Interstellar Missions Research Essay

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Problem Statement

Humans have always been fascinated by the stars in the sky and significant study has gone to develop telescopes to see far beyond our planet into these distant stars. We put satellites into orbit to better understand our planet, our close neighbors in the solar system, and distant star systems. The study of all this eventually manifests as a crewed mission like we did with the Moon in 1969 and what we will do on Mars. In preparation for these missions, science spacecrafts were sent to study the area planned for the crew. For interstellar travel, this process and the ultimate end goal will not be different. We have been studying beyond our

star for a long time, now we are arriving at the era where sending scientific spacecrafts to near star systems becomes feasible. It is important for us to explore beyond our star system because these understandings help us learn more about ourselves, provide technology benefits that can be used on Earth, but also they provide a great sense of collective pride in what it means to be a human. Every time we push beyond the boundary, we previously thought impossible, we create a milestone in human scientific development. However, a large challenge that comes with interstellar missions is the time to see results. It is difficult to get the public excited about a scientific mission that they or their children may not see benefits from. For this reason and many others, trying to reach the nearest star system within a human lifetime is increasingly valuable and is one of the highlights of initiatives like Breakthrough Starshot [1].

Current space propulsion methods do not have high enough specific impulse to accomplish these missions in a reasonable timeline. For this reason, different forms of beamed propulsion and solar sailing technology are being studied. The benefits of these methods are removing the requirement of housing propellant onboard the science spacecraft and having an increased thrust duration that can propel the spacecraft to very high speeds. Traditional projects evaluating beamed energy propulsion suffer from the divergence of light or particles used to transfer momentum to the science spacecraft. Reducing this effect has caused many designs to involve kilometer sized sails and transmitters which is a monumental task on top of another very difficult challenge. A propulsion method proposed by Limbach and Hara [2] uses a combined laser and particle beam to produce a self-guiding effect that nearly eliminates beam divergence over millions of kilometers. With this method, the sail and transmitter can remain on the order of meters in size, which reduces the challenge. A breakdown of this technology will be discussed in the following section.

Background

The fundamentals of the self-guiding beam propulsion method [2] is a high flux particle source, a laser cooling module that reduces the natural thermal divergence of the particles from the source, then an overlapped laser beam that will propagate with the particles and form the self-guiding, and finally the transmitter will need a way to ionize and accelerate the particles to very high speeds (10% the speed of light). The scientific spacecraft will need a way to accept the momentum transfer without the particles barraging the sail, and while this is a research challenge, it is left for future developments. The principles of the light and particle guiding are well understood. Like a step-index fiber optic cable, the laser light is confined to the higher index of refraction core or particle jet. The particle guiding has also been studied by experiments such as those by Grimm et al. [3] and Bjorkholm et al. [4].

The operating principles of the particle trapping comes from starting with a low temperature source of atoms and overlapping them with a high intensity laser. When the laser is tuned near the resonance of an energy level transition of the atom, it has different effects. Tuning the overlapped laser slightly to the red of resonance will produce a focusing effect and create a potential “well” that these low temperature particles cannot escape. Shifting the overlapped laser to slightly blue of the transition pushes the particles out of the center of the beam. The figure of the effects of tuning on this overlapped beam can be seen in Bjorkholm [4].

The area of study currently being researched at Texas A&M is the focusing effect of the particle guiding on the laser. The study of particle traps mentioned previously [3,4], focus primarily on the effect on the particles but not the output of the overlapped laser. In the self-guiding beam, it is crucial to understand the behavior of both the particles and the laser during the propagation.

Current Research

The current experimental research, led by Dr. Christopher Limbach, involves breaking apart the fundamental requirements of the propulsion method outlined in the Background section. The original goal of this initial study was to develop a custom, scalable rubidium particle jet source to study the light-matter coupling. This particle source is shown in Error: Reference source not found. The primary elements included a heated rubidium reservoir, a converging-diverging nozzle to accelerate the particles to supersonic speeds, a beam skimmer that extracted the low divergence center of the plume, and a surrounding chilled condensation chamber that will condense rubidium on contact with the walls such that reflections do not interfere with the central plume. This configuration was evaluated in an experiment in the Spring of 2020. The results of this experiment along with design improvements are the planned subject of a conference paper for the 2020 AIAA Propulsion and Energy Conference. Additionally,

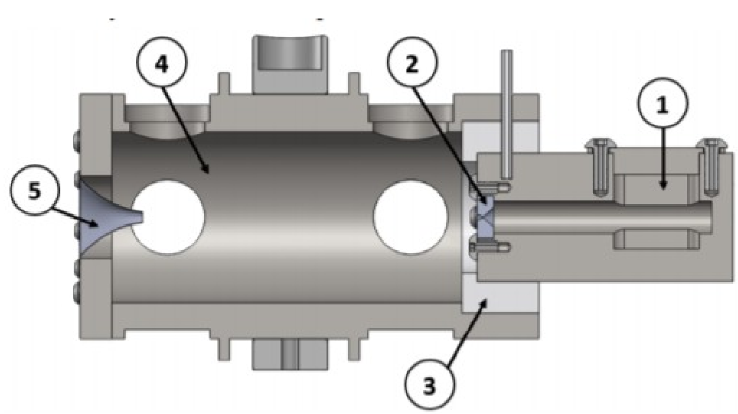

Figure 1. Rubidium particle jet source. 1. Heated rubidium reservoir, 2. Converging-diverging nozzle, 3. Ceramic insulator insert, 4. Chilled condensation chamber, 5. Beam skimmer

this experiment requires the use of a vacuum facility that is equipped with enough space to house the experimental setup, allow the beam significant propagation distance, and provide the capability for laser diagnostics of the jet. The vacuum facility design has, and continues to be, a sizeable portion of the effort. The initial vacuum configuration from the Spring 2020 experiment is shown in Figure 1. During this experiment, the absorption spectroscopy diagnostics, which will be discussed in detail in a following section, showed that there was a substantial ambient pressure of rubidium in the chamber. The conclusion from this experiment was the condensation chamber did not remain at the low temperature required and caused significant back pressure against the converging-diverging nozzle, causing the rubidium vapor to be subsonic upon leaving the skimmer. Several improvements to this experiment have been designed and constructed and awaits laboratory evaluation.

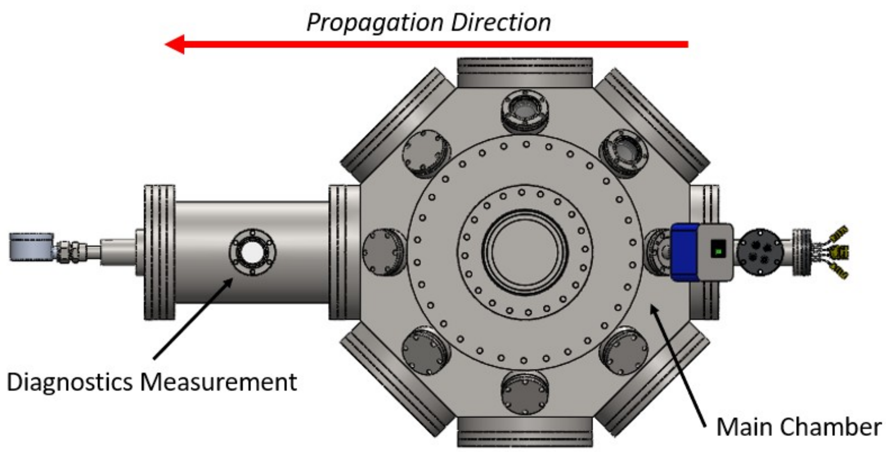

Figure 1. Initial vacuum facility configuration

Measurement Diagnostics

Understanding the behavior of the particles in the experiment is crucial to evaluating and modeling the behavior of the propulsion method. The primary particle jet parameters of interest are the density of the jet and the bulk velocity and temperature of the atoms. A tunable diode laser absorption spectroscopy (TDLAS) diagnostic method was employed in the Spring 2020 experiment, shown in Figure 2.

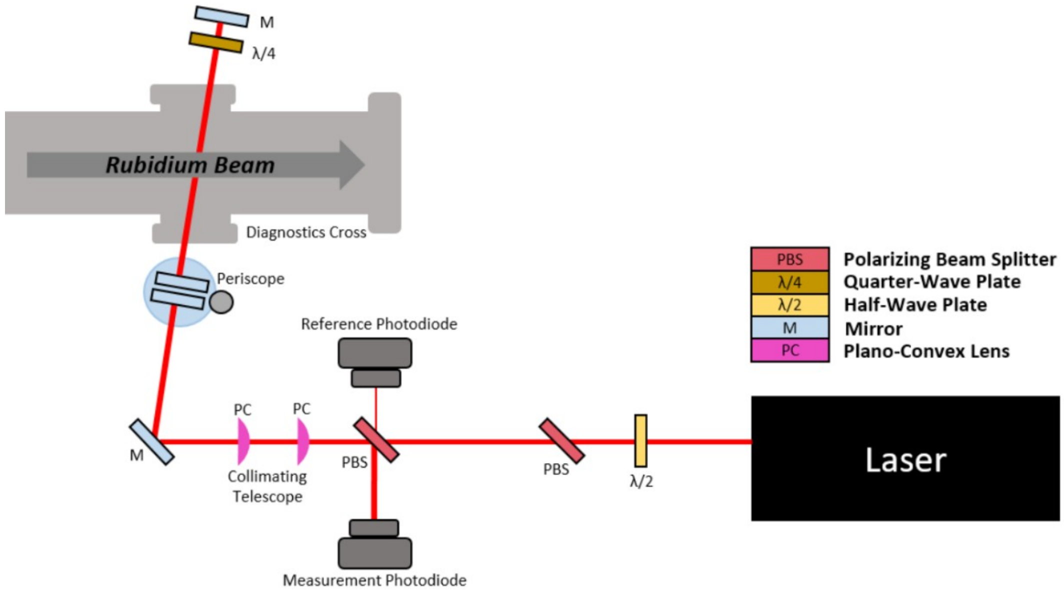

Figure 2. Tunable diode laser absorption spectroscopy experimental setup

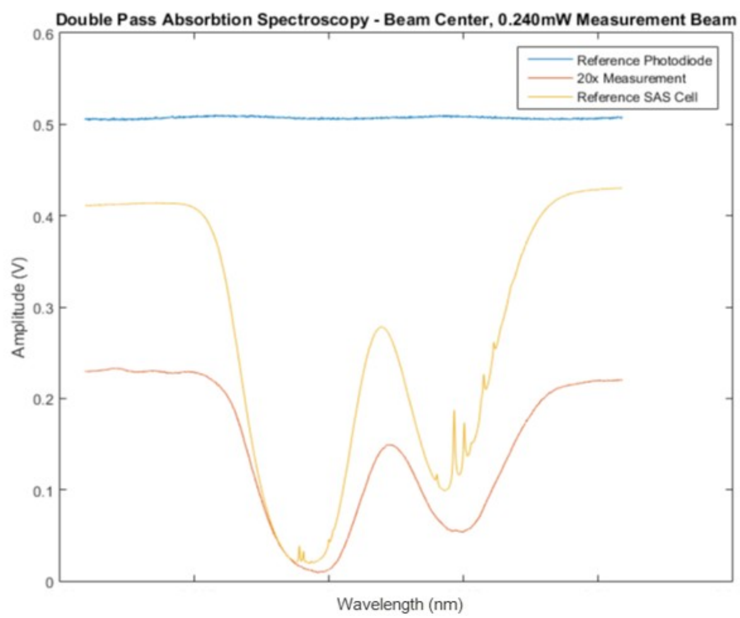

Figure 4. TDLAS measurement data compared with SAS reference cell

The experimental setup for this diagnostic method involves a saturated absorption spectroscopy (SAS) reference, an adjustable periscope to scan across the particle beam, and a series of optics to perform a double pass through the particle beam at an angle and isolate the return signal. The slight angle introduced to the diagnostic beam allows the bulk velocity of the particle jet to manifest as a combination of a red and blue shift in the double pass measurement. The temperature of the atoms is evaluated through traditional thermal Doppler broadening effects, while the jet density is seen as the intensity of the absorption feature. The saturated absorption spectroscopy reference measurement acts as a source of comparison for the bulk velocity Doppler shifting. An example of the results from this TDLAS experiment is provided in Error: Reference source not found

Another diagnostic planned to be implemented in future iterations of the experiment is laser induced fluorescence (LIF). With LIF, a laser sheet, generated by the same tunable diode laser in the TDLAS measurement, will be scanned across the beam to gather density and temperature. Additionally, an angle relative to the jet propagation direction can be introduced to also see a bulk velocity Doppler shift. The goal of this addition of LIF is to add another point of comparison as well as study locations in the beam that might not be possible or practical with absorption spectroscopy. In the previous jet source configuration, Error: Reference source not found, a series of four sapphire windows was installed onto the condensation chamber which served as an access point for the LIF beam and the collection optics to gather the fluorescence. With the experimental configuration, a TDLAS measurement in this location would be increasingly difficult. In the future experimental facility, it is possible to conduct a TDLAS measurement and then also collect the fluorescence in the same location. This dual measurement capability will aid in providing accurate results.

Future Research and Thesis Development

The goal of future research is to focus on the light-matter coupling and its effect on the focusing of both the rubidium atoms and the overlapped laser as a function of the laser tuning. To complete this, a transition from a high flux source to using an off-the-shelf rubidium vacuum getter cartridge was made. The rubidium getter releases a relatively low mass flux of rubidium out into the vacuum chamber when heated via an electrical current. An improved condensation shroud is then used to surround the getter source such that only the central region expands into the chamber, similar to the principal operation of the beam skimmer but now the particles are strictly in the free molecular flow regime, not continuum as before. This new source configuration is shown in Error: Reference source not found. The shroud has significant improvements from the previous version, starting from the change in material from the original stainless steel with low conductivity to high thermal conductivity copper. Additionally, the cooling system for this condensation shroud has changed from being an immersion probe chiller in a coolant reservoir to an actively pumped cooling coil brazed to the outside of the shroud.

From this new source development, an initial experiment with roughly the same vacuum facility as the Spring 2020 experiment will be conducted to get a baseline estimated for the behavior of this source. The key objective of this experiment is to see a significant reduction in the ambient rubidium pressure in the vacuum system, this will indicate that the condensation shroud is operating nominally and condensing the particles well enough to cryopump out the unwanted region of the flow. Since the source will now originate the rubidium atoms in a free molecular flow regime, the trajectory of the

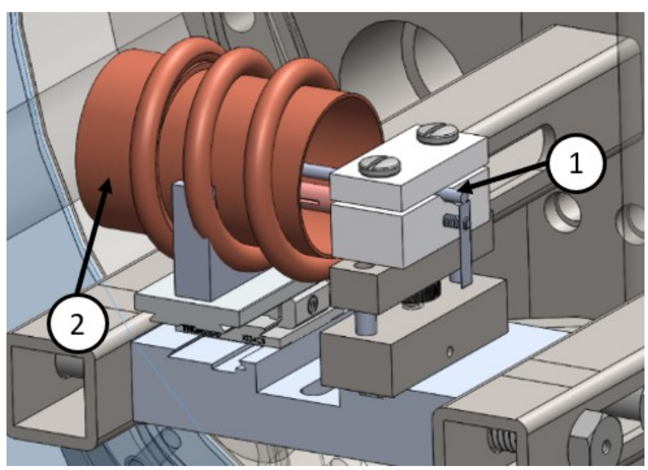

Figure 5. Revised jet source. 1. Rubidium getter cartridge in ceramic mounting block, 2. Chilled copper condensation shroud mounted to an adjustable rail system

atoms is purely the ballistic angles they have upon leaving the source. Using the equations provided by Cai and Boyd [5], the plots shown in Error: Reference source not found were produced. The benefits of using a free molecular source to study the interaction is that the initial beam parameters are much easier to model and simulate. From the density and velocity flow fields, the effective absorption signals can be hypothesized and compared to future experimental results to calculate the efficiency of the experimental source in relation to the theoretical maximum.

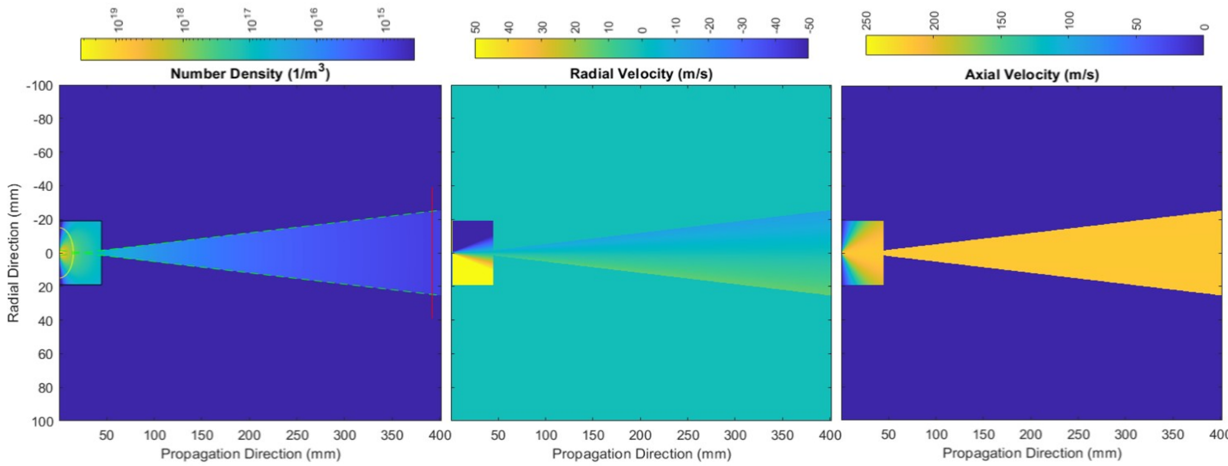

Figure 6. Free molecular flow regime number density, radial velocity, and axial velocity flow field profiles

In addition to the new source, a new vacuum facility has been constructed and will be implemented, this is shown in Figure 3. The new vacuum facility includes significantly more diagnostics access, as well as the ability to have an extended propagation section. This extended propagation section will allow the effects of divergence to be quite clear near the end of the run. The main highlight of transferring to this new vacuum chamber is the ability to introduce laser cooling.

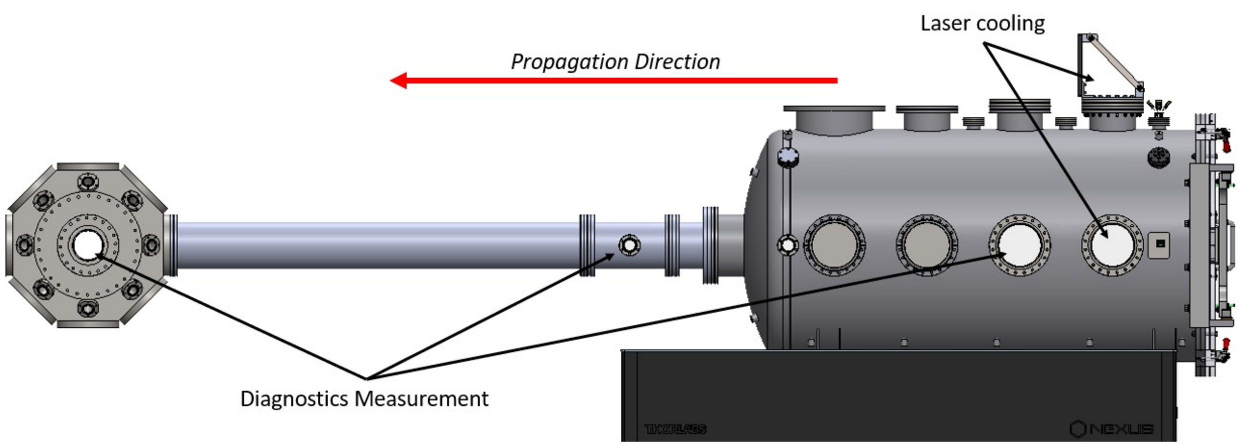

Figure 3. Future experimental setup with measurement locations and laser cooling location

The laser cooling works by creating an intersection of four orthogonal lasers, tuned slightly red of the atom's energy level transition of interest. The laser cooling intersection is referred to as an “optical molasses”. From this, if the atom has a velocity that is traveling towards one of the laser beams, it experiences a Doppler blue shift of the laser frequency which, paired with the laser tuning, will possibly cause it to fall right at the frequency of the transition. The atom then absorbs the photon, which imparts some momentum on the atom. Later, the excited atom emits this same photon and repeats the process until the atoms leave the optical molasses. The rate at which the atom releases the absorbed photon is equal to the inverse of the Einstein A coefficient for the transition. For this reason, rubidium and other alkali metals are ideal candidates for laser cooling as the A coefficients are orders of magnitudes higher than other species, meaning they can have momentum imparted on them significantly more times while in the laser cooling optical molasses. The ultimate result of this laser cooling is to lower the divergence of the jet significantly. However, there will still be some jet divergence after laser cooling. Diagnostics methods at discrete locations along the jet propagation will be able to identify the jet size, which can be used to calculate the divergence. An area of study of this research will involve fine tuning the laser cooling frequency to optimize the red shift such that the divergence of the resultant jet is minimized.

Now the overlapped laser beam can be introduced. This is the area that will be the primary focus of the thesis work. Using a pinhole mirror for the particles to pass through [4], the laser can be overlapped with the particle jet. The point at where in the jet the laser comes to a focus to maximize trapping potential is also an area of study for this research. With the laser overlapped, the same diagnostics along the propagation direction will be used the parameterize the jet and determine if the jet divergence has been significantly reduced relative to the laser cooling. Additionally, another measurement will be conducted at the end of the propagation axis: a heated window will be used to reflect the particles out of the beam axis where they will go to a condensing beam dump, but the laser will be allowed to pass through. From here, the laser beam will propagate out of the vacuum and go to a beam profiler. This addition to the experiment introduces a novel aspect that will provide significant insight into how the particles will then focus the light. This interaction can then be compared to theory and simulations. Various experiments will be conducted to see the effects of overlapped laser detuning on the shape of the particle jet as well as the end profile of the laser beam. These experiments will also show trends toward the optimal laser cooling frequency and overlapped beam frequency to produce a tight, low divergence combined beam.

Conclusion

The development of a ground-breaking propulsion method for interstellar travel is about overcoming hurdle after hurdle, not simply one giant leap. The goal of my Master of Science thesis is to study the fundamental physics behind light-matter focusing and coupling that could lead to a form of beamed energy propulsion capable of pushing a scientific spacecraft to speeds of a significant portion of the speed of light [2]. After this study has been conducted, the various other elements of the propulsion method can be evaluated. Understanding the fundamental physics and being able to simulate the propulsion method’s behavior is important for future funding of the project as well as knowing the capability and mission profiles. This work has the potential to provide greater understanding of a fundamental physics interaction that could be the key to helping develop a space propulsion system that could be used to orchestrate a planetary flyby of Proxima Centauri B within a human lifetime.

References

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