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A Cookbook For Building A High Current Dimpled H- Magnetron Source For Accelerators

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Abstract

A high current (> 50 mA) dimpled H- magnetron source has been built at Fermilab for supplying H- beam to the entire accelerator complex. Despite the many decades of expertise with slit H- magnetron sources at Fermilab, the dimpled H- magnetron source presented many challenges that needed to be overcome in order to make it operational. Dimpled H- sources for high energy physics are not new: BNL (Brookhaven National Laboratory) has operated a dimpled H- source for more than two decades. However, the transference of that experience to Fermilab took about two years because a "cookbook" for building this type of source did not exist and seemingly innocuous or undocumented choices had a huge impact on the success or failure for this type of source. Therefore, it is the goal of this paper to document the reasons for these choices and to present a "cookbook" for building and operating dimpled H- magnetron sources.

I. Introduction

The Fermilab H- injector was upgraded from a slit H- magnetron source with a Cockcroft-Walton pre-accelerator to a dimpled H- magnetron source with an RFQ at the end of 2012. [1] We made this safe technical choice rather than going to the more modern RF H- sources because of the decades of operational experience with magnetron sources. Furthermore, BNL (Brookhaven National Laboratory) has used a dimpled H- source reliably for more than two decades for their RFQ injector [2] and they would be able to help us get this type of source up and running quickly because of the good relationship between the BNL H- source group and us.

Therefore, once this decision was made, we allocated resources to start the dimpled H- source program here at Fermilab and by the middle of 2011, we had built and installed a dimpled magnetron H- into a test stand. Unfortunately, despite the help from BNL and our local expertise, we were unable to get the source working reliably, i.e. without sparking, until the end of of 2013. This program took a lot longer than expected because we discovered a major problem: the institutional memory loss of how dimpled H- sources are designed and built. This inspired us to write a "cookbook" for how to build one so that posterity would not have to rediscover the mistakes

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that we had made and solutions that we had found. We do not claim to have all the answers in this paper, but its contents should be a good starting point for anyone contemplating building one.

II. The History of H- sources at Fermilab

The FNAL Linac has been accelerating H- ions since 1977. The first source, brought to FNAL by C.W. Schmidt, was an early magnetron source shown in Fig. 1, purchased from BNL. The source was designed for fusion research and operated DC. It became clear during initial testing at 1 Hz, that the source volume was too large for 15 Hz operation due to the fill time of the source body to reach the required pressure for plasma production.

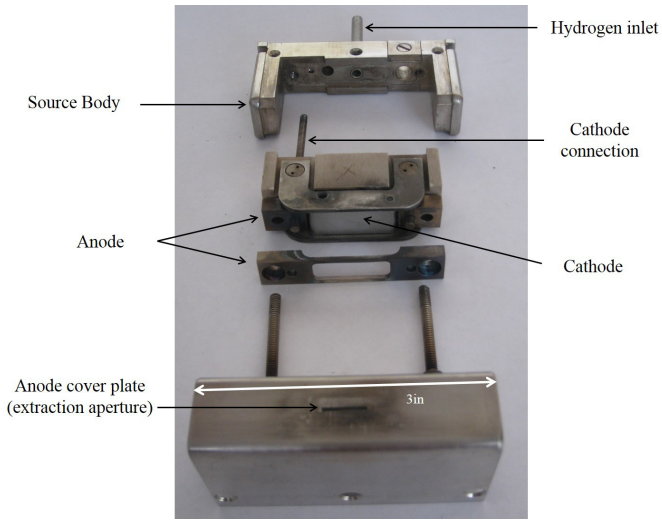


Fig. 1: BNL fusion research ion source which was purchased by FNAL in 1977.

A clever magnetron ion source design by C.W. Schmidt, shown in Fig. 2(a,c), has an internal volume a factor of 10 less than the BNL source which made 15 Hz operation possible. This design had a slit extraction aperture and a flat, non-grooved cathode Fig. 3(a) and was implemented in the Cockcroft-Walton pre-accelerators in 1977. [3]

The source was mounted pointing down with a 90 degree bend magnet to steer and shape the beam appropriate for injection into the Linac and a cesium cold trap to prevent cesium from entering the accelerating column is shown in Fig. 4. The extraction voltage was 18 kV which supplied $\sim$50mA of H- ions. This low extraction voltage required a high arc current around 150 A, in order to have enough extracted beam current. The high arc current resulted in a very low power efficiency of 2 mA/kW, which led to short lifetimes, on average of about one month. The lifetime of the sources was limited due to back streaming of positive particles striking the cathode that caused erosion. The cathode material that was removed ended up clogging the hydrogen gas and cesium inlets which can be seen in Fig. 5(b, c, d e). In extreme cases, the material would come off the cathode in flakes that would either block the anode aperture or cause cathode to anode shorts as seen in Fig. 5(a).

The flat cathode surface was replaced with a grooved surface (see Fig. 3(b)) in 1984. [4] The grooved surface provided focusing of the H- ions that leave the surface of the cathode to the exit aperture of the anode cover plate.

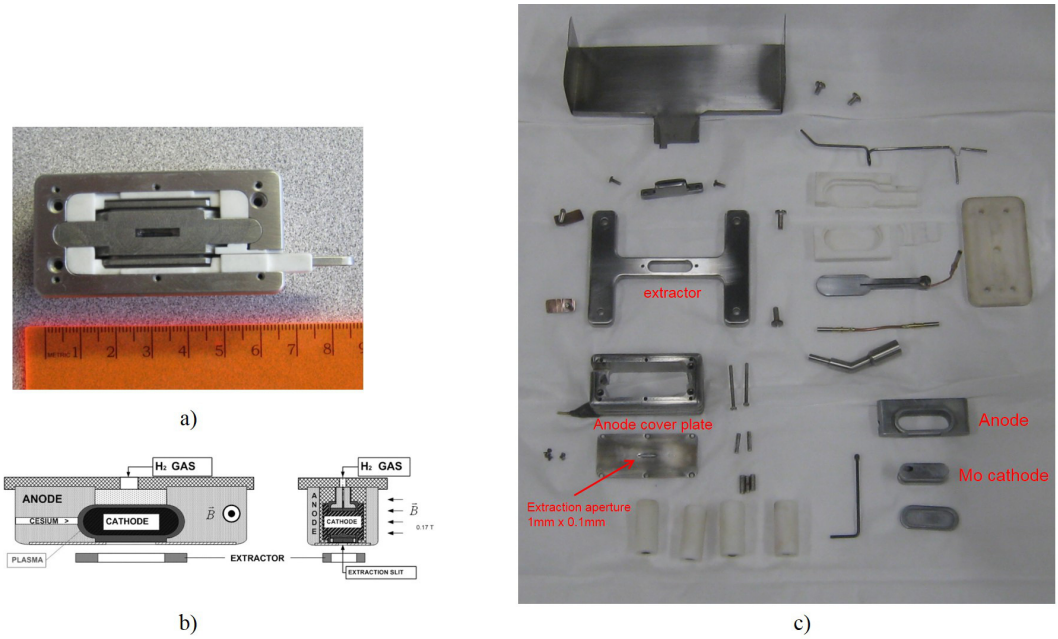


Fig. 2: (a) assembled magnetron, (b) schematic of the magnetron indicating the gas and cesium inlets along with the extractor, (c) a disassembled magnetron showing all of the parts associated with the source.

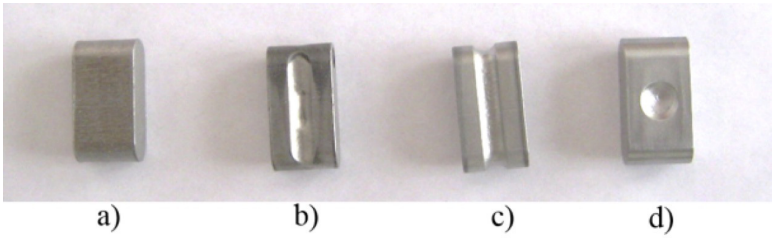
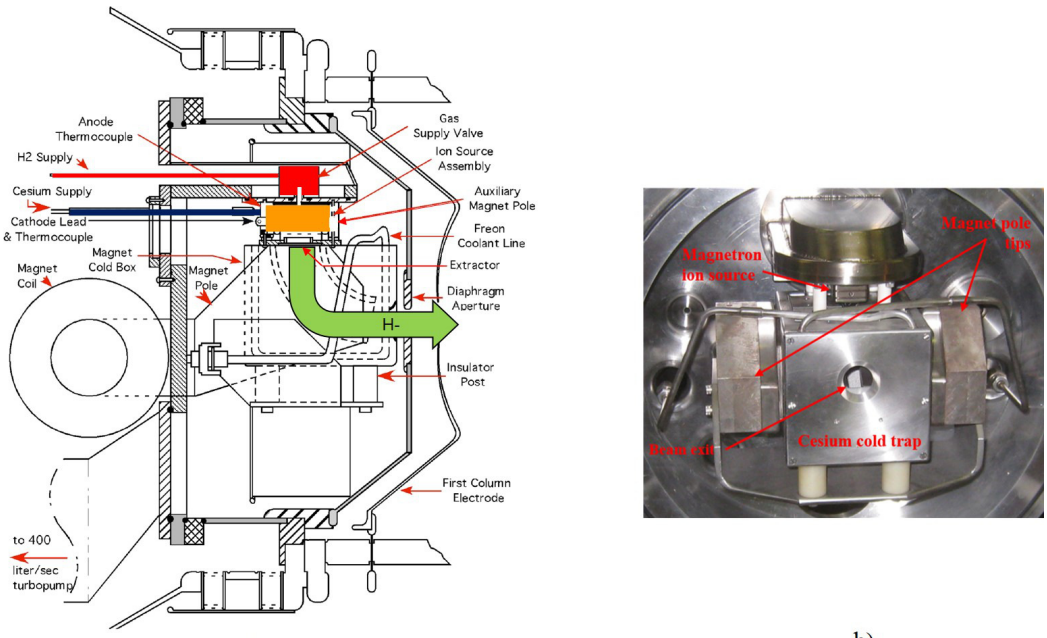


Fig. 3: The evolution of magnetron cathodes used at FNAL: (a) the original flat cathode with no focusing, (b) a partially grooved cathode with focusing on side of cathode facing the anode cover, (c) a fully grooved cathode with the groove from cathode b completely around the cathode surface. This cathode was used for over 25 years, and (d) a spherical dimpled cathode with a focal point at the circular anode aperture.

This modification greatly increased the power efficiency of the source from 2 mA/kW to 6.7 mA/kW, which allowed the source to run at a much lower arc current of ~ 50 A for 50 mA of extracted ion current at 18 kV extraction voltage. The increase in power efficiency and lower arc current improved the lifetime of the source by a factor of 3. Even with the improved power efficiency, the sputtered cathode material clearly affected the source lifetime and overall performance. The plots in Fig. 6 show the effects of aging: its performance would start to degrade as the hydrogen and cesium inlets would become clogged with the cathode material. Continuous tuning was required to maintain constant extracted beam current. This included starting the hydrogen injection earlier and increasing the



a) b)

Fig. 4: (a) A schematic view of the ion source mounting. (b) The downstream view of the ion source, cesium cold trap and magnet pole tips.

amount of injected hydrogen as shown in Fig. 6(c). Near the end of the source lifetime the average gas pressure in the vacuum chamber would be high enough for H- stripping to occur which reduces the amount of beam current out of the source. Eventually the source would need to be pulled out and cleaned.

With the installation of the RFQ, a round aperture, direct extraction magnetron shown in Fig. 7, based on a design by J. Alessi [5] was built. Photographs of our source installed on a beam line and operating are shown in Fig. 8. The source design is similar to the slit aperture source, but has a spherical dimple in the cathode and round anode cover plate aperture. The spherical dimple has a focal point located at the exit of the anode cover plate which helps to focus the surface produced H- ions. This spherical focusing allows the source to run at a much lower arc current than before. Another innovation is the extraction of the beam at 35 kV. With this high extraction voltage and well-focused ions, the extracted beam current is $\sim$100 mA, and the power efficiency improved to 67 mA/kV. As a result, BNL typically runs their source from shutdown to shutdown — implying a lifetime of about 9 months. The FNAL source has a power efficiency of 33 mA/kW at this time and its lifetime to date (Aug 2015) is also about 9 months.

Table I shows the evolution of H- ion sources used at FNAL. The increase in power efficiency has clearly been the biggest advancement in improving source lifetimes.

Although on the surface of it, the difference between a slit magnetron and a dimpled magnetron is just a simple change in geometry and thus operating both types of magnetrons should be similar. Unfortunately, to our chagrin,

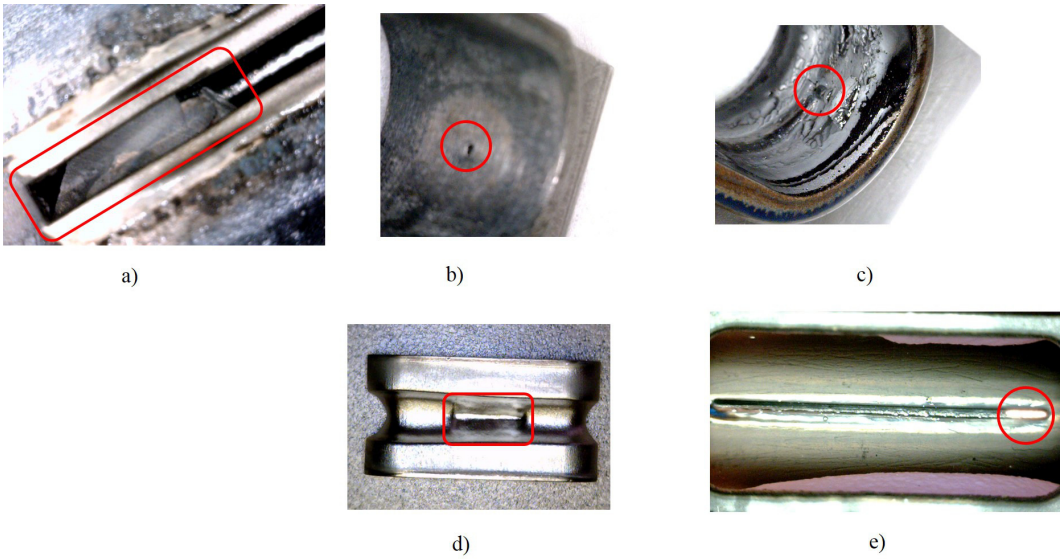


Fig. 5: Typical problems with magnetron aging: (a) anode aperture restriction caused by cathode material deposition. (b) Cesium inlet without blockage, compared with (c) the cesium inlet clogged by sputtered cathode material. (d) Cathode erosion caused by the back streaming of positive particles. The erosion is on the side of the cathode facing the anode aperture. (e) Hydrogen inlet almost completely blocked by sputtered cathode material.

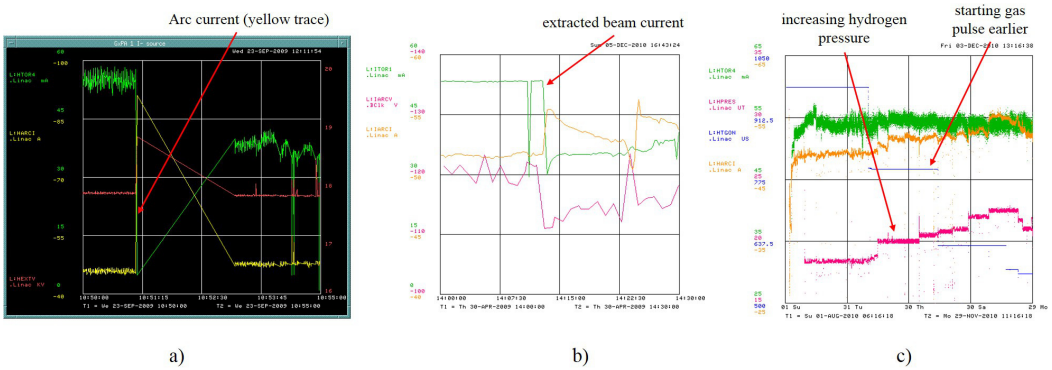


Fig. 6: Plots that are typical when the source ages. (a) anode to cathode short leading to very high arc current, (b) anode aperture restriction reducing the amount of extracted beam current by almost 50% and (c) as the hydrogen inlet aperture gets restricted, the gas valve on time needs to be moved earlier to allow more time for the source to fill because the cesium aperture is getting more restricted. The average pressure in the cube increases due to the need to keep the beam current as constant as possible.

it did not turn out to be this way. In fact, it took many changes of materals, magnetic field geometries, vacuum pressures and cesium flow rates in order to get to a good operating point for the dimpled source. The results of our explorations are discussed below.

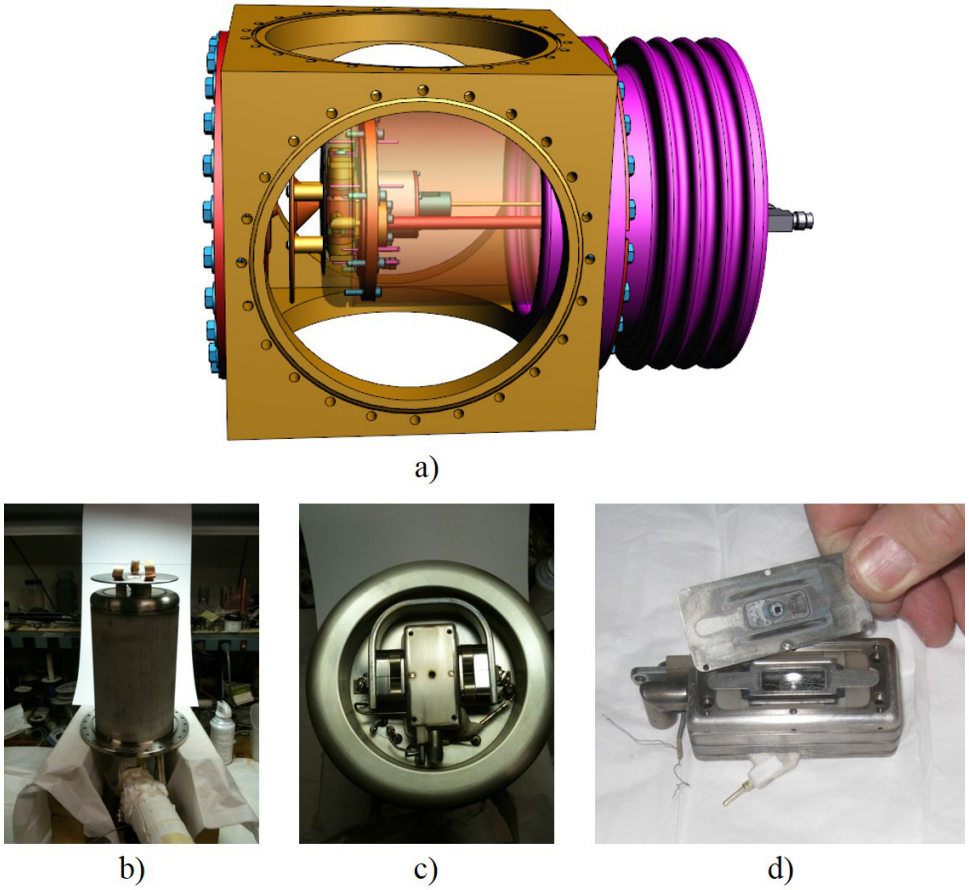


Fig. 7: Round aperture direct extraction magnetron ion source used in the FNAL RFQ injector. (a) The source is mounted reentrant in a vacuum chamber. (b) Can where the magnetron is mounted. (c) Downstream view of the magnetron source and magnets. (d) Magnetron ion source showing the round aperture, the anode cover plate and the spherical dimple in the cathode.

A. Choice of materials

In our original design of this ion source and extraction system, we used the same parts and materials that was in the original magnetron design by C.W. Schmidt. The source parts shown in Fig. 2(c) in section II, are made from a variety of materials based on where they are located in the source. Materials in contact with the plasma need to be able to withstand high temperatures and erosion from the plasma. As a result, hard materials with high melting points such as molybdenum are used to make the cathode, anode and extractor tip. The original design also called for an anode cover plate made of titanium.

1) Cone tip: In our original tests of the source, the extractor cone tip suffered extensive damage due to excessive sparking from the source anode cover plate to the extractor cone tip as seen in Fig. 9(a). The damage to the cone tip usually resulted in sharp edges that caused high electric fields and thus higher spark rates. At the point where

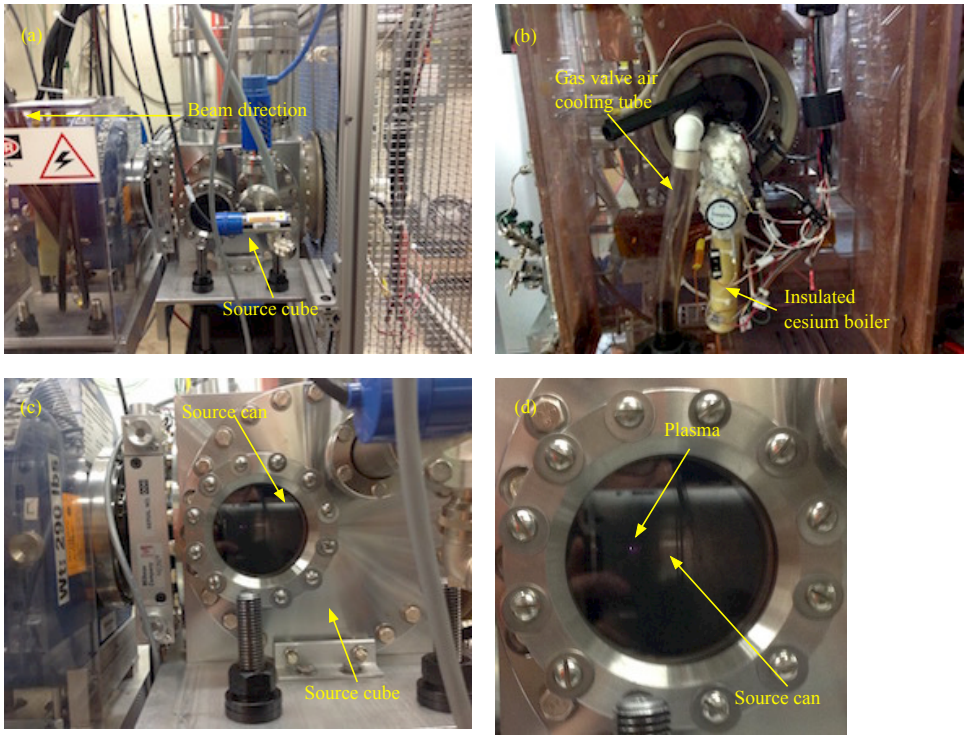


Fig. 8: These photographs show the outside of the source after it is assembled and installed on a beam line. (a) The source cube. (b) The back of the source cube showing the cesium boiler covered with insulation. (c) The window on the source cube that shows the source can. (d) A zoomed in view through the window that shows the plasma.

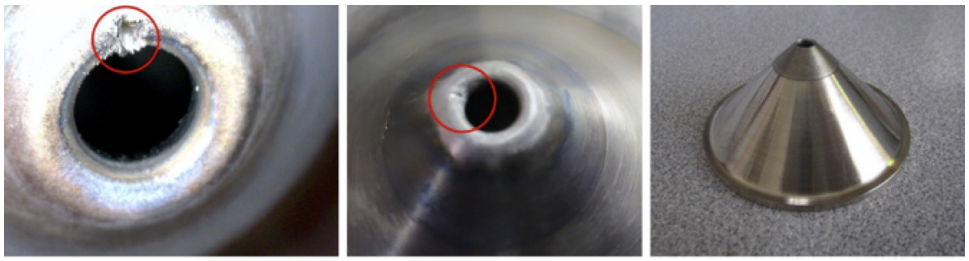
TABLE I: Source parameters for the three generations of the H- magnetron ion sources used at FNAL

Parameter	Flat cathode (slit aperture)	Grooved Cathode (slit aperture)	Spherical dimple (round aperture)	Units
Arc current	180	50	18	A
Arc Voltage	150	150	150	V
Hydrogen consumption	3	3.4	2.5	cc/min
Cesium consumption	22	12.5	8.5	mg/day
Extractor voltage	18	18	35	kV
Power efficiency	2	6.7	33	mA/kW
Duty factor	0.12	0.12	0.35	%
Lifetime	1	3	9[a]	months

[a]based on BNL experience, FNAL lifetime has been less up to this point in time (April 2015).

the spark rates became so high that we could not run the extractor at 35 kV, the source would need to be removed and the extractor cone tip either refinished to remove the sharp edges or it would need to be replaced. We can

approximate the amount of energy in an extractor spark by using the $CV^2/2$ formula, which for our system it would be 245 J concentrated into an area the size of the spark.



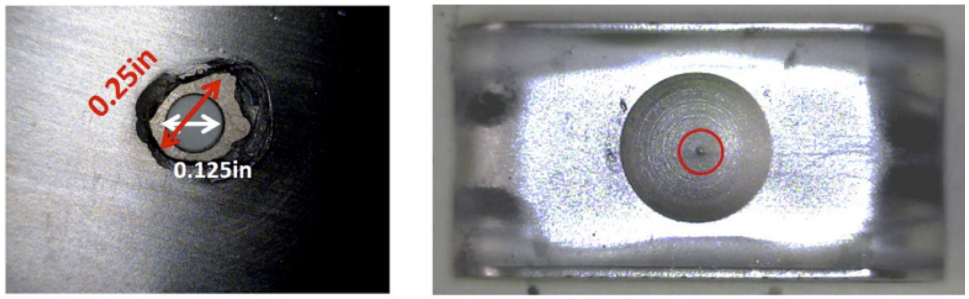
a) b) c)

Fig. 9: Extractor cone tip showing: (a) damage due to sparking between the grounded extractor cone and the source which is pulsed at -35 kV, (b) damage due to co-extracted electrons cutting into the cone tip in the direction of the magnetic bend field, and (c) a tungsten cone tip that has very little damage even after excessive sparking.

The other issue that appeared was cutting of the cone tip by the co-extracted electrons which can be seen in Fig. 9(b). The channel cut by the electrons left behind a sharp edge which would be a location where sparking would start. After consulting with BNL, we decided to change the extractor cone design to accommodate a tungsten cone tip. The new tungsten cone tip Fig. 9(c) is not affected as much by co-extracted electrons and suffers very little damage from extraction gap sparking.

2) Anode cover plate: The anode cover plate is in contact with the plasma region of the source as well as the point where the H- ions and electrons are extracted from the source. This plate was titanium and would suffer from erosion, especially at the round aperture as seen in Fig. 10(a). This aperture would end up being eroded in the direction of where the extracted negative particles are bent by the magnetic field. This would lead to the extracted beam being less round as the source aged and the erosion would leave behind sharp edges which would lead to extraction gap sparking. We decided to make plate out of both molybdenum and tungsten. Even though the molybdenum plates still showed signs of erosion, they performed better than titanium. We now use tungsten plates and see no signs of erosion.

3) Cathode: Even though the molybdenum cathode has erosion from back streaming positive ions, it is required for source operation. For surface production of H- ions, the magnetron depends on the cesiation effect discovered by Dudnikov [6]. The work function of cesiated molybdenum is 1.5 eV is due to cesium being one of the best electron donors. So, for high H- yields molybdenum is used, however it does suffer from erosion from not only the plasma, but also back streaming positive particles which can be seen in Fig. 10(b). Tungsten would be a possible candidate for cathode material. Its work function is slightly higher and H- yield is lower than molybdenum. However, it has a broader H- production peak [7] which may allow for a wider range of tuning. We do have plans to try a tungsten insert in a molybdenum cathode.



a) b)

Fig. 10: (a) A titanium inner anode cover plate showing the amount of erosion of a used one vs the aperture of a new plate. The aperture of new plates is 0.125", while the used plates can have eroded apertures of 0.25" or greater. (b) A cathode showing signs of erosion of the spherical dimple from back streaming positives. This material ends up sputtering onto the other surfaces and where the material was removed makes the dimple no longer spherical focusing.

B. Magnetic field

1) Simulations: The transverse magnetic field B_z[1] field is critical for the confinement of the electrons of the plasma. If the B_z field is too weak, too many electrons are lost from the plasma and the lost electrons can form a conductive path from the cover plate to the extractor that encourages sparks to occur. Simulations show that $B_z > 1$ kG is necessary for confining the electrons for our source geometry. However, there is a point of diminishing return, and a good range for B_z is between 1 and 1.5 kG. [8]

2) Yoke and magnetic field distribution: The original design for the source magnetic field used four disc shaped permanent magnets that were mounted on a yoke. See Fig. 11(a). These magnets were readily available due to their use in the HINS (High Intensity Neutrino Source) magnetron research that was in progress at that time. The ordering of new rare earth magnets had a several month lead-time so these available magnets were used. The magnets were $3/4$" in diameter and $1/4$" thick and were made from samarium cobalt. Two magnets were mounted on each side of the source body. Steel pole tips and back plates were used to both place the magnets close to the source body and to mount the magnets to the steel yoke. This design only delivered 980 G in the plasma region and 650 G in the extraction region. A study performed by Volk [9] indicated that the Hci (resistance to demagnetization) for the magnets was low, and the yoke was saturated because it was too thin. This led to excessive extractor sparking early in source development.

In an attempt to increase the B_z field strength, the number of disc magnets were doubled to eight with four mounted on each side surrounding the source as seen in Fig. 11(b). To make room for these extra magnets, the $1/4$" back plate was removed and replaced with a copy of the pole tip piece to keep the magnet placement as

[1]In this paper, the xyz axes are defined in Fig. 12. The z direction comes *out* of the page and is not in the beam direction.

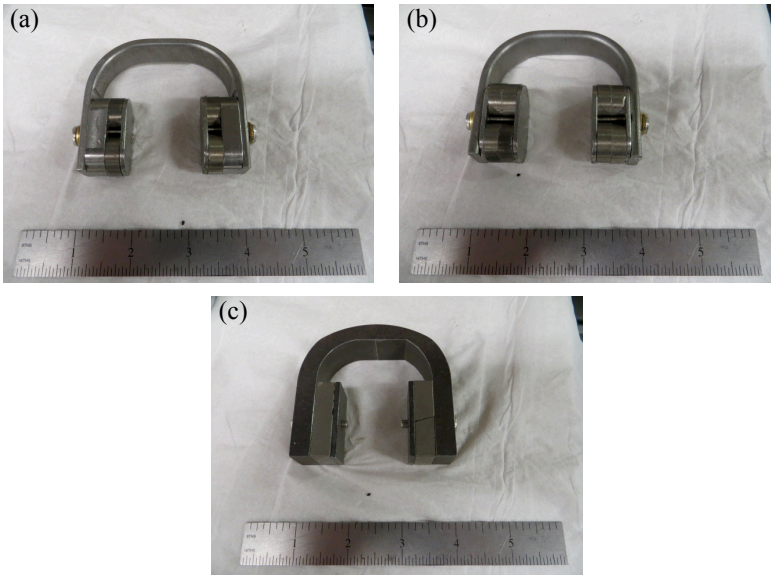


Fig. 11: Evolution of the yoke and magnet design. (a) The earliest design with a thin yoke and four disk magnets. (b) Increasing the number of disk magnets from four to eight. (c) Complete redesign of the assembly that uses a thicker yoke and two rectangular magnets.

close to the source body as possible. This did improve the B_z field strength but not quite enough to get 1 kG in the plasma region of the source. A redesign of the magnets and yoke assembly was done at this time to increase the field strength as shown in Fig. 11(c). New rectangular magnets were chosen to deliver a stronger, more uniform field across the cathode and the extraction area in particular. A thicker yoke made of low carbon steel was used to further increase the magnetic field strength in this area. Fig. 12 shows the relative B_z field in the center of the field region where the cathode dimple and beam extraction occurs for all three source magnet designs. The gains made with the rectangular magnet redesign are apparent in the higher B_z field strength in both the plasma forming and extraction areas. After upgrading the source with this new design, we have seen less signs of co-extracted electrons on the extractor cone and ceramic stand-offs.

3) Temperature effect: The samarium cobalt magnets used in the sources have a maximum working temperature of $300°$C from the manufacturer's published specifications. Above this temperature the magnetic field can be irreversibly changed and will not recover to its original value even after the magnet is cooled. The magnets are located 0.01" from the source body which operates at a temperature typically below $200°$C but can readily approach $250°$C during startup. While this may not be a high enough temperature to permanently affect the magnetic field strength, it is high enough to temporarily change the field strength of the magnets. For two months, a source was operated in the test stand while we monitored the temperature of the magnets and yoke. The 8 circular magnet assembly seen in Fig. 11(b) was used for this test. During this period, the magnet temperature did not exceed $75°$C as shown in Fig. 13.

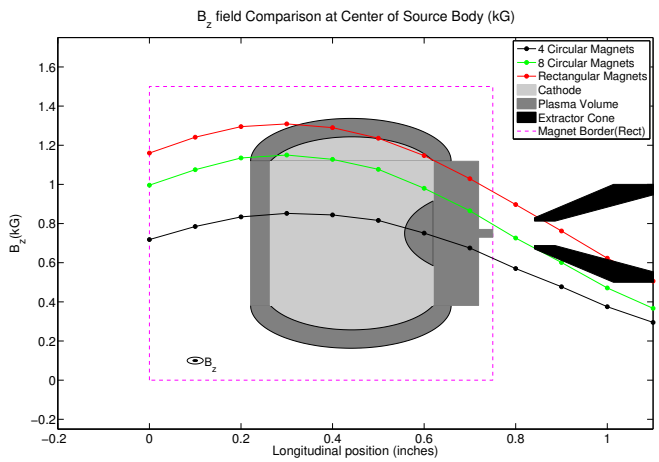


Fig. 12: Plot showing B_z field (pointing out of the page) strengths, for each magnet configuration, as a function of longitudinal distance from the base of the magnets. The source diagram is shown to accentuate the plasma region and beam extraction area. The rectangular magnet border is shown in magenta surrounding the cathode and plasma volumes.

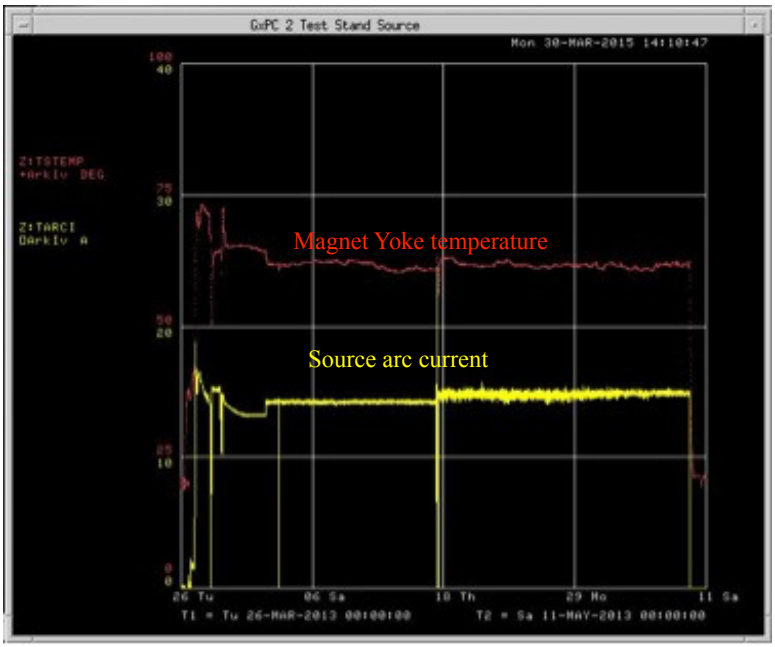
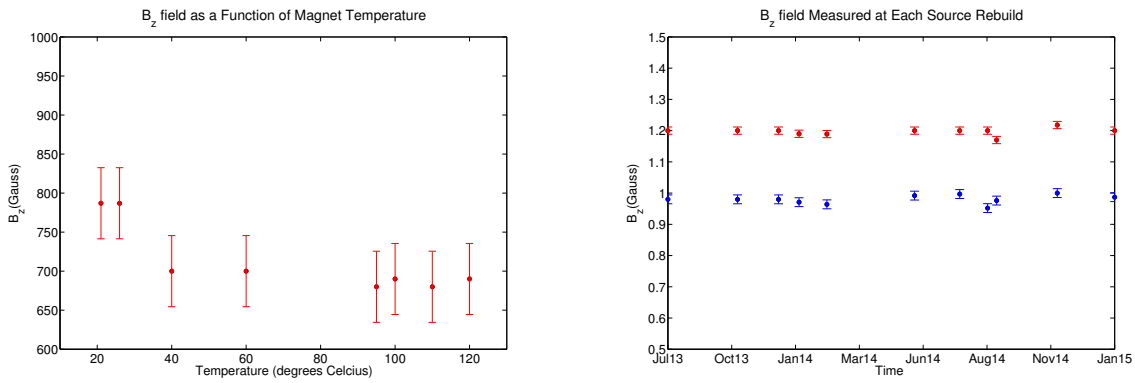


Fig. 13: Plot showing the magnet yoke temperature (Z:TSTEMP) and the source arc current (Z:TARCI) during a special run from March to May 2013 to understand source magnet heating during operations. Even during the source startup period when the source runs at the highest temperatures, the magnet yoke temperature never exceeded 75°C.



(a) (b)

Fig. 14: (a) The data shows that the B_z magnetic field is reduced at temperatures above nominal source operating temperatures. This data was taken with the disc shaped magnets and thin yoke. (b) This plot shows the magnitude of the B_z magnetic field strength measured in the plasma region (red) and the extraction gap (blue). These measurements were taken on the rectangular magnet design that has a thicker yoke each time this particular source was rebuilt or cleaned over the last two years.

Magnetic field measurements were also made in the atmosphere by heating the magnet yoke and source body assembly to 120°C and measuring the B_z field. This data is shown in Fig. 14(a) and the field is affected by the increased temperature even at 75°C because of the low Hci for the circular magnets. With the new rectangular magnets and thicker yoke, the temperature effect is now negligible. Also, the long term effects of the higher temperature operation have been monitored with each rebuild and cleanse of the source by measuring the magnetic field in the plasma region and at the extraction region while the source is rebuilt. The data for these measurements are shown in Fig. 14(b) which clearly shows that there is no long term degradation in the B_z field over a two year period.

C. Vacuum

Our initial vacuum system design was based on the amount of pumping speed that BNL used on their source vacuum chamber. We chose to use two 1200 L/s turbo pumps to closely match the BNL pumping of 2200 L/s. [1] It was assumed that this would be appropriate since the duty factor of the BNL and FNAL sources are similar.

With both turbos running at their maximum speed, the average vacuum chamber pressure was $\sim(1-2)\times10^{-6}$ Torr when the ion source was operating. This was our initial operating pressure, which happened to be during a time of high spark rates after the sources were installed in the operational beamline. It was noticed that the spark rate was lower in our test stand that only had 900 L/s pumping speed and had an average pressure of 1×10^{-5} Torr. Based on this, we turned off one of the turbos on the operating system which caused an increase in the pressure to $\sim 7 \times 10^{-6}$ Torr. As can be seen in Fig. 15, the extractor spark rate decreased. As a result of this experiment

we now use only one 1200 L/s turbo on each operational source vacuum chamber.

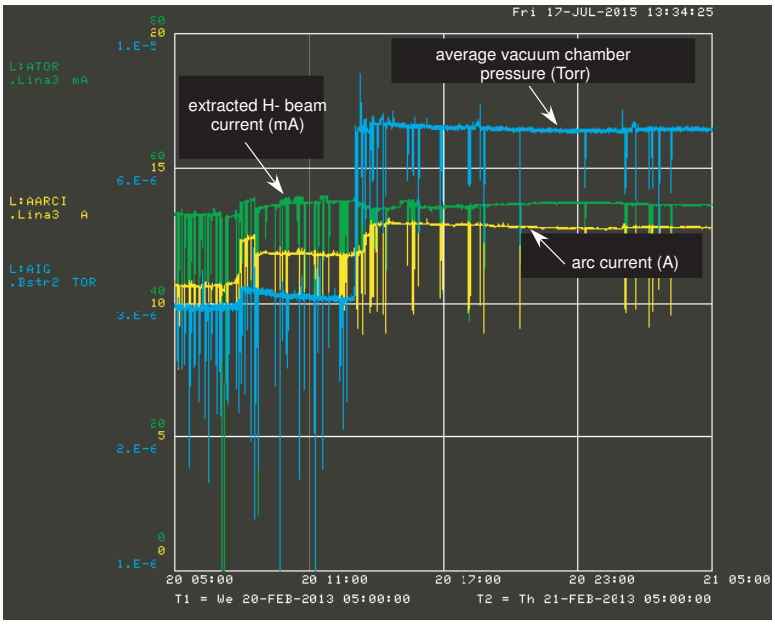


Fig. 15: The extractor spark rate decreased when the pressure increased.

Fig. 16 shows the bands of pressure in the vacuum chamber and the observed source performance within those bands.

- At pressures below 2×10^{-6} Torr there is not enough gas for the source to maintain a discharge. This is seen as the oscillations in the arc current seen in Fig. 17.
- At pressures between 2×10^{-6} Torr and 5×10^{-6} Torr the discharge is "noisy" and the extractor spark rates are high. The high spark rates due to this low pressure is not completely understood at this time. One possibility is there may be a high electron to H- ratio in the source which leads to a high number of co-extracted electrons.
- Pressures between 5×10^{-6} Torr and 9×10^{-6} Torr are the optimal operating pressures for the ion source. In this band of pressures the spark rate is at its lowest and H- stripping is not a factor.
- Pressure above 9×10^{-6} Torr is where H- stripping occurs due to residual gas.

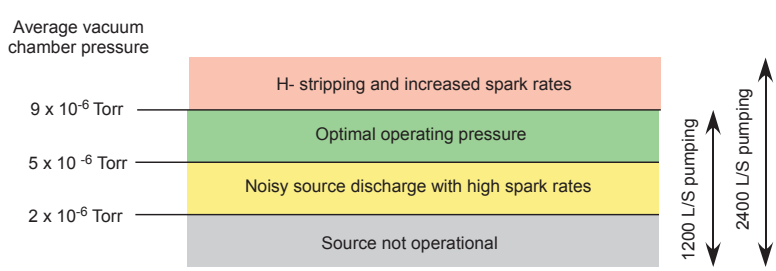


Fig. 16: This diagram summarizes the effect on the source at different pressures.

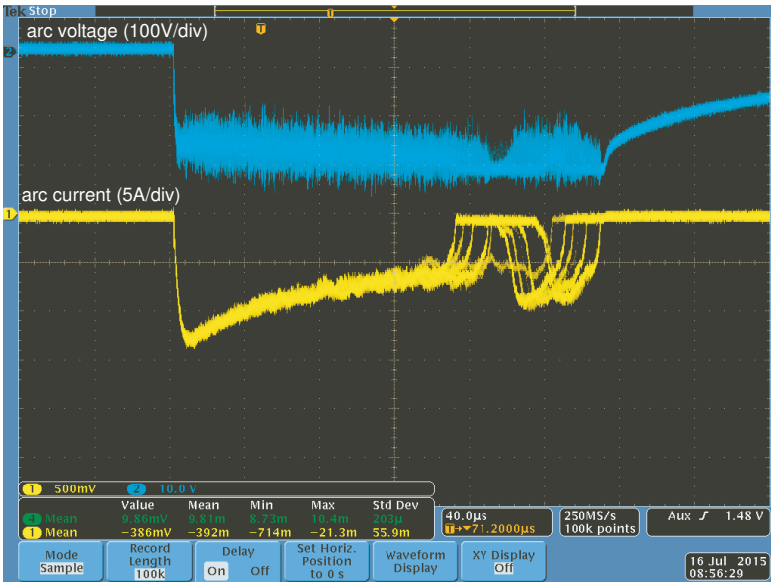


Fig. 17: The arc current oscillates whe the vacuum pressure gets below 2×10^{-6} Torr.

III. Operations

In this section, first we will discuss how to start a source because building a source is only one half of the equation. The other half is learning how to start it up so that the source can work reliably. In fact, the first week of source start up is an intensive process where we have to get the source to a stable point for operations. The recipe described here is the one that we have found that works well for us.

The second discussion is about cesium control and monitoring. Unfortunately, the only way we can control the flow of cesium is by changing its boiler temperature, which is operated open loop because there is no easy way to monitor the amount of cesium in the source. A method that we used to monitor the cesium and hydrogen concentrations in the plasma is with a simple, home made spectrometer. Long term monitoring of the spectra does show that the spectrum contains information about source problems. However, disentangling the data for more subtle changes in the source is a continuing challenge.

A. Starting a source

Source startup commences when the source cube average pressure reaches the mid 10^{-7} Torr range. Once this pressure is reached, we are confident that no vacuum leaks were introduced during the maintenance period, we can start the bakeout procedure.

We use the source body heater to bake out the source. The power supply is turned on to a current high enough to keep the source body over $250°$C so that the alcohol and water that are used to clean the source are baked out and the vacuum pressure reaches the low to mid 10^{-7} Torr. Fig. 18 shows a plot of the temperatures and vacuum pressure of one of our two operational sources (source B, in this case) during its cesium boiler system and source

bake for startup. In this instance, the source bake was allowed to run for three days over a weekend. This was a rare instance of starting a source after an accelerator maintenance period. Typically, source refurbishment is done during operational periods, with a turn around time of 24 hours after the source is turned off. The bake out also includes the cesium boiler system (see Fig. 8(b)) if a new 5 g, glass ampoule of cesium has been placed in the boiler. The bake out is done with heat tape wrapped around each of the three elements in the system: the boiler, valve, and tube. The glass ampoule is placed into the boiler unbroken and the cesium valve that connects the boiler to the tube, and thus the source, is opened. The heater power supplies for these three parts are then turned on. The temperatures are raised above 100°C for one hour to boil off any residual water in the system and then turned off and the cesium valve is closed. Once cool enough to the touch, the insulation is removed from the boiler and the copper boiler tube is pinched to break the glass ampoule inside, releasing the cesium.

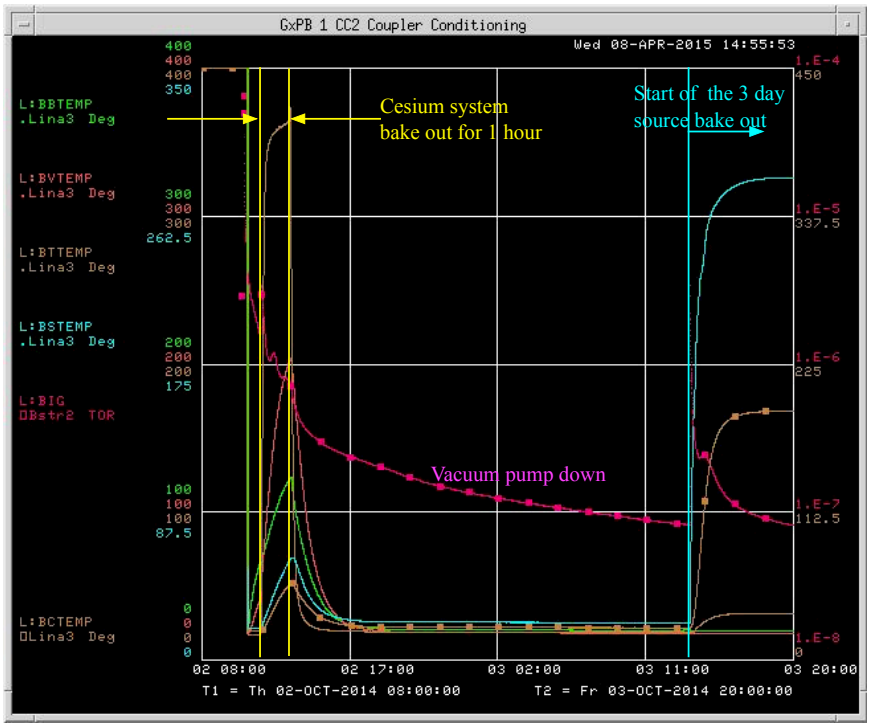


Fig. 18: The temperatures of the cesium heater system during a pre-startup bake out. The temperatures are: boiler in green, valve in pink, tube in magenta, cathode in brown, and source in blue. The vacuum pressure is in purple.

Once the source vacuum is further pumped down to the high 10^{-8} Torr range, the cesium valve is reopened and the cesium system heaters are turned on. If the source heater power supply was being used to bake the source body it is either reduced to a much lower value or it is turned off entirely. These heaters take roughly 6 hours to reach stable temperatures. At this time, the hydrogen gas valve is opened and the average cube pressure is set to about 1×10^{-5} Torr, and the arc modulator power supply is turned on at its upper limit of 300 V. Fig. 19 shows a plot during this period when the cesium system warms up and the gas and arc supplies are turned on.

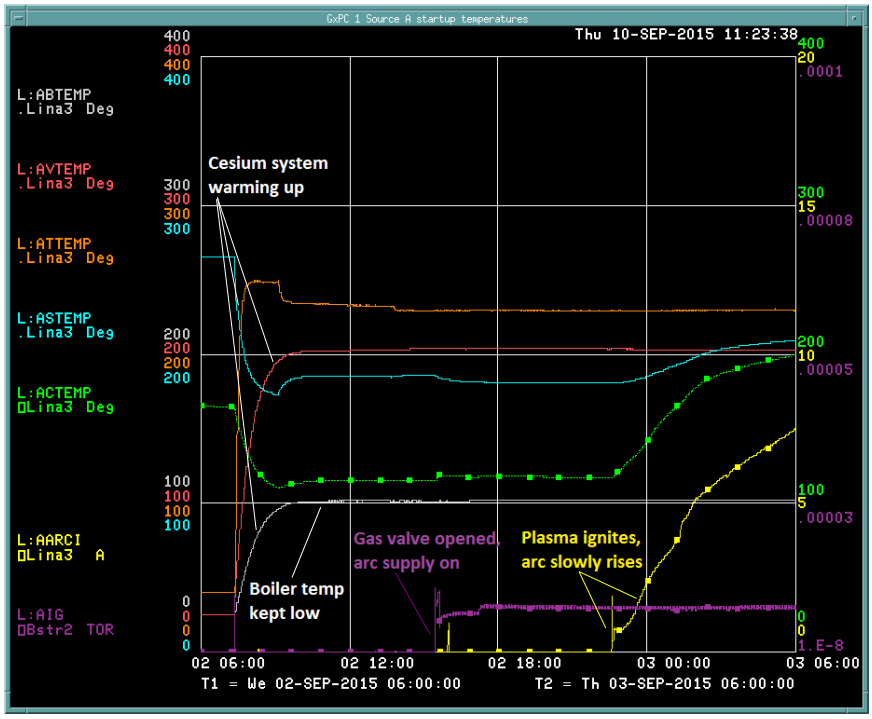


Fig. 19: The source temperatures starting from the end of the source bake-out, through the cesium heater system warmup period and finally into the source startup with the arc discharge current trace in yellow.

At this stage it can take hours for the cesium monolayer to reach optimal thickness for the generation of plasma as shown in Fig. 19 on the yellow trace labeled `L:AARCI`. `L:AARCI` is the arc discharge current in the source which is shown slowly rising as the source body and cathode temperatures rise to a new equilibrium with the plasma.

Over the course of the next day the arc discharge current will stabilize at some value that is typically lower than the operational level. Once this happens, the cesium boiler temperature is raised slowly over several days to increase the arc discharge current to the nominal range. This is done to limit the cesium in the source to just enough to allow for a stable arc discharge at the desired level and no more because this has been found to be critical for lower extractor spark rates.

Once the arc is stable, the gas pressure is lowered slowly to reach the usual operating pressure which is between 5×10^{-6} Torr to 7×10^{-6} Torr. The arc power supply is lowed similarly until the arc discharge current is near 15 A. The extractor power supply is now turned on, raised to 35 kV and the source is now able to provide beam if needed. The beam output of the source is usually $\sim$80 mA when measured on the first toroid in the beam line. The first toroid is about 0.5 m from the source and thus this value is dependent on how the beam line is tuned.

Once this has been done, the source usually behaves very well, and only small occasional tweaks in gas pressure, arc currents, and cesium boiler temperature are needed to maintain its performance.

B. Cesium

Cesium is an essential component for maintaining the plasma in the source. However, having too much cesium that does not participate in H- production causes the rate of sparking to inevitably increase to a rate of about once every few minutes. One way that we can demonstrate that there is too much cesium, is to shut off the cesium flow while still allowing the source to run. If there is too much cesium then the plasma can be sustained for hours (or even days) when the cesium boiler is off. Fig. 20 shows the result of this experiment.

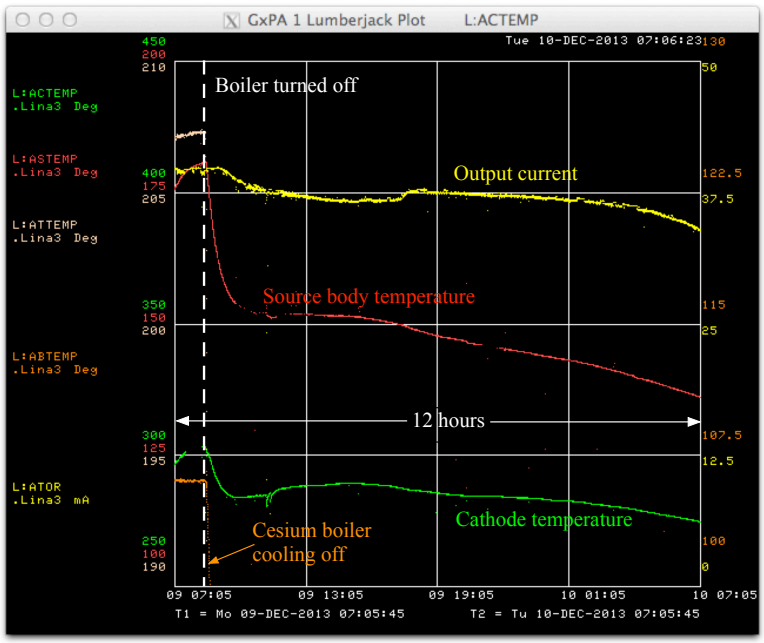


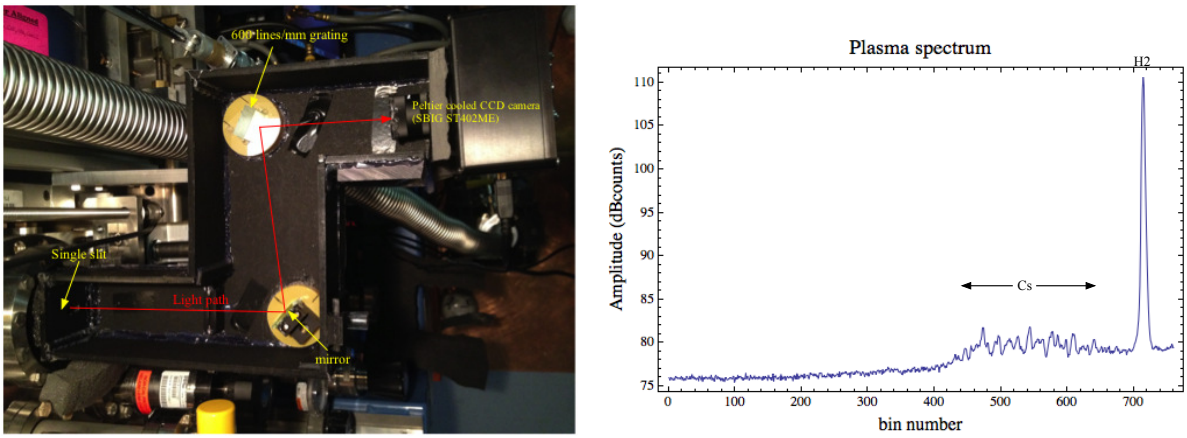
Fig. 20: After the boiler is turned off and the cesium valve closed, the plasma does not die off. In fact, there is still beam current after 12 hours.

The obvious question then becomes how do we measure the cesium flow rate and its concentration in the plasma. At the pressures and temperatures used in the cesium boiler system, the cesium is probably an admixture of both liquid and gas. If we want to measure the liquid flow of cesium, we can do the following back of the envelope calculation:

The amount of cesium in a freshly loaded cesium boiler is about $m = 5$ g that takes about $t = 600$ days to deplete. The cross sectional area of the cesium feed tube into the source is about $a = 4 \times 10^{-6}$ m^2, and since we are assuming that the cesium is liquid in the tube, the speed of the cesium v in the tube is approximately given by

$$v = (m/\rho)/(a \times t) = 13 \text{ nm s}^{-1} \tag{1}$$

where the density of cesium $\rho = 1.8$ g cm^{-3}. Therefore, the cesium flow rate is glacially slow and only indirect methods can be used to measure its speed if it is a liquid.



(a) (b)

Fig. 21: (a) Our homemade spectrometer installed on one of the operational sources. (b) The spectrum. The large peak is the hydrogen Balmer line at 656 nm and series of cesium lines from 560 – 620 nm.

However, if the cesium is gaseous, a surface ionization detector (SID) is one possible way for measuring flow rates. [10] However, again, the glacially low flow rates of ~ 0.7 mg/h using the above parameters, gives a signal that is in the μA range which is difficult to measure in the noisy environment where the source is installed.

1) Cesium concentration: The relative concentration of cesium w.r.t. hydrogen in the plasma is monitored using a spectrometer. The hypothesis is that the ratio between the hydrogen Balmer line and a cesium line gives this number. [11]. Fig. 21 shows the homemade spectrometer installed on one of the operational H- sources looking directly at the gas discharge (see Fig. 8(d)) and a typical spectrum of it. The hydrogen Balmer line at 656 nm and a cluster of cesium lines between 560 – 620 nm are very distinct. When the source is extremely over-cesiated, another hydrogen Balmer line pops up at 486 nm and the cluster of cesium lines become comparable in size to the hydrogen 656 nm line. More details of our spectrometer can be found in Ref. [11].

The cesium line can also predict that a large number of sparks is coming. For example, the cesium line that is monitored shows a huge increase over a few hours on Friday 05 Nov shown in Fig. 22. This is an indication that, for whatever reason, a burst of cesium was delivered to the source. Although the cesium line eventually drops back to its nominal level, the spark rate dramatically increases after that. In order to stop the source from sparking, the boiler temperature is repeatedly turned down and it is not until about 4 days later that the cesium contamination is burned off and the sparking stops.

IV. Beam noise

One problem with the magnetron source is that the extracted H- beam is quite noisy. Fig. 23 shows the beam noise at the exit of the source and at the 400 MeV end of the Linac after bunching through the RFQ. This noise is endemic in magnetron sources, and can be traced to the ratio of the scattering frequency ν of the electrons with

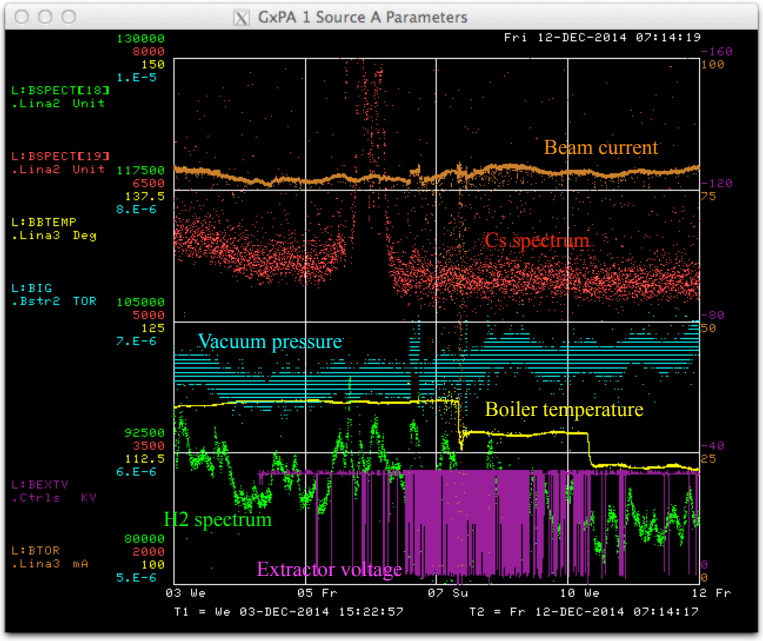


Fig. 22: The cesium spectral line indicates that a huge change in its concentration in the plasma. After the cesium line returns to its normal level, sparking of the source starts. The sparking is reduced only after the boiler temperature is lowered by 6°C which reduces the flow of cesium. Recovery takes about 4 days.

the ions to the electron cyclotron frequency ω. If $\nu/\omega > 1.5$, we have noiseless discharge. However, magnetrons are operated in such a manner that this ratio is always in the noisy regime. [12]

There are three known solutions for solving this problem. They are:

(a) Increasing the plasma volume.

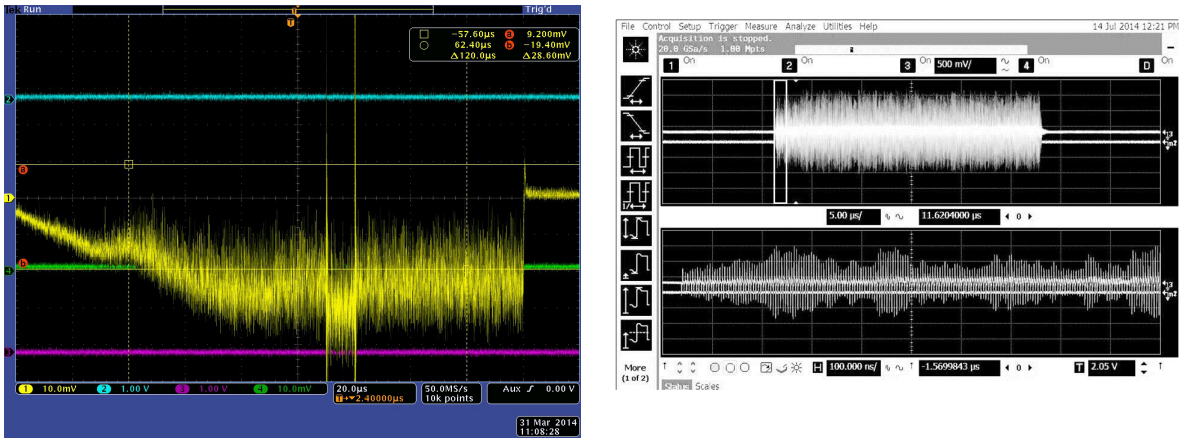
(b) Modifying the cathode so that it becomes a "hollow" cathode.

(c) Adding a small amount $\sim 1-5\%$ of nitrogen to the hydrogen.

We will discuss briefly these noise reduction techniques below. These techniques are covered more extensively in ref. [13]. Although we have studied these methods, we have not been able to conclusively state whether any of these methods work at this time due to the limitations of our test stand. These experiments will continue once our test stand has been upgraded.

A. *Increasing the plasma volume*

Alessi and Sluyters [4] observed that by increasing the spacing between the cathode and the anode on the back side of the magnetron, the discharge became more stable at a lower gas pressure than the normal grooved magnetron and the emission current density also increased. Other experiments by Wiesemann [14] also indicated that a larger plasma volume would lead to a less noisy source. Fig. 24 shows the different cathode geometries that we have tried in an attempt to increase the plasma volume.



(a) (b)

Fig. 23: The output of the H- source is quite noisy (yellow trace of (a)) The noisy spikes can be as large as 30% of the mean value of the beam current. The noise on the beam is preserved after bunching through the RFQ and manifests as beam drop outs (b) just before injection into Booster.

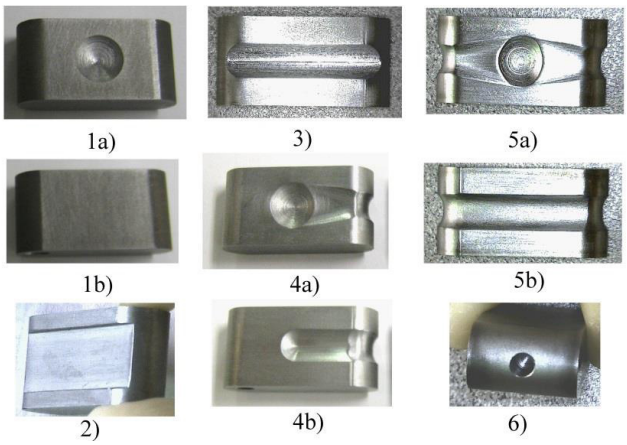


Fig. 24: Pictures of different cathode geometries studies. Initial studies involved incrementally increasing the size of the groove on the back of the cathode. All cathodes used the spherical dimple on the front of the cathode for focusing the H- ions to the anode aperture.

B. Hollow Cathode

A variation of the cathode called a “hollow cathode” was suggested by Dudnikov [15] as a means of discharge noise suppression in a magnetron. A hollow cathode that has a hole which is 3 mm in diameter and 6 mm deep is shown in Fig. 24(6) The idea behind a hollow cathode is that extra electrons are generated inside the hole which in turn, helps to generate more plasma and thus increases the plasma density. This technique has been used in other surface plasma sources. For example see [16], [17]. Again, this is the same idea that higher plasma density helps

to smooth out the noise on the extracted beam current.

C. Addition of nitrogen to hydrogen

The addition of a small amount of nitrogen to the hydrogen also smooths out the extracted beam. The physics behind this method is discussed in Ref. [12]. The addition of nitrogen to "cure" the noise problem was discovered by H.V. Smith *et al* in the late 1980s [18], [19] and is extensively used in Penning sources. Previous experiments at FNAL using a different style magnetron and operating point with 0.1% and 1.0% nitrogen to hydrogen ratio showed a reduction in noise [20]. Our experiments with 3%, 1%, 0.5% and 0.25% nitrogen to hydrogen ratios did not yield conclusive results. We attribute these results to (a) the difference in style of the present magnetron and operating point to that used in the previous study, and (b) the inadequacies of our present test stand.

V. Conclusion

The dimpled H- magnetron source has worked very well for operations. Small tweaks to the source are done every day to ensure that the source meets the high energy physics requirements. Although all the major problems that we have identified have been fixed, there are still a few improvements that need to be done. The list of upgrades are as follows:

(i) Replacing the piezo gas valve with a solenoid driven gas valve. The closure of the piezo gas valve is notorious for drifting with the ambient temperature and by replacing it with a solenoid drive gas valve this problem will be solved. This upgrade has been done and will be used for operations starting in October 2015.

(ii) Improving the entire cesium boiler system. The present system has very poor temperature regulation and there are many parts that need to be replaced to fix this problem.

(iii) Changing some aspect of the source to reduce beam noise. Although none of the experiments, so far, have shown a definitive cure for the noise problem, we believe that this is due to the limitations of our test stand. The test stand is presently being upgraded and should be operational by the end of 2015.

In conclusion, we have summarized our experiences for building H- sources for accelerators in this paper. We hope that this paper will be useful for users who plan to build this type of source and will help to get it started up and running quickly.

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