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Citation for published version (APA):
Schram, D. C., Vallinga, P. M., Hopman, H. J., Hoog, de, F. J., Dahiya, R. P., Graaf, de, M. J., & Beulens, J. J. (1990). Cascade arc hydrogen source for plasma neutralizers. In G. Briffod, A. Nijsen-Vis, & F. C. Schüller (Eds.), *Controlled Fusion and Plasma Physics : 17th European Conference, Amsterdam, 25-29 June 1990, Vol. 3 ler* (pp. 983-986). European Physical Society (EPS).

Document status and date:
Published: 01/01/1990

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
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CASCADE ARC HYDROGEN SOURCE FOR PLASMA NEUTRALIZERS

D.C. Schram, P.M. Vallinga*, H.J. Hopman⁺, F.J. de Hoog, R.P. Dahyia‡,
M.J. de Graaf, J.J. Beulens

Department of Physics, Eindhoven University of Technology
P.O. Box 513, NL–5600 MB Eindhoven

*KSEPL, Rijswijk
⁺NET–Team, München, BRD
‡Centre of Energy Studies, IIT, New Delhi, India

Abstract

Thermal plasmas offer a good possibility to obtain intense particle sources for neutralizers [1]. The principle is to produce a plasma at high pressure, since then a high energy efficiency and ionization degree can be reached. In this paper a conceptual design for a plasma neutralizer is presented and detailed numerical data on the cascade arc as the plasma source is given. Where available, these are verified with experimental results.

Introduction

In the present paper a new effective plasma source is discussed in the framework of neutralization of negative ion beams. Injection of 50 MW neutral beam power is considered in the next generation of tokamaks and plasma neutralization of D^-–beams could offer a significant gain in efficiency compared to the traditional gas neutralization. In a plasma neutralizer the electrons are most effective to strip the negative ion of its electron. Since the electron affinity of D^- is low (0.75 eV), a low electron temperature will suffice. Electric and magnetic fields have to be small to avoid degradation of the incoming beam brightness. Therefore a quiescent plasma with no currents and only buckettype magnetic fields for confinement will be the best line of approach. This requires effective plasma sources, which pair high ionization degree with low neutral flux and low power consumption. Similar demands are found in the field of plasma surface modification : here also a flux of particles (preferably ions) is needed with a low power flux and thus power consumption. For carbon and silicon deposition a cascade arc plasma source has been developed. In this paper, this source will be discussed for argon and hydrogen in the neutralizer context.

Neutralizer Concept

First, demands will be discussed shortly. The design of the neutralizer is as scetched in Fig. 1. A volume with dimensions 2.2x0.4x0.4 m (HxLxW) is filled with plasma from m sources at two sides with fluence Φ_i. The plasma will diffuse freely outwards with an anomaly factor of 4 compared to classical diffusion. In a buckettype confined geometry with a passive currentfree plasma in which no electric and magnetic fields exist this assumption seems to be conservative but needs experimental verification. The optimum target thickness depends slightly on the attainable ionization degree [2]. For an ionization degree $\alpha \sim 0.4$ a value of $n_eL \sim 2\ 10^{19}/m^2$ is optimum. The ambipolar diffusion time of deuterium atoms for the neutralization volume can be estimated as

$$\tau_{da} \simeq n_e L^2 \left(1 + \frac{1}{\alpha}\right) 2.5\ 10^{-23}\ \hat{T}^{-0.6},$$

in which n_eL is the effective target thickness, $\alpha = n_e/n_g$ the ionization degree and $\hat{T}$ the

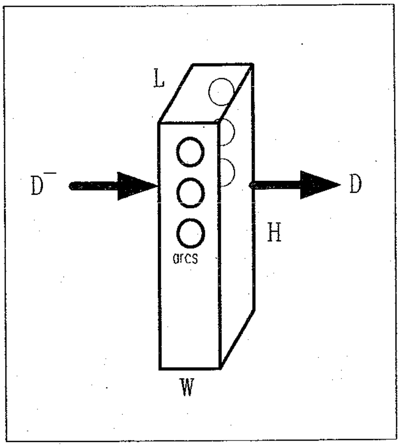

Fig. 1 plasmaneutralizer concept

temperature in eV. With this value and an anomaly factor of 4, a transversal dimension of 0.4 m and an electrontemperature of 0.5 eV we obtain

$$\tau_d=\tfrac{1}{4}\tau_{da}=2\cdot 10^{19}\cdot 0.4\cdot(1.25)\cdot 2.5\cdot 10^{-23}\cdot 1.5$$
$$\simeq 3\ 10^{-4}\mathrm{s}$$

This is only a few acoustic transit times, so it seems a very realistic estimation. The fluence of m plasma sources should compensate the losses in the neutralizer according to $n_e(LxWxH)/\tau_d \simeq m\Phi_e$. With electron fluences of $\Phi_e = 5\ 10^{21}/s$ the number of sources should be 10.

Using hydrogen or deuterium in the plasma source the estimated consumed power for such a unit (including the power consumed by the pumps) is 600 kW. This compares favourably with the saved power because of the gain in efficiency (20%) of 50 MW. With argon feeding the diffuse losses in the neutralization volume are appreciable lower and no possibility of recombination exists. This makes the alternative of an argon plasma neutralizer attractive.

At this point the problem of creating a power saving plasma neutralizer in a quiescent recombining current free mode is essentially a problem of designing an effective and very bright particle source. Extensive work has been done on cascaded arc argon plasmas, both theoretical and experimental. Here we present a quasi–two–dimensional model. This model has been adapted for hydrogen and deuterium, and numerical data on these are also given.

Model

To describe the plasma, a model for a strongly flowing cascaded arc by Beulens [3] is used. In the approach adopted in this model the plasma is treated as a two–phase medium, which consists of heavy particles (neutral atoms and ions) and electrons. The model is developed for the predictions of a strongly flowing monoatomic cascade arc plasma. The flow is assumed to be compressible and strongly non–isothermal. The argon plasma is considered as singly ionized, locally quasi–neutral ($n_e \simeq n_i$) with local temperature non–equilibrium ($T_e \neq T_h$). Influence of wall friction is included. For the full description of this two–phase flow one needs to solve the mass, momentum and energy equations for both phases. However, due to the small electron mass, their momentum is neglected in comparison with the heavy particle momentum. Therefore a two–phase flow character is kept only with respect to the heavy particle and electron temperatures which are assumed to be different and described by separate energy equations. Ohmic heat input is consumed by electrons, which in frequent collisions heat and ionize the heavy particles.

The Cascade Arc

The cascade arc (Fig. 2) consists basically of an anode (1), a stack of insulated copper plates (2) and three cathodes (3). These components are all water cooled. The cathodes are 1 mm diameter tungsten thorium tips for currents up to 30 A per cathode. The cascade plates have an inner bore of 4 mm and a thickness of 5 mm. Typical operation conditions are a gas flow of 100 scc/sec and an arc current of 10 Amps per cathode. The plasma has a temperature of about 1 eV. The pressure in the arc channel is between 0.1 and 1 bar. The thermal plasma is allowed to expand supersonically, through a hole in the anode plate of 4 mm diameter, into a vacuum vessel. Here the pressure is typical 1 Torr. The thought behind the cascaded arc is to constrict the plasma in the channel thermically, as the gas is cooled by the wall. This gives a very stable plasma.

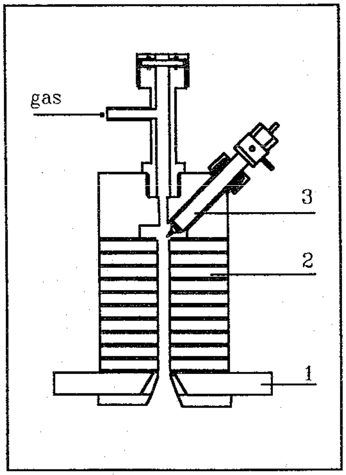

Fig. 2 cascade arc

Argon Neutralizer

We present results on the following conditions: arc current 50 A, flow = 200 scc/sec. For these settings experimental data by Kroesen [4] are available. Fig. 3a gives the ionization degree of the plasma. It appears to be approximately linear with the axial position. Fig. 3b shows the axial profile of electron and gas (heavy particle) temperatures. As can be seen, the electron temperature is nearly constant over the arc. The gas temperature relaxes towards the electron temperature but a noticeable temperature difference remains. Due to the expansion and acceleration of the plasma, temperature decreases at the end of the arc. There is good agreement between model and experiment.

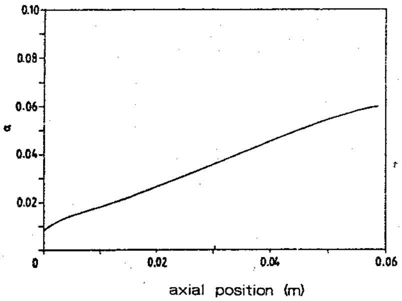

Fig. 3a axial profile of ionization degree

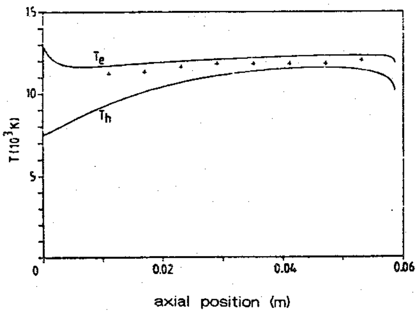

Fig. 3b electron and gas temperature. The + represent experimental data

Hydrogen or deuterium neutralizer

Calculations have been done on both hydrogen and deuterium. No significant differences between these two were found for ionization degree and plasma temperatures. This can be explained by the fact that ionization and dissociation are dominant in the energy balance. Ionization degree and temperatures are given for a gas flow of 100 scc/sec and a current of 95A. The arc lenght is in this case 11.8 cm. This longer arc gives a higher degree of ionization, at these plasma conditions $\alpha > 80\%$ at the end of the arc (fig. 4a).

In fig. 4b can be seen that, unlike the argon arc, within 1 cm temperatures of electrons and gas are equal. This is due to the much smaller mass of hydrogen.

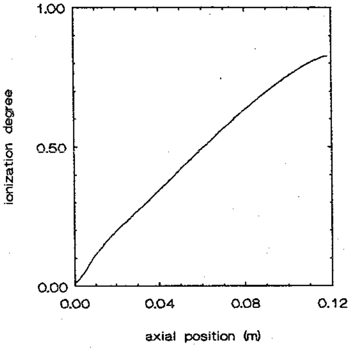

Fig. 4a ionization degree

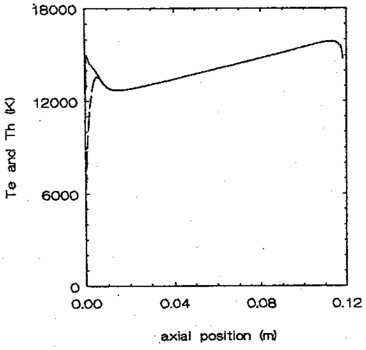

Fig. 4b electron (solid curve) and gas temperature

Concluding Remarks

According to Vallinga [1] the electron fluences from the presented cascade arc settings are $\Phi_e = 2\ 10^{20}$ for argon,

$\Phi_e = 4.8\ 10^{21}$ for deuterium,

so the calculations predict that when operated on deuterium, the electron fluence demands for a plasma neutralizer can be met with a cascade arc source at the presented settings. The argon source shows a much lower ionization degree than the deuterium source and seems less appropriate. However, this result was obtained with both a lower current (50 A for argon) and a shorter arc. As the ionization degree is almost proportional to the arc lenght, future work needs to be done on this.

Finally, we conclude that plasma neutralizers promise an effective method for neutralization of D^- –beams with an efficiency of approximately 80% compared to 60% for the traditional gas neutralizer.

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