900 atoms

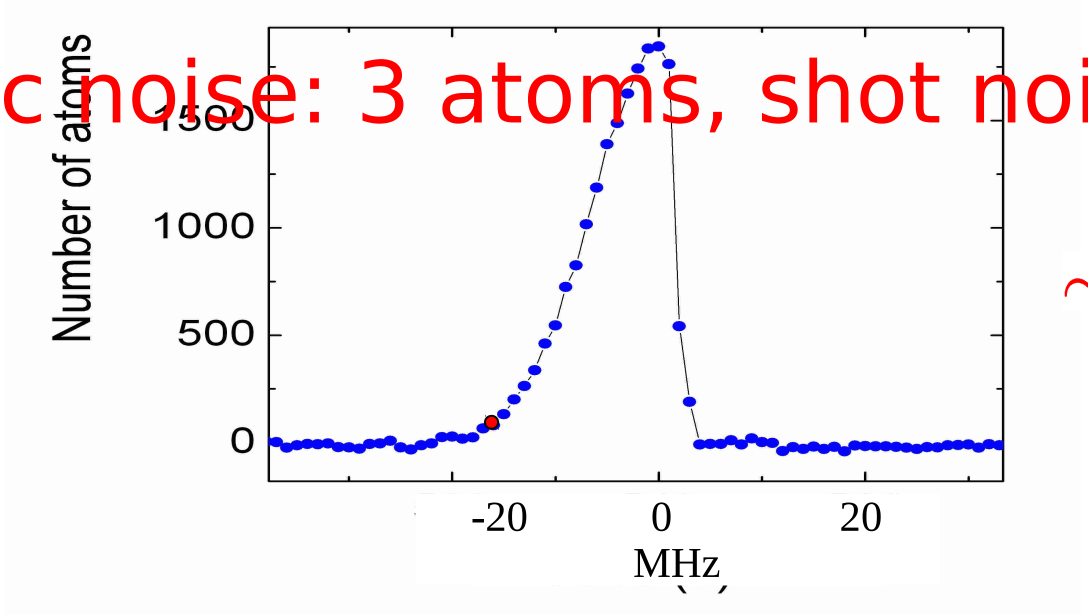
noise level less than 30 atoms

Tests on Rb MOT



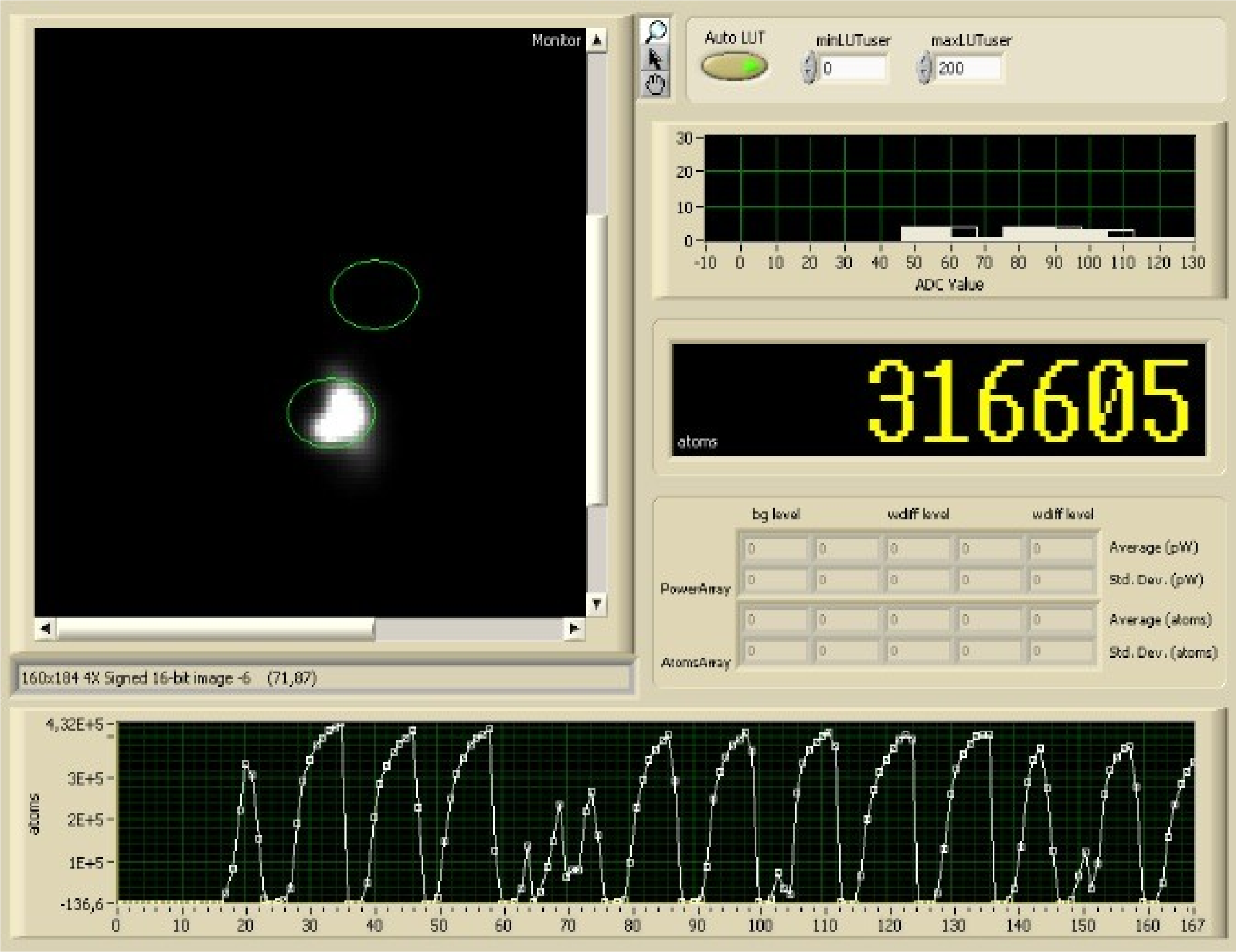


Electronic noise: 3 atoms, shot noise: 8 atoms



∼ 80 atoms

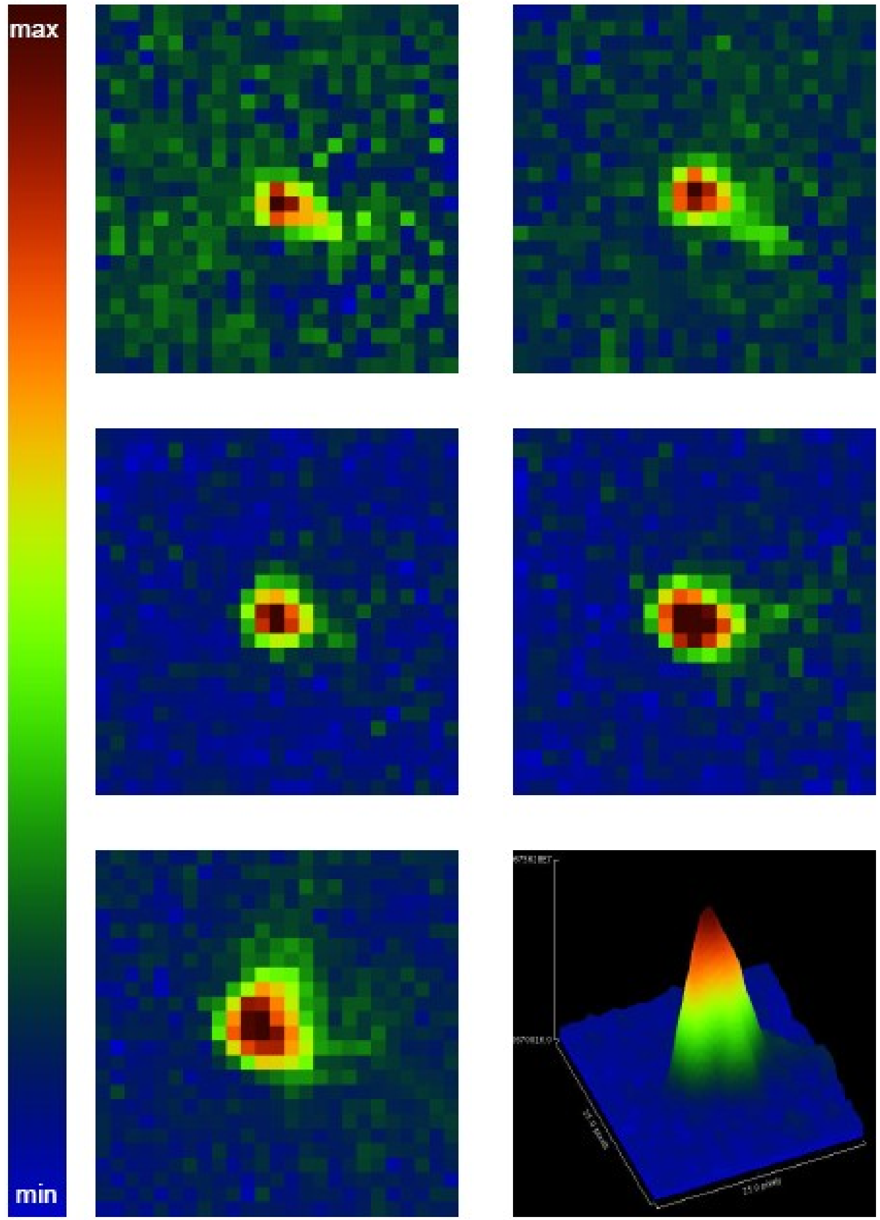
Tests on Rb MOT



Francium trapping

220 atoms

450 atoms



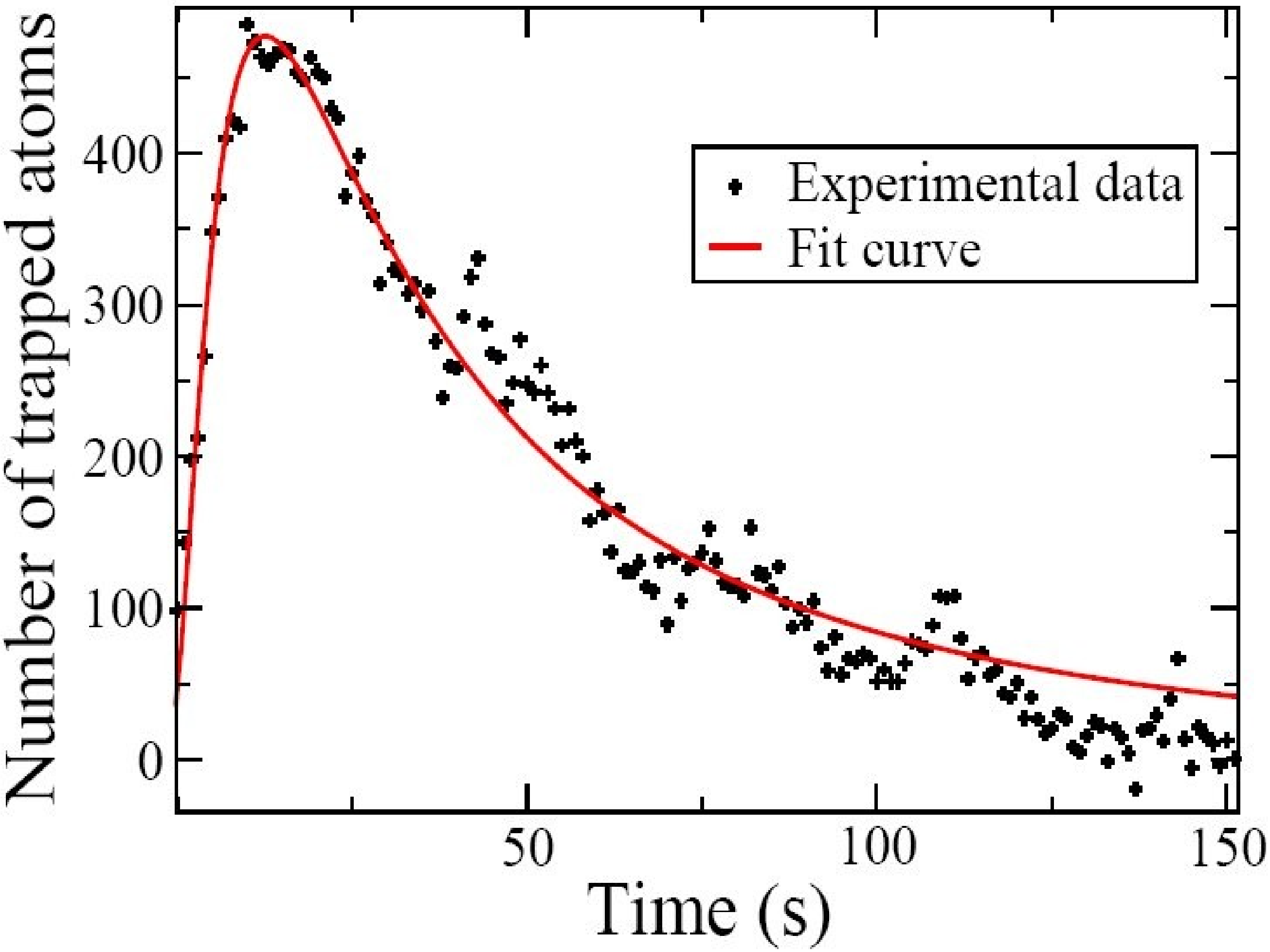
560 atoms

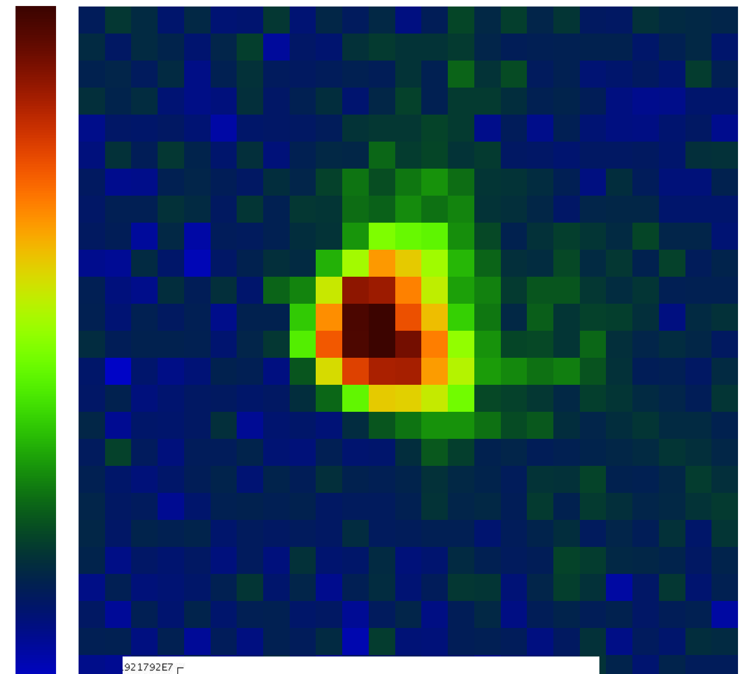
930 atoms

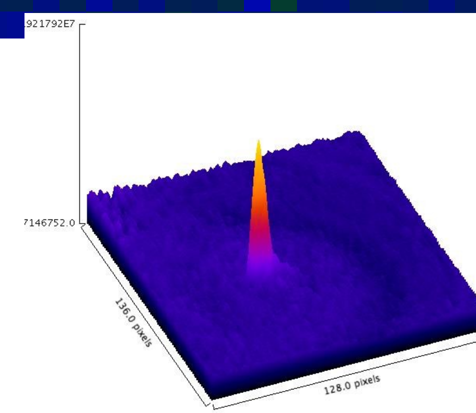
1100 atoms

...we wanted more...

accumulation in the cold yttrium and fast release
by suddenly switching on the heating of neutraliser

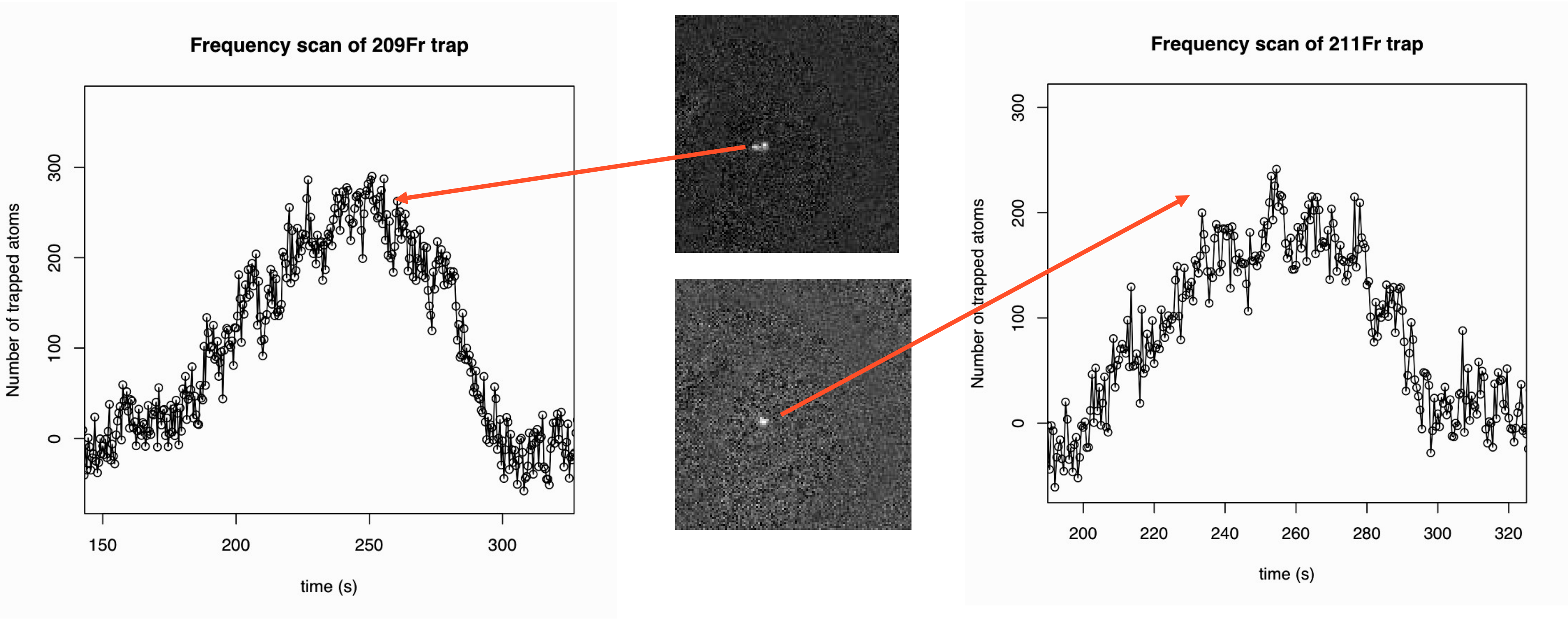






up to 10000 atoms !!

Fr 209, 211


Frequency scan of 209Fr trap
Number of trapped atoms
time (s)
0
100
200
300
150
200
250
300
Frequency scan of 211Fr trap
Number of trapped atoms
time (s)
0
100
200
300
200
220
240
260
280
300
320

Estimate of trapping efficiency

$$v_c \approx 3000cm/s, v_{th} \approx 1.7 \cdot 10^4 cm/s, R_b = 1cm, l = 12cm,$$

$$r = 1.25cm, C \approx 0.1s^{-1}, I \approx 10^5 atomi/s, R = 7cm, \chi \approx 10000$$

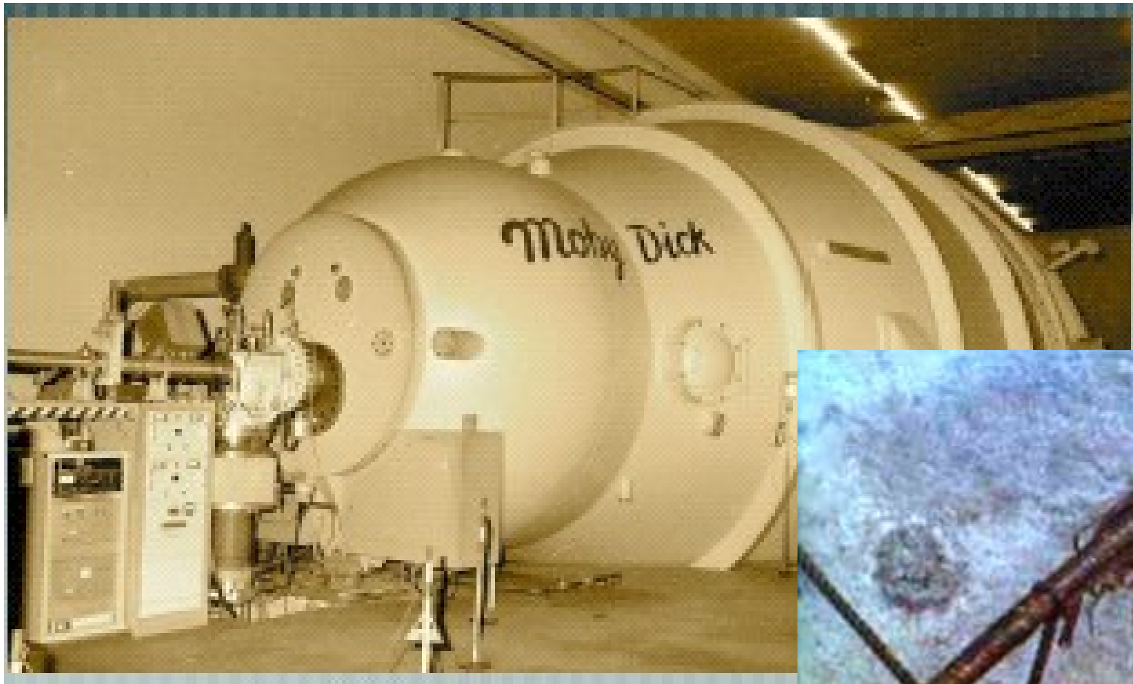
trapping efficiency

$$\eta \equiv \frac{N_t}{I\tau_c}$$

$\eta_{210} \simeq 2,3 \times 10^{-4}$

$\eta_{209} \simeq 3,2 \times 10^{-4}$

Experimentalists' life



Francium collaborator

10 days of beam time per year maximum

Melting the target.....

....means to start since the beginning!
(and fight with radioprotectors)

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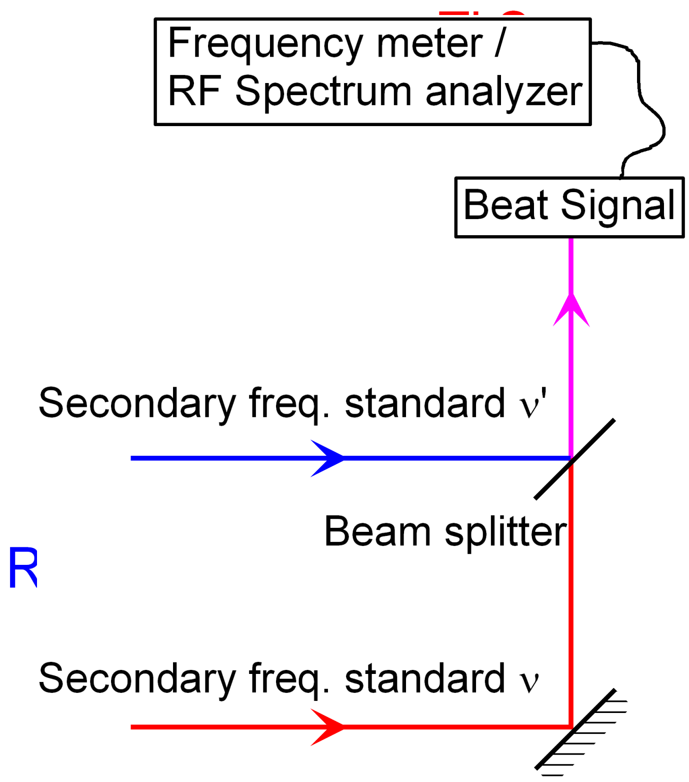
Precision measurements

We compare the frequency of 2 lasers transmitted by a confocal FP cavity (finesse 200, FSR 2 GHz) .....



$$\nu_i \cdot n(\nu_i) = \frac{c}{4d}\left(N_i - \frac{2\psi(\nu_i)}{\pi}\right), \quad i = 1, 2$$

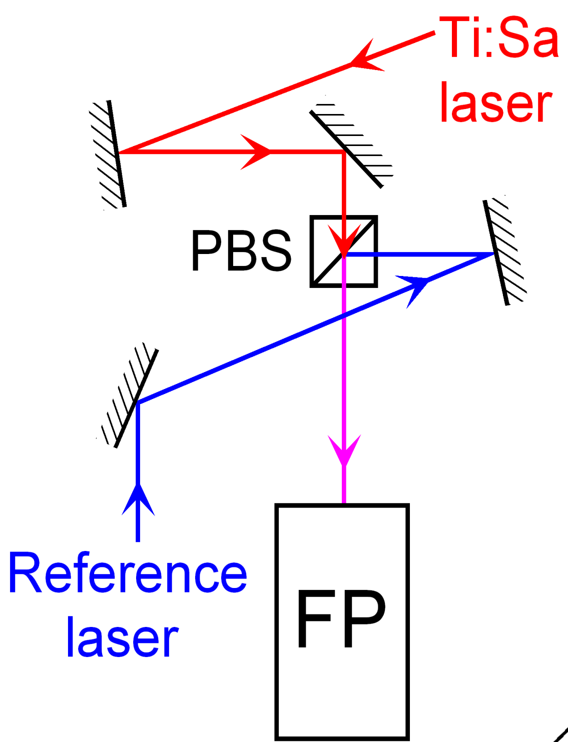
$$\Rightarrow \nu_2 \; n(\nu_2) - \nu_1 \; n(\nu_1) = \frac{c}{4d}\,(N_2 - N_1)$$

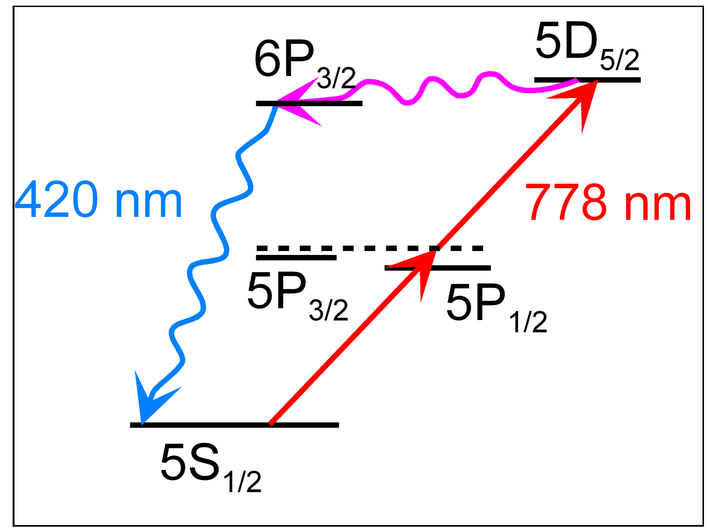
$$\nu_2 \, \frac{n(\nu_2)}{n(\nu_1)} = \nu_1 + \frac{c}{4d \; n(\nu_1)} \cdot (N_2 - N_1)$$

....Measuring the beat signal with a frequency meter (accuracy better than 300 kHz)

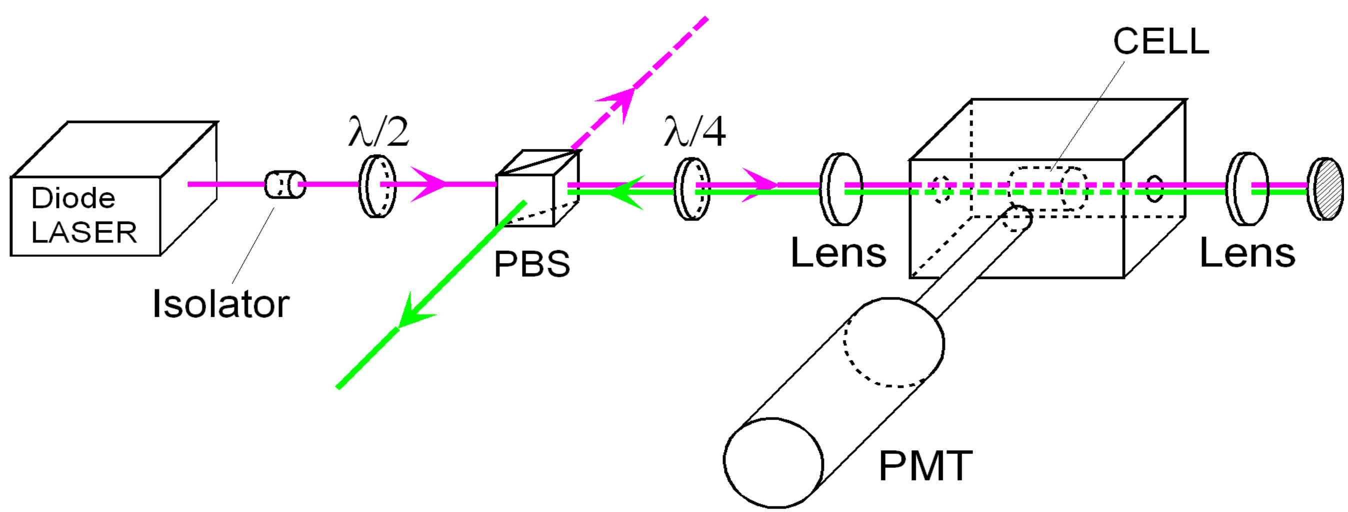
Precision measurements

Secondary frequency standard: Rb 5S – $5D_{5/2}$ 2 photon transition (@ 778 nm) measured with 8 kHz accuracy





Lock-in detection + stabilization



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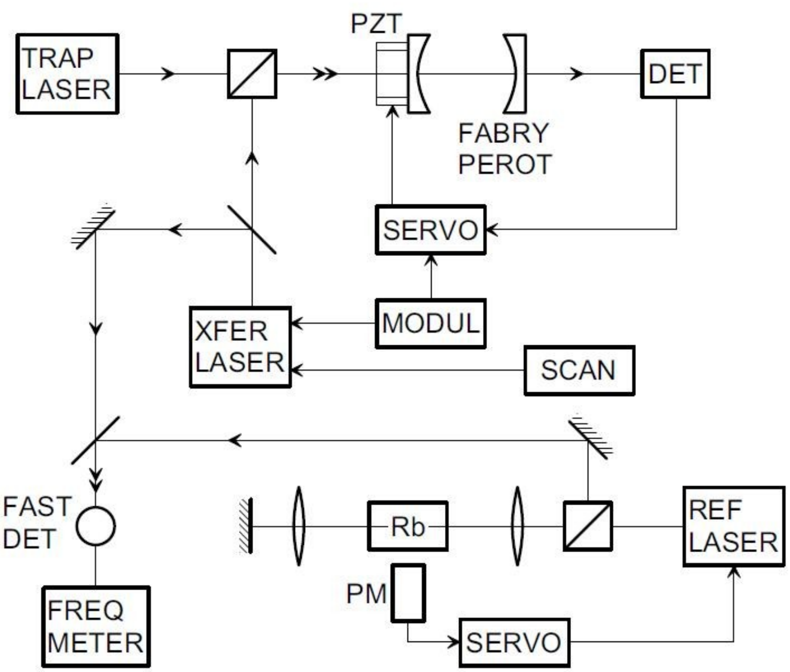

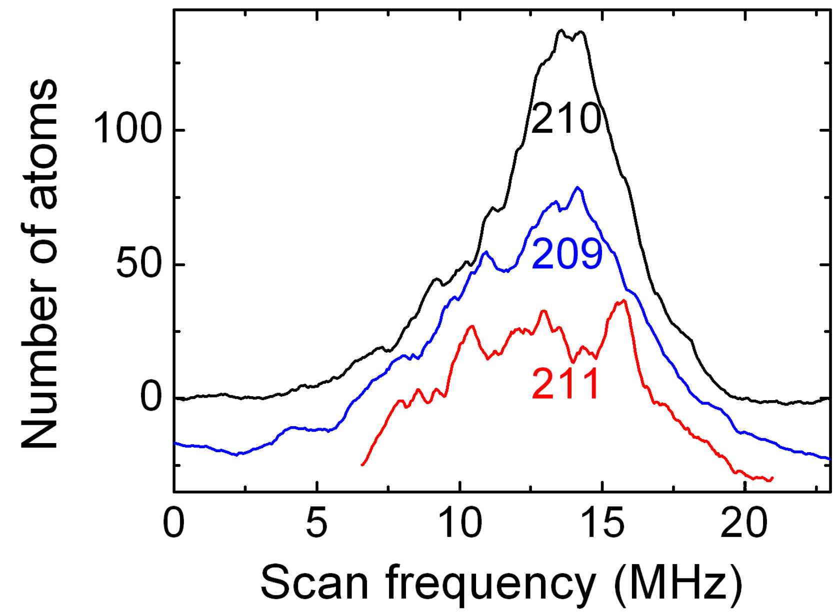

Preliminary measurements:

Isotope	209	210	211
Trapping freq. (GHz)	417415.0914(90)	417412.4493(90)	417412.6303(90)
Repumping freq. (GHz)	366897.43(5)	366898.70(5)	366895.57(5)

Accuracy:

Calibration ➠ 5 MHz

Fabry-Perot maxima ➠ 2 MHz

Refractive index of air ➠ 2 MHz

TOTAL ➠ 9 MHz

Published in Opt. Lett. 34, 893,2009

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MOT dynamics

$$\begin{cases} \dot{N}_t = LN_v - CN_t - BN_t^2 - AN_vN_t - \Gamma_r N_t \\ \dot{N}_v = -(L+W)N_v + CN_t + BN_t^2 + AN_vN_t - \Gamma_r N_v + f \end{cases}$$

$$\begin{cases} \dot{N}_t & = & LN_v - CN_t \\ \dot{N}_v & = & CN_t - LN_v - WN_v + I \end{cases}$$

collision rate

$$L = \frac{1}{4\sqrt{\pi}} \frac{{v_c}^4}{{v_T}^3} \frac{3\,\pi\, w^2}{4\,\pi\, R^3}$$

loading rate

$$W \equiv \frac{1}{\tau_{loss}} \equiv \frac{1}{\tau_{esc}} + \frac{1}{\tau_{sto}} + \frac{1}{\tau_{dec}}$$

250 ms

1500 ms

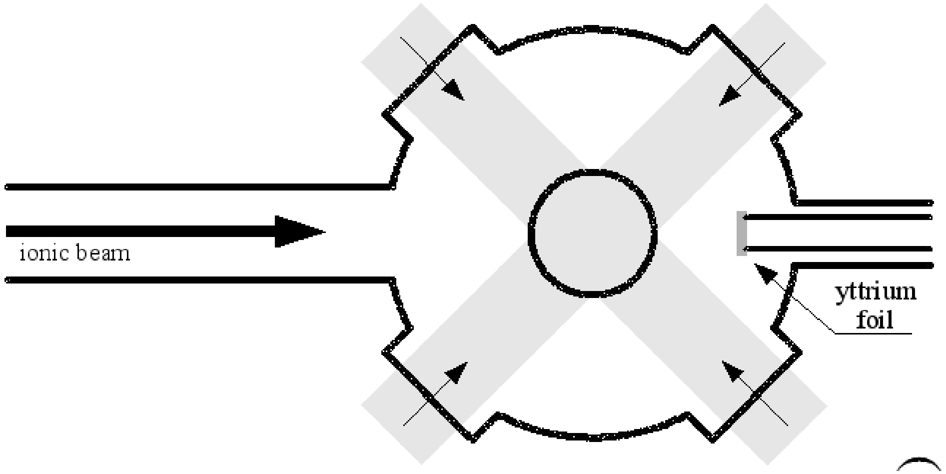
275 s

lossrate

$$N_t = \frac{LI}{CW} \quad N_v = N_{eq} = \frac{I}{W}$$

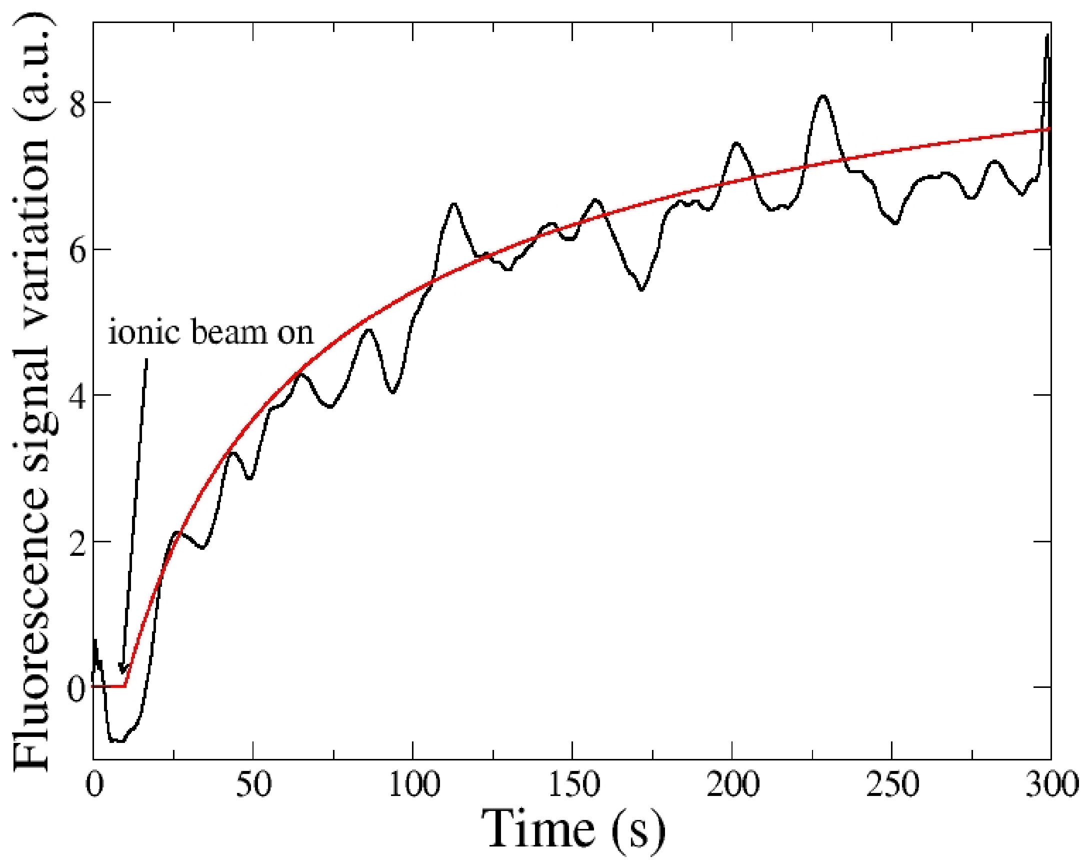
$$N_t = \frac{3}{8\sqrt{\pi}} \left(\frac{v_c}{v_{th}}\right)^4 \frac{R_b^2 lI}{Cr^3} \frac{1}{1 + \frac{6lR^2}{\chi r^3}}$$

Tests on neutraliser



from calculated implantation depth of 49 Å diffusion coefficient is determined

$$\frac{\partial N(x,t)}{\partial t} = D\frac{\partial^2 N(x,t)}{\partial x^2} - \Gamma_r N(x,t) + \varphi(x,t)$$

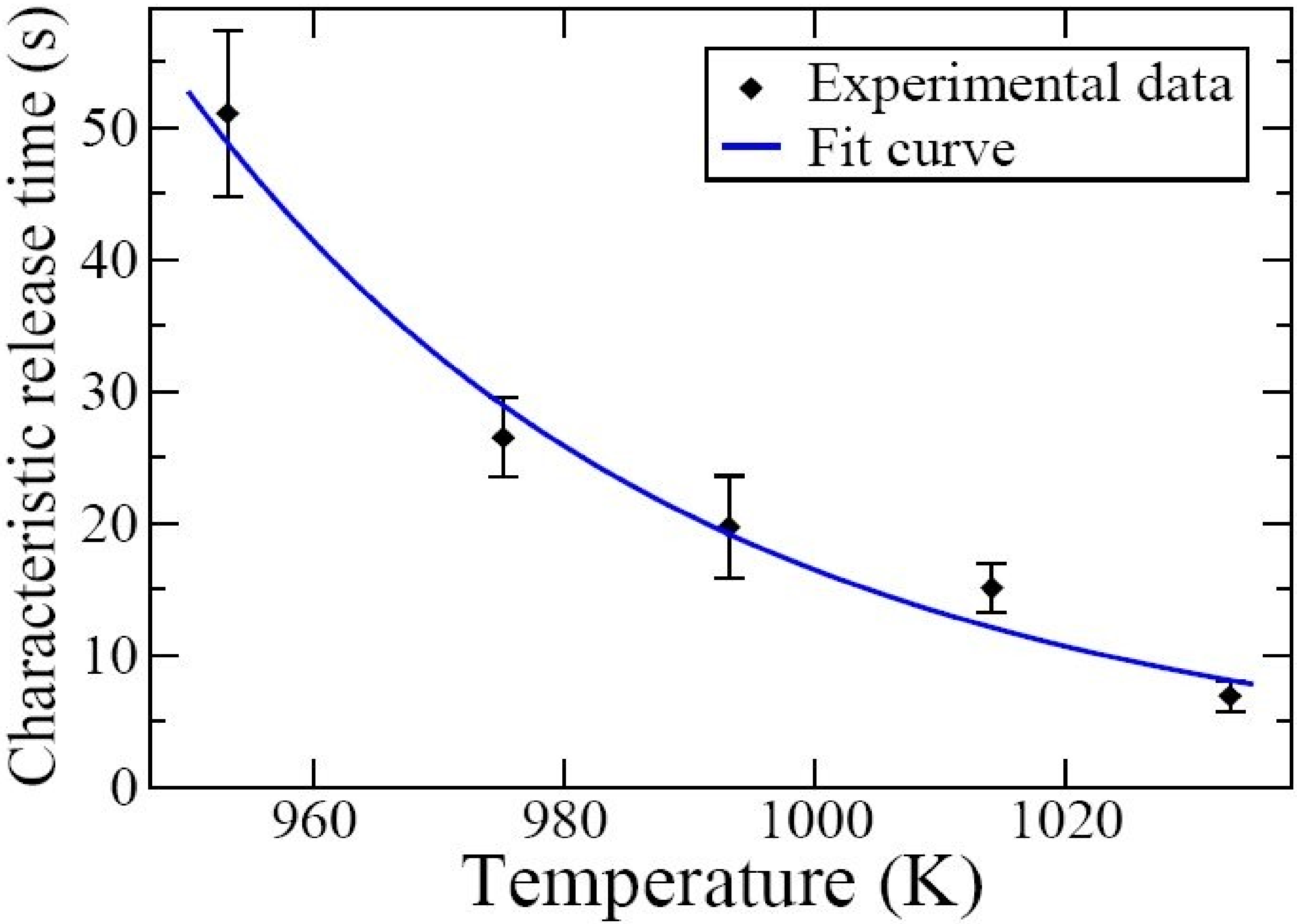


Diffusion time measurements

fit function comes from diffusion equation in the neutraliser

parameters of fit

τ_d , $A \propto N_0$



from calculated implantation depth of 51 Å diffusion coefficient of Fr is determined for the first time

Published in Phys.Rev.A**78**, 063415 2008

Diffusion time measurements

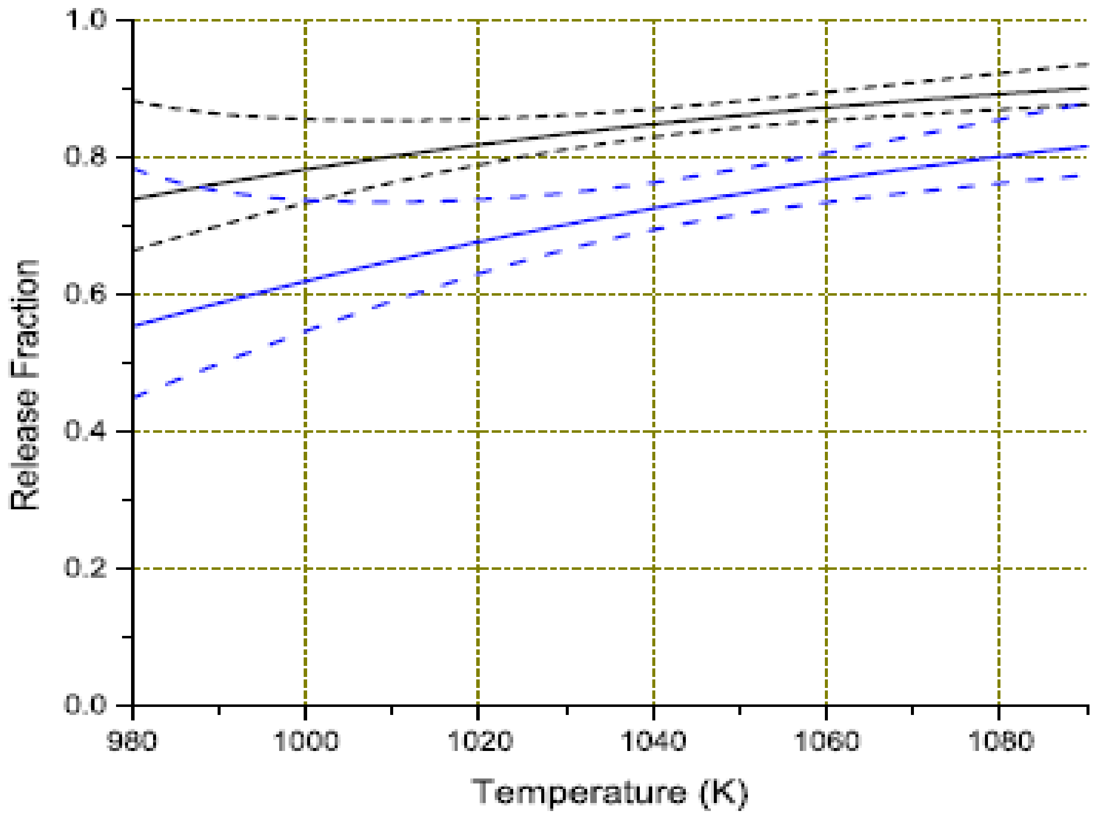
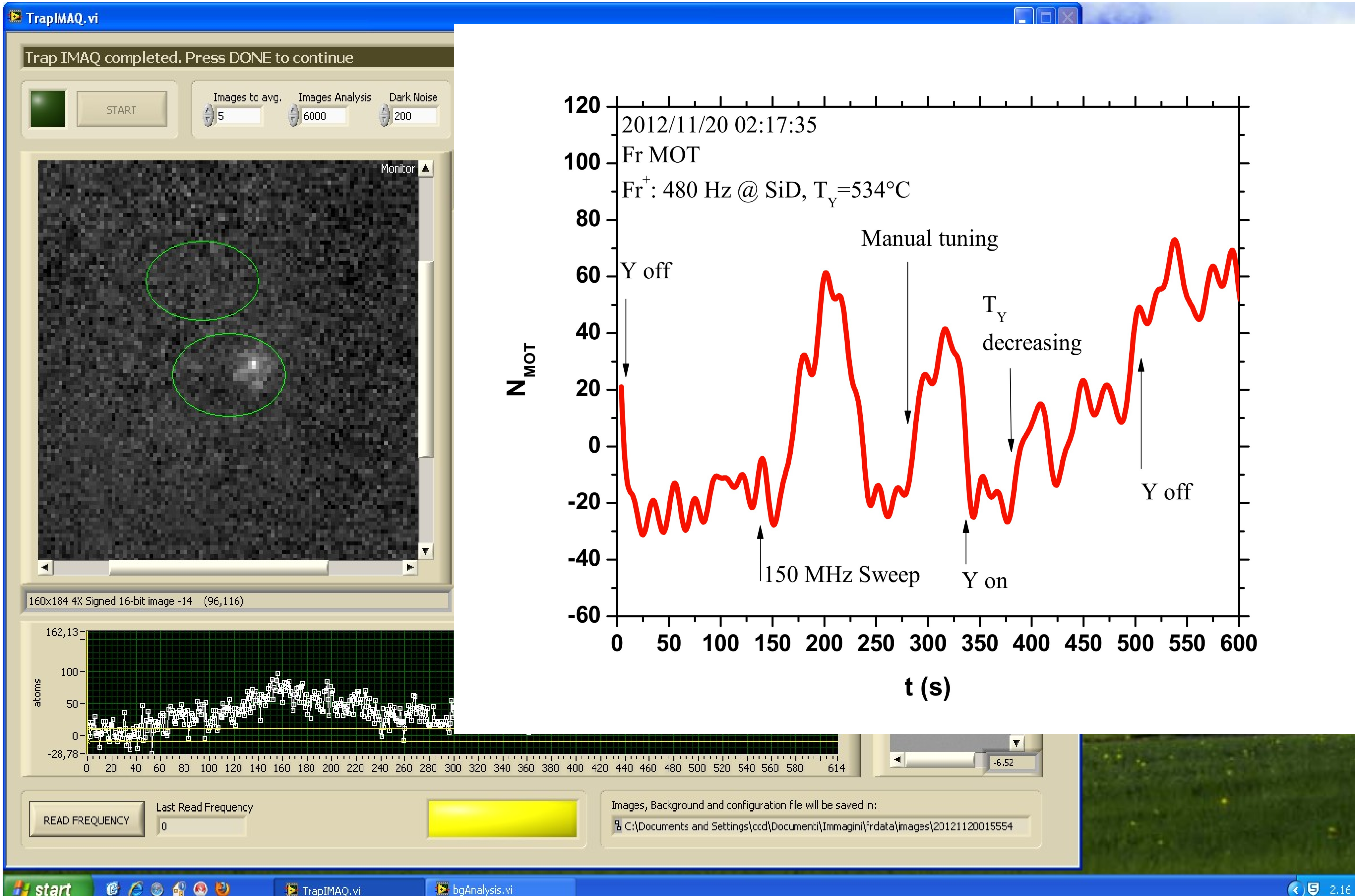


FIG. 8. (Color online) Calculated release fraction vs temperature for isotope 210 (black curve) and 209 (blue curve), according to the Arrhenius law and E_a and τ_{1000} given from our fit. Dashed curves give the uncertainty interval.

Neutralizer behaves pretty well!

Room temperature neutralizer trap!



beam time of november

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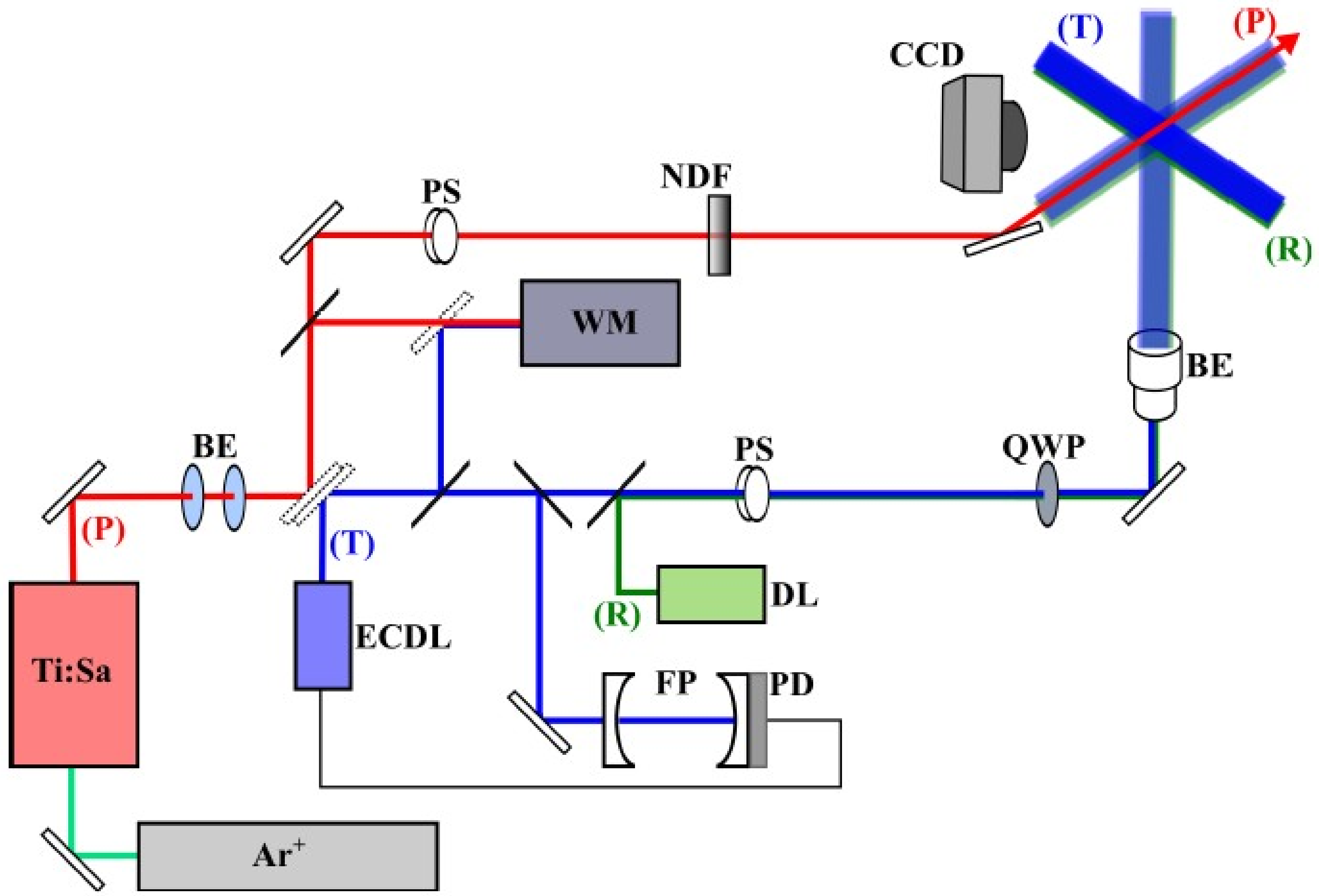
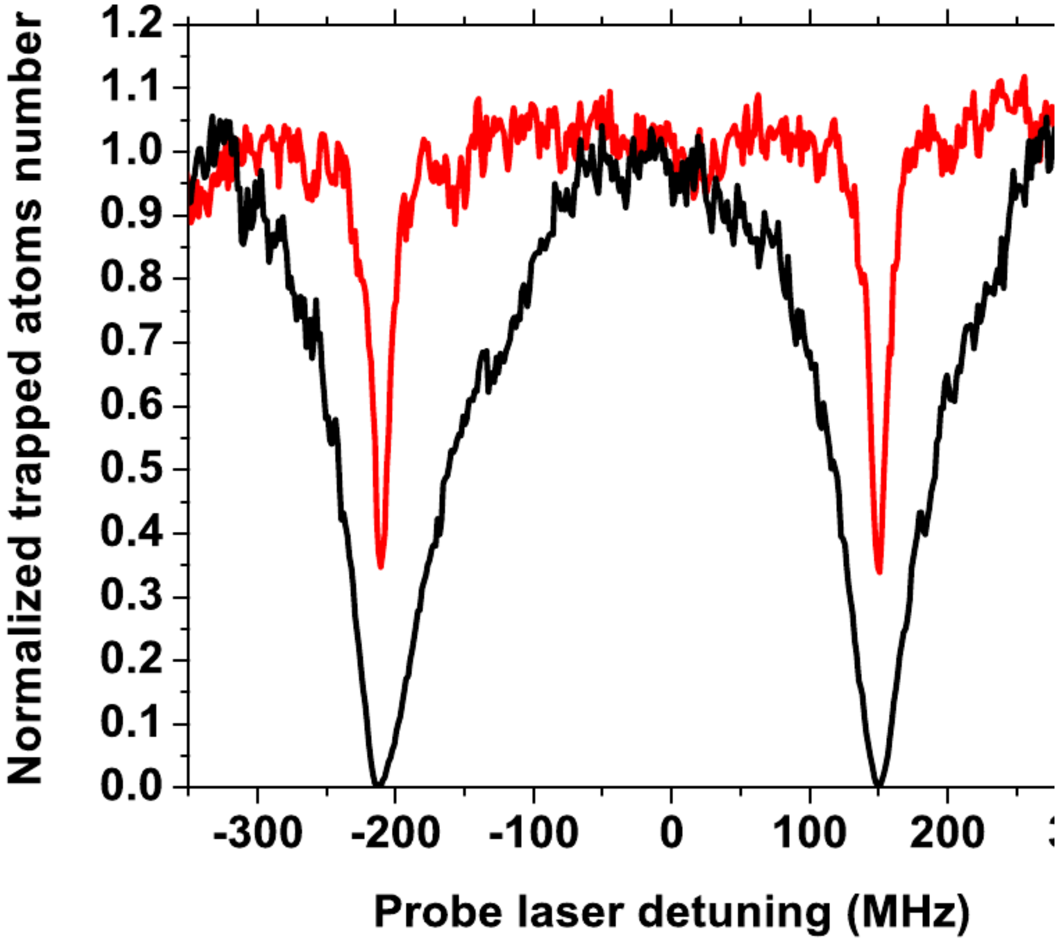
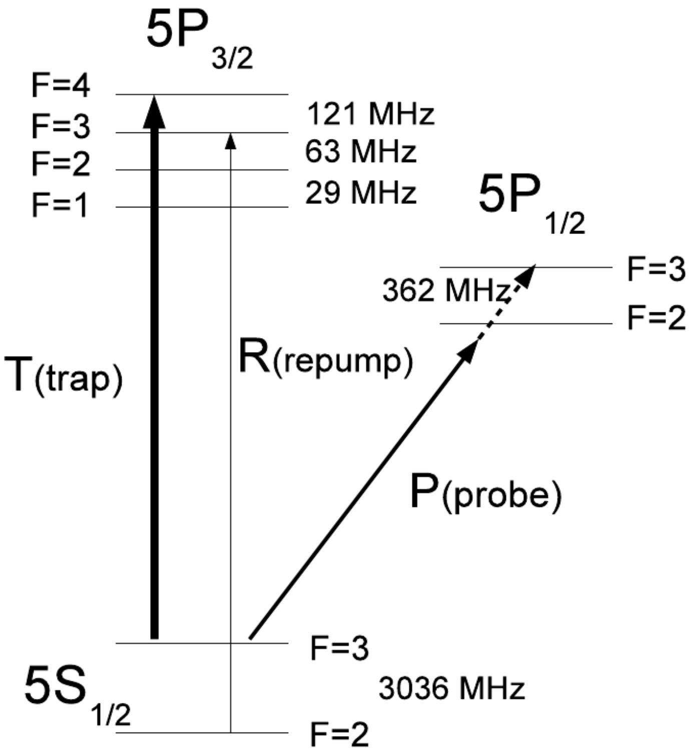
Detection setup (Rubidium)



Detection results (Rb)





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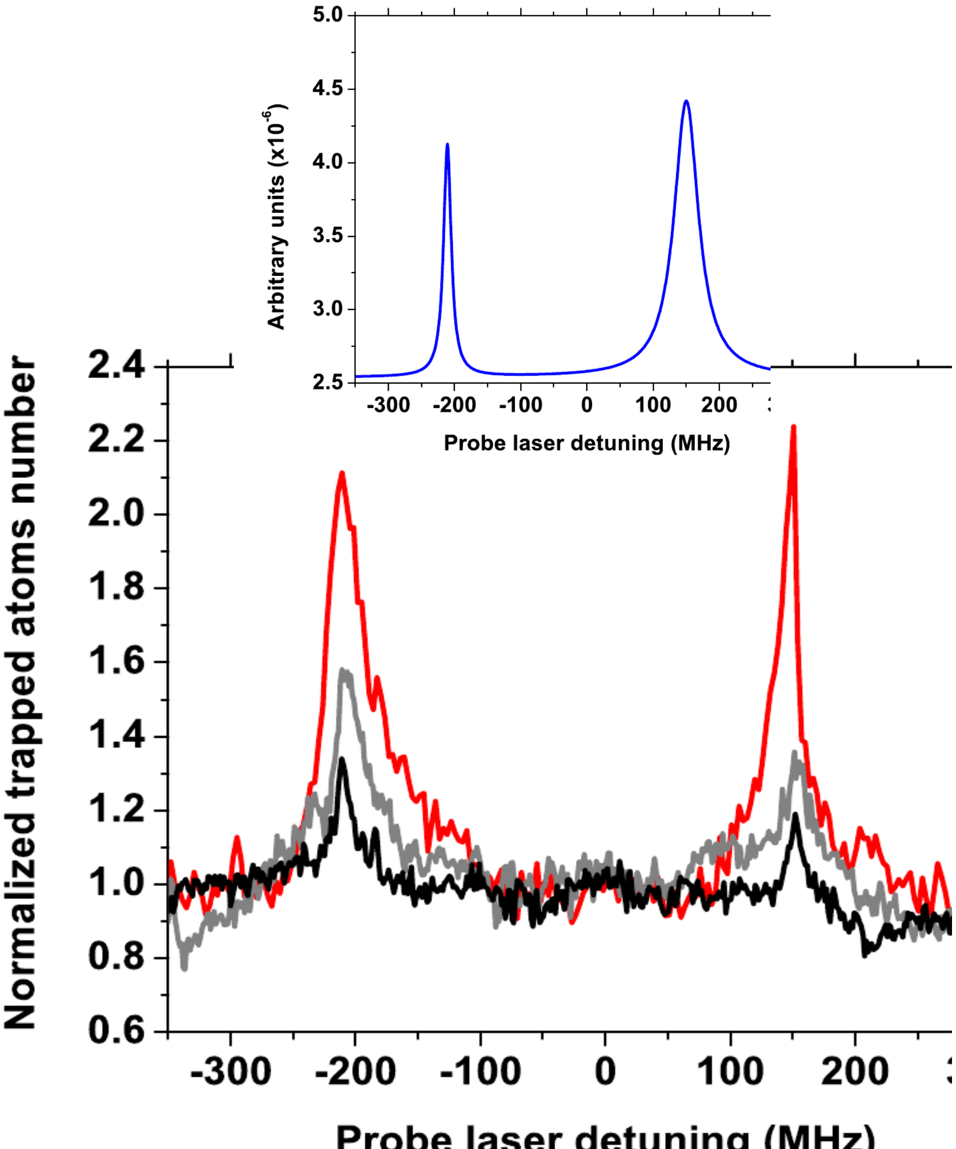

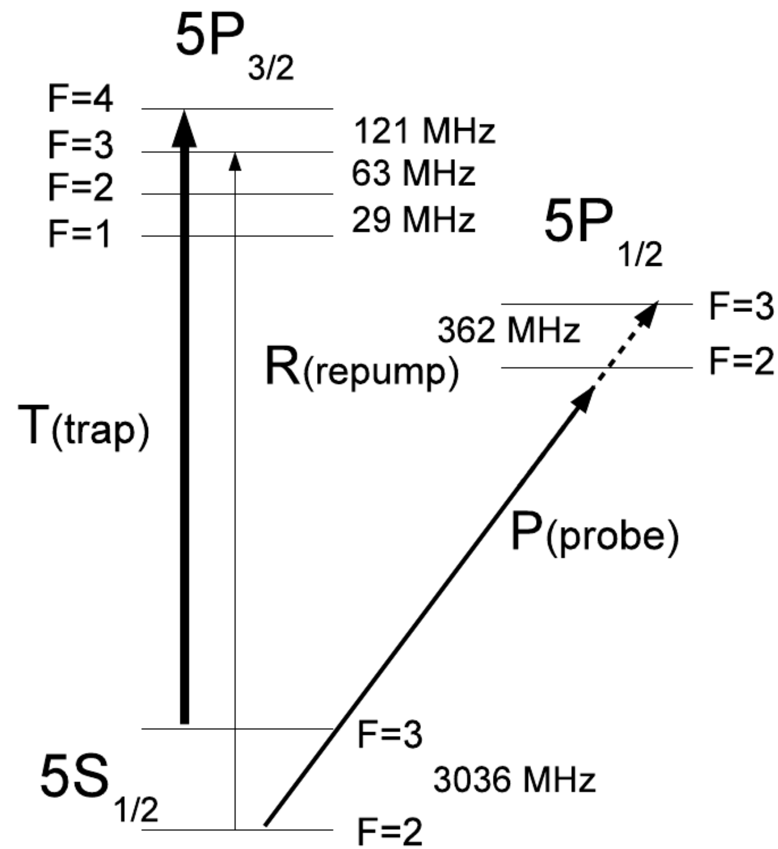

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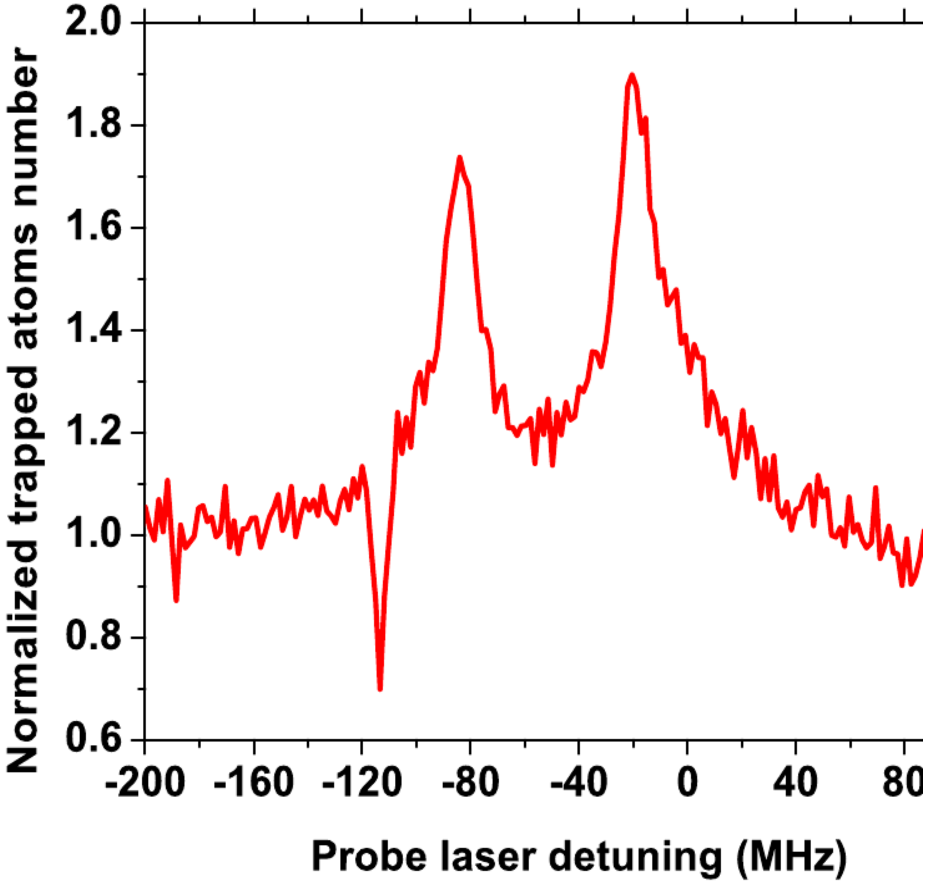

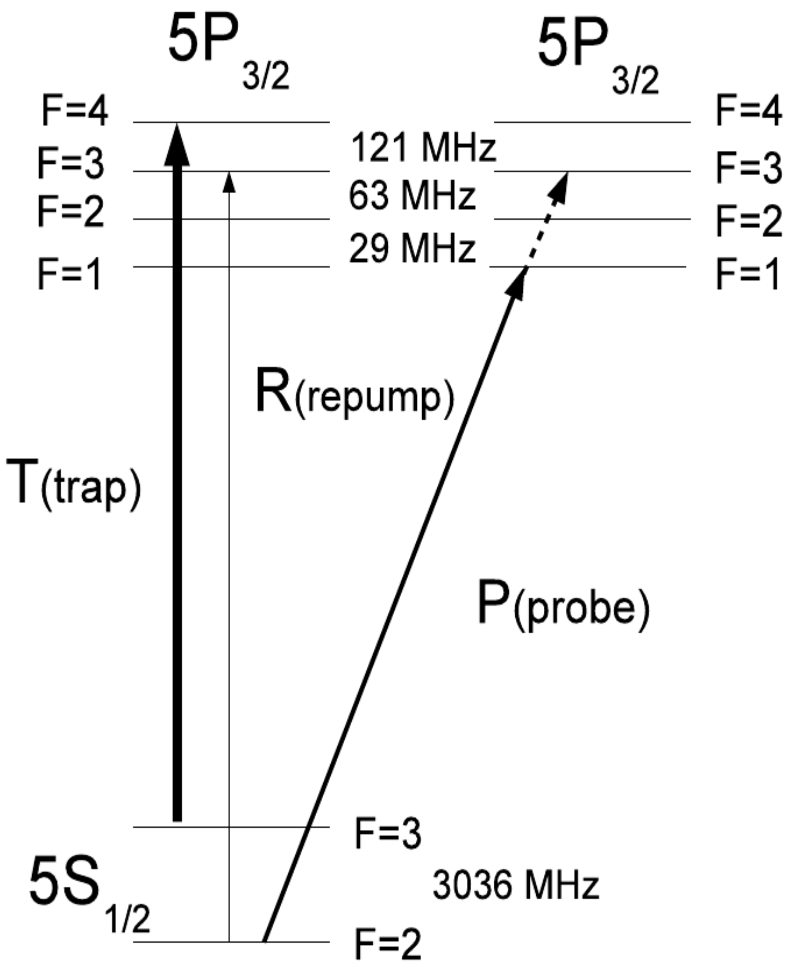

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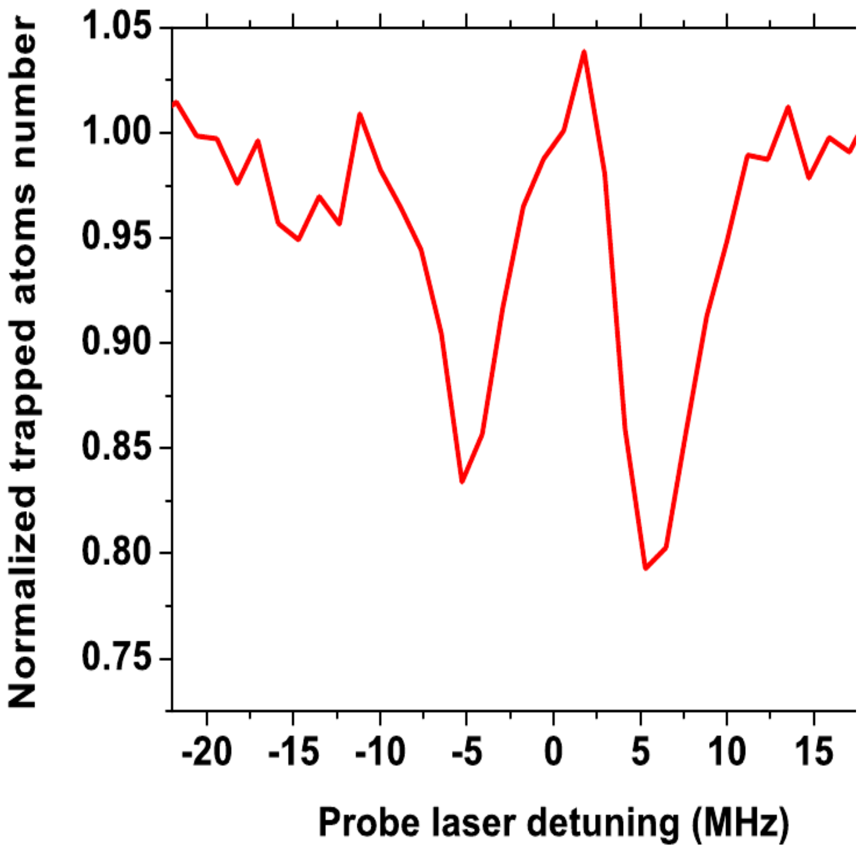

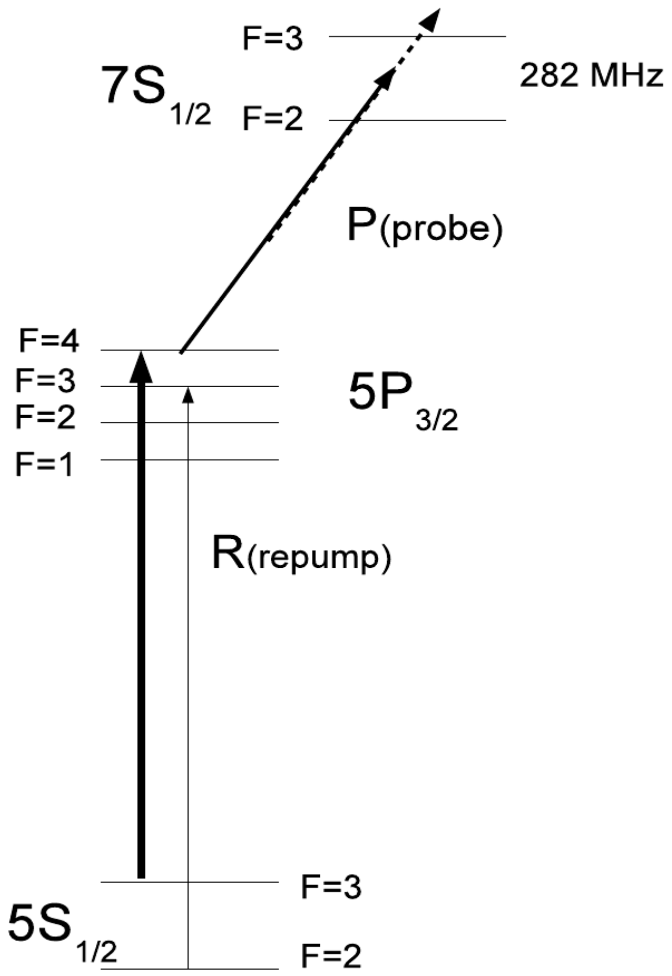

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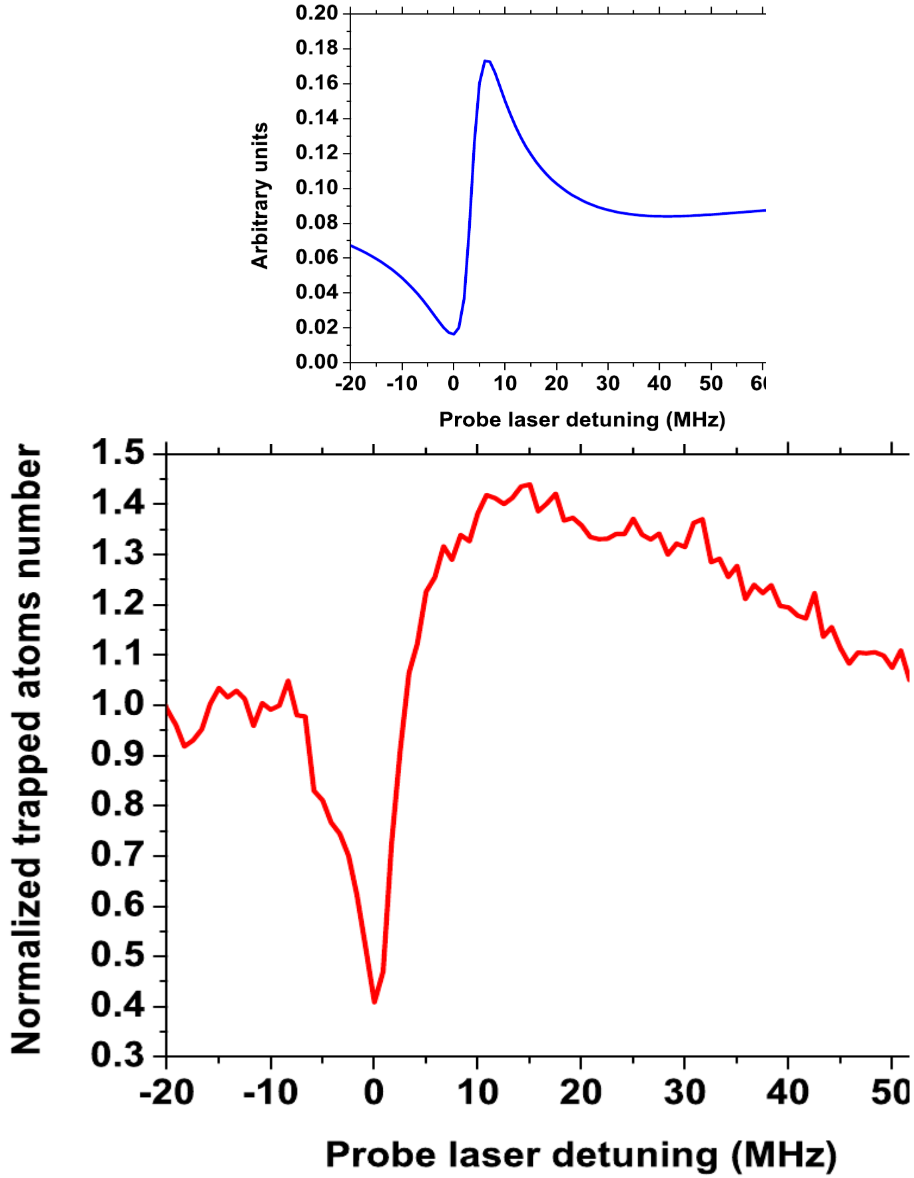

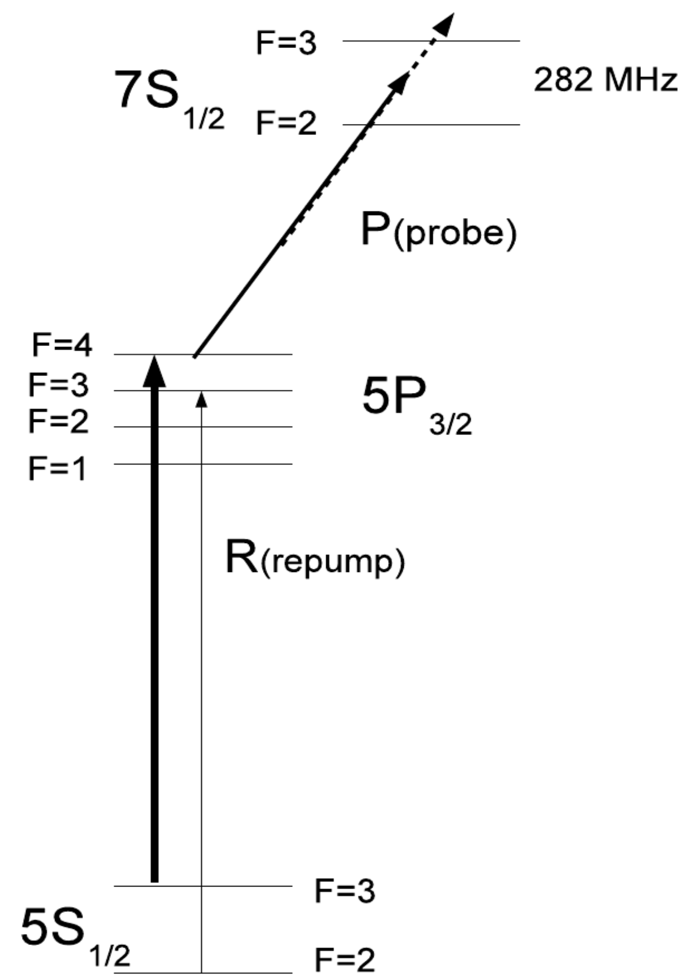

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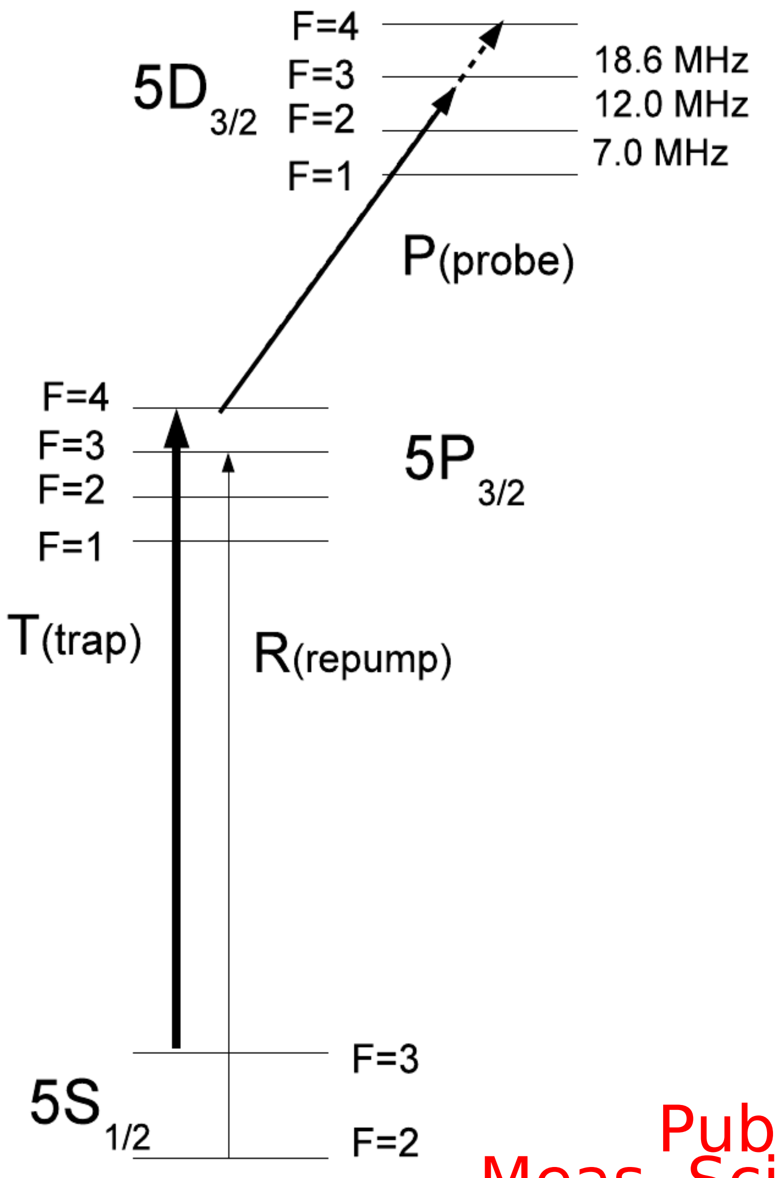

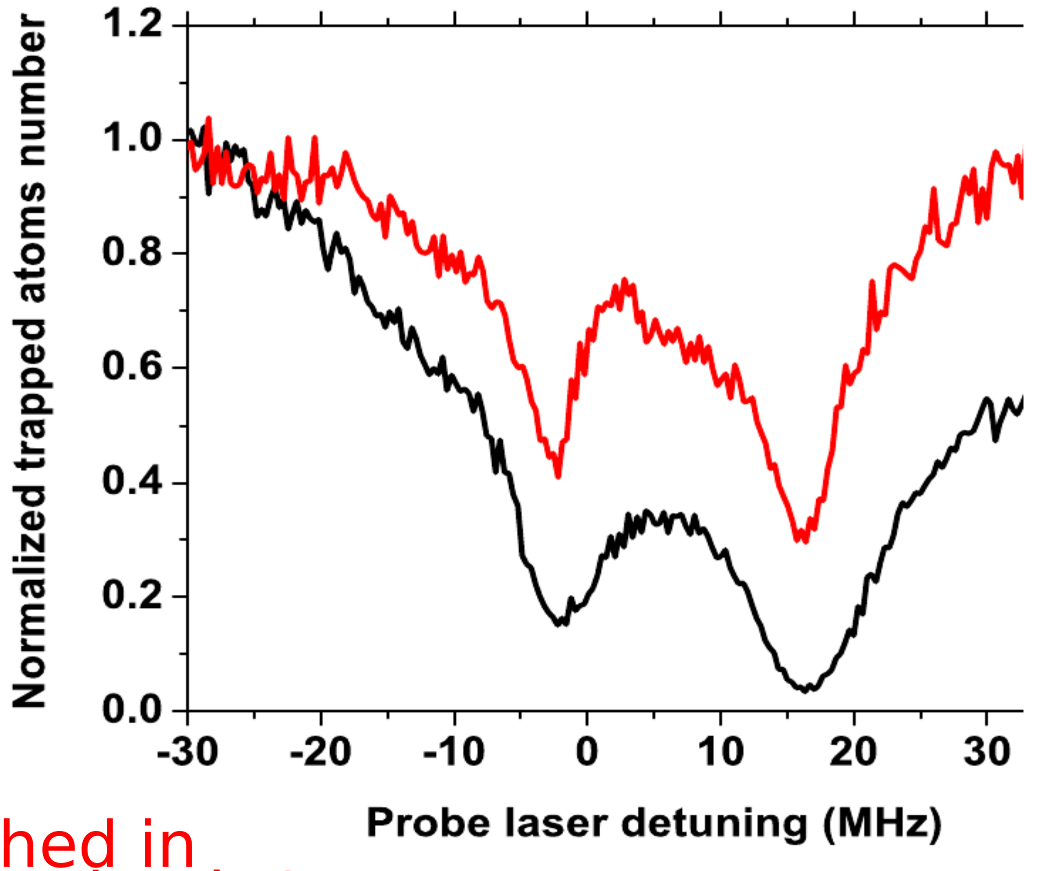

Published in
Meas. Sci. Technol. **24**,
015201 2012

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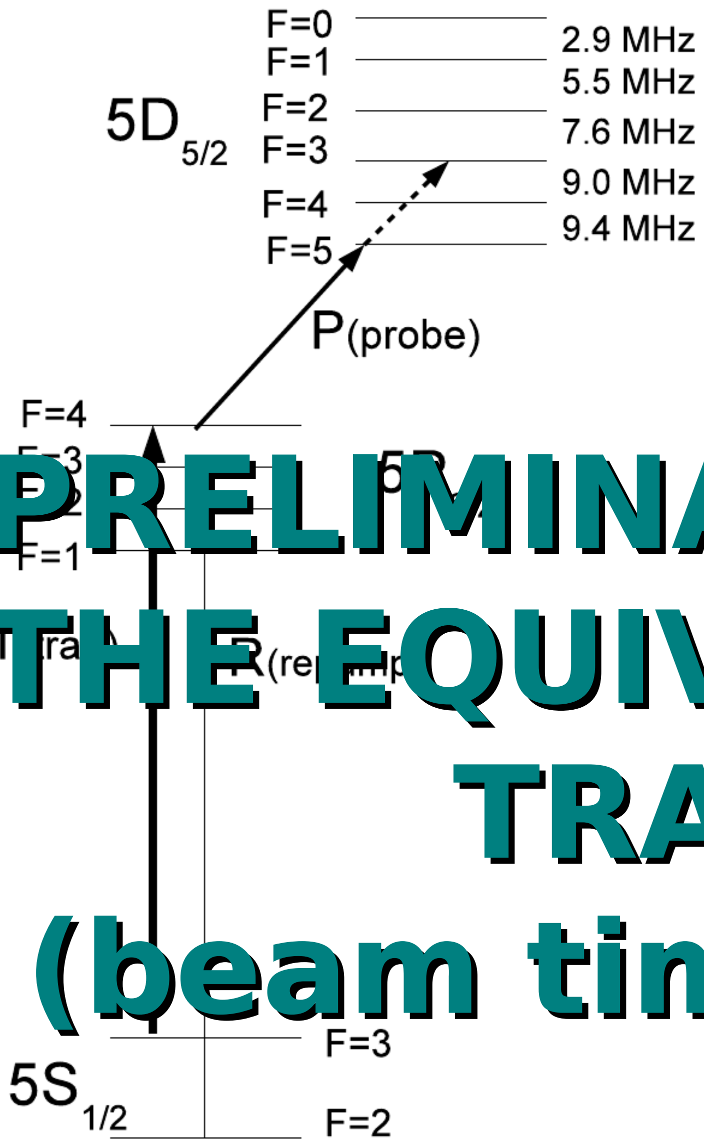

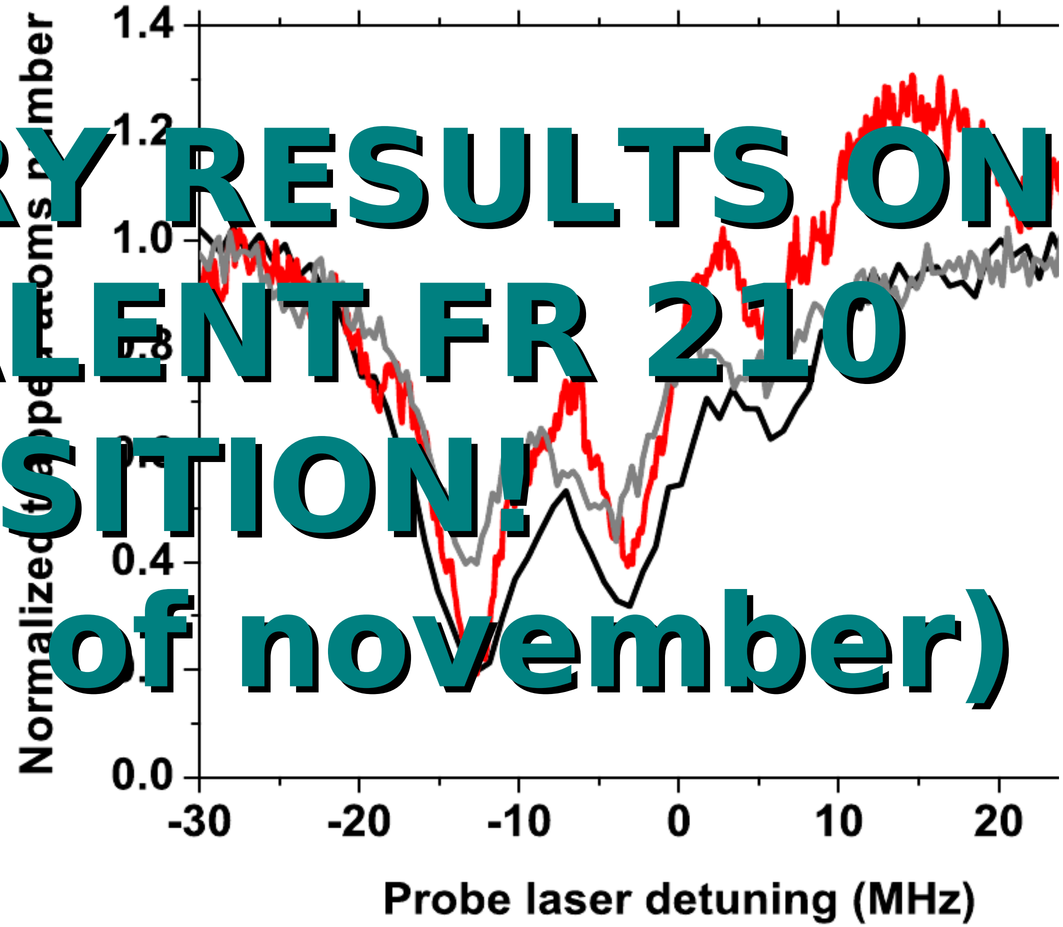

PRELIMINARY RESULTS ON THE EQUIVALENT FR 210 TRANSITION!

(beam time of november)

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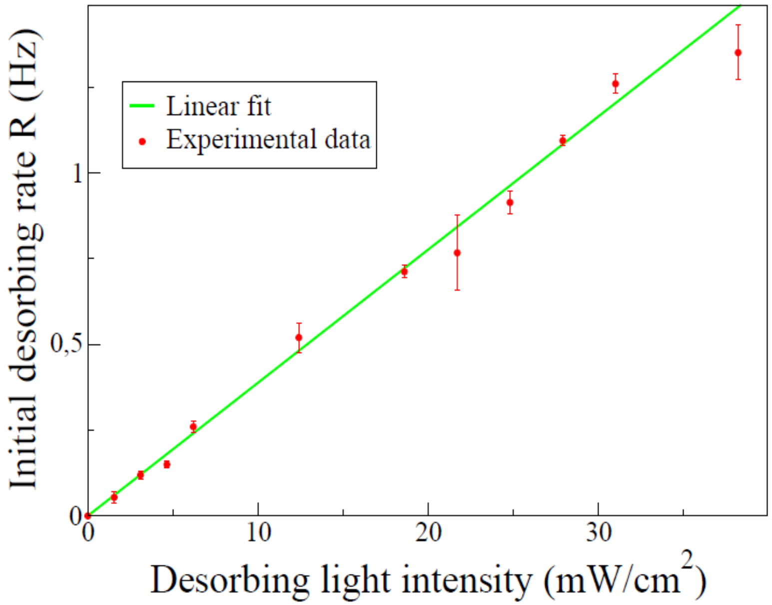
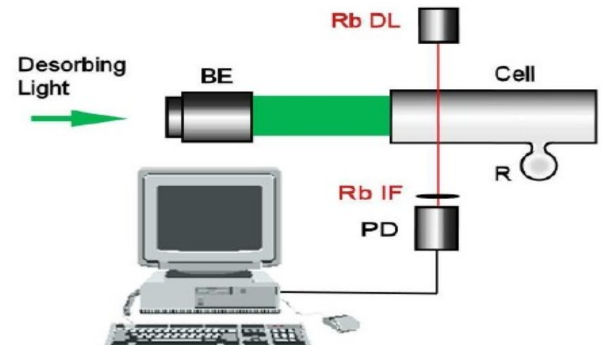
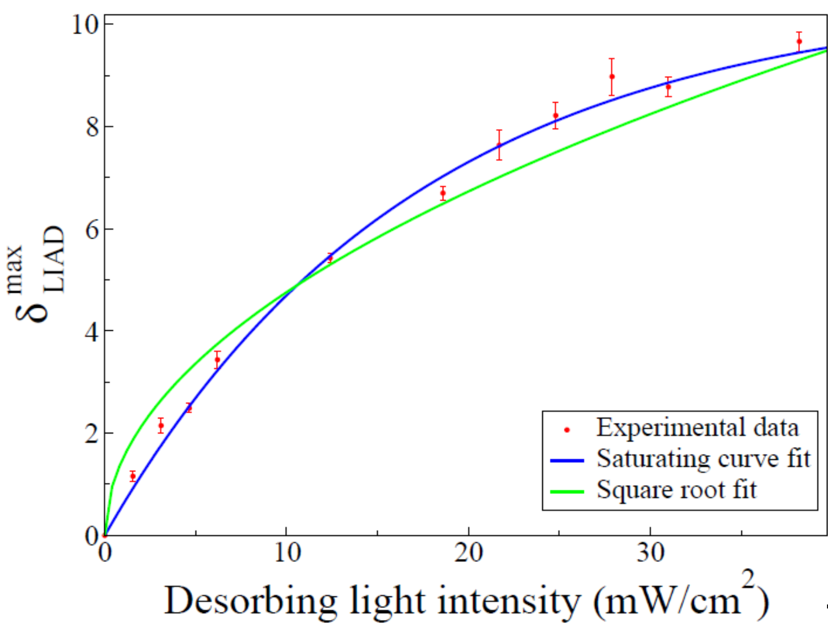
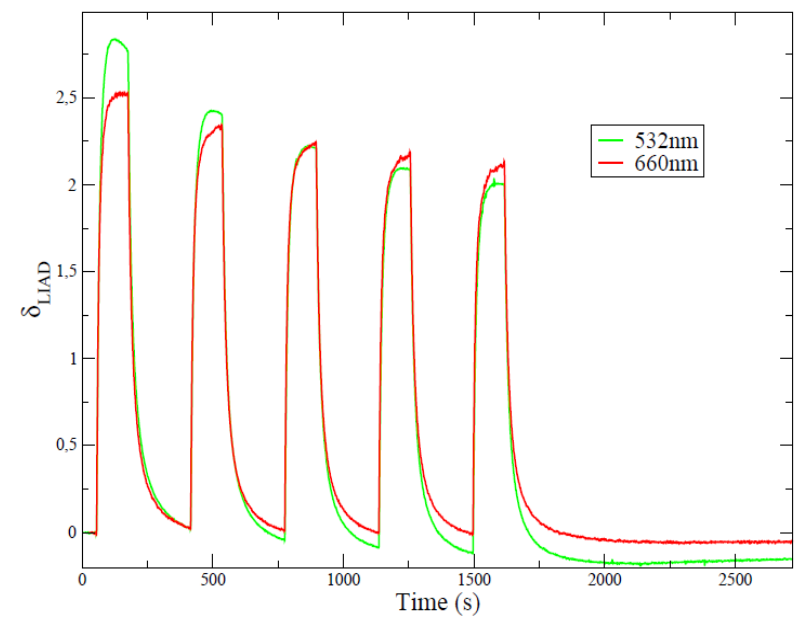
Rb desorption from OTS coated pyrex





$$\eta \sim 5,3 \times 10^{11} \frac{\text{atoms}}{\text{J}} \qquad \gamma \sim 2,1 \times 10^{-7} \frac{\text{atoms}}{\text{photon}}$$





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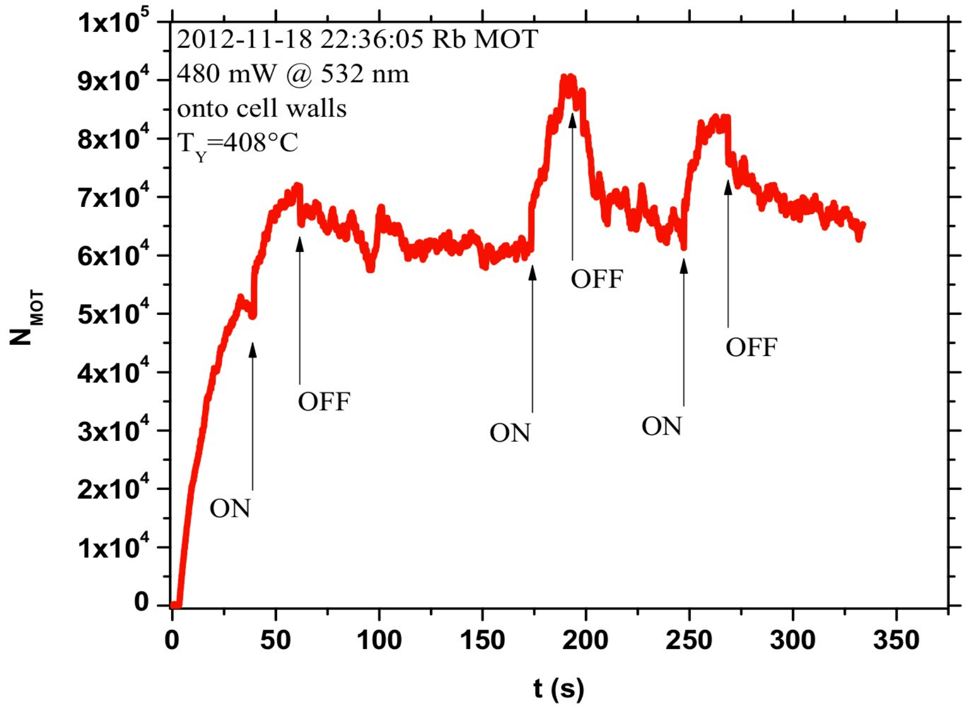
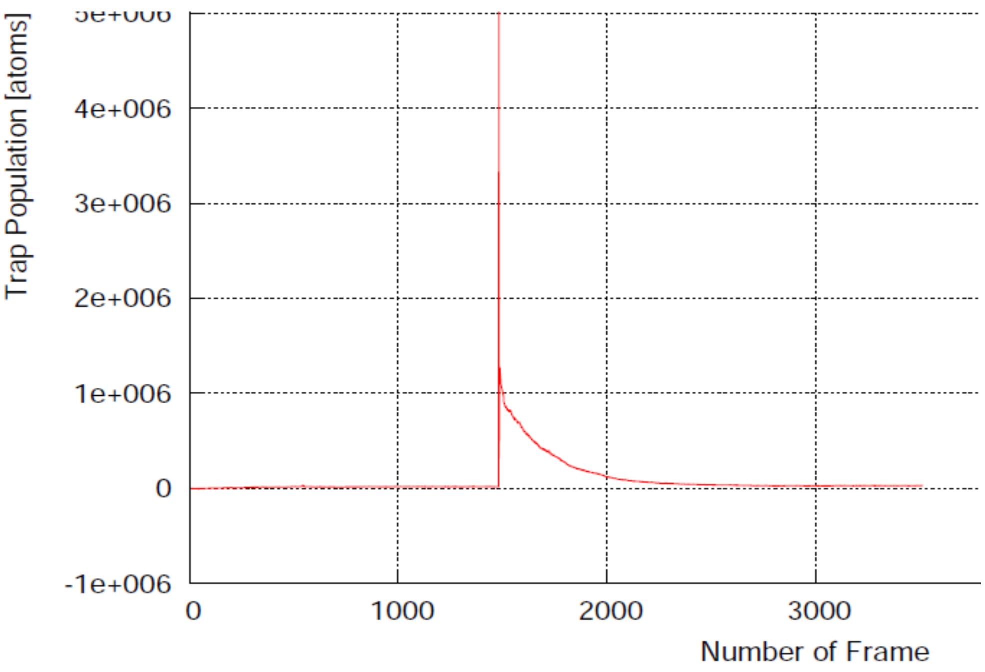
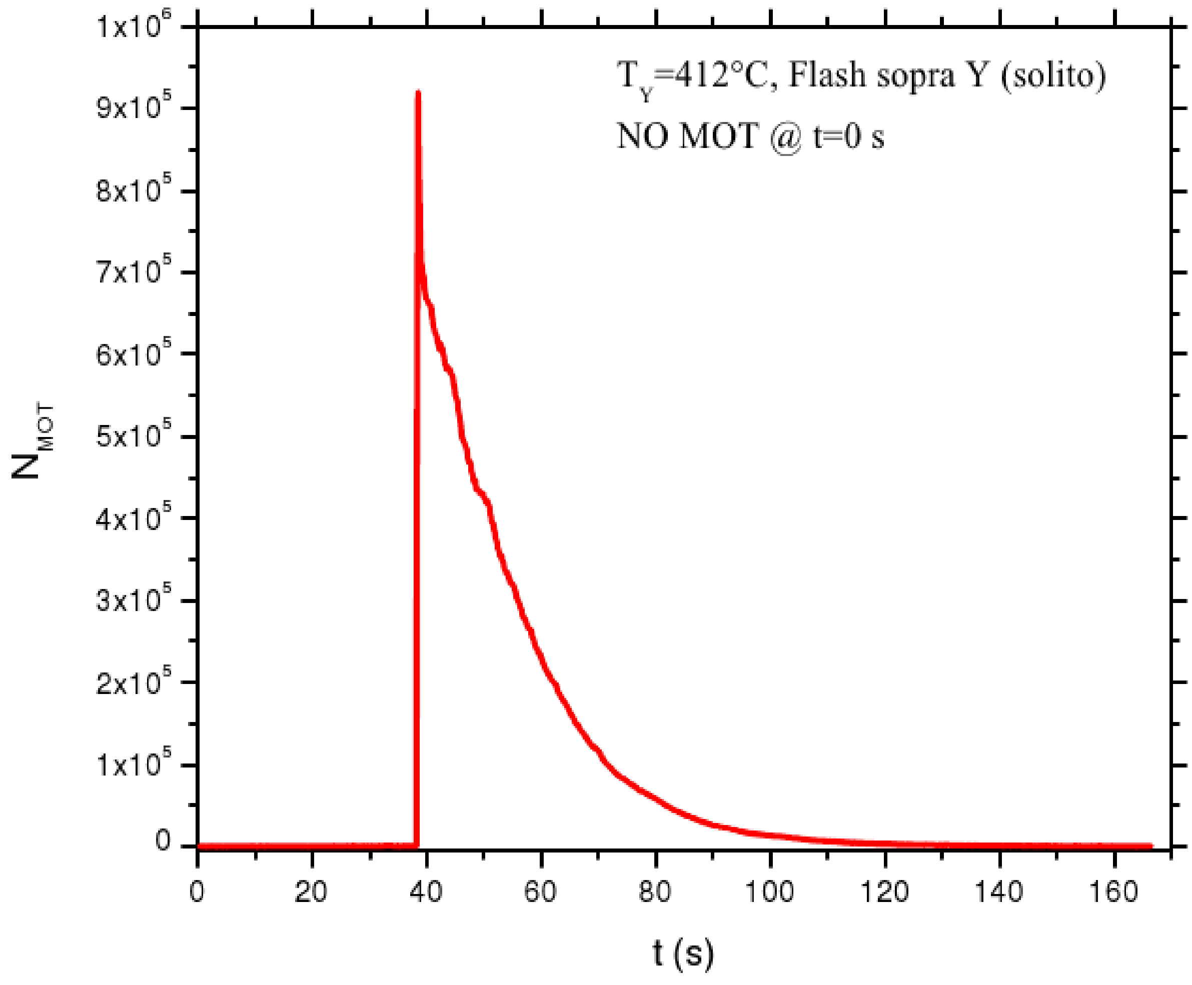
Rb MOT loading from OTS



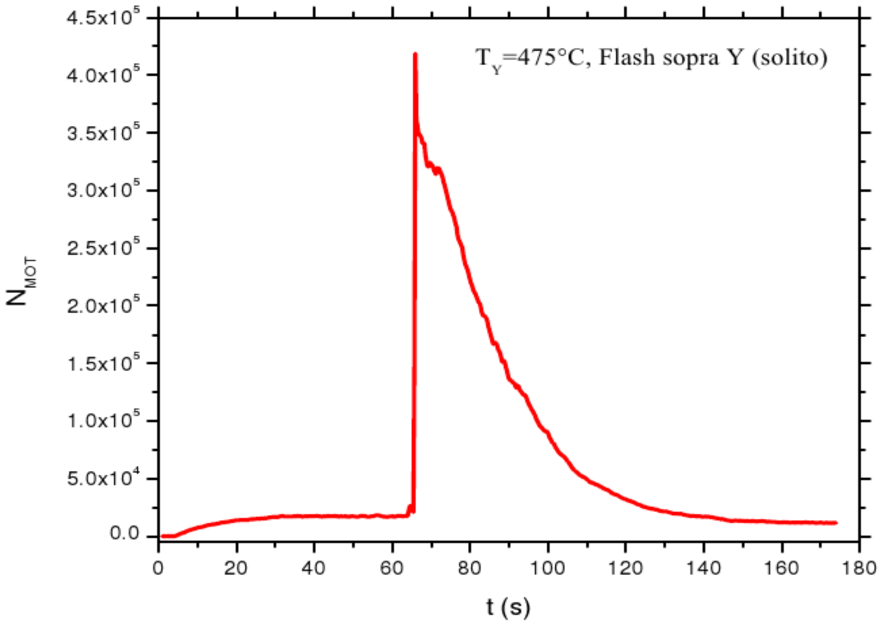


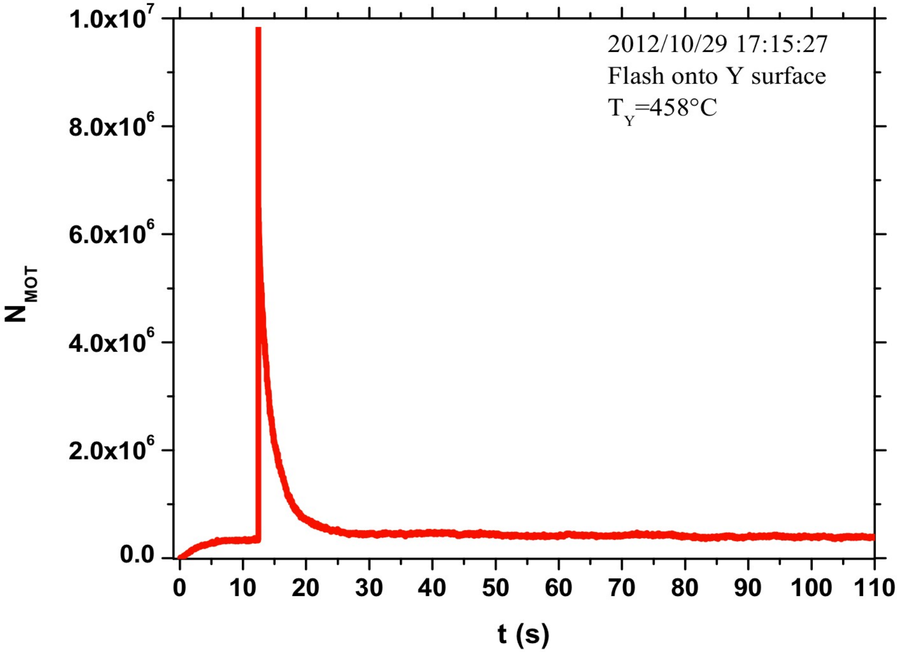
Rb MOT loading from Yttrium!



No MOT at the beginning
Very long restoring time

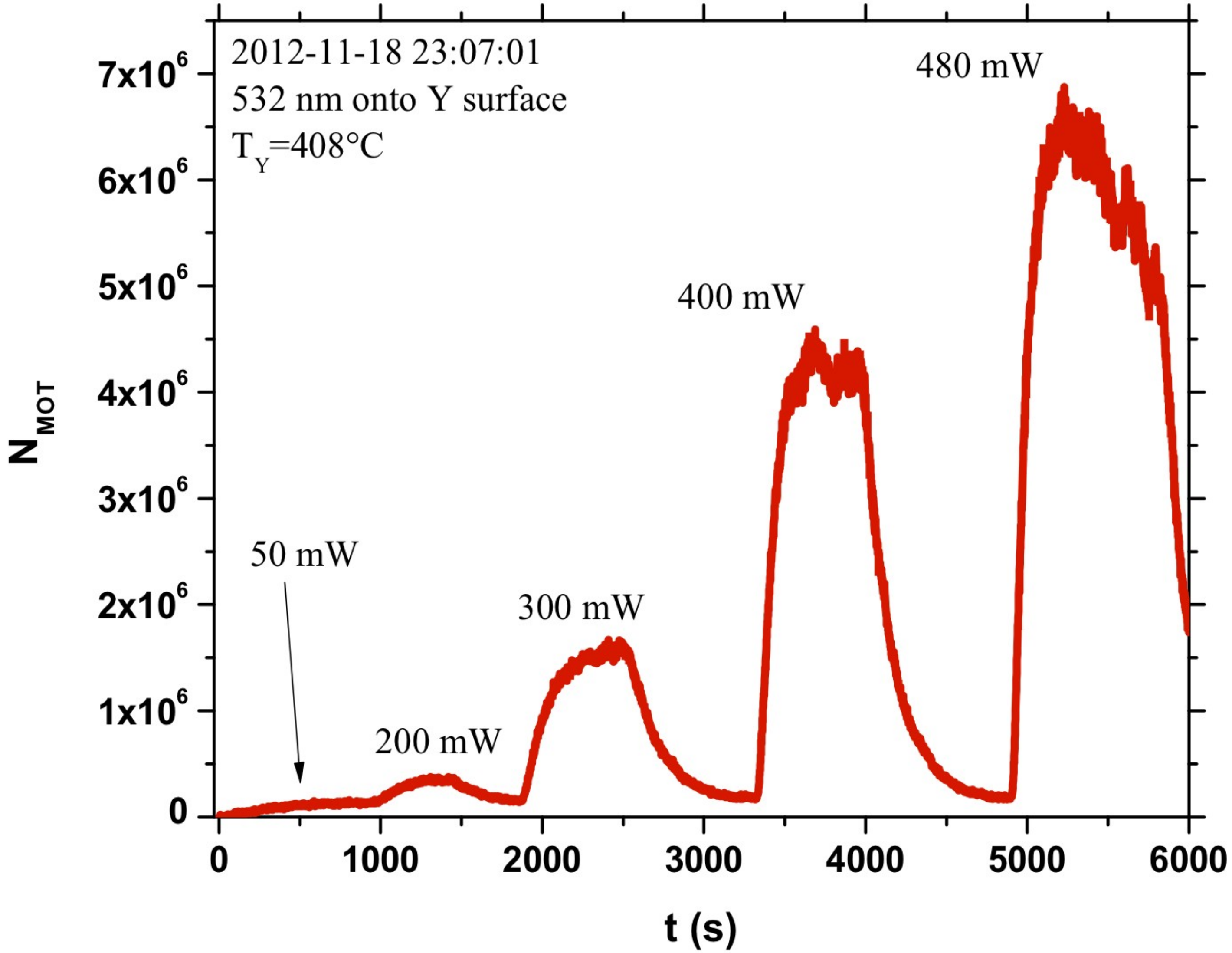
Rb MOT loading from Yttrium!





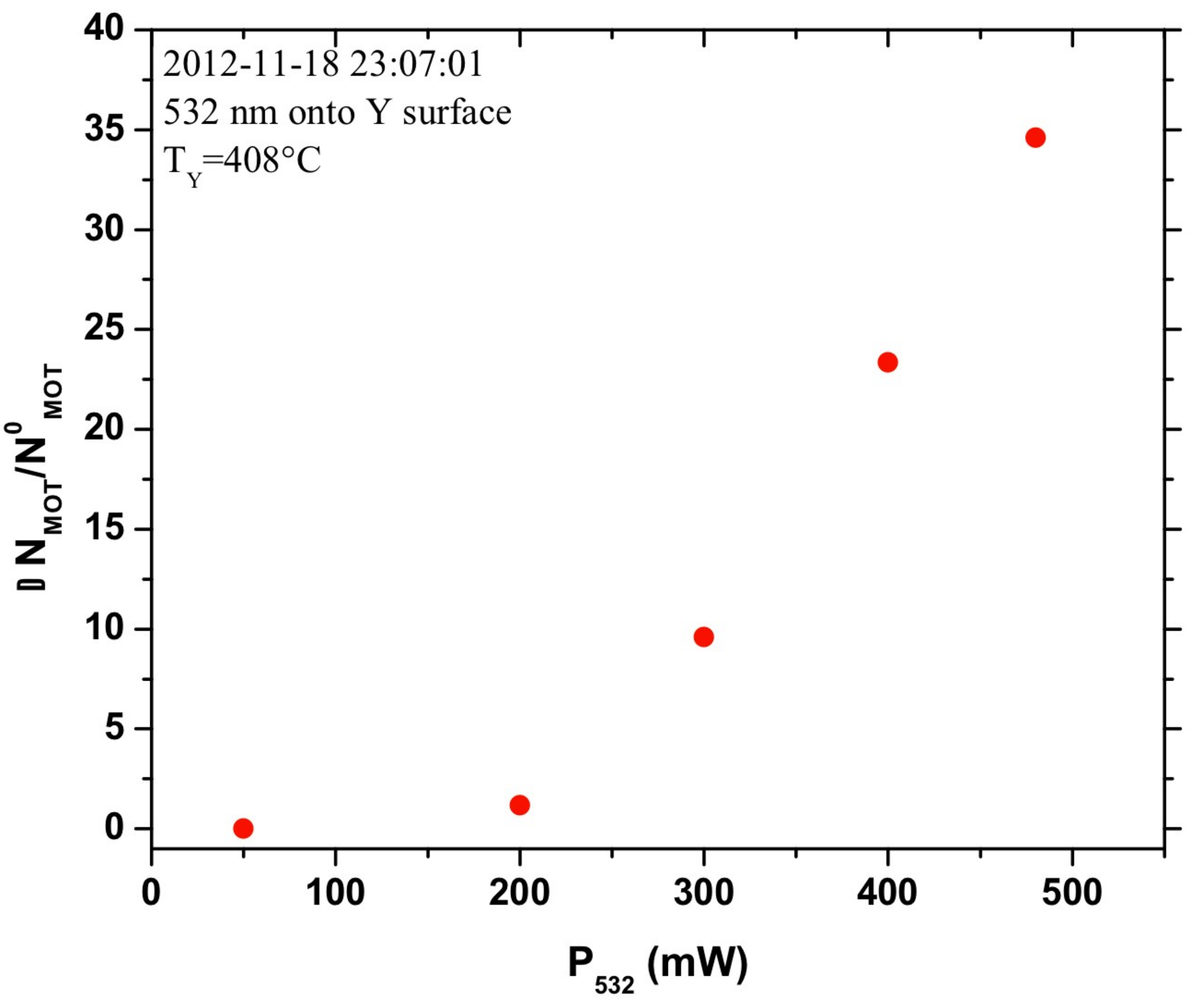
MOT at the beginning
Very long restoring time

Rb MOT loading from Yttrium!



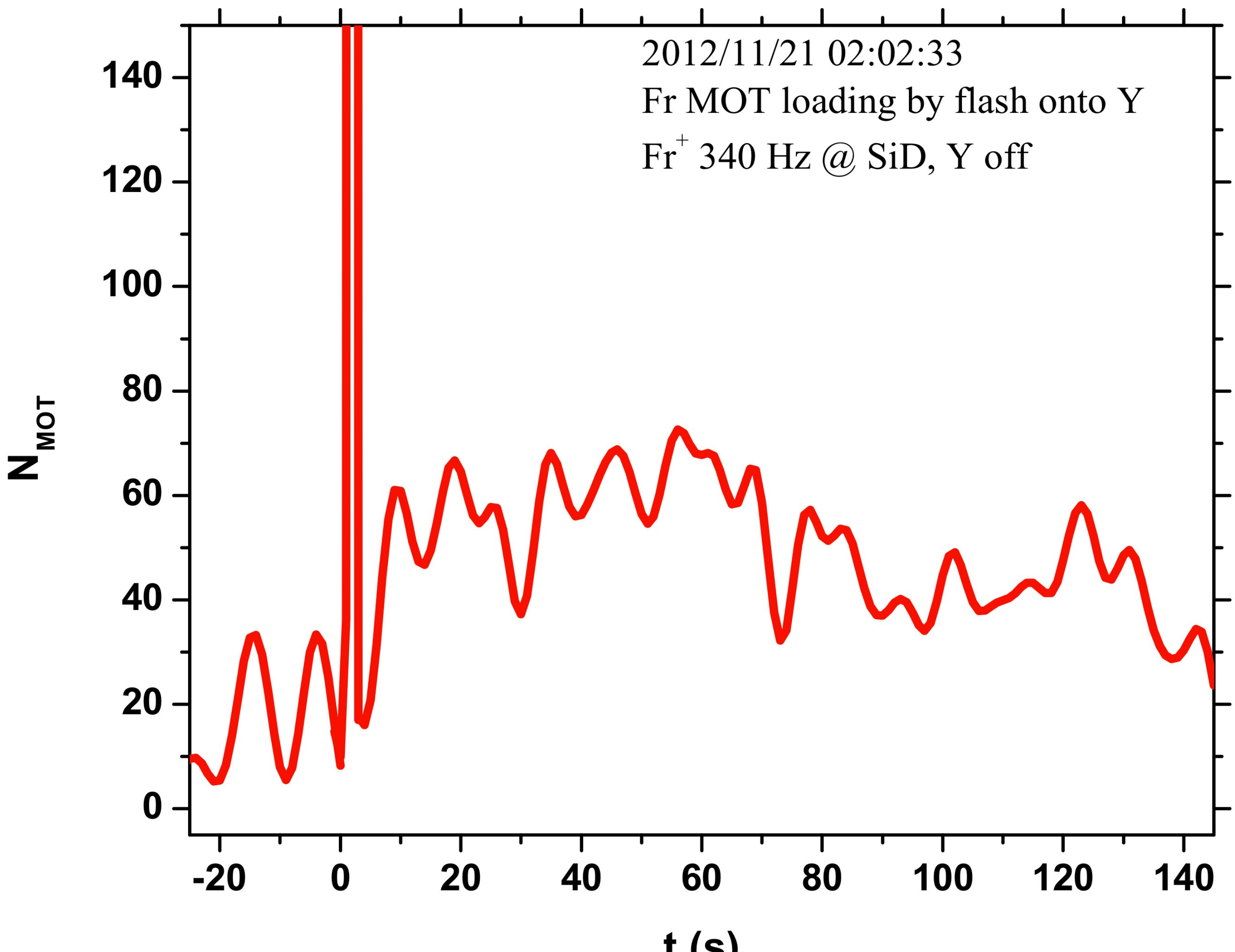
"Millennia" laser used as a desorption light

Rb MOT loading from Yttrium!



“Millennia” laser used as a desorption light

Fr LIAD MOT loading from Yttrium!!!

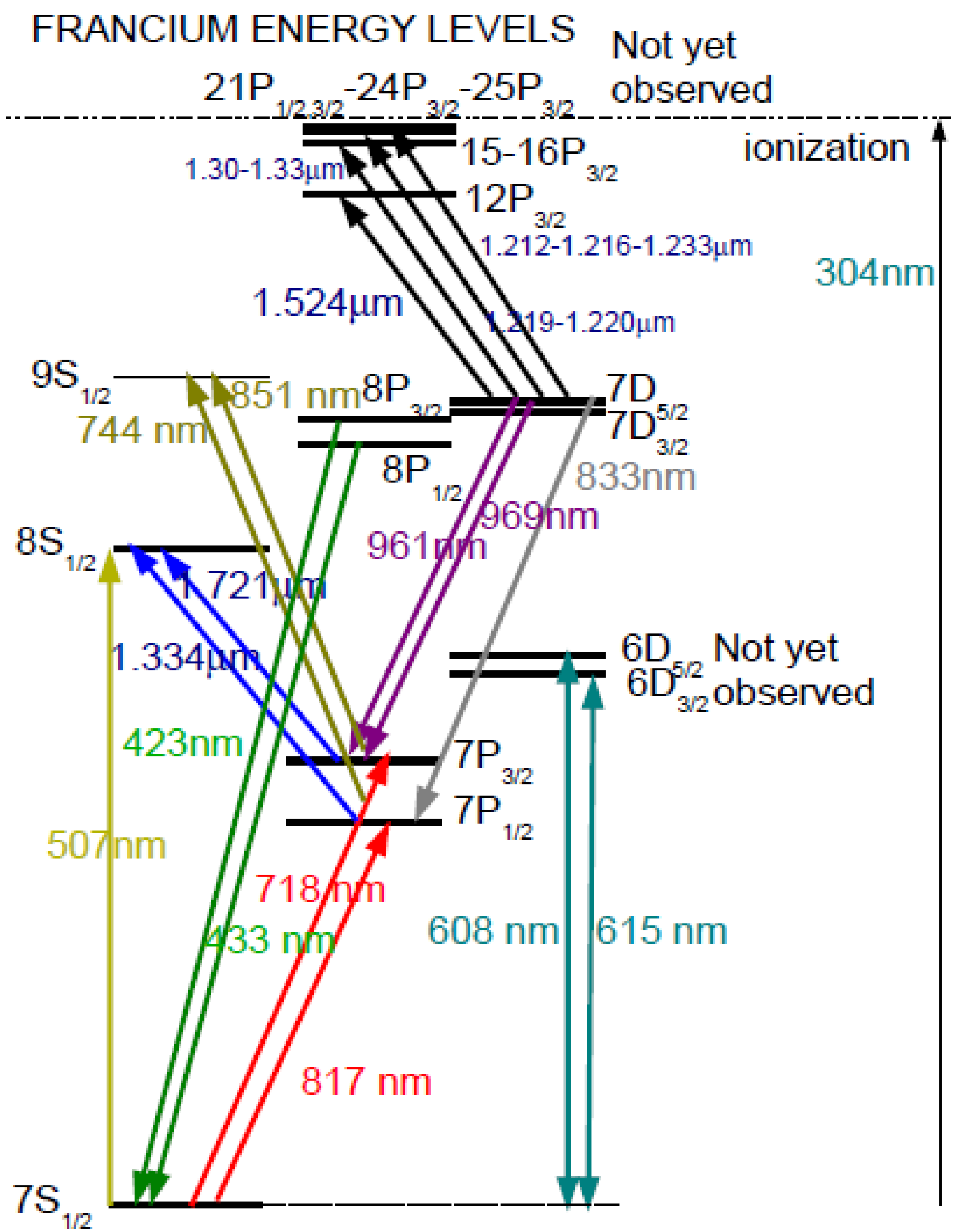


beam time of november

Outline

- **Introduction/Motivation (if any...)**
- The LNL apparatus
- Precision frequency measurements
  Laser spectroscopy diffusion coefficients meas.
  Detection of lines by change in trapped atom number
  Application of Light Induced Atom Desorption
- Perspectives

New spectroscopic measurements

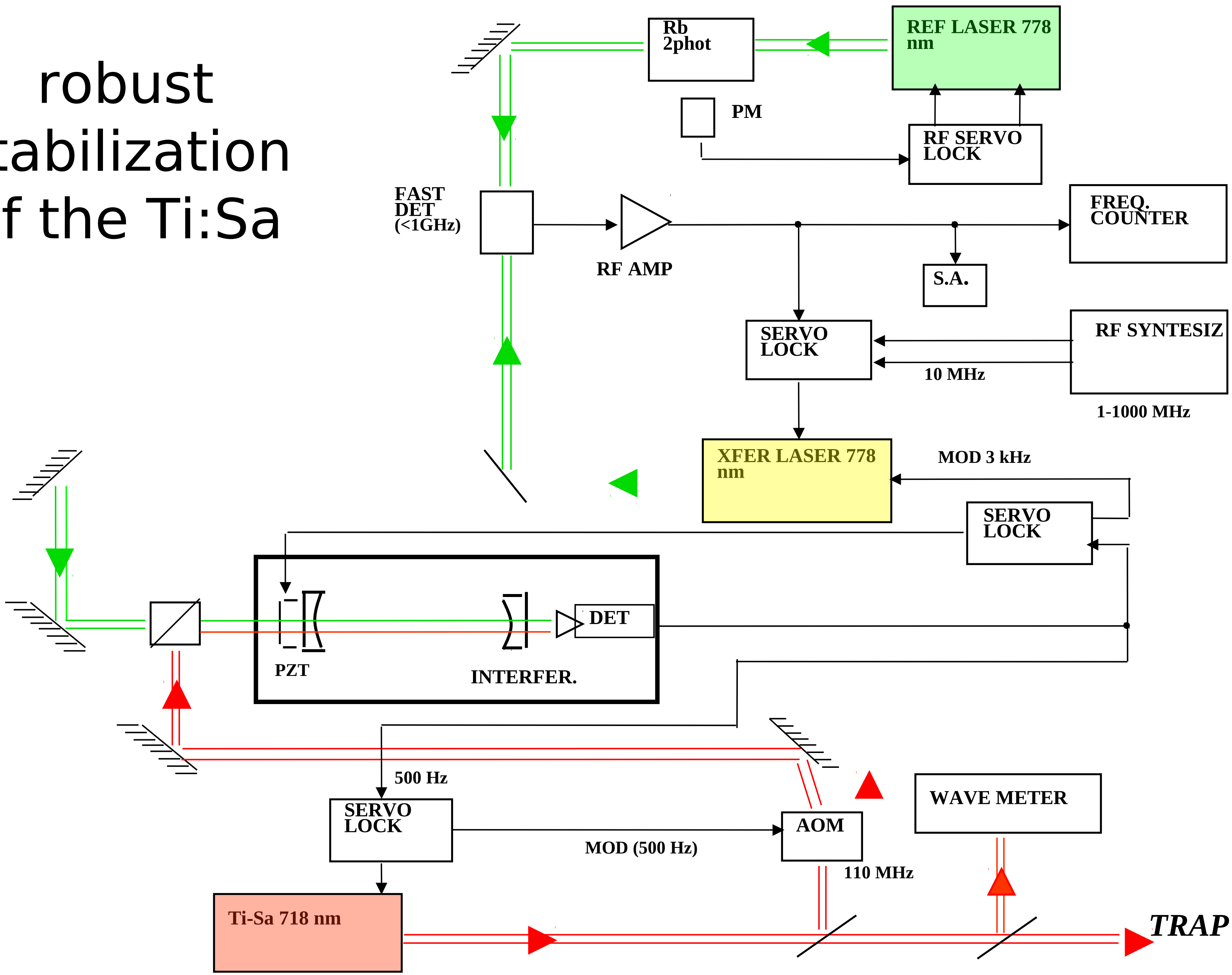


New spectroscopic measurements

- ENERGY LEVEL DETERMINATION
- LIFETIMES MEASUREMENTS
- COLLISIONAL STUDIES
- DIMER FORMATION (??)
- RELATIVISTIC EFFECTS CONTROLS

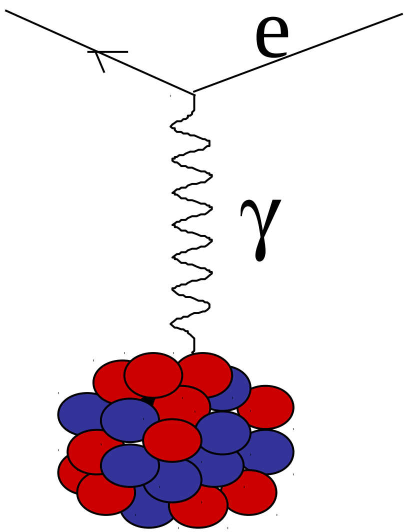
New spectroscopic measurements

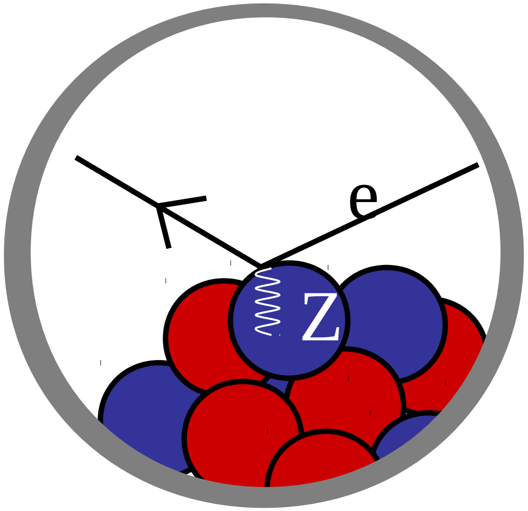
robust stabilization of the Ti:Sa



Atomic parity violation

RELEVANT ELECTRON - HADRON PROCESSES





$$A_{em} \propto \frac{e^2}{p^2}$$

$$A_W \propto \frac{e^2}{p^2 + M_{Z_o}^2 c^2}$$

p is the momentum transfer
(inversely proportional to the Bohr radius)

$$p \sim m_e \alpha c$$

Atomic parity violation

Different transition probabilities for two mirror - image experiments

The amplitude A_W contains a part that is odd under space reflection and gives rise to a left - right asymmetry A_{LR} by interference with A_{em}.

$$P_{L/R} = |A_{em} \pm A_W^{odd}|^2$$

$$A_{LR} = \frac{P_L - P_R}{P_L + P_R} \simeq 2\mathrm{Re}\frac{A_W^{odd}}{A_{em}}$$

$$\alpha^2 \left(\frac{m_{e^-}}{M_{Z_0}}\right)^2 10^{-15}$$

Atomic parity violation

Completely hopeless? No!

There are 2 factors of enhancement:

A. The so - called Z^3 law

- For valence electrons belonging to penetrating orbitals, the orbitals are deformed in the vicinity of the nucleus, where electrons “see” a Coulomb potential generated by a charge Ze. The orbital radius is given by a_0/Z, in such a way that p^2 is enhanced by Z^2.
- The various nucleons add for their contributions coherently: the number of nucleons grows as Z

Atomic parity violation

B. The second source comes from the possibility of exciting highly forbidden transitions like $nS_{1/2} \rightarrow (n+1)S_{1/2}$ in alkalis. The electromagnetic selection rules strictly forbid the electric dipole transition; dipole magnetic transitions M_1 are allowed by the symmetry, not by the change in radial number.

$$M_1 \approx 4 \times 10^{-5} \frac{\mu_B}{c}$$

The weak interaction associated with the boson exchange breaks this rule and gives rise to a parity violating electric dipole amplitude $E^{(PV)}_1$:

$$E_1^{PV} \approx 10^{-11} e a_0$$

$$Im\, E_1^{pv} / M_1 \simeq 0.5 \times 10^{-4}$$

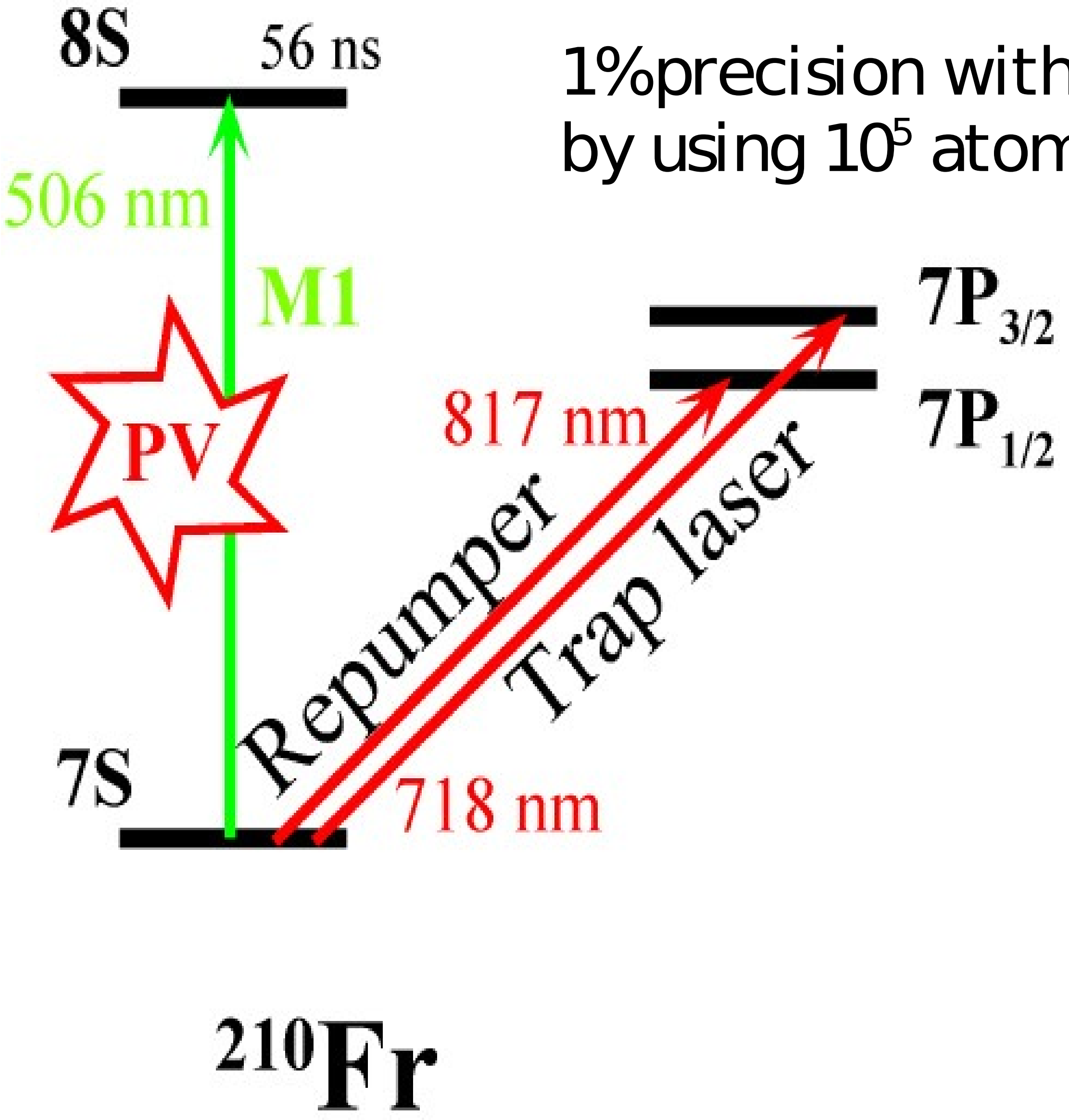
Atomic parity violation

A possible experimental approach:

1. Capture Fr atoms in a MOT
2. Accumulate and cool in the MOT
3. Transfer to a second trap (purely optical)
4. Establish a "coordinate system" by dc electric field, dc magnetic field, k vector of the exciting laser
5. Excite 7S to 8S using a build up cavity and detect using the 7S to 7P transition.
6. Reverse the coordinate axis.
7. Change isotope.

Towards APV measurement

$$\vec{d}^{\,\mathrm{eff}}_{F,F'} = -\alpha\vec{E} - i\beta\vec{\sigma}\wedge\vec{E} + M_1'\vec{\sigma}\wedge\vec{k} - iIm(E_1^{PV})\vec{\sigma}$$



1%precision with 3 weeks measurements by using 10^5 atoms

preliminary measure of the ratios α/β, β/M_1, M_1/M_1^{hf}: in the MOT cloud to “calibrate” APV

Expected signal to noise ratio

- Fr production rate in Legnaro: up to 10^6 ions/s.
- Trapping efficiency $\sim 10^{-2} \Rightarrow N = 10000$ atoms in 1 mm^3 (0.01 mm^3) (optical dipole trap).
- **Laser intensity: 100 mW/mm^2**, enhanced by a factor $\zeta = 1000$ with a Fabry-Perot cavity (cf. Boulder) $\Rightarrow P/S = 10$ kW/cm^2.
- Fluorescence detection efficiency: $\eta \sim 10\%$.

$$\Rightarrow S/N = \Im m E_1^{pv} \sqrt{\frac{4\pi}{3\hbar c} \frac{1}{\hbar \Gamma} \frac{P}{S}} \eta N \sqrt{t} = 0.009 \sqrt{t(s)} \quad (1 \text{ for t = 3 hours})$$

How can we improve S/N ?

- Higher laser power, BUT: – heating due to photon scattering
  – photoionization from $8S$ and $7P$.
- Higher Fr^+ Rate: $\geq 4 \cdot 10^9$ ions/s at the ISOLDE facility.
  $\Rightarrow S/N = \mathbf{0.55 \sqrt{t(s)}}$

➠ **In 9 hours we can get $S/N = 100$**

Conclusions