GRASIAN

UNIVERSITY OF TURKU

Wihuri
Physical
Laboratory

Towards Experiments with Hydrogen Atoms at Rest

Sergey Vasiliev

Department of Physics and Astronomy, University of Turku

Jarno Järvinen*
Janne Ahokas

* Now at BlueFors company

Aleksei Semakin
Otto Hanski
Slava Dvornichenko

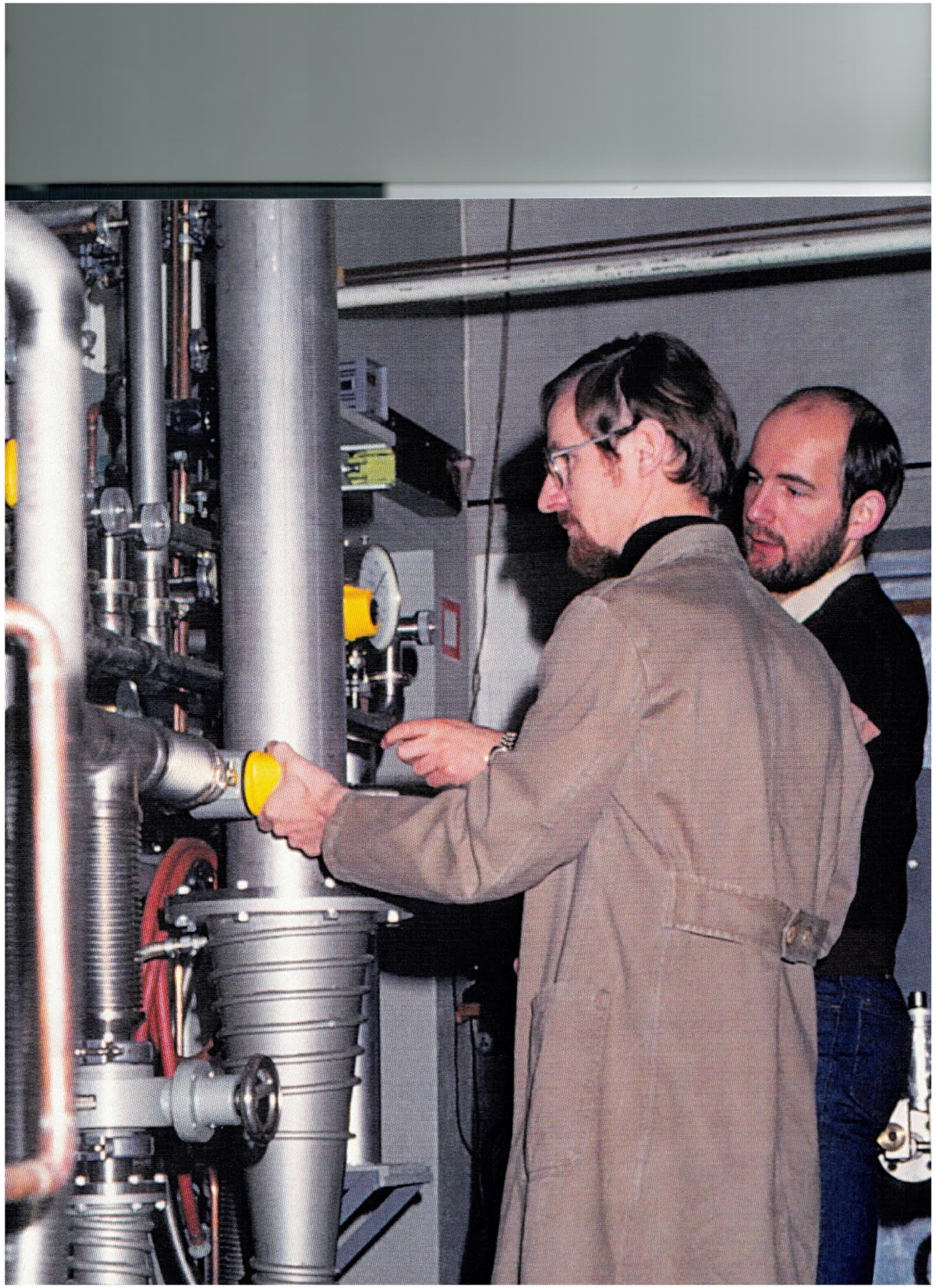
SUOMALAINEN TIEDEAKATEMIA
FINNISH ACADEMY OF SCIENCE AND LETTERS

ACADEMY OF FINLAND

”Jump into a darkness”

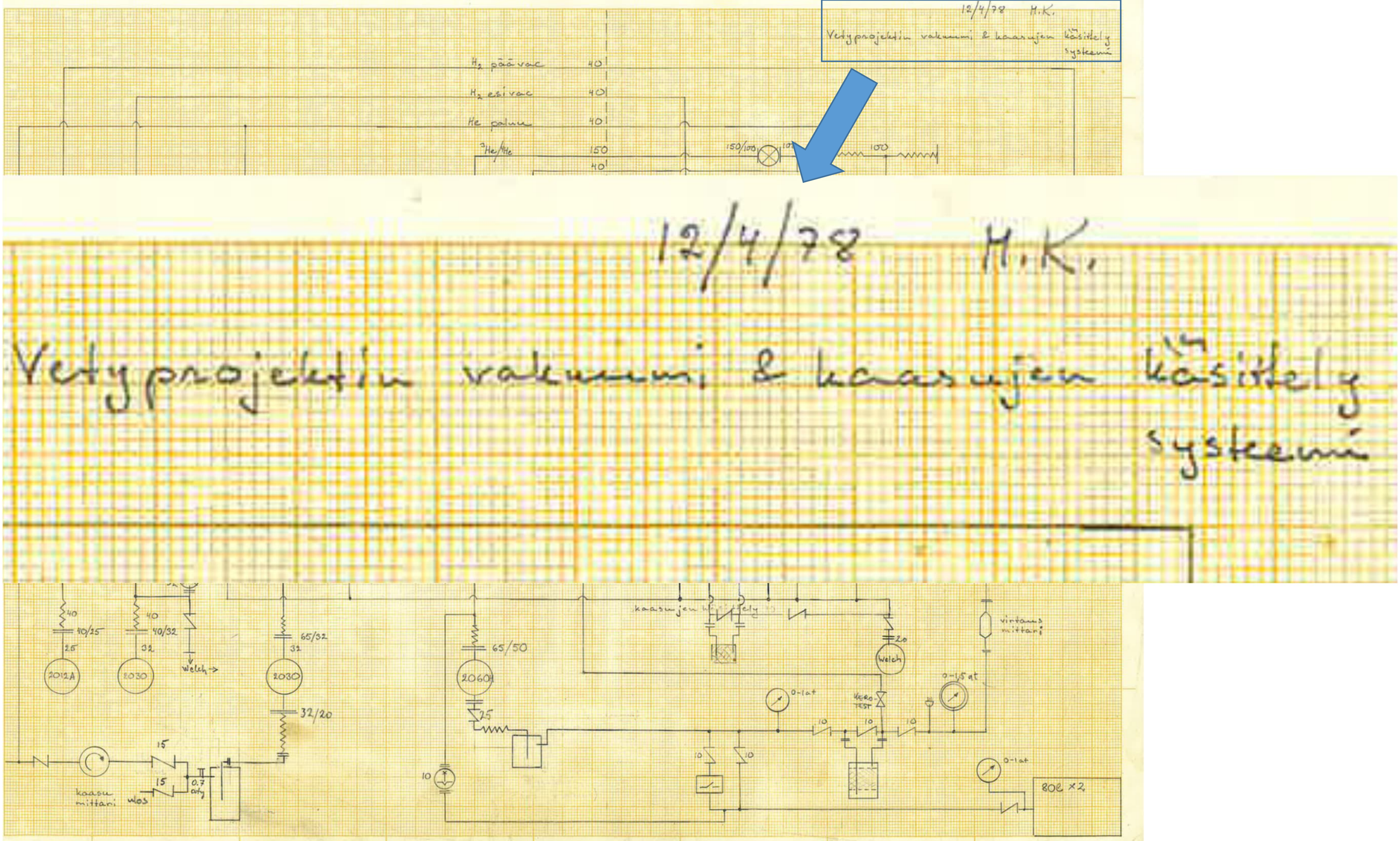
H↓ project in Turku

1976… 2022



12/4/78 H.K.

Vetyprojektin vakuumi & kaasujen käsittely systeemi



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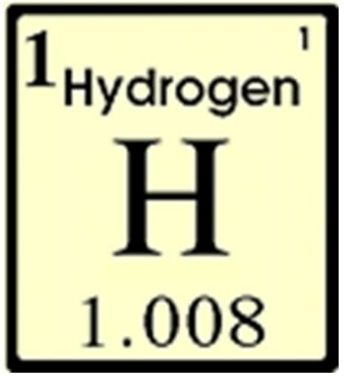


Major milestones :

Properties can be accurately calculated from basic principles

- Lamb shift:
  Development of QED
- Optical spectroscopy:
  Rydberg constant, proton radius
- Microwave spectroscopy:
  H maser
- BEC:
  magnetic trapping, evaporative cooling

All measurements done with fast moving atoms

Historical background. Race for BEC

	1959	C. E. Hecht proposed to stabilize atomic hydrogen by polarizing its electron spin : H↓ ⍰ Start of the race for BEC.		
Silvera and Walraven, Amsterdam	1979	First experimental stabilization of H↓ gas at low temperatures	$n \sim 10^{14}\ \mathrm{cm}^{-3}$, $T \approx 300$ mK	
Amsterdam, MIT, Harvard, Vancouver Cornell, Moscow, Kyoto	1981-1988	Studies of the main properties of 3D gas Hydraulic compression	$n \sim 5 \cdot 10^{18}\ \mathrm{cm}^{-3}$, $T \approx 600$ mK $n\Lambda^3 \approx 0.07$	
Turku	1978	Start of the H project in Turku by M.K.		
MIT, Amsterdam	1986-1998	Open traps, optical detection, evaporative cooling of H↑ ⍰ BEC	$n \sim 2 \cdot 10^{14}\ \mathrm{cm}^{-3}$, $T \approx 40\ \mu$K	
Turku+Moscow	1992-1998	Magnetic compression ⍰ quasicondensate	$\sigma \sim 2 \cdot 10^{13}\ \mathrm{cm}^{-2}$, $T \approx 200$ mK $\sigma\Lambda^2 \approx 9$	2D H gas
Turku	1998-2010	Thermal compression, “cold spot”. Clock shift, interactions between atoms in 2D and 3D	$\sigma \sim 5 \cdot 10^{12}\ \mathrm{cm}^{-2}$, $T \approx 100$ mK $\sigma\Lambda^2 \approx 0.6$	
Turku	2010-2018	Electrons spin waves in high density H↓ gas, ⍰ BEC of magnons	$n \sim 5 \cdot 10^{18}\ \mathrm{cm}^{-3}$, $T \approx 600$ mK $n\Lambda^3 \approx 0.07$	
Turku	2018-	Magnetic trapping and cooling of H	Mostly non-degenerate gas	

Evaporative cooling of magnetically trapped and compressed spin-polarized hydrogen

Harald F. Hess
Department of Physics and Center for Material Science and Engineering,
Massachusetts Institute of Technology,
Cambridge, Massachusetts 02139

(Received 19 February 1986)

A gas of spin-polarized atomic hydrogen can be prepared in the upper hyperfine states and loaded into a static magnetic trap. Evaporative cooling and magnetic compression of such a gas can produce temperatures of 30 μK and densities of 10^{14} cm^{-3}. Under these conditions a Bose-Einstein condensate may form.

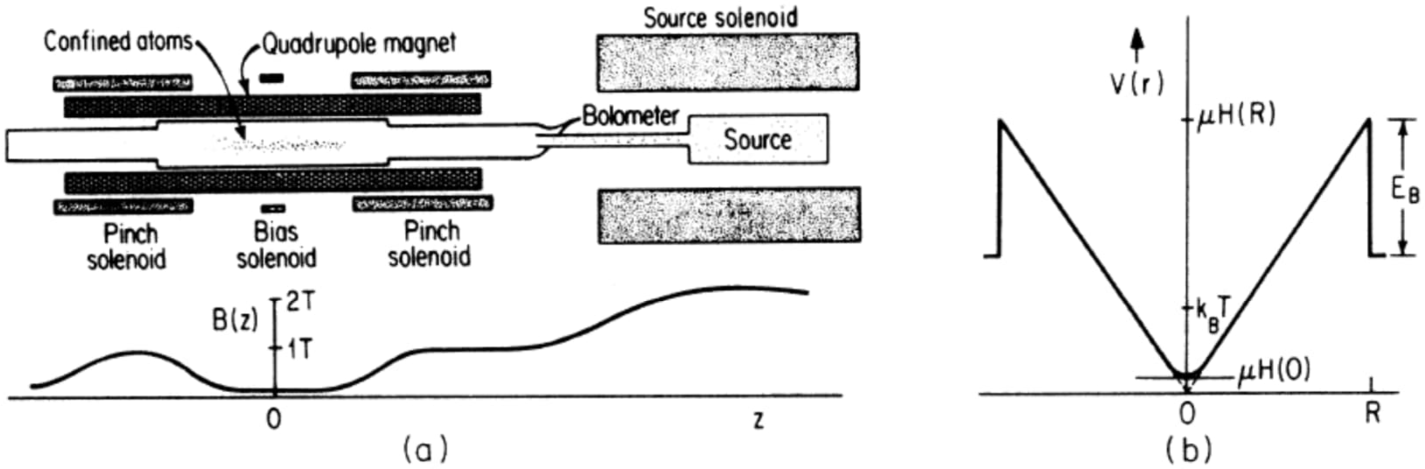


FIG. 1. (a) Schematic diagram of apparatus for production, confinement, and cooling of atomic hydrogen. The highest magnetic fields are at the source, and the lowest in the confinement region. (b) Potential energy of atoms as a function of radial distance from the axis. The dotted line near $r=0$ applies to a pure quadrupolar magnetic field. The bias solenoid produces a field $H(0)$ at $r=0$ to prevent nonadiabatic transitions to the lower hyperfine states. When the trap is emptied, $H(0)$ is reduced to zero.

Open traps

MIT, Amsterdam 1986-1998

Wall-free confinement of H↑

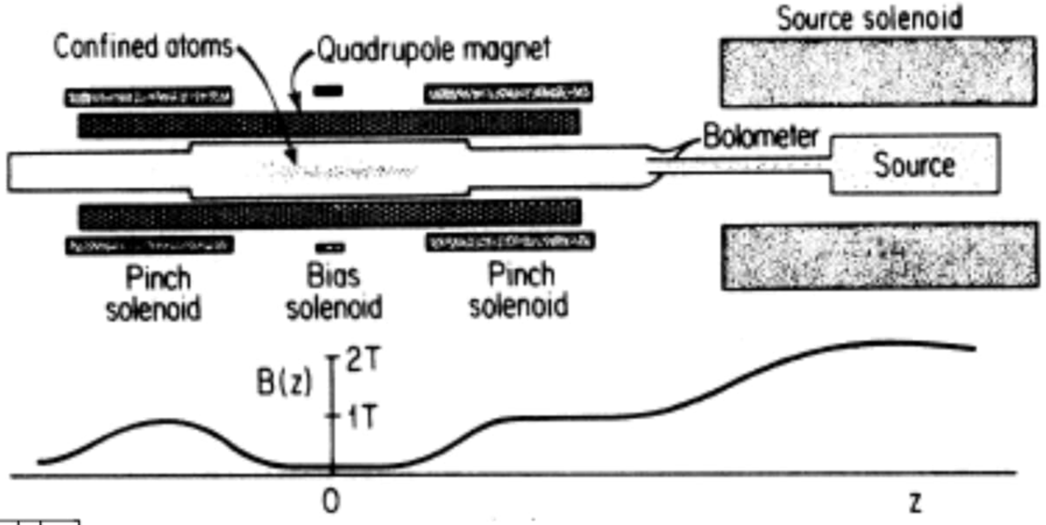
Evaporative cooling

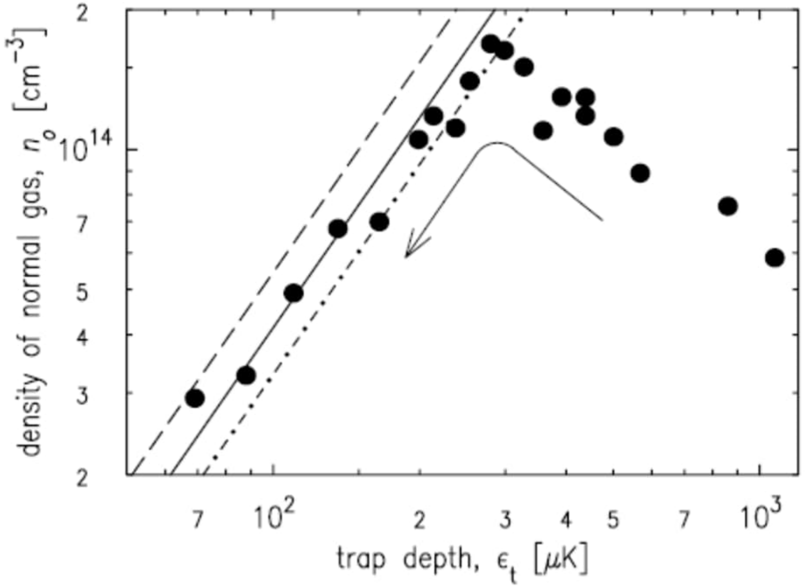
BEC reached!

at gas density $n_0=1.8\cdot10^{14}$ cm^{-3}, T=50 μK

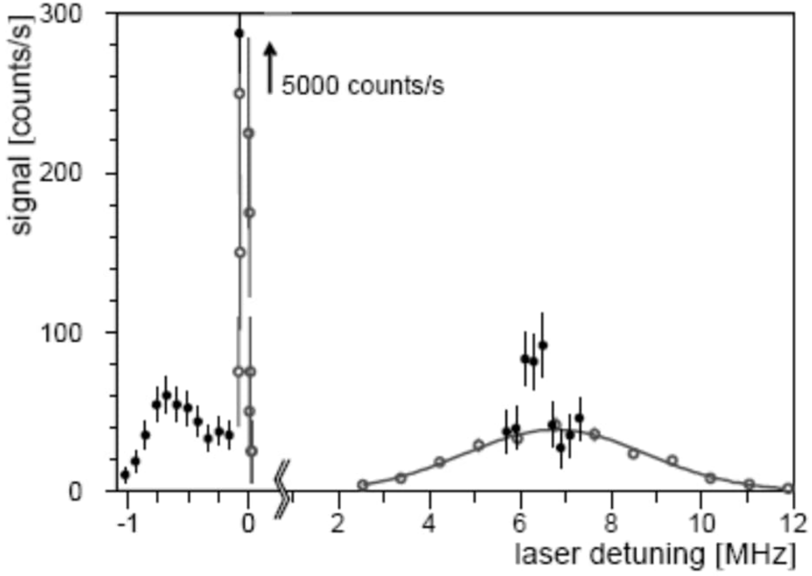
with the peak condensate density $n_p=5\cdot10^{15}$ cm^{-3}

The condensate is 15μm diameter and 5 mm long





D. G. Fried *et al*., Phys. Rev. Lett. 81, 3811 (1998)



Reaching BEC of H in MIT was a great result after 20 years of tough work by a large group of high level researchers.
However, this happened 3 years after the BEC of ^{87}Rb was done, (Nobel prize 2001).

MIT and Amsterdam groups stopped their H research at ~2000.
For >20 years nobody tried to trap and cool H. Why?

Cold H gas vs. other alkalis

Major difficulties:

- Optics requires UV (122 or 243 nm);
- Laser cooling is recoil-limited to 2-3 mK;
- Low collision rate;
- Absense of Feshbah resonances;
- Necessity of cryogenic methods, DR.

Advantages:

- Small 3-body recombination rate;
- Large number of atoms
- Studies of interaction with superfluid 4He;

What else with ultracold H, except BEC?

- Quantum reflection
- Gravitational Quantum States;
- Precision optical and microwave spectroscopy;
- Comparison with anti-H, GBAR;

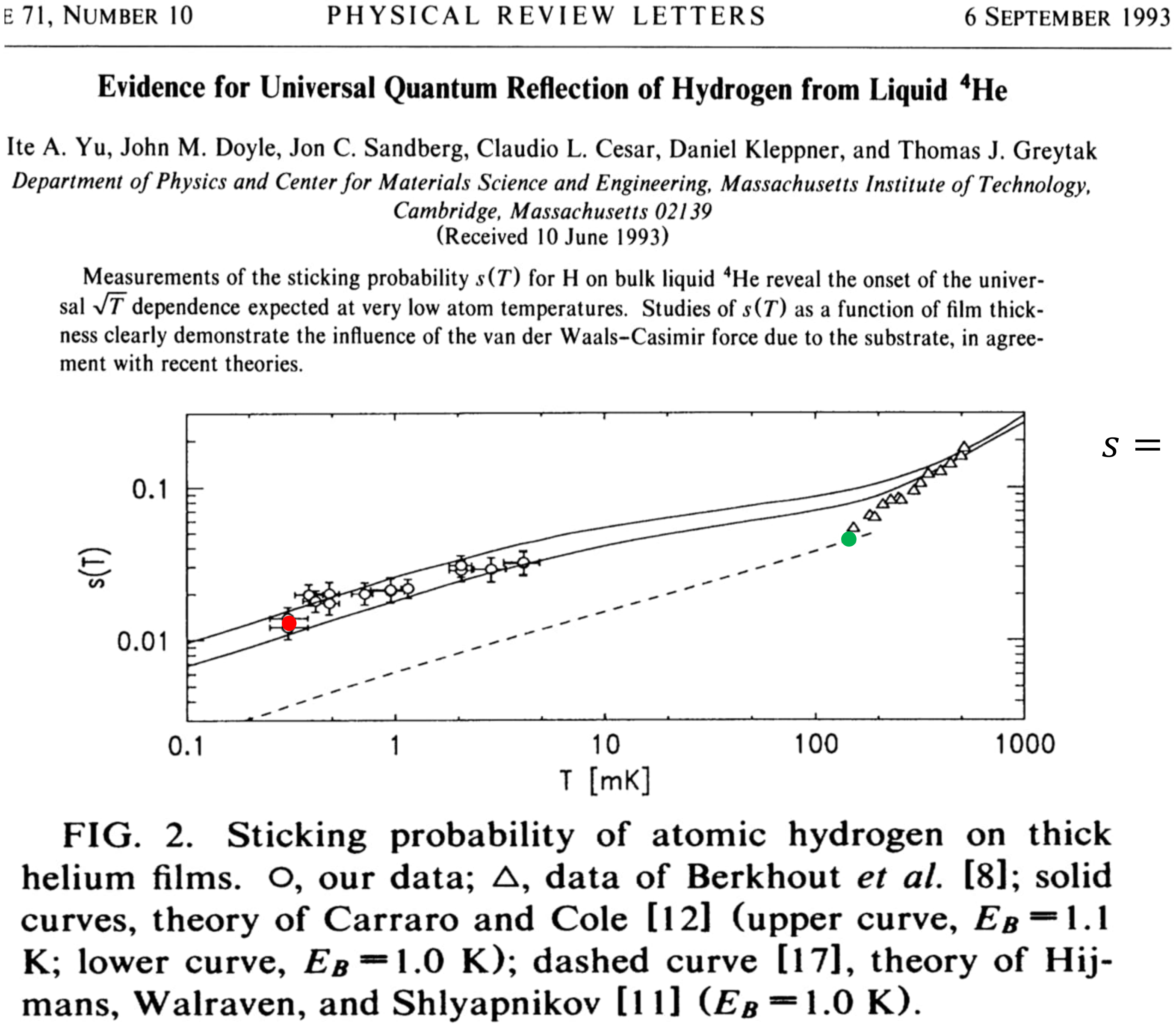
(Gravitational Behavior of Anti-H at Rest)

- Cryogenic H maser;
- Ultra-cold collisions;
- Bose-Fermi mixtures with strong mass imbalance

Our goal:

To provide a source of ultra-cold H to other researchers to do things above

Quantum Reflection



E 71, NUMBER 10 PHYSICAL REVIEW LETTERS 6 SEPTEMBER 1993

Evidence for Universal Quantum Reflection of Hydrogen from Liquid ^{4}He

Ite A. Yu, John M. Doyle, Jon C. Sandberg, Claudio L. Cesar, Daniel Kleppner, and Thomas J. Greytak
Department of Physics and Center for Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 10 June 1993)

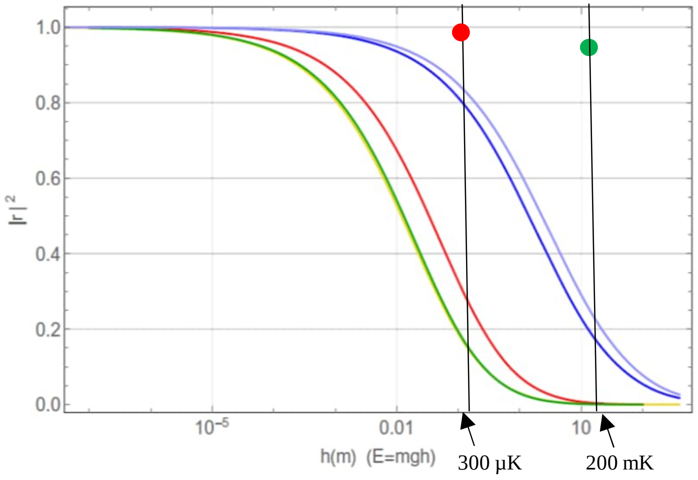
Measurements of the sticking probability $s(T)$ for H on bulk liquid ^{4}He reveal the onset of the universal $\sqrt{T}$ dependence expected at very low atom temperatures. Studies of $s(T)$ as a function of film thickness clearly demonstrate the influence of the van der Waals–Casimir force due to the substrate, in agreement with recent theories.

FIG. 2. Sticking probability of atomic hydrogen on thick helium films. ○, our data; △, data of Berkhout *et al.* [8]; solid curves, theory of Carraro and Cole [12] (upper curve, $E_B = 1.1$ K; lower curve, $E_B = 1.0$ K); dashed curve [17], theory of Hijmans, Walraven, and Shlyapnikov [11] ($E_B = 1.0$ K).

$$s = 1 - r$$

QR of anti-H

P.-P. Crepin *et al.*, Europhys. Lett. **119**, 33001 (2017)



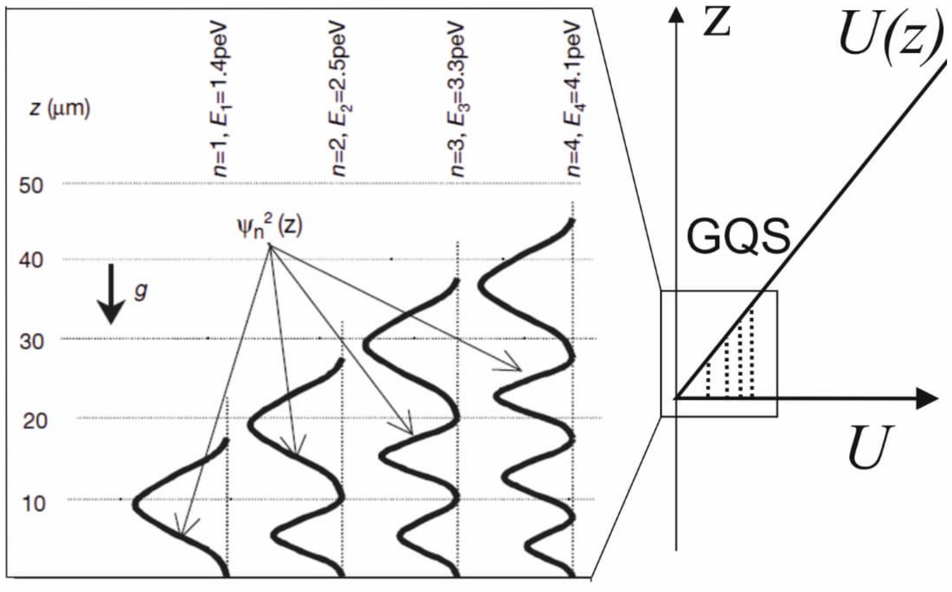
QR probability as a function of the energy E = mgh of the atom falling from the height h. The full lines correspond, from top to bottom, to bulks of ^{3}He (light blue), ^{4}He (dark blue), silica (red), silicon green) and gold (yellow). Solid vertical line corresponds to the atoms temperature 300μK, reached in experiments of MIT group.

Some extra reflectivity may occur at close approach,
distances shorter than 10 μm

Gravitational Quantum States.

Observed by V. Nesvizhevsky at ILL in 2002 with ultra-cold neutrons

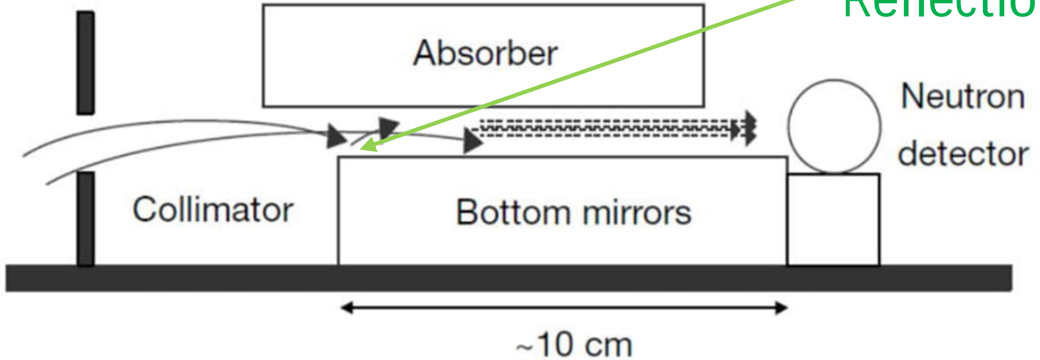
Nature, 415, 287 (2002)



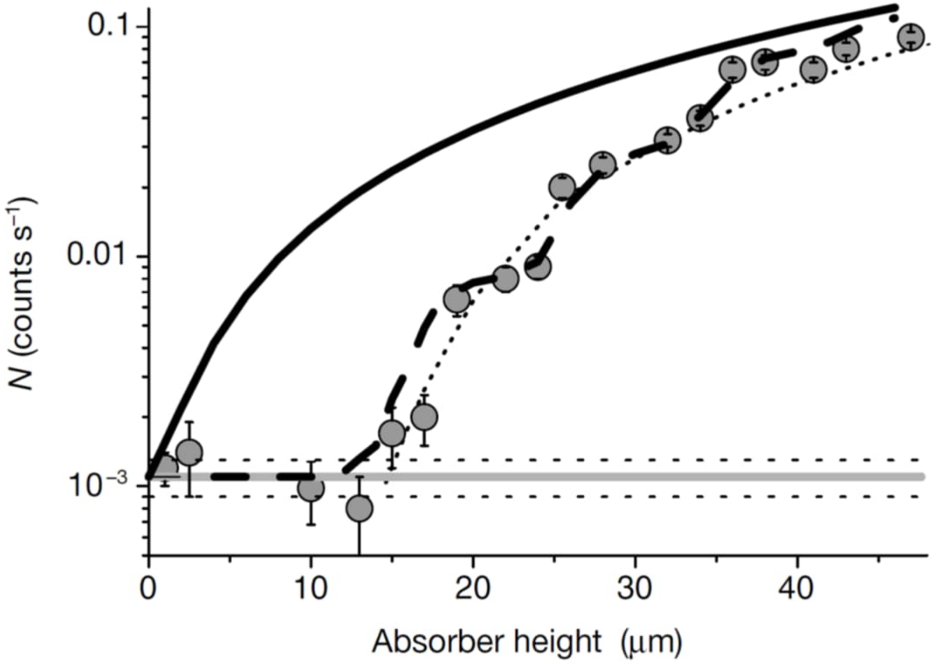
$$l_g = \left(\frac{\hbar^2}{2mMg}\right)^{1/3} \approx 6\ \mu m$$

$$\varepsilon_g = \left(\frac{\hbar^2 M^2 g^2}{2m}\right)^{1/3} \approx 0.6\ \text{peV} \approx 0.66\ \mu K$$

$v_\rightarrow \approx 5 - 15\ m/s$ $v_\downarrow \approx 5\ cm/s$



Quantum Reflection



GQS of H above superfluid ^{4}He

Small mass (same as *n*) allows probing distance range of 10-100 μm from the surface. Weak Casimir and VdW interactions.

$$l_g \sim \frac{1}{m^{2/3}} \approx 6\ \mu m$$

Search for unknown weak forces and physics beyond SM.

Interactions of H with liquid helium:

well studied (but not fully understood). Largest QR probability

Superfluid helium at 100 mK – ideal surface, smooth, uniform and clean

Large amounts/flux of H with velocities much smaller than with *n*

Trapped $N \sim 10^{12}$ at 0.1 mK (1.5 m/s)

In a beam $\dot{N} \sim 10^{15}\ s^{-1}$ at 5 K (320 m/s) further slowed by Zeeman decelerators

Quantum gravity?

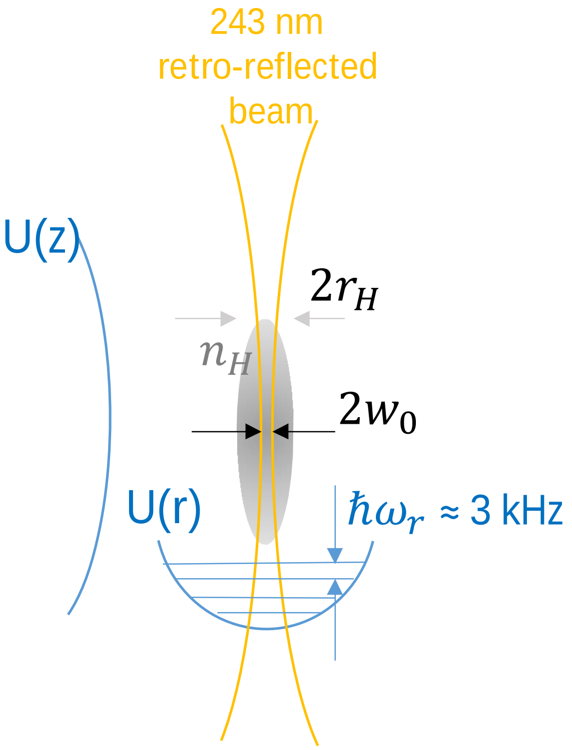
1S-2S spectroscopy of H gas

Best measurement by T. Hansch group: $f_{1S-2S} = 2.466\ldots \cdot 10^{15}(11)$ Hz

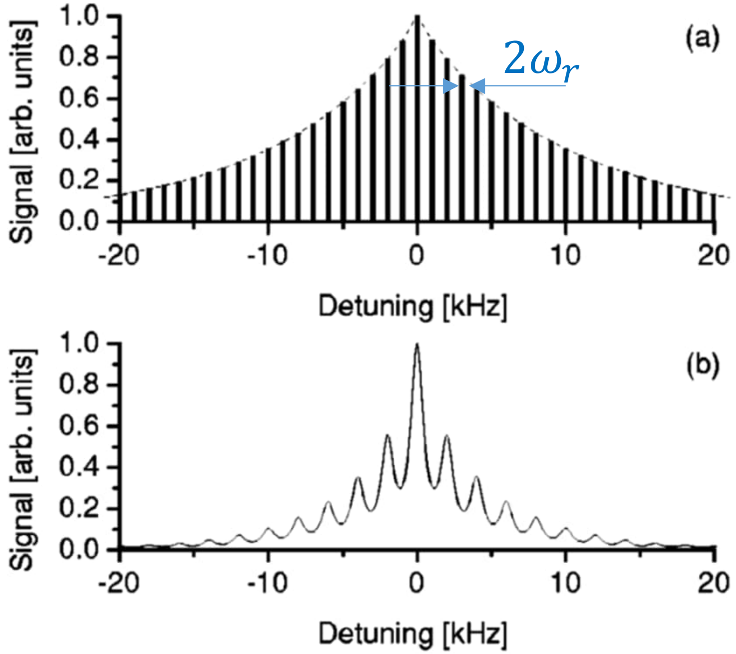
Natural linewidth (NLW) ≈ 1.3 Hz

limited mostly by high velocity of atoms ≥ 60 m/s

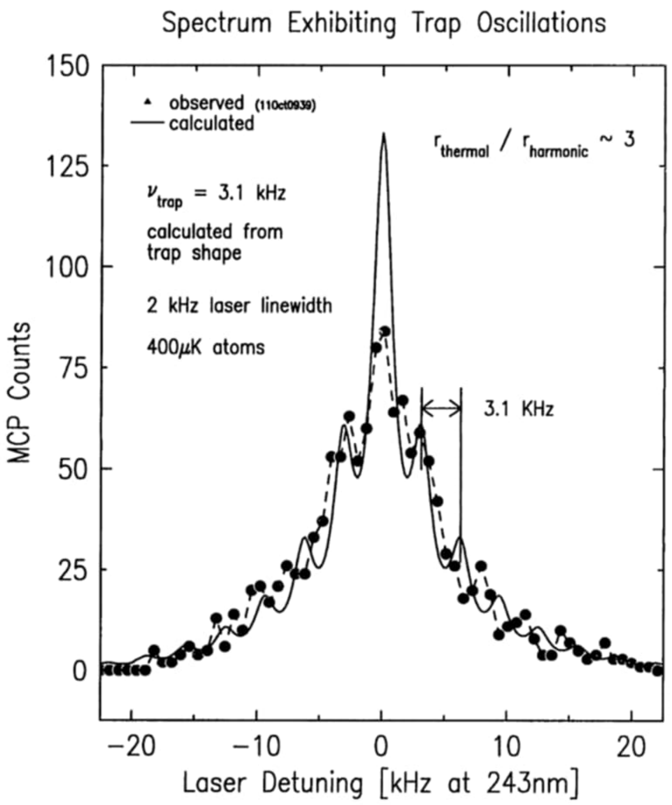
MIT: linewidth of the excitation laser ~2 kHz



Calculated spectrum



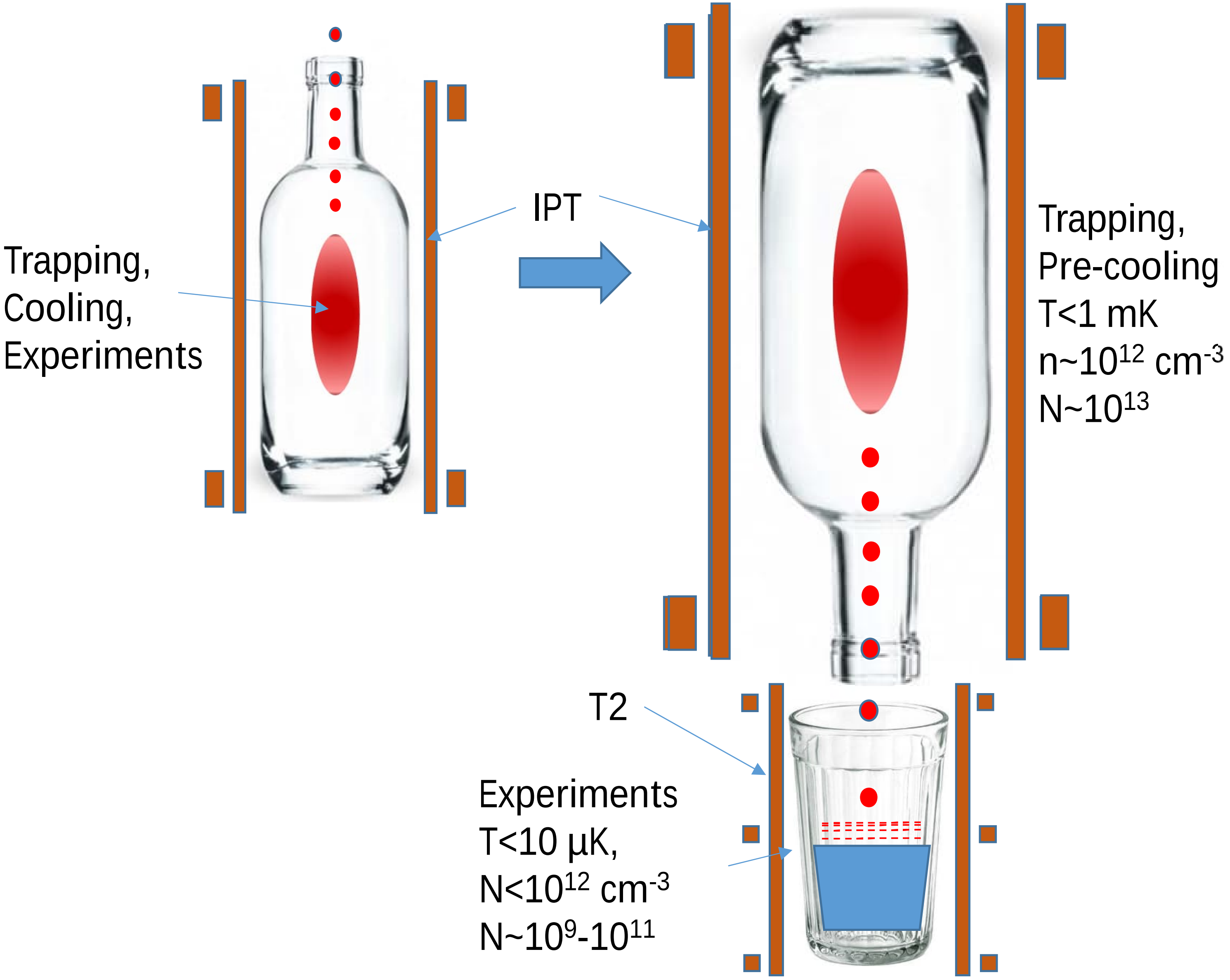
Observation



We are building laser with the linewidth 2-3 Hz

If we manage to do so, we will perform measurements at the NLW level and improve 1S-2S interval measurement by 1-3 orders of magnitude

Double trap scheme



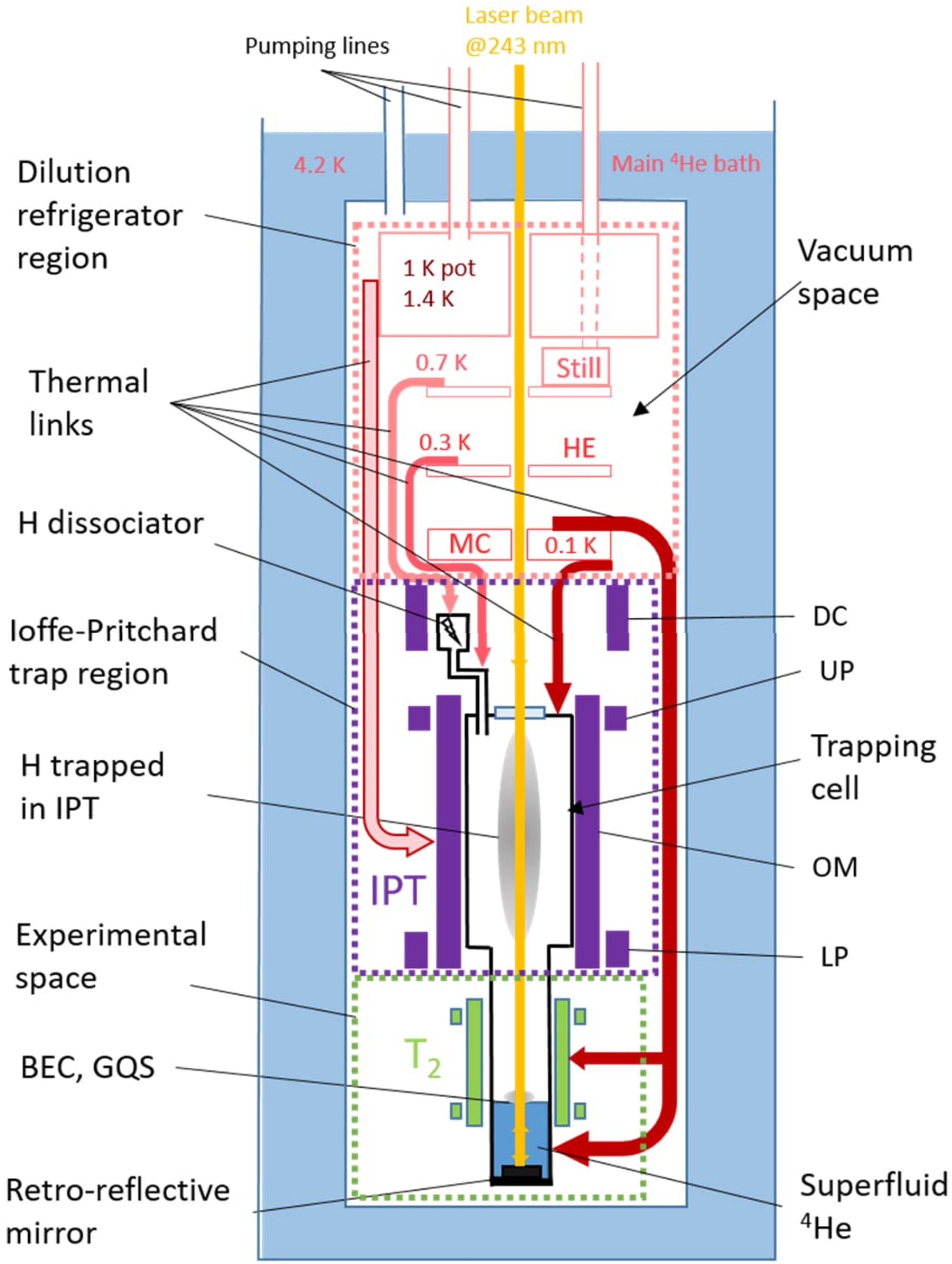
Trapping,
Cooling,
Experiments

IPT

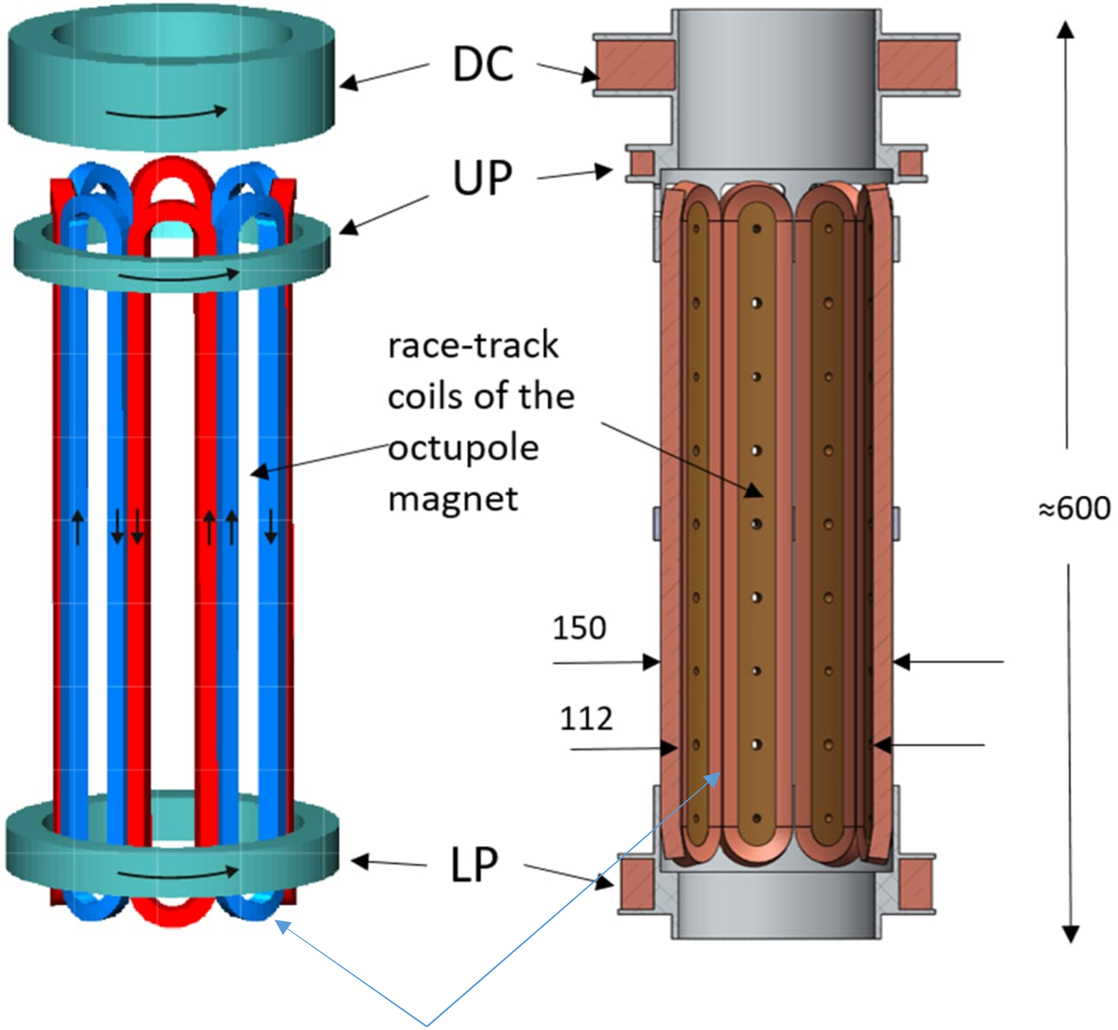
Trapping,
Pre-cooling
T<1 mK
n~10^{12} cm^{-3}
N~10^{13}

T2

Experiments
T<10 µK,
N<10^{12} cm^{-3}
N~10^{9}-10^{11}



IPT and trapping cell at Turku



Race-track shape coils are pressed together
by magnetic field forces like the staves in an old wooden barrel

Octupole geometry for
radial confinement

$$V(r) \sim r^3$$

Large effective volume:
≈0.6 l at 50 mK
with minimum trap barrier ≈ 0.9 T (0.6 K)

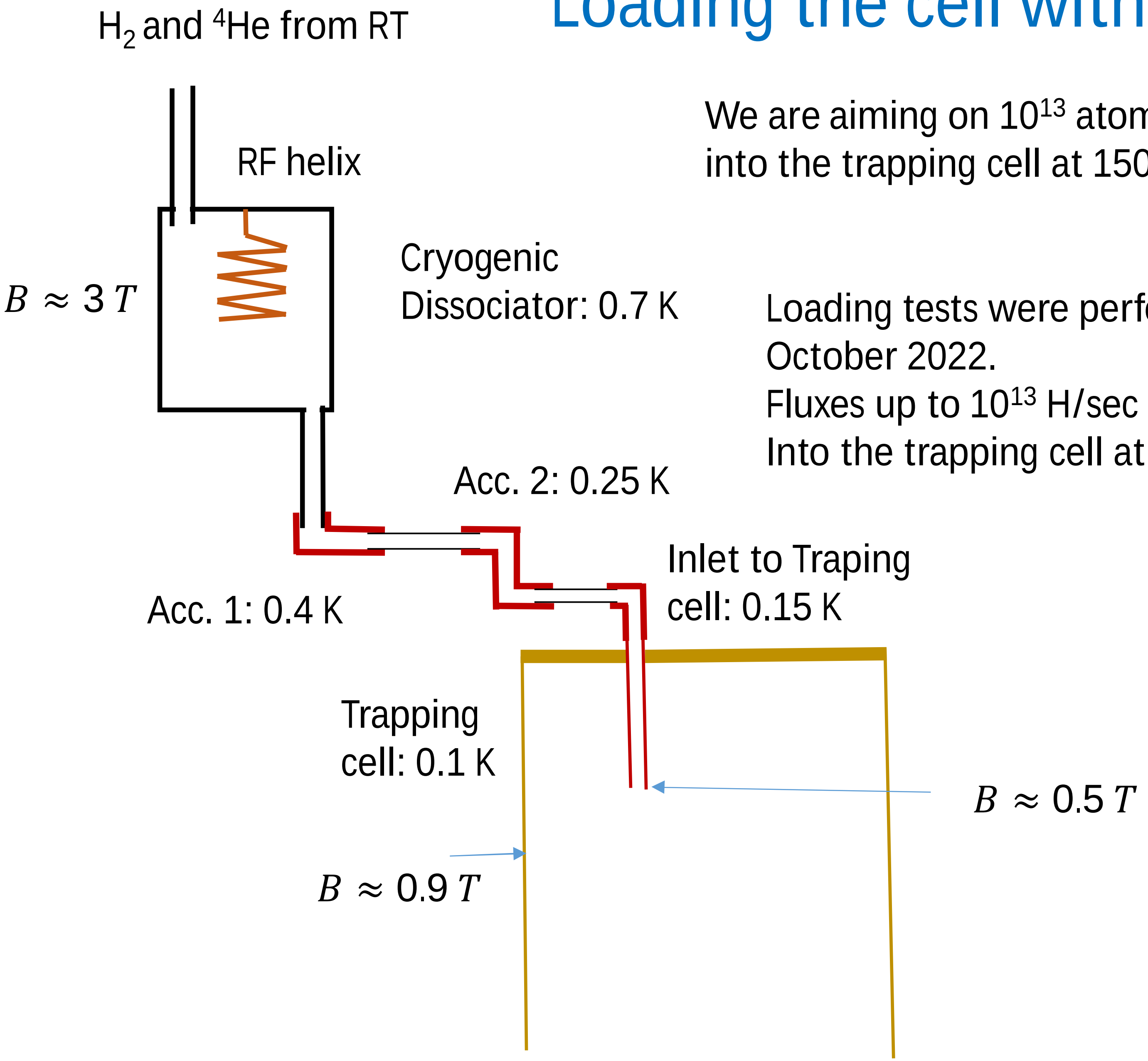
Built and tested in 2019-2022

J. Ahokas et. al., Rev. Sci. Instr. 93, 023201 (2022)

Loading the cell with H atoms

We are aiming on 10^{13} atoms/sec incident into the trapping cell at 150 mK

Loading tests were performed in October 2022.
Fluxes up to 10^{13} H/sec are obtained
Into the trapping cell at 150 mK



H_2 and ^{4}He from RT

RF helix

$B \approx 3\ T$

Cryogenic Dissociator: 0.7 K

Acc. 2: 0.25 K

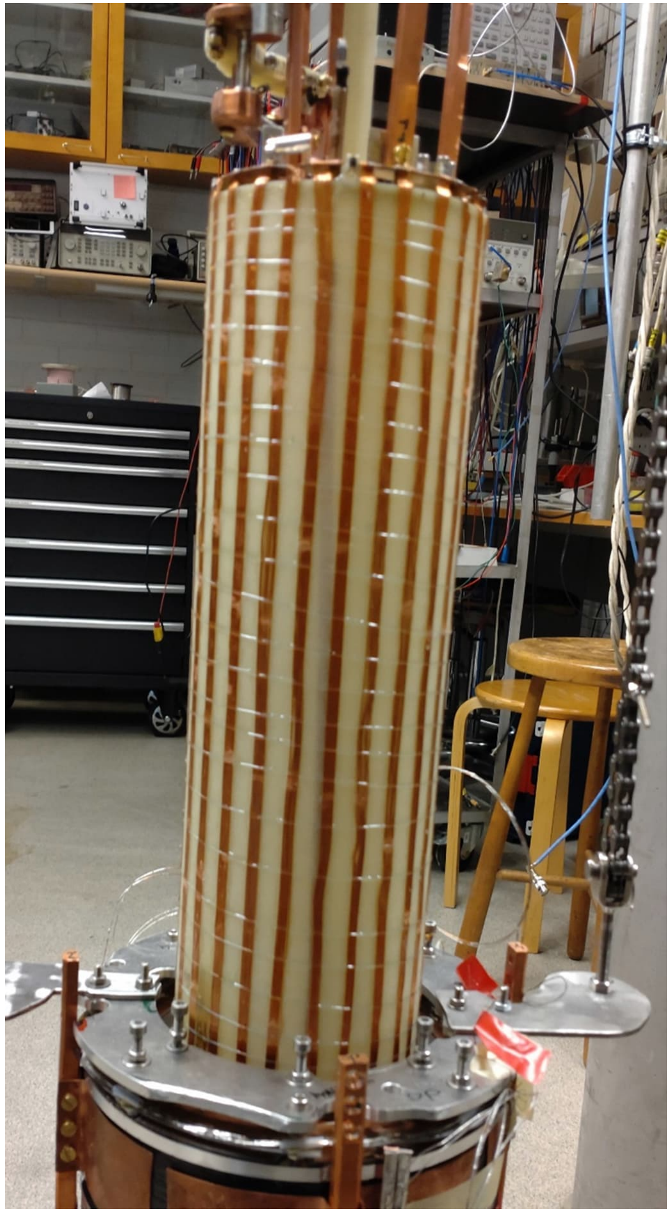
Acc. 1: 0.4 K

Inlet to Traping cell: 0.15 K

Trapping cell: 0.1 K

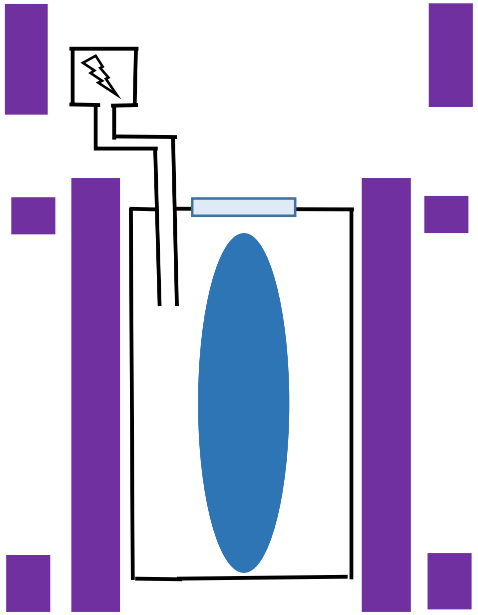
$B \approx 0.5\ T$

$B \approx 0.9\ T$



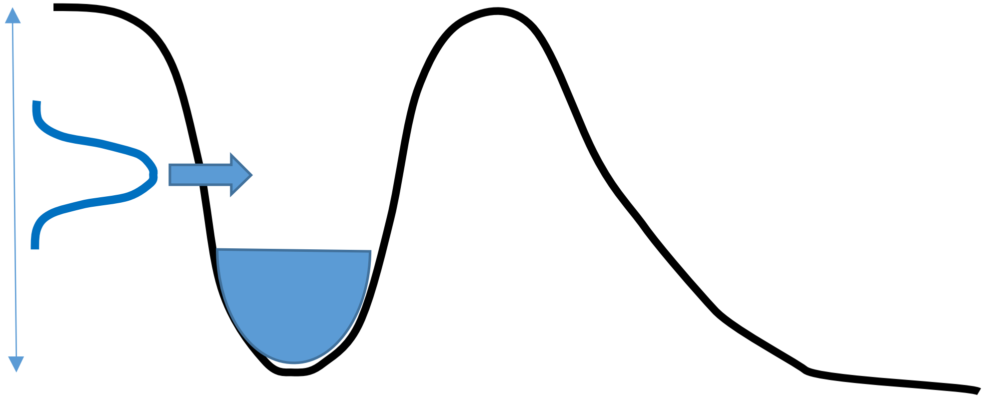
Loading atoms into the trap

$T_{in} \approx 150 - 200$ mK



To the middle of the barrier

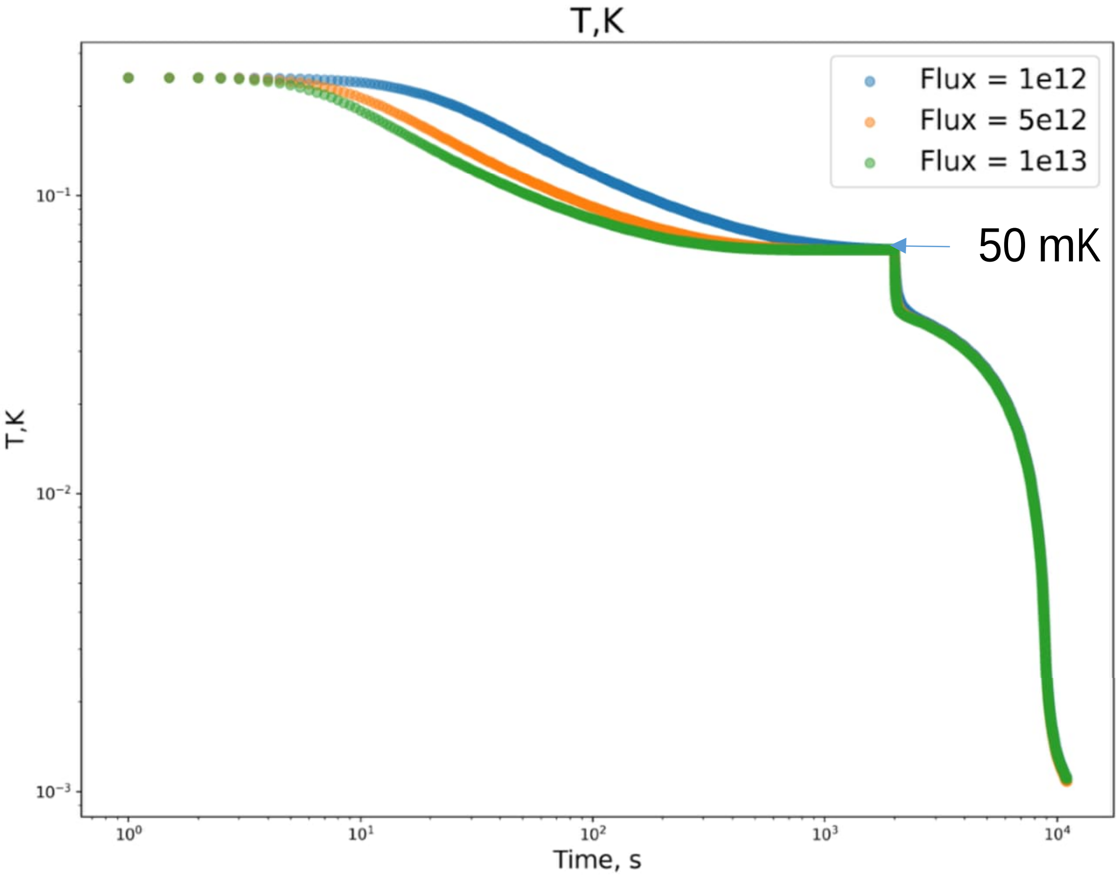
$\varepsilon_t \approx 0.5$K



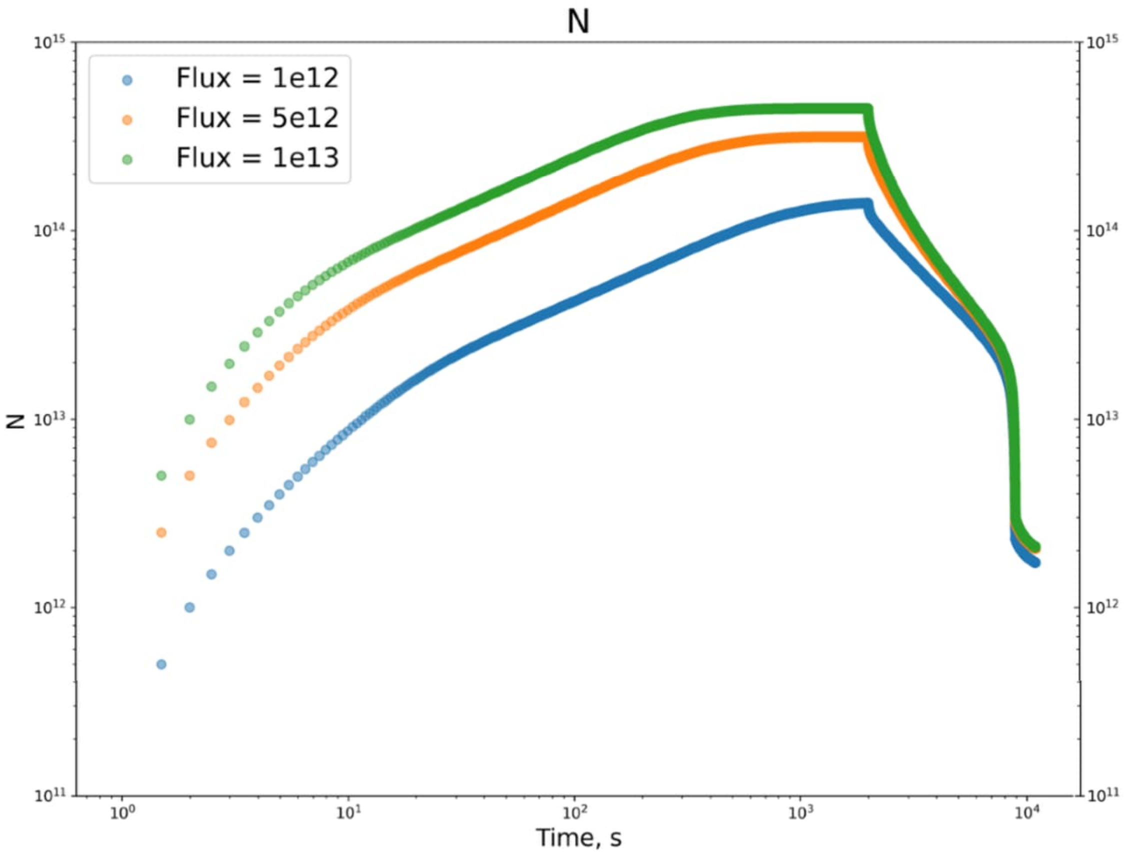
$T = 40$ mK

Loading and cooling simultaneously!

Loading with cooling. Simulations



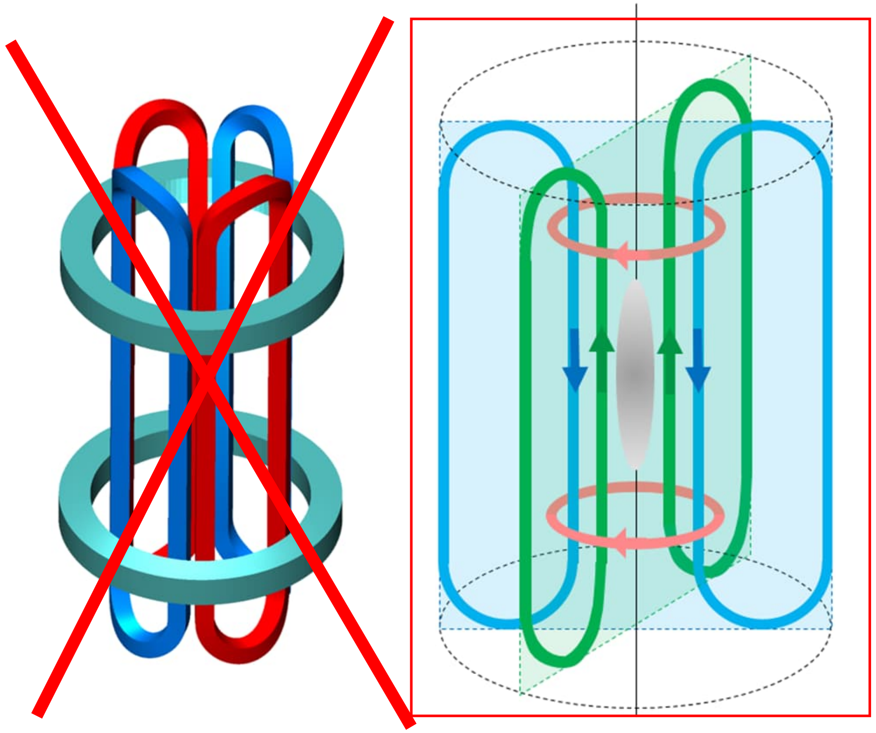
50 mK



Efficiency of evaporative cooling: $\alpha \equiv \frac{dlnT}{dlnN} \approx 1 \dots 2$

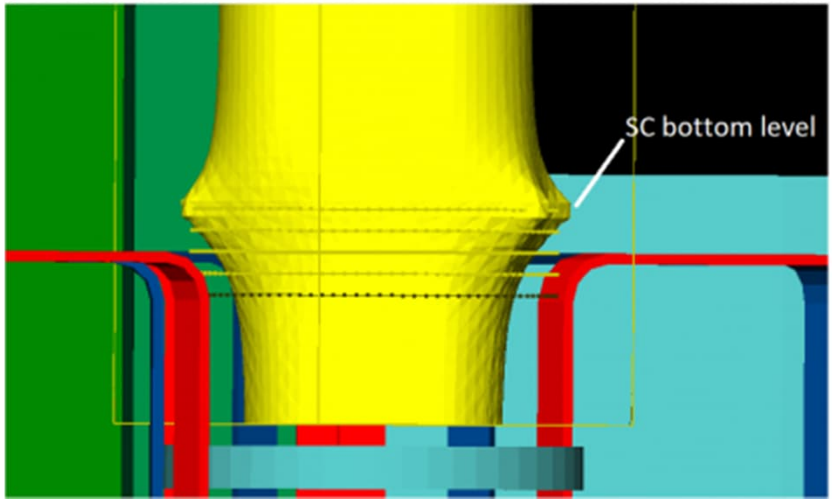
$\alpha \approx 1.5$ was reached in MIT

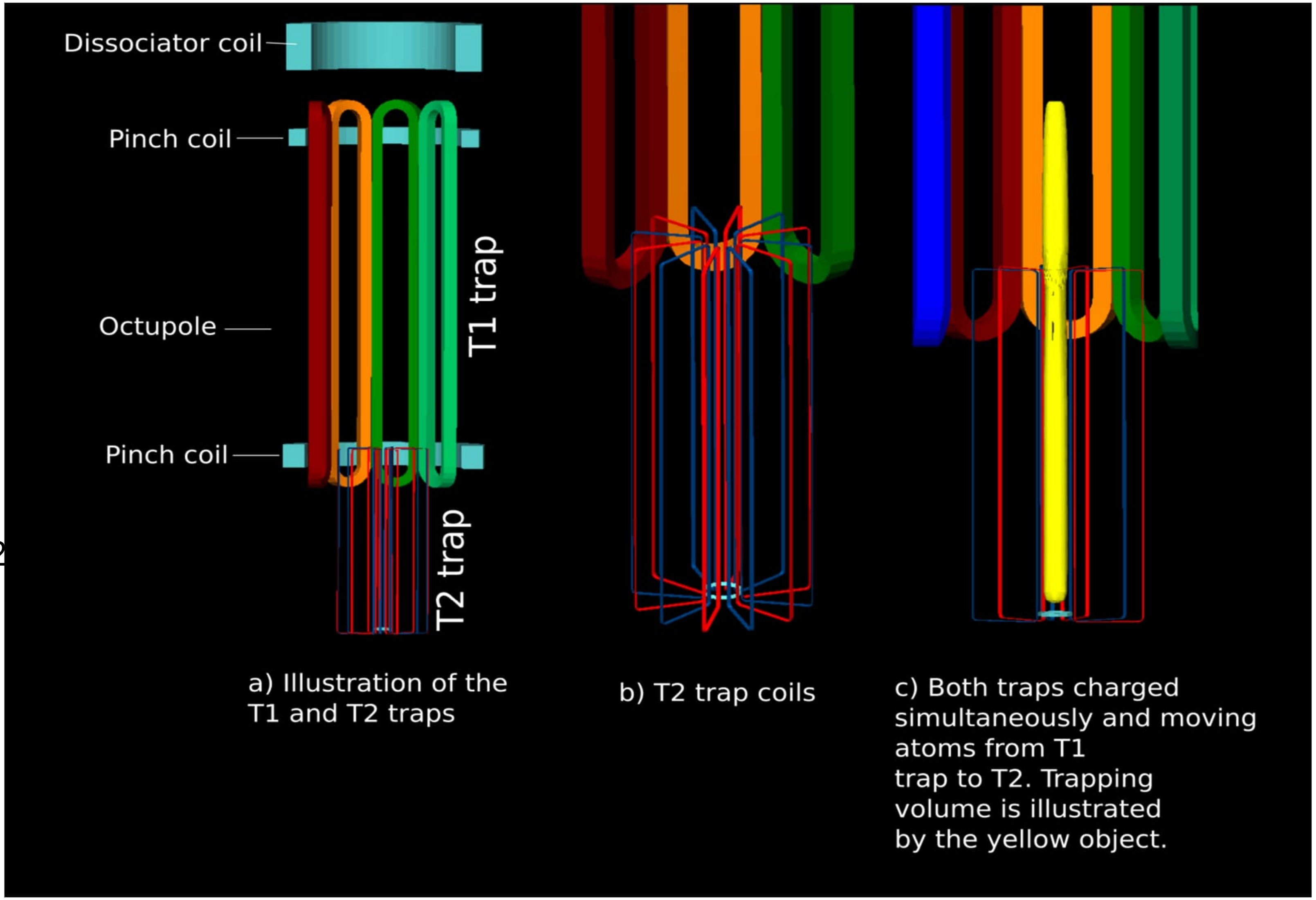
Design of the T2 trap



Possible leakage when transferring gas from IPT to T2

12 pole. T2 4A, Octu 50A. Leaks at 8-10G.





a) Illustration of the T1 and T2 traps

b) T2 trap coils

c) Both traps charged simultaneously and moving atoms from T1 trap to T2. Trapping volume is illustrated by the yellow object.

All magnetic field calculations are done by the BioSavart software developed my Meritt Reynolds in Vancouver.

Current status of the project

- A large Ioffe-Pritchard trap is built and tested inside the vacuum space of DR;
- A trapping cell is built together with the cryogenic H dissociator and H transport line;
- We measured flux of H↑ of ~10^{13} atoms/sec incident into the trapping cell at T=150 mK;
- We can trap and cool H, but do not have diagnostics of the density and temperature yet;
- Major components for the laser system aquired, including FP cavity for laser stabilization;
- T2 trap is designed and 15 race-track coils manufactured and tested at 4.2 K;
- We project first trapping, evaporative cooling and 1S-2S detection by summer 2023.