Basic properties of magnetic dipole discharges

R. L. Stenzel[2], J. M. Urrutia[2], C. T. Teodorescu-Soare[3], C. Ionita[1], R. Schrittwieser[1]
[1]*University of Innsbruck, Institute for Ion Physics and Applied Physics,*
A-6020 Innsbruck, Austria
[2]*Department of Physics and Astronomy, University of California, Los Angeles,*
CA 90095-1547, USA
[3]*Faculty of Physics, Alexandru-Ioan-Cuza University of Iaşi, RO-700506 Iaşi, Romania*

Abstract: A discharge is described which uses a permanent magnet as cold cathode and the metallic chamber wall as anode. The magnet is biased strongly negative which produces secondary electrons due to the impact of energetic ions. The emitted electrons are highly confined by the strong dipolar magnetic field and a negative potential in the equatorial plane of the magnet. The emitted electrons ionize near the sheath and produce further electrons which drift across field lines to the anode while the nearly unmagnetized ions are accelerated back to the magnet. A steady state discharge is maintained at neutral pressures above 10^{-3} mbar.

1. Introduction

By applying a strong magnetic field transverse to the electric field between a cathode and anode the electrons are confined which increases the ionization efficiency. Such cross-field discharges have received much attention as efficient plasma sources for various applications such as Hall thrusters [1], magnetron sputtering devices [2] and hollow cathodes [3]. For reviews on magnetron discharges see e.g. [4,5,6].

Here we describe a few properties of perhaps the simplest cross-field discharge consisting of a permanent magnet as cold cathode and the metallic chamber wall as anode. A strong cylindrical permanent magnet is mounted inside the vacuum chamber and biased negatively. The peak field strength at the poles ranges from 0,1 − 0,9 T.

2. Experimental arrangement

The experiments have been performed at UCLA (University of California, Los Angeles) and the University of Innsbruck, Austria, using similar cylindrical plasma devices of approximately 40 cm in diameter and 100 cm in length (see Fig. 1(a)). In a pressure range of $10^{-3} < p < 10^{-2}$ mbar argon plasma of density $n_e = 10^9$ cm^{-3} and electron temperature $k_B T_e = 2$ eV can be created by a hot cathode dc discharge. This plasma helps to start the magnetron discharge but is not required for high gas pressures ($p = 5\times10^{-2}$ mbar) and high discharge voltages (> 500 V).

In case of non-conducting ferrite magnets, the cylinder sidewalls were enwrapped with a metal foil (Ni, Al) as electrode. In case of conducting magnets (Nd, SmCo) the pole faces were covered by mica sheets so as to draw current only from the sidewalls. No discharge is

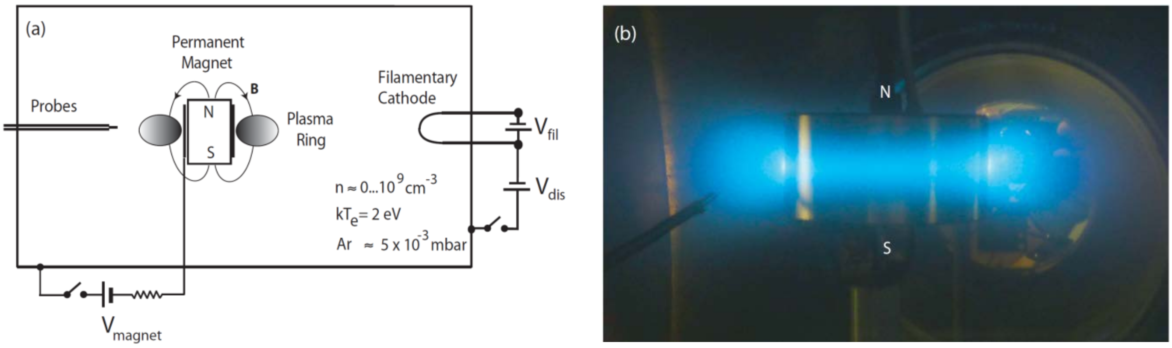

Fig. 1: Schematic diagram of (a) the experimental setup and (b) a picture of the plasma ring in the equatorial plane: the cathode is a cylindrical permanent dipole magnet biased at −400 V in Argon at pressure $p = 5{\cdot}10^{-3}$ mbar (Nd magnet, 5 cm diameter, 2,5 cm length, 0,4 T maximum field strength).

produced when the poles are biased and the sidewalls are isolated. Bias voltages of −200... − 800 V are applied relative to the grounded chamber wall. Series resistors of up to 1 kΩ limit the current in steady state operation to avoid overheating of the cathode, which may raise the magnet temperature beyond the Curie temperature ($T_{Curie,Nd}$ = 350° C) and demagnetizes it. Operation at higher currents (> 10 A) is possible in pulsed mode at a low duty cycle. Even higher current (> 200 A) short-duration (≅ 1 µs) discharge pulses are produced by relaxation instabilities triggered by cathode spots.

The impact of energetic ions on the magnet's walls produces secondary electrons. In our parameter regime the yield is well below unity so that the magnet current is dominated by ion collection [7,8]. The electrons emitted from the magnet surface are energized in the sheath. They follow the magnetic field lines which are nearly parallel to the side walls of the magnets whose permeability is close to unity. The electron energy is largest in the mid-plane where a luminous plasma ring appears as shown in Fig. 1(b). The field lines end again on the magnet surface where the electrons are reflected by mirror forces and the sheath electric field.

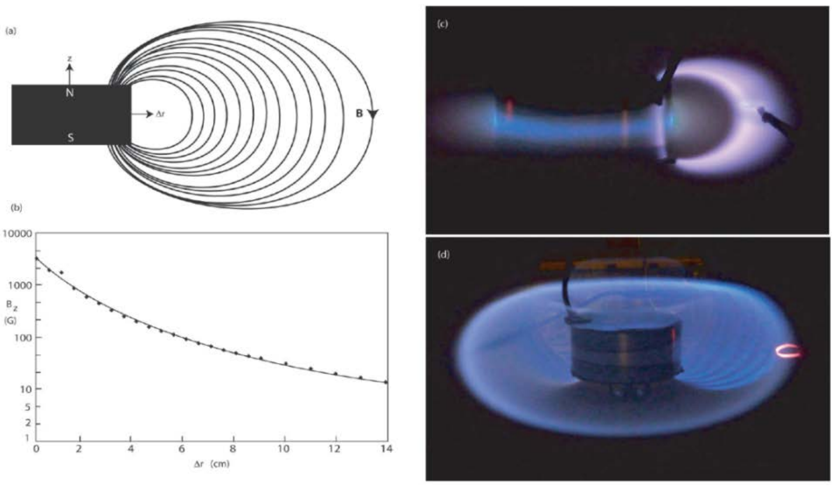

Fig. 2: Magnetic field and particle motions near a Neodymium permanent magnet (5 cm diam., 2,5 cm height). (a) Field lines. On the sidewalls the field lines are nearly parallel to the wall. (b) Field strength versus radius in the mid plane. (c) Light from secondary electrons produced by the biased magnet and by a negatively biased electrode in the equatorial plane. (d) Electrons from an emissive probe drifting around the magnet.

For a large cylindrical Nd magnet (5 cm diameter, 2,5 cm length) typical field lines in the region of inter interest are shown in Fig. 2(a). The radial field strength in the mid equatorial plane is shown in Fig. 2(b). The field lines are mapped by placing an electron source (e.g. an emissive probe) near the magnet and recording the light image as indicated in Fig. 2(c). To first order the electrons follow field lines but to second order they are drifting across $\boldsymbol{B}$ due to $\nabla|B|$, curvature and $\boldsymbol{E}\times\boldsymbol{B}$ drifts. Figure 2(d) shows that a single electron source can fill a plasma torus, depending on the electron mean free path.

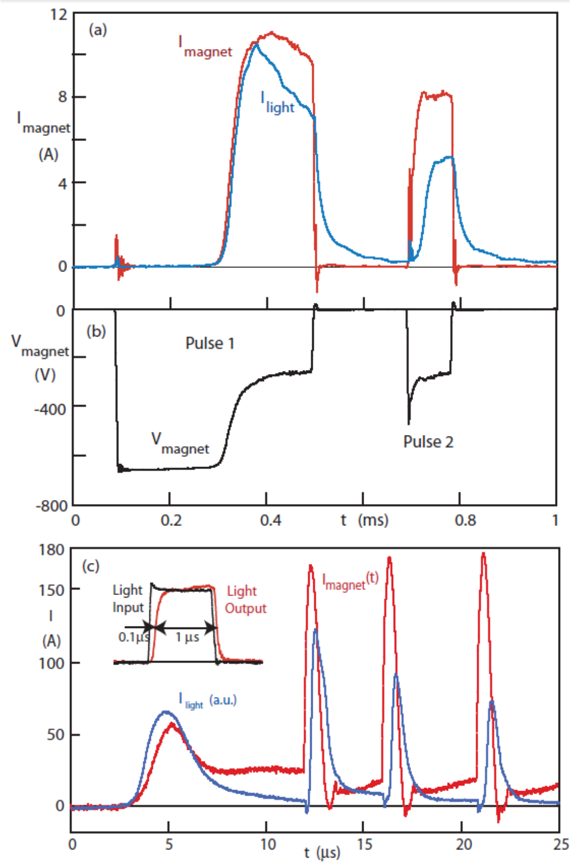

Fig. 3: Discharge current, voltage and light emission for double pulses. Without background plasma the first pulse has a long delay time between start of discharge current (a) and applied voltage (b) while the second current pulse starts immediately in the afterglow plasma of the first pulse. The light intensity is not proportional to the discharge current. (c) Light and current for intense short duration discharge pulses. Except for the first pulse, the light pulses are delayed with respect to the current pulses. es. The peak light intensity decays relative to the peak current or density. Insert shows the time response of the photodiode.

3. Basic features

When the magnet bias is below a certain threshold it not only collects ions but begins to emit secondary electrons. A glow discharge develops around the sides of the magnet. The threshold voltage depends on gas pressure, ambient plasma density, and magnet properties and typically lies in the range of −300... – 500 V. If in steady state operation a discharge power P_{dis} > 100 W is maintained the cathode magnet is heated so much that it turns red hot losing its magnetization and the discharge disappears.

In pulsed mode there is a considerable time lag between the start of the discharge voltage and the discharge current which is the current flowing from the magnet to ground. The delay time decreases when an ambient background plasma is present created by either a hot cathode discharge or a cold electrode biased to a high negative dc voltage. Prior to the onset of the discharge current a low density glow discharge forms which provides ions for secondary electron emission on the magnet. When the discharge begins to flow there is a voltage drop due to the series resistor (R = 100 Ω). Furthermore the discharge voltage decays since the supply capacitor (C = 2 µF) is discharged. The decay of the discharge voltage causes the current to drop and eventually to stop unless the supply capacitor is recharged.

Instead of supplying an external background plasma two or more successive voltage pulses can be applied. Figures 3(a,b) show that the first current pulse exhibits a 200 µs delay with respect to the voltage pulse, while the second one starts with negligible delay due to the presence of the afterglow plasma of the first pulse. Each current pulse produces a light pulse. While the magnet current scales linearly with ion saturation current to probes, i.e. density, the light intensity does not since it also depends on the electron energy. The highest electron energy arises during the rise of the first current pulse.

Short high current pulses are produced with a smaller charging capacitor (0,1 μF) and no current-limiting series resistor. The first 50 A current pulse in Fig. 4(c) is a regular magnetron discharge, while the subsequent pulses (> 150 A, ≅ 1 μs half width) are triggered by cathode spots. The light measurements show again differences in the current and light waveforms. During the first discharge light rises faster than current, implying that energetic electrons are needed to start the discharge.

Subsequently, the light drops at a constant current because the capacitor is discharged and the accelerating electric field decays. At the high current pulses the light emission is delayed with respect to the current. The > 0,5 μs delay is not instrumental since the photodiode has a time resolution of ≅ 0,1 μs measured with a pulsed light emitting diode (see insert). Since the measured light intensity depends also on the volume of hot plasma the delay is likely due to the expansion of hot plasma from a spot (arc) discharge. In successive discharge pulses the peak light intensity drops while the peak current, hence magnet voltage, remains constant.

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