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An atomic coilgun: using pulsed magnetic fields to slow a supersonic beam

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Abstract. We report the experimental demonstration of a novel method to slow atoms and molecules with permanent magnetic moments using pulsed magnetic fields. In our experiments, we observe the slowing of a supersonic beam of metastable neon from 461.0 ± 7.7 to $403 \pm 16\,\mathrm{m\,s^{-1}}$ in 18 stages, where the slowed peak is clearly separated from the initial distribution. This method has broad applications as it may easily be generalized, using seeding and entrainment into supersonic beams, to all paramagnetic atoms and molecules.

Contents

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1. Introduction

It has long been recognized that controlling the velocity of cold atoms and molecules in supersonic beams would provide a means for trapping of species where no other methods are currently available. Many atoms and molecules can be entrained or seeded into supersonic beams and are cooled to sub-kelvin temperatures. However, internal energy lost in adiabatic expansion is converted to kinetic energy leading to high velocities in the laboratory frame. Velocities of supersonic beams vary between a few hundred to several thousand metres per second, depending mainly on the source temperature and the atomic or molecular weight of the carrier gas [1]. The temperatures reached in supersonic expansion can be as low as several tens of millikelvin. There have been two general approaches to slowing of supersonic beams. One school of thought treats the atoms and molecules in the beam as billiards, using motion of other objects or particles to slow the cold atoms. Several notable examples of this method include the slowing of helium via specular reflection from a receding crystal [2], mounting the supersonic source on a spinning rotor [3], and elastic collisions of crossed beams [4]. The other approach uses interactions with time varying external fields. This includes the pulsed electric field decelerator [5], and slowing with pulsed laser fields [6].

We recently proposed a new method of controlling the velocity of a supersonic beam using pulsed magnetic fields [7]. The method is quite general for atoms since most elements are paramagnetic, and can also be applied to certain molecules as well as electronically excited metastable states. We now present results of slowing for metastable neon using 18 pulsed coil stages, with these results showing a clear separation of the slowed peak from the initial distribution. In parallel to our work, slowing of atomic hydrogen and deuterium with seven stages has been demonstrated [8, 9].

2. Principle of operation and apparatus

The operational principle of our magnetic decelerator is based on the Zeeman effect, similar to the way the pulsed electric field decelerator is based on the dc Stark effect. The electronic states of atoms or molecules that have a non-zero total angular momentum split into magnetic sublevels in the presence of magnetic fields. As our slowing is optimized for low field seeking electronic states, we will now describe such an atom's interaction with our coils.

As a low field-seeking atom moves along the axis of an energized electromagnetic coil it loses kinetic energy by climbing the magnetic 'hill' (see figures 1(a) and (b)). If the coil were left on as the atom passed through, it would ride the magnetic 'hill' down and gain back the same amount of energy lost. However, if we switch off the current flowing through the coil suddenly as the atom passes through the center, the atom loses the amount of kinetic energy equal to the Zeeman shift at the top of the 'hill' as seen in figure 1(c). As such, with an ideal coil (zero switching time) the energy lost per stage would be $\Delta E = \mu_B g_j m_j H$, where μ_B is the Bohr magneton, g_j is the Landé factor, m_j is the projection of the total angular momentum on the quantization axis, and H is the peak magnetic field. The process can be repeated again with another coil until the particle comes to rest in the laboratory frame. The slowing process conserves phase space density and only reduces a specific target velocity of the distribution without affecting the temperature. The stopped atoms can then be transferred into a magnetic trap.

We create the high magnetic fields needed for efficient magnetic slowing in an electromagnetic coil that has 30 copper wire windings (0.5 mm diameter) and a bore diameter of

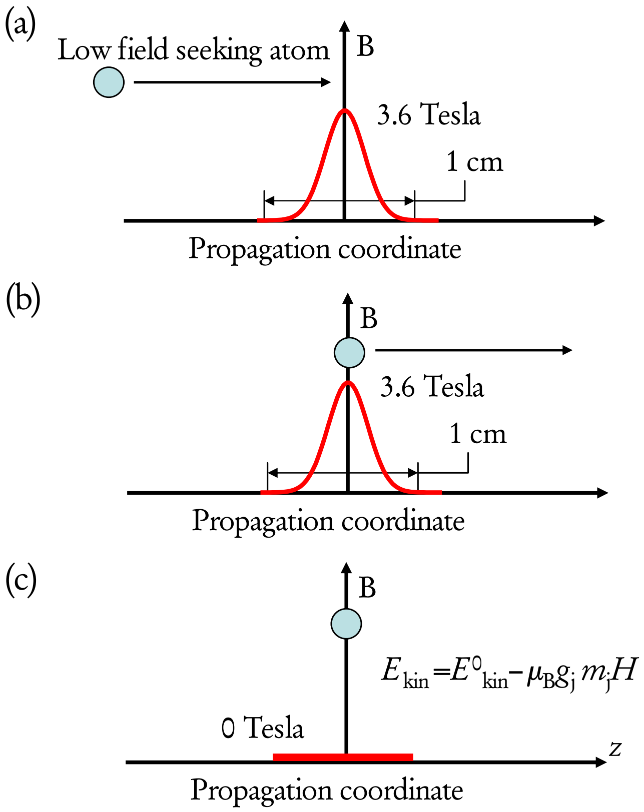

Figure 1. A descriptive diagram of the slowing process. In (a) we see the atom entering the coil, and as it does so it must climb a magnetic 'hill'. Part (b) shows the atom at the center of the coil with the coil still on, when it has maximized its potential energy. Part (c) shows the atom in the center of the coil with the field switched off. On the right is the equation showing how much kinetic energy would be lost with an ideal coil.

3 mm. The coil is encased in a magnetic steel shell with Permendur discs (see figure 2), which confines the field, leading to higher peak magnetic fields, and minimizes inductance between adjacent coils. Permendur has a saturation magnetization of 2.3 T and allows us to achieve a peak magnetic field density of 3.6 T with a current of 400 A flowing through the coil, according to our finite element calculations (see figures 3(a) and (b)). Our driver circuitry allows independent operation of each coil and enables overlap between two adjacent pulses. This means that an atom always sees some magnetic field and will not lose its quantization axis. Maximum current is reached within 35 μs and stays nearly constant for the additional 25 μs. When the coil is switched off, current falls linearly to zero in 6 μs. Having an electrically conductive material close to the coil windings complicates the magnetic field switching characteristics. Although we switch off the current in our coil in 6 μs the magnetic field falls to 35% of the initial value in the same time. Eddy currents induced in the conductive shell and discs create magnetic fields that decay exponentially with a time constant of 11 μs. It is possible to compensate for the slow decay by reversing the polarity of the current flowing through the coil [10].

We produce a pulsed supersonic beam of neon using the Even–Lavie supersonic nozzle [11, 12]. To reduce the initial velocity of the beam, we cool the nozzle to liquid nitrogen

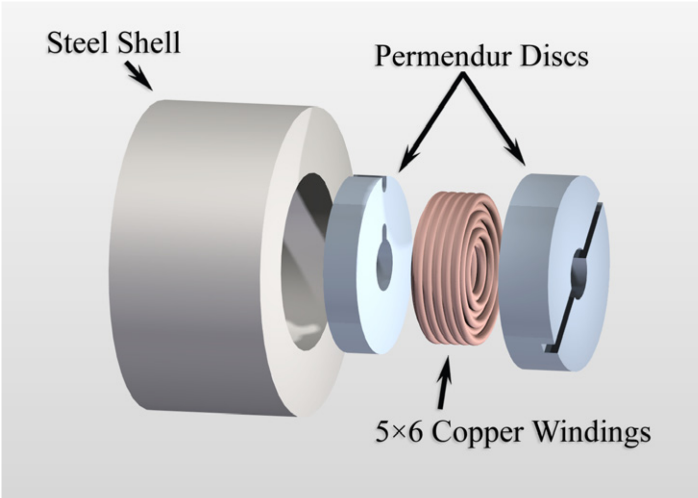

Figure 2. A schematic blow up of our electromagnetic coils. The bore diameter is 3 mm and the axial length is also 3 mm.

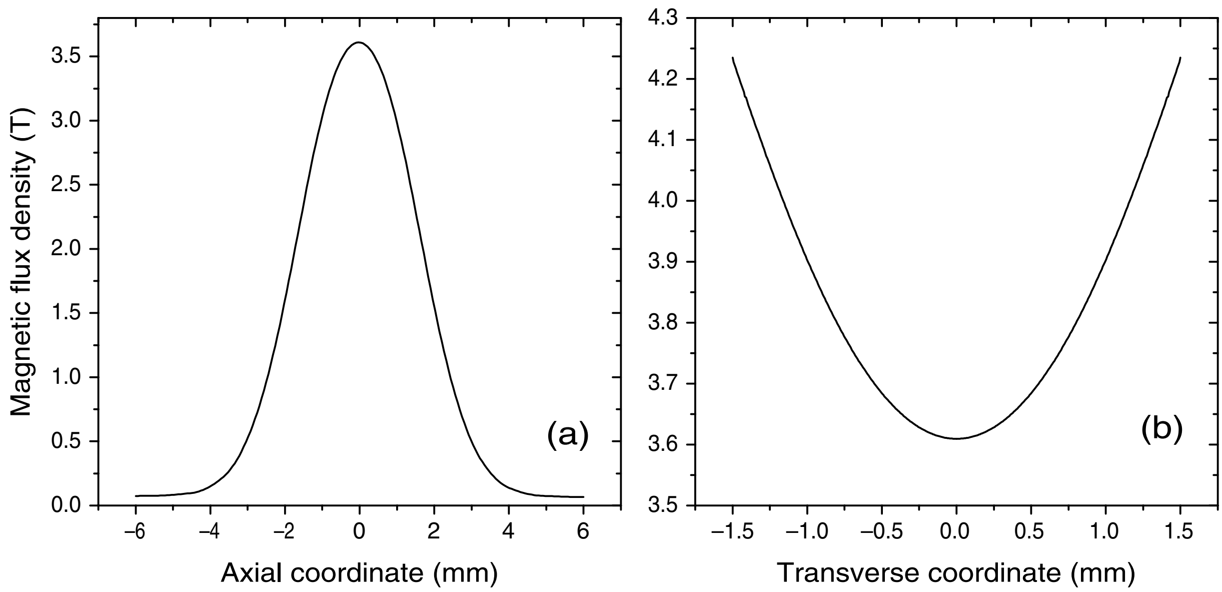

Figure 3. A plot of the axial and transverse magnetic fields in our coils. These curves are determined by finite element analysis that takes into account the Permendur and steel casing of the coil. The axial and transverse fields are measured along and across the center of the coil.

temperatures. We then use a pulsed dc discharge between stainless steel and aluminium electrodes mounted 1 mm from the exit cone of the nozzle to excite the neon to the $2p^5 3s^1$ electronic metastable configuration. We slow the $^3P_2$ state, where $m_j = 1, 2$ are low field seeking states and can be slowed with our apparatus. The Landé factor for the $^3P_2$ state is nearly 1.5 which leads to an effective magnetic moment of 3 or 1.5 Bohr magnetons. This holds for low magnetic fields where the Zeeman level splitting is small compared to the fine structure of

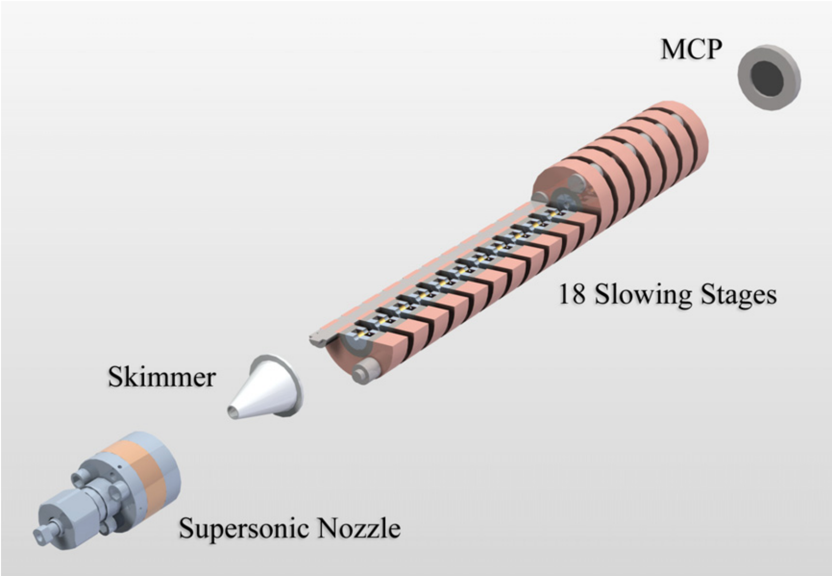

Figure 4. A Schematic drawing of our apparatus (not to scale). Actual distances are as follows: nozzle to skimmer is 30 cm, skimmer to first coil is 29 cm, first coil to last coil is 28 cm, and last coil to MCP is 167 cm (172 cm) with the translation stage retracted (extended).

the $2p^53s^1$ configuration. At high fields the orbital and spin angular momentum are decoupled (Paschen–Back regime), level mixing occurs and the effective magnetic moment becomes field dependent. The exact energy level diagram as a function of magnetic field has not been measured in the case of the metastable $2p^53s^1$ neon configuration. As such our coil switching times can only be determined by empirically optimizing the intensity of the slowed beam signal.

A description of the full apparatus follows (see figure 4). Our beam first passes through a 5 mm diameter skimmer mounted 30 cm from the nozzle. The center of the first coil is mounted 59 cm from the nozzle. The 18 slowing stages are 1.4 cm center to center, with twice this for the last two stages, resulting in an overall length of 28 cm. The coils are mounted in copper rings that are themselves water-cooled. We detect our beam using a micro channel plate (MCP) which has an active area diameter of 18 mm and a gain of up to 10^6 (El Mul Technologies Ltd). When the metastable neon atoms hit the front surface of the MCP, an electron is released and this current is then amplified. We mount our MCP on a 5.08 cm translation stage, which allows us to determine the speed of our beam using time of flight at two different locations. The MCP is located 2.54 m (2.59 m) away from the nozzle in the retracted (extended) position and 1.67 m (1.72 m) from the end of the slowing stages, which allows the slowed peak to separate from the unslowed atoms. One disadvantage to this additional length is that not all of the slowed beam makes it to the detector due to a larger angular spread at the exit of the slower as compared to a reference beam.

3. Results

The results we present show the slowing of metastable neon from an initial velocity of $461.0 \pm 7.7\,\mathrm{m\,s^{-1}}$. This is the target velocity we selected from a beam with center velocity of

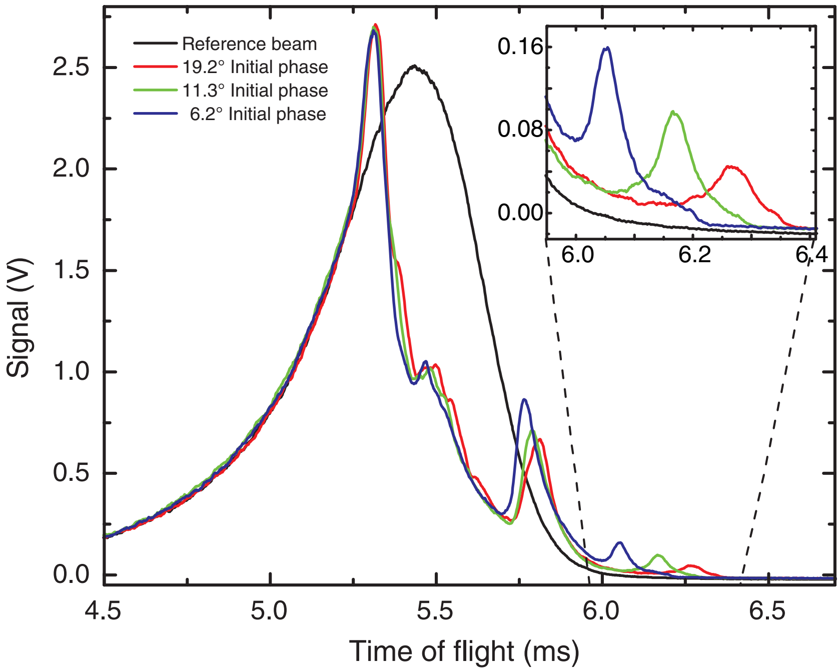

Figure 5. A plot of the arrival time of metastable neon atoms at our MCP detector, with varied switching phases. Each curve is an average over 10 shots, at a current of 400 A and a repetition rate of 0.2 Hz. The reference beam is the beam detected without pulsing the coils. Here, a larger phase angle leads to greater slowing, but a smaller region of phase stability. The slowed peaks are seen at the right side of the graph, and in the expanded inset.

$470 \pm 1.8\,\mathrm{m\,s^{-1}}$ and full width at half maximum (FWHM) of $43.0\,\mathrm{m\,s^{-1}}$. We first calculate an appropriate pulse sequence by numerically integrating the equations of motion with magnetic fields obtained via finite element analysis. We then optimize the pulsing sequence empirically by tuning the effective magnetic moment as a free parameter in our calculations and changing the time at which the pulsing sequence starts, effectively scanning the target velocity.

We initially calculate our pulse sequence such that the atoms to be slowed are at a particular position in each coil when the fields are switched, where the position is adjusted linearly from one coil to the next. This position on the magnetic potential hill corresponds to a certain phase angle, in analogy to the electric field decelerator [13]. We calculate this phase angle by determining the magnitude of the magnetic field at the position of the target bunch when switching occurs. The phase angle we use is the arcsine of the ratio of this magnitude to the peak magnetic field at the center of the coil. We calculate our phase in this manner because the length of one coil is much shorter than the coil-to-coil distance. Due to the finite switching times of our coils, the phases at which we operate are much lower than those commonly used by the pulsed electric field decelerator. Our system also displays phase stability [13], and we can vary the phase angle to alter the degree of slowing. We also find that the size of the region of phase stability is varied with the chosen phase and the flux of slowed atoms depends on this parameter.

We now present time of flight results of varying the phase of the switching in figure 5, along with a comparison reference beam. We use initial phase angles of 6.2°, 11.3° and 19.2°

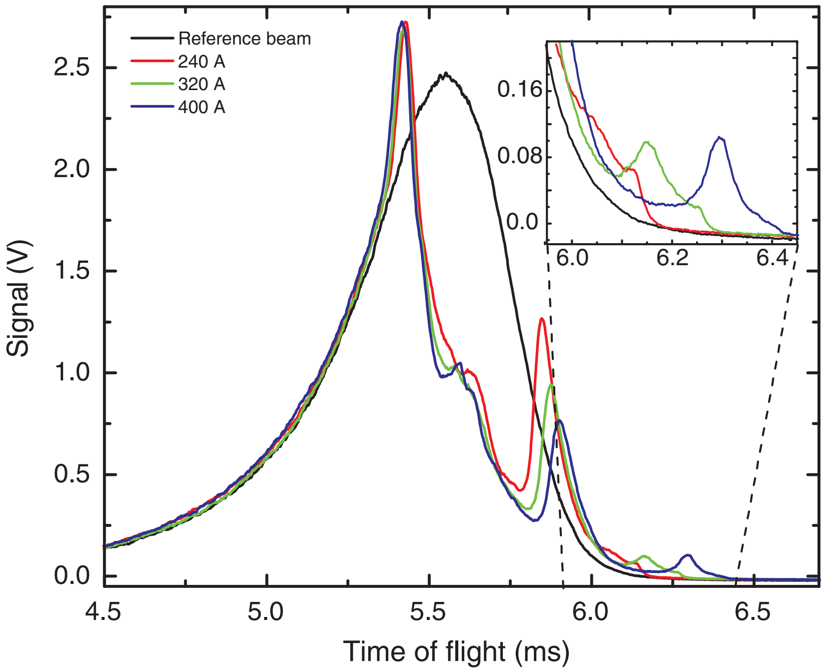

Figure 6. A plot of arrival time at the MCP detector, with varied currents in the coils. Each curve is an average over 10 shots, using an initial phase angle of 11.3° and a repetition rate of 0.2 Hz. The higher currents lead to greater magnetic fields and thus more slowing. The slowed peaks are on the right side of the graph, and in the expanded inset.

(final phase angles are 9.5°, 16.9° and 26.8°, respectively) to demonstrate the difference in slowing due to a variation in phase angle, as well as changes in flux. Using the translation stage as described above, we calculate speeds of 431.2 ± 6.0, 409.3 ± 9.1 and $403 \pm 16\,\mathrm{m\,s^{-1}}$, corresponding to a slowing of 30, 52, and 58 $\mathrm{m\,s^{-1}}$ from the original 461 $\mathrm{m\,s^{-1}}$. Taking an initial phase angle of 19.2°, we find that our slower removes a kinetic energy of 0.288 meV (2.33 $\mathrm{cm^{-1}}$) per stage.

To examine the effects of magnetic field strength, we vary the current in the coils. The currents we use are 400, 320 and 240 A, as currents lower than this do not separate the slowed peak from the main beam. These currents correspond to maximum magnetic field densities of 3.6, 3 and 2.4 T. As can be seen in figure 6, we see less slowing for lower fields. The corresponding velocities, as calculated by the translation stage, for these currents are 409.3 ± 9.1 and $416 \pm 22\,\mathrm{m\,s^{-1}}$ for 400 and 320 A, respectively. We are not able to definitively determine the velocity for 240 A as the peak is not resolved.

Comparing the resulting beam shape to the reference beam in figures 5 and 6, we observe that the original beam is greatly disturbed by the pulsing of the coils. We explain the shape of the resulting beam qualitatively. The metastable atoms in the reference beam do not all have the same angular momentum projections, and while our coils focus low field seekers, the high field seekers are defocused, leading to a loss of atoms compared to the reference beam. While this explains the minimum seen in the plots, we must still address the two peaks seen on either side of this minimum. These occur because not all atoms that feel the pulses of the field are slowed.

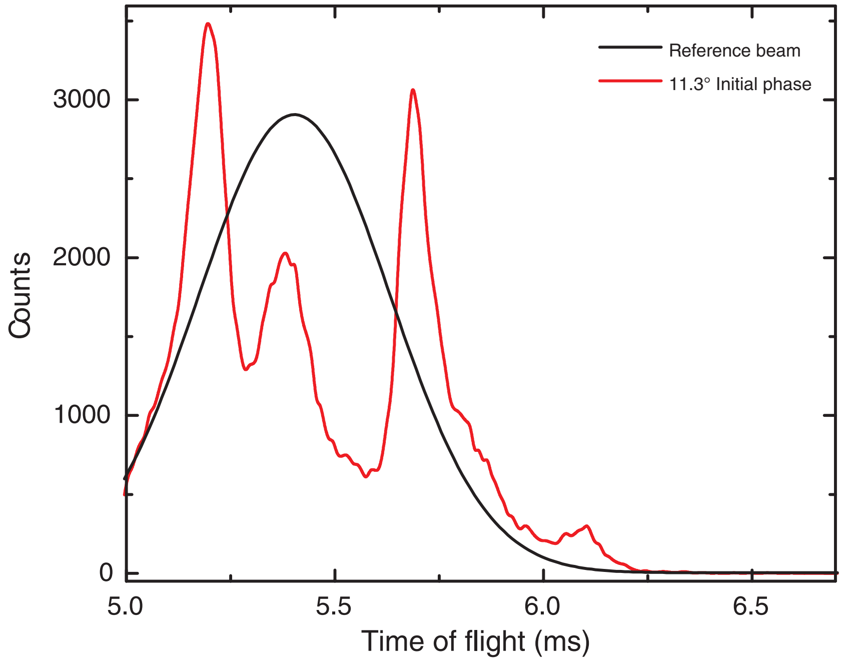

Figure 7. Numerical simulation of the time of flight signal. The target velocity of 461 m s^{-1} is slowed to 404 m s^{-1} using an initial phase angle of 11.3°. The initial Gaussian distribution with a center velocity of 470 m s^{-1} and FWHM of 47 m s^{-1} is shown as a solid line. This Monte Carlo simulation has 50 000 trajectories for each magnetic sub-level of the $^3P_2$ state.

Some atoms will be accelerated slightly by one or two coils before falling out of sync with the pulses, which produces the peak leading the minimum. The peak trailing the minimum can be explained in the same manner, except that the atoms are slowed slightly instead of accelerated.

We present a numerical simulation for our slowing for a single magnetic sub-level in figure 7. As one can see the numerical simulation is in a qualitative agreement with our measurements. We integrate the equations of motion using magnetic field strengths calculated by finite element analysis, time dependence as measured by a pick-up coil and a magnetic moment of 3 μ_B. The initial Gaussian distribution has a center velocity of 471 m s^{-1} with FWHM of 47 m s^{-1}. The target velocity is 461 m s^{-1} and the initial phase angle is 11.3°. The calculated slow beam velocity is 404 m s^{-1}.

4. Conclusion

We demonstrate the slowing of a supersonic beam of metastable neon with a pulsed magnetic field decelerator of 18 stages. We are able to manipulate the slowed peak by varying magnetic field, as well as phase angle, and we are able to clearly separate our slowed peak from the initial distribution. Our data show good agreement with simulations. To achieve greater slowing, we are currently implementing a 64 stage apparatus.

Acknowledgments

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