

Vacuum arc plasma transport through a magnetic duct with a biased electrode at the outer wall

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Metal plasma formed by a vacuum arc plasma source can be passed through a toroidal-section magnetic duct for the filtering of macroparticles from the plasma stream. In order to maximize the plasma transport efficiency of the filter the duct wall should be biased, typically to a positive voltage of about 10–20 V. In some cases it is not convenient to bias the duct, for example if the duct wall is part of the grounded vacuum system. However, a positively biased electrode inserted into the duct along its outer major circumference can serve a similar purpose. In this article, we describe our results confirming and quantifying this effect. We also show the parametric dependence of the duct transport on the experimental variables. © 1999 American Institute of Physics.

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I. INTRODUCTION

The vacuum arc (or cathodic arc) plasma is a low voltage, high current plasma discharge that takes place between two metallic electrodes in vacuum, and can be used for the production of metal plasma streams for a variety of research and technological purposes.^{1–4} Contamination of the vacuum arc metal plasma stream by “macroparticles” — micron-size resolidified cathode debris — is for most applications a disadvantage, and several different means have been developed for removing or at least reducing the macrocontent of these kinds of plasmas. The approach to macroparticle filtering that has seen the most significant progress is the use of curved magnetic guide fields, first introduced by Aksenov and co-workers in the 1970's.^{5–7} Plasma from the cathodic arc source is injected into a bent solenoidal magnetic field region, 45° and 90° toroidal sections, for example, being typical. The plasma is transported through the duct, with some loss, while the macroparticles are not magnetically guided and are lost from the plasma stream by the time they reach the substrate location. A detailed experimental investigation of duct plasma transport as a function of various parameters was made and reported by Anders, Anders, and Brown.⁸

The importance of the flow of magnetized electrons (electron gyro radius $\rho_e < r_d$, the duct minor radius) in determining the transport of unmagnetized ions (ion gyro radius $\rho_i > r_d$) via ambipolar electric fields has been pointed out. For good plasma transport the duct must be biased with respect to the plasma, typically by about +10–+20 V, an

effect noted in the pioneering work of Aksenov and co-workers. This feature was recognized also by Bilek *et al.* who showed that a similar effect could be produced by applying a positive bias to a strip electrode that is located near the outer wall of the interior of the duct.⁹ These kinds of optimized ducts can achieve a plasma transport efficiency up to about 25% or more. The goal of filter research is thus to increase the plasma transport efficiency through the duct and to reduce the residual macroparticle flux.

The magnetic field strengths used in curved magnetic filters are usually several hundred gauss, which for a typical duct minor radius of some centimeters implies that the plasma electrons are magnetized but the ions are not. This in turn means that the plasma losses in the curved sections of the filter are due primarily to ions colliding with the walls. The effect of the magnetic field is to reduce the electron mobility perpendicular to the field lines and so reduce greatly the electron losses to the duct walls. The greater inertia of the ions and the lack of a strong magnetic force allow the ions to reach the walls of curved sections more readily. This is confirmed by the fact that the entire duct floats at a positive potential with respect to the plasma gun anode potential when isolated from the rest of the system,^{8,9} provided a good guiding magnetic field configuration is applied. By “good” we mean field lines essentially parallel to the duct wall and of strength high enough to ensure that the electrons are well magnetized. Moreover, floating potential⁹ and ion saturation current^{10,11} measurements made using small electric probes located at various positions near the wall of the duct indicate that the ion losses occur predominantly at the outer (large major radius) wall, while the ion current collected at the inner (small major radius) wall is close to zero.^{10,11} The floating potential of the plasma near the inner wall is found

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to be essentially at ground,⁹ indicating that the ion and electron current losses are matched. The potential of the plasma near the outer wall was consistently positive,⁹ indicating that ion losses dominate electron losses there. Application of a bias that is positive with respect to ground at the inner wall would lead to drawing an additional electron current with little effect on ion losses. Hence, the optimal duct biasing solution is one in which the bias is applied only to the outer wall. In this way, ion losses can be reduced while keeping the electron current drawn by the bias plate to a minimum.

II. EXPERIMENT

The experiments were carried out using the vacuum arc facility at the City University of Hong Kong.¹² The plasma source incorporated a 1-cm-diam titanium cathode and a stainless-steel mesh anode (2 mm mesh size) positioned about 16 mm in front of the cathode. The plasma gun was located at the entrance to a 45° magnetic duct, a vacuum elbow 8 cm in diameter and 50 cm long, about which was wrapped a solenoid to establish the duct magnetic field. For the experiments reported here the arc current pulse was 150 A and of duration 200 μ s, with repetition rate 33 pulses per second. The duct magnetic field was varied from 0 to 560 G.

An aluminum electrode (the "Bilek bias plate") was positioned at the duct wall and biased so as to enhance the plasma transport through the duct. The plate was insulated from the vacuum chamber wall by a sheet of plastic, and was of 90° azimuthal extent against the inside surface of the outermost (large radius) side of the duct. The plate was biased positively to a voltage that was varied up to +50 V for these experiments. Because the plate drew a sizeable electron current during the plasma pulse (several tens of amperes), a 1 mF capacitor was used to minimize the voltage sag during the pulse. The plate voltage was monitored to ensure the voltage stayed at a reasonably constant level.

A large area plane collector plate was positioned within the vacuum chamber to which the plasma duct was attached, about 10 cm from the duct exit, so as to monitor the plasma transported through the duct. The plate was negatively biased to -50 V to collect ion current. We varied the bias voltage over a range to confirm that this bias voltage was comfortably within the ion saturation current regime. There was no suppression of secondary electrons produced by impact of the ions with the collector plate and thus the monitored current is the sum of the transported plasma ion current and the secondary electron current. However, the electron current is not expected to be dominant at this ion energy.

The vacuum chamber pressure was typically about 5×10^{-3} Pa (4×10^{-5} Torr). A simplified schematic of the experimental setup is displayed in Fig. 1. For the experiments reported here we monitored the collector plate current (transported plasma ion current) as a function of Bilek bias plate voltage and duct magnetic field strength.

III. RESULTS AND DISCUSSION

The plasma ion current transported through the duct (the collector plate current) as a function of the Bilek bias plate voltage, with duct magnetic field strength as a parameter, is

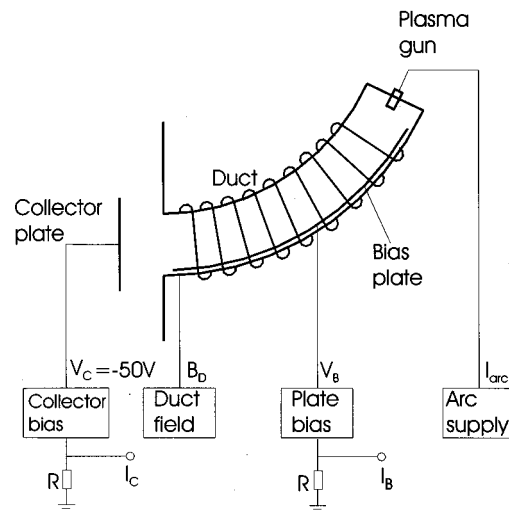


FIG. 1. Schematic of the experimental configuration.

shown in Fig. 2. The duct transport efficiency is seen to maximize at a value of bias plate voltage in the range +10–+20 V, independent (within our limit of measurement) of the duct field strength. The optimal improvement in plasma transport — the factor by which the transported ion current is increased by the Bilek bias plate, or ratio of maximum collector plate current to the current at zero bias — is depicted as a function of duct magnetic field in Fig. 3. The maximum transport efficiency improvement is seen to be about a factor of 4.

The plasma output monotonically increases with the duct magnetic field B_D . There is almost no plasma output when the duct magnetic field is zero. This indicates that the duct magnetic field is a critical factor of the plasma output. In contrast to the case of zero duct magnetic field, the plasma output increases with duct magnetic field when the Bilek plate is grounded. The ions are weakly magnetized (Larmor radius $\approx 50\text{--}140\text{ mm} > \text{minor radius}$) compared with the electrons (Larmor radius $\approx 0.1\text{--}0.5\text{ mm} \ll \text{minor radius}$) at the magnetic field strengths employed here (except $B_D = 0$). The

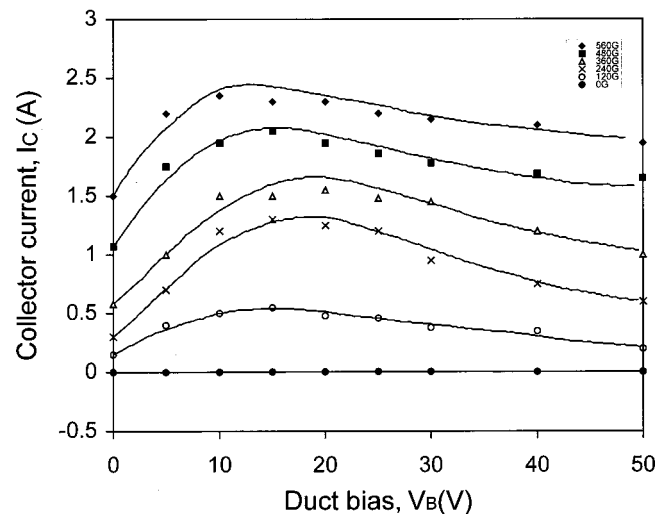


FIG. 2. Measured collector plate current I_C as a function of Bilek bias plate voltage V_B , for several different duct magnetic field strengths B_D .

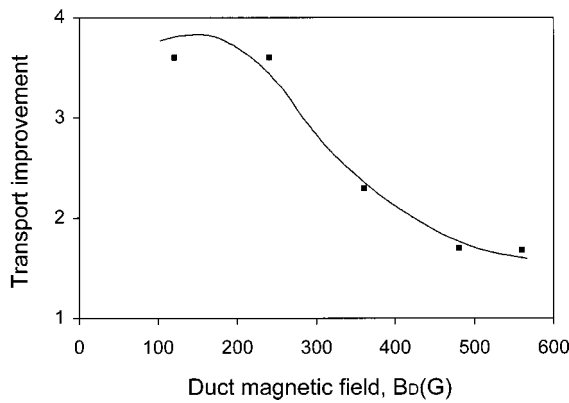


FIG. 3. Plasma transport efficiency enhancement factor, $I_c(\text{max})/I_c(V_B=0)$, as a function of the magnetic duct field strength B_D .

electrons move along the magnetic field line and the ions move along almost in a straight line and strike the duct wall. In this way, the ions and the electrons in the plasma will separate from each other. However, the quasineutrality condition of the plasma prevents the ions and the electrons from separation. The Debye length of the plasma in the duct is given by the following relationship:

$$\lambda_D = (\epsilon_0 k T_e / e^2 n_e)^{1/2}, \tag{1}$$

where k is the Boltzmann constant, T_e is the electron temperature, and n_e is the electron density. The electron temperature was experimentally determined to be about 3 eV for the metal arc and curved magnetic filter system, and n_e can be approximated by¹³

$$n_e = \gamma I_{\text{arc}} / d^2, \tag{2}$$

where $\gamma = 10^{13} \text{ A}^{-1} \text{ m}^{-1}$, I_{arc} is the arc current, and d is the distance to the cathode spot. Here, $I_{\text{arc}} = 150 \text{ A}$ and, for estimation of the largest λ_D , $d = 0.5 \text{ m}$ (the length of the magnetic duct). Hence, the highest λ_D is 0.166 mm. The Debye length is small and the ions are bound to the electrons by the space-charge electric field.

When the bias plate is grounded (duct bias=0) and $B_D = 560 \text{ G}$, the bias plate current I_B is larger than 0 (see Fig. 4), meaning that there is a net ion current received on the bias plate. The ion flux is directed to the outer wall of the curved duct, and the inertia of the ions overcomes the electric force resulting from the quasineutrality of the plasma. Even when the bias plate has a positive potential of up to 5 V, there is still a net ion current. On the other hand, the electrons are magnetized to such an extent that they are not drawn by the electric field resulting from the ions moving into the bias plate. Therefore, the ions and electrons of the plasma in the duct are separated from each other by the duct magnetic field. The duct magnetic field alone is not enough to confine the ions completely, but a positive biased plate at the outer wall of the duct reinforces the confinement.

Our experimental results show that the plasma can be transported efficiently through a curved magnetic duct with an electrode installed on the large radius side of the inner wall of the duct, biased to a voltage of about +10 to +20 V. Duct biasing is necessary in order to maximize the plasma transport through the duct and a grounded duct has poor

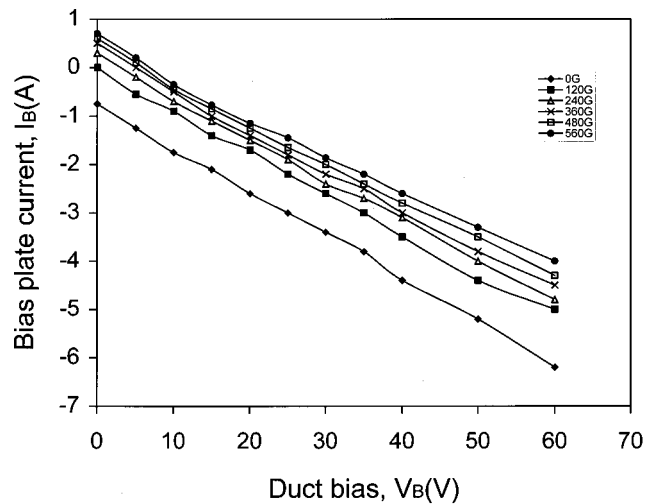


FIG. 4. Bias plate current vs bias plate voltage as a function of the duct magnetic field as a parameter. Positive current means that the plate receives net ion current and negative current implies the net electron current.

transport efficiency. The advantages of this approach include convenience and practicality, especially when the duct has been manufactured as an integral part of the vacuum chamber wall with the solenoid positioned externally around the grounded duct. Our success also opens up the possibility of employing different configurations, such as different shape, size, and location of the Bilek plates, to achieve further enhancement in plasma transport efficiency. For example, longitudinally or azimuthally segmented and separately biased sections of the biased plates may attain an improvement better than the factor of 4 reported in this article.

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