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Breakdown minimum in magnetic field-driven metal plasmas

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Abstract. The minimum breakdown requirement in magnetic field-driven sources, like inductively coupled plasmas, is examined. The minimum breakdown requirement is dominated by the ionization energy of the considered element. Therefore, a zinc plasma is relatively difficult to ignite compared to other metal plasmas.

1. Introduction

Starting from the Paschen curve for electric field-driven plasma sources, breakdown curves for time-dependent magnetic field-driven plasma sources can be derived as shown in [1]. Similar as for the Paschen curve, this magnetic flux density breakdown curve shows a minimum.

The electric and the magnetic Paschen curve uses two coefficients A_0 and B_0, usually experimentally obtained, to determine at which applied electric voltage a plasma will be self-sustaining after its generation. Experimental data for A_0 and B_0 are not available for metal plasmas. Examining the first Townsend coefficient α, analytic expressions for the two parameters A_0 and B_0 can be obtained, see [2].

Here, the minimum of the magnetic flux density breakdown curve is examined. The minimum of the magnetic flux density breakdown curve turns out to be related to the ratio of the two Paschen parameters, such that this minimum is dominated by the ionization energy of the considered gas. This outcome is of practical importance with respect to the ease of plasma ignition inside inductively coupled plasmas (ICPs). In Section 5, examples are given using several metal plasmas.

2. The Paschen curve

The Paschen curve of the Townsend discharge [3–6] is used to predict gas breakdown inside electric field-driven plasma sources. The electric field is drawn from a voltage difference V between two electrodes at a distance d. These electrodes form a gap, in which the gas is at pressure p. In order to describe the Townsend discharge, two coefficients are used.

The first Townsend coefficient α describes the success rate for accelerated electrons to collide and ionize the background gas. The first Townsend coefficient depends on two parameters A_0 and B_0,

$$\alpha = A_0 p \exp\left(-\frac{B_0 p d}{V}\right). \tag{1}$$

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The parameters A_0 and B_0 have been determined experimentally for the most common plasma gases like argon and nitrogen [7]. For other plasmas, these parameters are theoretically determined by [2]. The parameters A_0 and B_0 are roughly constant over a range of voltages and pressures for any given gas [3].

The second Townsend coefficient γ describes the success rate of newly created electrons at the electrodes. The created positive ions may collide with the cathode creating new electrons, called the secondary electrons, out of the electrode.

The Paschen curve [3–6] relates the required voltage V versus pressure p times the electrode distance d, in order to burn a self-sustaining plasma inside the gap,

$$V_{\text{breakdown}} = \frac{B_0 pd}{\ln(A_0 pd) - \ln\left(\ln\left[\frac{\gamma+1}{\gamma}\right]\right)}. \tag{2}$$

3. The breakdown magnetic flux density

The Paschen curve can be modified for time-dependent magnetic field plasma sources [1] like ICPs.

For an ICP, an induced current is created inside the plasma gas. According to Ohm's law, this current is related to an electric field E. The electric field is related to the applied magnetic flux density B according to the Maxwell relations. The magnetic flux density B is generated by the induction coil current of the ICP.

In case of a self-sustaining ICP, accelerated particles may create new electrons and ions by collisions while electrons and ions are lost due to recombination. The ICP is self-sustaining as long as the amount of created new electrons and ions is equal or larger than the losses because of recombination. Note that the first Townsend coefficient α is again the success rate for accelerated electrons to collide and ionize the background gas. Assume that ions may recombine with a probability β. The magnetic breakdown curve for a time-dependent magnetic flux density B relates the required magnetic flux density B versus pressure p, applied angular frequency ω, and induction coil radius R as

$$B_{\text{breakdown}} = \frac{B_0 p}{\omega R\left[\ln(A_0 \pi pR) - \ln\left(\ln\left[\frac{\beta+1}{\beta}\right]\right)\right]}. \tag{3}$$

In order to determine the conditions at which breakdown occurs most easily, the derivative of expression 3 has been taken and set to zero. The minimum breakdown magnetic flux density,

$$B_{\text{breakdown, min}} = \frac{\exp(1)}{\omega \pi R^2}\frac{B_0}{A_0}\ln\left(\frac{\beta+1}{\beta}\right), \tag{4}$$

is obtained at

$$p_{\min} = \frac{\exp(1)}{A_0 \pi R}\ln\left(\frac{\beta+1}{\beta}\right). \tag{5}$$

Interesting is the fact that $B_{\text{breakdown, min}}$ is directly related to the ratio of the Paschen parameters $\frac{B_0}{A_0}$.

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4. The Paschen parameters

In [2] analytic formulas have been presented in order to estimate the values of the two Paschen parameters A_0 and B_0:

$$A_0 = 0.224 \frac{e^4}{16\pi\epsilon_0^2 E_{\text{ion}}^2} \frac{3}{kT_h}, \tag{6}$$

and

$$B_0 = \frac{5}{4} \frac{\pi a_r^2}{kT_h} \frac{E_{\text{ion}}}{e}, \tag{7}$$

with e the electron charge, ϵ_0 is the dielectric constant of vacuum, E_{ion} is the ionization energy, k is the Boltzmann constant, T_h is the heavy particle (ions and atoms) temperature, and a_r is the atomic radius. In the derivation of the parameters, step ionization is considered dominant.

Expressions 6 and 7 have been successfully tested against experimentally obtained values [2].

Examining the ratio $\frac{B_0}{A_0}$ yields

$$\frac{B_0}{A_0} = \frac{20}{3} \frac{a_r^2}{0.224} \left(\frac{\pi\epsilon_0}{e}\right)^2 \left(\frac{E_{\text{ion}}}{e}\right)^3 = 8.97 \cdot 10^{17} a_r^2 \left(\frac{E_{\text{ion}}}{e}\right)^3. \tag{8}$$

Note that the atomic radius a_r is typically a few times the Bohr radius, such that this parameter does not vary a lot between atoms.

Expressions 4 and 8 indicate that the minimum in the required magnetic flux density to force breakdown is strongly related to the ionization energy of the gas. The minimum magnetic flux density to force breakdown is further inversely related to the frequency of the applied magnetic flux density and the geometry of the gas discharge. Since

$$\ln\left(\frac{\beta+1}{\beta}\right) \geqslant \ln(2), \tag{9}$$

the minimum breakdown condition can be simplified to

$$B_{\text{breakdown, min}} \geqslant \frac{5.38 \cdot 10^{17}}{\omega R^2} a_r^2 \left(\frac{E_{\text{ion}}}{e}\right)^3. \tag{10}$$

5. Example

A commercially available ICP source operated at relative low frequency has been used to examine expression 10. In Table 1 $B_{\text{breakdown, min}}$ and p_{min} have been calculated for three different operating conditions.

Within this source, several metal vapors were fed, increasing the pressure such that the location for the minimum breakdown condition will be passed. The magnetic flux density of the source has been varied till 50 mT by changing the voltage and the current from the power supply.

From the metals in Table 1, the generation of a zinc plasma at 10 kHz has never been successful. A zinc plasma has been very difficult to generate at 100 kHz. Only at maximum power we were successful and that also on few occasions. At 300 kHz, the generation of a zinc plasma was relatively easy.

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Table 1. Minimum breakdown magnetic flux density for three different operation conditions (f is the applied frequency and R is the radius of the container).

	10 kHz 50 mm	100 kHz 17 mm	300 kHz 17 mm
f R	$B_{\text{breakdown, min}}$ [mT] $-p_{\text{min}}$ [Pa]	$B_{\text{breakdown, min}}$ [mT] $-p_{\text{min}}$ [Pa]	$B_{\text{breakdown, min}}$ [mT] $-p_{\text{min}}$ [Pa]
Al	15 – 0.4	13 – 1.2	4 – 1.2
Cr	22 – 0.5	19 – 1.5	6 – 1.5
Cu	32 – 0.7	28 – 2.0	9 – 2.0
Mg	31 – 0.7	27 – 2.0	9 – 2.0
Sn	27 – 0.6	24 – 1.8	8 – 1.8
Zn	58 – 1.0	50 – 3.0	17 – 3.0

A plasma could be generated from the other metals at all the above operating conditions as long as the applied magnetic flux density is sufficiently high. When the applied magnetic flux density is just high enough, plasma ignition indeed occurs only at a very small pressure range around p_{min}. At lower as well as higher pressures a plasma cannot be ignited or the existing plasma is extinguished.

6. Conclusion

The minimum magnetic flux density to force breakdown in a gas is strongly related to the ionization energy of the considered gas, and is also inversely related to the frequency of the applied magnetic flux density and the geometry (the square of the radius) of the gas discharge.

Examining the minimum breakdown magnetic flux density for several metal vapors (Al, Cr, Cu, Mg, Sn, and Zn), it can be concluded that zinc is more difficult to ignite than other metal vapors because of the relative high ionization energy of zinc.

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