Flow Rate Limitations in the Self-Field Accelerator

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Theme

IN utilizing the self-magnetic effect for plasma acceleration, much effort has been directed towards operation at high discharge currents and low mass flow rates. In the course of various investigations, it became evident that current and flow rate may not be chosen independently from one another. In particular, if a continuously working self-field accelerator was operated at and above conditions, which can be well correlated by $J^2M^{1/2}/\dot{m} \approx$ const (J = current, M = atomic weight, $\dot{m}$ = flow rate), the otherwise stationary discharge mode changed to an instationary one. In order to obtain more understanding of this phenomenon, detailed experimental investigations were performed which included measurements of thrust and energy balance, distribution of floating potential within the accelerator, optical investigations of the anode region, and diagnostic measurements in the plasma flow. The experiments indicated that the phenomena involved in the change of discharge mode occur in the anode region. An attempt was undertaken to explain this behavior qualitatively by means of a theoretical model.

Contents

The accelerator under investigation is schematically shown in Fig. 1. The propellant is fed along the cathode which is made of thoriated tungsten. The arc-chamber and the expansion nozzle consist of individual segments that are electrically floating and insulated against each other. The largest segment at the nozzle exit serves as the anode. The electrodes and each of the segments are connected to a separate branch of the cooling water, thus permitting the measurement of local power loss in the device. The accelerator was continuously operated at discharge currents

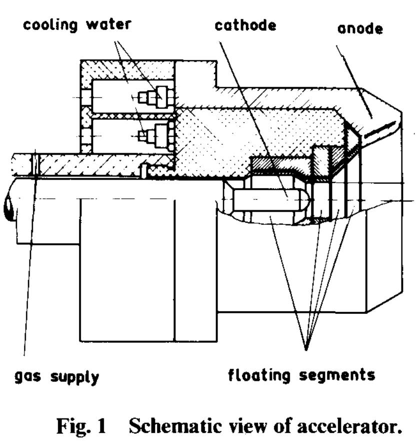

Fig. 1 Schematic view of accelerator.

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Table 1 Operating parameters and performance data for argon

Reference	J [10^3 A]	$\dot{m}$ [10^{-3} kg/s]	$J^2/\dot{m}$ [10^{10} A^2 s/kg]	$T/\dot{m}$ [10^3 m/s]	$T^2/2\dot{m}P$ [%]
Plasmadynamik, present paper and Ref. 1	2.66	0.3	2.36	13.3	16.2
	3.9	0.6	2.53	13.6	20.0
	4.86	1.0	2.36	10.2	14.3
	6.0	1.5	2.4	11.6	20.2
Princeton Univ., Ref. 2	8.6	1.9	3.7	11.8	11.1
	15.6	5.9	4.1	13.4	21.0
	27.5	23.0	3.3	10.4	15.5
	36.5	36.0	3.7	12.7	26.0
AVCO Corp., Ref. 3	10.0	2.5	4.0	8.3	
	15.0	5.6	4.0	9.2	
	20.0	10.0	4.0	7.0	
	30.0	22.5	4.0	8.4	

of 1000–6000 amp and at flow rates of 0.15–1.5 g/sec. The ambient pressure in the vacuum tank was maintained at 0.02–0.07 torr. Most of the investigations were carried out with argon and krypton as a propellant. Some preliminary experiments were performed with neon and helium.

Oscillograms of the arc voltage and photos of the anode region taken by an image converter camera reveal that a completely stationary discharge mode with a diffuse anode attachment exists over a wide range of operating conditions. If, however, at a constant mass flow rate the current is increased or at constant current the flow rate is reduced so that the ratio of $J^2/\dot{m}[10^{10}\ A^2$ s/kg] attains values close to 2.5 or 1.9 for argon and krypton, respectively, a change of the discharge mode occurs. Since by this behavior the range of the stationary mode is limited, the aforementioned values of $J^2/\dot{m}$ may be referred to as the "limiting" ones. The other mode, then, is characterized by an elevated arc voltage which undergoes strong fluctuations. The image converter camera displays discharge structures with and without spots of high light intensity at the front face of the anode. The evaluation of a series of arbitrarily taken shots proves that these spots preferentially exist at the voltage peaks. An operation at conditions beyond the limiting ones leads to arc-spots and eventually results in severe damage of the anode.

Since the physical phenomena, which are discussed herein, as well as the performance data (if compared at meaningful scaling parameter, e.g., $J^2/\dot{m}$, see Table 1), are basically the same as those observed with pulsed operation, our results appear of general interest for the self-field acceleration concept. The quantitative deviation of the here reported "limiting" values $J^2/\dot{m}$ from those of the Princeton and AVCO groups (see Table 1) might be explained as possible effects of parameters such as insulator ablation, cathode effects, and others.[4]

For a constant flow rate with argon, some typical results are shown in Fig. 2. After a rather moderate and uniform increase with the current the voltage rises strongly within a narrow region of current variation. The floating potentials, however, do not display a simultaneous increase. On the other hand, the dependence of the anode loss voltage, defined by $U_A = P_A/J$, shows a close resemblance to the arc voltage itself, i.e., it abruptly rises if the limiting conditions are approached. In contradiction to this, the heat loss to the electrically floating segments rather tends towards a saturation. At operation corresponding to the last data points the instationarities begin

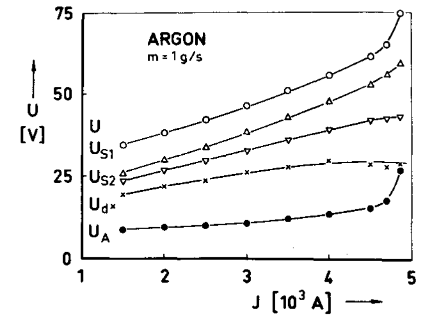

Fig. 2 Variation of arc voltage U floating potential of the conical segments and of the nozzle throat, U_{S1}, U_{S2}, and U_{d^*}, and equivalent anode loss voltage U_A with current at constant flow rate.

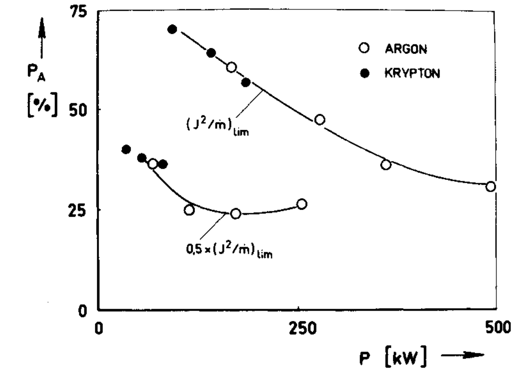

Fig. 4 Fractional power loss to the anode P_A vs arc power P for two constant values of $J^2/\dot{m}$.

to develop. The results of a number of test runs with different mass flow rates are summarized in Fig. 3. The anode loss voltage U_A and the difference between arc voltage and floating potential near the anode, $\Delta U = U - U_{S1}$, are well correlated by the parameter $J^2/\dot{m}$. The sharp rise of both quantities at the limiting conditions is particularly striking. Of interest is further the ratio of the limiting values $(J^2/\dot{m})_A/(J^2/\dot{m})_{Kr} \approx 1.33$ as compared with 1.44, which is the square root of the inverse ratio of the atomic weights.

Hence, by standard methods, estimations can be made of the anode fall. Both procedures, utilizing either energetic or potential measurements, yield values which are in sufficient agreement. For stationary operating conditions the anode fall turns out to be of the order of 1–5 v, whereas values as high as 25 v are found for the limiting conditions. This result may be interpreted in terms of the "random flux" of the electrons.[5] In the stationary discharge mode this mechanism is to a large extent capable of sustaining the current transport to the anode, but it is rendered

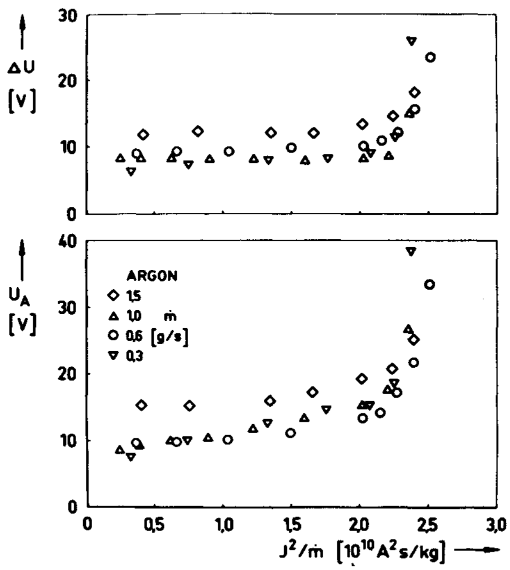

Fig. 3 Equivalent anode loss voltage U_A and difference between arc voltage and floating potential of the segment next to the anode, $\Delta U = U - U_{S1}$, as functions of $J^2/\dot{m}$ for various flow rates.

more difficult as the limiting conditions are approached. In order to maintain the (current-stabilized) discharge under the latter conditions, the field strength in the anode region must rise.

Calculations of current and electromagnetic force distribution according to a simplified theoretical model indicate that a starvation of charge carriers in a zone near the anode occurs for conditions that can be characterized by $J^2M^{1/2}/\dot{m} \approx$ const.[6] In the framework of that model the parameter $J^2M^{1/2}/\dot{m}$ represents the ratio of the magnetic to the gas-kinetic pressure.

The phenomena marking the change of discharge mode impose limitations to the performance data attainable with this particular accelerator. At stationary conditions the highest values of specific impulse as calculated from thrust amount to the order of 1300 s (argon). Prior to the thrust measurements various investigations of the plasma flow made sure that entrainment effects definitely could be excluded.[7] As the limiting conditions are approached the thrust efficiency shows a levelling off at approximately 20%. Similar observations have been made with a pulsed self-field thruster.[8] As a consequence of the severe power loss to the anode the fractional power in the plasma is considerably reduced at operation near the limiting conditions. Finally, from Fig. 4, it becomes evident that the fractional power loss to the anode decreases with increasing arc power.

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