High Voltage Deuterium Ion Accelerator

by

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Abstract

     The objective of this project was to construct a Penning ion generator (P.I.G.), described in Reference 1, which produced a continuous beam of deuterium ions that were accelerated through a high voltage electric potential into a target. The target is loaded with deuterium atoms absorbed into a thin sheet of titanium foil. The desired goal of the overall project is to produce as many neutrons as possible in a preferential direction within the availability of laboratory equipment. The successful and efficient operation of the P.I.G. is critical to the overall production of neutrons, since neutron production is a direct function of the number of ions produced by the P.I.G. Penning ionizer technology was first developed in 1927 by Frans Michel Penning for use in use applications such as gas-discharge neon lamps. The Penning effect entails the use of an anode-cathode configured body to create an electrostatic potential to ionize gas localized in the center of the body. The application of the P.I.G. technology in this project was to create deuterium ions which were then accelerated towards a target to undergo D-D fusion.

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Background

High energy neutrons are produced when deuterium nuclei undergo nuclear fusion with other deuterium or tritium nuclei. The neutron energy of the D-D reaction is 2.45 MeV, whereas the neutron energy of the D-T reaction is 14.1 MeV. This can be accomplished on a laboratory scale by ionizing a gas of deuterium atoms and accelerating the deuterium nuclei into a target containing a high density of deuterium or tritium atoms. Deuterium gas is a non-radioactive isotope of hydrogen. It is easily and economically obtained. It is no more dangerous than normal hydrogen gas, which, of course, must be handled with precautions. Tritium, on the other hand, is a highly radioactive isotope of hydrogen. It is extremely expensive, highly radioactive, and requires a difficult to obtain license. It does have a reaction cross section that is approximately 100 times higher than that of deuterium and will produce proportionately more neutrons at a higher energy. Due to practical experimental and logistical constraints, only deuterium was used in this experiment, even though it produces a substantially lower neutron output.

The key to production of high neutron output for an electrostatic neutron generator is the creation of a high current of deuterium ions. This requires a high output ion source. This ion source was fabricated as a Penning ion source with cold electrodes to form a high voltage, low pressure plasma discharge. This ion source functions by allowing electrons to oscillate between two cathode electrodes contained inside an anode in the shape of a cup ring. An axial magnetic field created by a small samarium cobalt magnet increases the path length of the electrons after ionization. This allows the production of the plasma to be more efficient. The orientation of this magnetic field is critical to the ultimate objective of the project. The primary goal of this experiment is not only to produce a significant quantity of neutrons, but to produce them in a preferred direction. Currently, all neutron generators produce neutrons isotropically, that is, equally in all directions. This presents a major limitation to the use of neutron generators because, in most situations, only the neutron flux in a highly specific and limited direction is needed. For example, when performing fast neutron cancer therapy on glioblastomas (brain tumors), only the tumor must be irradiated. Allowing the neutrons to strike other brain tissue would achieve the same result as on the tumor: necrosis (cell death).

This limitation creates two major problems: 1) neutrons traveling in directions other than toward the desired target must be shielded. Shielding 2.45 MeV neutrons produced by the D-D nuclear reaction require approximately 2 feet of borated polyethylene to reduce the radiation flux level to below 2 mREM per hour, the current standard for radiation exposure to the general public. The 14.1 MeV neutrons produced by the D-T reaction require even more polyethylene shielding, typically as much as 3 feet. These thicknesses of shielding cause serious clinical logistical challenges. 2) Current neutron generators typically produce neutron outputs of 1 X 10^8 to 1 X 10^{10} neutrons per second into a solid angle of 4 π steradians (complete sphere). Shielding simply removes the great majority of the neutrons from the total flux. It does not focus or collimate any of the neutrons into the desired direction. Thus, shielding drastically reduces the dose able to be delivered to the tumor in the patient.

The overall goal of this project is to produce a neutron beam that is highly anisotropic, that is, the neutrons are strongly emitted in a narrow preferred direction. If successful, this neutron generator would revolutionize fast neutron cancer therapy and boron neutron capture therapy.

The key technique used to create a highly anisotropic beam of neutrons through the process of nuclear fusion is the polarization of the nuclei at the moment of fusion. In current neutron generators, the orientation of the deuterium and tritium nuclei is completely random at the moment of fusion. Consequently, neutron production is a completely stochastic process and the neutrons are emitted equally in all directions. However, the laws of physics of conservation of momentum apply to the fusion process. Each nuclei has a specific linear, angular, and most importantly, spin angular momentum. Each of these momentums must be conserved after the process of fusion, where the two nuclei collide, combine to form a compound nucleus, and then immediately split apart into a neutron and an alpha particle. Thus, to conserve angular and linear momentum before and after the collision, the direction the neutron and alpha particle are limited to very discrete deterministic angles from the original ion beam direction. This causes the neutrons to be emitted in a highly anisotropic fashion.

This paper describes the part of the anisotropic neutron generator where the deuterium atoms are efficiently ionized to allow acceleration at 120 kilovolts into the target. The atoms entering the P.I.G. ion source have been previously polarized by a laser pumped rubidium vapor

polarizer described in Reference 2. When the atoms are polarized in the rubidium vapor polarizer, they are polarized by a laser in a large magnetic field generated by a Helmholtz coil to prevent radiation trapping. All of the polarized deuterium atoms align with the magnetic field of the Helmholtz coil. The orientation of the atoms at this point determines the orientation of the nuclei at the moment of fusion. Every effort is made experimentally to maintain this orientation. The orientation of the nuclei are not rapidly disturbed by electric fields and collisions. However, magnetic fields with orientations other than the Helmholtz coil rapidly couple to the atoms and reduce the degree of polarization.

The high voltage acceleration was achieved with a Glassman High Voltage DC Power supply. The output of this high voltage power supply can be easily controlled between 0 and 125 kilovolts. The maximum current output of the supply is 2 milliamps. A target with a high density of deuterium atoms is formed by a thin foil of titanium covering a solid copper disc cathode. The target is electrically polarized with negative high voltage to attract the positively charged deuterium nuclei. The properties of the titanium foil allow the foil to hold two atoms of deuterium for every single atom of titanium, creating a deuterium dense target cathode.

Great care has been taken to avoid the existence of magnetic fields or ferrous metals between the polarizer and the main accelerator. Every component is made from aluminum, brass, copper, or glass. However, to efficiently ionize the deuterium atoms in the P.I.G., a small samarium cobalt magnetic is required. Fortunately, the orientation of the magnetic field of the samarium cobalt magnet and the large Helmholtz coil can be achieved experimentally by proper alignment of instruments. The remaining issue is the passage of the polarized atoms into the ion source. The polarized deuterium gas must pass through the aluminum face plate that forms the cover for one of the four arms of the glass accelerator chamber. Even though the polarized atoms have the same orientation as the magnetic field of the samarium cobalt magnet, the possibility exists that a torque on the polarized nuclei could occur from the cross product of the velocity of the atoms traveling into the ion source and the angle the that velocity makes with the short range field of the magnet. This effect, if any, is believed to be small, and hopefully, insignificant, due to the fact that the velocity of the atoms entering the ion source is very low.

Once the mono-atomic deuterium atoms are ionized, the deuterium ions are accelerated towards a target where the initial beam of ions will impregnate the titanium target and the

following ions will slam into the initial deuterium ions and undergo D-D fusion. Once D-D fusion is achieved, a 2.45Mev neutron will be produced as desired. However, D-D fusion can produce one of two events roughly fifty percent of the time as portrayed in Figure 1 below.
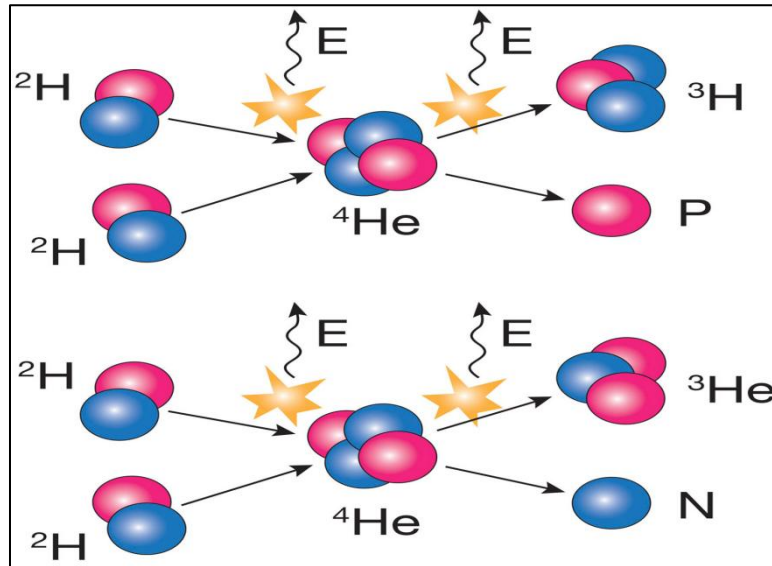

Figure 1. D-D (Deuterium-Deuterium) Nuclear Fusion Reactions

This figure describes how one of two possible events can occur when two nuclei of deuterium undergo fusion. The first is the production of Tritium (Hydrogen-3) and a proton (Hydrogen-1). The second, and the only one of interest in this experiment, is the production of Helium-3 and a neutron. These reactions occur with equal probability. Unfortunately, for every fusion reaction, the completing reaction cuts the overall efficiency for neutron production in half.

Construction

All parts were provided by General Neutronics, Inc. All specialty components were constructed at the General Neutronics machining facilities. The P.I.G. ion source consists of four main components: cathode body, cathode faceplate, anode cup, and samarium cobalt (Sm_2Co_{17}) permanent magnet.

- Cathode Body: The cathode body was constructed from a 2.0" 1018 Solid Steel Cylinder. Once the outside of the cylinder was cut to the required dimensions, the inside was lathed to accommodate the Sm_2Co_{17} magnet and anode. The cathode body is shown in Figure 2 during the machining process with the magnet placed appropriately.
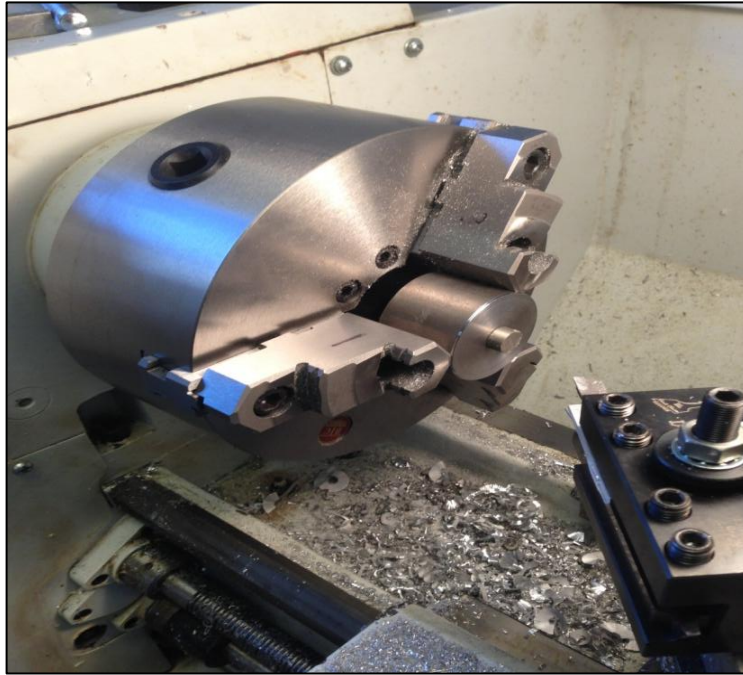
Figure 2. Cathode body with Samarium Cobalt Magnet

The interior of the cathode body was machined to allow the insertion of a stainless steel anode cup. The gap between the cathode body and the anode cup was carefully controlled to a distance of from between 1 and 2 millimeters. With an applied voltage that ranged from a few hundred volts up to 6 kilovolts, the kilovolt electric potential difference formed an electric field strength across the gap in the several hundred thousand volts per meter range, which was ample to strip the electron from the deuterium atoms, thus causing ionization.

A 0.125 inch hole was drilled into the back of the cathode body and a small stainless steel tube was inserted to allow the polarized deuterium gas to pass from the rubidium vapor polarizer into the P.I.G. ion source. The stainless steel tube was insulated from the cathode body with an aluminum oxide (alumina) ceramic tube and was sealed to the cathode body with the industrial adhesive Ceramabond. The stainless steel tube was insulated from the cathode body to prevent an electrical ground loop between the accelerator chamber and the polarizer apparatus. An electrical ground issue forms between the ion source and the main part of the accelerator. The ion source cathode body is negatively grounded with respect to the high voltage positive anode cup inside the cathode body. The cathode body is also positively grounded with respect to the 120 kilovolt high voltage power supply of the accelerator. The accelerator target has to be at

negative high voltage to accelerate the positive deuterium ions into it. Thus, great care must be taken to prevent unwanted current flowing in a ground loop, since the cathode body is both negative ground for the ion source and positive ground for the main high voltage accelerator.

- Cathode Faceplate: The cathode face plate was cut from the same 2.0" 1018 Solid Steel cylinder and machined to fit on a machined ledge inside the cathode body lip, sealing the anode cup inside the cathode. A 0.25 inch diameter orifice was drilled into the center of the cathode faceplate to allow the deuterium ions to be accelerated out of the source toward the target.

- Anode Cup: The anode had to match the geometry of the interior of the cathode body to maintain a uniform electric field strength where the atoms underwent ionization. The shape that best suited this geometry was a cup shape where the bottom (or back side) and the outside round sides of the cup would maintain the correct and constant distance from the cathode body wall. Also, since virtually all the power into the ion source would be sinked into the anode, a material which could withstand very high temperature and maintain its shape had to be chosen. Through several experiments it was determined that .005" stainless steel was best for fire-formation and electrostatic conductivity. The beginning of the fire forming process can be seen in Figure 3. After the stainless steel foil was heated to a glowing red temperature, it was placed on a 0.25 inch thick piece of mild steel with a hole the outside dimension of the anode cup. Another piece of mild steel was then placed over the foil and the foil hammered into the hole in the bottom piece of steel. After many attempts at this process, a cup was finally formed from the stainless steel foil and the sides of the cup spot welded to force them to retain their shape.

Stainless steel 24 gauge wires were spot welded to the back of the anode cup. Very small holes were then drilled into the back of the cathode body to allow the stainless steel wires to transfer the high voltage to the anode cup. These wires were insulated from the cathode body by single bore aluminum oxide (alumina) tubes. With great difficulty, the wires were aligned through the alumina tubes and the spot welds on the back of the anode cup. The wire completely supported the anode cup inside the cathode body. Extreme effort was required to properly mount the anode cup inside the cathode body.   Many attempts were required to spot weld the wires to the back of the anode cup at the proper spacing of the holes drilled into the back of the cathode body. Once the holes were drilled into the back of the cathode body, there were no means to

adjust or change the spacing between the holes. Thus, all adjustments had to be implemented by welding new wires onto the back of the anode cup.   After many attempts, a satisfactory configuration was finally achieved and utilized.

- Samarium Cobalt (Sm_2Co_{17}) Permanent Magnet: Much work was spent in developing the appropriate environment for the Samarium Cobalt magnet. As purchased, the Samarium Cobalt magnet was bare, with no protective case.   In order for the magnet to withstand ion gas temperatures exceeding 1000 °C, a stainless steel shell was made to enclose the magnet. The stainless steel shell was constructed from .005" Stainless Steel as in the anode cup and annealed to prevent magnetic interference with the Samarium Cobalt magnet.   The magnet shell was fabricated in much the same fashion as the anode cup, with the addition of a lip on the underside of the magnet to hold the stainless steel cup in place. This was accomplished only after many frustrating attempts.

Figure 3. Stainless Steel foil Preparation

Results

Deuterium gas was bled into the back of the ion source by an adjustable needle flow valve through the stainless steel tube that was installed into the back of the cathode body. The flow pressure was varied from less than 1 mTorr to several 10's of mTorr. It was experimentally determined that the Alcatel Drytel 1025 vacuum pump with turbo molecular pump could maintain a vacuum in the main accelerator chamber of 1 mTorr or less, even though the flow pressure into the ion source was increased up to over 50 mTorr. Operation at 1 mTorr in the main chamber allows the accelerator to operate with reasonable efficiency.

An ampere meter was placed in the target electrical loop back to ground to measure the positive ion current striking the target. The Glassman High Voltage power supply was varied from a minimum of 1 kilovolt to its maximum output of 6 kilovolts in increments of 1 kilovolt. The power supply has a built in meter to allow direct and immediate measurement of the current leaving the power supply. It was experimentally determined that for deuterium gas flow rates ranging between 1 and 50 mTorr into the ion source cathode body, the following ion currents were measured:

Ion Source Voltage (kV)	Discharge Current (mA)	Ion Current (mA)
0	0	0
1	0.4	0.003
2	0.9	0.01
3	1.8	0.08
4	3.9	0.2
5	8.2	0.6
6	12	0.85

Thus, at maximum high voltage power supply output of 6 kilovolts and a deuterium gas flow rate of about 50 mTorr into the source, the ion current striking the target achieved a maximum of 0.85 mA. The target for this project was to produce 1 mA of ion current. After analyzing the target geometry, it was determined that the output of the ion source may have been greater than that measured because some of the ions did not strike the target and were not

measured.   A further improvement to this experiment would be the addition of magnetic or electrostatic focusing of the beam onto the target.

Conclusion

In conclusion, the project was laborious and required much on-site training, but was however successful. Future developments of this experiment might include varying the distance between the anode and cathode to determine what distance is best for efficient ionization. Additionally, further anode cup tests might be conducted in an attempt to form the cup more uniformly. At its current state, the Penning ion generator constructed in this project is functional and provides a deuterium ion current of nearly one milliamp. A picture of the finished ion source is shown in Figure 4 mounted on the aluminum faceplate.
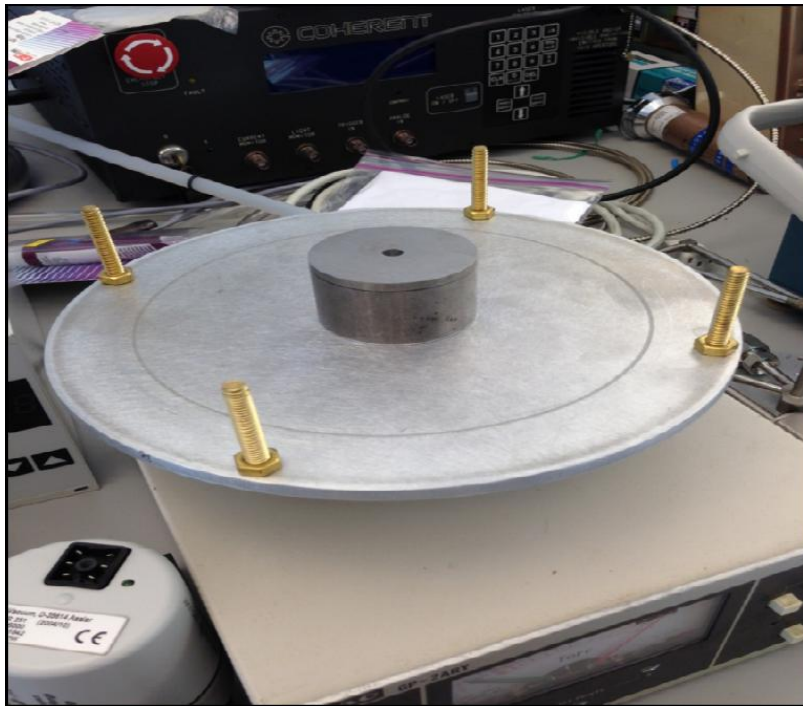

Figure 4. Completed P.I.G. Mounted on Aluminum Faceplate

References

1. Rovey, J.L., Ruzic, B.P., and Houlahan, T.J., "Simple Penning Ion Source for Laboratory Research and Development Applications", *Review of Scientific Instruments* **78**, 106101 (2007).

2. Dent, Christina, "Laser Pumped Rubidium Vapor Polarizer", Honors 499 Senior Thesis, University of Alabama, Huntsville (2014).