

STABILITY AND HOMOGENEITY OF DIRECT-CURRENT DISCHARGES FOR SLAB LASERS

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Abstract

A magnetically stabilized slab-shaped DC-excited discharge is investigated in terms of plasma stability and uniformity of the current distribution. The observed existence of different discharge regimes is explained by means of a one-dimensional model for a discharge in crossed electrical and magnetic fields. The model is validated by measurements of the magnetically induced shift of the plasma column. To assess the homogeneity of the electrical power distribution in the slab, profiles along the slab of the discharge current and the electrical field strength are recorded. Model and experiment are applied to CO₂ laser mixtures.

1. Introduction

Direct-current discharges in thin rectangular cavities (“slabs”) are the key to more compact and less expensive gas lasers. However, since at high power loadings the discharge is subject to constriction, the plasma has to be homogenized in some way to make it fill the entire cavity. One approach is to impose a transverse magnetic field that is sufficiently strong to smear out the plasma in the $E \times B$ direction, i.e. in the plane of the slab [1].

2. Experimental set-up

A CO₂ laser mixture is flown through a 140×10 mm² duct between 140×170 mm² dielectric plates [2]. The electrode configuration consists of an array of ballasted anodes and cathodes placed along either long side of the slab (anode-cathode distance: 140 mm). To allow visual observation of the discharge a pyrex plate closes the discharge chamber on one side, while on the other side an enamel-coated cooling plate is installed. The magnetic field is generated by ferrite magnets mounted on magnetic yokes enveloping the discharge chamber.

The experiments of section 4 pertain to an upscaled version of the described slab module, measuring 456 mm in the $\mathbf{E} \times \mathbf{B}$ direction, with a 7 mm gap between two cooling plates and an anode-cathode distance of 200 mm. The investigated discharges are sustained in a 6:20:74 CO₂/N₂/He mixture, at pressures $p = 1\text{--}5$ kPa and power densities $jE = 1\text{--}10$ W/cm³.

3. Discharge stability

At typical working pressures and input power densities a CO₂ laser discharge is thermally unstable and contracts to a thin current channel (“plasma column”) with a radius of a few mm, connecting the “launcher” anode with the nearest cathode. The launcher anode is the first anode upstream in the $\mathbf{E} \times \mathbf{B}$ direction and is positioned deeper in the plasma in order to create a high field region where the discharge initiates. When a transverse magnetic field is applied, the column is bent in the $\mathbf{E} \times \mathbf{B}$ direction, forming an arc spanning the launcher electrode pair. At a critical value B_{c1} the column “breaks” and is swept through the slab, interconnecting subsequent electrode pairs. As soon as the column is convected out of the discharge region, a new current channel is launched upstream. The velocity of the column increases with increasing B until for $B > B_{c2}$ the slab appears to be filled with a uniform glow discharge.

To gain some insight in the observed phenomena, a 1-D model is developed that calculates the magnetically induced shift of a constricted plasma column. As the current is carried by the electrons, the electron continuity equation is solved to yield the density profile in the $\mathbf{E} \times \mathbf{B}$ direction (z coordinate):

$$-D_{ae} \frac{d^2 n_e}{dz^2} + v_L \frac{dn_e}{dz} = \frac{n_e}{\tau_g}$$

where D_{ae} is the ambipolar diffusion coefficient, $v_L \approx \mu_e \mu_i E B$ is the magnetic drift velocity and $\tau_g \propto (jE)^{-1/2}$ is the growth time of the thermal instability. Fig. 1 shows the influence of the magnetic field on the normalized electron density profiles. Despite its simplicity, the model reveals a nonlinear dependence of the resulting $\mathbf{E} \times \mathbf{B}$ shift on the magnetic field (Fig. 2), and indeed the existence of a critical field

$$B_{c1} = \frac{2}{\mu_e \mu_i E} \sqrt{\frac{D_{ae}}{\tau_g}}$$

at which the magnetic shift goes to infinity and no stable position of the column is found. For $\tau_g = 0,2$ ms the model is in fair agreement with the experimentally observed shifts.

Earlier data [2] suggest that the transition to the homogeneous glow regime ($B > B_{c2}$) occurs when the transit time $\tau_t = L/v_L$ (L : distance between neighbouring anodes) for the moving current channel between subsequent electrode pairs is smaller than the instability growth time, i.e.

$$B_{c2} = \frac{L}{\mu_e \mu_i E \tau_g}$$

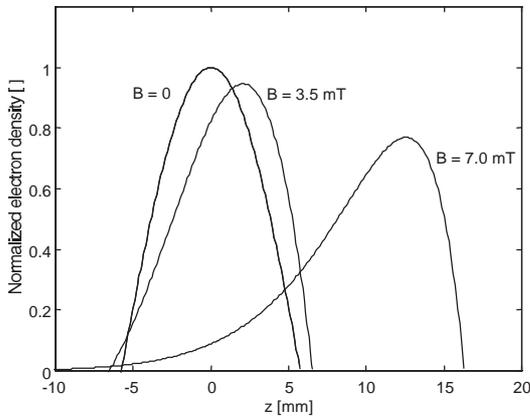


Figure 1: Normalized electron density profiles in the $\mathbf{E} \times \mathbf{B}$ direction for different values of the magnetic field

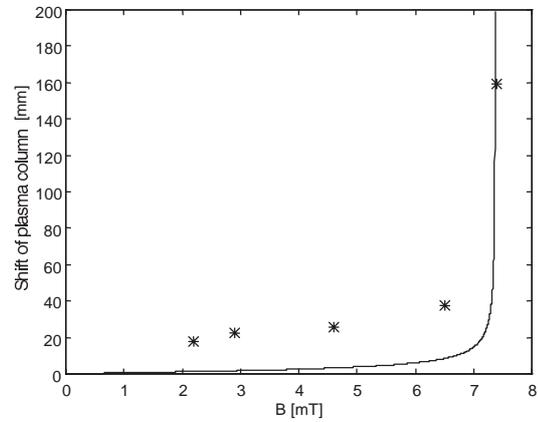
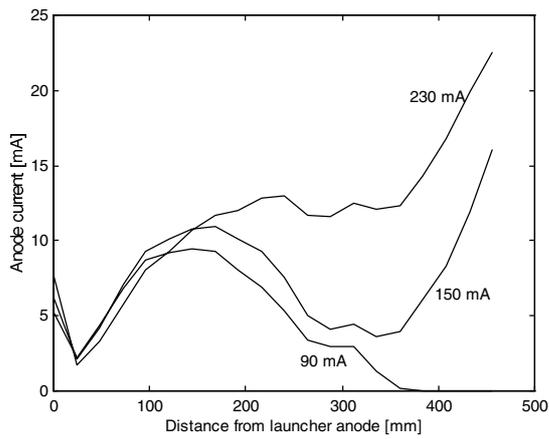


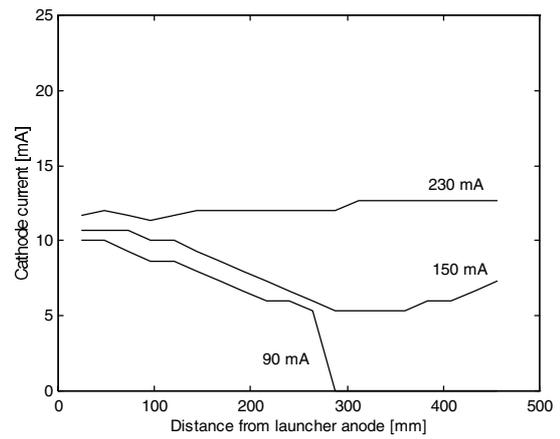
Figure 2: Magnetically induced shift of the plasma column – model (curve) and experiment (symbols)

4. Discharge homogeneity

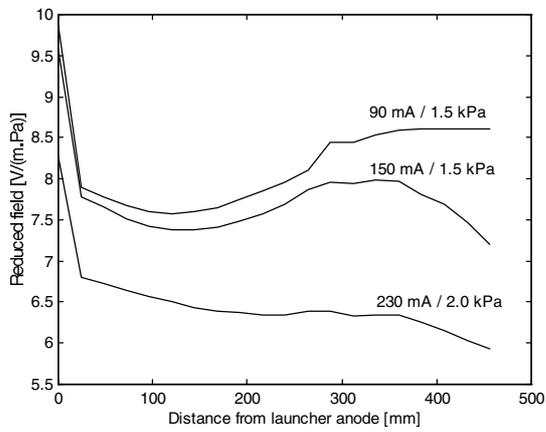
At supercritical magnetic fields, the aspect of the discharge is that of a homogeneous glow. However, probing the current and voltage on the array of anodes and cathodes reveals the non-uniformities of the plasma arising from the magnetic stabilization scheme. The anode current profile (Fig. 3a) indicates a region of low current density close to the launcher and a sharply increasing current density towards the end of the slab. In contrast, the cathode current density (Fig. 3b) is uniform throughout the slab, provided the total current is sufficient to cover all cathode surfaces. Outside of the launcher region, the reduced electrical field E/p is fairly uniform and, due to heating of the gas, drops with increasing current (Fig. 3c). Nonuniformities like the ones observed obstruct efficient laser operation and should be minimized by a careful design of the electrode geometry.



(a)



(b)



(c)

Figure 3: Distribution of anode current (a), cathode current (b) and reduced electrical field (c) along the slab ($\mathbf{E} \times \mathbf{B}$ direction).

Acknowledgements

The authors acknowledge the financial support of the COPERNICUS Programme of the European Commission under contract CIPA-CT94-0183.

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