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Development of Millimeter Wave Plasma Interferometry for the Measurement of Precursor Electron Density

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Abstract

In this study, a 28 GHz millimeter-wave interferometer was constructed to measure precursor electron number density. Measurements were made using a 9 m long free-piston driven expansion tube. Air was used as the test gas. The electron number density corresponding to the precursor in front of the strong shock wave was generated behind the shock wave at about 3 km/s. Measurements were made using an expansion wave tube. A Teflon window was attached to the observation section of the expansion wave tube and a transmitter/receiver antenna was installed so as to pass through the observation section. Microwaves were focused to a diameter of 50.1 mm using a dielectric lens to increase the spatial resolution of the interferometer. The transmitter and receiver antennas were horn antennas. The electron number density behind the shock wave with a shock wave velocity of 3.58 km/s was obtained as $3.43 \times 10^{18}\ \mathrm{m}^{-3}$.

Keywords: *Expansion Tube, Microwave Plasma Interferometry, Precursor*

Nomenclature

I – In phase signal (V)
Q – Quadrature signal (V)
ϕ – phase (rad)
N_e –electron number density (m^{-3})
L – pathlength traversed by microwave through the plasma (m)
m_e – electron mass
ε_0 – free-space permittivity
c – speed of light
e – electron charge
λ_0 – microwave wavelength
t – time
P – microwave power

1. Introduction

In future deep space exploration sample return missions, re-entry into the Earth's atmosphere will take place at speeds of 14 km/s or more. In such hypersonic flows, strong shock waves cause chemical reactions such as plasma, dissociation and ionisation of air [1][2]. In particular, non-equilibrium thermodynamics and thermal radiation occur in the plasma. In the case of sample return missions by satellites, there is the problem that the heat flux is increased by the plasma. Therefore, it is necessary to study the plasma phenomena generated by such strong shock waves. One of the plasma phenomena generated by shock waves is called precursor. In order to improve the results of numerical calculations of plasmas, Yamada et al. measured the precursor electrons generated in front of the shock wave in argon gas using a free-piston shock tube from the Stark width of the Balmer series Hβ line [1]. In this method, two laser Schlieren systems are installed in the observation section of the shock tube, and the Hβ spectrum of the region in front of the shock wave is measured. The electron number density was measured from the Stark width of the spectrum. Lederman et al. measured the precursor electron density in argon gas inside the shock tube using a microwave resonant cavity [2]. This method uses microwave interferometry with a 2.7 GHz transmitter. The electron number density is measured from

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the change in frequency produced in the cavity by precursor electrons, and the velocity of precursor electrons is obtained from the two cavities. Dufrene et al. measured the electron number density using millimeter-wave plasma interferometry in the LENS XX expansion tunnel [3]. The instrument uses two antennas set across the plasma. The electron number density of the plasma is measured from the phase difference between the millimeter wave passing through the plasma and the transmitted wave. Similarly, Omura et al. measured the precursor electron number density using a shock tube and an 8.5 GHz millimeter wave interferometer [4]. In air at an initial pressure of 26.7 Pa and a shock velocity of 10 km/s, the precursor electron number density at 1 m in front of the shock wave to be about $2 \times 10^{16}\ \mathrm{m^{-3}}$. This electron number density corresponds to the electron number density behind the shock wave of about 3 km/s [3]. However, these methods can only measure the electron number density at the measurement position. Precursor electron number density varies with distance from the shock wave, so a measurement method is needed that can measure the distribution in the flow direction.

In this study, a millimeter-wave interferometer with an antenna in the flow direction in a free-piston driven expansion tube was developed to measure the electron number density distribution in the tube. A free-piston driven two-stage expansion tube was used for the experiment. The frequency of the millimeter-wave interferometer should be higher than the cutoff frequency of the plasma. For an electron number density of $2 \times 10^{16}\ \mathrm{m^{-3}}$, the cutoff frequency of the plasma is 1.27 GHz. The higher the frequency of the millimeter-wave interferometer, the higher the electron number density can be measured. Therefore, the frequency of the millimeter-wave interferometer is set to 28 GHz. The upper limit of the electron number density that can be measured at 28 GHz is $9.7 \times 10^{18}\ \mathrm{m^{-3}}$. This electron number density corresponds to a shock velocity of about 4~5 km/s [3].

Experiments were carried out using an expansion tube to generate a shock wave of about 3 km/s using air as a test gas, and the precursor electron number density during atmospheric re-entry can be simulated behind the shock wave.

2. 9m length free-piston expansion tube

The expansion tube used in the experiment is consists of a high-pressure reservoir, a compression tube, a 1st diaphragm, a medium-pressure tube, a 2nd diaphragm, a low-pressure tube, and a test section. The piston is driven by the gas in the high-pressure reservoir and travels inside the compression tube. The 1st diaphragm is ruptured by this pressure. After the rupture of the 1st diaphragm, a shock wave is and a hypersonic flow can be obtained at the test section. Four static pressure transducers (PCB PIEZOTRONICS 113B28) are mounted on the sides of the medium-pressure tube and low-pressure tube. The shock velocity can be measured from the time difference between the rise of these sensor signals and the distance between the sensors.

3. 28 GHz millimeter wave plasma interferometry

Fig. 1 shows the measurement theory of MW interferometry. The theory of interferometric measurement makes use of the phase change that occurs when microwaves pass through a plasma. The microwaves are split into two paths, one of which is passed through the plasma and the phase change between the two is measured. The phase is calculated using a component called the IQ Mixer.

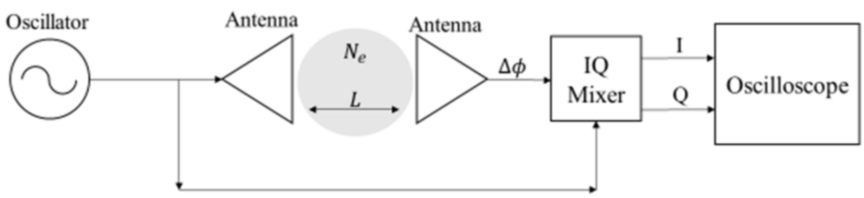

Fig 1. MW interferometry.

As plasma passes between the two antennas, a phase difference is created. The mixer outputs the in-phase signal I and the quadrature signal Q from the transmitted and received waves. This IQ signal is measured with an oscilloscope. From this IQ signal, the antenna received power is obtained by the following equation [3].

$$P = I^2 + Q^2 \quad (1)$$

The phase difference is obtained by the following equation [3]

$$\phi = \tan^{-1}\frac{Q}{I} \quad (2)$$

The phase difference and electron number density have the following equation [5].

$$N_e L = \frac{4\pi m_e \varepsilon_0 c^2}{e^2 \lambda_0}\Delta\phi \quad (3)$$

In this study, a microwave lens was attached to the end of the transmitting antenna to increase the spatial resolution of the microwave interferometer. To measure the beam waist of the MW Lens, a radio absorber is placed at the focal point as shown in Fig. 2 and the temperature rise of the absorber is measured by an IR camera. The distance from the horn antenna to the MW Lens is 60 mm, and the distance from the MW Lens to the absorber is 110 mm.

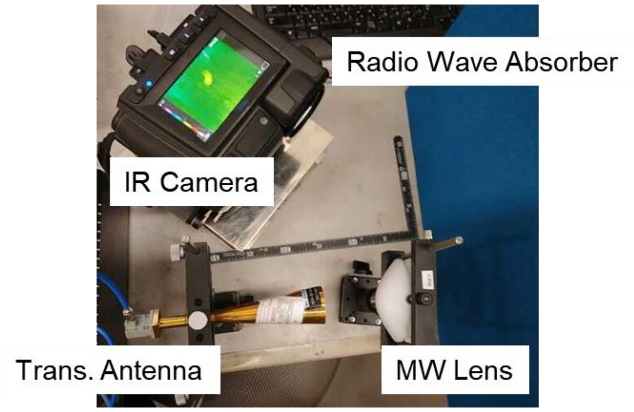

Fig 2. beam waist measurement of MW lenses

The left-hand diagram in Fig. 3 shows the results of the IR camera. The right-hand diagram shows the temperature distribution at Y=240 mm. The diameter of the beam at $1/e^2$ of the peak temperature is 50.1 mm.

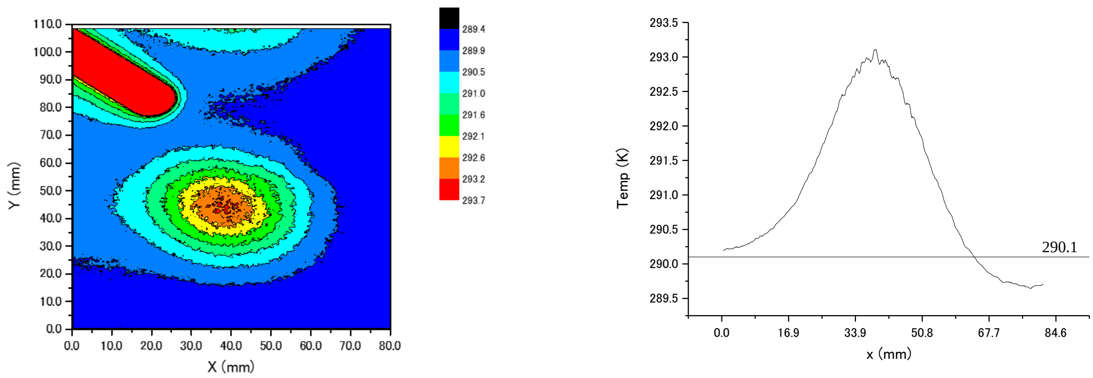

Fig 3. temperature measurement results

The millimeter-wave interferometer consists of a 28 GHz oscillator (Vega technology Inc. VG14-28G), an isolator (DiTom Microwave Inc. D312731), a driver amplifier (Advanced Microwave Inc. WPAC472PG) and IQ mixer (Marki Microwave MMIQ1037H). A schematic diagram of the experimental setup is shown in Fig 4. The receiving and transmitting antennas are mounted on the observation section. The side of the observation section is fitted with a Teflon window with low dielectric constant. The distance between the transmitting antenna and the MW lens is 60 mm. The distance between the MW lens and the centre of the observation section is 110 mm.

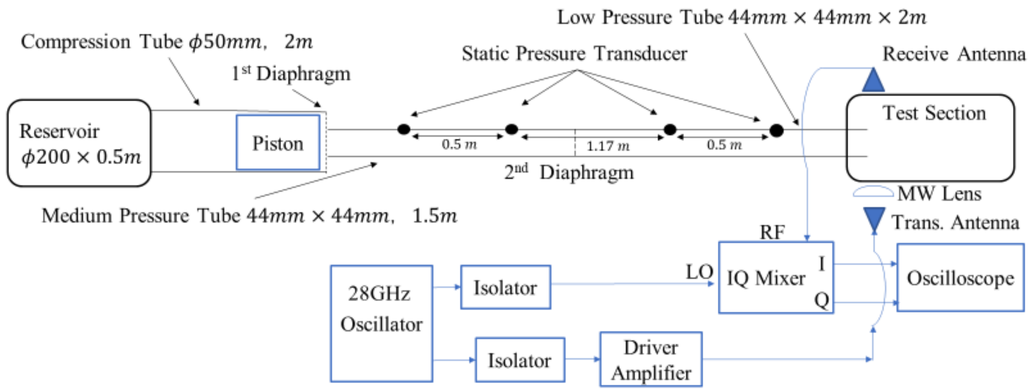

Fig 4. System of Expansion Tube. Antennas are installed in the observation section. MW lens is used to increase spatial resolution.

Millimetre-wave interferometers only work when plasma is present and the electron number density is below the cut-off; an RF detector was installed separately from the interferometer to ensure that the 28 GHz microwaves were penetrating the plasma through the plasma.An antenna circuit with a rectifier is mounted above the receiving horn antenna to measure the attenuation of the microwaves due to the plasma. Fig. 5 shows the antenna with rectifier.

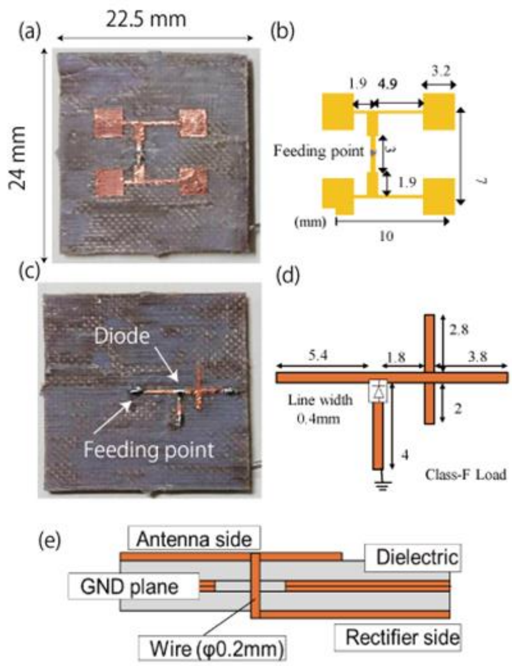

Fig 5. patch antenna with rectifier circuit (Matsukura 2019[6])

4. Result and discussion

Electron number density distribution measurement

Electron number density measurements in the direction orthogonal to the expansion tube were made with Shot#309. The initial pressure of the low-pressure tube is 800 Pa. The shock velocity after the 2nd diaphragm was obtained to be 3.58 km/s from the static pressure transducers. From this shock velocity, the arrival time of the shock wave at the receiving antenna position is estimated to be 4.7 ms. This indicates that the microwaves are attenuated by the shock wave.

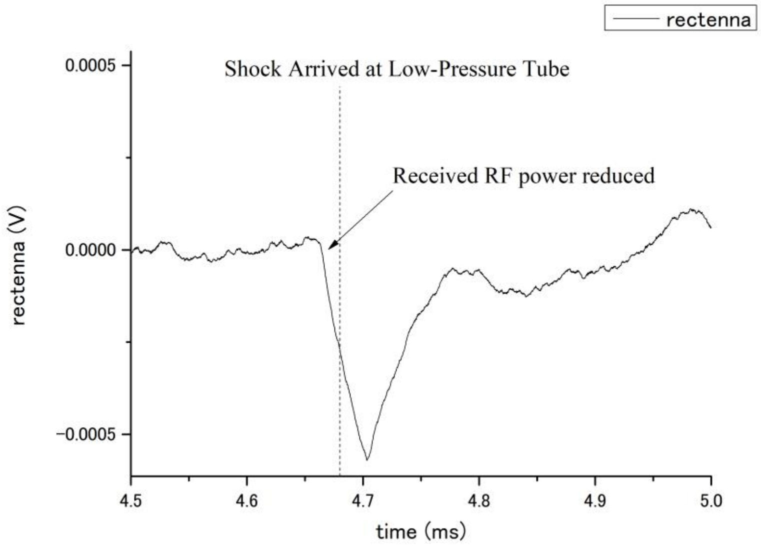

Fig 6. Time history of the rectenna output signal. The dashed line in the diagram shows the arrival timing of the shock wave determined from the rise of the IQ signal. The timing of the peak of the received power drop coincides with the peak of the electron number density.

Fig. 7 shows the measurement results of the IQ signals. Since the IQ signals are rises sharply around 4.68 ms, it is considered that the measurement is performed as a millimeter-wave interferometer.

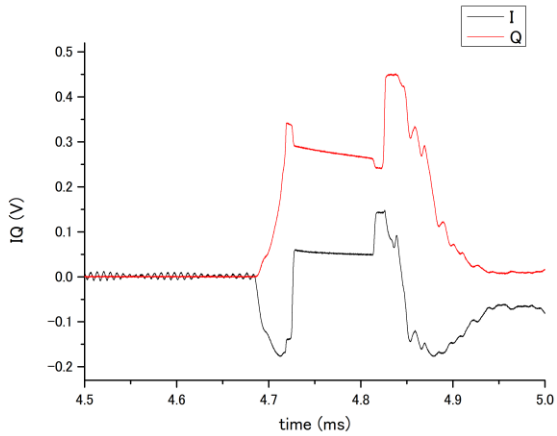

Fig 7. Measurement results for an initial pressure of 800 Pa and a shock wave velocity of 3.58 km/s. The figure shows the IQ signals.

Fig. 8 shows the phase calculated from the IQ signals from Eq. 2 The reflected signal from the low−pressure tube is measured up to the arrival of the shock wave.

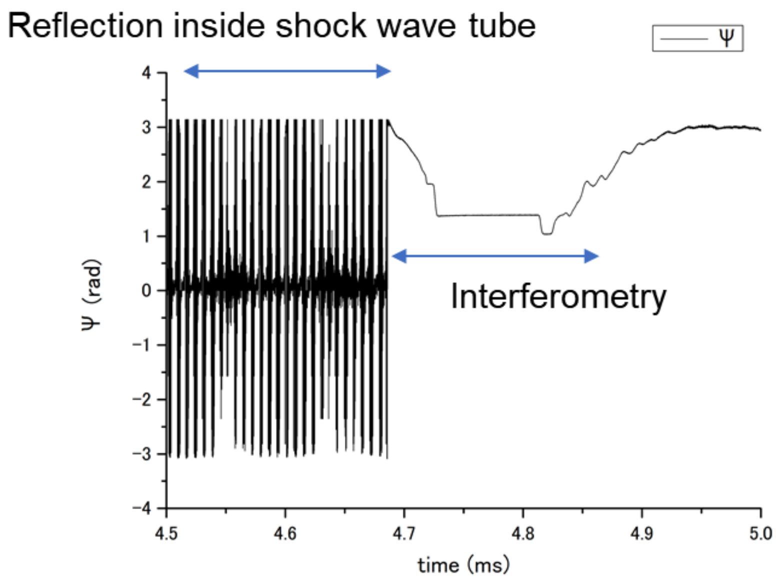

Fig 8. Measurement results for an initial pressure of 800 Pa and a shock wave velocity of 3.58 km/s. The figure shows the phase from Eq. 2.

To obtain the electron number density, phase unwrapping is required to make the phase continuous [7]. Fig. 9 shows the phase unwrapped and the electron number density calculated from Eq. 3 The phase was offset to zero at the time of arrival of the shock wave. The distance the millimeter wave travels through the plasma is $\mathrm{L} = 44\ \mathrm{mm}$, which is the width of the low-pressure tube. From the measurement results, the peak value of the electron number density after the arrival of the shock wave was $3.43 \times 10^{18}\ \mathrm{m}^{-3}$.

On the other hand, there is an increase in the electron number density behind the shock wave, but this is not known. The RF measurements confirm that some electrons are present and that the microwaves are decreasing, but the waveforms do not match. This is due to the spatial resolution of the RF antenna. The 50 mm diameter beam interferes and the area is too large for the measurement of very thin shock waves. For this reason, the resolution will be improved in the future by using antennas with high directivity and by devising the transmitting and receiving system.

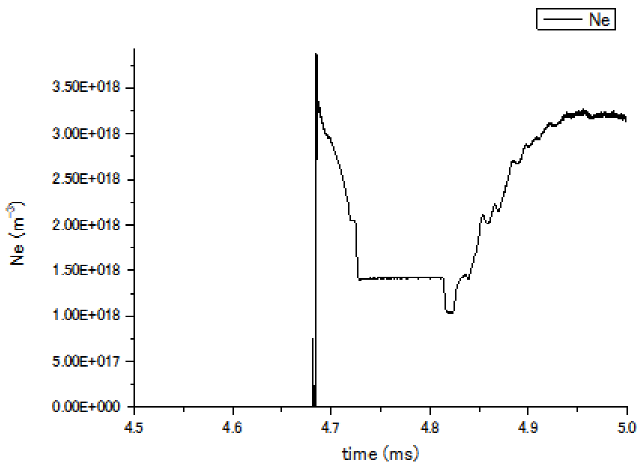

Fig 9. The figure shows electron number density calculated from Eq.1 and Eq. 3.

Conclusions

In this study precursor electron number density was measured using a free-piston driven expansion tube. Air was used as the test gas. A millimeter-wave interferometer was developed to measure the electron number density. The frequency of the millimeter-wave interferometer was set to 28 GHz. The upper limit of measurable electron number density is $9.7 \times 10^{18}\ \mathrm{m}^{-3}$. Experiments were carried out using an expansion tube to generate a shock wave of about 3 km/s using air as a test gas, and the precursor electron number density during atmospheric re-entry can be simulated behind the shock wave. To increase the spatial resolution of the microwave interferometer, a MW lens is attached to the end of the transmitting antenna. A Teflon window is attached to the observation section of the expansion tube and the antenna is set up so that the microwaves pass through to the observation section. A rectenna is mounted above the receiving antenna to measure the attenuation of the microwaves due to the shock wave. The transmitted microwaves are focused to a diameter of 50.1 mm by a MW lens. As a result of the expansion tube experiment, the electron number density was measured to be $3.43 \times 10^{18}\ \mathrm{m}^{-3}$. The timing of the peak of the rectenna output signal decay coincided with the peak of the electron number density.

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