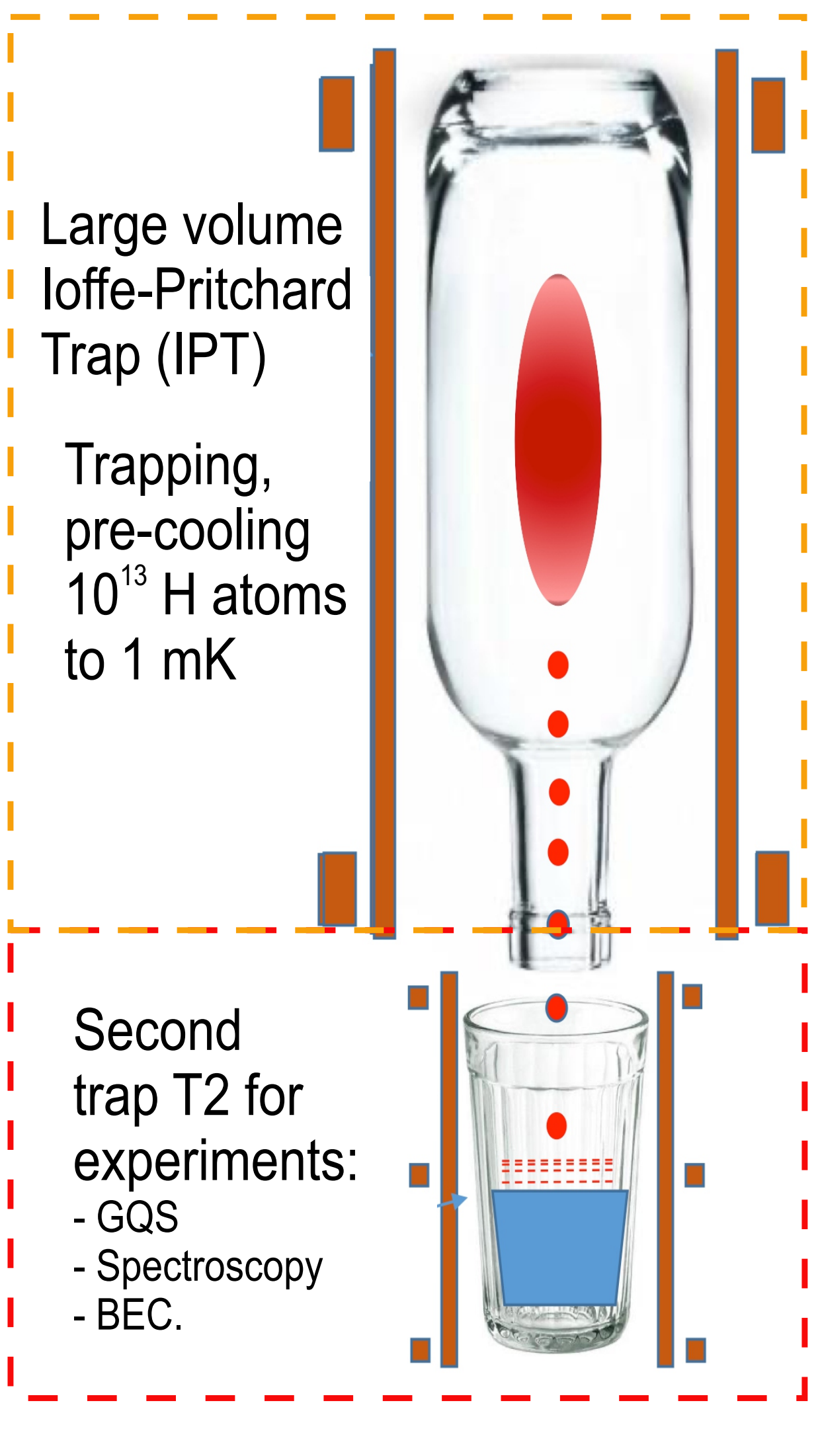
Experiments with hydrogen atoms at ultra-low energies

Aleksei Semakin, Otto Hanski, Janne Ahokas, Sergey Vasiliev*
Wihuri Physical Laboratory, Department of Physics and Astronomy, University of Turku, Turku 20014, Finland
*servas@utu.fi

*We present a recent progress towards experiments with hydrogen atoms at ultra-low energies, nearly at rest planned by an international collaboration **GRASIAN*** (Gravity, Spectroscopy and Interferometry with Atoms and Neutrons, https://grasian.eu/). We will probe the ultralow-energy domain with hydrogen, the lightest and simplest of neutral atoms, which has served as a test probe of the fundaments of physics throughout the era of modern physics. The thermal motion of atoms has set limits to the accuracy of experiments. Therefore, using hydrogen atoms nearly at rest one expects to obtain unprecedented levels of precision.*

***GRASIAN** combines experimental and theoretical activities of several groups and institutions: Institut Laue Langevin, Grenoble,France (V. Nesviszhevsky), Laboratoire Kastler Brossel, Paris, France (F. Nez, S. Reynaud, P. Yzombard), Stefan Meyer Institute, Vienna, Austria (E. Widmann), University of Turku, Turku, Finland (S. Vasiliev), Eidgenössische Technische Hochschule, Zürich, Switzerland (P. Crivelli).

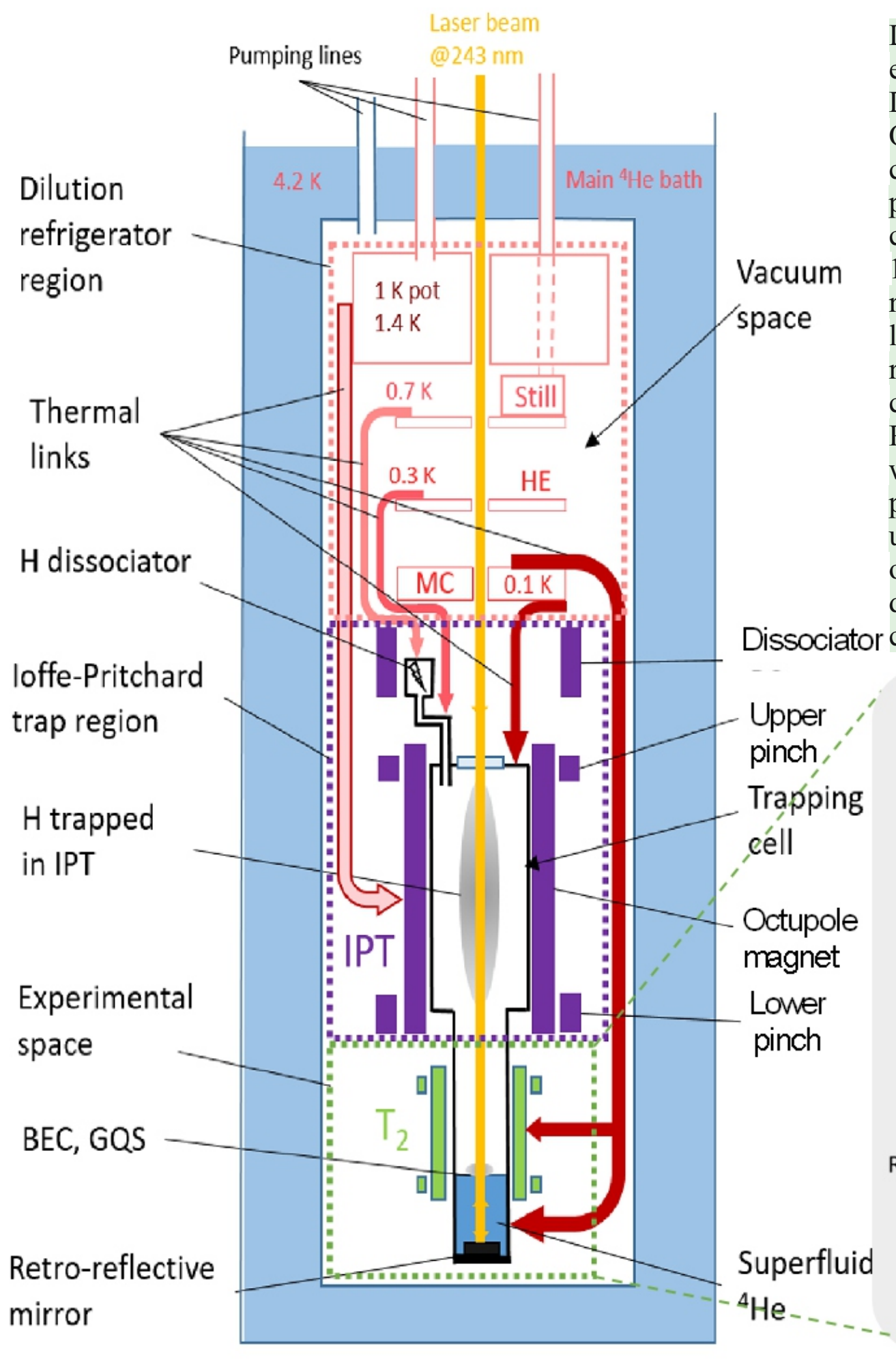
Motivation and Concept

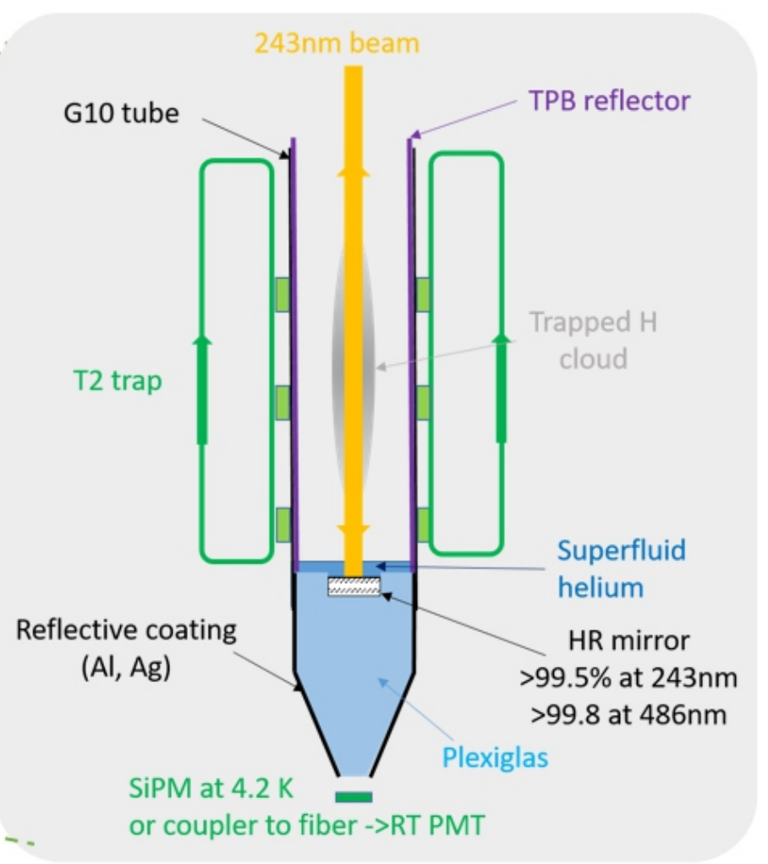

Large volume Ioffe-Pritchard Trap (IPT)

Trapping, pre-cooling 10^{13} H atoms to 1 mK

Second trap T2 for experiments:
- GQS
- Spectroscopy
- BEC.

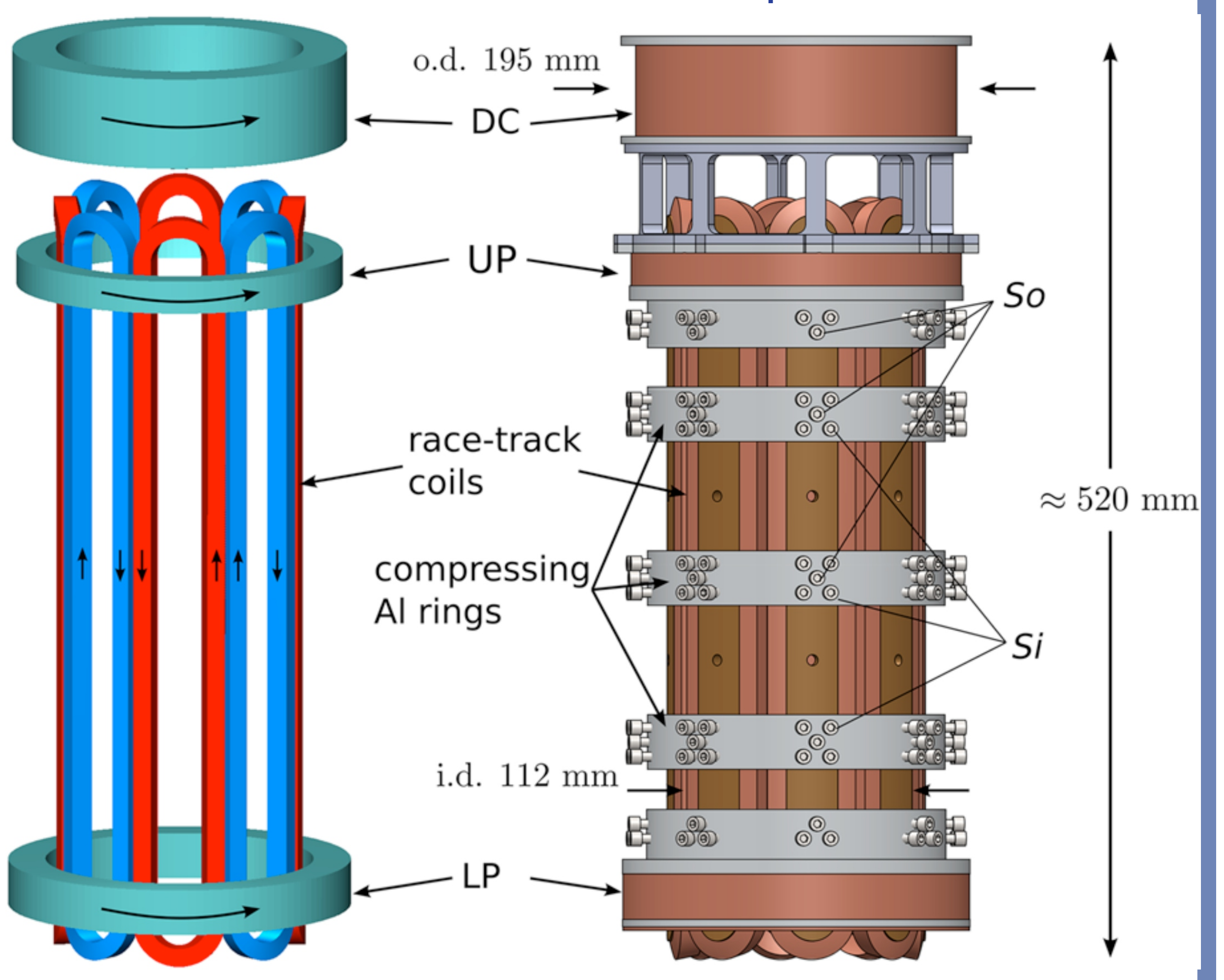
Studies of atomic hydrogen have been a great source for scientific discoveries, because of the H simplicity. We plan experiments with H atoms at lowest energies and veliocities, nearly at rest. Search for unknown weak interactions and forces is the main motivation of our research. We will release ultra-slow atoms onto the ideally flat surface of superfluid helium, where they will settle in the Gravitational Quantum States (GQS) formed in the triangular potential well created by the Earth gravity and quantum reflection from the surface. Precise measurements of the GQS energies will improve constraints on the existence of the unknown short-range forces between atoms and materials surface. Atom-fountain experiments with optical Ramsey spectroscopy will improve the accuracy of the 1S-2S interval. We are going to re-visit BEC of hydrogen and resolve several questions remaining after pioneering experiments at MIT [1]. Bose-Einstein condensation (BEC) of H bound in the GQS will be attained and used for matter-wave interferometry. Our methods and results will be useful for experiments with antihydrogen pursued at CERN. Our experimental concept will utilize a double trapping scheme. We will first trap and evaporatively cool H gas below 1 mK using a world largest Ioffe-Pritchard trap recently built in our llaboratory [2]. After that, the gas of H will be transferred to a second, more shallow trap T2 where temperatures below 10 μK will be reached. With further selection in the velocity space we will select atoms with velocities of the order of several cm/s. Working with atoms below 1 mK in the trap T2 can be done with fairly weak magnetic fields below 10 mT which can be easily manipulated for a variety of different experiments including switching off magnetic field for purposces of precision spectroscopy.





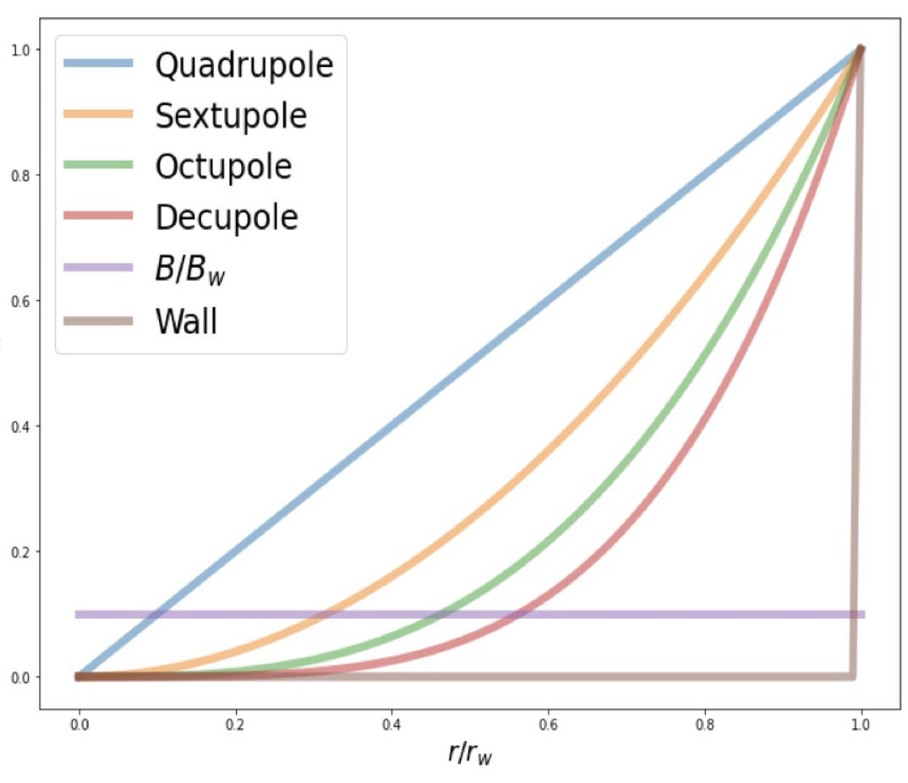
Left: Schematics of the experimental setup for experiments with ultra-cold atomic hydrogen. DC: dissociator solenoid. UP: upper pinch. OM: octupole magnet. LP: lower pinch. Main components of the dilution refrigerator are shown: 1 K pot, still, heat exchangers (HE), and mixing chamber (MC). A laser beam at 243 nm for two-photon 1S–2S spectroscopy passes along the setup axis and is retroreflected by using a mirror at the bottom. Thermal links between different components of the dilution refrigerator, the traps, and other experimental components are shown with the red arrows.
Right: Optical detection setup. 2S state willl be mixed with 2P and subsequent illumination of 121 nm photons. They will be converted to blue (470 nm) light using Tetraphenil butadiene film on the inner surfave of the sample cell. Finally blue photons will be directed to the SiPM detector ot to the optical fiber coupler, bringing light to RT

Ioffe-Pritchard trap

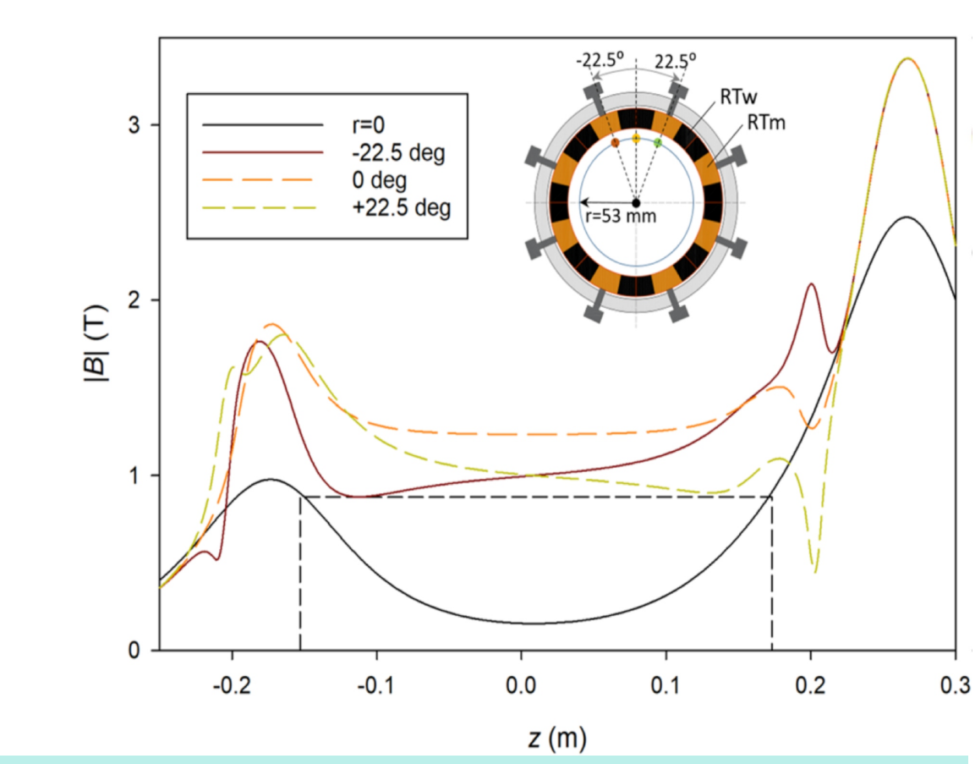


The configuration of currents and coils chosen for the Turku IPT trap (left) and an IPT outlook with all coils and compressing Al rings (right). The octupole magnet inner bore is 112 mm, and its outer diameter is 150 mm. The overall height of the IPT including the dissociator solenoid (DC) is ≈600 mm. The race-track coils of the octupole magnet are put together with three 1 cm thick Al compressing rings in the center of the system plus two rings extending from the upper (UP) and lower (LP) pinch forms.

Magnetic field profiles



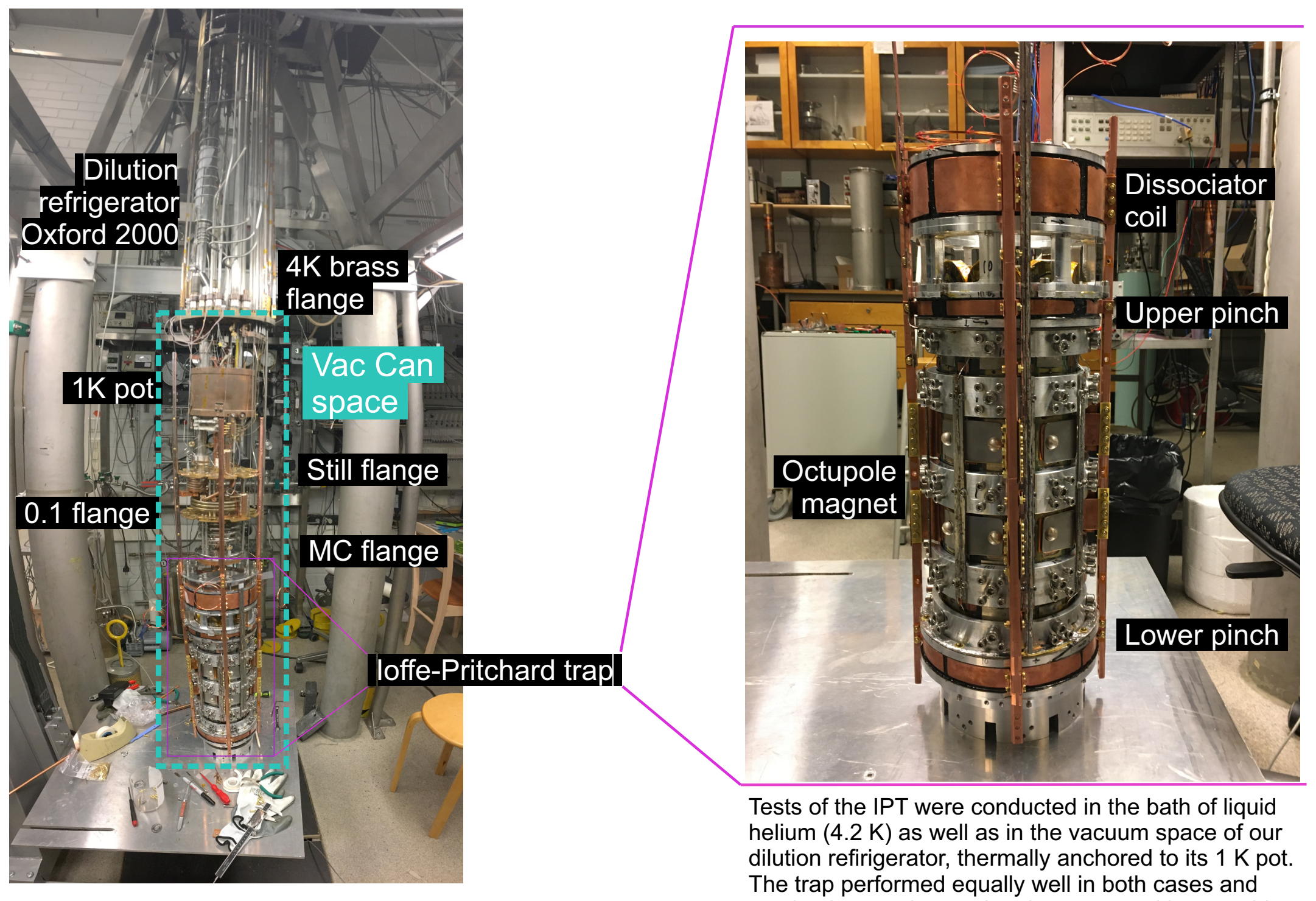
Magnetic field profiles along radial axis (z = 0) for different types of trap. Purple line shown a ration $B/B_w = 0.1$.



Magnetic field profiles along several vertical lines parallel to the IPT axis (z axis) at the distance of 53 mm from the trap axis. The locations of these lines in the horizontal cross section are shown in the inset. The vertical dashed lines mark locations of the top and bottom of the trapping cell. Plots are calculated for 100% of I_t (0.8 T trap depth).

Current status of the project

Ioffe-Pritchard trap inside vacuum space of a dilution refrigerator



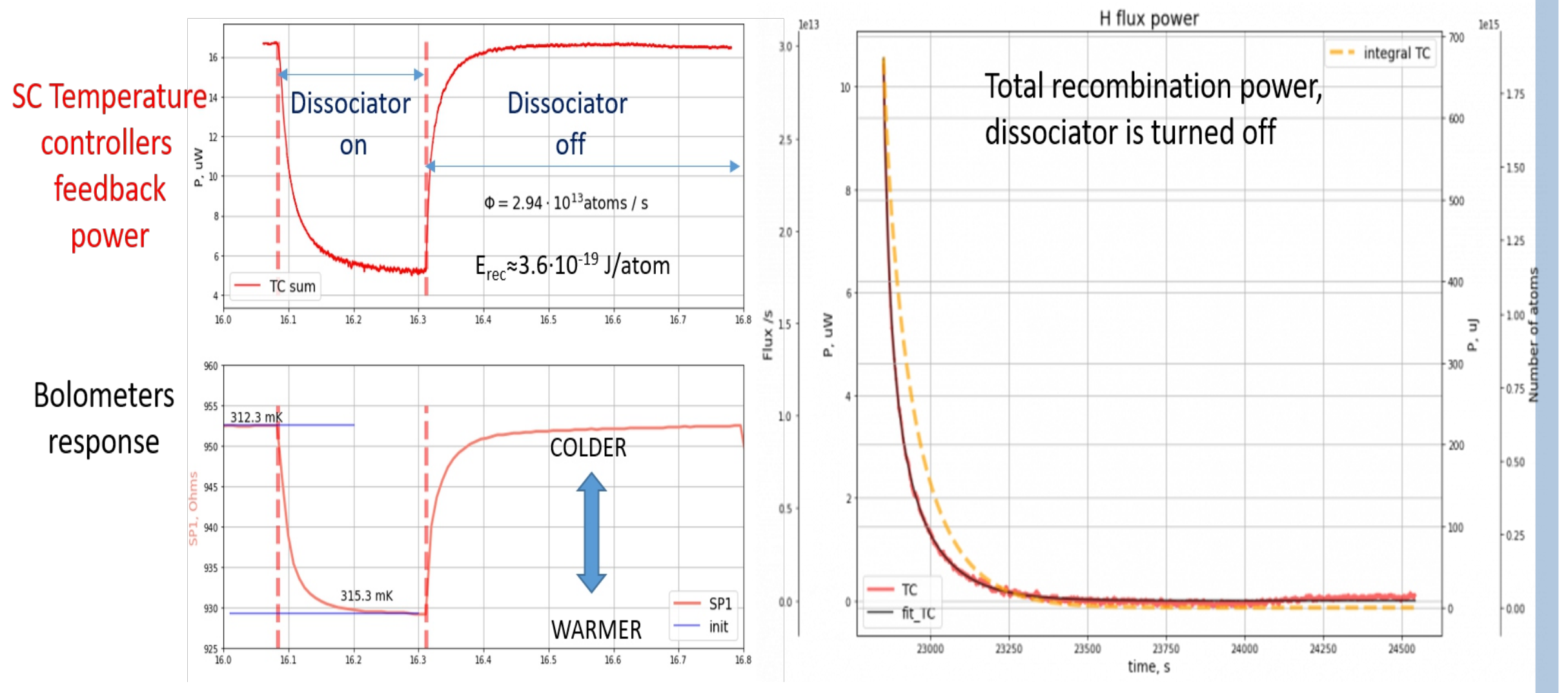
Tests of the IPT were conducted in the bath of liquid helium (4.2 K) as well as in the vacuum space of our dilution refrigerator, thermally anchored to its 1 K pot. The trap performed equally well in both cases and survived several quenches in vacuum without problems

Comparison of magnetic traps used for H and anti-H

Trap	Max height E_t, [T/K]	Number of poles	Diameter Trap/cell wall/ [mm]	Effective diameter for trapped gas at T≈0.1E_t, [mm]	Length of multipole system, [mm]	Effective volume for gas at 50 mK, [cm³]	Operating current, [A]
MIT	0.73/0.5	4	51/36	3.6	350	5	100
Alpha-2	0.82/0.56	8	50/45	22	280	70	1000
Turku	0.8/0.56	8	112/106	50	350/400	500	100-130

First trapping experiments

In the first trapping experiments we have successfully loaded H atoms from cryogenic dissociator into the plastic trapping cell. The temperature of incident H beam was 120-200 mK. At present the only way to evaluate the incoming flux and trapped number of atoms is to measure calorimetrically the heat released in recombination of the atoms. This is done using the feedback power of temperature controllers stabilizing trapping cell top and bottom as well as the mixing chamber of our DU. In addition we have more sensitive power meters inside the trapping cell: Aquadag bolometers, which receive about 10^{-3} of total recombination power.. The graphs below demsotrate behavior of these sensors as well as the TC signal during accumulation and following the decay of trapped gas ifter switching off dissociator.

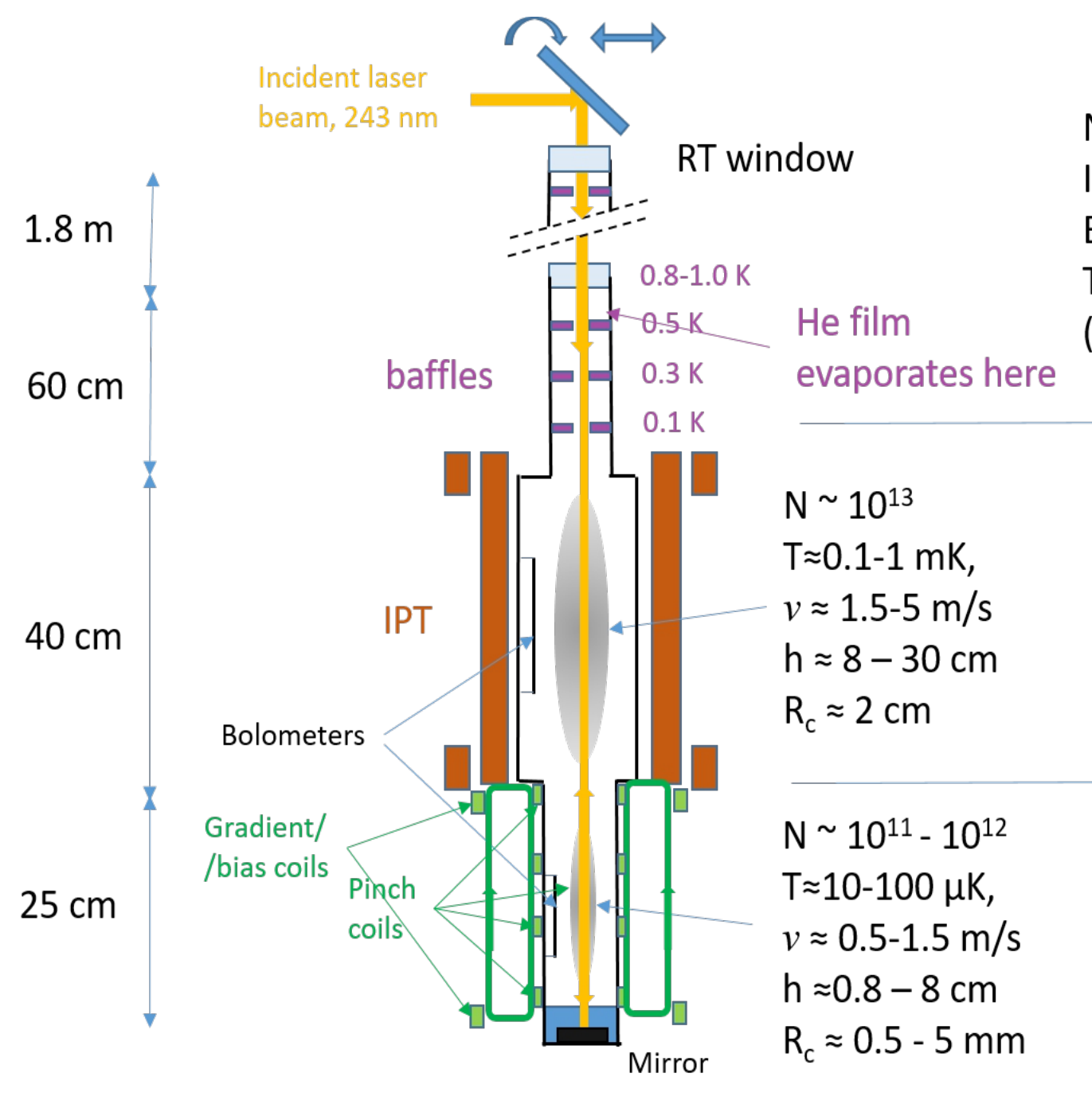


We reached:

Incoming H flux into the SC ˜ $3\cdot10^{13}$ s^{-1}
Number of loaded atoms: N˜ $2\cdot10^{15}$ at T˜120 mK just after loading
and N˜ $3\cdot10^{14}$ at T˜60 mK after thermallization in the trap

With the current (poor) diagnostic technique we are able to monitor the decay of trapped H on the time scale over 1 hour. Atoms disappear from the trap after a process of two-body dipolar relaxation. Based on the observed decay rate we conclude that the average density in was of the order of 10^{12} cm^{-3} after loading and thermallization.

Next step: building double trap



NOT using enhancement cavity;
Incoming beam alignment at RT;
Entrance window in SC at ~ 1 K – free of He film;
Thermallization baffles at 0.1...0.5 K
(also for recondensing He film)

N ~ 10^{13}
T≈0.1-1 mK,
$v \approx$ 1.5-5 m/s
h ≈ 8 – 30 cm
$R_c \approx$ 2 cm

IPT
Octupole radial confinement;
density 10^{12}-10^{13} cm^{-3}
Life time 10^3 – 10^4 sec

N ~ 10^{11} - 10^{12}
T≈10-100 μK,
$v \approx$ 0.5-1.5 m/s
h ≈0.8 – 8 cm
$R_c \approx$ 0.5 - 5 mm

T_2
4, 8, or 12 pole radial confinement;
density 10^{10}-10^{12} cm^{-3}
Life time 10^3 – 10^5 sec

Superconductive coils for the second trap T2 are manufactured and tested. We can reach trapping fields exceeding 200 G and switch them on/off on a time scale of few milliseconds. Assembling rest of the T2 setup will start in August 23 and hopefully first double trap tests will start by the end of the year.

Diagnostics: two-photon 1S-2S spectroscopy at 243 nm

We are preparing a laser system at 243 nm for the two-photon excitation of the trapped H gas. After the excitation, we will apply a short electric field pulse and mix 1S with 2P with subsequent relaxation to the gound state and emission of Lyman-alpha photon. The VUV luminescence will be converted to blue (470nm) light using thin layer of tetraphenyl butadiene covering inner surfaces of the trapping cell. Converted light will be detected by SiPM operating at cryogenic temperature below the trapping cell or collected to the fiber and transferred to room temperature photomultiplier.
We have aquired a master laser at 972 nm (Toptica) and stabilized it to a high finesse Fabry-Perot resonator. Then, two second harmonic generating stages will quadruple the laser frequency ending at 243 nm. We expect to get about 50 mW, which is more than enough for effective excitation and detection.

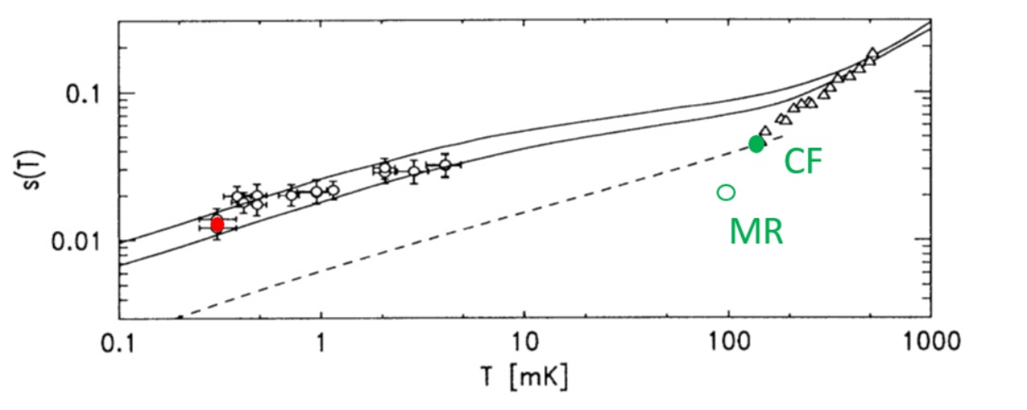
References
[1] Dale G. Fried et. al., Phys Rev Lett 81, 3811 (1998);
[2] Ahokas, J. et. al., Review of Scientific Instruments, *93*(2), 023201 (2022)
[3] A. Yu. Voronin, P. Froelich, and V. V. Nesvizhevsky, Phys. Rev. A 83, 032903 (2011);
[4] P.-P. Crepin et al., Europhys. Lett. 119, 33001 (2017);
[5] G. Cronenberg, Nature Physics 14, 1022 (2018);
[6] V. Bagnato, D. E. Pritchard, and D. Kleppner, Phys. Rev. A 35, 4354;
[7] Cesar, C. L., Hyperfine interactions, 109(1), 293-304 (1997)
[8] J. Alnis et al, Phys. Rev. A 77, 053809 (2008) ;
[9] N. Kolachevsky et al, Opt. Lett. 36, 4299 (2011)
[10] Kostelecký, V.A., Vargas, A.J., Phys. Rev. D 92, 056002 (2015)
[11] Malbrunot, C., et al., Phys. Eng. Sci. 376(2116), 20170273 (2018)
[12] M. D. Hurlimann et. al., Phys. Rev. A 34, 16065 (1986)
[13] I. A. Yu et. al., Phys. Rev. Lett., 71, (1993)
[14] J. J. Berkhout and J.T.M. Walraven, Phys. Rev. B, 47 (1993)

Planned experiments

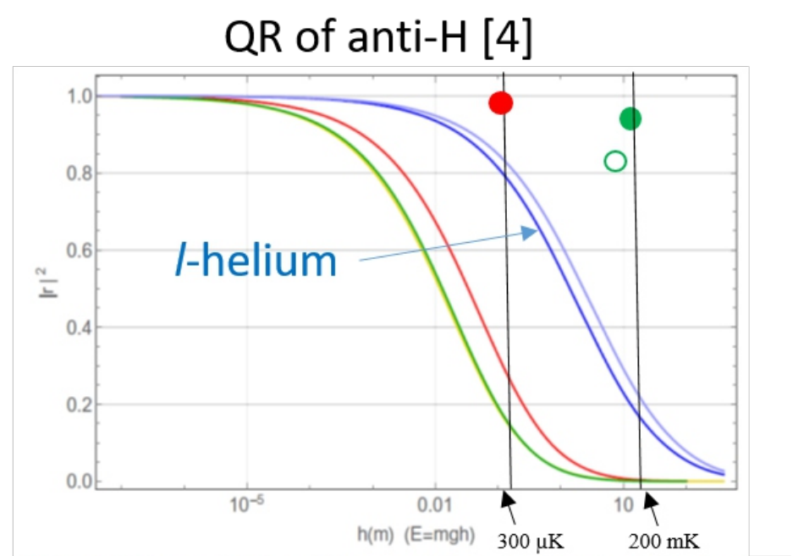
Quantum Reflection (QR) and Gravitational Quantum States (GQS)

Atoms have non-zero polarizability and interact with liquid helium surface via the Van der Waals/Casimir-Polder forces. This attractive interaction is responsible for quantum reflection of atoms which has high probability at low atomic energies.

Stcicking probability (*s=1-r*) of ultra cold H oin the surface of superfluid helium was measured by the MIT [13] and Amsterdam [14] groups. The lkatter experiments were performed by measuring enhanced capillary flow (CF) and mirror reflection of H from helium coated concave surface. results of these measurements are summarized below. QR for antihydrogen on liquid helium surface was calculated by Crepin [4], as shown on the right. Clearly there are certain discrepancies between the above mentioned experiments and heory. Some extra reflectivity appears in experiments compared with the theory (right).

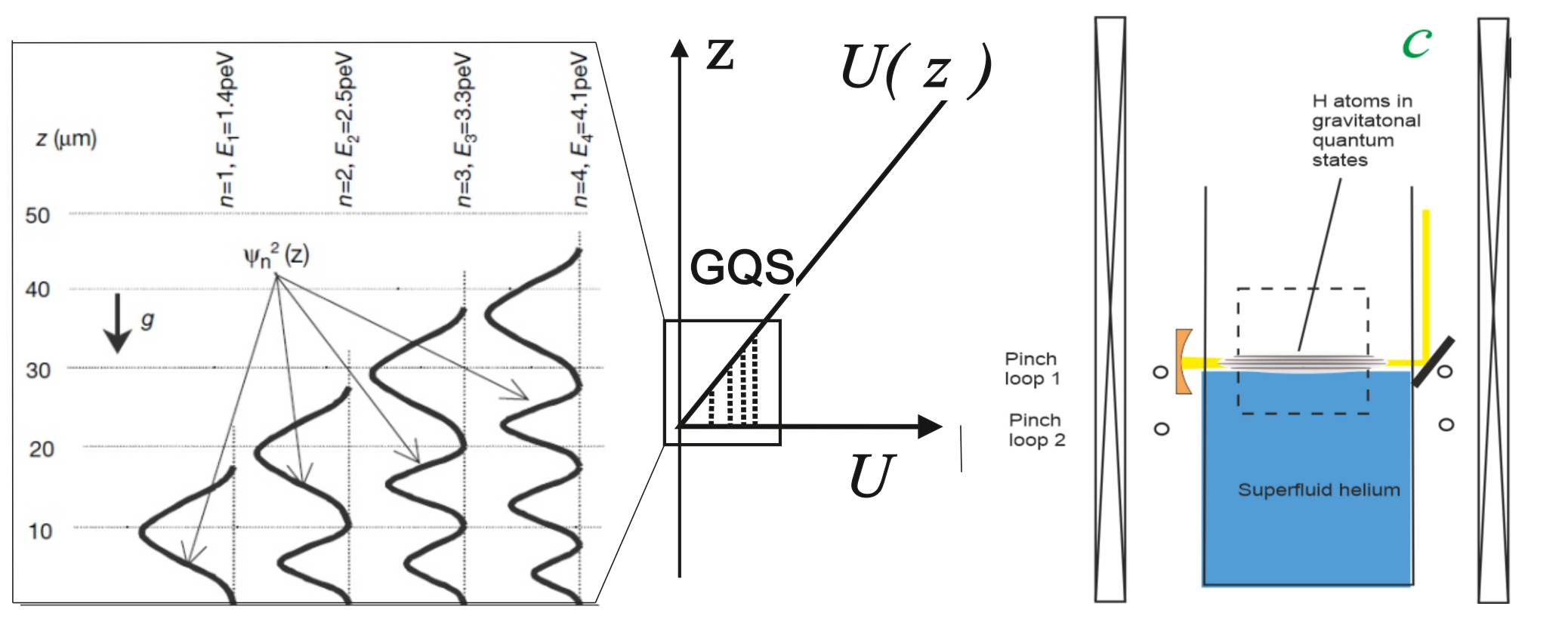


QR of anti-H [4]



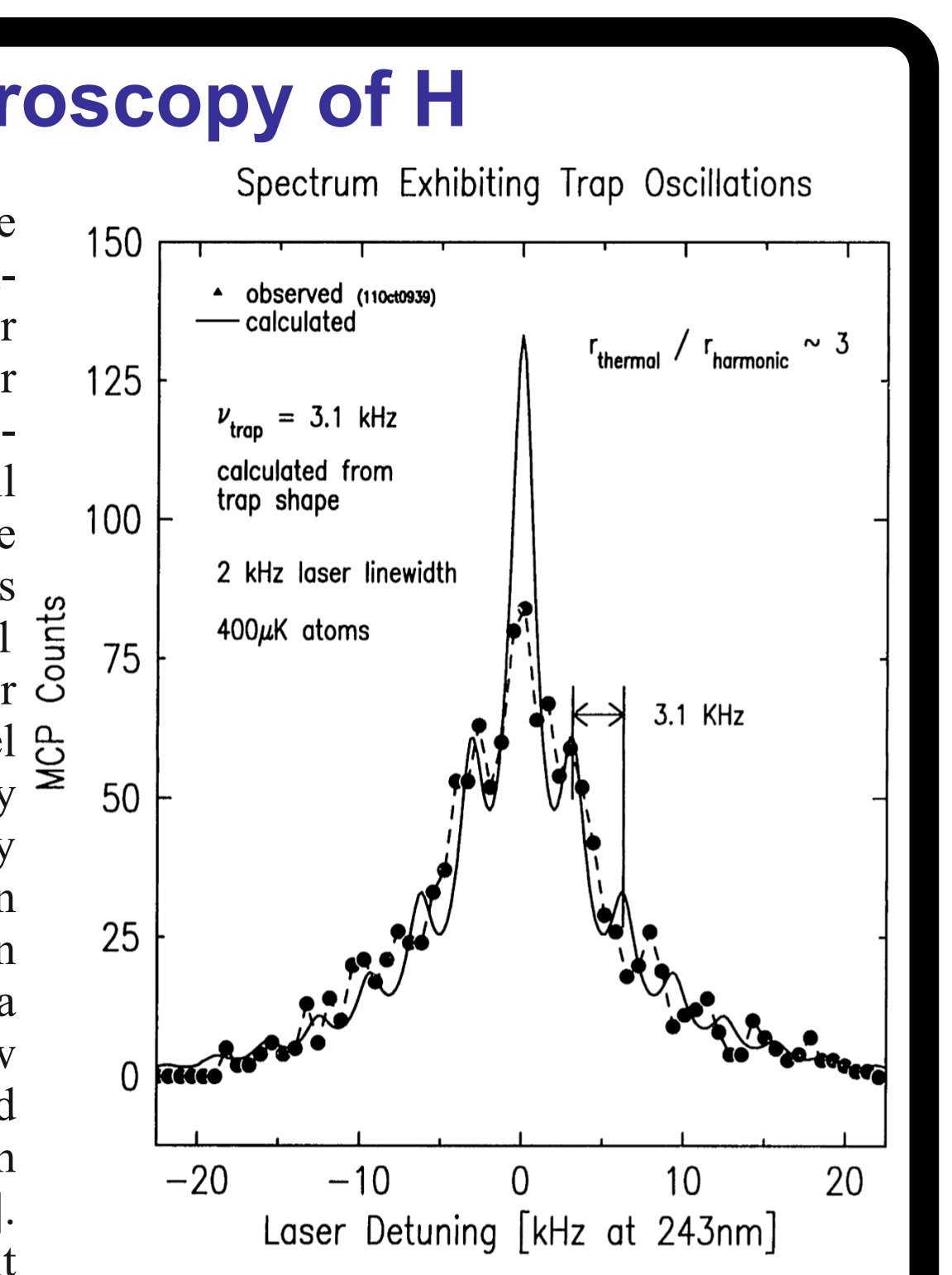
QR probability as a function of the energy E = mgh of the atom falling from the height h. The full lines correspond, from top to bottom, to bulks of ³He (light blue), ⁴He (dark blue), silica (red), silicon green) and gold (yellow). Solid vertical line corresponds to the atoms temperature 300μK, reached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

Combined with the Earth gravity quantum reflection leads to a triangular shape potential with a number of quantum states for atoms (GQS). Accurate measurements of the GQS energies and comparison with theory may reveal existence of unknown short-range forces (SRF) acting at the characteristic distance of several tens of microns [3]. For H on liquid helium the interaction is much weaker than on solids and the shifts of the GQS energies caused ny CP and VdW interaction are smallest [4], which makes the H-He system most sensitive for the search of the SRF. Several constraints on possible effects beyond the Standard Model were made from neutron GRS, which reached the resolution of 10^{14} eV [5]. Due to the high reflectivity of helium surface, hydrogen atoms have longest life-time in the GQS which yields the best resolution and sensitivity to the SRF effects. We will try reaching BEC in the trap formed by the Earth gravity and quantum reflection from helium surface, i.e. condensing atoms into the lowermost GQS. The triangular potential experinced by the atoms is very sharp and provides tighter confinement than can be reached with magnetic forces. We evaluate that for N=4·10¹¹ atoms BEC critical temperature is $T_c \approx 3$ μK [6]. This temperature is 1.5 times higher than for the case of the pure magnetic confinement. Above T_c a lifetime of the sample τ>300 sec will be determined by the loss of atoms sticking to the surface.

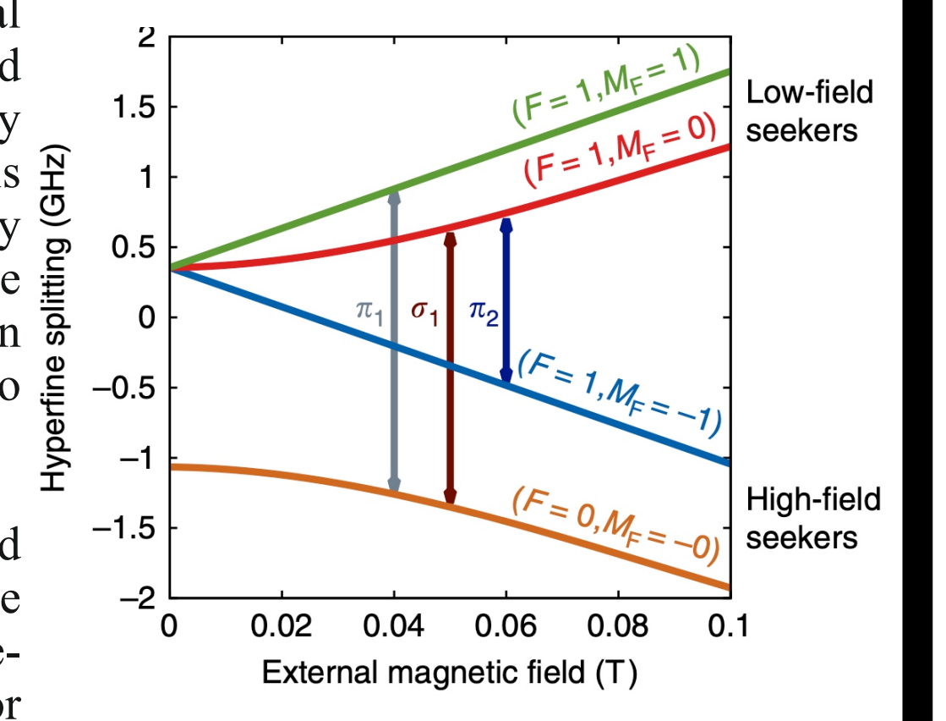


Precision spectroscopy of H

Optical spectroscopy 1S-2S,2S-nP:
Reaching a natural linewidth (NLW) of ~1.3 Hz for the 1S-2S transition is an ambitious goal for ultrahigh-resolution spectroscopy. Progress in the laser technology allows nowadays reaching the laser linewidth close to 1 Hz [8, 9]. Using such a state-of-the-art light source for studies of ultra-slow atoms, we will push the 1S-2S H spectroscopy to the NLW level. The total estimated uncertainty due to systematic effects was estimated to be at the level of 0.02 Hz for atoms at 1 mK. Since we are planning to work at much lower temperatures with large numbers of atoms, this level seems plausible to be reached. The absolute accuracy will be limited by the precision of the frequency standard available for the project. For our location in Turku the best solution is to use a GPS clock and an active local reference (Cs or hydrogen maser) using a frequency comb for laser locking. Accuracy of below 10^{-15} can be reached using such a system. The quantized change of energy of the atom gives rise to a spectrum with well defined peaks resembling a comb of lines [7]. With a harmonic trap, the level spacing is constant independently of the atom’s energy. In this case a thermal sample of atoms can produce a spectrum with well defined lines whose widths are much narrower than the usual time-of-flight broadening. The envelope of these peaks still follows the shape of a time-of-flight spectrum. Another way of describing this spectrum is through the picture of Ramsey’s fringes in a multi-pass excitation experiment, or yet, as a Raman spectrum where the Stokes shifted lines come from changes of the atom-trap vibrational energy.



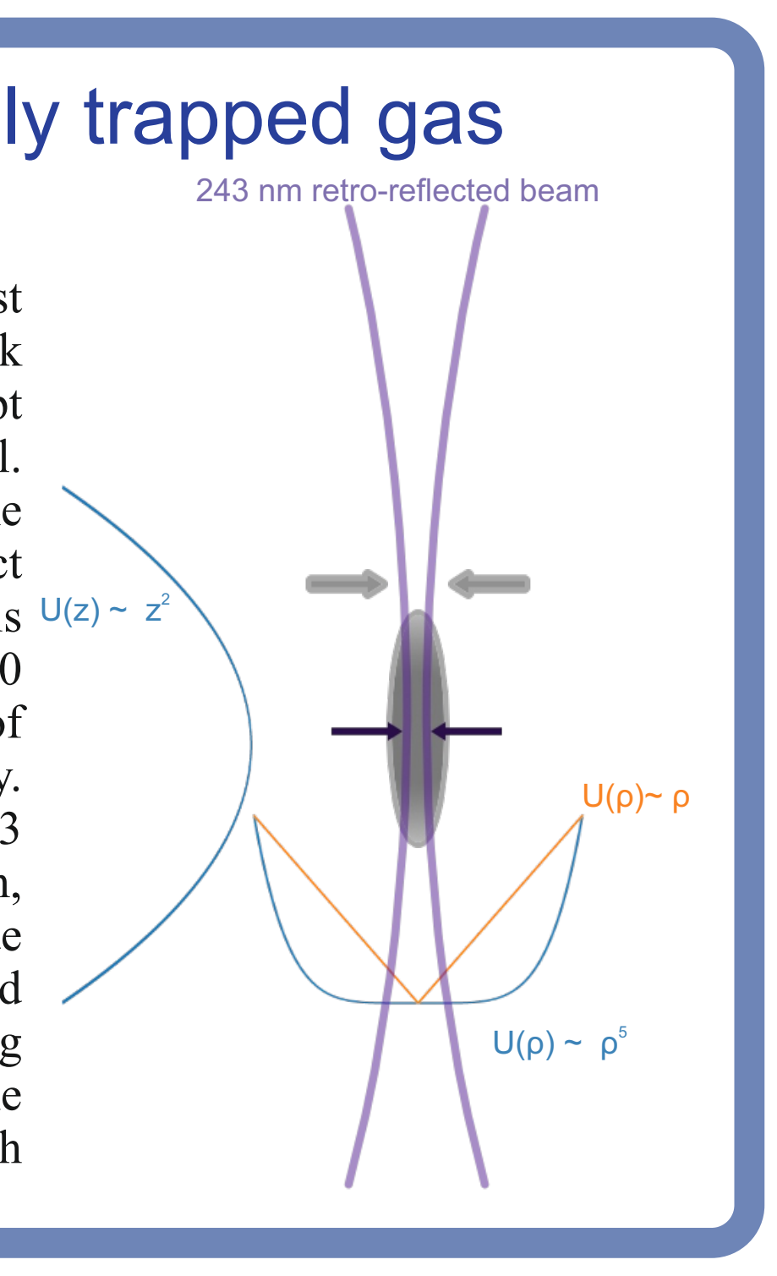
Hyperfine spectroscopy of hydrogen, antihydrogen, and deuterium can provide highly sensitive tests of CPT symmetry and Lorentz invariance.
The hyperfine splitting measurements enable sensitive test of the theory ensuring high confidence in the calculations. While many coefficients of the minimal Standard Model Extension (SME) have been constrained by hydrogen maser measurements, in the newly developed non-minimal SME a set of coefficients is present that has not yet been investigated experimentally [10], especially those depending on the orientation of the static magnetic field with respect to the Earth rotation axis [11]. Within the SME, the π_1 transition is sensitive to CPT violations while the σ_1 transition is not.



Cryogenic hydrogen maser
One of the most precise measurements of the ground state hyperfine structure of H was done with the hydrogen maser. The frequency stability of state-of-the-art H maser is typically better than one part in 10^{15} for averaging intervals of 10^4 seconds. A cryogenic hydrogen maser (CHM) operating at temperatures below 1K could have a frequency stability that is two to three orders of magnitude better than a room temperature H maser due to: lower thermal noise, a reduced H-H spin-exchange relaxation rate and the resulting higher operational signal power. Several prototypes of the CHM were built and demonstrated performance comparable with the room temperature device [12]

Re-visiting BEC of magnetically trapped gas

After transfer of the H gas from the IPT into the T2 we will first use evaporative cooling in the multipole potential with the weak confinement. Then, we will switch off all radial T2 coils except four, and compress the gas in the linear quadrupole potential. Further forced evaporative cooling will allow crossing BEC line in the phase space. We will ramp down the trap barrier or eject energetic atoms after RF excitation to untrapped states. This scenario is similar to that used in MIT. Our advantages are: >10 times larger starting number of atoms, flexibility in the choice of the evaporation method, improvement of the trapping geometry. For the latter, we decrease the trap diameter by the factor of 3 compared to what it was in MIT. Thanks to the double trap design, it is easy to change the T2 diameter. Tighter trap will provide smaller condensate fraction, higher critical temperature and longer life-time of the sample. The sample diameter, including normal fraction, will be also reduced. It is easier to fit it inside the laser beam waist thus increasing interaction time of atoms with the light.



Acknowledgments
This work supported by Academy of Finland (grant No. 317141) and Jenny and Antti Wihuri Foundation.