Influence of voltage pulse rise-time on initiation and propagation of fast ionization waves in extended capillaries

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Abstract. Creating stable and efficient compact X-ray sources based on fast capillary discharges that do not incorporate preliminary ionization circuits poses additional restrictions on parameters of voltage pulses and capillary geometry. Applying a voltage pulse with a rise rate of the order of 1 kV/ns results in gradual breakdown of non-ionized gas in the capillary which takes the form of an ionization wave that initiates at the powered electrode and propagates with typical velocities of 1 cm/ns. After the wave reaches the grounded electrode, a plasma channel with gradually increasing conductivity is formed. The current onset therefore appears only after a certain time delay after beginning of the voltage pulse. The ratio between the delay and the applied voltage rise-time will eventually influence the current rise rate that defines plasma heating and compression. It is therefore necessary to have the ability to estimate this delay time for a given capillary geometry and understand its dependence on the properties of a voltage pulse. In this work numerical simulations of fast ionization waves created in an extended Al2O3 capillary filled with nitrogen at 2 Torr were performed for cases of voltage pulses of negative polarity with rise-times varying in the range 10-50 ns. The numerical model was based on fluid approach with drift-diffusion approximation for charged particle fluxes. Influence of voltage rise-time on initiation and propagation of a fast ionization wave as well as on consequent rate of current rise is investigated.

1. Introduction

In the past decades fast capillary discharges have been the subject of numerous investigations. The interest is mostly connected with two applications, namely tabletop soft X-ray sources [1-3] and laser waveguides [4-6]. Extensive experimental data on discharge properties in a wide range of conditions had been accumulated to date. It is generally accepted that the discharge stability can be ensured by creating a weakly ionized plasma inside the capillary prior to application of the main voltage pulse. Therefore, the discharge setups typically consist of a combination of electrical circuits that create a microsecond pre-pulse of about a few tens of amperes and main power supplies (typically Marx generators or Blumlein transmission lines [3,7]) that provide current pulses with nanosecond current rise fronts.
A few recent experimental investigations have focused on the possibility of creating fast capillary discharges without using any preionization circuits whatsoever [8,9]. A high-voltage nanosecond pulse is applied on the powered electrode, which results in a gradual breakdown of the nonionized gas inside the capillary in the form of a fast ionization wave (FIW). The mechanism can be briefly described as follows [10-12]. The start of an ionization wave is preceded by the build-up of space charge in the vicinity of the powered electrode where the applied electric field is the strongest. When the space charge density reaches sufficient values, plasma is formed, which screens the electric field and “pushes” it further down the capillary, again leading to space charge accumulation there. This continuous process results in formation of localized wavefront with high electric fields and ionization rates which propagates along the capillary and leaves behind a conducting plasma channel. Typical values of wave velocities for voltage pulses with rise rate of ~1 kV/ns are somewhere around 1 cm/ns depending on gas pressure, type and capillary geometry. When the wavefront reaches the grounded electrode, the conduction current starts flowing through the circuit. However, at this moment plasma is still weakly ionized (degree of ionization is typically less than 1%), its conductivity is small and increases gradually as the current and plasma density increase. After a certain time delay the conductivity becomes high enough, eventually resulting in a fast current increase, plasma heating and compression.

Omitting preionization from the electric circuitry can potentially allow developing more simple and compact experimental setups for creating fast capillary discharges. Additionally, some properties of plasma created during the FIW stage (such as radial electric fields and higher plasma densities in the vicinity of the capillary surface) can potentially contribute to discharge stability during the main stage [9,13]. However, several restrictions are placed on the properties of capillary and the voltage pulse that need to be taken into account. As such, the onset of current in the discharge will take place after a certain time delay \( \Delta t \) after the voltage pulse of the order of voltage rise time \( t_0 \), and the resulting current growth rate and consequent plasma compression and heating will depend on the ratio between \( \Delta t \) and \( t_0 \). In this paper we will show how numerical simulations could be used to study the process of discharge ignition in setups without preionization circuits and investigate its dependence on voltage pulse rise times.

2. Model description and simulation results

We consider a discharge in an extended alumina capillary with inner radius \( R_1=2.5 \) mm, outer radius \( R_2=10 \) mm and length \( L=100 \) mm filled with nitrogen at pressure \( p=2 \) Torr. The cathode was chosen to be a solid metal cylinder with radius \( R_c=2 \) mm. The problem was considered in a 2D axially symmetric formulation. Geometry of the numerical domain used in simulations (is presented in Fig. 1.

![Figure 1](image-url)

Figure 1. Discharge geometry considered in simulations (not in scale). Domain I - gas (nitrogen), domain II - dielectric capillary, 1 - powered electrode (cathode), 2 - grounded boundary, 3 - dielectric surface, 4 - axis of symmetry.

The self-consistent numerical model was based on system of balance equations for charged particle densities with the drift-diffusion approximation for charged particle fluxes and Poisson’s equation. The electron transport properties and ionization rate coefficient were calculated from the solution of the Boltzmann equation in two-term approximation and tabulated as functions of local reduced electric field.
in a sufficiently wide range [14]. Boundary conditions included the “wall” condition for solid surfaces and charging of the dielectric surface. The capillary was enclosed in a grounded metallic screen with anode placed at the end of the capillary. A time-varying voltage pulse \( U(t) \) applied to the cathode was set as follows:

\[
\begin{align*}
U(t) &= -U_0 \frac{t}{t_0}, \quad t \leq t_0 \\
U(t) &= -U_0, \quad t > t_0
\end{align*}
\]

Here \( U_0 \) is the pulse amplitude, \( t_0 \) – voltage rise time. A more detailed description of the model and discussion of its applicability to the case under consideration is presented in [12], together with investigation of basic properties of discharge propagation in an extended capillary. The main goal of the simulations presented here was to investigate the influence of voltage rise time on processes of fast ionization wave initiation and propagation as well as on current growth rate during transition to the main discharge stage. Thus, simulations have been performed for voltage pulses with amplitude \( U_0 = 10 \text{kV} \) and rise times \( t_0 \) varying in the range 5–50 ns with a step of 5 ns.

First, let us consider wave initiation. Figure 2(a) shows spatial distributions of electron density in the vicinity of the cathode at times \( t = 5.12, 5.50 \) and 6.02 ns calculated for the case \( t_0 = 40 \text{ ns} \). It can be seen that electron density is at first accumulated along the cathode surface and then starts increasing in the vicinity of the dielectric surface, forming the front of the wave which then propagates along the capillary. For the present case the moment \( t = 5.12 \text{ ns} \) was chosen as the time of wave initiation \( t_{\text{init}} \).

For the rest cases of voltage rise time, \( t_{\text{init}} \) was obtained in a similar way. Fig. 2(b) shows the overall dependence of initiation time on voltage rise time. It can be seen that dependence is linear, and increase in \( t_0 \) by an order of magnitude leads to increase in \( t_{\text{init}} \) only by a factor of 2. However, note that the ratio of \( \frac{t_{\text{init}}}{t_0} \) decreases from 0.6 to 0.12.

Further we consider the wave propagation along the capillary. Fig. 3(a) shows spatial distributions of decimal logarithm of electron density \( \lg(n_e) \) for three cases of \( t_0 = 20, 30 \) and 40 ns, taken at 10 ns after the wave initiation for each case. Radial distributions of electron density are almost identical as well. The difference in the position of the wavefront comes from different propagation velocities, with shorter rise times resulting in higher velocities. Fig. 3(b) shows the overall dependence of total propagation time \( t_p \) (which was defined as the moment when the wave front reaches the grounded electrode) on \( t_0 \) for the considered cases. The dependence is linear similarly to the time of initiation. Based on Fig. 3(b) one can obtain estimations of mean front velocity for each case. It ranges from 1 cm/ns for the case of \( t_0 = 5 \text{ ns} \) to 0.3 cm/ns for \( t_0 = 50 \text{ ns} \). In the figure we also depict the \( y = t_0 \) line in order to highlight whether the front has reached the grounded electrode before or after the voltage had risen to maximum values. It can be seen that for the
shortest rise time $t_0=5$ ns almost whole propagation takes place with maximum voltage on the powered electrode, whereas for the longest $t_0$ the voltage only reaches about 60% of its maximum value.

Figure 3. a) - dependence of total discharge time $t_p$ on voltage rise time $t_0$, b) - spatial distribution of $\log(n_e)$ for moments in time corresponding to $t=t_{\text{init}}+10$ ns for cases of $t_0=20,30$ and 40 ns.

As it can be seen from Fig. 3(a), plasma density inside the conducting channel is only about $3 \times 10^{18}$ m$^{-3}$, which corresponds to 0.1% ionization degree. Therefore, in the first few moments after the wave front reaches the grounded electrode the plasma conductivity and the current growth rate are still relatively small. In order to calculate the resulting currents that would be qualitatively representative of those observed in experiments, simulations have been performed with external circuit that consisted of capacitor (initially charged to 10 kV), parasitic inductance (1 nH), capillary load whose resistance was calculated from discharge simulations, and a nominal switch that provided linear increase of the voltage pulse. Fig. 4 shows temporal dependence of discharge current for cases of $t_0=10, 20, 30, 40$ and 50 ns. It can be seen that the maximum current growth rate begins with a certain delay after $t_p$. It is interesting that shorter rise times do not lead to significant increase neither in current growth rate nor in maximum current.

Figure 4. Temporal dependence of total discharge current for cases $t_0=10,20,30,40$ and 50 ns.

3. Conclusions
Presented sample simulation results demonstrate that depending on the experimental conditions there can be a considerable and intricate relation between the voltage pulse rise time and resulting currents in a fast capillary discharge initiated without preliminary ionization. Although the question still requires more rigorous investigations, especially experimental, obtained results hint that for a given capillary length there is an optimal rise time beyond which no significant increase in current growth rate can be achieved.

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