1 Introduction 1

2 Experimental Setup 1

2.1 Magneto-Optical Trap 2

2.1.1 Principle of Magneto-Optical Trap 2

2.1.2 Saturated Absorption Spectroscopy 5

2.1.3 Ultra High Vacuum Chamber 7

2.1.4 Performance of the MOT 8

2.2 Lasers and Amplifiers 9

2.2.1 Nd:YAG Lasers 9

2.2.2 Diode Lasers 10

2.2.3 Mode Lock Lasers 11

2.2.4 Chirped Pulse Amplification 13

2.2.5 Regenerative Amplifier 15

2.2.6 Linear Amplifier 16

2.2.7 Dye Laser and Dye Amplifier 16

2.3 Tera Hertz Pulses 19

2.3.1 Tera Hertz Generation 19

2.4 Detection and Data Collection 19

2.4.1 Selective Field Ionization 19

2.4.2 Synchronization System 20

2.4.3 Measurement Operation 22

2.5 Maintenance and Daily Operation 23

2.5.1 Daily Examination 23

2.5.2 Operation of Regenerative Amplifier 24

2.5.3 Operation of MOT 25

Figure 2.1: Simplified one dimensional model for MOT [2]. 3

Figure 2.2: Schematic for MOT design. It’s a combination of anti-Helmholtz coils and six counter-propagating beams. 4

Figure 2.3: 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. 5

Figure 2.4: Plots of the saturated absorption spectrum near the repumping and trapping resonances.[3] 7

Figure 2.5: Schematic of Nd:YAG transition [6]. It is a typical Four-level Transition Scheme. 9

Figure 2.6: Layout of Continuum Surelite Nd:YAG laser. It can output beams of 4 different frequencies. 10

Figure 2.7: 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. 12

Figure 2.8: 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. 14

Figure 2.9: 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. 15

Figure 2.10: Schematic of linear amplifier. Beam passes the gain medium multiple times and gets amplified. 16

Figure 2.11: Schematic for a Hansch dye laser and 2nd harmonic generation. The angle of the tuning grating determines the output frequency. 17

Figure 2.12: Schematic for double cell dye amplifier used in the lab. 18

Figure 2.13: 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. 20

Figure 2.14: Schematic of the Synchronization System. White cycles are inputs and dark cycles are outputs. 21

Figure 2.15: 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. 22

# Introduction

# Models in Simulation

This chapter introduces general knowledge about the mathematical models used in the simulation. These models include Rydberg Atoms, Two-Body Effect, Dipole-Dipole Interaction Model, THz Pulse Simulation and etc. They compose a mathematical background for the simulation implemented in Chapter 4, Chapter 5 and Chapter 6. Other than specifically mentioned, all the units in this chapter are atomic units.

## Rydberg Atoms

Back to 1885, Balmer found the wavelengths of the visible series of atomic H is given by [1]:

|  |  |  |
| --- | --- | --- |
|  |  | (3.1) |

where *b* = 3464.6 . We now know equation (3.1) is the formula for the wavelengths of the Balmer series of transitions from the *n* = 2 states to the higher lying levels.

After quantitatively describing the wavelengths from H, people started to work on other atoms to unravel the mystery of atomic spectroscopy. Living and Dewar found that the observed spectral lines of Na could be grouped into different series [2]. Hartley found the significance of describing Balmer’s formula in terms of the wavenumber of the observed lines instead of the wavelength during his reach on spectra of Mg, Zn, and Cd [3]:

|  |  |  |
| --- | --- | --- |
|  | . | (3.2) |

Now it’s more clear what Balmer discovered reflects the energy difference between the *n* = 2 states and the higher lying levels.

Following those precedents’ work, Rydberg began to classify the spectra of other atoms, notably alkali atoms, into sharp, principal, and diffuse series of lines [4]. He found the wavenumbers of lines connoting the *s* and p series, for example, are given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3.3) |

where + sign and constant n describe a sharp series of *s* states and the minus sign and a constant m describe a principal series of *p* states. If and m = 2 we can get Balmer’s formula for the H transition from n = 2.

Due to his significant contribution, people are now naming atoms in states of high principal quantum number Rydberg Atoms.

### Modern Model of Rydberg Atoms

If we consider Rydberg states of H and Na, as shown in Figure 3.1, they are essentially similar. The only difference is that Na atom has a core which is composed of 11 positive charges and 10 electrons. For most of the time, the highest external electron (Rydberg electron) is far from the core and the difference between Na, H and all Rydberg atoms is minimal. But when the Rydberg electron comes near the core, it can both polarize and penetrate the core, and change the wavefunctions and energies of Na Rydberg state from their hydrongenic counterparts.



Figure .: Rydberg atoms of (a) H and (b) Na. In H the electron orbits around the point of charge of the proton. In Na it orbits around the +11 nuclear charge and ten inner shell electrons. In high l states Na behaves identically to H, but in low L states the Na electron penetrates and polarizes the inner shell electrons of the core [5].

We know how to calculate wavefunctions of H [6]. This process can be easily extended to generate wavefunctions for single valence electron atoms with spherical ionic cores. Such an approach is called Quantum Defect Theory [7]. Quantum Defect Theory (QDT) assumes that the core is spherically symmetric and frozen in place. So the effective potential, seen by the valence electron is spherically symmetric and only depends on r. This potential is lower than the coulomb -1/r potential only at small r, and the effect is to increase electron kinetic energy and decrease the wavelength of the radial oscillations relative to H. Suppose the phase shift is . The bound state radial wavefunctions are given by:

|  |  |  |
| --- | --- | --- |
|  |  | (.) |

where and are commonly termed the regular and irregular coulomb functions. This radial function will derive the the allowed eigen energies:

|  |  |  |
| --- | --- | --- |
|  |  | (.) |

where n is an integer. Equation (3.5) is the equation used in the simulation to calculate the energies of Rydberg atoms.

### Properties of Rydberg Atoms

Table summarizes the properties dependent on principal quantum number n of Rydberg atoms [8].

|  |  |
| --- | --- |
| property | n dependences |
| Binding energy  Energy between adjacent n states  Orbital radius  Geometric cross section  Dipole moment <ns|er|np>  Polarizability  Radiative lifetime  Fine-structure interval |  |

Table .: Properties of Rydberg Atoms.

As introduced in later sections, dipole-dipole interaction between Rydberg atoms is proportional to . And the Rydberg electrons are far from cores, which makes the them easy to be affect by external forces. The very long enough lifetime of Rydberg atoms also reduces the threshold of detecting phenomenon. All these superior properties make them ideal objects for researching dipole-dipole interaction and electron dynamics.

Figure .: Schematic for MOT design. It’s a combination of anti-Helmholtz coils and six counter-propagating beams.

The above discussion gives an idea about trapping two-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 in F = 3 decay 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 = 3 and be transferred again 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. The function of this branch is to help find the right frequency. 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 pump beam from the trapping beam has been increased by 36 MHz using an acousto-optic modulator (AOM) before being sent to the cell. In this way, the main trapping beam sent into the MOT is detuned by 36 MHz.

Once the right spectrum pattern has been found, lock the lasers.

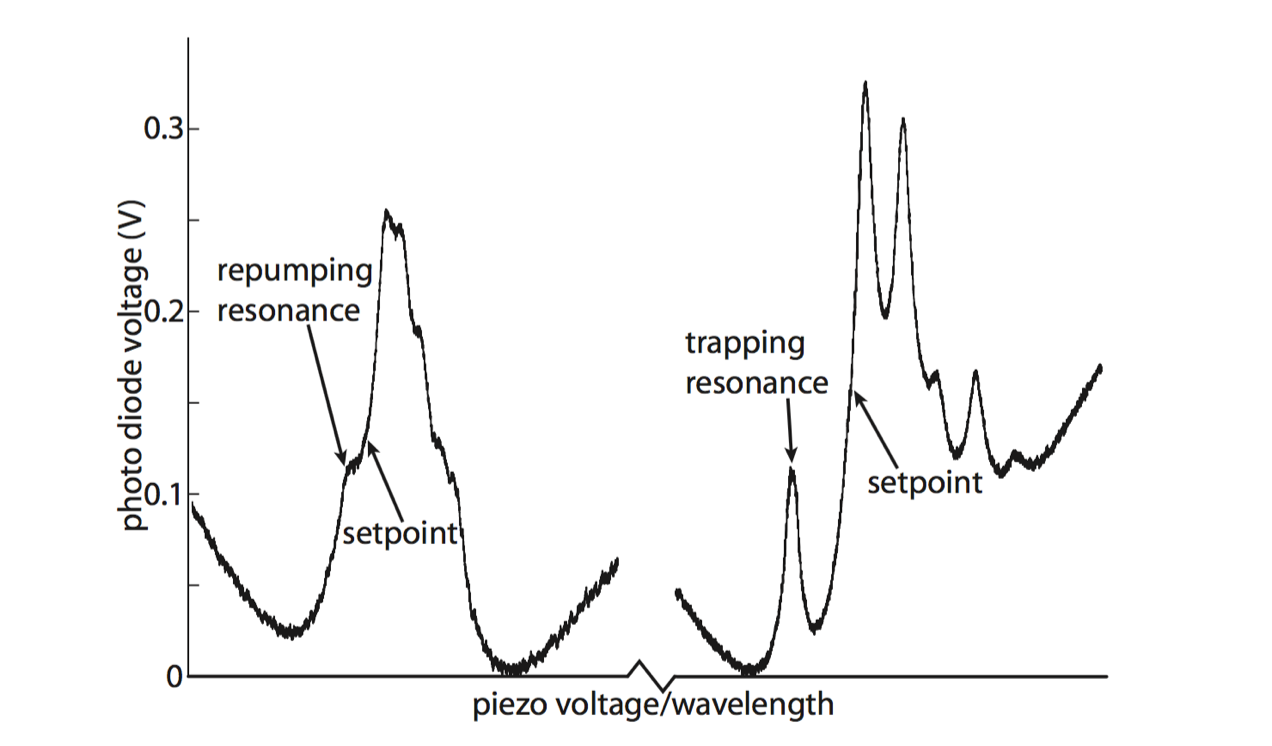


Figure .: Plots of the saturated absorption spectrum near the repumping and trapping resonances.[3]

### 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 for reference [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 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 we can then 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 measure 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. When the laser pulses fire is controlled by flash lamps and Q-switch [refer to Figure 2.6]. The infrared output 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.



Figure .: Layout of Continuum Surelite Nd:YAG laser. It can output beams of 4 different frequencies.

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.



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. It’s easier to amplify low energy peaks than high energy peaks. As shown in Figure 2.7, the combination of reflecting mirrors and a 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 amplifiers and linear amplifiers. 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 a 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 surface 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 (usually 5 to 6 runs) to gain 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. The highest output from linear amplifier in our lab is over 600 mw. Its structure 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 amplified 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 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 which gets maximum in 1 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.

### Synchronization System

Before taking any measurement, we have to make sure the timing is right. The timing is controlled by a synchronization system in the lab. It’s a combination of clocks, delay generators and synchronization boxes. The principal behind such a system is that it’s flexible enough to adapt to changes. Figure 2.13 shows the synchronization system working in the experiment described in chapter 6. A little changes need for this system to work for experiments described in chapter 4 & chapter 5. “Master” is a divider which divides the commercial 60 Hz electricity supply by 4 and provides a 15 Hz source to trigger a digital delay/pulse generator, Model DG535 from Stanford Research Systems, INC. One channel of this delay generator will be the trigger of another DG535 which controls the time of firing the lamps inside Surelite Nd:YAG laser. Another channel will trigger the lamp of GCR-100 Nd:YAG laser. The GCR-100 will provide a “ready” signal when the lamp is outputting power. This signal is synchronized in the SM-1 synchronization box with one pulse from the seed light. SM-1 outputs trigger signals for DG645 and another DG535. DG535 controls the Q-switch of GCR-100 Nd:YAG and pockels cells in the Regenerative Amplifier to get seed light amplified. DG645 controls the Q-switch of Surelite Nd:YAG, the ionization filed, scopes and etc. The delays are easy to change on these delay generators so this system can handle different timing for different experiments.



Figure .: Schematic of the Synchronization System. White cycles are inputs and dark cycles are outputs.

### 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. It controls the interlock of most lasers in the lab. If any laser is on, a red bulb outside the lab will be on to give a warning signal.

### Daily Examination

1. Check the MOT chamber pressure. The reading from the ion pump should be no more than orders of torr. If the pressure is higher than this reading, there might be some leakage.
2. Check pressure of canned nitrogen which is used to keep GCR-100 laser head clean and dry. The inner pressure should be higher than zero and the output pressure should be around 5 psi. From previous experience, the nitrogen needs to be replaced every two to three weeks.
3. Check the room temperature readings. The readings should be from 72 to 74 . For some extreme climates, the temperature may be out of this range.
4. Check temperature of cooling water from external sources. The supply water should have a temperature around 60 .
5. Check cooling water level for each laser before turning on the laser. The water level should be in the proper range marked in the box.
6. 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 it needs adjustment.
2. Turn on the regenerative pump GCR-100 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 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 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 stably increasing 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 and the last replacement date are 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 the flow is too slow, power supplier of the main anti-Helmholtz coils should not be turned on. Check the water supply in and out pressure to make sure water can flow. The normal in pressure is 14 psi. Make sure 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 the operating value. A normal operating current is from 1.9 A to 2.5 A. When this value has to be as large as 3.5 A to generate an observable cloud of atoms shown on the TV monitor, it means the getter has been used up. 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. (If the absorption signal is no way similar to the proper pattern, use a spectrometer to check the output frequency. For the trap laser, the output frequency range should cover the value 384232.6 GHz and for the repump laser 384231.2 GHz. If a diode laser could not reach the required value, it is possible that the piezo in the laser head is damaged and needs to be replaced.) Lock lasers.

At this point, there should be a bright spot shown on the TV monitors. It’s the scattered infrared light from the cold atom source. A good MOT on the screen is a stable bright spot with a clear circular shape. 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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