Probe diagnosis and Schlieren visualization for 28GHz microwave rocket

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Beaming Energy propulsion

The method of propulsion that thruster get propellant energy by being irradiated electromagnetic wave from ground.

- need not to load propellant or fuel
- can increase other payload and simplify structure
- easy to inspect beam-oscillation facility
- can use the facility again and again
- compensate for initial cost

process

1. Incident microwave to cylindrical body is focused at the conical head.
2. Plasma front propagates with sonic wave.
3. It gets thrust by evacuating the sonic wave.
Plasma diagnostics of mmW induced discharge phenomena

$T_e$ and $N_e$ are important parameters for Microwave rocket performance.

**Examples of diagnosis**

- **laser interferometry** (Schabu 2016, MIT)
  *electron and gas density* (110 GHz, 750kW Gyrotron)

- **optical emission spectroscopy** (Hummelt 2012, MIT)
  *vibrational and rotational temperature* (110GHz, MW Gyrotron)

- **propagation velocity** of ionization front from photographs
  *taken by streak camera*
  (Bogatov, 1986 USSR)

As this plasma generates in several milliseconds, it is difficult to measure electron temperature and number density.
Objectives

Our objective is to measure $T_e$ and $N_e$ of the plasma caused by air breakdown with double probe diagnosis.

Advantages of double probe diagnosis
1. easy to assemble circuit such as probes
2. can measure locally with the high spatial resolution
3. can measure with no electrodes
Using double probe diagnosis, we can measure $T_e$ and $N_e$ from $IV$ characteristics.

To get the current variation easily, the sweep voltage of several Hz is usually applied.

However as the plasma is thought **unsteady**, we apply **fixed** voltage. And we get some data every voltage to plot characteristics assuming that the phenomena are **reproducible**.
Experimental setup: Double probe

![Diagram of experimental setup]

- **Oscilloscope**
- **Resistor (0.2 Ω)**
- **Fixed voltage**
- **Shield room**
- **300 mm**
- **600 mm**
- **Conical head Φ100 mm**
- **Waveguide**
- **Cassegrain antenna**
- **Gyrotron owned by Plasma Research Center**
- **Probes**
  - **Tungsten φ0.3 mm**
  - **Allumina-insulating tube φ3 mm**
Experimental conditions

use high-speed camera (Ultra-cam) to visualize plasma

<table>
<thead>
<tr>
<th>gyrotron</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>28 GHz</td>
</tr>
<tr>
<td>Wavelength</td>
<td>10.7 mm</td>
</tr>
<tr>
<td>Power</td>
<td>350 kW</td>
</tr>
<tr>
<td>Duration</td>
<td>8 ms</td>
</tr>
<tr>
<td>Mode</td>
<td>linearly polarized gaussian beam</td>
</tr>
<tr>
<td>Beam waist</td>
<td>20.3 mm</td>
</tr>
</tbody>
</table>

Bias voltage
As described above, we apply fixed voltage from -40 V to +40 V with AA batteries because the plasma is thought unsteady.
Visualized plasma (self emission)

Propagation speed about 20 m/s estimated from sequent photos

Peak intensity 17 MW/m² measured with rectenna

There are different structures between wave front and other section.

Schlieren method

Schlieren method represents density’s gradient as contrasts between light and dark.

• As shown in the movie, density of heavy particles varies at not only wave front.

• At the wave front gradient is larger than at any other point.
Visualization results

We try to measure $T_e$ and $N_e$ after plasma arrives at probes.

- As shown Image(b), wave front has high density gradient. But $T_e$ and $N_e$ can’t be measured from IV characteristics.

- As shown Image(a), there are no differences in this section.

$T_e$ and $N_e$ are measured at 3 mm behind wave front.
Probe current from -42 V to +42 V

Output voltages are as large as noise signal and the sections that current flows are different from each other.

Each time axis is arranged on the basis of the peak values after smooth fitting by Kaleidagraph.

- can measure partial $T_e$ and $N_e$
- The larger bias voltage is, the more probe current flows.

plot $IV$ characteristics at some time points extracting in vertical direction
**$T_e$ and $N_e$ from IV curve**

Example of IV characteristics

Left side is slope of the right graph. $\rightarrow T_e$ is calculated 71500 K

$$I_i = \kappa N_e e S \sqrt{\frac{kT_e}{m_i}}$$

$\rightarrow N_e$ is calculated $0.9 \times 10^{19}$ /m³
Comparison with Numerical Calculation

By numerical calculation, the electron temperature is calculated 20000 K. (170 GHz, 0.5 GW/m²)

As peak intensity of this experiment is 0.017 GW/m², $T_e$ is too high.

By numerical calculation, the electron number density is calculated up to about $1.2 \times 10^{21} \text{ /m}^3$ (170 GHz, 0.5 GW/m²) at the wave front and half of this value is seen after several dozen μs.

But $N_e$ can be $0.9 \times 10^{19} \text{ /m}^3$ after 0.1 ms because it is difficult to calculate the $N_e$ in 0.1 ms by numerical calculation.
Conclusion

Our objective is to measure $T_e$ and $N_e$ of the plasma caused by air breakdown with double probe diagnosis.

We measured partial $T_e$ and $N_e$ of the plasma caused by air breakdown with double probe diagnosis.

Our problems

• The phenomena don’t have reproducible.
• Probe voltages are as small as noise signal.
  →need to think how to measure accurate current
• Big error on the process of calculating $T_e$ and $N_e$
  →find accurate equation can apply in this case
That’s all. Thank you.
予備
Calculation

\[
\frac{d \ln \left( \frac{\sum i_i}{I_{e1}} - 1 \right)}{dV_d} = -\frac{e}{kT_e}
\]

\[
I_i = \kappa N_e e S \sqrt{\frac{kT_e}{m_i}}
\]

In this case, \( \kappa = 0.61 \)

\( k \) [J/K]: Boltzmann’s constant  
\( T_e \) [K]: electron temperature  
\( e \) [C]: elementary charge  
\( N_e \) [/m³]: electron number density  
\( S \) [m²]: surface area of probe  
\( m_i \) [kg]: ion’s mass

Example of IV characteristics

Other parameters are contained in above graph.
Objectives

The electron temperature ($T_e$) and the electron number density ($N_e$) have relation to plasma propagation.

Thus, it is necessary to analyze plasma behavior for evaluation of microwave rocket’s performance.

Our objective is to measure $T_e$ and $N_e$ of the plasma caused by air breakdown with double probe diagnosis.
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process

1. Incident microwave to cylindrical body is focused at the conical head.
2. Plasma front propagates with sonic wave.
3. Get thrust by evacuating the sonic wave
先行研究

1. 円筒状の機体に照射し、頭頂部で集光する。
2. プラズマの電離波面が衝撃波を伴って伝播する。(MSD)
3. 衝撃波排気後、膨張波が機体内に伝播する。
4. 吸気して、再びマイクロ波を照射する。
Output data

-42 V

![Graph showing voltage variation over time for -42 V.]

-12 V

![Graph showing voltage variation over time for -12 V.]

0.08 ms

0.01 ms

the time thought that plasma arrived at probes

about -0.8 mV

• Output voltage is as small as noise signal.
• Even if bias voltage is the same, that of probes doesn’t show the same values.
• Also, the time thought that plasma generates is different every shot.
Output data

Both figures are under the same bias voltage (+15 V).

• Output voltage is as small as noise signal.

• Even if bias voltage is the same, that of probes doesn’t show the same values.

• Also, the time thought that plasma generates is different every shot.
Arrangement

Each time axis is arranged on the basis of the peak values after smooth fitting by Kaleidagraph.

Stineman function
- not as smooth as classical methods
- has matches slopes (first derivative) only, while splines matches second derivatives.
Calculation

\[
d \ln \left( \frac{\sum i_i}{I_{e1}} - 1 \right) = -\frac{e}{kT_e}
\]
Calculation

Calculated $T_e$ and $N_e$ at some points

- $T_e$ varies from 90,000 K to 50,000 K.

- $N_e$ has the same tendency of $T_e$ and varies from $1.6 \times 10^{19}$ m$^{-3}$ to $0.8 \times 10^{19}$ m$^{-3}$.

The temperature is thought too high.

And error gets big on the process of calculation.
実験系
5W級電力実験(2018.10)
理想的なガウシアンビーム

電力密度相対強度

位置 x [mm]
• $N_e$ は大気圧で$10^{21}\text{m}^{-3}$の範囲内であり、周波数によって変化する。
予備実験

レーザー入射方向

グラフ タイトル

12.93V 平均  11.31V 平均  9.7V 平均  8.08V 平均
6.463V 平均  4.847V 平均  3.232V 平均  1.616V 平均
-1.616V 平均 -3.232V 平均 -4.847V 平均 -6.463V 平均
-8.08V 平均 -9.7V 平均 -11.31V 平均 -12.93V 平均
-14.55V 平均 -16.16V 平均
プラズマ

・マイクロ波エネルギーを推進力に変換する役割を担う。
→プラズマの挙動と推進性能との関係

左側からマイクロ波が照射され、右側にある放物面鏡で集光される。発生したプラズマはマイクロ波を吸収するため、ビーム源に向かって進む。
プラズマの伝播速度

出力Pが276kWのとき175m/s、592kWのとき453m/s
このとき衝撃波は401m/s、480m/sで伝播する。

P→大  ⇒  伝播速度→大
P→小  ⇒  衝撃波との距離→大
プラズマの伝播速度

また、
気圧→小
周波数→小
↓
伝播速度→大