Original Research Article

Potential of the Penning Ionization Gauge (PIG) Ion Source in attaining High Energy Rydberg States

ABSTRACT

Aims: The Morgan's Lab, at Wesleyan University – Connecticut, experimentally probed the dynamics of an atom /molecule using Semi-Classical approach. The experimental setup at Morgan's Lab is designed to generate a neutral atomic or molecular beam, which is then excited with a finely tuned laser to Rydberg states; the highest quantized energy states the electron can be in before ionization.

Study design: In this current study, the potential of the Penning Ionization Gauge (PIG) as an ion source was evaluated for the Hydrogen atom.

Place and Duration of Study: Physics Department, Wesleyan University, Middletown, Connecticut, USA, between June 2007 and August 2009.

Methodology: The experimental setup is designed to generate a neutral atomic or molecular beam, which is then excited with a finely tuned laser to Rydberg states; the highest quantized energy states the electron can be in before ionization. The setup consists of an ion beam system consisting of a fast- metastable machine, vacuum pumping systems, an oven, a laser system consisting of a master YAG laser and a slave tunable dye laser, a second harmonic generator for doubling the frequency of the laser beam, Stark plate assembly, an ion detection system and a computer based data acquisition system with LABVIEW software.

Results: The PIG found to populate the Hydrogen Rydberg states at 300 % times more than the conventional ion source (8 µ Amp Vs. 2 µ Amp). Such high populations of ions lead to a high population of Rydberg states which in turn aided the overall experiment.

Conclusion: A better understanding of the dynamics of an electron can aid experiments in condensed matter physics and molecular physics. Obtaining high population of Rydberg states can aid in increasing electron dynamic experiments by increasing the resolution of the scaled-energy absorption spectra. Penning Ionization Gauge (PIG) showed to have a better potential in producing high energy Rydberg states for the hydrogen gas.

Keywords: Penning Ionization Gauge (PIG), Rydberg states, Semi Classical Mechanics, electron dynamics, hydrogen.

1. INTRODUCTION

The dynamics of an electron in an atom is intriguing to understand and, as a result, more research are being conducted on electron dynamics, and such research is very vital in the fields of condensed matter physics and atomic and molecular physics. Due to the fact that the quantum theory for electron dynamics is complex and obscure, recent studies have attempted to investigate the electron dynamics using classical and semi-classical approaches.

In recent years scientists have found that research on Rydberg atoms will play a vital role in the analysis and testing of semi-classical and quantum theory. This is due to the fact that the in Rydberg atoms, the perturbations of the core are negligible as the Rydberg electron spends very little time near the core of the atom and mostly is present far away from the core. As a result there is no need to explicitly integrate the motion of the core electrons but rather can treat them as perturbations.

During the course of this study, the Morgan's Lab, at Wesleyan University – Connecticut in USA, aimed to produce the recurrence spectra (the Fourier transform of the absorption spectra) of the desired atom. To arrive at the recurrence spectrum, there is a need to arrive at electrons in high principal quantum numbers (n), or in other words have atoms/molecules with their valence electrons in high energy states. A Rydberg atom/molecule is one with a principal quantum number (n) greater than 15 and is considered to be highly excited. These highly excited Rydberg are then subjected to a Stark field for dynamic perturbation. As a final product, an absorption spectrum of Rydberg atoms / molecules is obtained. This absorption spectrum will then be analyzed via a Fourier transform to decipher the electron dynamics. This special type of spectroscopy is known to be well suited for systems that can be explained via classical and quantum theories. The details on the dynamics of such an electron will add proof for existing atomic theories and also find applications in condensed matter physics [1,2,3].

The Morgan lab is experimentally well equipped to highly populate electrons in metastable energy levels (i.e. highly excited levels), which can later can be excited to the desired high principal quantum numbers (n). The presence of powerful and stable ion beam sources, high voltages to steer and collimate the ion beam to pass through high vacuum chambers, a high energy tunable laser system and a precise ion detection system make Morgan lab one of the best places for conducting research on Rydbergs. With such facility, it was possible to understand the potential of different ion sources to produce stable ion beams for Rydberg state population. In addition, comparison between commercial and in-house built instruments will lead to better fabrication of in-house instruments and enable cost saving measures for research. Also, comparison of ion sources will help future scientists to choose suitable methods for populating Rydberg states, depending on their research needs.

The motivation of the current study was to investigate a cost effective method to populate highly excited states, which in turn will lead to a high population of Rydberg states. The main objective of this study is to document the potential of the Penning Ionization Gauge (PIG) as an ion source and how the PIG can help in obtaining a high population of Rydberg states. The paper will initially discuss the PIG source and the experimental setup at Morgan's Lab. A discussion on the enhancing the performance of the PIG source will follow leading to a comparison between the PIG and a conventional ion source.

2. EXPERIMENTAL DETAILS

The main experimental set up in the Morgan lab consists of an ion beam system consisting of a fast- metastable machine, vacuum pumping systems, an oven, a laser system consisting of a master YAG laser and a slave tunable dye laser, a second harmonic generator for doubling the frequency of the laser beam, Stark plate assembly, an ion detection system and a computer based data acquisition system with LABVIEW software.. More information on the experimental setup can be obtained from [1, 2, 3, 4, 5].

2.1. Fast – Meta Stable Machine:

The Fast - Meta Stable Machine is the major component of the experimental setup, where in an ion beam with high energy is generated, neutralized to a metastable state and then collimated to collide with a laser beam to attain a particular Rydberg energy state [figure 1]. This machine consists of an ion source, a small chamber with vacuum pumps, a mid- post to detect and monitor the intensity of the ion beam, connector valves consisting of horizontal and vertical steering plates to steer the ion beam, a big chamber with high – vacuum pumps attached to liquid nitrogen traps and an end cup to monitor the beam at the entrance point of the laser. In the past, an off-the shelf ion source - Colutron ion source was bought from

Colutron industries. In the current study another ion source, the PIG – Penning Ionization Gauge ion source came from Prof. Manshukh Shah Lab at Queens's University of Belfast, Northern Ireland. It is to be noted that most of the remaining apparatus were fabricated and made in Wesleyan University's machine shop, while the rest were bought from Colutron [6,7,8,9].

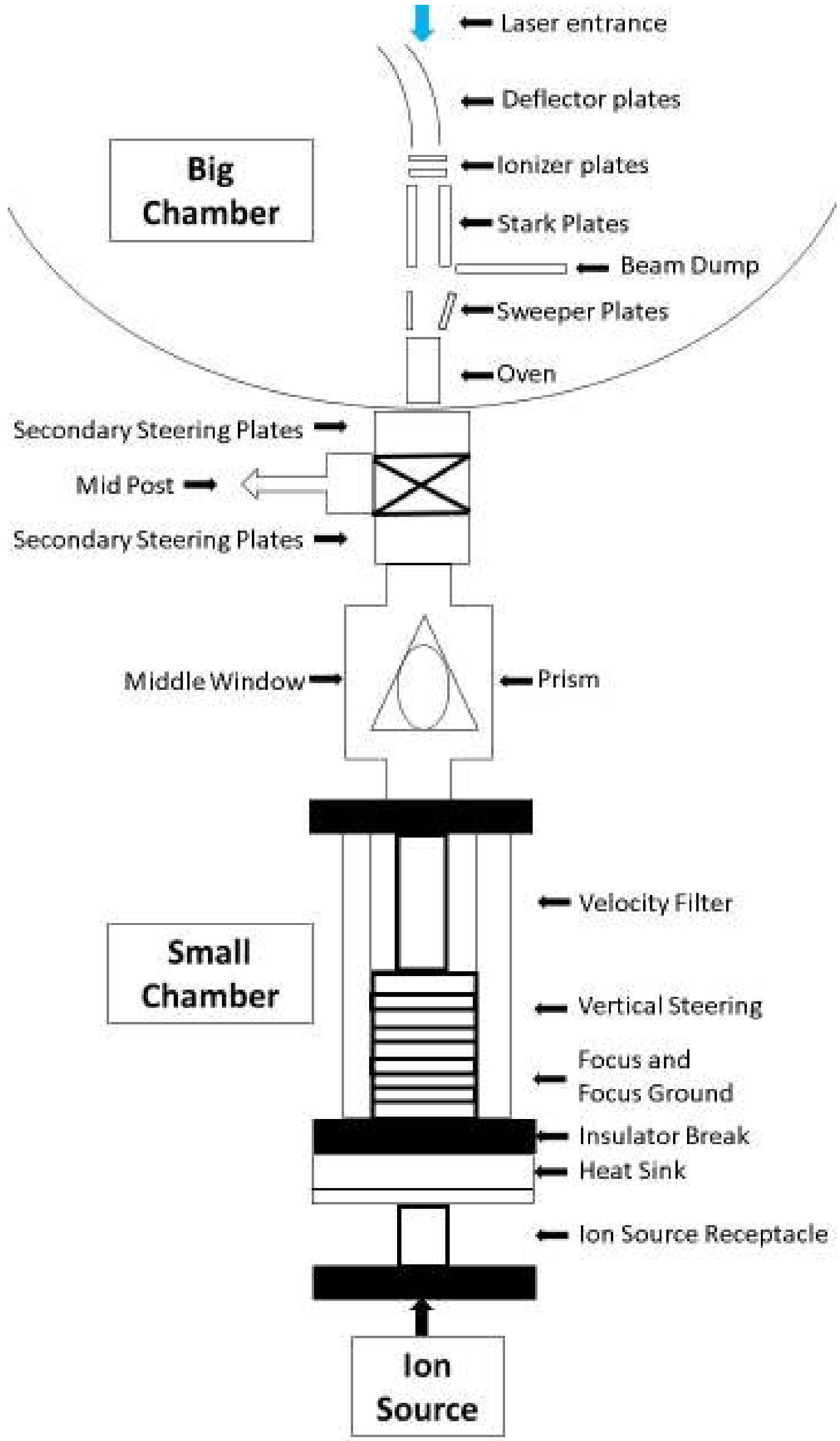

Figure 1: Fast Meta Stable Machine – schematic diagram

2.2. Ion Gun:

The purpose of the Ion Gun is to produce a stable ion beam (positive charged) of the atom / molecule. The ion gun/ ion source plays one of the most important role in the study, as this is the starting component in our experimental setup and forms the basis for aligning the entire experimental setup. The ion gun is mounted to the small chamber in a receptacle with a heat sinks [figure 1] so that the heat generated while producing the ion beam is not excessive and to prevent heat damage to other parts of the experiment. Colling water is flushed in continuously in and out of the heat sink to prevent heat build up and heat transfer to other parts of the chambers.

2.3. Gas inlet system:

The gas inlet system determines the gas input to the experiment. The gas inlet system consists of numerous connections that are made using special Swagelok barrel screws. These clamp on to the plastic tube to the ion source. This gas inlet system is managed by Vernier screw dials fitted micrometers and consists of a thin needle that slides into a hole on a base. Gas flow stops when the needle fits into the hole, and the gas flows as needle gradually goes out of the hole. Industrial pressure gauges (purchased from Kurt J Lesker company) were used to measure and monitor the pressure changes in the system [6, 7, 10, 11].

2.4. Penning Ionization Gauge (PIG) Source*:*

The Penning Ionization Gauge [figure 2], hereafter referred to as the PIG, is a high energy/stable ion source designed and fabricated at Dr. Mansukh Shah's laboratory in Belfast. The PIG source was known to produce a high intensity beam of ions, especially using hydrogen gas. It was known to be a very stable ion source and the maintenance was almost zero. The PIG, with some help from Wesleyan's machine shop, was able to fit perfectly with the entrance of the small chamber in Morgan's lab. The PIG initially had its own optic column, however, as the Morgan's lab already had a sophisticated system to focus ion beam, the PIG's ion optic column was decoupled so that the PIG can mount easily in exactly the same place as the Colutron source (a conventional ion source). The Colutron source has a hot tungsten filament to generate electrons, but the PIG uses plasma discharge to generate electrons. The plasma electrons generated are confined by an axial magnetic field and a repulsively biased cathode and anti-cathode pair. As a result, the PIG is not dependent on an external cooling system. Further information on the characterization of the PIG can be obtained from Chinnasamy [3]. In addition, because of the close tolerances in the machining of the PIG, the solidity of its components is a unique feature. It is to be noted that changing any component in the PIG was easy/quick and as a result, the experiment stoppage time was limited.

2.4.1. Beam production in the PIG Ion Source

The schematic of the PIG is shown in Figure 2. A beam is produced in the PIG when a discharge ionizes the gas. Hence, producing a powerful and steady discharge is key. At the PIG ion source, a floating high voltage is supplied to the PIG's cathode from a transformer. A threshold voltage of 3 KV was maintained, as a voltage above that would result in overloading and would lead to a transformer meltdown and burning of transformer coils. In addition, to produce a stable beam, a steady and stable discharge and accelerating voltage was applied. Stray voltages can easily flow from the cathode to other connections in the experimental setup, especially the gas tee (Figure 2). A high voltage/current on the gas tee can easily harm the user and hence care was taken to avoid this by replacing the connection between the gas tee and gas cylinder with non-conducting plastic tubes. Also direct contact with the power supply was avoided at all times by using mica or Mylar enclosures and knobs.

For beam production, a discharge voltage can be applied to the Mollies (molybdenum cathode and anode parts of the PIG) up to 500 hours, i.e. lifetime of 500 hours which is much higher than conventional industrial cathodes. Regular maintenance can increase the lifetime of these Mollies and can result in a steady and stable beam. In particular, the surface of the mollies should be smooth and clean. An uneven surface will cause uneven discharge and will lead to the emergence of an ion beam that flows in random directions leading to difficulties in beam collimation. In addition, for maintenance purposes, it is handy to have an extra set of Mollies to readily replace when needed. To provide insulation between the anode and cathode connections, insulating papers are used. In order to check any charge buildup or improper connections due to wear and tear of insulation papers, the conductivity should be checked periodically at different locations.

2.4.2. Beam confinement in the PIG

Beam confinement in the PIG is one of the most important aspects for the experiment, as the PIG produces a massive amount of ions, which without proper focusing can lead to a lot of stray charge build up. In the PIG, a powerful axial magnet is used for beam confinement. Since a massive magnetic field is needed for confinement of a massive ion beam, a permanent strong magnet is used. In addition, due to the massive weight of the PIG, there is a possibility of misalignment arising due to bending of the source over time. Hence, proper non conducting ceramic spacers are placed between the PIG and the experiment table. In order to be safe in handling high voltages, the PIG is also enclosed in a mica box to isolate the user and the high voltages that are applied to the source. In addition, the high voltage should not affect the ion beam flow path. Also, the extractor should be grounded by a hard grounding supply. This is very important, as with a safe and hard grounded supply, any high floating voltage is prevented from flowing along the entire length of the experiment.

Once the ion beam is focused into the small chamber, it starts to diverge a lot as it moves away from the collimating magnets. The reason for this is because the PIG's nature is to produce a massive beam that diverges, unlike the Colutron which produces a narrower ion beam. As a result, the ion beam produced by the PIG can be harder to control when compared to that in the Colutron. However, once the PIG's ion beam is effectively focused, the resulting ion beam is stable and can serve the experiment's objectives. An electrometer is used to measure the strength of the ion beam, by measuring its current.

In the next stage of the experiment, there is another set of beam focusing apparatus - the vertical steering plates are powered by a high voltage supply. Since, there are a number of locations in the experiment with high voltages, it is essential to check proper grounding and to isolate the measurement readers. At the steering plates, the beam has to be focused both vertically and horizontally so that most of the beam hits the detector plate. In addition to vertical and horizontal steering, it is essential to reduce the divergence of the beam for proper focusing. For this a good vacuum in the chambers is an essential component that enables the beam to propagate with less deflection/divergence. Past studies in the Morgan lab have estimated, after numerous trial and error, that a typical operating pressure for the experiment should be in the low 10^{-6} Torr. In the current study, it was found that by using liquid nitrogen traps and diffusion pumps can result in pressures in the 10^{-7} Torr range. Such pressures can eliminate straying of the ion beam from the PIG by a huge amount.

It is to be noted that the entire ion beam produced from the PIG cannot be completely neutralized, as the oven for producing electrons for neutralization is a small one. As a result, some of the remaining ion beam should be deflected from passing on to the further stages of the experiment. In order to deflect extra ion beam, a set of sweeper plates (Figure 2) are operated. Voltages that are applied to the sweeper plates effectively sweep off the un-neutralized ion beam. The un deflected neutralized metastable beam progresses further along the experiment and is monitored and read at the endcup, which has a bias voltage. A bias voltage of 300 V (positive as it needs to attract electrons) is applied to attract all the electrons ejected from the detector plate, which in turn prevents the ejected electrons from being re-attracted back to the detector plate. This prevents errors in the electrometer.

2.4.3. Monitoring strength of beam produced by the PIG

Since it is important to know the ion beam's behavior along the experiment, the strength of the beam is monitored at different stages in the experiment. A midpost is present in the experiment (Figure 2) to monitor the strength of the ion beam at the initial stages of the experiment. It is to be noted that the application of power to the electromagnets should be unidirectional as if the power is raised and lowered without sufficient time, any hysteresis in the magnet can lead to errors in the reading and in assessing the strength of the ion beam. On the other hand, the voltages on the shim plates are set according to the system's geometry. The power of the ion beam can also be measured here using detector plates.

Once the ion beam passes these monitors, it enters into the big chamber through an aperture with diameter in a couple of mm. The collimated beam is then exposed to the potassium vapor from the oven and is neutralized.

Details on the processes occurring beyond this point and the small chamber are beyond the scope of this current paper, however, interested readers are directed to JD Wright's work [1,2,3,4,5].

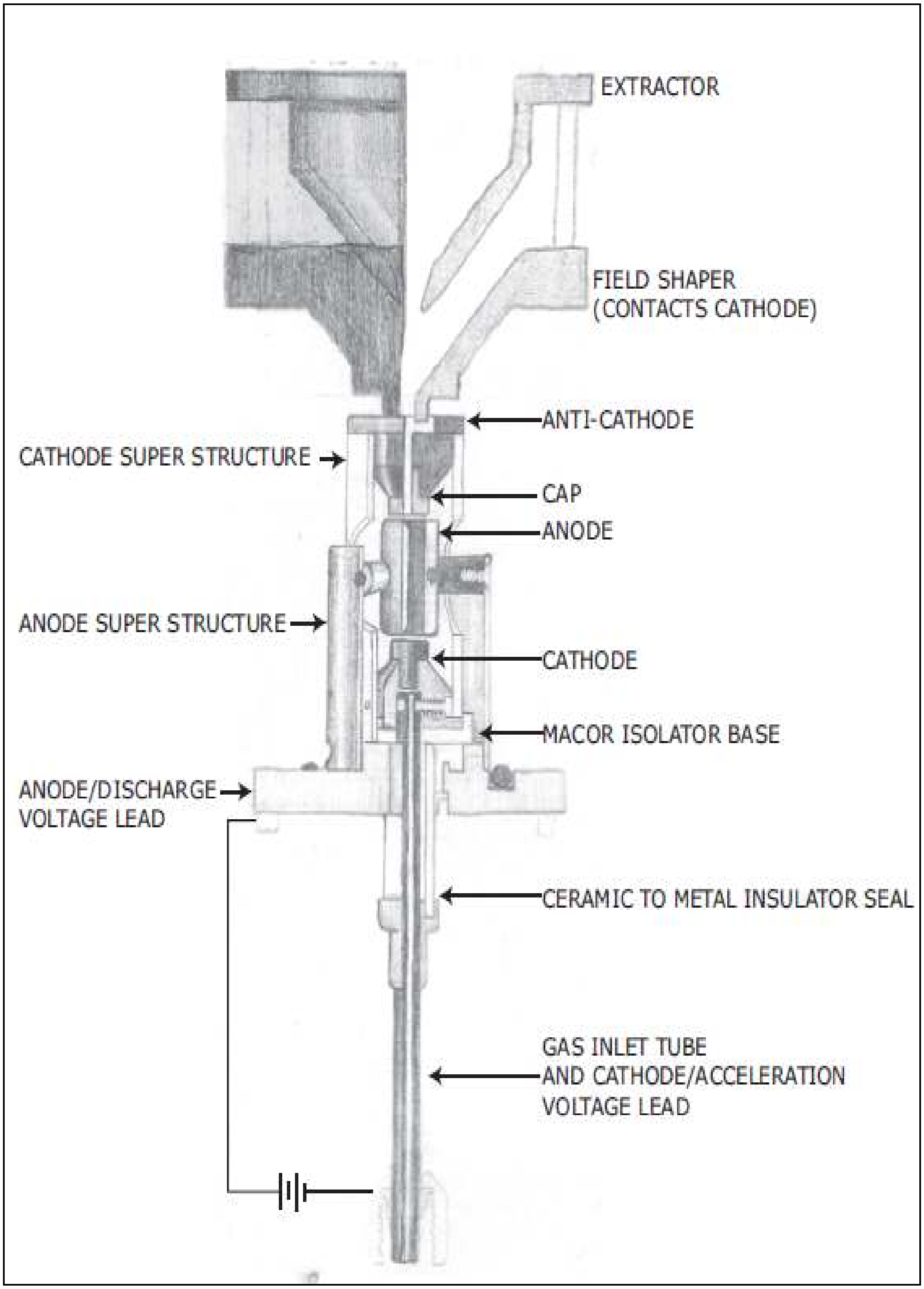

Figure 2: Schematic of the PIG – Penning Ionization Gauge, John David Wright [5].

The regular monitoring of the ion beam also aided in finding errors with the alignment of the system. However, since the PIG was a massive producer of ion beams, the alignment was not a big factor (when compared to the Colutron) as even a fraction of the PIG's ion beam was sufficient for the experiment's objectives. But, as discussed above, the remaining beam can lead to unpredictable charge build up as they can crash into the chamber. To avoid this, the strength of the ion beam has to be monitored at regular intervals, and loose ends hardly grounded. Also, as per David Wright [1, 2,3, 4, 5] a beam with a lot of ions may produce a lot of background noise as the ions may bounce off from the walls of the apparatus, and thus lead to a low signal to noise ratio.

It is to be noted that the PIG's discharge unit was powered by high voltage supplied from an isolation transformer. A floating power supply was avoided by setting the discharge voltage to float on top of the acceleration voltage as described in [10, 11, 12]. As a result, any high voltage hazard to the user was prevented.

3. RESULTS AND DISCUSSION

In order to compare the ion source potential between the PIG and a conventional/industrial ion source (Colutron) it was necessary to compare the stability and the strength of the ion beams produced by the PIG and Colutron at different stages in the experiment. Of the different stages, the most important stage was at the endcup (Figure 2). The endcup is the stage where the powerful laser beam collides with the neutralized ion beam. Therefore, the neutrals that can reach the endcup have high probability of being excited by the laser beam by collision to reach the Rydberg state. Hence the study compared the power of the ion beam at the end cup (Figure 3 and Table 1). However, the initial stage (midpost) and error checking stages (beam dumps) were also compared to show the efficacy of one ion source over the other (Figure 3).

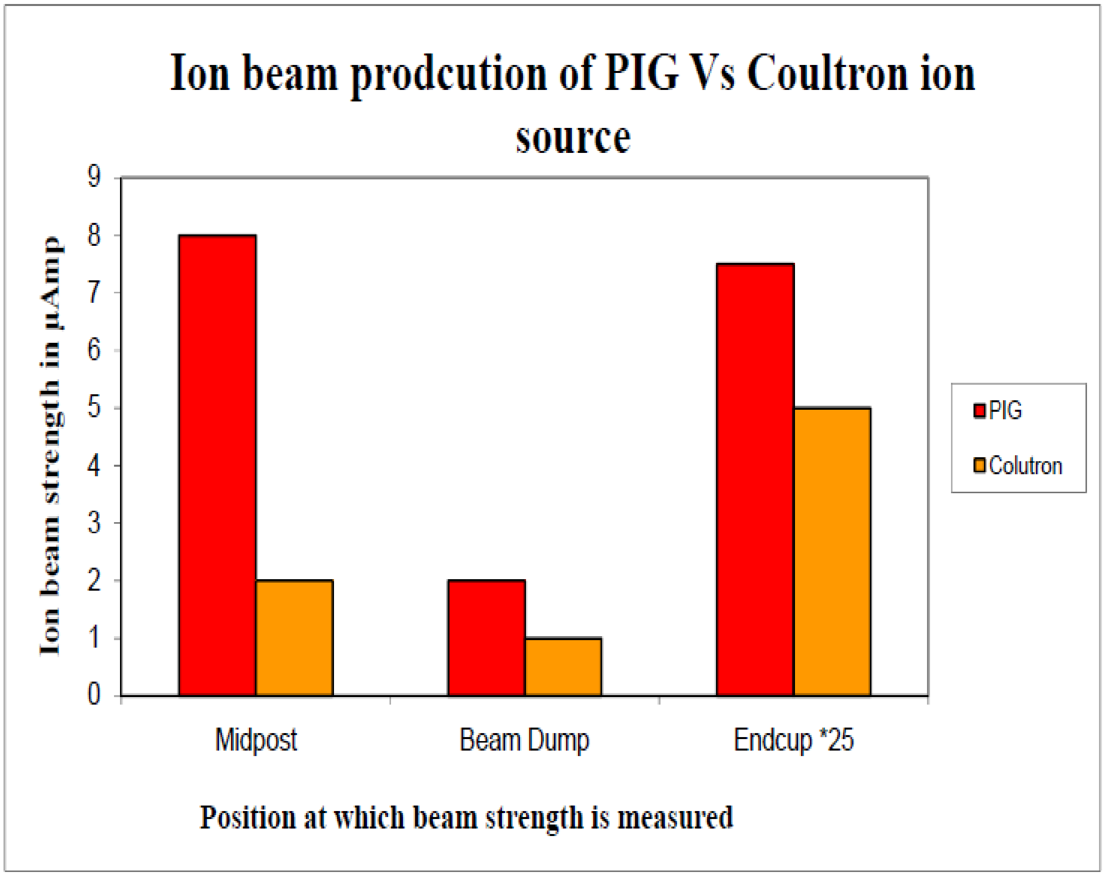

Figure 3: Comparison of ion beam strengths produced by two different sources in the Morgan lab - the PIG and the Colutron.

It is to be noted that in both cases the experimental gas used was hydrogen. In addition, the oven apertures and other experimental settings were consistent between the two ion sources to avoid any bias. In addition to estimating the strength of the ion beams produced by the PIG and Colutron, the two setups were run for three hours to compare the stability of the beam after three hours.

In both cases the PIG source was better for the study's objective. From Figure 3, it is clear that the PIG source is capable of producing a much stronger neutral beam than the Colutron, a commercially available off-the-shelf instrument, which is also costlier than the lab made PIG. It is to be noted that the endcup's values in Figure 3 for both the PIG and Colutron are multiplied by a factor of 25 to show the comparison of the two ion sources. The PIG's results indicate that at least 50% more beam is produced. In addition, the PIG's ion beam was still on the same strength even after three hours of continuous running, which adds to the PIG's stability. Also the maintenance of the PIG ion source is less when compared to that needed while using the Colutron. Furthermore, the PIG setup does not require regular opening of the experimental setup.

However, it was noted that the ratio of neutrals to ion beam was lower in case of the PIG than that of the Colutron. This is due to the fact that the ion beam is huge in PIG setup, and that a huge portion of most of the ion beam is not neutralized. The ratio of neutrals to ion beam is necessary factor to understand the signal to noise ratio, that can affect the overall objective of the study. Hence, a bigger beam is not always a better beam, but with proper measures, the unwanted beam can be effectively channelized without affecting the overall experiment. One such measure is the use of shielding elements such as plates that are grounded. Such shielding elements can effectively shield the main detection system, the Micro Channel Plate (MCP). In our study, the MCP is shielded with a plate hood and as a result the MCP only detects the neutralized signal and not the un neutralized beam. These noise producing un neutralized beam collides with materials inside the chamber, and hence a strong ground can be used to eliminate their influence.

Table 1: Table showing the measurement of the beam at various positions in the experiment.

Position in the experiment at which strength of beam measured	PIG ion source	Colutron ion source
Midpost (µ amps)	8	2
Beam Dump (µ amps)	2	1
Endcup *25 (namps)	7.5	5

These results show that the PIG is a much stronger ion beam source compared to the Colutron ion source. As a result, it is inferred that the PIG is a much better ion source and is suitable for producing high *n* Rydberg atoms / molecules.

4. CONCLUSION

A better understanding of the dynamics of an electron can aid experiments in condensed matter physics and molecular physics. Obtaining high population of Rydberg states can aid in increasing electron dynamic experiments by increasing the resolution of the scaled-energy absorption spectra. Even though many conventional and in house techniques are available for production of high energy ion beams, there has not been a comparison between them. This study compared the potential of two ion sources in producing Rydberg atoms that can aid electron dynamics research. The in-house made, cost effective Penning Ionization Gauge (PIG) showed to have a better potential in producing high energy Rydberg states for the hydrogen gas. Results indicated at least 50% increase in ion beam strength when using the PIG. In addition, the costs associated with the procurement and maintenance of the PIG source was negligible when compared to a conventional source like the Colutron. Hence, in the future, reserachers with limited resources can make use of the Penning Ionization Gauge (PIG) technique to achieve high energy ion beams with a fraction of the cost. The current paper, for the first time, provides details of working of the PIG source, and could be of much interest for the future physicists.

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