Chapter 7
Plasma Dynamics in Capillary Discharges

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Abstract Capillary discharge plasma is used frequently as a source of UV radiation, as active media for EUV and soft X-ray lasers, for the formation of plasma wave-guides to transport high power laser beams, and as plasma lens to focus beams of accelerated charged particles. A brief review of main physical processes responsible for dynamics of plasma in capillary discharges is presented in this chapter. The review takes into account results of a lot of MHD simulations as well as their comparisons with different experiments. Two quite different types of capillary discharges that are used in many experiments are considered. Main physical processes that play an important role in plasma-wall interaction and determine wall material evaporation rate, are also considered.

7.1 Introduction

A through duct in a dielectric filled initially with a gas may conduct electric current that leads to the formation of plasma from the gas inside the duct. Such form of gas discharge is called usually as capillary discharge. Capillary discharge plasma has different applications: (a) as a source of UV radiation [1]; (b) as an active media for EUV and soft X-ray lasers [2, 3]; (c) as a plasma wave-guide for long enough transportation of power laser beams in laser particle accelerators [4]; (d) as a plasma lens to focus beams of accelerated charge particles [5, 6]; etc. This talk presents a review of physical processes that govern the main properties of capillary discharge plasma. This review is based on a lot of MHD computer simulations and their comparison with experimental data.

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7.2 General Properties of Capillary Discharges

We list here ranges of typical parameters of the capillary discharges:

- capillary length, 3–30 cm;
- its diameter, 0.2–2 mm;
- capillary materials: plastic, glass, ceramic, sapphire, etc.;
- peak electric current, 100 A–40 kA;
- electric current half period, 30–500 ns;
- filling: H_2, Ar,…;
- initial gas pressure, 0.3–50 mbar.

The main physical processes determining parameters of the capillary plasma and its dynamics can be sorted between the following types: mechanical, electromagnetic, thermal, and others. Two mechanical forces that move the plasma are gradient pressure force and Ampere's force ($\propto \boldsymbol{j} \times$ B). The capillary discharge is distributed along its radius inductance and resistance. They determine electromagnetic properties of the discharge and, in particular, characteristic time of electric field penetration into the discharge. The main thermal processes that govern plasma temperature are Joule heating, electron thermal conduction and radiation of the relatively hot plasma. Other physical processes may play an important role in the dynamics of the capillary discharge plasma. We mention among such processes: ionization (recombination) and capillary wall material evaporation. The latter process is caused by energy deposition in the wall due to energy flux from the capillary plasma.

All of these physical processes for the capillary discharges are taken usually into account in the frame of magnetic hydrodynamics (MHD). A two-temperature one-dimensional version of such an MHD model is described for example in [7, 8]. It takes into account possible differences between electron and ion temperatures.

7.3 Two Types of Capillary Discharges

Electric current and the magnetic field caused by it leads to the following two effects that affected plasma dynamics. The first of them is the Ampere's force ($\propto \boldsymbol{j} \times$ B), and the second one is Joule heating ($\boldsymbol{j}^2/\sigma$) that heats the electron component of plasma. The relative importance of these two effects for plasma dynamics is determined by the following dimensionless parameter, magnetic Reynolds number:

$$\mathrm{Re}_m = \frac{av}{\nu_m}, \tag{7.1}$$

where a is typical size of the plasma (capillary diameter); $\nu_m = c^2/(4\pi\sigma)$ is the so-called magnetic viscosity, defined by the electric conductivity, σ; and v is typical velocity of plasma motion, that is usually of the order of Alfven velocity, c_A: $c_A^2 = B^2/(4\pi\rho)$. Here B is magnetic field, and ρ is plasma density.

If $\mathrm{Re}_m \gg 1$, then:

- Effects of the Ampere's force are much stronger than the effects caused by the Joule heating;
- Plasma pressure due to Joule heating cannot be prevented from magnetic compression;
- Plasma is detached from the capillary walls;
- There is a strong pinch effect;
- Plasma is heated mainly by shock waves; and
- Plasma is screened from electric and magnetic fields due to strong skin-effect.

In the opposite case, when $\mathrm{Re}_m \ll 1$, we have that:

- Effects caused by the Joule heating is more important than the effects caused by the Ampere force, tending to compress the plasma;
- Ampere's force is of relatively small effect;
- Plasma pressure tends to be constant across the discharge;
- Plasma is confined by the capillary walls;
- It is heated by the Joule heating, that is balanced by the thermal conduction towards relatively cold capillary walls; and
- There is no skin-effect, and electric current distribution is smooth across the discharge.

We will call the capillary discharges of the first type, when $\mathrm{Re}_m \gg 1$, as ***pinching*** capillary discharges, whereas the capillary discharges of the second type, when $\mathrm{Re}_m \ll 1$, as ***dissipative*** capillary discharges.

We may say very roughly that the type of capillary discharge is controlled mainly by the amplitude of electric current. We have exemplary dissipative capillary discharge at the peak current of 0.3 kA [4], while for 40 kA we have exemplary pinching capillary [2]. The transition between these two types takes place approximately at a few kilo-amps.

7.3.1 Capillary Discharges with Strong Pinch Effect

The typical capillary discharge of the pinching type is the capillary discharge used in [2] in the 46.9 nm Ar laser. It was used to compress strongly Ar plasma at the axis of a polyacetal capillary of 4 mm diameter and to get hot and dense Ar plasma with temperature of about 60 eV and electron density of about $4 \cdot 10^{19}\ \mathrm{cm}^{-3}$. These parameters are favourable for Ne-like lasing in Ar plasma. To obtain such Ar plasma a current pulse with 40 kA amplitude and 60 ns duration was applied to the poly-acetal capillary of 4 mm diameter prefilled with Ar gas of 0.85 mbar initial pressure. The volume compression of the Ar gas-plasma was as high as about 200 times.

Many teams performed 1d MHD simulations of such discharges. See, for example [9–11]. The MHD codes take into account all physical processes mentioned above, accompanied by simulation of atomic levels population dynamics and by simulation of laser beam propagation. Such simulations show good agreement with experiments. Scaling laws describing plasma parameters at stagnation as function of initial Ar gas pressure, capillary diameter and amplitude and duration of the electric current pulse were obtained in [7] using such MHD simulations.

The capillary discharge used in [2] and simulated in [7, 9–11] leads to evaporation of polyacetal walls. This evaporation leads, in turn, to the formation of a plasma sheath. It begins capturing part of the total electric current, so that the ablated plasma takes part in Ar plasma compression. This effect leads to less effective compression of Ar plasma and hence demands higher electric current. Using more refractory capillary materials [3] such as ceramics allows applying considerably lower electric current, providing complete absence of wall material evaporation and 46.9 nm Ar lasing. MHD simulations of such discharges are significantly simpler.

Assuming absence of plasma ablation from the capillary walls, we may achieve in MHD simulations lasing for much shorter wavelength. See for example [12, 13] and the experiments [14].

7.3.2 Dissipative Capillary Discharges

Dissipative capillary discharges tend, as it was explained above, to mechanical and thermal equilibrium, with the Ampere's force being negligible. As a result, such discharges have a maximum of electron temperature at the axis and a minimum of electron density. Such long-lived radial electron density distribution is favourable for optical guiding. This property of dissipative capillary discharges was first demonstrated in [15]. They used initially evacuated plastic capillary. As a result, plasma of the discharge was formed from wall material, and hence its chemical composition was poorly controlled. Usage in [16] of ceramic capillary prefilled with hydrogen demonstrated almost complete suppression of capillary wall evaporation, that leads to the well-controlled chemical composition of plasma wave-guide. This situation is suitable for long transportation of power femtoseconds laser pulses, and hence to acceleration of electrons due to wake field effects. It was demonstrated in [4]. A 4.2 GeV electron beam of high quality was produced by propagation of 0.3 PW laser pulse in capillary discharge of 9 cm length and 0.5 mm diameter with 0.3 kA peak current of ~300 ns duration. The sapphire capillary was filled with hydrogen up to ~40 mbar initial pressure.

Owing to the existence of mechanical and thermal equilibrium, and tendency to its establishing for the dissipative capillary discharges, there are very simple scalings [8] that describe plasma parameters in the capillary discharges of this type as well as profile of refraction index in this optic wave-guide. They were checked with the MHD simulations as well as in part experimentally.

7.4 Evaporation of Wall Material

Possible wall material evaporation is an important feature of capillary discharges. The evaporation is caused by energy deposition in a relatively thin layer of the wall. The deposition is caused, in turn, by the contact of discharge plasma with the wall. Sometimes, it is an unavoidable effect (for discharges in initially evacuated capillaries, for example), and sometimes, it is a parasitic one.

It is useful to introduce the term "cost of evaporation", *W*. It can be measured for example in mJ/cm^2. It is important that it does not originate from specific heat of evaporation of wall material. The latter value can be usually neglected, because it is much lower than the specific energy of discharge plasma. Instead of this, the value of *W* says: how much energy should be deposited into the wall (per its unit area) to heat a certain thin layer of it to sufficiently high temperature, so the saturated vapour pressure becomes comparable with the discharge plasma pressure.

For reasonable evaluation of *W*, we should consider transport of heat into the capillary wall and determine a depth of this layer. This process was considered and simulated in [10, 11] simultaneously with the MHD simulations of the discharge plasma. The simulations show that a small fraction ($\sim 3 \times 10^{-4}$) of electrons from the valence band in the wall dielectric layer of about 0.5 μm thickness is exited into the conduction band, and that temperature of the electrons component becomes ~1.5–2 eV, that is much higher, than typical lattice temperature, several hundreds of K. The lattice temperature grows gradually in time due to energy exchange between electrons and lattice. The layer thickness is determined by this energy exchange and by transport of heat due to electron thermal conduction and radiation.

Typical value of *W* for fused materials like plastics is of the order of 10 mJ/cm^2, whereas for refractory ceramics or sapphire, it is of the order of 100 mJ/cm^2. This value depends on many factors like impurities and current pulse waveform. The above numbers are presented for orientation only.

It is important that time-integrated energy flux towards the capillary wall (*F*) during the important part of the electric current pulse is determined completely by the capillary plasma dynamics and not by processes in the capillary walls. It is the consequence of that typical temperature of the capillary plasma that is much higher than the temperature of the solid capillary wall.

The process of evaporation is easily simulated in two cases: $F \gg W$, and $F \ll W$. The former case corresponds to the situation when the evaporation is limited only by the energy flux from the discharge plasma [10], whereas the latter one corresponds to the complete absence of evaporation [8]. The case $F \sim W$ demands detailed simulation of heating of the thin layer of wall.

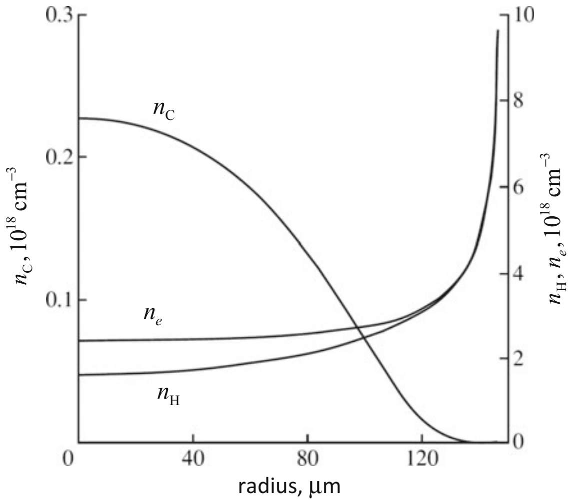

Fig. 7.1 Radial distributions of electron (n_e), hydrogen (n_H) and carbon (n_C) densities across the capillary discharge

The capillary wall evaporation supplies admixtures to the capillary plasma. Radial distribution of highly ionized heavy impurities in the discharge was considered in [17]. See Fig. 7.1.

7.5 Conclusions

We may conclude that theory of the capillary plasma dynamics is presently well developed. We mean here 1D radial MHD dynamics of the plasma in thin and long capillaries. The only unresolved problem is quantitative description of capillary wall evaporation, when time-integrated energy flux toward the wall is close to the threshold of the beginning of intensive evaporation: $F \sim W$. We have good description of the evaporation process in two limiting cases: $F \gg W$ and $F \ll W$.

It is now a good time for the beginning of 2D and 3D MHD simulation of capillary discharges to have an adequate description of electron density distribution in the vicinities of open ends of capillaries and gas supplying channels. Another 2D MHD problem, that could be interesting for applications, is discharges in capillaries of noncircular cross sections. See postal presentation by G. Bagdasarov et al. at this conference.

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