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# Introduction

# Experimental Setup

This chapter contains the general experimental setup for researches discussed in this dissertation. It introduces the setup for state excitation, laser cooling, pulse amplification, Tera Hertz (THz) pulses generation, data collection and etc. It also provides some suggestion for maintenance and daily operations. All experiments are performed on Newport RS 3000 optical tables to reduce mechanic vibrations, in a temperature controlled room to reduces external thermal effects. Other than specifically mentioned, the repetition rate of all experiments is fifteen hertz. Before getting into experiments in the lab, people are supposed to have already taken the safety training.

## Magneto-Optical Trap

Since its invention in 1987 [2], Magneto-Optical Trap (MOT) has become a very important and popular technology in the area of atomic research and has been widely used to generate cold neutral atoms. This technology is a combination of magnetic field gradient and counter-propagating laser beams. Gradient magnetic field is used to generate position dependent energy levels of atoms so that atoms not in the trap center would absorb purposely prepared photons of fine-tuned lasers and be pushed back to the center.

Due to its ease of operation and low cost, MOT has been used to trap cold atoms in all the experiments described in this dissertation. We use as the atom source in all experiments. Trapped in the MOT, the atoms have a temperature which could be as low as about 70 K. A MOT system contains high vacuum chambers, pump and repump lasers, pressure gauges, atomic beams generation and etc. Since Mary has already given a very good and detailed description about this system [3], a simplified version will be given here.

### Principle of Magneto-Optical Trap

A simplified one-dimensional two-state system can help to understand the cooling process. As shown in Figure 2.1, suppose one atom has a spin S = 0 ground state and a spin S = 1 excited states. In the one-dimensional system with axis *z*, the weak inhomogeneous magnetic filed varies linearly so where *M* is a constant. Due to Zeeman effect , this field splits the degeneracy of the excited states. creating positon dependent energies for the atoms. In the system, a beam of light propagates in the direction and anther beam of light propagates in the counter direction. Both beams are red detuned from the zero-field resonance. On one hand, an atom with a position is more likely to absorb photons from the to jump from ground spin state to state since state is closer to resonance. On the other hand, an atom with a position is more likely to absorb photons from the to jump from ground spin state to state. The atom absorbs a photon and is pushed back to the center. It will then scatter the absorbed photon. But as long as the field is weak, the scattering direction is random, which generates a net force of pushing back on the atom. So the atom will be cooled and confined in the MOT.

detuning

MOT

Figure .: Simplified one dimensional model for MOT [1].

As shown in Figure 2.2, a three dimensional Magneto-Optical Trap is similar to one dimensional model. The gradient magnetic field in a three dimensional MOT is provided by anti-Helmholtz coils. The counter-propagating beams are produced by a combination of quarter waveplates and reflecting mirrors.

Figure .: Schematic for MOT design. It’s a combination of anti-Helmholtz coils and six counter-propagating beams. Other than the 2 main anti-Helmholtz coils as shown in this schematic, there are 6 more shim coils which enable fine tuning of the magnetic field inside the MOT. The six laser beams are from the same laser head. We use three beam splitters to split the main beam into six with equal strength. These three beams are then reflected by mirrors to generate six counter-propagating beams in total.

The above gives an idea about trapping three-level atoms. When dealing with , there are more states involved, although the basic principal is as same as described above. As shown in Figure 2.3, there are complicated hyperfine levels involved in a realistic MOT. The ground state has been split into two hyperfine levels F = 2 and F = 3. The excited state has been split into four hyperfine levels F = 1, 2, 3, 4. Ideally, the trap laser intends to transfer atoms from F = 3 to F = 4. But because F = 3 and F = 4 are so close that the trap laser transfers a portion of atoms to F = 3. The atoms on F = 3 decays quickly back to F = 2 and escape from the MOT. To avoid such a loss, a second repump laser is introduced into the system. The repump laser transfers the atoms in F = 2 back to F = 3. These atoms can later decay back to F = 2 and be transferred by the trap laser.

F=4

F=3

F=2

F=1

F=3

F=2

Trap 780.030 nm

Repump 780.024 nm

3 GHz

120 MHz

Figure .: Hyperfine energy structure of . Trap laser is driving transition from F = 3 to F = 4 and repump laser is driving transition from F = 2 to F = 3.

### Saturated Absorption Spectroscopy

To find the well defined frequency for the trap laser and repump laser, we utilize a method called Saturated Absorption Spectroscopy or SAS. The basic idea is this:

1. Split a small branch from the main beam of the laser. Pass it through a cell containing rubidium vapor. Call this branch “pump” beam. It’s strong enough to saturate the absorption along the path.
2. Reflect back the pump beam and pass it through the cell again. Call the coming back beam “probe” beam.
3. Detect the probe intensity using a photo detector. If the beam frequency is a little off the well defined frequency, due to Doppler effect, the atoms in the cell will absorb both pump and probe beams. If the beam frequency is right the well defined frequency, only zero-velocity atoms can absorb photons from the pump beam. The probe beam would not decrease its intensity since the pump beam has already saturated the absorption. Thus there will be an intensity increase of the probe beam when the frequency of the beam is the right Doppler-free frequency.

In the experiment, the real setup is a little more complicated than the above description. The beam passing through the cell has ben split further into two beams. One comes back as a probe and the other is detected directly. The detected signal from the probe is then subtracted by the signal from the other beam, which creates a push-pull configuration. In this way, we can get rid of the fluctuation of the main beam intensity and stabilize the absorption spectrum.

The right spectrum for trap and repump lasers are shown in Figure 2.4. It’s generated by sweeping the piezo voltage of the laser head with a tringle or sine wave. The trapping beam has been increased by 36 MHz using an acousto-optic modulator (AOM) before sending to the cell. In this way, the main trapping beam sent into the MOT is detuned by 36 MHz.

Once finding the right spectrum pattern, lock the lasers.

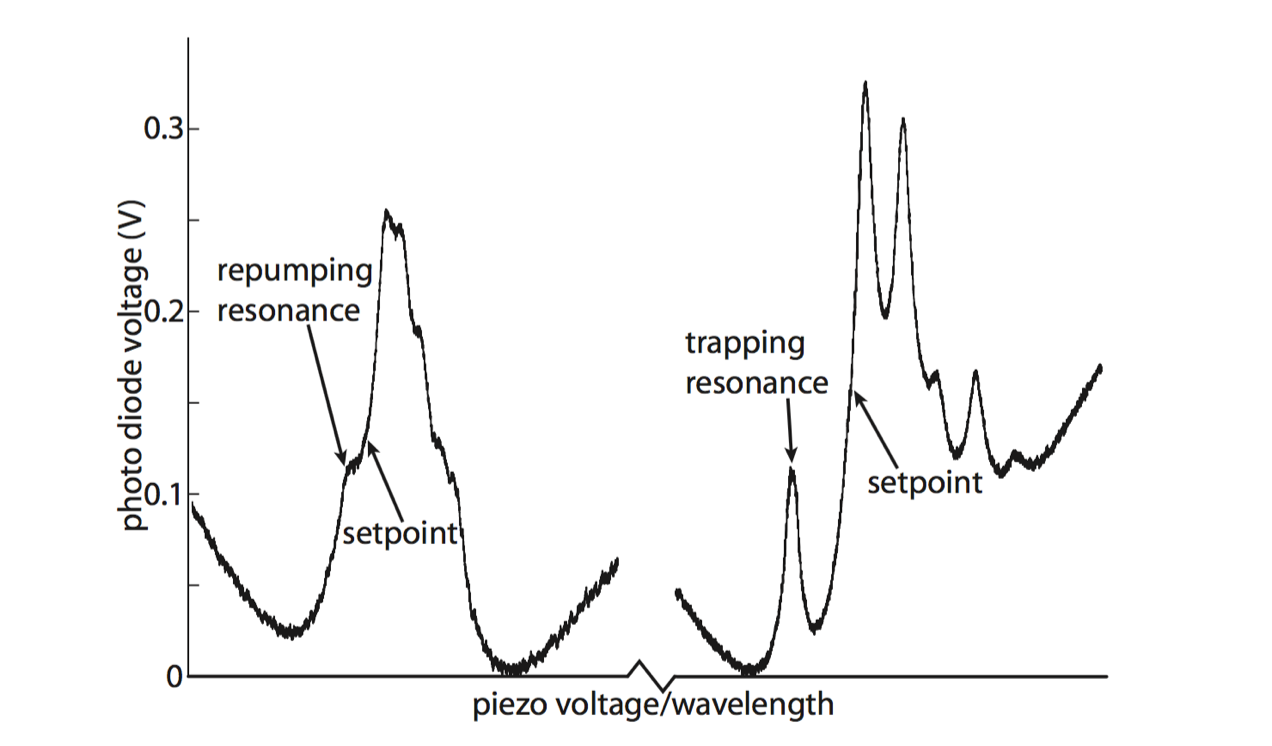


Figure .: Plots of the saturated absorption spectrum near the repumping and trapping resonances.[3]

### Ultra High Vacuum Chamber

The MOT is sitting inside an ultra high vacuum chamber. When pressure goes higher, because of the collision by high speed atoms, less atoms will stay in the trap. The usual operation pressure is between torr to torr. To achieve such a low pressure, a serial of pumps: rough pump, turbo pump and ion pump have been utilized. It does not need to use all of these pumps often, but if needed, Hyunwook has given a detailed description of the operation of these pumps [4].

The pressure in the UHV chamber is measured by two types of gauges: thermocouple and Bayard-Alpert ionization gauges, both of which are monitored by Varian senTorr gauge. The thermocouple gauge measures pressure from to torr, while Varian senTor gauge can measure as low as torr. The ion pump can also display the pressure and we usually refer to that reading for daily operation.

### Performance of the MOT

The temperature of the atoms trapped in the MOT can go down as low as about 70 K. And the density of the MOT can go up to more than . Mary discussed the details to measure the atom’s temperature and calibrate the density [3].

Before getting temperature or density, we first need to get the diameter of the atom cloud. This is done by producing a thin horizontal “film” of excitation laser beam which will excite all the atoms in the film from to and then to . The ion signal is correlated with the atoms distributed in the vertical direction. Using the same method and then we can find the atoms’ horizontal distribution, which should be the same as the vertical distribution if the MOT is ideally round. Using Gaussian curve to fit the distribution and we can get the diameter of the MOT. A typical MOT has a diameter from 0.4 to 1 mm.

The basic idea for temperature measurement is to turn off the trapping beam and observe the expansion of the atom cloud, since there is correlation between temperature and expansion rate according to Boltzmann distribution: .

The basic idea for measuring atom number in the could is to measuring the total power scattered from the cloud or the fluorescence . The scattered power contributed by an individual atom, which decays from to once every two natural lifetime, is calculated by

where is the wavelength of the scattered photon and is the natural lifetime. Then we can get the total atom number : .

## Lasers and Amplifiers

### Nd:YAG Lasers

Nd:YAG lasers are one kind of solid state lasers. The lasing medium in this laser is neodymium-doped yttrium aluminum garnet (). Such a medium is pumped by flash lamps and absorbs mostly in the bands between 730–760 nm and 790–820 nm [5]. It then emits light which mostly centered at 1064 nm. This infrared wavelength is not very useful either for directly pumping dye laser or exciting atoms in our experiments, but it can be used to generate other frequencies. For the experiments described in later chapters, Potassium Dihydrogen Phosphate (KDP) crystals are used to generate 2nd or 3rd harmonics of the source frequency. 2nd and 3rd harmonic lasers are centered at 532 nm and 355 nm respectively. The green light at 532 nm is used to pump Regenerative amplifier, linear amplifier and dye laser. The ultraviolet light at 355 nm is commonly used to pump dye amplifiers.

pump

igure 2.5n Figure 2.5. ong the gain medium h. r and a polarizer, , not larger than the normal pump level. Dipole interaction.ump

1064 nm

Figure .: Schematic of Nd:YAG transition [6]. It is a typical Four-level Transition Scheme.

One Nd:YAG laser combined with KDP can generated 2nd and 3rd harmonics at the same time. But some experiments require more 2nd and 3rd harmonics at different times. There are two Nd:YAG lasers used in the lab. One is Spectra-Physics GCR-100 Series. Its function is to generate 532 nm green light. This green light is the pump light for Regenerative Amplifier and Linear Amplifier, both of which will be discussed in following content. The other one is Continuum Surelite and it’s used to generate ultraviolet light. It’s used to pump dye lasers and dye amplifiers in the experiments.

### Diode Lasers

Diode lasers are lasers using a *p-n* junction or a *p-i-n* structure to generate gain. Semiconductor components are usually compact so diode lasers are commonly used in space-limited cases. Another advantage of diode lasers is that their output frequency is tunable. The cavity of a diode laser is controlling by a small grating in the diode laser head and the grating is usually attached to a piezo. By changing the voltage applied on the piezo, it is convenient to tune the output frequency. In the experiments, following diode lasers are used:

* Vortex tunable diode lasers from New Focus. Continuous Wave or CW laser. Typical output frequency is 780 nm and output power 40 mW. They are used as trap and repump lasers for the Magneto-Optical Trap.
* Millennia Vs diode laser from Spectra-Physics. CW laser. Typical output frequency is 532 nm and output power around 300 mW. It’s used as the pump of seed light.
* TA-SHG pro High Power Frequency-Doubled Tunable Diode Laser System. CW laser. Typical output frequency is 480 nm and output power 150 mW. It’s used to generate Rydberg excitation pulses.

### Mode Lock Lasers

Mode locked lasers are commonly used to generate ultra short laser pulses. A mode locked laser is a laser to which the technology of mode locking is applied. A bunch of different independent oscillations with different frequency components in a cavity could not compose a pulse, since there is no fixed phase between each other. But if the phase between each oscillation is fixed, these oscillations could generate intense bursts periodically or a train of pulses consistently. Such phase fixing process is the so called “mode locking” process, and there are two major ways to achieve the mode locking: active mode locking and passive mode locking.

The mode lock laser used in the experiments is model MTS mini Ti:Sapphire laser kit from Kapteyn-Muranen. It uses Kerr-lens mode locking technology which is one of passive mode locking technologies to mode lock laser. Its diagram is shown in Figure 2.6. When the CW pump beam going through the Ti:Sapphire crystal is not stable, because higher intensity light can pass the crystal easier than low intensity light, the cavity is in favor of high intensity light pulses. So the routine operation is to touch the 2nd prism to produce disturbance to generate pulses. The outcome are pulses of light as short as sub 15 femtoseconds at a repetition rate about 90 MHz. The output pulse spectrum is monitored using a spectrometer. If the output is not mode locked, it is a CW beam and the spectrum is a line with no bandwidth. For well mode locked pulses, the spectrum is very stable and has a bandwidth. The narrowness of the output pulses is enough for our experiment but the power is too small. To get narrow pulses with large enough power, we use the pulses from the mode lock laser as “seed light” and amplify them. The amplification process is discussed in later content.

high reflector

output coupler

1st curved

2nd curved

crystal

lens

fold mirror

1st prism

2nd prism

pump input

Figure .: Basic layout of the mode lock laser [9]. Dashed line is the pump light from Millennia Vs diode laser and solid line is the oscillation in the cavity which is centered at 780-800 nm. By tapping the 2nd prism, we can produce a temporary unstable beam. Stronger intensity part in this beam will be enhanced thus produce pulsed outputs.

### Chirped Pulse Amplification

As mentioned above, the output from the mode locked laser has very short duration but its amplitude is not large enough for the experiments. So the output beam from mode lock laser or the so called “seed light” has to be amplified. This is achieved through a popular technology called “Chirped Pulse Amplification”. The basic idea is this:

1. Stretch the short pulses to a broad duration so that the peak energy is not very high. As shown in Figure 2.7, the combination of reflecting mirrors and grating in the stretcher acts as a pair of gratings and disperses the seed light’s spectrum. By stretching the seed light pulse, the energy in each pulse is much smaller and it’s much easier to amplify the pulse.
2. Amplify the stretched pulses using amplifiers such as regenerative amplifier and linear amplifier. How the regenerative amplifier and linear amplifier amplify the pulse is discussion in the following content.
3. Compress the amplified stretched pulses to high intensity short pulses back using a compressor. Compressor acts as an opponent of the stretcher, but it also utilizes a grating. In the experiments, the compressor is adjusted to find the best performance of the Tera Hertz generation.



initial short pulse

pulse stretcher

regenerative amplifier

linear amplifier

pulse compressor

Figure .: Schematic of chirped pulse amplification system. Seed light is at first stretched using stretcher. Then the stretched pulse gets amplified. At last the pulse is compressed to be very short pulse with high energy.

### Regenerative Amplifier

The first amplifier in the chirped pulse amplification is a regenerative amplifier. It use a solid-state medium Ti:Sapphire as the gain medium. Pulses are switched into the optical resonator by an optical switch realized with an electro-optical modulator and a polarizer, multiply pass through the gain medium in an optical resonator being amplified, and finally are switched out by another optical switch. This schematic is shown in Figure 2.8. The input beam has a vertical polarization to the paper and is reflected by the first polarizer to the switch-in pockels cell. When the switch-in pockels cell is triggered, it works as a quarter wave plate and rotates the beam’s polarization from vertical to horizontal before the beam comes back to the first polarizer. The beam with horizontal polarization goes through the first polarizer and comes into the gain medium to get amplified. After a few runs in the cavity to get maximum intensity, the beam will be switched out by the switch-out pockels cell with a vertical polarization.

switch-out pockels cell

gain medium

pump pulse

polarizer 1

switch-in pockels cell

polarizer 2

input pulse

output pulse

Figure .: Schematic of regenerative amplifier. Switch in pockels cell controls when the pulse comes into the resonator and switch out pockels cell controls when the pulse comes out.

### Linear Amplifier

Linear amplifier is used when the pulse intensity from the regenerative amplifier is still not large enough. A pulse also achieves the amplification by multiply passing through the gain medium Ti:Sapphire crystal, but it’s relatively simpler than regenerative amplifier. Its diagram is shown in Figure 2.9.

pump pulse

input pulse

output pulse

Figure .: Schematic of linear amplifier. Beam passes the gain medium multiple times and gets amplified.

### Dye Laser and Dye Amplifier

Different from Nd:YAG laser, which is a solid state laser, a dye laser is a laser which uses an organic dye as the lasing medium, usually as a liquid solution. Its advantage, compared to solid state lasers, is that it can be tuned for a much wider range of wavenumbers. The wide bandwidth makes it particularly suitable for tunable lasers and pulsed lasers. (At the same time, its disadvantage is the frequency instability.)

Organic dye is dissolved in solvent and circulated through a dye cell which is shot by pulsed pump light. When it’s excited by pump light, it fluoresces over a range of wavelengths. Certain wavelengths will be stimulated when the dye cell is placed in a cavity and thus a laser will be generated. By changing the cavity, the frequency which is to be stimulated, is tunable. This is the basic idea of dye lasers.

There are two main styles of dye lasers. One is Hansch-style and the other Littman-style. In our experiments, only Hansch-style dye laser [7] has been used for Rydberg excitations.



Nd:YAG light

tuning grating

telescope

dye cell

coupler

output

doubling crystal

Figure .: Schematic for a Hansch dye laser and 2nd harmonic generation. The angle of the tuning grating determines the output frequency.

This dye laser is used to generate 25*s* Rydberg atoms. The proper laser dye is LDS 925, which is dissolved in methanol solvent, with a concentration of 250 mg/L. This solution is pumped by 2nd harmonic from Continuum Surelite. The pump light has been focused about a millimeter into the dye cell by a cylindrical lens, creating a line of gain medium across the face of the cell. The dye cell works as a fluorescence generator, as well as an amplifier. The telescope expands the beam to reduce the intensity of light on the tuning grating. The grating is rotatable, which determines the frequency of the light diffracted back to the cavity. The light then comes back to the dye amplifier, being amplified and escapes from the cavity. Its infrared output laser is then frequency doubled to generate blue pulses which frequency is centered at 486 nm. For most of the time, a pulse from the dye laser does not only contains the frequency we want but a broad range of wavelengths. A typical line width for this kind of dye laser is on the order of 1 . To reduce the line width, we usually put a bandwidth filter or an etalon before sending the beam into the MOT chamber. In the chamber, the beam drives Rb atoms from 5*p* state to 25*s* state.

The dye cell can also work separately as an amplifier in Figure 2.11. This double amplifier can be used to amplify seed light from other lasers. We do not know exactly the output power of light coming from the dye amplifier, but we make sure the state transition is saturated by the laser beam. If there is no observable reduce of the population on a state such as 25*s* when inserting a 20% beam reducer in the path, we are confident that the state transition is saturated and the power of the beam is large enough.

dye cell 1

dye cell 2

pump beam 1

pump beam 2

seed light

amplified light

Figure .: Schematic for double cell dye amplifier used in the lab.

## Tera Hertz Pulses

### Tera Hertz Generation

Tera Hertz (or THz) pulse generated in our lab are pulses with a frequency of on the order of Tera Hertz and the duration a few ps.

The THz pulses work as pump and probe tools.

## Detection and Data Collection

### Selective Field Ionization

In some experiments, we want to detect wavepackets. But wavepackets cannot be detected directly. Instead, state distribution has been detected to reveal the wavepacket dynamics. As an efficient state distribution detection technology, Selective Field Ionization has been used to widely [8].

The highest electron is trapped in a 1/r potential trap in alkali atoms. When an offset field is applied to the atom, the trap will be tipped as shown in Figure 2.12, which lowers the barriers trapping the electron. When barrier is low enough, the electron would be able to escape from the trap. During the tipping process, higher state electrons tend to be ionized earlier than low state electrons.

In the MOT chamber, there are four metal rods. Two of them are connected to high voltage pulse supply and the other two connected to ground or low static voltage. These 4 rods create a strong electric field in 2 s (slow ionization field) or 500 *n*s (fast ionization field). Atoms in this field will be ionized and the ions will fly to a detector composed of micro-channel plates (MCP). Atoms in different states are ionized at different times, so the electric signal have different arrival time thus the population of states can be distinguished.

Figure .: Schematic of the tipping of electron potential. Solid line is the 1/r potential when there is no external field applied to the atom. Dashed line shows the tip of potential when a filed is applied to the atom. When such a field is strong enough, electrons are able to escape from the trap.

### Measurement Operation

The electric signal from MCP is collected using oscilloscopes. And the oscilloscopes transfer the data on the screen to computers which a using programs written in Labview. A typical electric signal representing a state population is a peak with some width. Usually, the larger a state population is, the higher the peak is. But the height is not an accurate value to measure the population. Instead, the area of peak is proportional to the state population. As show in Figure 2.13, the main peak crossed by a gate is the ionization signal of states. When there is no ionization signal, the peak will disappear and there is only background left. Using the program written in Labview, we can easily measure the area under the peak in the gate. After subtracting this area by the area when there is only background, we can get the real area representing the excitation population. As the population changes, the integrated value in the gate changes accordingly.

Figure .: A typical ionization signal shown on an oscilloscope. The central peak representing the population of state 32*s* + 32*p*. The measurement program puts a gate across the peak and integrates the area under the peak in the gate.

## Maintenance and Daily Operation

Before doing experiments, people should have finished the safety training.

Before turning on lasers, internal lock switch has to be flipped on at first. It controls the interlock of most lasers in the lab and gives a warning signal which is a red light outside the room, if there are lasers on.

### Daily Examination

1. Check the MOT chamber pressure. The reading from the ion gauge should be no more than orders of torr.
2. Check the room temperature readings. The readings should be from 72 to 74 .
3. Check temperature of cooling water from external sources. The supply water should have a temperature around 60 F.
4. Check cooling water level for each laser before turning on the laser. The water level should locate in the proper area marked in the box.
5. Check the fume hoods to make sure they are working properly.

### Operation of Regenerative Amplifier

Turn on the seed light pump laser power switch. When the temperature is stabilized, turn on the laser. The pump should be in mode “power” and the setup for power is “3.75 W” shown on the display screen.

1. Let the pump laser warm for at least half an hour. Then lock the mode. If the mode lock is not very stable, usually it’s because the alignment of the seed light is off and needs adjustments.
2. Turn on the regenerative pump Nd:YAG laser. Slowly increase the power of the pumping lamp until it heats the maximum. It usually takes several seconds or minutes for the dimmer light to turn on. If it takes too long, it’s probably because there are two many ions in the cooling system and the charge of lamps is not working properly. Reflush the cooling system of the laser using deionized water and try again.
3. Let the Nd:YAG laser warm for at least one hour to acquire thermal balance.
4. Change the output pockels cell’s timing to be the long timing set, which is 4us longer than the short timing set (which should be almost the same every day). This is to enable the self lasing of the amplifier. Switch on all the pockels cells in the setup. Increase the Nd:YAG pump light to be a little higher than the threshold. (The threshold may vary a little bit every day. The recent value should be marked down in the log book.)
5. There should be a bright spot showing in the TV monitor, which means the regenerative amplifier is now lasing itself. If there is no bright spot, increase the pump light a little higher but not larger than the normal pump level. Adjust the coupling mirrors to make sure the threshold is minimized.
6. Block the pump light. Change back the output pockels cell’s timing to the short timing set. Increase the pump light to the ordinary operation level (which is also written down in the log book). Unblock the pump light. Now on the scope, there should be a stable five-pulse train.

At this point, Regenerative amplifier is ready. Fine tuning includes decreasing the threshold and making the pulse train more stable. The pump Nd:YAG laser needs to replace lamps every 700 hours under current repetition frequency. The normal output is marked underneath the laser head on the optical table.

### Operation of MOT

1. First turn on the cooling water waives. Check the flow meter to make sure cold water is flowing through the coils’ cooling tubes. If there is no flow or flow is too slow, power supplier of the main anti-Helmholtz coils is forbidden to be turned on. Check the water supply in and out pressure to make sure water can flow. The normal in pressure is 14 psi. Check there is no leakage of water from the cooling tubes.
2. Turn on diode lasers of trap and repump beams.
3. Turn on AOM driver, voltage ramp of the diode grating, scopes, TV monitors and power supplies of coils. Increase the output of the power supply of the main coils to 10V. The resistance of the main coils is 1 ohm, so the output current of the power supply should be around 10A.
4. Turn on the getter and slowly increase it to operating value. A normal operating current is from 1.9 A to 2.5 A. When this values goes to as higher as 3.5 A to generate an observable cloud of atoms shown on the TV monitor, it means the getter has expired. Under ordinary usage, this process could take about 4 to 5 years. Once the getter has been used up, it should be replaced by a new one.
5. Let the trap and repump lasers warm for at least one hour to achieve thermal balance. Then adjust the piezo voltage of the lasers to find the right absorption signal [3].(If the absorption signal is no way similar to the proper signal, it’s very possible the frequency range of the laser head is off. In such a case, the piezo in the laser head needs to be replaced.) Lock lasers.

At this point, there should be a bright spot shown on the TV monitors. It’s is the reflection of infrared light from the cold atom source. A good spot is a stable bright spot with round shape and clear edge. If the spot is not stable or the shape is not round, the first step to try is to adjust the shim coils to make it good. If the shim coils do not do the work, more dedicated adjustments of the laser beams are necessary.

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