Construction of a Zeeman Slower for Ytterbium Atomic Beam

R. Paudel, L.W. Lupinski, and M.J. Madsen

Department of Physics, Wabash College, Crawfordsville, IN 47933

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In this project, we constructed a Zeeman slower, which is designed to slow Ytterbium atoms from speeds of 325 m/s to 1 cm/s. This paper describes how a low cost Zeeman slower can be built in an undergraduate laboratory. We chose Ytterbium atoms because we have access to direct diode laser that at 398.8 nm which corresponds to the $^1S_0$ to $^1P_1$ atomic transition.

Slow atoms are useful in performing high resolution spectroscopy and studying quantum behavior as their decoherence time is longer. However, the atoms coming out of a typical oven move at a speed hundreds of order of magnitude greater than we want. A technique introduced by Phillips and Metcalf [1] called Zeeman-slowing, the scheme of atomic beam cooling by laser radiation in a magnetic field, has been shown useful to slow Na [2], Rb [3], and various other atoms. The limitation of laser cooling because of the Doppler shift can be compensated using the linear Zeeman effect, keeping the atoms on resonance as they slow down [5]. Zeeman slowing has the further advantage of slowing atoms continuously and having a large velocity capture range limited only by the difference in magnetic field between the start and end of the slower [2].

The construction of Zeeman slower consists of a long solenoid with a varying number of turns to match the desired magnetic field (as in Figure 1). Atoms are fed into the slower from an atomic oven and are usually trapped in a Magneto-Optical Trap (MOT) on the output of the slower [6]. There are three types of Zeeman slowers: increasing field slower, decreasing field slower, and a combination of both types of slowers, called a spin-flip Zeeman slower.

In an increasing field slower, the atoms entering the slower initially encounter a very low magnetic field, such that the laser beam must be detuned by the entire Doppler shift of the fastest atoms to be slower [5]. The disadvantage of an increasing field slower is that the magnetic field has a large maximum at the far end of the slower closest to the MOT, which will interfere with the magnetic field in the MOT.
In a decreasing field slower, the atoms entering the slower initially encounter a very high magnetic field. So, a MOT can be placed at the end of the slower [5]. However, the fringing fields at its end decay in a way which tends to extend the slowing process resulting in a broadening of the velocity distribution of the slowed atoms.

![Graph showing magnetic field profiles](image)

**FIG. 1:** The three graphs represent the magnetic field profile of a) a decreasing field, b) a spin-flip, and c) an increasing slower.

In this project, we combine the advantages of both increasing and decreasing field slowers in a spin-flip Zeeman slower. This slower is designed so that the atoms are first slowed in a decreasing-field slower and then sent to an increasing field slower. The first slower will provide a significant compensation for the Doppler shift, however, only relatively small laser detunings will be required. At the end of this first stage of slowing, the second slower will produce a field which increases in the opposite direction. This small increasing field slower will produce a fringing field which is small and decays quickly (Figure 2). Hence, we can construct a MOT at the end of the slower.

The laser radiation possesses a $\sigma^+$ and $\sigma^-$ polarization and excites transitions between the Zeeman sub-levels corresponding to a change in the magnetic quantum number $\Delta m = +1$ and $\Delta m = -1$ respectively [6]. The Zeeman shift of the atomic transition frequency is proportional to the magnetic field strength (magnetic induction) $B$: $\Delta \omega_{Zeeman} = \alpha B$, where $\alpha$ is a constant determined by the Zeeman effect. The resonance interaction between atoms and laser radiation in the Zeeman slower is determined by the condition:
\[ \Delta + kv - \alpha B = 0, \]  

(1)

where \( \Delta \) is the detuning laser frequency in a zero magnetic field, \( v \) is the atomic velocity, and \( k \) is the wave number. The atom is in resonance with the laser if the magnetic field varies such that equation is valid [6].

For the slower we are constructing, the ideal field is given by [7],

\[ B(z) = B_b - B_t \sqrt{1 - z/z_0} \]  

(2)

where \( B_b \) is a constant bias field, \( B_t \) is the magnitude of the spatially varying component, and \( z_0 \) is the distance over which slowing takes place. We select the length by the deceleration, \( a \), the laser beam imparts on the atom given by

\[ a = \frac{\hbar k \Gamma}{2m} \]  

(3)

where \( \Gamma \) is the linewidth of the atomic beam.

There is some limitation to this deceleration that can be achieved in a laboratory. We introduce a design parameter \( \eta \) which affects the deceleration and is the empirical efficiency of the slower. The length of the slower follows from Newton’s second law of motion, assuming constant acceleration,

\[ z_0 = \frac{m v_f^2 - v_i^2}{\eta \hbar k \Gamma} \]  

(4)

where \( v_f \) is the final velocity, \( v_i \) is the initial velocity, and \( m \) is the atomic mass of Ytterbium atoms. We choose \( \eta \) using the available laser power and how well the magnetic field profile matches the ideal magnetic field. For our case we choose \( \eta = 0.4 \). The initial velocity corresponds to the melting point of Yb (1100K)[9].

In our case \( \Gamma = 2\pi \times 29 \text{ MHz} \), the initial velocity is expected to be about \( v_i = 325 \text{ m/s} \) based on the oven temperature of 1100K (the melting point of Yb), the final velocity \( v_f = 1 \text{ cm/s} \), and the mass of Yb \( m = 173 \text{ amu} \). Using these parameters, the length of the slower is \( z_0 = 29.1 \text{ cm} \). The saturation intensity \( I_s \) for Yb on the \( S_1 \rightarrow P_1 \) transition is \( I_s = 39.6 \text{ mW/cm}^2 \).

In order to aid in the construction of the Zeeman slower, we created a simulation modeling the magnetic field inside the slower along the middle of the tube, as we added and subtracted
FIG. 2: The figure above shows a model of the actual Zeeman slower design. The position from one end to the other is on the horizontal axis, and the height of the slower from the center is on the vertical axis. The left side is the positive polarity and the right side is the negative polarity with a small gap in the middle. There is also an anti-phase part at the right end of the negative polarity coil which is used to decrease the magnetic field before going to a MOT. We wound the wire layer by layer. The first layer of the positive polarity had 87 turns. The number above each sections represents the number of turns across the tube for that layer.

We used the Biot Savart law to find the magnetic field at the center of a coil,

$$B_i(z) = \frac{\mu_0 R_i^2}{2[(z - z_i)^2 + R_i^2]^{3/2}}$$

where, $B_i$ is the magnetic field generated by the $i^{th}$ layer, $I$ is the current in the coil and $R_i$ is the radius of the $i^{th}$ layer, $z_i$ is the position of the $i^{th}$ layer. The direction of the magnetic field is given by the right hand rule involving the direction of the current in the coil. To get the magnetic field at each $z$-position along the length of the slower, we summed over the magnetic field given by Eq. 5 for the total number of layers at each position.

$$B_{Total}(z) = \sum_i B_i(z)$$

Using the simulation we were able to find a coil design that should match the ideal magnetic field. (Figure 2).

We constructed a Zeeman slower on a 12-inch-long stainless steel nipple with stainless steel vacuum 1 1/3′′ flanges on both sides. We used 14 gauge magnetic copper wire to make coils. We started with winding one layer of positive polarity around the nipple starting from the flange, wrapping towards the middle, which is 87 turns of winding (see Figure 2), and
FIG. 3: The Zeeman slower tube is first wrapped with coils of positive polarity in layers of decreasing thickness, then switches to coils of negative polarity in increasing thickness, the last antiphase coil is of positive polarity to reduce the effect of the magnetic field outside of the slower.

We glued it using epoxy so that it will stay there while winding the subsequent layers on the top of the first layer. We then came back 20 turns and started winding from the middle towards the flange side and glued it again. We repeated this until we had the positive polarity of the slower ready. We applied the same method for the negative polarity, and again for the three turns of anti-phase coils which are after the negative polarity coils. Figure 2 shows a cross-section of the slower and Figure 3 shows a photograph of our Zeeman slower.

FIG. 4: Photograph of the Zeeman slower, positive polarity coils on the left side and negative polarity coils on the right side.

After the construction of the slower was finished, we used a hall probe to measure the magnetic field in the center of the tube. Starting from the zero position at positive polarity,
we measured the magnetic field at every 1 mm. Figure 5 shows the plot of ideal, model and measured magnetic field as a function of position.

We ran the current at 6 A and the voltage at 24 V. In the steady-state, the heating of the wire was hot to touch but not enough to melt the epoxy or affect the design of the slower by expanding.

![Diagram](image)

FIG. 5: a) the ideal (dashed), model (solid) and measured (dotted) magnetic fields. The Zeeman slower model is in the background. b) The set of residuals: (model - ideal) and (model - real). The solid curve represents the residuals of ideal with modeled magnetic field and dot points are the residuals of measured magnetic field with the ideal magnetic. We can see the residuals of the measured magnetic field with the ideal in the region from 5 cm to 25 cm is less than 10 Gauss.

Our data shows that magnetic field produced by the winded coil is close enough to load Ytterbium atoms in the slower. We can see the residuals of the measured magnetic field with the ideal in the region from 5 cm to 25 cm is less than 10 Gauss. Hence, we believe this much variation in magnetic field can be corrected by tweaking the current while loading the atoms, thus leaving it to the experimental parameter to get the slower to work.

The second phase of this project will involve the construction of a Ytterbium oven and
attaching the oven to the slower. Then, we can measure the velocity distribution of the atomic beam at the end of the slower. We can also measure the isotope shift of Ytterbium atoms using the slowed atomic beam.

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