

General Heater and Heaterless Cathode Operating Information

Cathode Information

Plasma Controls offers cathodes with and without heaters. See Figure 1 for terminology which outlines the low work function emitter, which goes inside a cathode tube called the “cathode tip”, which typically integrates into a “cathode assembly” which can include the cathode mount, keeper, and optionally a gas flow isolator.

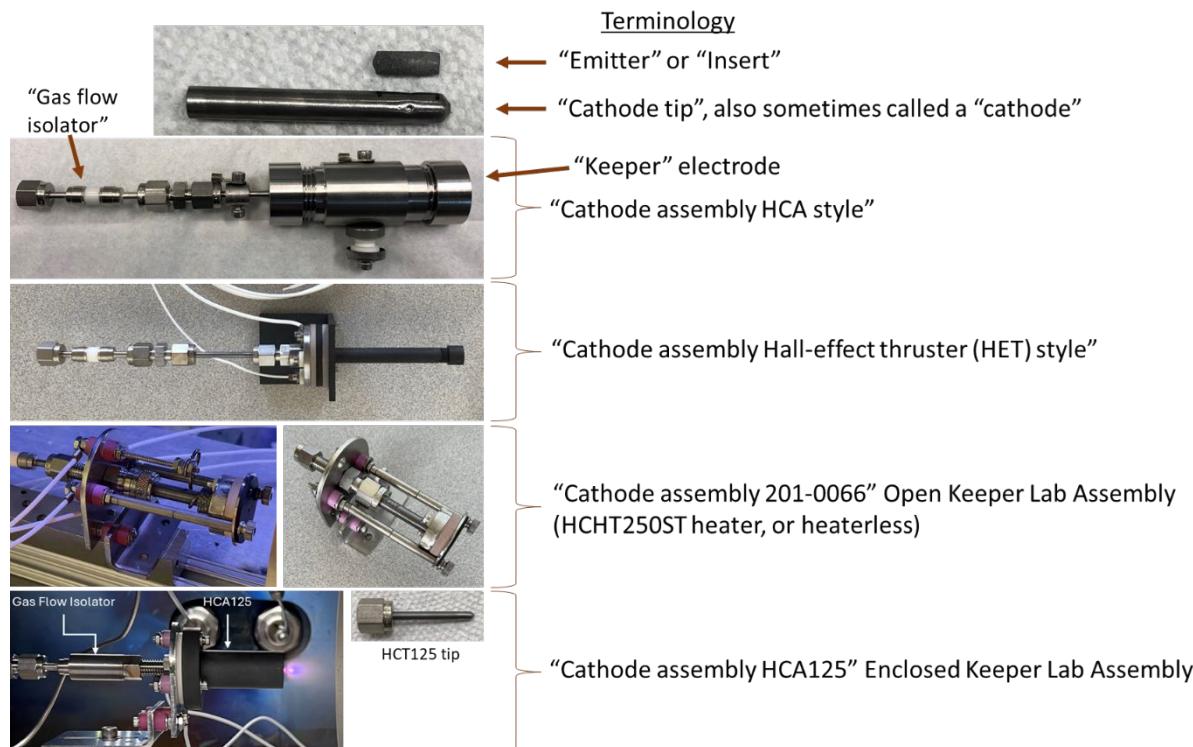


Figure 1. Cathode terminology of an emitter, cathode tip, and cathode assembly.

Emitter

Plasma Controls’ emitter is a porous tungsten metal matrix with a combination of barium calcium aluminum and scandium ceramics with BaO as the primary low work function component. The cathode cermet (ceramic + metal) emitter is moisture sensitive and will degrade in humid environments (many months to years), and therefore the cathode tip may need to be replaced periodically. The cathode assembly can be re-used. Typical cathode tip costs as of 2024 are \$500 to \$1600 dollars.

Heater Cathode Tip

For cathodes with heaters, Plasma Controls generally offers cathode tips in 3/16" or larger tubular outer diameter (OD) only. The 1/4" OD cathode tips are called the HCHT250ST and the HCHT500ST. They are virtually the same except for the final wrapping and termination of the coaxial heater winding. They are designed as drop in cathode tips in commonly used ion sources as the neutralizer and source cathodes. See Figure 2 for photos. The HCHT250ST does not have a heater lug on the end of the heater coil.



Figure 2. Plasma Controls offers 1/4" heater cathodes as well as a range of "heaterless" options.

Electrical Schematic

Figure 3 shows an electrical schematic for a cathode assembly with a heater. The schematic shows a heater power supply, keeper power supply, and a discharge power supply. If it is desired to float the cathode or bias the cathode with respect to ground, then a flow isolator must be used if the flow line is not already isolated.

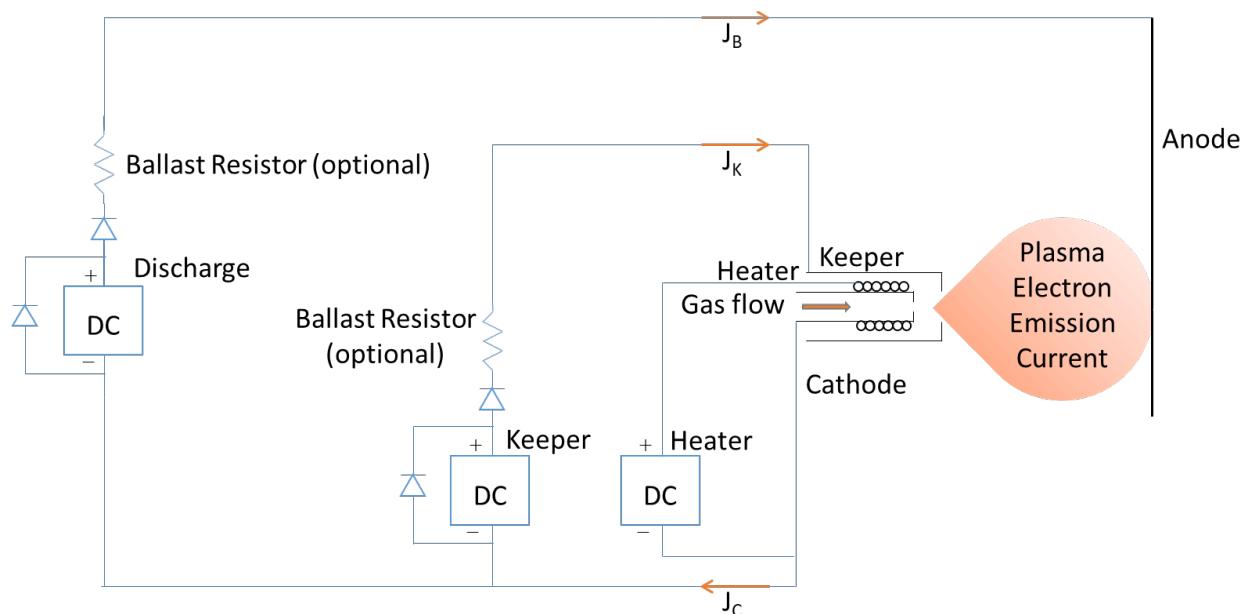


Figure 3. Electrical schematic with heater installed. [Ballast resistors and diodes are generally optional with a heater.]

The heater power supply is used to resistively heat a swaged tantalum heater cable that is wrapped around the cylindrical hollow cathode tube. A tip temperature of 1100 °C of the hollow cathode is typically sufficient to start the cathode using the keeper power supply (through application of ~ 100 V). Once an arc discharge is established between the keeper and the cathode, the anode power supply is used to establish a higher current discharge between the cathode and the anode structure. At this point, the heater power to the hollow cathode can be switched off as the hollow cathode will operate in a self-heated mode.

Heater Power Supply

In both conditioning and starting modes, the heater power supply is used in a current controlled mode and must be capable of operation from 0 A to 8 A over a voltage range from 0 V to 12 V. The heater coil has a resistance of about 1 Ohm and a maximum current of 7 A, which allows about 50 to 60 W of heating power to heat the cathode to operational temperature.

Heater and Emitter Cathode Conditioning

To ensure long lifetime when using this type of emitter and swaged heater, the hollow cathode must be prepared (or conditioned) for operation. The preparation consists of slowly heating the cathode over time to drive off unwanted contaminates that react with the insert when it is exposed to air. The hollow cathode should be conditioned prior to operation every time it is exposed to laboratory air, rough vacuum conditions, or to gas flow containing atmospheric gases (Table 1).

Table 1. Recommended cathode heating schedule.

Heater Power Supply Current	If the cathode has not been operated within the last month:	If the cathode has been exposed to atmospheric conditions:	If the cathode has been kept under vacuum and operated within the last month:	Notes:
(Amps) Heating Current Duration (minutes)				
2.0	30	15	5 (skip if < 2 days)	
3.0	30	15	5 (skip if < 2 days)	
4.0	5	5	5 (skip if < 2 days)	
5.0	5	5	5 (skip if < 2 days)	
5.5	5	5	5 (skip if < 2 days)	
6.0	5	5	5	Perform start attempt.
6.5	5	5	5	Perform start attempt.
7.0	5	5	5	Perform start attempt. Do not exceed 7.0A on the heater.

Heaterless Cathodes

The Heaterless cathode takes away the coiled heater to remove the component itself as well as the associated heater power supply. In exchange, the heaterless cathode must be ignited by a combination of elevated gas flow and/or keeper voltage and the user must accept the lack of cathode conditioning. Heaterless cathodes have been fabricated in a range from 1/16" to 3/8" cathode tube outer diameters to supply a range of electron currents (Table 2, graphically in Figure 4). The minimum current required to sustain the cathode tips is estimated in the table.

Table 2. Cathode tip operating range.

Cathode tip OD (inches)	Typical Orifice Dia. (inches)	Emitter Type	Est. Emission Rating (A)	Minimum Emission (A)
0.062	0.015	Plug	Up to 0.7 A	0.2*
0.081	0.020	Plug	Up to 2.0 A	0.2*
0.125	0.020	Plug	Up to 5.0 A	0.3*
0.188	0.020	Plug	Up to 7.5 A	0.4*
0.250	0.040	Plug/Tubular	Up to 20 A	0.5*
0.375	0.090	Plug/Tubular	Up to 40 A	1.0*

*Min emission currents have not been verified.

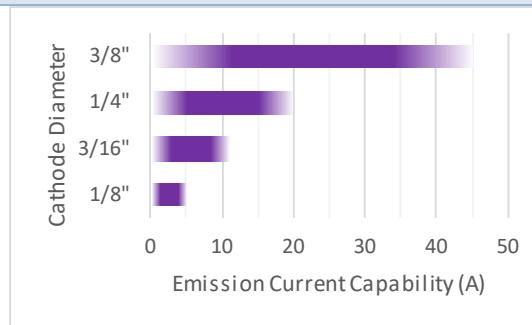


Figure 4. Graphical representation of cathode diameter and typical emission current.

Heaterless Hollow Cathode Ignition

An electrical schematic is shown in Figure 5 for basic operation of the Heaterless hollow cathode as an electron source. Two DC power supplies are used, one power supply for the keeper electrode to start and maintain the cathode discharge and a second bias power supply to draw electrons from the cathode assembly to the surrounding vacuum environment.

Note: it is highly recommended that ballast resistors and blocking and freewheeling diodes be used to limit peak currents and protect the cathode tip and bias and keeper power supplies, especially during plasma ignition. Suggested diodes can include VS-RA220FA120 (heat sink VXA-55-101E), or diode DSIK45-16AR (heat sink could be WV-T247-101E). If the plasma ignition is roughly arcing, large currents and oscillations can easily damage the power supplies.

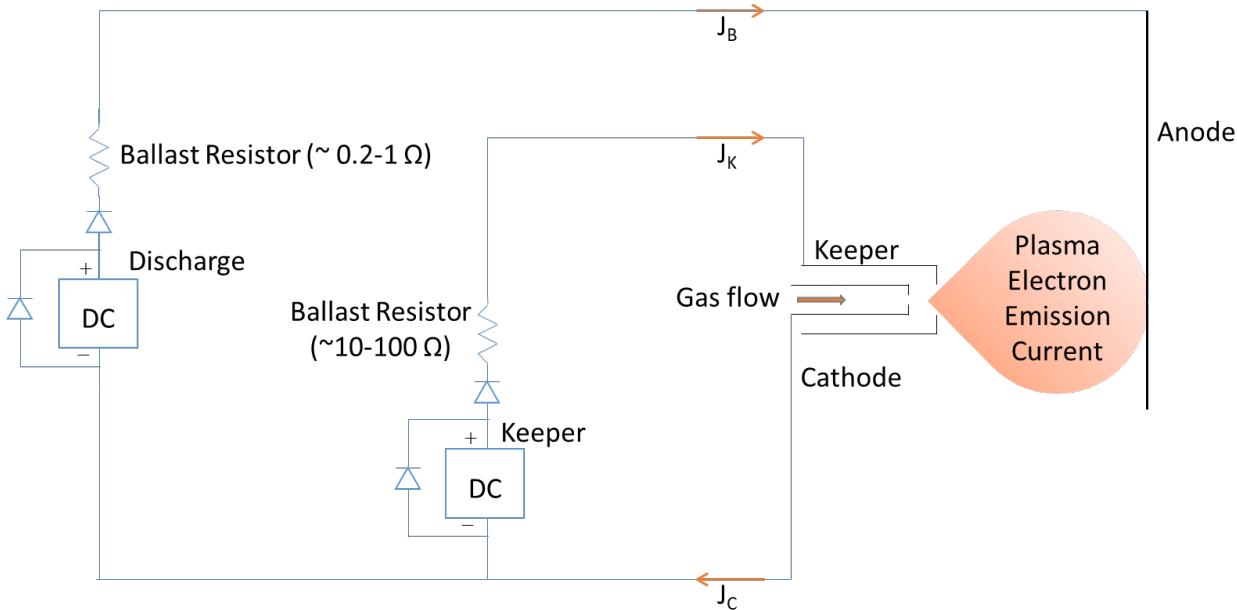


Figure 5. Example electrical setup for heaterless hollow cathode testing. The electron current emitted from the cathode is the current to the keeper plus the bias/emission current to the anode. Note the use of ballast resistors and protection diodes.

Ballast Resistors: Take care to size the resistor power capacity according to steady-state current values. For instance, if the keeper current is 500 mA, and a 20 Ω resistor is used, the resistor power is 5 W. A 100 Ω resistor and 1 A keeper current would require a substantial 100 W of power dissipation on the resistor.

Starting the heaterless cathode requires a combination of elevated gas flow rate and keeper voltage. In heaterless cathodes, a moderate to high gas flow (in the range of 15 to 50 sccm and above) and keeper voltage (in the range of 400 to 1500 V) are usually necessary to create an arc discharge that heats the cathode up to the 1000 °C and higher temperature range to allow for thermionic emission of electrons (see (Lev and Appel, Heaterless Hollow Cathode Technology - A Critical Review 2016 May 2-6), (Daykin-Iliopoulos, et al. 2015), (Belt and Mankowski 2008), and (Lev, et al. 2015) for example). On ignition, it is very desirable to provide enough flow and voltage with appropriate ballast resistors and diodes to yield a single-arc ignition, as opposed to a “rough” cathode start which can have repeated on-off arc events. **A smooth transition from a volumetric ion production process (for supplying the desired electron emission current) to a thermionic process over a period of 3 to 6 seconds is desired, avoiding any short-lived, repeated cathodic arcs, most commonly observed during startup.** The smooth transition is ideal for both the cathode tube tip wear and to avoid breaking output capacitors inside laboratory DC power supplies.

Figure 6 shows an example plot of voltage versus flow required to start the heaterless hollow cathode. Two methods can be used to start the cathode:

Method one is to apply a steady state gas flow through the cathode (15 sccm to 100 sccm values are shown in the plot for example), set the keeper power supply to current regulate to a nominal value (say 300 to 500 mA), and then apply and increase the keeper voltage as required until the keeper discharge starts (from 425 V at high flow to 1300 V at low flow shown in the plot).

A second method (preferred) is to begin at reduced gas flow (to not cause initial arcing), apply a constant keeper voltage, 600 V for example (with the keeper power supply set to regulate in current mode to a nominal value say 300 to 1500 mA), then temporarily increasing the gas flow to the cathode, called a fixed volume release (FVR) (Figure 7). If the operator's mass flow controller is limited, the user may choose to install a shut-off valve in the gas line downstream of the flow controller. A gas surge through the cathode tube may be accomplished by setting a gas flow rate and temporarily closing the shut-off valve for a set period of time to allow gas to build in the gas line(s) between the mass flow controller and the shut-off valve. For example the tubing could be $\frac{1}{4}$ " tubing with a line length of 1 meter. We recommend attempting a FVR time sequence of 15-30 seconds to begin to ensure a smooth ignition, then the user can experiment with reduced FVR times or fill rates until rougher ignition is observed (want to avoid rough ignition, so use a FVR that results in smooth ignition). See work by Ham et al. for xenon in $\frac{1}{4}$ " cathodes (Ham, Williams, Hall, Benavides, & Verhey, 2019) and ways to effectively size the FVR volume for a single-arc smooth start.

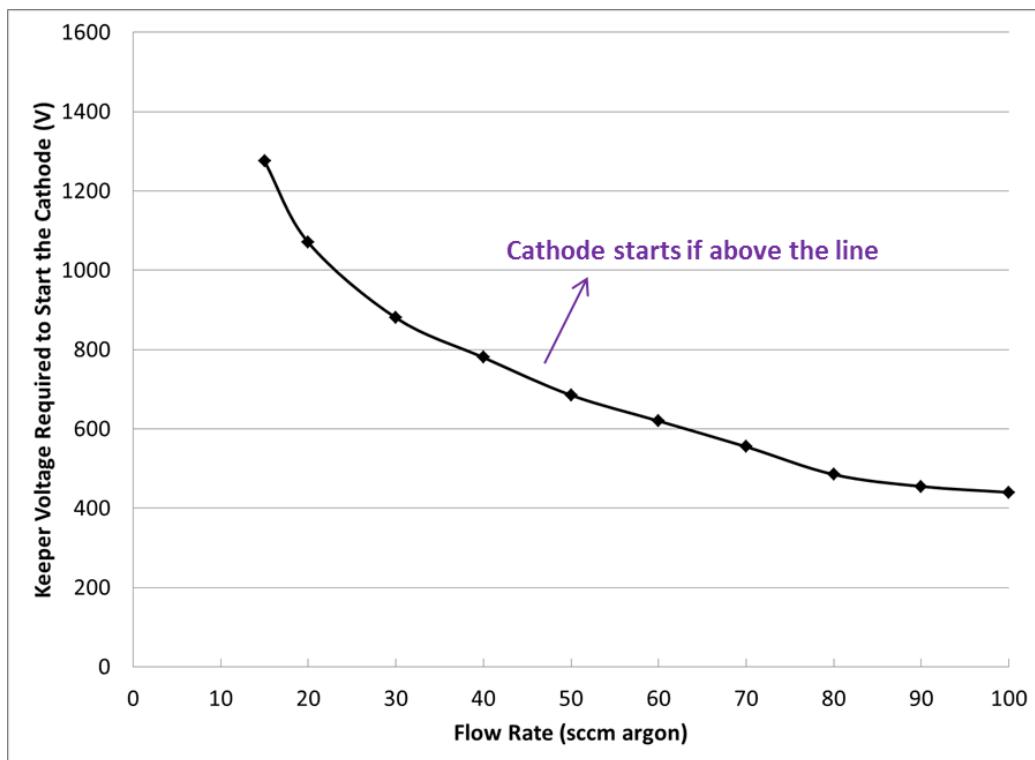


Figure 6. Example keeper voltage vs flow rate curve showing the required combination of voltage and flow necessary to start the plasma discharge in the heaterless hollow cathode assembly. Note: curve will be unique to each cathode, keeper, assembly configuration, and gas type.

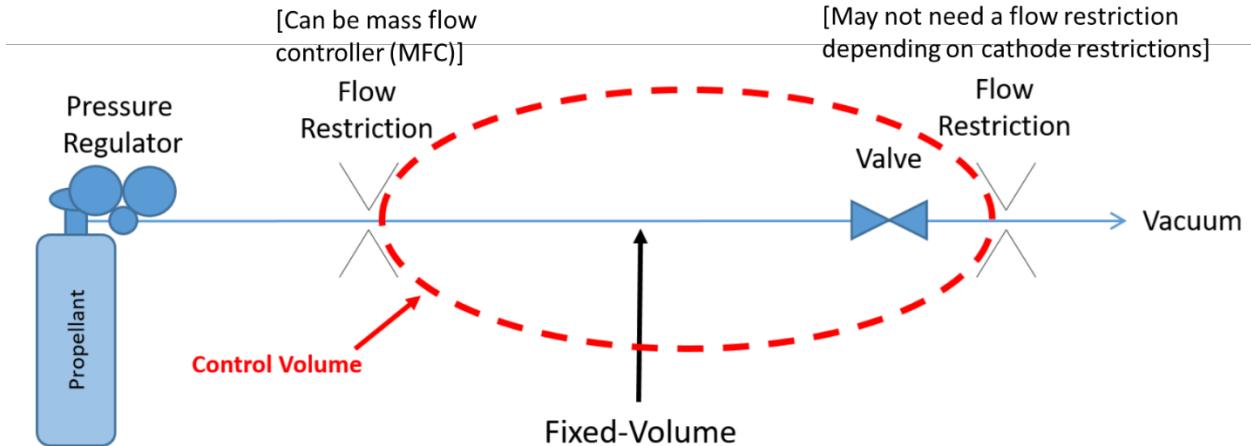


Figure 7. Simple fixed volume release scheme (Ham). A MFC can be set to a steady state flow and a downstream valve can be closed to build up a volume of gas to temporarily increase flow to ignite the cathode.

After plasma initiation, the keeper and bias power supplies will then be normally current-regulated.

Table 3. Typical hollow cathode operating values.

	Discharge Initiation	Steady-State
Keeper Voltage	400 to 600 V (dependent upon gas flow and gas type)	15 to 40 V (no emission) (lower voltages possible with emission current)
Keeper Current	Set to a desired steady-state regulation value before discharge initiation (>300 mA is recommended, typically starts easier if keeper current is greater at 0.5 to 1.5 A)	200 to 500 mA (can be adjusted outside of this range if desired, or when using larger cathode tips)
Gas Flow Rate	30 to 100 sccm typical	2 to 10 sccm typical (argon)

Bibliography

- Belt, D., and J. Mankowski. 2008. "Diagnostics of the Start-Up Process of an Arc Hollow Cathode." *IEEE TRANSACTIONS ON PLASMA SCIENCE* 36 (4): 1210-1211.
- Daykin-Iliopoulos, A., S. Gabriel, I. Golosnoy, K. Kubota, and I. Funaki. 2015. "Investigation of Heaterless Hollow Cathode Breakdown." *34th International Electric Propulsion Conference IEPC-2015-193 / ISTS-2015-b-193*.
- Ham, Ryan K, John D Williams, Scott J Hall, Gabriel F Benavides, and Timothy R. Verhey. 2019. "Characterization of a Fixed-Volume Release System for Initiating an Arc Discharge in a Heaterless Hollow Cathode." *IEPC*. Vienna.

Lev, D., and L. Appel. 2016 May 2-6. "Heaterless Hollow Cathode Technology - A Critical Review." *SPACE PROPULSION 2016*. MARRIOTT PARK HOTEL, ROME, ITALY.

Lev, D., G. Alon, D. Mikitchuk, and L. Appel. 2015. "Development of a Low Current Heaterless Hollow Cathode for Hall Thrusters." *34th International Electric Propulsion Conference IEPC-2015-163* / ISTS-2015-b-163.