Ultracold Hydrogen

RLE Groups
Atomic, Molecular and Optical Physics Group; MIT-Harvard Center for Ultracold Atoms

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Research in the Ultracold Hydrogen Group centers on studies of the structure of atomic hydrogen, ultracold collisions, the properties of hydrogen as a quantum gas and ultrahigh precision spectroscopy. Principal activities during the past year include construction and demonstration of a mode-locked laser for optical frequency metrology of hydrogen, and construction of an apparatus designed to frap and cool hydrogen that employs a thermallzing agent—a second species of trapped atom—and uses buffer gas cooling techniques.

1) HYDROGEN-LITHIUM BUFFER-GAS COOLING AND TRAPPING (in collaboration with Prof. John Doyle, Harvard University)

Work supported by the NSF through the Center for Ultracold Atoms

The search for Bose-Einstein condensation in dilute gaseous systems originated with studies of atomic hydrogen. The simplicity of the hydrogen atom, combined with its small mass made it a particularly attractive candidate for realizing BEC. Although Bose condensation was obtained in atomic hydrogen [1], the technical difficulties involved in producing and cooling a magnetically confined gas of hydrogen atoms have limited both the scope and the efficiency of the possible experiments.

The established technique for creating samples of ultra-cold atomic hydrogen involves a two-step process. First, a superfluid helium film is used to thermalize the atoms to temperatures cold enough to enable magnetic trapping. Then, once the atoms are magnetically confined, evaporative cooling [2] is implemented for achieving the final phase space compression needed to reach BEC. It is important to note that evaporative cooling just barely works for hydrogen due to its anomalously small elastic scattering cross section in the S-wave scattering regime. This small cross section severely limits the elastic collision rate and results in inefficient evaporation. Although this two-step technique is extremely effective in creating large samples of ultra-cold hydrogen, the practical challenges introduced by the need for superfluid helium not only set experimental limitations for working with hydrogen, but also make the technique unsuitable for working with deuterium. There is currently no proven experimental technique that can be used to create ultracold samples of atomic deuterium.

In this CUA core project, we are pursuing an entirely new approach to cooling and trapping hydrogen. It is based on the buffer-gas loading technique of Doyle [3]. The beauty of this technique lies in its complete generality in enabling virtually any species to be loaded into a magnetic trap. Not only does this permit the trapping of atomic deuterium, it also enables the

possibility for simultaneously confining atomic lithium and hydrogen (or lithium and deuterium) in the same magnetic trap. This has important implications for evaporative cooling. The H-Li elastic scattering cross section is predicted to be about 1200 times larger than that of H-H [4]. Introducing Li into the trapped hydrogen cloud should dramatically increase in the elastic collision rate, thereby accelerating the evaporative cooling process and increasing its efficiency.

This new approach to trapping and cooling hydrogen represents a radical departure from all previous cold-hydrogen experiments. It addresses two of the major technical issues that have placed limitations on the previous work. It requires, however, the creation of a major new apparatus built around a dilution refrigerator. After months of design and test work, we are in the final stages of assembling a new apparatus that will implement these improved techniques and set the stage for studying the physics of ultra-cold atomic hydrogen and deuterium.

Hydrogen and lithium source The standard technique for producing atomic hydrogen involves the use of an RF discharge to disassociate molecular hydrogen. This technique, however, cannot be used to create atomic lithium from its natural metallic form. We are using laser ablation to vaporize the surface of a solid sample of LiH. In a preliminary run of our experiment, we confirmed that laser ablation in our cryogenic cell efficiently produces large samples of atomic Li. Although we did not directly measure the amount of hydrogen produced, we have reason to believe that the hydrogen production numbers are similar to those of lithium.

Buffer Gas Loading Figure 1 illustrates the buffer gas loading process. Hot H and Li atoms are released from the ablative source having energies of around 1000K. They then thermalize with a cryogenically cooled ^{3}He buffer gas in the presence of a quadrupole magnetic trapping field. Once the atoms have reached sufficiently low temperatures to be confined in the magnetic trap, the buffer gas is removed to thermally disconnect the trapped atoms from their surroundings. At this point evaporative cooling can be used to cool the atoms into the ultra-cold regime. A detailed analysis of buffer-gas loading requires numerical modeling of the diffusion and flow processes that govern the dynamics of the system. A crucial parameter in this modeling is the elastic scattering cross section between H and ^{3}He in the temperature region of interest. This has been computed for us by Dalgarno [5], and is smaller than we had hoped. However, putting these numbers into our quantitative model produces encouraging results. We are optimistic about being able to simultaneously load both lithium and hydrogen in our magnetic trap.

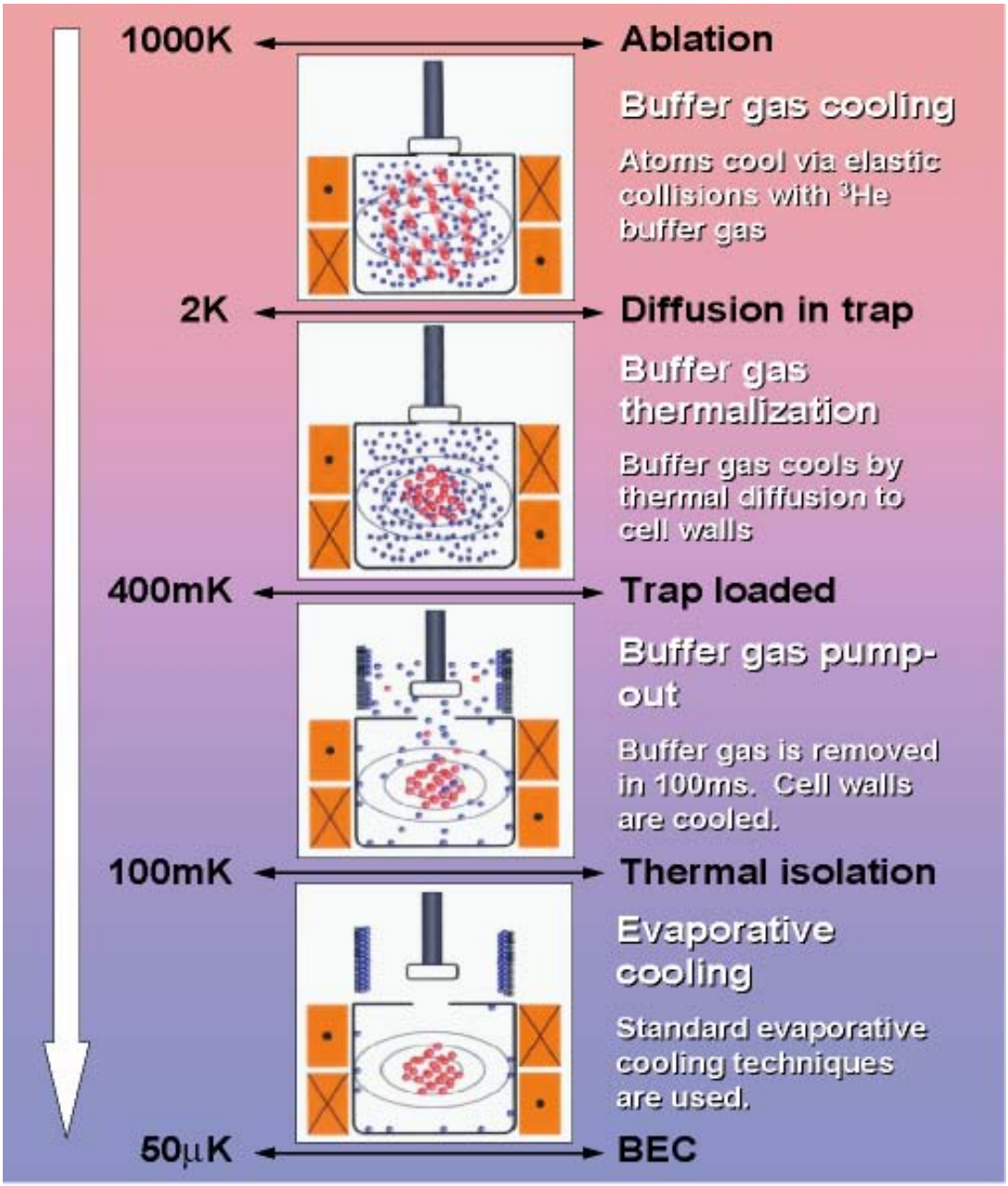

Figure 1. Overview of the buffer-gas loading technique

New Trapping Apparatus A diagram of our apparatus is shown in Figure 2. It consists of a double-chambered copper cell inserted into the bore of a superconducting anti-helmoltz trapping magnet. A spring actuated mechanical valve separates the lower experimental chamber from the upper pumping chamber. With the valve closed, ^{3}He buffer gas is introduced into the lower cell chamber from a "waiting room" not shown in the diagram. An ablation laser passes through the window at the bottom of the cell to vaporize the surface of a solid piece of LiH. The atoms liberated by this ablation thermalize with the cold buffer gas until they settle into the bottom of the magnetic trap. At this point, the valve separating the two chambers is opened and the buffer gas is cryopumped onto the large surface area of the charcoal sorb that resides in the pumping chamber. The thermally isolated atoms, now trapped in the lower chamber, are detected by

passing a resonant probe laser through the trapping region and collecting the resulting fluorescence on a multi-channel plate positioned just outside the cell window.

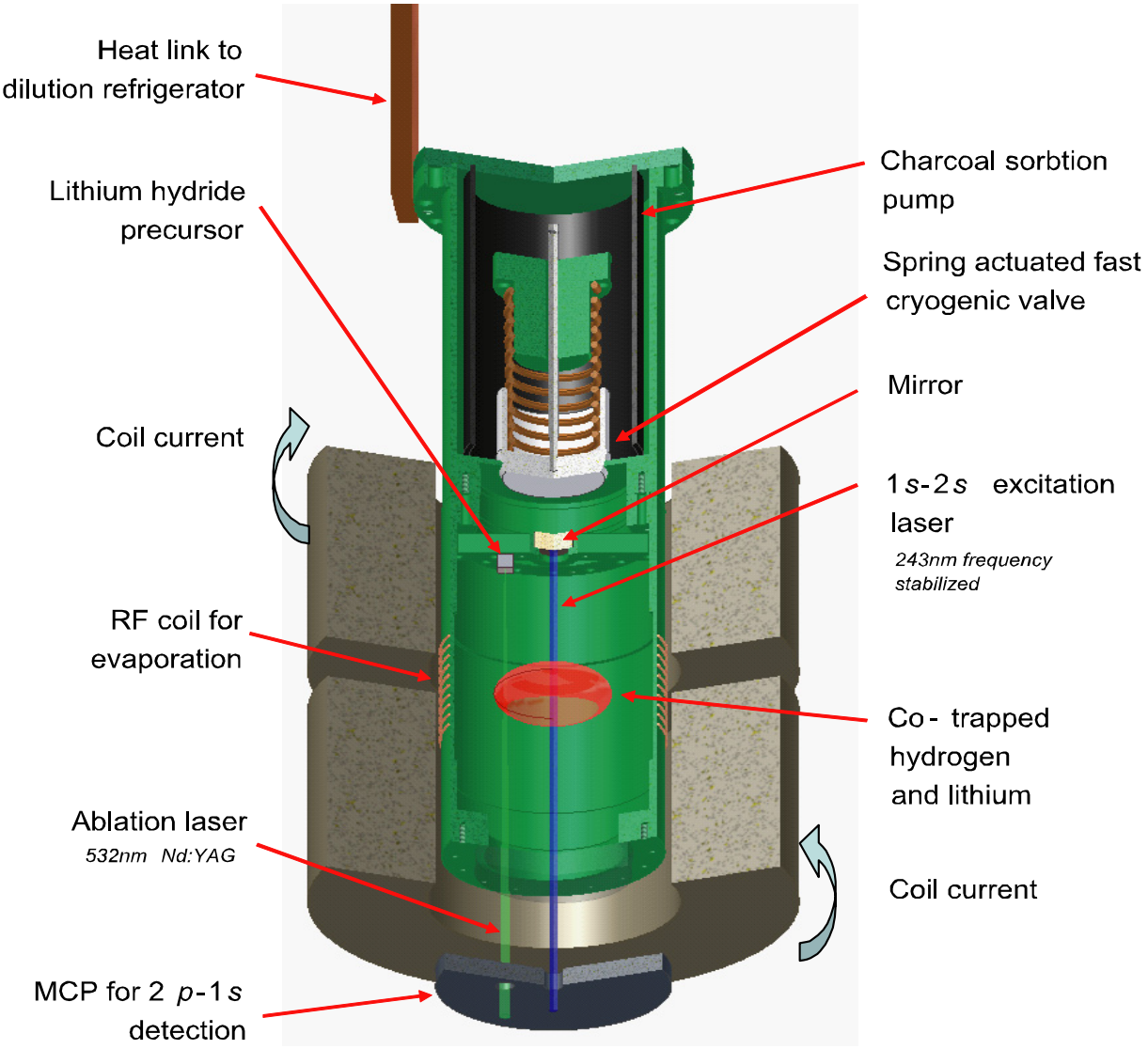

Figure 2. Apparatus diagram

More efficient H detection All our past studies of ultracold hydrogen have detected the gas by exciting the 1S-2S two-photon transition, then applying a small electric field, and detecting the Lyman-alpha radiation. Due to geometric limitations in the viewing angle and inefficiencies in photon detection, our efficiency has been less than 10^{-5}. Our new apparatus opens opportunities for major improvement. Some improvement can be achieved by better optical access. However, exciting the 2S atoms to a Rydberg state, which is then field-ionized, or directly photo-ionizing the 2S atoms, would improve the detection efficiency by many orders of magnitude. Such an improvement would have a major impact on nearly every aspect of ultracold hydrogen research.

Current state of the project We have spent the last year designing the components for our new apparatus. The large diameter, fast acting cryogenic valve is a completely new technology that we spent quite some time perfecting. All of our components have been built and tested. We are in the final stages of assembling the apparatus.

Goals The new apparatus opens many research opportunities. By co-trapping H and Li we will have the opportunity for using a two-step Raman excitation process to create diatomic LiH in the triplet state [6]. This molecule is of particular interest because it has a remarkable property: LiH possesses but a single vibrational state. We should be in an excellent position to create this unusual molecule as well as it's close relative, LiD.

A longer term goal is high-precision spectroscopy. For example, a precise measurement of the two photon transition between the 2S and 8S states of hydrogen would immediately improve our knowledge of a quantity containing the Rydberg constant, the Lamb shift and the proton radius. The 1S-2S transition is also of great interest. This transition is currently the touchstone for high precision hydrogen spectroscopy [7] and is a potential candidate for an optical atomic clock. Resolution close to the natural linewidth, 1.3 Hz, should be possible using ultracold hydrogen. Pursuing this research requires high performance lasers and state of the art equipment for optical frequency metrology to be used in conjunction with the new hydrogen apparatus. The laser systems are being developed under a separate program sponsored by NSF, ONR and a MURI program.

2) Octave-spanning frequency comb generator (in collaboration with O. Kuzucu, T. R. Schibli, J. Kim, E. P. Ippen, and F. X. Kaertner)

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A. Introduction:

The purpose of this project is to perform precision measurements of several optical frequencies in trapped, ultracold hydrogen. To achieve this goal, we have worked over the past 2.5 years to develop a clockwork based on an octave-spanning prismless Ti:sapphire laser. Our choice to use this type of system stems from the fact that such a setup offers the potential for improved stability, reliability and simplicity compared to fiber broadened combs, producing more reliable optical clockworks. In the past year, technical improvements have been made to take advantage of the full potential that this kind of system has to offer: making the laser more compact by increasing the repetition rate from 80 to 200 MHz; improving the fceo detection setup, eliminating long term misalignment problems completely. Details will be described in the next section.

The first measurements we wish to perform are of two-photon transitions originating from the metastable 2S state. While technical problems with the dilution refrigerator used as the cooling source for the hydrogen atoms have kept us from performing the spectroscopic measurements, we have completed the construction of the clockwork which phase coherently links the diode lasers used to excite the 2S-8S transitions to the dye laser used to excite the 1S-2S transition, via the frequency comb. The details of such setup will be described in section 3. Here, it should be made clear that the 1S-2S transition will be used as our reference initially.

In parallel, the group is working towards an improved cooling and trapping apparatus for hydrogen as well as a narrower dye laser, which we hope will allow us to observe a 1S-2S line closer to the 1 Hz natural linewidth. We hope to have both of these components ready for operation in 2006.

B. Improvements on the comb stability

In the past year, the Ti:sapphire laser has been re-built to operate at 200 MHz repetition rate. This new cavity is much like the one in reference [8], but the cavity is significantly shorter and the average output power has increased from 80 mW to about 250 mW. The advantages of this new version are two-fold: first, the more compact setup allows for better isolation against environmental perturbations, such as temperature changes in the lab and vibrations due to air-

flow; second, the increase in power per mode comb due to the higher repetition rate has resulted in improved signal-to-noise of the heterodyne beats between the comb and the single frequency lasers which perform the spectroscopy. This has the advantage of making the whole system alignment less challenging and of minimizing cycle slips in the phase locks.

The other significant improvement has been in the f-2f self-referencing setup [9]. In the previous version, the short and long wavelength portions of the spectrum were separated spatially and then recombined to allow for proper adjustment of the time delay between these spectral components. This setup was bulky and very sensitive to the unavoidable misalignment of the laser. In the new version, the time delay is adjusted by 7 bounces on chirped mirrors (DCMs), as can be seen in figure 1. This eliminates completely all misalignment problems, such that from day-to-day operation no optimization is necessary. When comparing this new approach to fiber broadened combs, the advantage is dramatic. There, without feedback control it is a difficult task to maintain efficient coupling to the small core diameters of the micro-structured fibers.

With these improvements it is now possible to operate the frequency comb with the self-reference lock over a full day (10-12 hours) without touching the laser, and day-to-day alignment has become a simple task, even without any type of climate control in the laboratory.

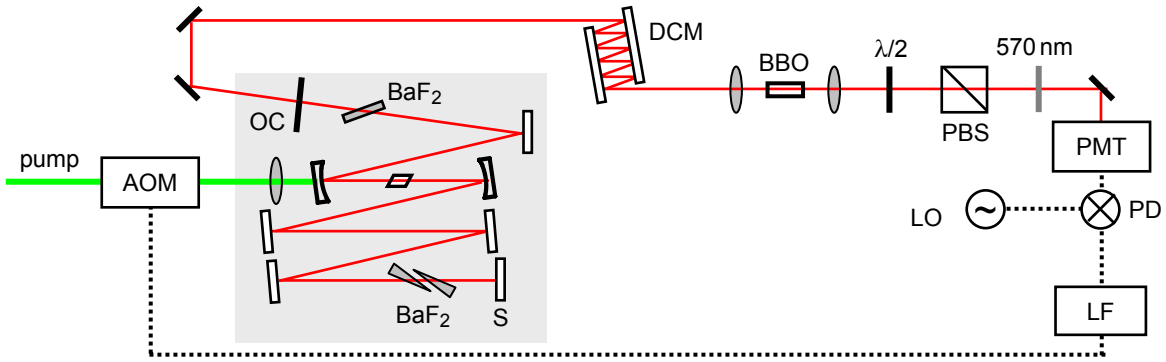

Figure1: Schematic of carrier-envelope phase stabilized 200 MHz octave-spanning Ti:sapphire laser. The laser itself has a compact footprint of 20 X 30 cm and is isolated vibrationally and thermally from the rest of the setup. AOM: acousto-optic modulator, S: silver mirror, OC: output coupling mirror; PBS: polarizing beam-splitter; PMT: photo-multiplier tube; PD: digital phase detector; LF: loop filter.

C. A complete clockwork for spectroscopy of ultracold hydrogen

Our initial approach to performing precision spectroscopy on ultracold hydrogen of transitions originating from the metastable 2S state has been to make these measurements relative to the very well know 1S-2S transition, using the comb to bridge the large frequency gap. Specifically, we have constructed a clockwork which will allow us to perform spectroscopy of the two-photon 2S-8S transition, at around 778 nm and measure this frequency relative to the 1S-2S frequency.

The complete experimental setup is shown in detail in figure 2. To fully stabilize the comb, we phase lock an appropriate comb line to the dye laser which excites the 1S-2S transition. Since the offset frequency of the comb has already been determined by the self-reference lock described in the previous section, the phase lock to the dye laser phase coherently links every comb line to the 1S-2S transition. The diode lasers which excite the 2S-8S transition are then phase-locked to the comb providing a link between the 1S-2S and the 2S-8S transitions.

The main challenge in performing the phase locks just described is obtaining enough signal-to-noise in the heterodyne beats between the comb and the cw lasers to avoid cycle slips in the phase locks. While one might think that having enough power in the cw lasers is enough, this

turns out not to be true. The main limitation will be the ability to eliminate unwanted neighboring lines in the comb which do not contribute to the signal, only to the shot noise. For the beat between the comb and the dye laser, this spectral filtering naturally comes from the narrowband doubling of the comb to allow for overlap with the dye laser at 486 nm. This results in a spectral bandwidth of only 0.1 nm, which is enough to generate S/N ratios of 35 to 40 dB in 100 KHz RBW (resolution bandwidth). For the beat between the comb and the diode lasers, since there is no frequency doubling involved, this task becomes more challenging. As can be seen in figure 2, precise overlap of the two lights is necessary (obtained by coupling both lights through a fiber), with subsequent spectral filtering in a grating, which generates beats of 30 dB S/N, enough to avoid cycle slips.

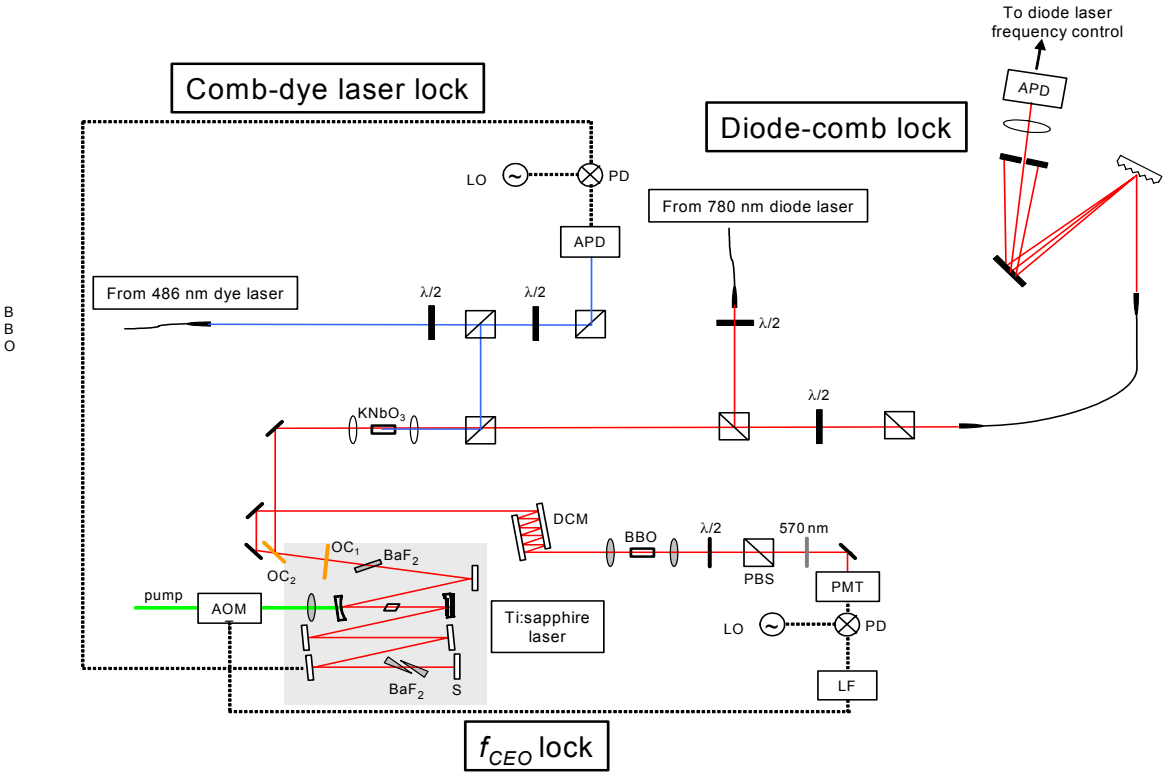

Figure 2: Detailed setup of optical clockwork. The diode laser used to excite the 2S-8S transition is phase locked to the comb, which is phase-locked to the dye laser at 486 nm. The dye laser is frequency doubled to 243 nm to excite the 1S-2S transition. This clockwork provides a phase-coherent link between the 1S-2S and the 2S-8S transitions.

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