Cylindrical and coaxial surface-wave-sustained plasma for environmental applications

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Surface-wave-sustained plasma is theoretically investigated using self-consistent numerical model. Several discharge configurations are studied. It is shown that these plasmas obtain appropriate characteristics for various applications. The dependence of plasma parameters on the geometry factors and discharge conditions is used as an easy way for optimization of the operating conditions for each application.

Plasma sustained by travelling electromagnetic wave exists in various geometrical configurations: (i) plasma cylinder (inside a dielectric tube or surrounded by vacuum/air – plasma torch); (ii) coaxial (outside the dielectric tube when there is a metal antenna at the tube axis); (iii) plasma produced around dielectric cylinder without metal antenna; (iv) planar discharge. The first three types are subject of our investigation. All they are easy to operate; the wave applicators' size is much smaller than the discharge vessel. The produced plasma is clear (no electrodes), stable and well reproducible in wide range of discharge conditions: gas pressure from a few mTorr to several atmospheres; wave frequency from 10 MHz to above 10 GHz; plasma radius from 0.5 mm up to 12.4 cm produced till now; plasma length depends on the wave power and can reach several meters but also microplasma of a few millimetres length is in use. Surface-wave-sustained discharges (SWD) can operate in rare gases, molecular gases and gas mixtures. These advantages give opportunities for applications in environmental protection, sterilization, biomedical treatment. It is necessary to make a choice of the most appropriate reactor configuration and to control and optimise the plasma parameters for each application. This requires depth study and understanding of the processes in the discharge.

Self-consistent model describing both the gas discharge kinetics and the wave propagation along the axially inhomogeneous plasma is used for the theoretical investigation. A steady-state Boltzmann equation coupled with collisional-radiative model for argon discharge at various pressures is solved together with Maxwell's equations.

The three configurations under investigation are presented in Fig. 1.

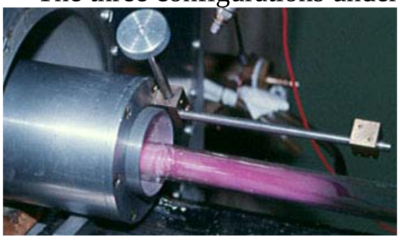

Fig. 1a: SWD inside a dielectric tube – cylindrical configuration [1]

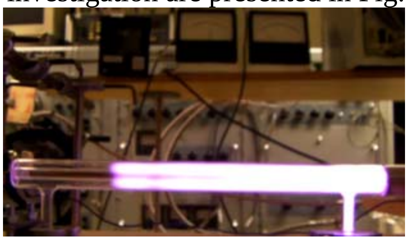

Fig. 1b: SWD between two dielectric tubes with metal antenna at the axis – coaxial configuration [2 –4]

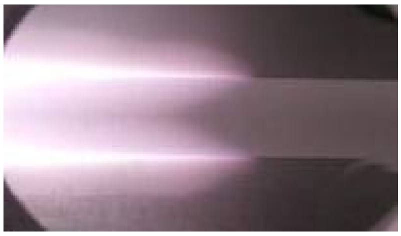

Fig. 1c: SWD arround dielectric rod [5]

The geometric parameters used for describing these configurations are presented in Table 1. It is found out a strog dependence of wave and plasma characteristics on these parameters for all configurations. In addition, for coaxial discharge and SWD arround dielectric tube a multy-mode regime of operation is possible and the aziluthal wave number m is one additional parameter for these configurations. In cylindrical configuration only azimuthally symmetric wave propagates and produces plasma.

The phase diagrams and the axial distributions of normalized plasma density obtained for cylindrical and coaxial configurations at corresponding discharge conditions and m = 0 (azimuthally symmetric wave) are compared in Fig. 2 ($\zeta = z\nu/R\omega$ is the dimentionless axial coordinate, where ν is the electron–neutral collision frequency and ω is the wave angular frequency). From the behaviour of the phase diagrams one can obtain information about the ability of the wave to produce plasma and to find out the optimum conditions. The plasma density is very sensitive to all geometric factors. Keeping the other factors the same, the tube thickness increasing leads to increase the plasma density in both coaxial and cylindrical discharges, as can be seen from Fig. 2a. This corresponds to shifting of the phase diagrams down (Fig. 2b).

Table 1.

Geometric factors	Cylindrical configuration	Coaxial configuration
Plasma radius	R (**inner** radius of the dielectric tube) $\Rightarrow \sigma = \omega R/c$ (c – speed of light)	R (**outer** radius of the dielectric tube) $\Rightarrow \sigma = \omega R/c$ (c – speed of light)
Dielectric tube radius	R_d (**outer** radius of the dielectric tube) $\Rightarrow \gamma = R_d/R$	R_d (**inner** radius of the dielectric tube) $\Rightarrow \gamma = R_d/R$
Tube thickness	$d = R_d - R \Rightarrow \gamma = 1 + d/R$	$d = R - R_d \Rightarrow \gamma = 1 - d/R$
Radius of the metal screen/rod	$R_m \Rightarrow \eta = R_m/R$	$R_m \Rightarrow \eta = R_m/R$
Vacuum space between the tube and the metal	$l = R_m - R_d \Rightarrow \eta = \gamma + l/R$	$l = R_d - R_m \Rightarrow \eta = \gamma + l/R$

The investigation shows also that the plasma radius (parameter σ) produces stronger effect on the plasma density at coaxial configuration. And much higher plasma density can be obtained at coaxial configuration if a thick metal antena is used.

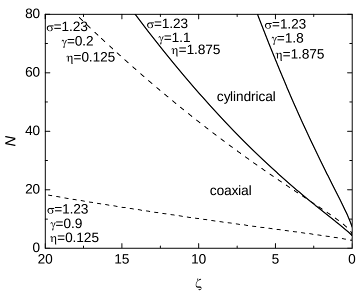

Fig. 2a: Plasma density axial distribution

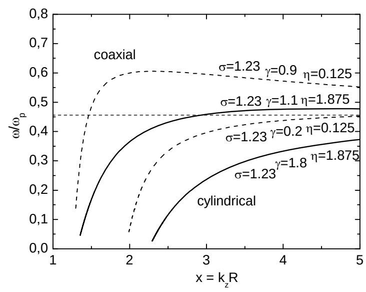

Fig. 2b: Phase diagrams of cylindrical and coaxial discharges

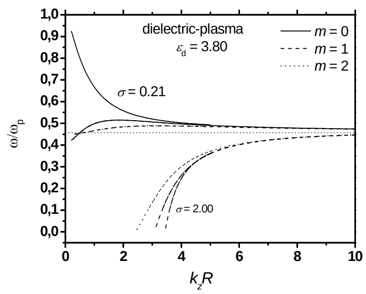

Fig. 3: Phase diagrams of SWD arround dielectric cylinder

The phase diagrams of plasma produced around dielectric rod (Fig. 3) shows completely different behaviour at small plasma radius (small σ) while at $\sigma = 2$ they are similar to the phase diagrams of cylindrical and coaxial discharges. At small σ there is not region of forward wave propagation at $m = 0$ and for all wave modes the phase diagrams are only in the region corresponding to plasma density lower tan the resonant density. We assume that at such conditions plasma cannot be sustained. Thus, plasma can be produced around dielectric cylinder by travelling wave only if the dielectric radius is big enough. There exists a critical value of σ dividing the phase diagrams into two groups. At $\sigma < \sigma_{cr}$ plasma cannot be produced by the wave. We have found out that σ_{cr} decreases with dielectriv permittivity increasing.

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