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Spectral measurements of inductively coupled and helicon discharge modes of a laboratory argon plasma source

Murat Celik *

Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, MA 02139, United States

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ABSTRACT

An experimental study was conducted to investigate the effects of several operational parameters in the emission spectra, in the 400–850 nm wavelength region, of a laboratory Argon plasma source. In particular, the emission spectra of the inductively coupled plasma and the Helicon plasma modes of operation were compared. Comparisons of spectra point to a significant increase in the ionization fraction of the plasma for the Helicon mode of operation. The spectral measurements allow one to determine the major trends in the plasma electron density for various parameters such as power delivered to the helical antenna, propellant mass flow rate, and applied external magnetic field intensity.

Analysis of a prominent Argon single ion line, at 434.8 nm, points out that the plasma electron density increases linearly with the power delivered to the helical antenna, and that there is an optimum propellant mass flow rate for maximum ionization fraction. Additional analysis of the same line shows that above a minimum applied axial magnetic field intensity, the variation in the magnetic field strength has little effect on the plasma electron density.

1. Introduction

The use of helical shaped Radio Frequency (RF) antennas to create high density plasmas ($n>10^{18}m^{-3}$) has been widely studied. In the *inductively coupled plasma* (ICP) sources, typically, the region of plasma generation is surrounded by a helical shaped coil that creates a time varying magnetic field around it when supplied with RF currents. The time varying magnetic field induces a solenoidal RF electric field which accelerates the free electrons and creates the plasma [1,2]. In the *helicon plasma* sources, similar to the ICP sources, a radio frequency driven helical antenna is placed around a dielectric cylinder but with a direct current (DC) axial magnetic field applied in the region of the plasma generation allowing the excitation of a helicon wave within the source of the plasma [1]. Because of their efficient high density plasma production, the helicon plasma sources are getting increased attention over the past few decades [3–6]. However, the detailed mechanism of the helicon mode plasma generation is still an ongoing scientific debate [7–10].

The mini Helicon Thruster Experiment, mHTX, has been built to characterize the helicon plasma source in order to gain a better understanding of the plasma generation by helical shaped RF antenna, and identify methods by which plasma parameters can be tuned to accelerate the obtained high density plasma in order to achieve an efficient propulsive system [11–13]. In electric thrusters external energy is used to ionize gas and then accelerate the resulting plasma using electric and magnetic field forces. In thruster concepts such as the Variable Specific Impulse Magnetoplasma Rocket (VASIMR), a helicon source is used to produce high density plasma, while a secondary stage is used to heat the ions by ion cyclotron resonance heating using radio frequency waves and a magnetic nozzle is used to convert azimuthal momentum into axial momentum to accelerate the gas particles [14–16].

For the mHTX concept, the goal is to obtain high density plasma using a helicon discharge and then accelerate it through thermal pressure which creates ambipolar potential gradients. The power is delivered to the particles through wave–particle coupling using the helicon waves. In the current study, emission spectroscopy is used as a means to deduce information about the plasma through the measurement of line radiation emitted from the plasma particles [17]. It is shown that change in the operational parameters significantly affects the ionization fraction of the plasma.

2. Experimental setup and procedures

All spectral measurements were conducted at the MIT Space Propulsion Laboratory. The plasma source was placed inside the 1.5 m diameter 1.6 m long vacuum chamber that is equipped with a mechanical roughing pump and two cryogenic pumps with a total pumping capacity of 7000 L/s for Xenon [18].

* MIT Space Propulsion Laboratory, currently Assistant Professor at Bogazici University, Istanbul, Turkey. Tel.: +90 212 359 7372; fax: +90 212 287 2456.
E-mail address: murat.celik@boun.edu.tr.

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2.1. The plasma source

The mHTX Helicon plasma source consists of a pair of cylindrical electromagnets surrounding a long 2 cm diameter cylindrical quartz tube where the propellant gas flows through. A 9.86 cm long 2 cm diameter right hand polarized half-helical antenna made of copper is placed over the quartz tube between the electromagnets [11]. The length of the antenna, 9.86 cm, was chosen to be the half wavelength of the 13.56 MHz frequency m = 1 Helicon waves in a plasma of 10^{20} m^{-3} in density for 20 eV electron energy [11]. A schematic of the experimental Helicon plasma source is shown in Fig. 1. One end of the quartz tube is attached to a propellant gas flow line, and the other is open to the vacuum of the chamber. The gas flow is controlled by a digital flow meter located outside of the vacuum chamber. Even though in this study only the tests on Argon gas are presented, the plasma source was run on xenon, nitrogen, neon and air as well as nitrogen–argon mixture of varying ratios.

The helical antenna is powered by a 1200 W RF power supply, Advanced Energy RFPP-10, operating at 13.56 MHz. The antenna is connected to the RF power supply by an in-house built coaxial transmission line located inside the chamber, a 13.56 MHz vacuum RF power feedthrough, and an impedance-matching network attached to the vacuum port on the outside of the chamber. The impedance-matching network has a classic L-network circuit structure that employs two adjustable vacuum capacitors [11].

In order to produce the helicon discharge, the external magnetic field is generated through the use of a pair of electromagnets in Helmholtz configuration. The magnet system produces a maximum axial magnetic field intensity of 210 mT at the center, axial region between the electromagnets for 35 A of current to each coil. The helicon antenna is located in this high, axial magnetic field region. During the experiments the magnet current is modified for the desired magnetic field intensity. The plasma source was located in the center of the vacuum tank on a metal platform, and the antenna region was aligned with one of the side windows.

2.2. Spectral measurement setup

The radiation collection, from the plasma region of interest, is accomplished by a pair of 2.54 cm diameter collimating–focusing lenses with 100 cm and 10 cm focal lengths, respectively. The whole optical setup is placed on a metal shelf attached to the vacuum tank window as shown in Fig. 2. The end of a 91.44 cm long Oriel fiber bundle is placed at the focal point of the focusing lens. In order to reduce the stray light from inside the vacuum tank, the window is covered with a black optical card board with a 2.54 cm hole cut in the middle, in line with the lens axis. A mechanical diaphragm is placed before the collimating lens in order to adjust the intensity of the collected light. The shelf is covered with an optically opaque black cloth during the data acquisition. Mechanical translation stages were used to adjust the exact location and the proper alignment of the optical components. A fiber adapter is used to hold the fiber bundle directly at the entrance slit of the spectrometer.

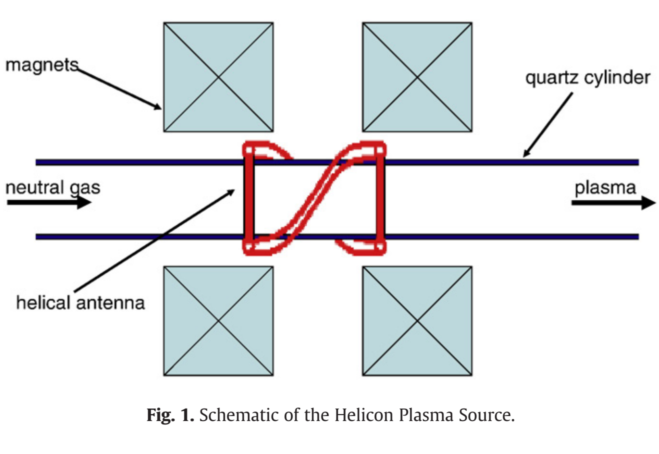

Fig. 1. Schematic of the Helicon Plasma Source.

A Thermo Jarrel Ash Monospec-18 spectrometer was used as the dispersive instrument. This 15.6 cm focal length, f/3.8 aperture Czerny turner type spectrometer provides a resolution of ~0.7 nm for 1200 g/mm grating. An Andor iDus DU420A CCD detector was attached to the exit port of the spectrometer for the presented spectral measurements.

The intensity calibration of the measured spectra was achieved by using a tungsten lamp with known continuum emission intensity. The tungsten lamp was placed in the same location as that of the helicon plasma source inside the vacuum chamber. The emission intensity produced by the tungsten lamp was measured with the same optical path and exposure time for each spectrometer dial setting that a helicon plasma emission data was taken.

2.3. Spectral measurement procedure

A vacuum pressure level of 1.2×10^{-7} Torr was obtained before the plasma source started operating. First, the propellant flow was turned on by digitally setting the flow rate on the flow-meter located outside of the vacuum chamber. For 20 sccm of argon flow, the background pressure inside the vacuum tank stabilized around 3.2×10^{-5} Torr. Second, the magnet power supplies were turned on and currents of up to 35 A were delivered to the electromagnet coils to create the desired magnetic field intensity in the antenna region between the electromagnets. Next, the RF power supply was turned on and was set to a desired power level up to the maximum 1200 W. As the RF power was delivered to the antenna, a plasma discharge was observed. The capacitance of the impedance-matching network circuit was adjusted by changing the dial settings on the two capacitors until the best impedance match for the plasma discharge was obtained. The best impedance-match was verified by monitoring the total RF power delivered to the plasma on the RF power supply display. The match was also confirmed by visibly observing the brightness and stability of the obtained plasma from a vacuum window port. Spectral measurements were then taken for varying operational parameters.

3. Results and discussion

During the spectral measurements, several operational parameters were varied and the plasma emission spectra were recorded. The RF power delivered to the plasma was varied from 400 W to 1200 W. The magnet currents were varied from 0 to 35 A. An ampere of magnet coil current corresponds to ~6 mT maximum axial magnetic field intensity in the antenna region. Thus the maximum axial magnetic field strength of up to 210 mT was obtained. The argon propellant flow rate was varied from 10 to 100 sccm.

Spectral data were taken for the wavelength range of 400–850 nm as this was the high sensitivity range for the available CCD detector. A study of the prominent argon neutral and single-ion emission lines in this wavelength region shows that the spectrum is dominated by the argon single-ion lines in the 400–550 nm region, however in the 700–850 nm region all the prominent lines are those of the neutral argon atom according to NIST Atomic Spectra Database [19].

3.1. ICP vs. helicon regimes

From the visual observation of the plasma, the increased magnetic field makes a significant difference in the color and the intensity of the radiation emanating from the discharge. Also, for the case with no magnetic field, which can be called Inductively Coupled Plasma mode,