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July 1977

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Prepared for U.S. Energy Research & Development Administration under contract No. W-7405-Eng-48.

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by

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ABSTRACT

The applicability of Magneto-plasma-dynamic (MPD) arcs as a source of warm, streaming plasma for start-up and for the suppression of instabilities is discussed. The plasma source emits a high particle flux (1000-5000 amp) of well directed ions having kinetic energy in the 10-100 eV range. The construction details of an MPD plasma source are given and a sequence of proposed tests are presented. The tests are designed to demonstrate the large flux and good gas utilization of the source as well as investigate the behavior of the streaming plasma in a high magnetic field environment.

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AN MPD STREAMING PLASMA SOURCE FOR MFTF

Introduction

The MFTF machine is anticipated to require a large (~5000 amps) flowrate of streaming plasma to serve both as a start-up target and as a stabilizing stream to prevent DCLC instability. The plasma source discussed here is a magnetoplasmadynamic (MPD) arc source that is capable of producing a directed, highly ionized stream of plasma having kinetic energy in the 10-100 eV range and a equivalent particle current of thousands of amps. A co-axial magnetic field on the order of kilogauss is integral to the operation of the source; as a consequence, the source can be placed in the fan of the MFTF magnetic field without adverse effects.

The high density ($10^{13} - 10^{14} \text{ cm}^{-3}$) stream of plasma produced by the MPD source appears to be suitable as a start-up target for the high energy beams. The mirror ratio ($R=40$) seen by the streaming plasma corresponds to a divergence angle of $\sim 10^\circ$. Photographs of the MPD exhaust jet showing that the divergence is less than this angle indicates that mirroring of the warm ions is not a problem. The effectiveness of the streaming plasma in penetrating and following magnetic fields will be investigated, as described below.

The cold plasma requirements of the 2XIIB machine have been satisfied by the use of either a gas box or pulsed titanium washer guns. The response of the confined plasma to either of these means of providing cold plasma for stabilization is nearly the same. It is expected that the MPD arc will provide ions with better gas utilization than the gas box while being capable of steady state operation. Control of the arc parameters allow a corresponding control over the streaming plasma parameters such as ion energy

and flux, and their effect upon the confined plasma can be investigated. The problem of neutral gas loading in mirror machines is becoming more severe as the particle flux in the neutral beams and warm plasma is increased. One means of alleviating this problem is to employ plasma sources that operate at a high level of ionization. Due to the large specific power input (arc power/particle flux) of the MPD plasma sources, they are able to combine good gas efficiency with large particle flux and thus serve as a plasma source for the high current beam lines that will be needed in the near future.

Description of the MPD Arc Source

The basic configuration of the MPD arc source is shown in figure 1. The geometry of the device is axially symmetric, with a centrally located cathode and an annular anode. The cathode material is usually thoriated tungsten, though other materials have been used. The shape of the cathode appears to affect the operation and a number of geometries have been tested, with the conical geometry shown here being the most common. The anode is shaped in the form of a nozzle, with the orifice located immediately downstream of the cathode. A typical physical size is represented by an anode orifice diameter of one to a few cm. A co-axial magnetic field is provided by one or more sets of coils. The applied magnetic field is required for the acceleration mechanism (discussed in references 2 and 3) and also to reduce heat transfer and eliminate hot spots due to a stationary spoke. The shape of the magnetic field (self-induced plus applied) should be compatible with the anode-cathode geometry, such that these elements are not linked by surfaces of magnetic flux that allow the easy transfer to energy. The warm plasma is expelled from the source as a highly directed

stream with ion energies in the range of 10 to 100 eV.

Operating Principles

The MPD arc can operate in several different modes. The primary mechanism of energy deposition and plasma acceleration is dependent upon the source density, applied magnetic field and arc power, and source geometry. Thus, at low arc power, high density, and without an applied magnetic field, the source operates primarily in an ohmic heating mode, with resultant low (≤ 1 eV) particle energy and degree of ionization. At high current and low density, $j \times B_{\text{induced}}$ forces act to expel the plasma at high energies. The current required in this "high current" mode is in excess of several thousand amp. Addition of a large, axially directed magnetic field lowers the current requirement and increases the efficiency of energy addition to the gas. Operation in this mode depends upon the interaction of an induced azimuthal electron Hall current with the axial magnetic field to produce a compression in the radial direction. The mode is identified as a "Hall current" mode. The compression increases the density and temperature in the arc. A subsequent expansion in the axial direction can yield streaming neutral plasmas having ion energies of 10 to 100 eV. Most configurations tested to date have had applied magnetic fields on the order of 1000 to 6000 gauss, densities of 10^{14} to 10^{16} cm^{-3} , arc currents in the 500 to 3000 amp range, and arc power of around 100 kilowatt.

Results of Previous Experiments

The MPD arc was originally developed as a space propulsion device. It is unique in its relatively high thermal efficiency, thrust, and specific impulse. The data that is available consists for a large part of thrust measurements, with relatively little having been done to investigate the details of the plasma flow, e.g. composition and energy distributions. In the application of the arc as a source of streaming plasma, the operating parameters and geometry will be chosen to emphasize the production of highly ionized plasma, having high ion energy and electron temperature.

Some of the original experiments conducted with the MPD source were done by Ducati, et. al.⁽⁴⁾ The source was operated in the high current mode and achieved kinetic energies on the order of 50 eV with a particle flux of 2500 amp of hydrogen. A high degree of ionization was achieved in these tests. The arc current was on the order of 3000 amp with a source pressure of ~50 Torr. Later experiments were performed by Grossman, et. al.,⁽⁵⁾ at NASA Langley who applied an axial magnetic field to the source. Operating with argon at a lower arc current (~600 amp) and an external magnetic field of 3000 gauss, i.e. in the Hall current mode, kinetic energies approaching 200 eV were achieved. The mass flow for these experiments was 0.016 to 0.034 gram/sec, i.e. an equivalent current of 40 to 85 amp.

Electron density and temperature measurements in the plume of an MPD source operating in the high current mode were conducted at JPL by Kelley, Nerheim, and Gardner.⁽⁶⁾ At an arc current of 1000 to 1500 amp and an argon flowrate of 5000 to 1250 amp, the electron temperature in the jet was measured to be in the range 0.5 to 2.0 eV.

The work by Patrick and Schneiderman⁽⁷⁾ at AVCO showed that the arc voltage of an MPD source operating in the Hall current mode depends linearly upon the applied magnetic field. The effect of the fluid is included through the velocity U_c that corresponds to the average energy required to dissociate and ionize the constituent molecules; the arc voltage V can be written

$$V = V_0 + U_c BL,$$

where V_0 is a constant associated with the sheath voltage drop (and thus heat transfer) and L is a characteristic dimension of the device, e.g. the throat radius. The arc powers for these tests ranged from 10 KW to 100 kW and the average ion energy was on the order of 10 to 20 eV. The thermal efficiency, defined as the quotient of the power deposited in the gas and the power delivered to the source, is about 75% over a wide range of operating conditions. The thermal efficiency of the source appeared to be independent of the applied magnetic field.

The current density distribution in the jet was studied by Powers⁽⁸⁾ at AVCO. It was found that the discharge plume conforms to a magnetic nozzle shaped by the field. An account is given of induced field measurements and the current components. The point of attachment of the arc to the anode was found to be dependent upon the mass flow, moving upstream as the mass flow is reduced. The current range for these experiments was -1000 amp, the applied magnetic field was 0 to 1500 gauss, and the power was 25 to 75 KW. It was shown that the applied magnetic field "pinches" the expanding plasma downstream of the nozzle. The mass flowrate in these experiments were about 1000 to 5000 amp, with the degree of ionization ranging from 5% to 75%.

On the basis of the results of experiments that have been conducted with the MPD source, it appears reasonable to expect that highly ionized flows having a particle flux in the thousand amp range can be produced with little difficulty. Operation in a pulsed or continuous mode depends upon the heat transfer to the material components of the MPD source, upon the requirements of the vacuum facility (see below) and the diagnostic instruments. It appears typical of MPD arc performance that it can operate at the 100 KW level without undue heat transfer problems. Since it is desirable for the streaming plasma application to operate at as high a power as possible, the limits of performance and methods of improving the heat transfer characteristics will be investigated.

Design of the MPD Source

The experiments discussed here are designed to demonstrate the utility of the MPD source in the production of streaming plasma in the 10 to 100 eV range. The type of performance required has been achieved in previous experiments, and the design discussed here is similar to tested devices. The source geometry has been made as flexible as possible in order to optimize geometry related parameters. Furthermore, the magnetic field lines in the anode-cathode region have been shaped such that, to the largest possible extent, the source is protected from excessive heat transfer. Consequently, the source should be able to operate at energy densities equal to or in excess of those achieved previously.

The design of the MPD source is shown in figure 2.* The anode and cathode are co-axial and their relative position is adjustable. Both are water cooled in order to protect the device from excessive temperature and to facilitate handling between experiments. The hardware has been designed such that the

*The assistance of Paul Marshall in the design and construction is acknowledged.

source geometry is as changeable as possible. Thus, the cathode tips are replacable, and the magnet-anode position is variable. The field line shape is changed by varying the relative current in the set of coils* and/or by iron inserts.

Previous investigators⁽⁹⁻¹²⁾ have found that the MPD source may operate in a low frequency (~100 khz) rotating spoke mode at particular values of applied magnetic field and arc current. There is evidence^(13,14) that this behavior is, in part, dependent upon the geometry of the cathode, and this is the primary reason for the interchangeable cathode tips. The main purpose for the variable anode geometry is to change the diameter of the source orifice. This orifice will aid in controlling the source density-particle flux relationship.

The anode is electrically insulated from the cathode by a Kapton sheet. The Kapton is protected from the plasma by a ceramic ring. The ring is also designed to serve as a gas manifold, such that the gas feed to the arc is spatially uniform. Due to its simplicity and flexibility, the Kapton-ceramic ring design was chosen over an alternative design which incorporated metal-ceramic vacuum seals, in a fashion similar to the tested designs of references 5, 7, and 8.

*The magnet was obtained through the courtesy of John Osher.

Test of Arc Characteristics

The streaming plasma requirements imply that the power deposited in the arc should be sufficient to create a highly ionized plasma with as high directed kinetic energy as possible. At the power levels considered here (~100 kW), material damage to the arc source is likely to occur if a significant fraction of the applied power is lost in heat transfer. An initial task in the development of the MPD arc as a source of streaming plasma is to delineate the operating parameters and geometries for which the source will operate reliably at large arc power; these tests, in conjunction with the investigation of the exhaust jet properties, are intended to provide the operator with information that relates the streaming plasma properties (ion flux and energy, etc.) with source parameters (mass flow, geometry, arc power, applied magnetic field).

For the initial tests of arc behavior the quantities that will be measured are arc current and voltage, the gas supply pressure and flowrate, the temperature rise of the anode and the cathode cooling water, and the magnetic field intensity (magnet current). These data are obtained as a function of source and magnetic field geometry. The magnetic field is varied by the use of soft iron flanges of several thicknesses, as illustrated in figure 1.

Test of Jet Properties

The primary purpose of the exhaust jet tests is to measure the properties of the streaming plasma as a function of source parameters. The properties of interest are the ion energy distribution, the spatial divergence of the plasma stream, the particle flux, the electron temperature, and the degree of ionization.

The ion energy distribution and particle flux must be known in order to correlate experimental result with theory; the divergence is related to the effectiveness of the flow in penetrating the magnetic mirror. The degree of ionization is expected to be an important parameter since neutral gas can contribute significantly to the gas load on the mirror machine.

The diagnostic tools that will be employed to probe the streaming plasma are Langmuir probes, Faraday cups, and calorimeters. The availability of momentum (bending magnet) and energy analyzers is presently being investigated.

Tests of Streaming Plasma Transport

The tests of jet properties were performed without a magnetic field downstream of the nozzle other than the field associated with the arc operation. The streaming plasma source is to be placed in the fan of the MFTF mirror machine and will, as a consequence, be subjected to a large energy flux from the confined plasma. Two of the possible magnetic field configurations are shown in figures 3a and 3b; in figure 3a, the magnetic field of the fan is in the same direction as the magnetic field from the MPD source, resulting in a nozzle shaped field configuration downstream of the arc. This configuration will cause the high energy flux to enter the MPD arc. At arc densities less than $\sim 10^{17} \text{ cm}^{-3}$, the high energy flux may pass through the arc and impinge upon material surfaces, resulting in erosion and other damage. At very high arc densities, it is possible that the incoming flux may become thermalized in the arc and re-emitted as streaming, warm plasma. The streaming plasma from the arc will tend to follow the field lines into the confinement region.

In figure 3b, the magnetic fields are opposing. This configuration has the advantage that the high energy flux from the mirror is diverted around the MPD arc. However, the streaming plasma must penetrate the cusp in order to follow the field lines to the mirror and the confinement region.

Each of the illustrated arrangements will be tested for the ability of the plasma to penetrate a magnetic mirror. The properties of the transmitted plasma that will be measured is the ion flux and the kinetic energy.

The Vacuum Facility

The large particle flux emitted by the MPD source can be pumped by either of two methods: The tank pressure can be low (10^{-6} - 10^{-4} T) and the MPD arc pulsed, or the tank pressure can be relatively high (10^{-1} T and up) and the arc can operate continuously.

A low pressure vacuum system normally has pumping capability in the 10^4 l/s range. Operation with 1000 amp of particle flux corresponds to a throughput of roughly 200 Tl/s. Stipulating a maximum pressure of 10^{-4} T and a facility volume of 10^4 l, the run (e.g. gas pulse) duration is limited to

$$\tau = \frac{V P_{\max}}{Q} = 5 \times 10^{-3} \text{ sec}$$

Operation on a millisecond time scale places a premium on the design of the pulsed gas supply as well as some diagnostic difficulties, primarily associated with the calorimetric measurements of the energy content of the beam and the measurement of neutral particle flux.

Investigation of heat transfer levels at large power and flowrates requires continuous (>1 sec) operation. A vacuum facility that is pumped by a blower backed by a mechanical pump will operate at $\sim 100\mu$ pressure at a continuous particle flux of 1000 amp.

The facility in which most of the MPD source tests will be conducted is the "Bicentennial" tank in B-435. The experiments will be pulsed, with an existing arc pulse line providing 750 amp of arc current. The same facility has adequate power supplies for the magnetic coils. In accordance with the above considerations, detailed investigation of long pulse performance at large flowrates requires pumping in excess of that provided by the "Bicentennial" vacuum facility.

Conclusion

The MPD arc appears to be capable of satisfying the high particle flux, long pulse streaming plasma requirements of the MFTF mirror machine. The particle current is 1000-5000 amp and the ion energy is in the 10-100 eV range. A series of tests are described here that will quantify the performance of the MPD plasma source such that streaming plasma properties can be selected by operation of the source at the corresponding operating parameters.

Due to the growing requirements of large particle fluxes in mirror machines, the problems associated with gas handling and disposal are becoming more severe. The pumping required is becoming a critical factor in the experimental design, and it is important to increase the degree of gas utilization for each component. This leads to the requirement that the neutral beam and plasma sources must operate at a high level of ionization, e.g. with a high specific power input to the plasma. The configuration of

the MPD plasma source does allow a high specific power input; it is therefore a viable candidate as a source of plasma for high current, gas efficient beam systems.

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SCHEMATIC OF MPD PLASMA SOURCE

FIG. 1

SUBJECT ANODE HOUSING		SKETCH LAWRENCE LIVERMORE LABORATORY UNIVERSITY OF CALIFORNIA		JOB NO. 6140-45		TAG NO.	
DRAWN BY PAUL MARSHALL				SERIAL NO.		NO.	
DATE 7/1/77		BUILDING NO. 431		ROOM NO.		APPROVED BY	
DATE		DATE		DATE		DATE	
DELIVER TO		RECD.		RECD.		RECD.

FIG. 2b

SUBJECT CERAMIC INSULATOR			SKETCH LAWRENCE LIVERMORE LABORATORY UNIVERSITY OF CALIFORNIA			JOB NO. 6140-45		TAG NO.	
DRAWN BY PAUL MARSHALL			APPROVED BY			SERIAL NO.		NO. 2 EACH	
DATE 7/1/77		BUILDING NO. 431		ROOM NO.		DATE ISSUED		DATE REQ.	
DELIVER TO PAUL MARSHALL						EXT. 7077			

SCALE: 2/1

2 EACH

FIG. 2c

SUBJECT			<h1 style="text-align: center;">SKETCH</h1> <p style="text-align: center;">LAWRENCE LIVERMORE LABORATORY UNIVERSITY OF CALIFORNIA</p>		JOB NO.		TAG NO.
DRAWN BY					SERIAL NO.		NO. REQD.
DATE			APPROVED BY	DATE	DATE ISSUED		DATE REQD.
BUILDING NO.			ROOM NO.	JOB ORDER INFORMATION		DELIVER TO

FIG. 2 d

SUBJECT ANODE			SKETCH LAWRENCE LIVERMORE LABORATORY UNIVERSITY OF CALIFORNIA		JOB NO. 6140-45		TAG NO.
DRAWN BY PAUL MARSHALL					SERIAL NO.		NO.
DATE 7/1/77	BUILDING NO. 431	ROOM NO.	APPROVED BY	DATE	DATE ISSUED	DATE REQD.	DATE REQD.
					DELIVER TO

FIG. 2 e

ENGINEERING NOTE

SUBJECT

CATHODE CONTROL ROD

NAME

PAUL MARSHALL

DATE

6/28/77

FIG. 2 f

FIG 3 b

FIG. 3 a

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