Preparing antihydrogen at rest for the free fall in GBAR

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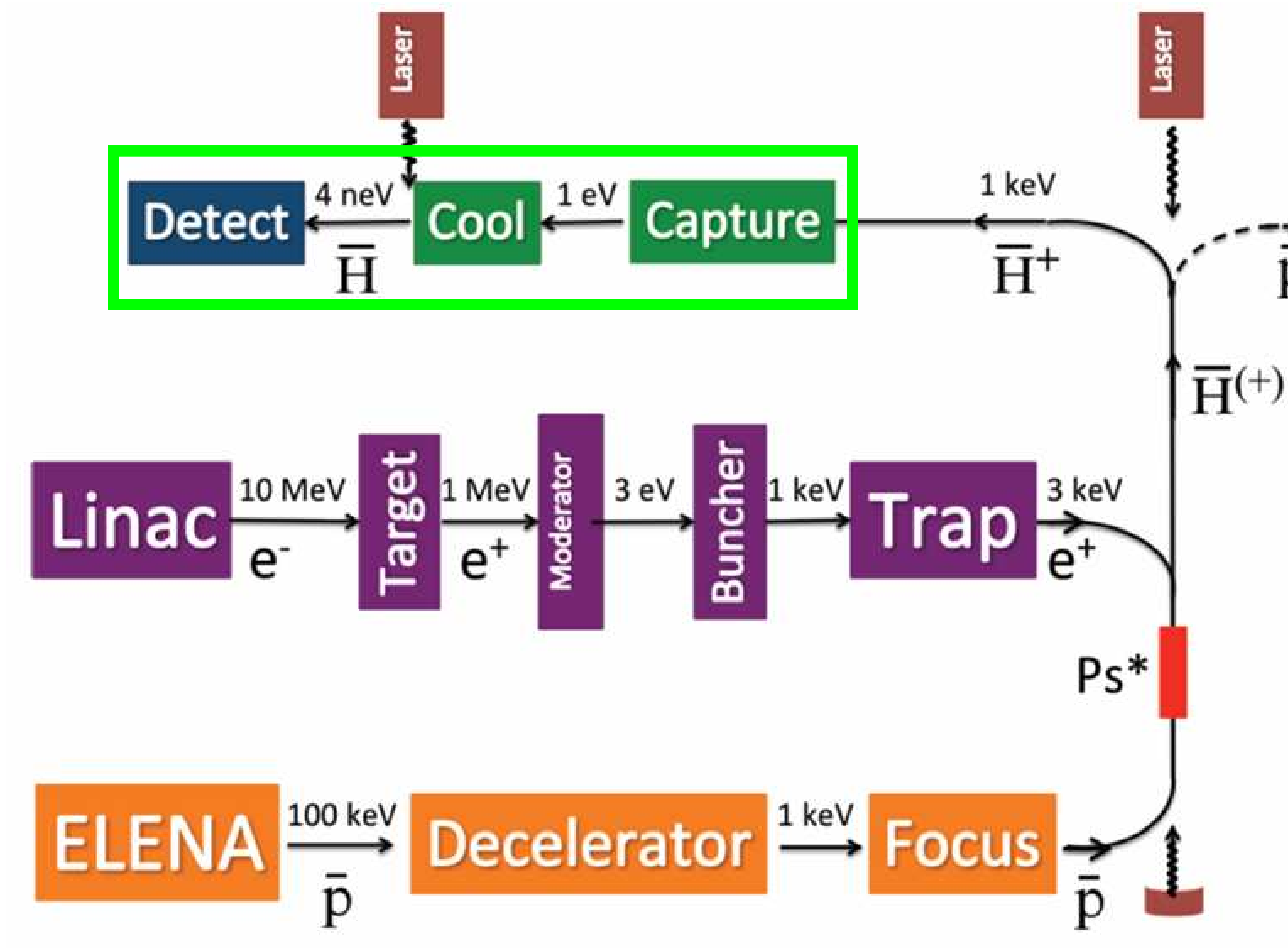
2014 – 2017
Bescool project

WAG 13-15 November 2013 Bern

Outline

- $\overline{\mathrm{H}}^+$ motion control requirements
- Capture and cooling challenges
- Experimental progress

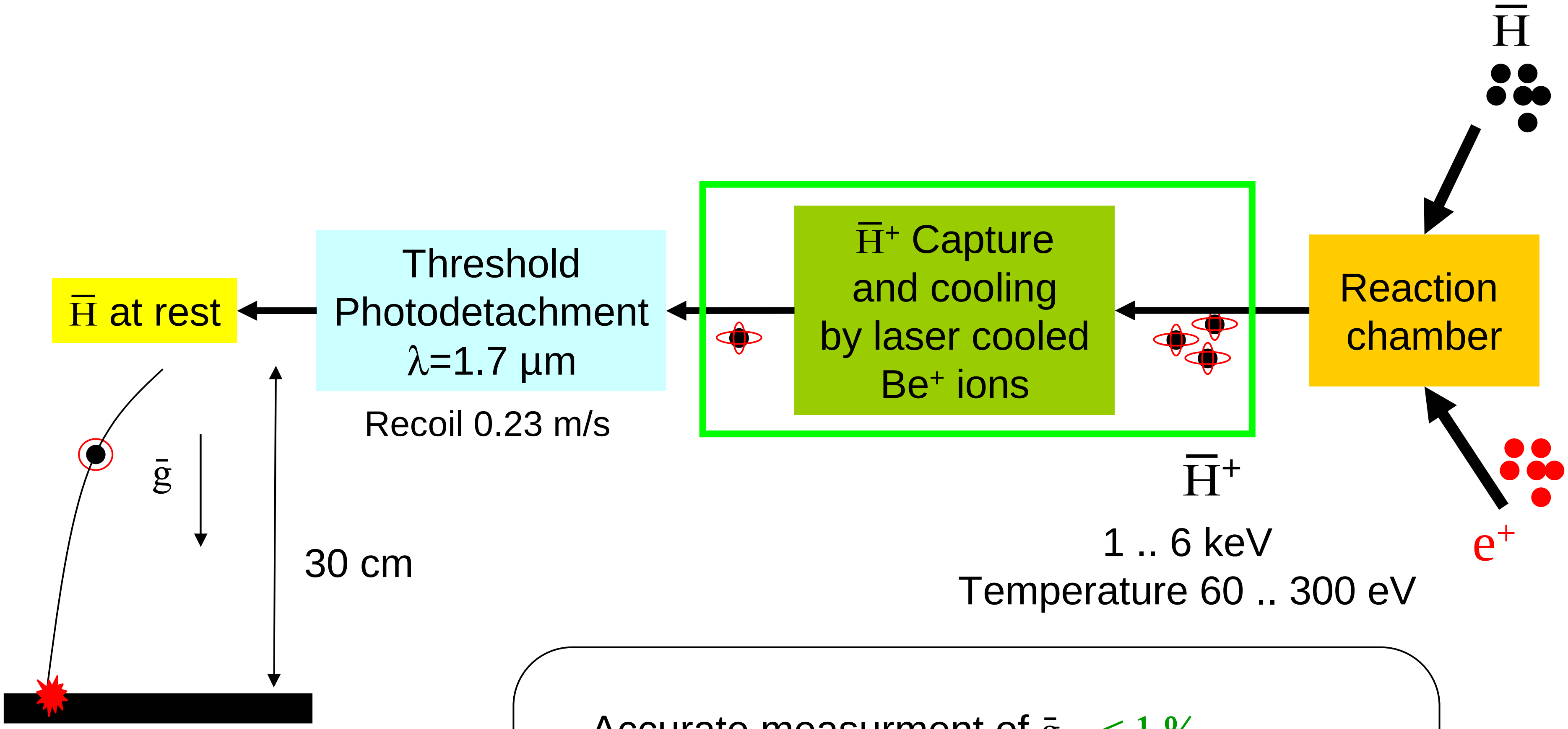
GBAR overview



no (^{22}Na) source

no p-bar trap

Last GBAR steps



Accurate measurement of $\bar{g}$ $< 1\ \%$

$\bar{H}$, $\bar{H}^+$ } initial velocity $\Delta v_0 < 0.8$ m/s

3 neV, 20 µK

$\bar{\mathrm{H}}$ with v_0 < 1 m/s ?

Ground state quantum **harmonic oscillator** $p = \sqrt{m\hbar\omega}\,\frac{a - a^{+}}{i\sqrt{2}}$ $\Delta v = \sqrt{\frac{\hbar\omega}{2m}}$

m = 1.67 10^{-27} kg , $\Delta v_0 < 0.8$ m/s → $\omega < 3$ MHz

Cooling challenges

Reaction chamber → Capture + Cooling — Cold trapped $\bar{\mathrm{H}}^{+}$

Kinetic energy 1 .. 6 keV
Temperature 60 .. 300 eV
700 000 K

÷ $10^{10..11}$

Trapped particule
Temperature 3 neV
20 µK

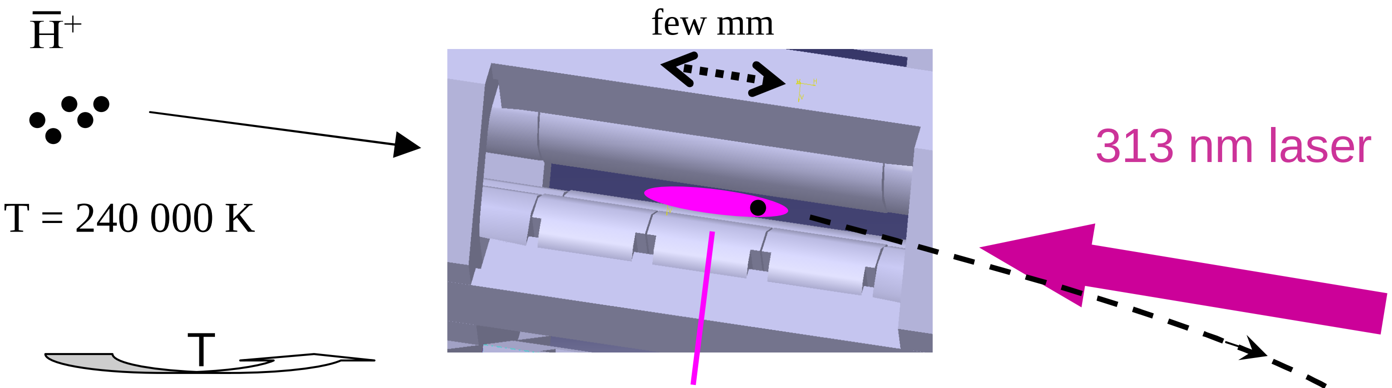
Classical world → Frontiers of Quantum world

NIST D. Wineland
Innsbruck R. Blatt

Two Cooling Steps

First step Capture and sympathetic Doppler cooling by laser cooled Be^{+} ions

in the linear **capture trap** (Paul trap, r_0 = 3.5 mm, Ω = 13 MHz)

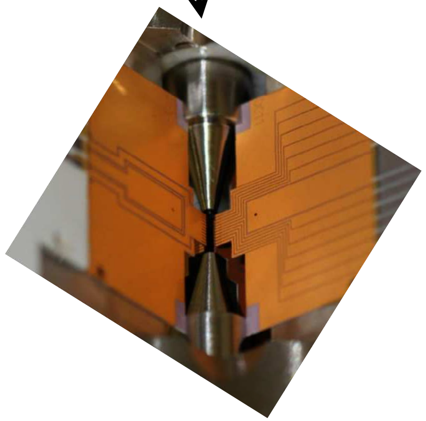


300 eV, T = 240 000 K

T
÷ 3 10^9

> 10 000 laser cooled Be^{+} ions
100 neV, T ~ mK

Second step

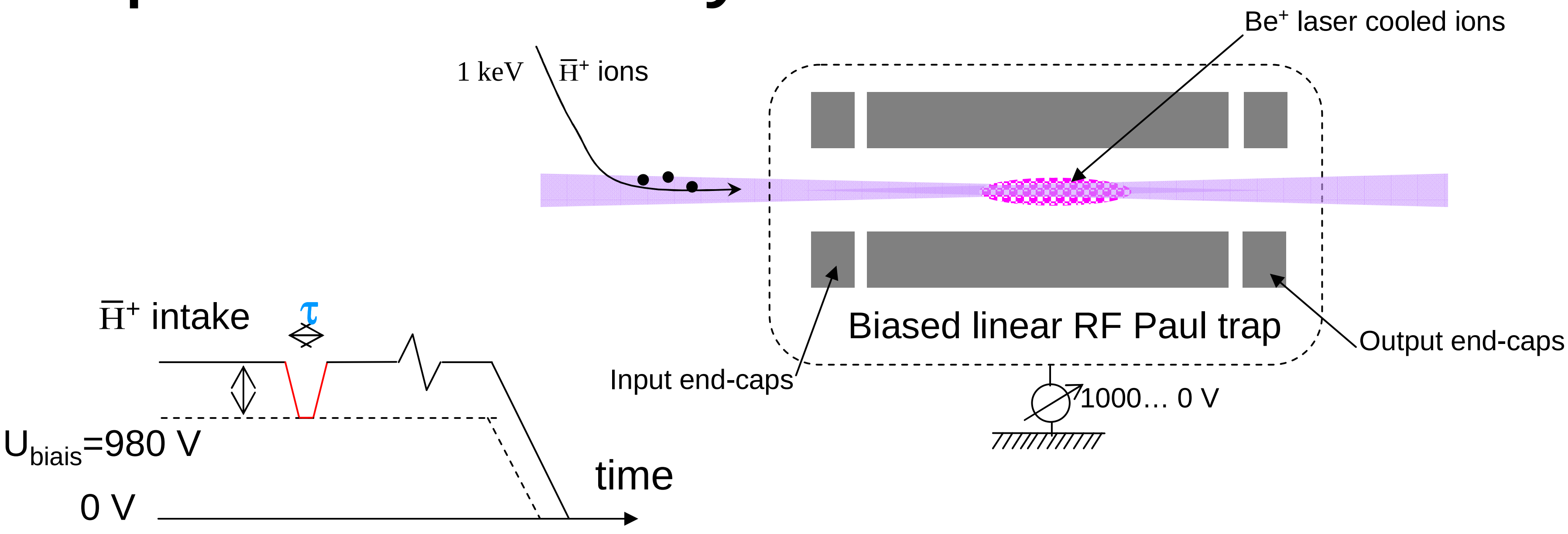


Transfer and ground state cooling
of a $Be^{+}/\bar{H}^{+}$ ion pair in the **precision trap**

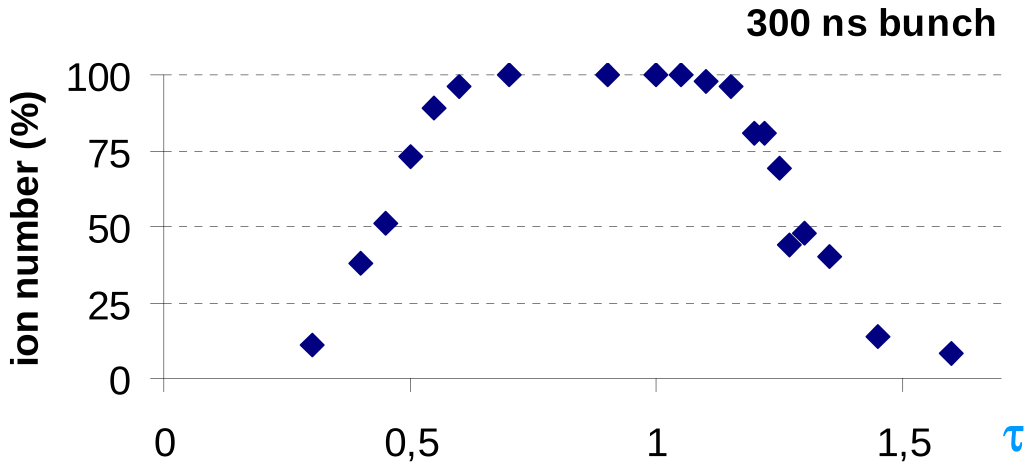
F. Schmidt Kaler, S. Wolf , Mainz
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Capture efficiency

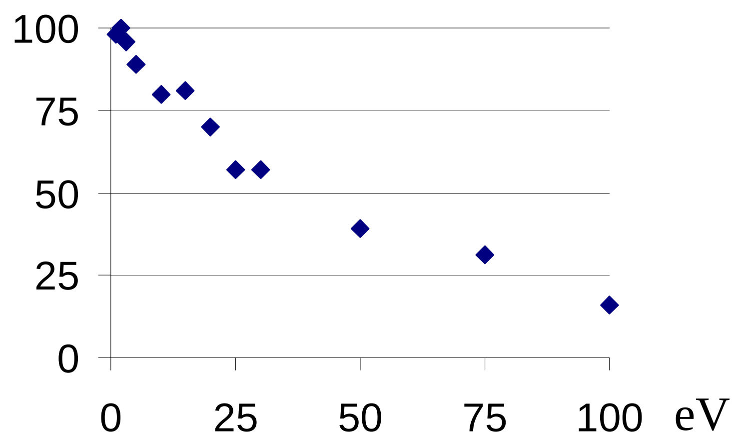
First step



Versus intake delay



Versus initial temperature (eV)



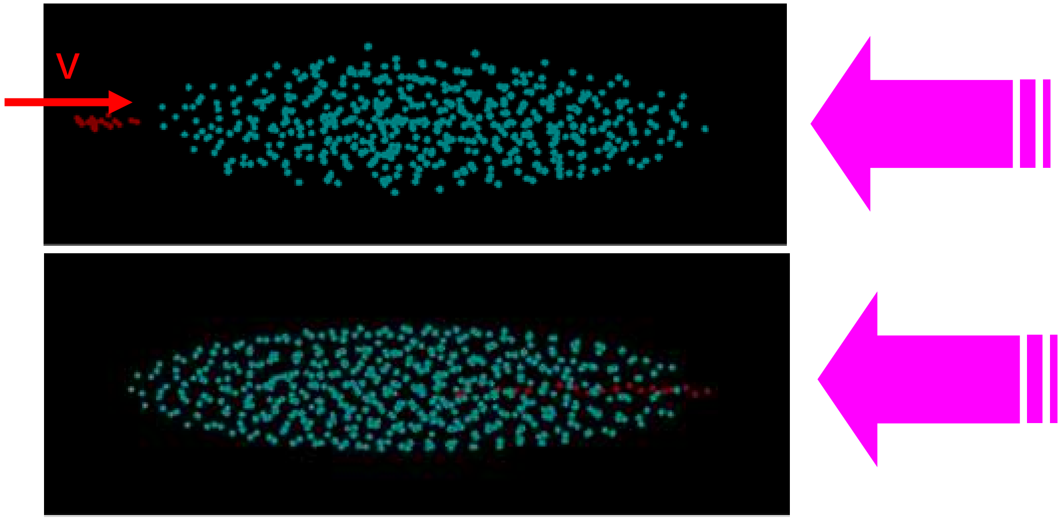
Sympathetic cooling time First step

- Numerical simulation 500 Be^+ and 20 $\bar{H}^+$

t = 0 s

E_c= 2 meV

t = 8 ms

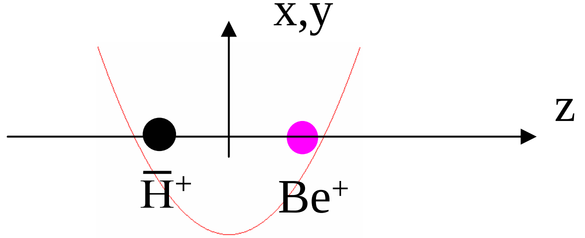


313 nm laser

- Hotter H+ ions and larger ion clouds ➡ numerical challenge

Work plan : Experimental tests with matter ions H_2^+ or H^+

Precision trap – motional couplings



Two coupled oscillators in an external potential

- z trapping DC potentials
- x,y trapping RF effective potentials
- Coulomb interaction coupling

Newton equations → equilibrium positions → small oscillations

normal modes

in phase mode
out of phase mode

individual ion modes
x, y, z

$$q_1(t) = b_1\, \overbrace{z_{in} \sin(\omega_{in} t + \varphi_{in})} + b_2\, \overbrace{z_{out} \cos(\omega_{out} t + \varphi_{out})}$$

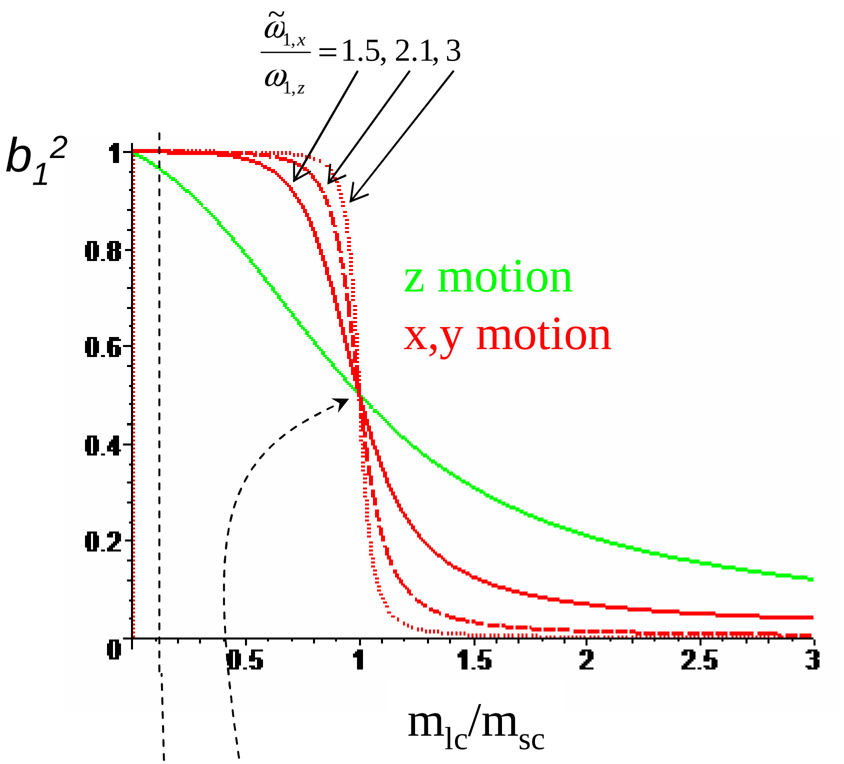
$$q_2(t) = b_2 \frac{z_{in}}{\sqrt{m_2/m_1}} \sin(\omega_{in} t + \varphi_{in}) - b_1 \frac{z_{out}}{\sqrt{m_2/m_1}} \cos(\omega_{out} t + \varphi_{out})$$

$$b_1^2 + b_2^2 = 1$$

T. Hasegawa, Phys. Rev. A 83, 053407 (2011) **1D**
J. B. Wübbena, S. Amairi, O. Mandel, P.O. Schmidt, Phys. Rev. A **85**, 043412 (2012) **3D**

Precision trap – motional couplings

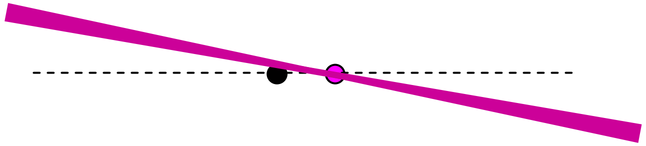
Second step

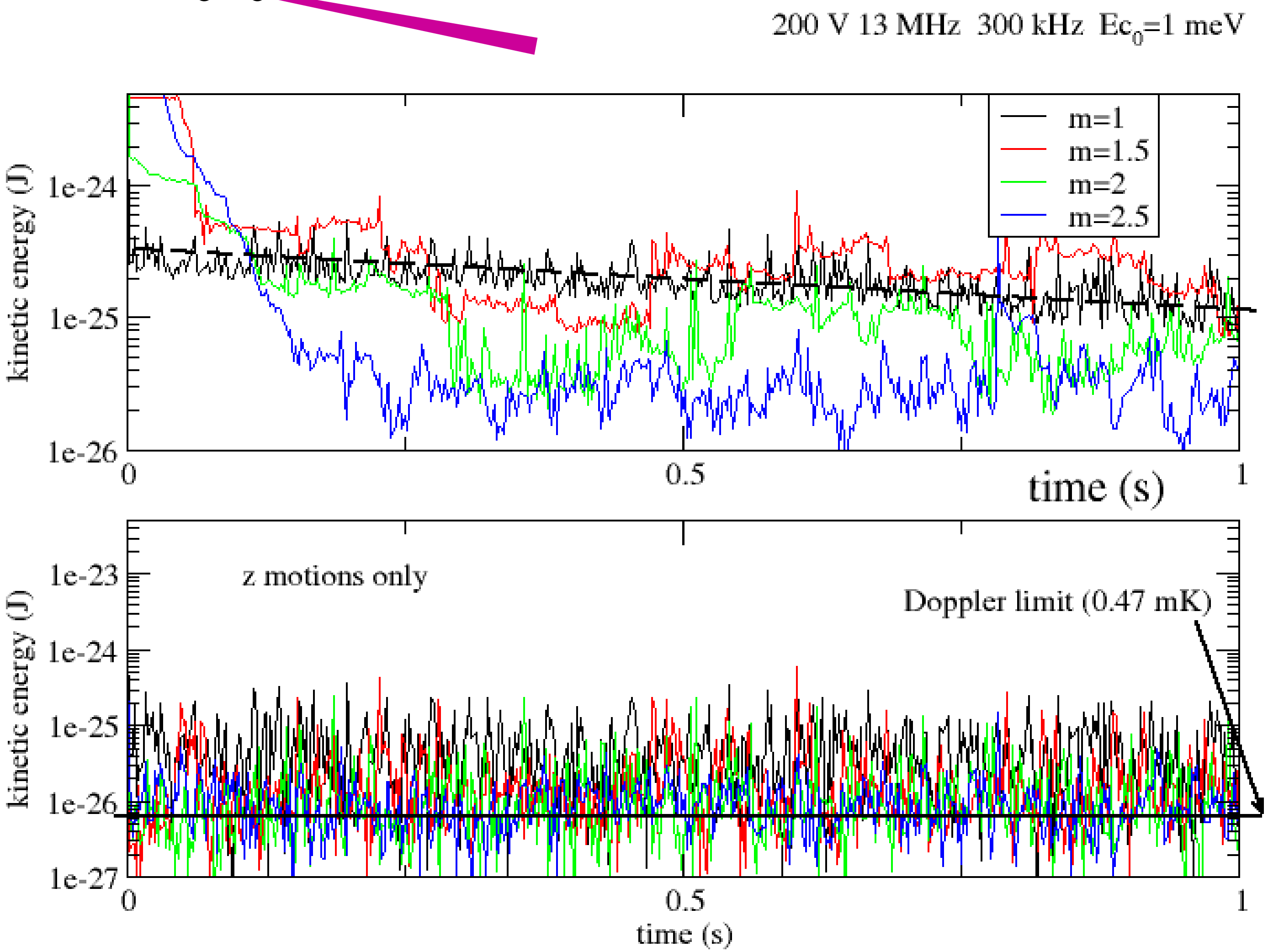


$m_{LC}/m_{SC} \sim 1$ $b_1 = 50$ % $b_2 = 50$ % Efficient sympathetic cooling

$m_{LC}/m_{SC} = 9/1$ $b_1 = 99.996$ % $b_2 = 0.872$ % ?

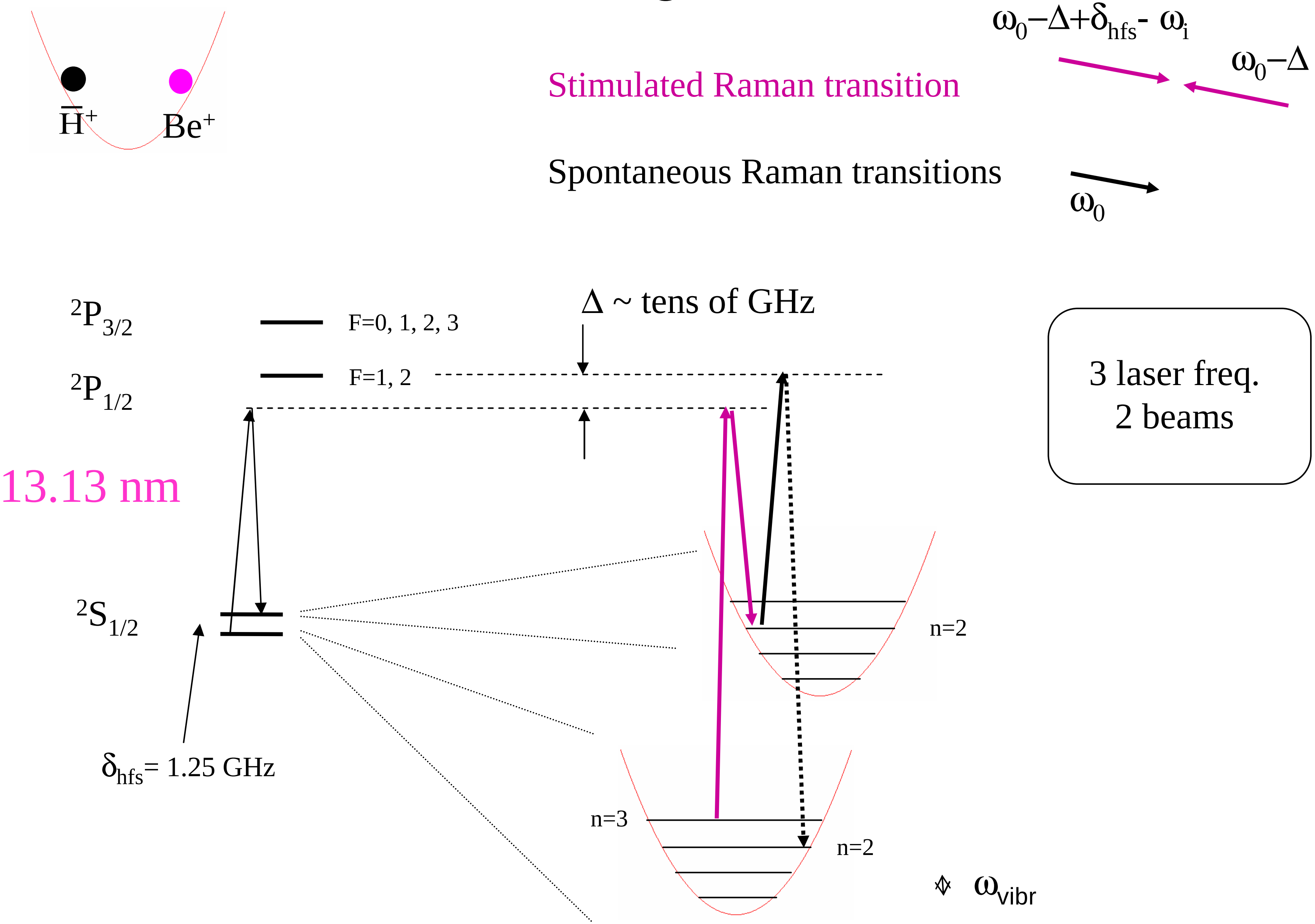
Doppler cooling in precision trap





>> 20 μK

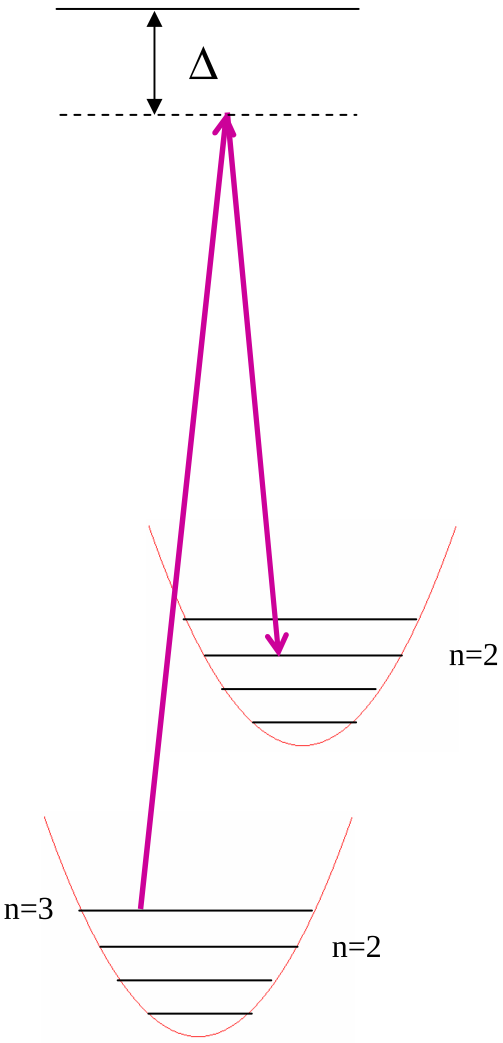
Raman side band cooling



Raman side band cooling

Second step

Stimulated Raman transition ➡ no spontaneous emission ➡ coherent process



Rabi oscillation

Population transfert probability $P(n=3 \rightarrow n=2) = \sin^2(\Omega_{3,2} t)$

$$\Omega_{n',n} = \frac{\Omega_1 \Omega_2}{\Delta} \langle n' | e^{i\eta(a+a^+)} | n \rangle$$

Lamb Dicke parameter $\eta = (\vec{k}_1 - \vec{k}_2).\vec{u}$

For n ⟶ n-1, $\Omega_{n,n-1} \approx \frac{\Omega_1 \Omega_2}{\Delta} \eta \sqrt{n} \propto \frac{\Omega_1 \Omega_2}{\Delta} \sqrt{n}\, b_2$

π pulse duration $\tau \propto \frac{\pi}{2} \frac{\Delta}{\Omega_1 \Omega_2} \frac{1}{\sqrt{n}} \frac{1}{b_2}$

Single ion	$b_1 = 1$	3 modes	τ ~ 100 µs /n/mode
$Be^+/\bar{H}^+$	$b_{1z} = 0.18$	2 modes	x 5
	$b_{1x,y} = 0.0872$	4 modes	x 15

~ 10 ms

< 1s

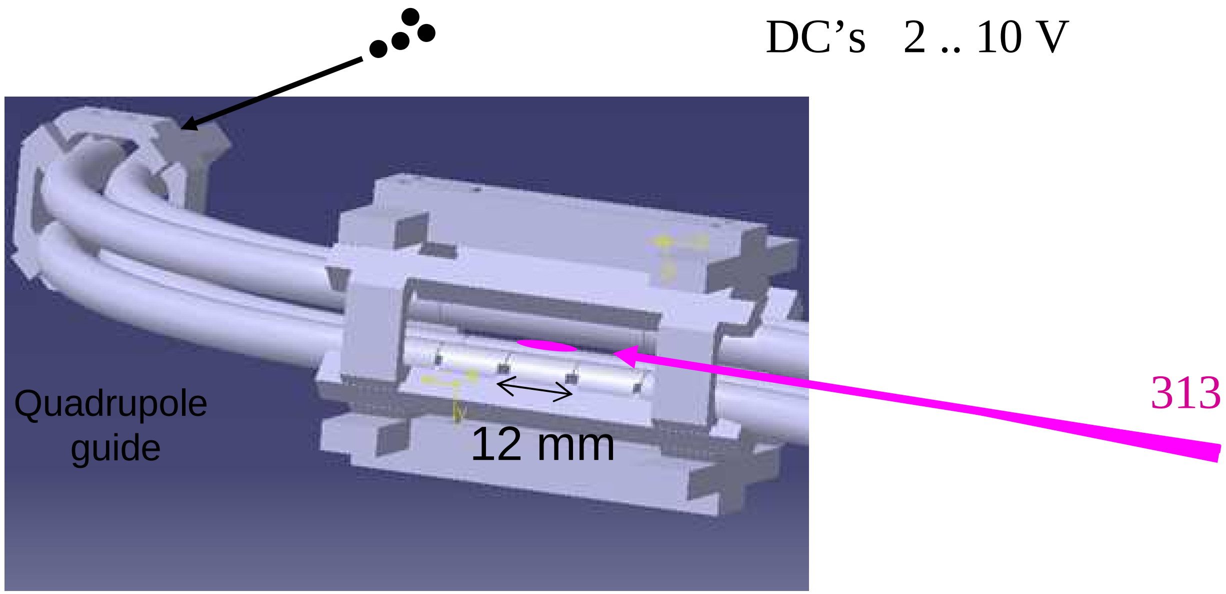
Experimental progress

Capture trap design

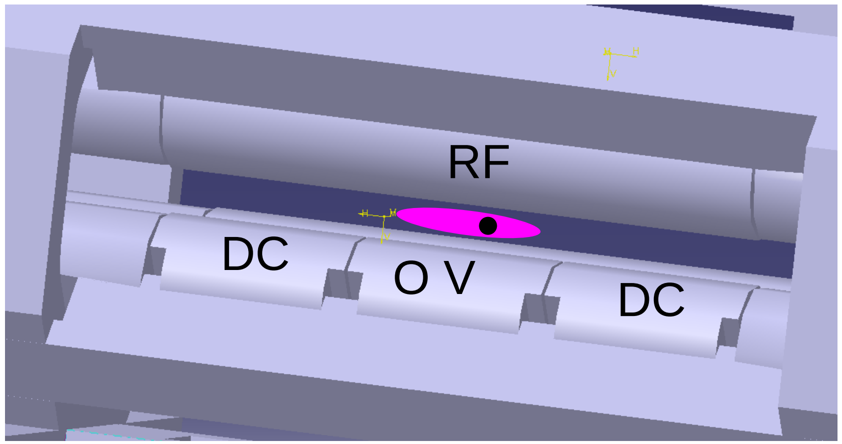
Jean-Philippe Karr

RF 250 V at 13.3 MHz, r_0 = 3.5 mm
DC's 2 .. 10 V

Hot $\bar{H}^+$

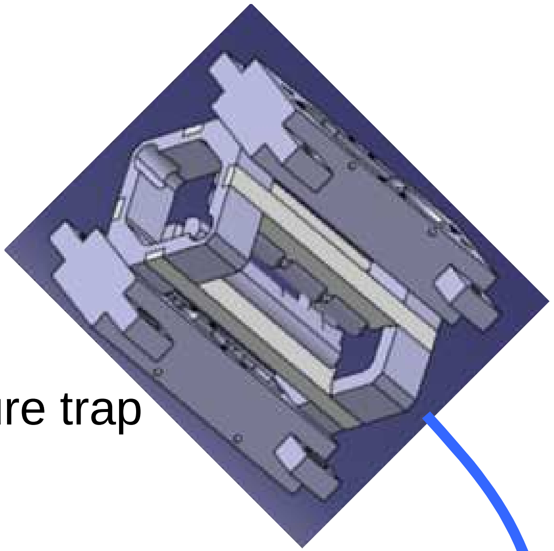


313 nm cooling laser



Transfer to precision trap

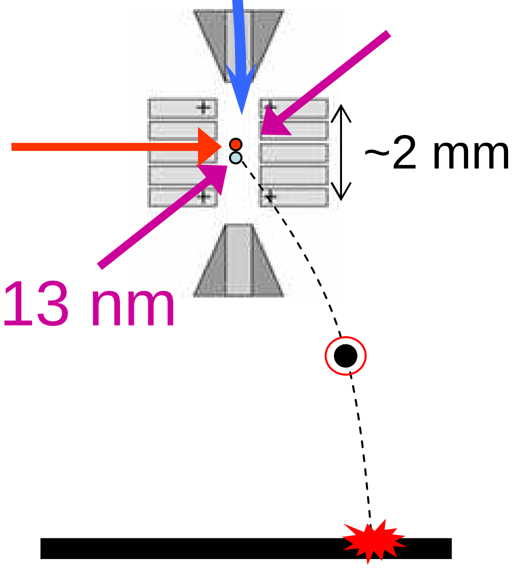
Design: Sebastian Wolf, Mainz



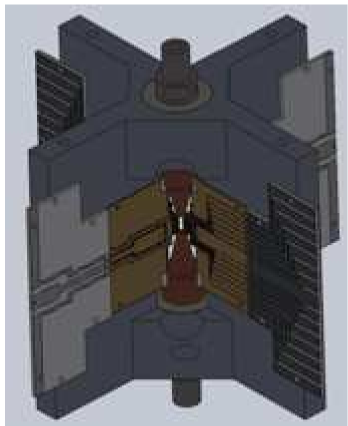
Capture trap

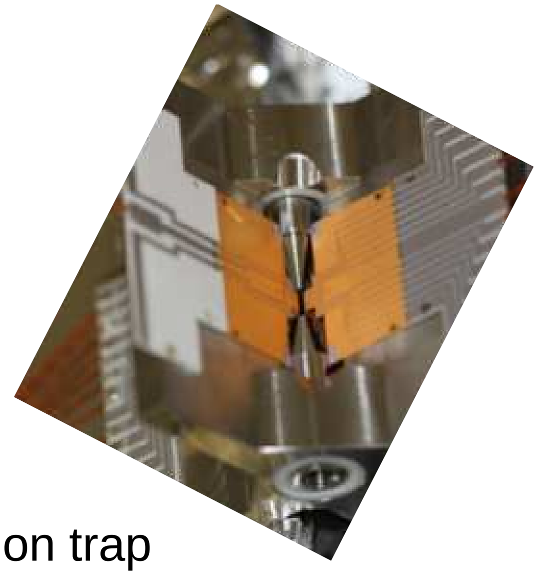
Photodetachment

$\lambda = 1.64\ \mu m$



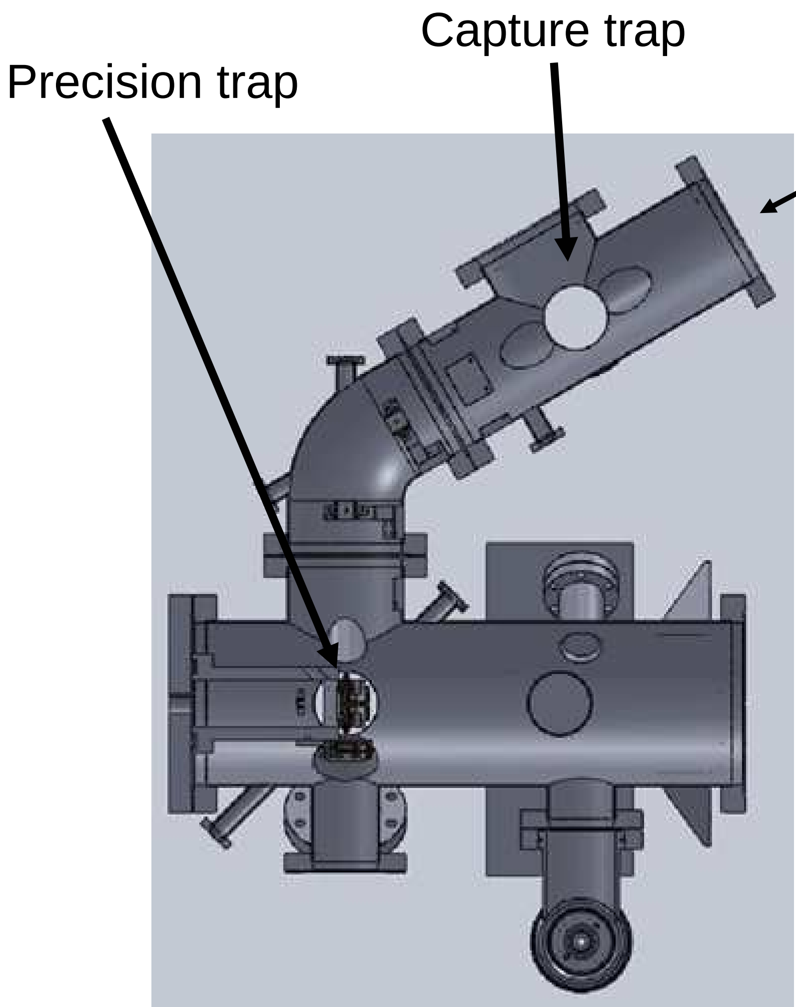
Cooling $\lambda = 313\ nm$

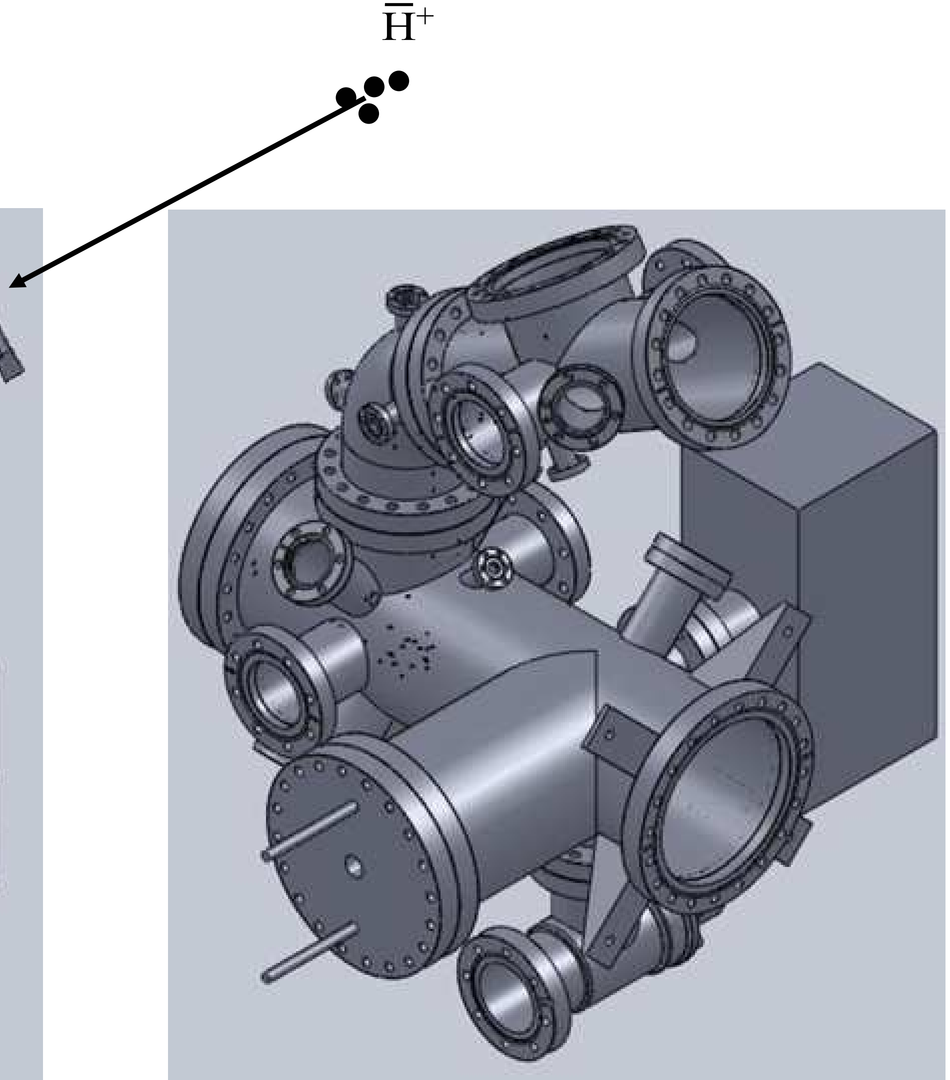




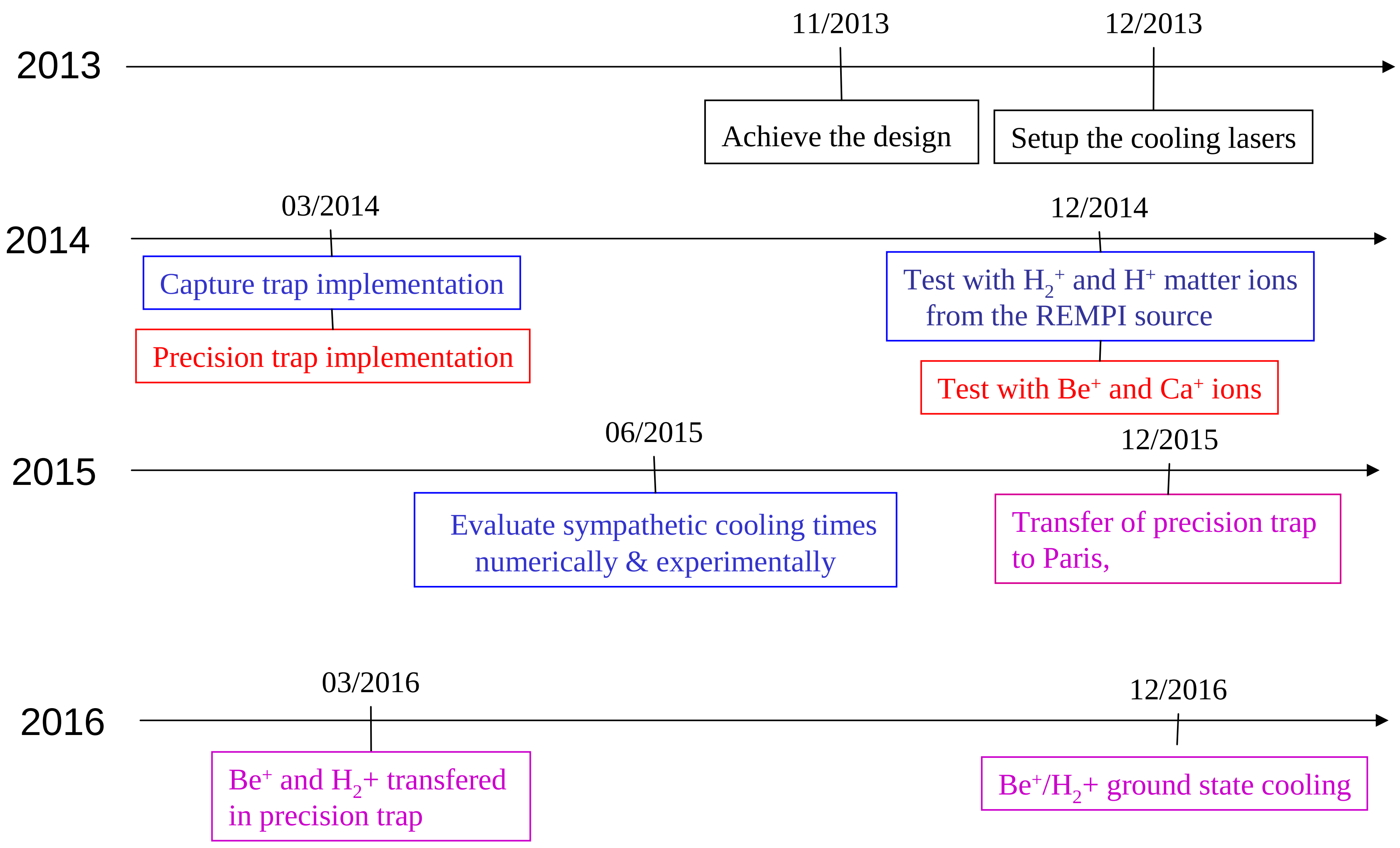
Mainz implantation trap

Vacuum vessel with cryopumping

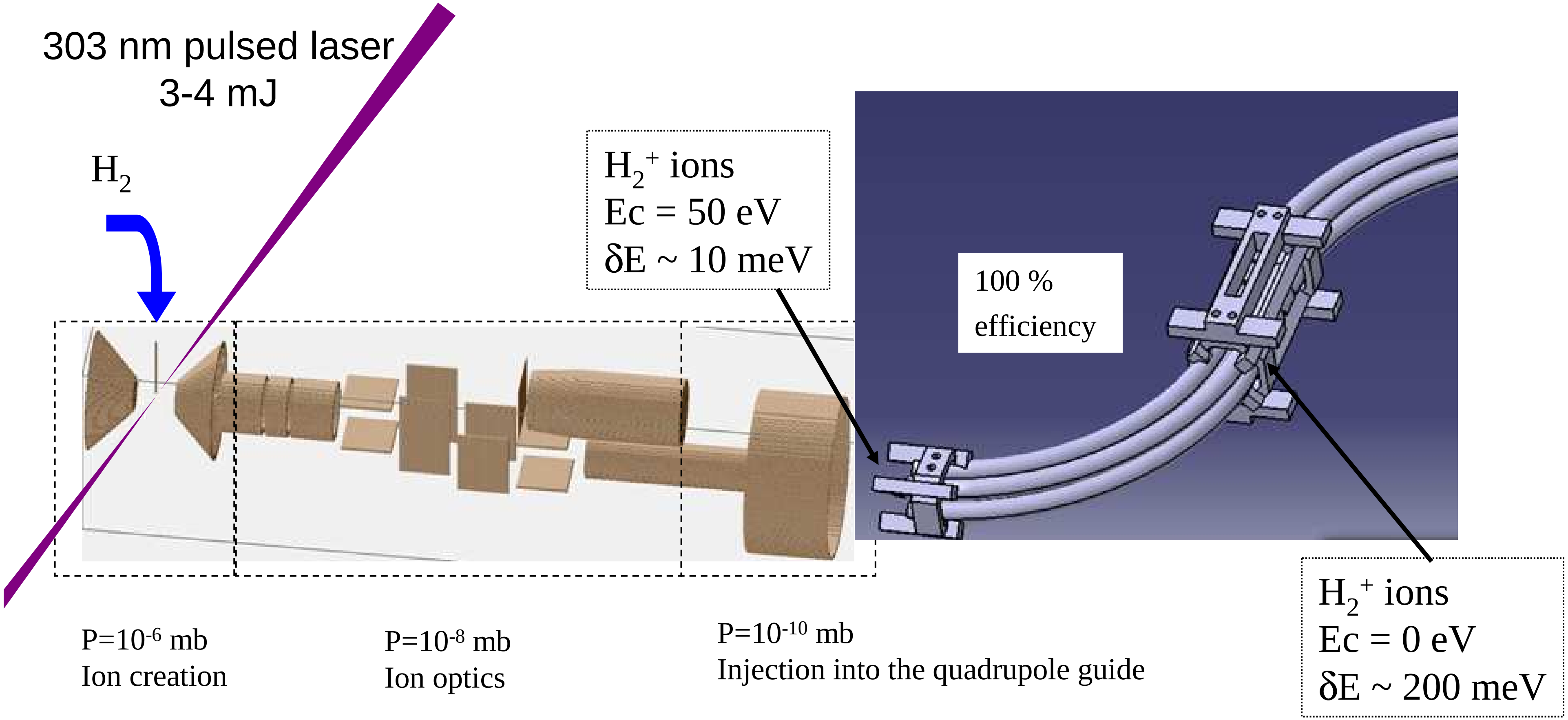




Work plan


2013
11/2013
12/2013
Achieve the design
Setup the cooling lasers
2014
03/2014
12/2014
Capture trap implementation
Precision trap implementation
Test with H_2^+ and H^+ matter ions from the REMPI source
Test with Be^+ and Ca^+ ions
2015
06/2015
12/2015
Evaluate sympathetic cooling times numerically & experimentally
Transfer of precision trap to Paris,
2016
03/2016
12/2016
Be^+ and H_2+ transfered in precision trap
Be^+/H_2+ ground state cooling

Tests with a H_2^+ / H^+ REMPI source



Synergies

- $\overline{H}^+$ Gbar
- H_2^+ metrology project
- HCI highly charged ions $^{40}Ar^{13+}$, P. Indelicato, C. Szabo

Conclusion

✓ **Capture** of > 10 eV $\overline{\mathrm{H}}^+$ and Doppler cooling in a linear Paul trap

✓ Transfer to precision trap **OK**

✓ Doppler and ground state cooling in precision trap **OK**

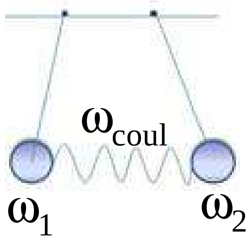
PhD positions available

- ANR BESCOOL
- ITN ComiQ

COLD MOLECULAR IONS AT THE QUANTUM LIMIT
A MARIE CURIE INITIAL TRAINING NETWORK
FP7-PEOPLE-2013-ITN

Can we improve the motional couplings ?

Idea



$|\omega_1 - \omega_2| \approx \omega_{Coul}$ ➡ Efficient coupling

Trapped ions $\omega_1 \sim \omega_2 \sim 1.0$ MHz ➡ $\omega_{Coul} \sim 100$ kHz

Coulomb coupling $\omega_{Coul} = \sqrt{\frac{2}{m}\frac{q^2}{4\pi\varepsilon_0 z_{12eq}^3}}$ ➡ $z_{12eq} < 40\ \mu m$

$\longleftrightarrow$ z_{12eq}

Single well with $m_1 = 9$, $m_2 = 1$

$\omega_{z\,2} \sim 3\ \omega_{z\,1}$

$\omega_{x\,2} \sim 9\ \omega_{x\,1}$ ➡ poor couplings

Possible solution ➡ Double well structure with very small electrodes ?