Improvements on the stability and operation of a magnetron H^- ion source

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The magnetron H^- ion sources developed in the 1970s currently in operation at Fermilab provide beam to the rest of the accelerator complex. A series of modifications to these sources have been tested in a dedicated off-line test stand with the aim of improving different operational issues. The solenoid type gas valve was tested as an alternative to the piezoelectric gas valve in order to avoid its temperature dependence. A new cesium oven was designed and tested in order to avoid glass pieces that were present with the previous oven, improve thermal insulation and fine-tune its temperature. A current-regulated arc modulator was developed to run the ion source at a constant arc current, providing very stable beam outputs during operations. In order to reduce beam noise, the addition of small amounts of N_2 gas was explored, as well as testing different cathode shapes with increasing plasma volume. This paper summarizes the studies and modifications done in the source over the past three years with the aim of improving its stability, reliability and overall performance.

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I. INTRODUCTION

Schmidt developed a version of the magnetron ion source at Fermi National Accelerator Laboratory (FNAL) in the late 1970s. Alessi at Brookhaven National Laboratory (BNL) further optimized the FNAL design, reducing the discharge current, increasing the extraction voltage and introducing a dimpled cathode that used permanent magnets [1]. Operational experience from BNL has shown that this type of source is more reliable with a longer lifetime due to better power efficiency [2]. The magnetron source design currently used at FNAL is similar to both the BNL ion source and the source developed by Schmidt for the High Intensity Neutrino Source (HINS) project at FNAL [3]. The source shown in Fig. 1 has a round aperture with direct extraction using a 45° extraction cone. The source cathode has a spherical dimple which provides focusing of the H^- ions leaving the surface to the anode aperture increasing the power efficiency to 48 mA/kW. The source is mounted reentrant inside a ten-inch stainless steel cube and was designed with “ease of maintenance” in mind. The operational parameters for this source are listed in Table I.

The extraction method is single stage with the extraction cone at ground potential and the source biased to -35 kV. This bias voltage is pulsed at 15 Hz. This extraction method allows the source to run in the space charge limited regime with high extracted beam currents. The extractor pulser is a

new design that uses solid state switch plates [4]. The source electronics are installed in a high voltage rack with a floating ground.

High frequency noise in the beam current is an issue for users of one-turn Booster operations. Significant changes in the H^- population of extracted bunches propagate throughout the linac and can be visualized using a high-bandwidth beam position monitor [5], as shown in Fig. 2. In this figure irregularities in the linac beam pulse can be seen where one would expect a more uniform beam pulse. For this reason, a set of studies was performed with the aim of reducing the beam current noise. This paper summarizes the studies and modifications done in the source over the past three years with the aim of improving its stability, reliability and overall performance.

II. SOLENOID GAS VALVE

The typical gas pulse width used to operate the ion source is about $100\ \mu\text{s}$. An H^- ion production cycle starts with injection of a single H_2 gas pulse into the ion source, as shown in Fig. 3, which is electrically heated to $\sim 200^\circ\text{C}$ and contains a cesiated cathode. Approximately 1 ms later, a $230\ \mu\text{s}$ pulse provides -300 V for an arc discharge between anode and cathode, igniting the plasma. The 1 ms

FIG. 1. Schematic of Fermilab's magnetron H^- source.

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TABLE I. FNAL H^- source parameters.

Parameter	Value	Units
Arc current	15	A
Arc voltage	180	V
Extractor voltage	35	kV
Beam current	80	mA
Power efficiency	48	mA/kW
Repetition rate	15	Hz
Arc pulse width	250	μ s
Extracted beam pulse width	80	μ s
Duty factor	0.375	%
Cathode temperature	380	$^{\circ}$ C
Cs boiler temperature	130	$^{\circ}$ C
Emittance $\varepsilon_x/\varepsilon_y$ (normalized, 95%)	0.17/0.28	π mm mrad
Extraction gap	4.67	mm
Lifetime	9	months

gap between the gas and the arc pulse is the time it takes for the pulse to arrive at the ion source, and this time gap also optimizes the stability of the arc discharge pulse. Surface produced H^- ions from the cathode are extracted with a -35 kV, 150 μ s pulse synchronized with the last portion of the 230 μ s arc pulse and centered on the chopped beam for the linac. The magnetron H^- ion sources currently in operation at Fermilab use Veeco PV-10 piezoelectric gas valves (Fig. 4) to pulse H_2 gas into the ion source [6].

FIG. 2. Linac beam pulse (top) at a $5 \mu\text{s}/\text{div}$ scale with visible 50 to 100 ns microstructures at a shorter scale of $200 \text{ ns}/\text{div}$ (bottom). Vertical scales are $500 \text{ mV}/\text{div}$.

FIG. 3. Schematic of the H^- production cycle showing the gas pulse and arc discharge.

FIG. 4. (a) Piezoelectric valve case. (b) Piezoelectric valve shown with the Viton disk glued on it.

These valves have long been used in H^- ion sources for gas injection under vacuum conditions [7,8]. These valves open at 20 V, flexing proportionally to the applied voltage until they reach 100 V. A Viton disk has been glued to the center of the valve and provides a good vacuum seal. In general, these piezoelectric valves work well and are very reliable for our application but their flexibility tends to decrease with increasing temperature. As room temperature increases, the piezoelectric valve flexes less, allowing less gas into the source, thus affecting the arc current and beam output. This means a 1°C change in room temperature can translate into a $1 \mu\text{Torr}$ change in vacuum pressure and as much as 1 A change in arc current. Operators frequently need to adjust gas valve voltage and/or gas pulse width to keep up with changes in room temperature. In addition, calibration issues with the installation of the gas valve and its tension spring account for significant performance differences from one piezoelectric valve to the next. This inconvenience motivated the need to find an alternative way of injecting H_2 gas into the source to avoid its temperature dependence.

A commercial pulsed solenoid valve has been characterized in a dedicated off-line test stand to assess the feasibility of its use in the operational ion sources. The valve is a Series 9 by Parker Hannifin Corporation (see Fig. 5).

Figure 6 shows the behavior of an ion source with a piezoelectric valve over five days. The arc and beam currents tend to follow the vacuum pressure in the source. This fluctuating arc current is an issue for operators, requiring periodic tuning to stabilize the source output.

Figure 7 shows the performance of the ion source with the solenoid gas valve over a period of three days. Note that in this case the arc current is much more stable around the nominal value of 15 A than with the piezo valve, leading to a more stable beam current. The change in vacuum pressure is similar in both cases.

The performance of the solenoid gas valve has been characterized by measuring the beam current output of the magnetron source with respect to the voltage and pulse width of the signal applied to the gas valve.

A VESPEL[®] poppet was used due to its thermal and mechanical properties [9]. The valve aperture is 0.5 mm in

FIG. 5. (a) Picture of the Series 9 gas valve. (b) Schematic of the gas valve and its different parts.

FIG. 6. Datalog plot of the beam current, arc discharge current, vacuum pressure and local temperatures over a five-day period using the piezoelectric gas valve in the source.

diameter. Preliminary beam runs allowed the source to operate in similar conditions as when using piezoelectric valves. The typical gas pulse width used with the piezoelectric valves is about 90 to 115 μs , compared to a range of 100 to 150 μs when using the solenoid gas valve in order to obtain similar arc current and beam output.

When running the ion source with this valve, biased at 275 V and 124 μs gas pulse width, 840 μs before the arc discharge, the beam output was maximum. Vacuum pressure, extraction voltage, arc voltage and arc current remained constant during this test at 4.2 μTorr , -35 kV, 189 V and 15 A, respectively.

In these conditions, the arc pulse width was increased from 100 to 275 μs and beam current and cathode

FIG. 7. Datalog plot of the beam current, arc discharge current, vacuum pressure and local temperatures over a five-day period using the solenoid gas valve in the source.

FIG. 8. Beam current and cathode temperature vs arc pulse width using the solenoid gas valve in the H^- source.

temperature were recorded. All measured beam current values are sampled at the center of the flattop part of the pulse, allowing at least one hour between changes for beam current stability. Results are plotted in Fig. 8. An arc pulse width ranging from 150 to 250 μs yielded the highest beam currents, *ceteris paribus*. In this range the ion source can deliver beam currents above 50 mA, which satisfies the needs of the injection line downstream.

H^- ion beams with beam currents >50 mA have been extracted at 35 keV using the solenoid gas valve. This type of valve shows a lower temperature dependence than the piezoelectric valve, and it avoids the calibration problems experienced with the piezoelectric valves. This represents a step forward towards a more stable arc current and less tuning from operators.

III. CESIUM OVEN

The magnetron ion source is a surface plasma source [10], which relies on cesium to lower the work function of

the cathode for H^- production [11]. A cesium oven is used to heat elemental cesium so that it flows to the rest of the cesium transport system to replenish the cesium layer on the cathode, which is depleted due to the high cathode temperature and plasma erosion. The cesium oven is used to cesiate the cathode in the ion source. The cesium ovens currently in operation at FNAL are 139.7 mm long, 14.29 mm diameter tubes made of copper [Fig. 9(a)]. A commercially available 5 g cesium vial is inserted into the copper tube, then sealed on top with an isolation valve. This assembly is then connected to the rest of the ion source.

Prior to starting an ion source with an unused boiler, the ion source is pumped down and the cesium oven is baked out with the valve open to ensure a good vacuum is achieved. Then the oven valve is closed and the copper tube is pinched with a tool in order to crack the cesium vial inside and release it. To finish, the cesium oven is wrapped up in insulating material and warmed up to operational temperatures along with the rest of the cesium transport elements going into the ion source. This method has worked well for many years, but it presents several challenges. Glass fragments from the cracked cesium vial pose a risk when performing cleaning and maintenance tasks on used cesium ovens. The procedure involves a solution of sulfuric acid to react away the cesium residue. This can sometimes build up pressure pockets and bubbling in the metal cylinder and turn the glass fragments into projectiles.

The cesium oven is heated using a heat tape made by BriskHeat® Corporation [12]. The excess heat tape was wrapped around both the valve and cesium transport tube. This meant that the temperature of the boiler, valve and tube were all interactive so it was hard to balance the difference in temperatures. Another issue with the cesium oven is that copper being a very good heat conductor made it hard to obtain the low nominal oven temperature of 110°C as the cesium oven is heated not only by the heat tape, but by the valve heater as well. The heat tape had to be run at very small currents along with thinning out the exterior cesium oven insulation. As a result, the

FIG. 9. (a) Cesium oven made of copper (left) and vial with 5 g of elemental cesium (right). (b) New cesium oven made of stainless steel with 2 Ω/m heating wire around it.

FIG. 10. Temperature response of the different oven configurations as a function of current.

cesium oven temperature would start following the room temperature.

A new cesium oven made of stainless steel was designed to fix the aforementioned problems [Fig. 9(b)]. It is 63.5 mm long and 19 mm in diameter. The more compact design helps with thermal insulation of the cesium oven from the rest of the cesium delivery systems. The smaller design also requires pouring the cesium into it from the glass vials by means of a glove bag purged with N_2 . Stainless steel was chosen as a material for the new oven because, although stainless steel has about 30 times less thermal conductivity, it avoids heat dissipation from the oven into the sealing valve sitting on top of it.

To select a suitable heating wire for the new oven, a quick test was done comparing the copper and stainless-steel ovens with two different types of wire: 5.33 and 2 Ω/m . These wires are AerOcoax® made by ARi Industries Inc. [13]. In Fig. 10 the temperature response of the copper oven is shown with four turns of 5.33 Ω/m wire and ten turns of 2 Ω/m wire. The line for the stainless-steel oven corresponds to four turns of 2 Ω/m wire, as the 5.33 Ω/m wire takes very little current to heat up resulting in a slope too steep to be useful. In our application it is desirable to have the ability to fine-tune the temperature (ideally to less than 1 °C) for every step in current from the power supply. Although the copper oven with four turns of the 2 Ω/m wire has the smallest slope of the three, the stainless-steel oven also provides the ability to fine-tune the temperature with small current increments as well as the benefits of avoiding glass fragments from the glass vial and better thermal insulation.

IV. CURRENT-REGULATED ARC MODULATOR

The arc pulser currently used in the operational sources is voltage regulated. The main inconvenience of running an ion source with a voltage-regulated arc modulator is the drift of the arc current over time. Since arc current and beam output are intimately related, a drifting arc current means an unstable beam output over the course of beam operations. In order to avoid this, a current-regulated arc

FIG. 11. Circuit diagram of the current-regulated arc modulator.

modulator was designed at FNAL, inspired by the current-regulated arc modulator from BNL [14]. It consists of a high-voltage card and a trigger/feedback loop card as shown in Fig. 11.

The voltage to current converter comprises an op-amp set up as a positive high gain amplifier connected to a power MOSFET which acts as a gate for controlling the large current flowing out of the high voltage power supply.

The high current power MOSFET IXFN132N50P3 [15] is spark resistant at -35 kV. It has a forward dc current rating of 112 A and a drain-source voltage rating of 500 V. The fast rise and fall times of ~ 100 ns of this MOSFET help significantly reduce the fall and rise times of the arc

current pulse. Notice that the high-voltage card is floating (not connected to the ground reference) as shown in Fig. 11. The different components of the current-regulated arc modulator and their layout in the chassis are shown in Fig. 12.

In Fig. 13 the performance of the current-regulated modulator over three days of beam time is shown. The arc current is very steady at 15 A even though the arc voltage and vacuum pressure change over time. This represents a major improvement towards more steady beam outputs during operations. Further studies will be done

FIG. 12. Prototype of current-regulated arc modulator chassis showing the 700 V transformer, dc power supplies, high-voltage card, trigger/feedback card and the MOSFET.

FIG. 13. Performance of the current-regulated modulator over three days running in the ion source. The arc current remains constant whereas the arc voltage and vacuum pressure wander.

TABLE II. Arc Modulator Specifications.

Parameter	Value	Units
Pulse width	100–300	μs
Rise/fall time	<20	μs
Regulated current range	1–20	A
Current ripple amplitude	<1	%

when the system is installed in an operational system since the effects of changing source impedance on downstream machines is unknown yet. Table II summarizes the design specifications for the current-regulated modulator.

V. BEAM CURRENT NOISE

Earlier studies have been performed exploring different methods of reducing the beam current noise of the magnetron [16]. It has been previously suggested that adding a small amount (1% in volume) of N_2 gas decreases the modulation or noise of the extracted beam current [17,18]. An experiment was done in the SPS off-line test stand to mix H_2 and N_2 gases very accurately at different ratios on the gas line that feeds the source with the aim of exploring the effect of different N_2/H_2 ratios on the beam current noise. In this study, beam current noise was defined as the ratio (as a percentage) between the standard deviation and the mean signal from the beam line toroid:

$$\text{Noise ratio} = \frac{\sigma}{\bar{I}} \times 100. \quad (1)$$

The experimental setup is depicted in Fig. 14. Two mass flow controllers (MFCs) which are calibrated for each pure gas regulate the amount of each gas flowing into the source. These MFCs measure pressure drop in laminar flows of gas (10 to 15 psi) which make them accurate down to 0.8% of the reading and 0.2% of their full scale [19]. The full scale of the N_2 MFC is 0 to 0.5 sccm whereas that of the H_2 MFC is 0 to 5 sccm. With this setup, N_2/H_2 ratios between 0.5% to 3% could be tested, and the mean beam current noise was

FIG. 14. Experimental setup for gas mixing into the ion source.

FIG. 15. Scope picture of the beam current signal from the toroid downstream of the source. Beam extracted at -35 kV. Horizontal and vertical scales are $20 \mu\text{s}/\text{div}$ and $10 \text{ mV}/\text{div}$, respectively.

measured connecting the output of the current toroid to an oscilloscope.

Figure 15 shows a scope picture of the high frequency noise of the beam current signal from the downstream toroid. Noise ratio was calculated from the values measured within a $50 \mu\text{s}$ window in the signal flattop.

In Fig. 16 the noise ratio of a magnetron ion source with a regular dimpled cathode is shown as a function of the percentage of nitrogen. For every data point, the maximum beam current was recorded at an extraction voltage of -35 kV. A slight increase in noise ratio is seen as more nitrogen is added to the source, however the noise ratio is very low in every data point, at under 1%. The observed trend in the data also reflects that, as more nitrogen is added to the source, the beam current signal decreases while the standard deviation of the signal remains unchanged, hence the increase in the noise ratio. No significant reduction in the noise ratio was observed in these conditions. Above 3% N_2 the arc current is severely affected or even terminated in a matter of minutes.

In Fig. 17 the noise ratio was studied for different arc currents at the same extraction voltage of -35 kV. In general, the extracted beam current increases linearly with arc current, therefore a lower noise ratio is observed at higher arc currents with and without N_2 . No significant difference is observed in the plot by adding N_2 to the source. From the data set, the only magnitude that changes appreciably is the beam current signal but not its standard deviation.

FIG. 16. Noise ratio as a function of N_2/H_2 ratio.

FIG. 17. Noise ratio as a function of arc current with and without N₂ in the gas mixture.

The addition of nitrogen to the ion source in the conditions of these experiments has not proven to be useful in reducing the beam current noise, contrary to expected. This might be due to the heavier nitrogen gas molecules eroding the cesium layer on the cathode surface. The effect of beam current noise was also studied for different types of cathodes. The main hypothesis is to verify whether a smaller source cathode which allows for a larger plasma volume in a magnetron source yields a smaller noise ratio. The cathodes used in this test were the standard dimple cathode, the hollow cathode (see description in next section), a thin cathode and a cathode with the dimple drilled through. These cathodes are illustrated in Fig. 18. The standard cathode [Fig. 18(a)] has a dimple 8.4 mm in diameter and 1.59 mm deep. This cathode is 9.04 mm thick from front to back. The so-called hollow cathode is just a standard cathode with a hole 2.9 mm in diameter and 5.54 mm deep on one side. The thin cathode [Fig. 18(c)] is 6 mm thick and has a groove 0.3 mm deep on the front side. The drilled through cathode is a standard cathode with a hole 8.41 mm in diameter drilled all the way through the cathode. The first three cathodes can achieve high extracted

FIG. 18. Cathodes used in the ion source: (a) Standard dimpled cathode; (b) hollow cathode; (c) thin cathode; (d) drilled through cathode.

FIG. 19. Noise ratio as a function of arc current for different cathodes. Extraction voltage is -35 kV.

beam currents (>50 mA), whereas the drilled through cathode usually achieves lower beam currents (12–14 mA).

The ion source was installed with each cathode described above and run to a stable operational point with the extractor voltage set at the nominal value of -35 kV. With the current-regulated (CR) arc modulator, the arc current was set anywhere from 10 to 22 A and the noise ratio was recorded by measuring the mean current signal from the toroid and its standard deviation. When plotting the noise ratio as a function of arc current (Fig. 19), no significant trend can be observed from the data except for the thin cathode, and noise ratios remain relatively low ($<2\%$) for all cathodes in this arc current range. The hollow cathode performs best for arc currents >15 A.

In addition, the average pressure in the source chamber was changed from 4.5 to $10 \mu\text{Torr}$ by adjusting the gas valve voltage to allow more or less H₂ into the source. In Fig. 20, noise ratio data for all the different cathodes was recorded while running the source at 15 A of arc current and extracting at -35 kV. A few data points could not be taken with certain cathodes at high pressure due to excessive sparking.

From this data, no clear pattern indicates a change in noise ratio for different cathodes within this pressure range. Note that the noise ratio remains low ($<2\%$) for all cathodes in this pressure range.

FIG. 20. Noise ratio as a function of pressure for different cathodes. Arc current is 15 A and extraction voltage is -35 kV.

In the case of the drilled through cathode not many surface produced ions can be extracted, as no surface is directly facing the exit aperture of the source. In this condition, the argument can be made that most of the extracted ions come from the plasma volume between cathode and anode. If that is the case one can compare the low beam currents (12–14 mA) extracted from the drilled cathode to the nominal 60–70 mA of a standard dimpled cathode. This would imply that surface produced ions account for 80% of the extracted beam current.

VI. CONCLUSIONS

When using the solenoid gas valve and an arc pulse width of 150 to 250 μs , the magnetron ion source can deliver beam currents above 50 mA, which satisfies the needs of the injection line downstream. This solenoid gas valve was observed to be spark resistant in addition to running stably with no observed correlation to changes in room temperature.

The new stainless steel cesium oven provides the ability to fine-tune the temperature with little current increments. In addition, it avoids the glass fragments from the broken ampoule and provides easier thermal insulation with a reduced oven surface. This means that room temperature has less effect on the boiler temperature.

The CR arc modulator represents a major improvement towards more steady beam outputs during operations. Very steady arc currents can be achieved over days of beam run with minor offsets (<1 A) relative to the set point defined by the user. During operation in current-regulated mode, the arc voltage and arc impedance can swing accordingly while providing a stable beam current output. Further studies will be done in an operational system to evaluate the effects of changing source impedance on downstream machines.

No reduction in the noise of the beam current or arc discharge was observed with the proposed ideas. The magnetron ion source is known to be inherently noisy. As shown in Fig. 21, the gas density n required for the

FIG. 21. Diagram of the magnetron discharge stability as a function of magnetic field B and gas density n . The diagram was by V. Dudnikov.

magnetron ion source in order to achieve noiseless discharge is above the gas density n_m in which extraction voltage breakdown and/or ion stripping is high [20]. For noiseless discharge, the magnetic field in the magnetron source would need to be less than 1 kG, but in that case the extracted beam current drops and the amount of coextracted electrons increases sparking. This renders the noiseless discharge regime of the magnetron in an unprofitable region to deliver beam operationally.

A viable alternative would be installing a Penning source, which is known to achieve noiseless arc discharge [20], which would translate into a reduction of the extracted beam current noise.

The Penning is the brightest H^- ion source with current densities at extraction above 1 A cm^{-2} . The lifetime of the Penning source is limited to a few weeks because of cathode sputtering by cesium ions. This type of source will not operate without cesium vapor and requires the electrode surfaces to be between 400°C and 600°C . This source has been developed by D. Faircloth and his team at Rutherford Appleton Laboratory. 60 mA, 1 ms, 50 Hz pulses can be routinely produced with this source [21].

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