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Joshua L. Rovey

*Missouri University of Science and Technology, roveyj@mst.edu*

Brandon P. Ruzic

Thomas J. Houlahan

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## Simple Penning ion source for laboratory research and development applications

Joshua L. Rovey,<sup>a)</sup> Brandon P. Ruzic, and Thomas J. Houlahan  
*Starfire Industries LLC, Champaign, Illinois 61820, USA*

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A simple Penning ion generator (PIG) that can be easily fabricated with simple machining skills and standard laboratory accessories is described. The PIG source uses an iron cathode body, samarium cobalt permanent magnet, stainless steel anode, and iron cathode faceplate to generate a plasma discharge that yields a continuous 1 mA beam of positively charged hydrogen ions at 1 mTorr of pressure. This operating condition requires 5.4 kV and 32.4 W of power. Operation with helium is similar to hydrogen. The ion source is being designed and investigated for use in a sealed-tube neutron generator; however, this ion source is thoroughly described so that it can be easily implemented by other researchers for other laboratory research and development applications.

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A Penning ion generator (PIG) works with cold or heated electrodes to establish a high-voltage, low-pressure plasma discharge. In a typical configuration, electrons oscillate between two cathode electrodes inside an anode ring. An axial magnetic field increases the path length of ionizing electrons, making plasma production more efficient. This type of device was originally proposed by Penning as a low-pressure manometer (i.e., cold cathode or Penning gauge)<sup>1</sup> and was later adapted to also function as an ion source. PIG ion sources have been used for a variety of applications, such as sputtering and evaporation of surfaces, electromagnetic separation of isotopes, and fusion applications.<sup>2-4</sup> Another possible application is in a sealed-tube neutron generator.<sup>5</sup> In fact, Penning applied his low-pressure manometer as an ion source in a sealed-tube neutron generator.<sup>6</sup>

Although PIG sources have been used for many applications and many different sources have been researched, many of these previous designs are complex, expensive, or developed for a specific application. Further, many references do not thoroughly describe the source dimensions, fabrication, and capabilities, making it difficult to construct and implement in a different application. This paper describes a simple, inexpensive PIG ion source that can be fabricated with basic machining skills and standard laboratory accessories. It is being developed for a sealed-tube neutron generator; however, the goal is to thoroughly describe the fabrication and operation of the device so that it can be easily implemented by other researchers for other laboratory research and development projects. The goal for this source was a continuous output of 1 mA positively charged hydrogen ion beam at a pressure of 1 mTorr. Data for both hydrogen and helium are described in the following.

The PIG source consists of four main components: (1) cathode body, (2) anode, (3) samarium cobalt ( $\text{Sm}_2\text{Co}_{17}$ ) permanent magnet, and (4) cathode faceplate. The cathode body is a 5.1-cm-diameter iron rod that has been machined to the dimensions and geometry shown in Fig. 1. A samarium co-

balt permanent magnet with a surface flux density of approximately 3 kG is encased in a 0.13-mm-thick nonmagnetic stainless steel sleeve and centered inside the cathode body. The magnet is held in place by its own magnetic force. The anode is fabricated by forming 0.13-mm-thick nonmagnetic stainless steel sheet metal into the shape of a cup with a hole in the bottom. This shape is obtained by cutting a strip of sheet metal and then bending and folding it into the require form. The anode is then spot welded at multiple locations to hold its shape. Finally, the cathode faceplate is fabricated using the same iron rod as the cathode body. A 3.2-mm-thick, 5.1-cm-diameter disk is cut from the iron rod and machined with a 6.4-mm-diameter hole on centerline. Schematics and the dimensions of all of these parts are shown in Fig. 1.

Three holes are machined in the cathode body; two are used to support the anode and the third is used as a gas inlet. Alumina tubes are inserted into the two holes used for anode support, and a stainless steel tube is inserted into the gas inlet hole. Ceramic epoxy (Ceramabond™) is used to mate the alumina and stainless tubes to the back of the cathode body. Stainless steel wire with 0.5 mm diameter was spot welded to the anode, and the wires were threaded through the alumina tubes in the cathode body. These wires provide support for the anode and provide an anode electrical connection. Essentially the anode floats inside the cathode body, being supported only by the two stainless steel wires that protrude through the alumina tubes and out the back of the cathode body. Finally, the cathode faceplate is placed over the cathode body. The magnetic force created by the permanent magnet may hold the faceplate in place; however, if necessary, copper tape can be used to attach the faceplate to the cathode body. A schematic of the assembly of the ion source is shown in Fig. 2.

The PIG ion source is inserted into a 45.7-cm-long, 5.1-cm-inner-diameter glass tube that is connected to a vacuum chamber cross. A Welch Duoseal rough pump and Pfeiffer turbo pump evacuate the tube to a base pressure of  $1 \times 10^{-7}$  Torr. Flow rate of either hydrogen or helium into

<sup>a)</sup>Electronic mail: [jrovey@starfireindustries.com](mailto:jrovey@starfireindustries.com)

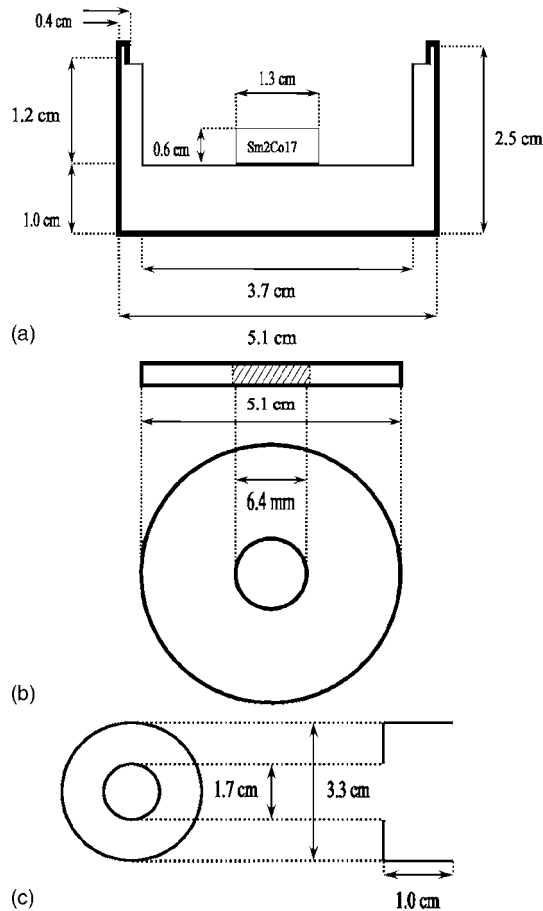


FIG. 1. Schematic with dimensions of the PIG ion source: (a) cathode body with permanent magnet, (b) cathode faceplate, and (c) anode.

the ion source is controlled using a locally controlled Alicat Scientific 1000 SCCM (SCCM denotes cubic centimeter per minute at STP) mass flow controller. A Pfeiffer PKR-251 pressure gauge monitors the pressure in the vacuum system. The ion source anode is powered by a 6 kV 200 mA Hipotronics dc power supply and a 100 k $\Omega$ , 100 W resistor is connected in-line with the power supply to current limit the discharge. The ion source cathode is grounded. A grounded 2.5-cm-diameter stainless steel shimstock target electrode was placed 1.3 cm downstream of the ion source to measure extracted ion current. All data were recorded with two Na-

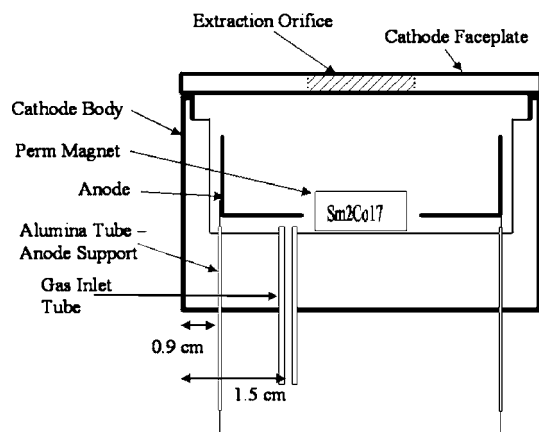


FIG. 2. Assembly schematic of the investigated PIG ion source.

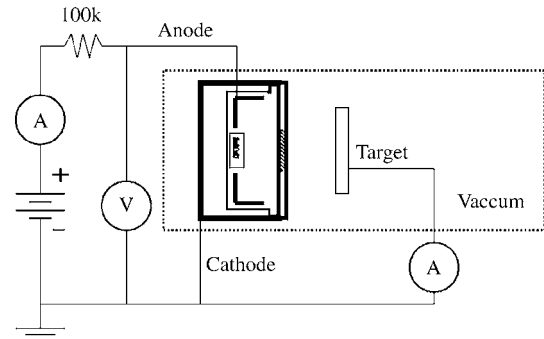


FIG. 3. Schematic of the electrical setup of the PIG source.

tional Instruments USB-6009 data acquisition pads. A schematic of the setup is shown in Fig. 3.

The PIG source was setup inside the vacuum chamber and gas injected directly into the source. As gas is inputted into the ion source, the vacuum system pressure increases. The gases, flow rates, and vacuum chamber pressures for this investigation are given in Table I. A first-order calculation shows that, due to the small size of the vacuum chamber setup, the pressure internal to the ion source is only approximately a factor of 2 larger than the chamber pressure. Therefore, with this setup, gas input directly into the ion source is not necessary, and source operation has also been achieved by simply backfilling the chamber. However, because this ion source may be operated in larger vacuum systems that can maintain a lower background pressure, all results presented here are for gas injection directly into the source.

For each flow rate, the anode power supply voltage is adjusted from 500 to 6000 V in 500 V increments. At each point, the ion source voltage, discharge current, and target current were recorded. Because the 100 k $\Omega$  current-limiting resistor develops a voltage drop during source operation, the ion source voltage (anode-to-cathode voltage) is reported instead of the power supply voltage. Reporting this value is more beneficial to the user because other applications of this source may choose to use a different current-limiting resistor value.

Data for hydrogen and helium are shown in Figs. 4 and 5, respectively. In general, the plasma discharge ignites easily at 1 kV or less for all cases and produces a continuous

TABLE I. Vacuum system pressure for the different gases and flow rates investigated.

Gas	Flow rate (SCCM)	Flow rate ( $\mu\text{g/s}$ )	Pressure ( $\times 10^{-5}$ Torr)	Pressure ( $\times 10^{-3}$ Pa)
H <sub>2</sub>	1	0.7	2	2.7
H <sub>2</sub>	2	1.5	5	6.7
H <sub>2</sub>	3	2.2	16	21.3
H <sub>2</sub>	5	3.7	35	46.7
H <sub>2</sub>	7	5.2	64	85.3
H <sub>2</sub>	8	5.9	75	100.0
H <sub>2</sub>	9	6.7	100	133.3
H <sub>2</sub>	15	11.2	250	333.2
He	5	14.9	34	45.3
He	9	26.8	50	66.6
He	20	59.5	100	133.3
He	30	89.2	180	239.9
He	39	116.0	230	306.6

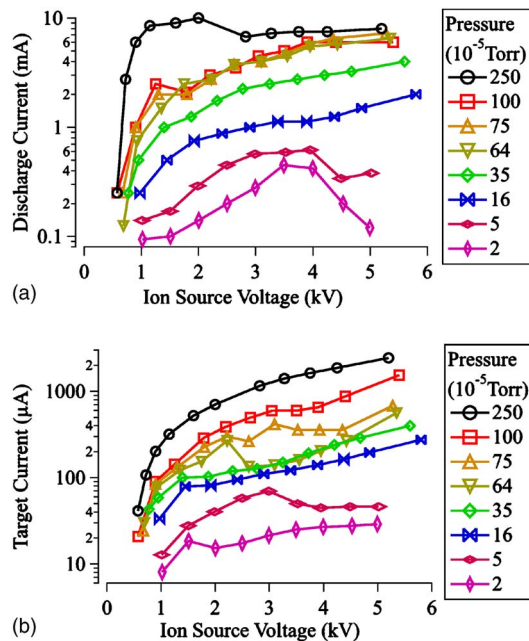


FIG. 4. (Color online) (a) Discharge characteristics and (b) target current for hydrogen operation.

positively charged ion beam. As pressure (flow rate) increases, the discharge current and target current increase. As the discharge voltage increases, the discharge current and target current increase. In general, these results are expected. As pressure increases, more gas becomes available for plasma production and the discharge current increases. As discharge voltage increases, electrons present in the discharge gain more energy, have more ionization collisions, and produce more plasma. The target current is related to the discharge current. An increase in discharge current signifies more plasma present in the ion source, which means more plasma is available for extraction to the target.

Figure 4 shows the results for the hydrogen discharge. Visual observation shows bright pink plasma inside the ion source. As discharge voltage or pressure increases, the plasma becomes visually brighter. For the 1 mTorr case, at 580 V, the discharge current and target current are 0.3 mA and 20.8  $\mu\text{A}$ , respectively. As the ion source voltage increases to 5.4 kV, the discharge current and target current increase to 6.0 and 1.5 mA, respectively. Thus, the ion source must be operated at 5.4 kV to meet the design goals of this investigation. At this operating point, the source has a current utilization efficiency (ratio of target to discharge current) of 25% and requires 32.4 W of power. Including the power dissipated by the current-limiting resistor, the total power supplied by the power supply is 36.0 W.

Figure 5 shows the results for the helium discharge. Visual observation of the helium discharge reveals green plasma that becomes brighter with increasing pressure and discharge voltage. For the 1 mTorr case on helium, the discharge current is 1.5 mA at 820 V and increases to 7.0 mA at 5.4 kV, while the target current increases from 66.8  $\mu\text{A}$  to 1.5 mA. This represents a current utilization efficiency of 21% and requires 37.8 W of power. Including the current-limiting resistor, the total power supplied by the power supply is 42.7 W.

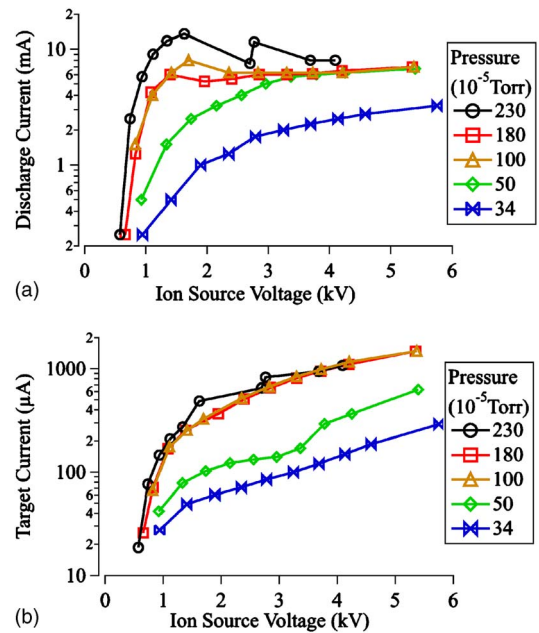


FIG. 5. (Color online) (a) Discharge characteristics and (b) target current for helium operation.

Although the developed PIG source can be used for a variety of applications, our primary application is a sealed-tube neutron generator that requires relatively large ion beam energies. Therefore, the source has been recently implemented in a setup using beam focusing and accelerating optics. In this configuration, the PIG source was operated as described above and two high-voltage electrodes were placed downstream of the source to accelerate the ion beam. The electrode closest to the source was the suppressor and was located 2.5 cm from the cathode faceplate. A target electrode was placed 7.6 cm from the suppressor. During high-voltage operation, the suppressor and target were biased negative with respect to the ion source cathode (i.e., ground). Operation of the source in this setup has been very successful. Specifically, at a pressure of 0.4 mTorr and 10.5 W PIG source power, a continuous 1 mA positive hydrogen ion beam has been focused onto the target and accelerator voltages up to  $-30$  kV have been investigated. Future experiments are planned to increase the acceleration voltage to  $-100$  kV.

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