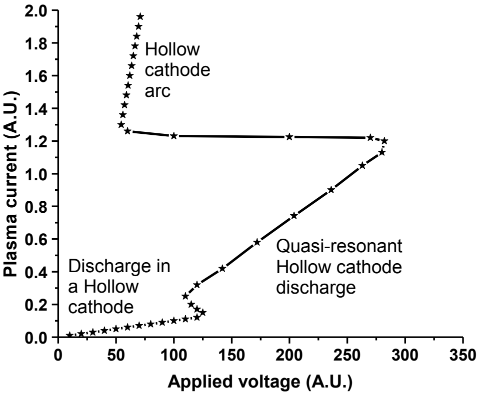
Hollow Cathode Discharges

S. Muhl[1] & A. Perez[2]

[1] *Instituto de Investigaciones en Materiales, Universidad Nacional Autónoma de México, México, DF, México.*
[2] *Facultad de Ciencias, Universidad Nacional Autónoma de México., México, DF, México*

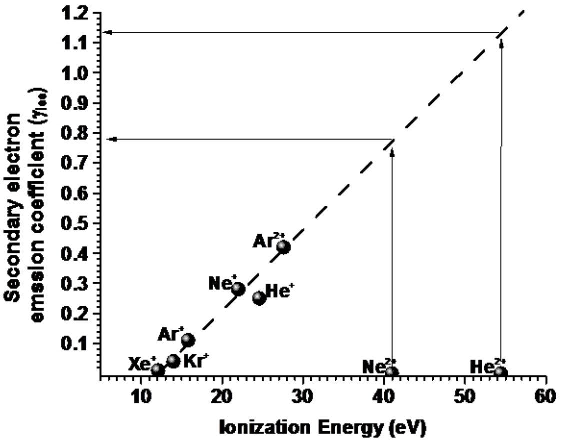
The hollow cathode discharge was first report by F. Paschen in 1916. That study showed that the arrangement was capable of producing a high electron flux and plasma density. Since then the term "hollow cathode" has been used to describe almost any cathode with a cavity-like geometry, such that the plasma is partially bound by the walls which are at the cathode potential. Just as the magnetic trapping of the electrons in a magnetron results in an increase in the plasma density (10^8 – 10^{11} cm^{-3}) for magnetron sputtering, in the hollow cathode the geometry produces a high-density plasma by reducing the loss of electrons (10^{11} to >10^{13} cm^{-3}). However, at least 3 types of discharge can exist in a hollow cathode, at low power and/or a low gas pressures the plasma is a "conventional" discharge characterized by low currents and high voltages (here we call this a Discharge in a Hollow Cathode or D-HC).). Even this simple plasma has a higher density, 10^{10} – 10^{11} cm^{-3}, than that of a normal planar parallel electrode system because of the significant reduction in the loss of electrons. For an appropriate combination of gas pressures and applied powers, and an adequate hollow cathode diameter and length, the negative glow of the plasma in front of the cathode surface can expand and almost completely occupy the interior volume of the electrode. Under this condition the plasma current can be 100 to 1000 times the values for the "simple" D-HC discharge and the plasma density is correspondingly large, up to almost 10^{14} cm^{-3} (we call this a true Hollow Cathode Discharge or HCD). If the cathode is not cooled the discharge can change into a dispersed arc as the electrode temperature increases and thermal-field electron emission becomes an important additional source of electrons (we call this a Hollow Cathode Arc or HCA).



The accepted explanation for the formation of the HCD phenomenon involves the existence of high energy "pendulum" electrons which are reflected from the sheaths on either side of the inside of the cathode; the long trajectory of these electron is considered to produce a large number of secondary electrons, with this resulting in the high plasma density and plasma current. Indeed many authors have proposed that a significant part of the gas phase ionization occurs within the sheaths and cathode dark space on either side of the inside of the cathode.

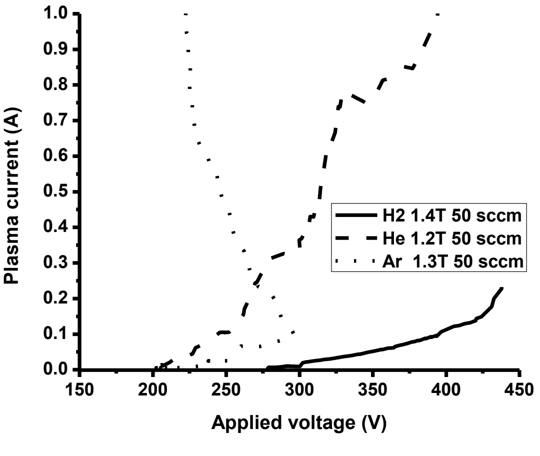
In this study we first describe in detail the structure of a typical parallel-plate argon gas discharge. In particular, we consider the gas-phase excitation and ionization processes produced by electron and ion collisions with the gas atoms, together with the secondary electron emission from the cathode. We explain how published data shows that the luminosity of the cathode glow is primarily due to ion-impact rather than electron-impact excitation, and we discuss the implication of this on the distribution of the energy of the electrons between the cathode surface and the edge of the negative glow region.

We will discuss some of the problems associated with the well-accepted "pendulum" electrons model and we propose a new explanation based on the formation of doubly charged ions. Using ideas from the description of the structure of the DC discharge together with published values of secondary electron emission coefficients for singly- and doubly-charged noble gas ions, we propose a new model of the quasi-resonant hollow cathode discharge, HCD, based on the formation of doubly-charged ions within the negative glow region. The basic hypothesis is that inside the negative glow the flux of relatively high-energy electrons, together with the accumulation of singly-charged ions, is sufficient to promote the formation of doubly-charged ions. The secondary electron emission coefficient of such ions is approximately 4 times greater than that of singly-charged ions, and therefore the generation of doubly-charged ions strongly enhances the production of electrons from the cathode and this consequently produces more ions including additional doubly-charged ions. This quasi-resonant process explains the super-linear increase in the plasma density, plasma current and light emission of the discharge as the hollow cathode discharge condition is established. We also describe based on this new model the effect of the cathode geometry, the gas pressure / cathode-diameter product, the use of a pulsed-DC or RF power supplies and magnetic fields on the formation of the HCD condition.



Many studies have shown that there are conditions under which the HCD state can and cannot be established. In general, groups have observed that for values of the product of the pressure, *p*, and the diameter of the cathode, *d*, between approximately 0.1 and 37 Torr.cm, the HCD mode can be established fairly easily but outside this window only the low density D-HC state can be formed. Various studies of atmospheric micro-plasmas and other high-pressure hollow cathode devices have shown that the maximum value of *p.d* for HCD state is 5-6 Torr.cm, and this implies that the high-pressure limit is inversely proportional to the operating pressure of the hollow cathode. The upper *p.d* limit is also dependent on the gas or gas mixture used. Furthermore, for a given value of *p.d* the operating voltage required to maintain a certain value of discharge current is lower for smaller values of *d*. Research has shown that the length of the cathode also plays an important role for the characteristics of the discharge. It was shown that for a 4-mm-diameter cathode operated at 2.3 kPa (17 Torr, *p.d* ~6.9 Torr.cm) the optimum length of the cathode to produce a uniform axially-excited plasma density was 20 mm. A strong axial non-uniformity in the plasma density was found for longer cathodes with two maxima near the exit of each end of the cathode and a minimum in the central region. In general, it has been concluded that the ratio of the length to the radius of the cathode should be 7 to 10.

The application of a magnetic field along the axis of the hollow cathode has an effect similar to that of the field in a magnetron cathode. If the magnetic field is applied perpendicular to the electric field, then the electrons adopt a helical trajectory and this extended path length increases the probability of ionization events. In the case of the planar magnetron, it is clear how the trapping of the electrons in a helical trajectory can be beneficial. The optimum field intensity is such that the electrons are trapped near the presheath, i.e. close to the edge of the negative glow, and in this way the additional ions produced are accelerated by the full sheath potential. In the hollow cathode, electrons are confined inside the discharge by the geometry of the cathode and it is not completely clear how the magnetic field increases ionization. However, the use of magnetic fields has been reported to increase the plasma density and, correspondingly, the plasma current.



One important implication of the new doubly-charged ion model is that a hydrogen quasi-resonant hollow cathode discharge should not be possible. In order to study this, we performed hollow cathode discharge experiments in argon, helium and hydrogen, using the same conditions of plasma power, gas pressure and flow. The current-voltage characteristics of the discharge were measured for each experiment. A quasi-resonant discharge was clearly observed for argon and helium but only a lower-density, low-current plasma could be formed in hydrogen.

The doubly-charged ion model has some important implications for the existing and extensive applications of hollow cathode discharges; Gas flow sputtering, PECVD, e-beam evaporation, e-beam PECVD, ion beam sources, spectral lamps, atmospheric micro-plasmas, etc.

Much of the work included in this talk can be found in the paper “The use of Hollow Cathodes in deposition processes: a critical review” by Stephen Muhl and Argelia Pérez, published in Thin Solid Films.