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.

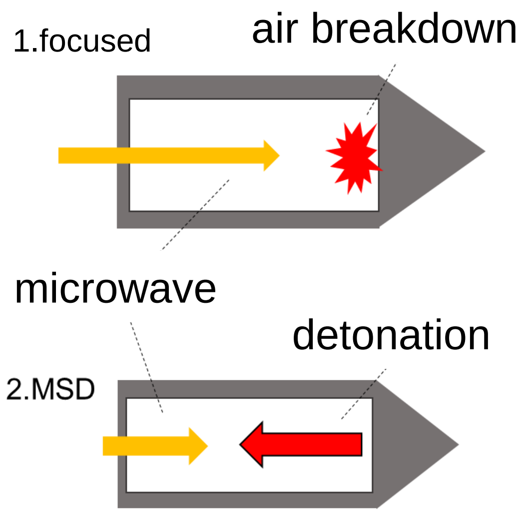
・need not to load propellant or fuel

→can increase other payload and simplify structure

・easy to inspect beam-oscillation facility

・can use the facility again and again

→compensate for initial cost



<u>process</u>

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)

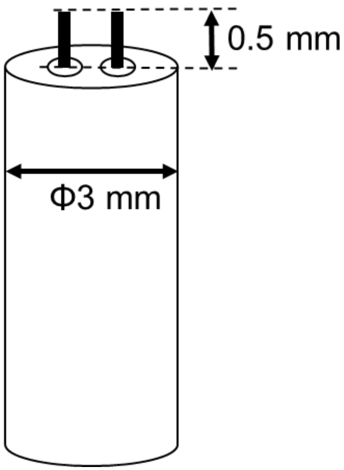
- optical emission spectroscopy (Hummelt 2012, MIT)
  vibrational and rotational temperature (110GHz, MW Gyrotron)

- 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.



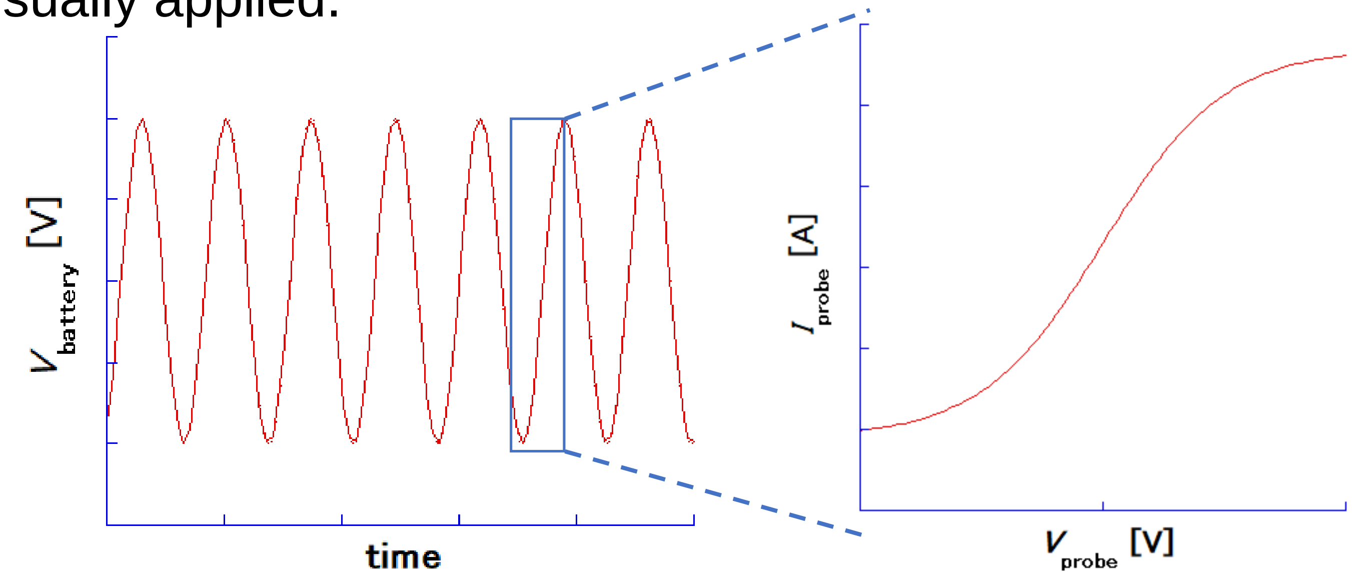
Advantages of double probe diagnosis

1. easy to assemble circuit such as probes
2. can measure locally with the high spatial resolution
3. can measure with no electrodes

Double Probe Diagnosis

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.

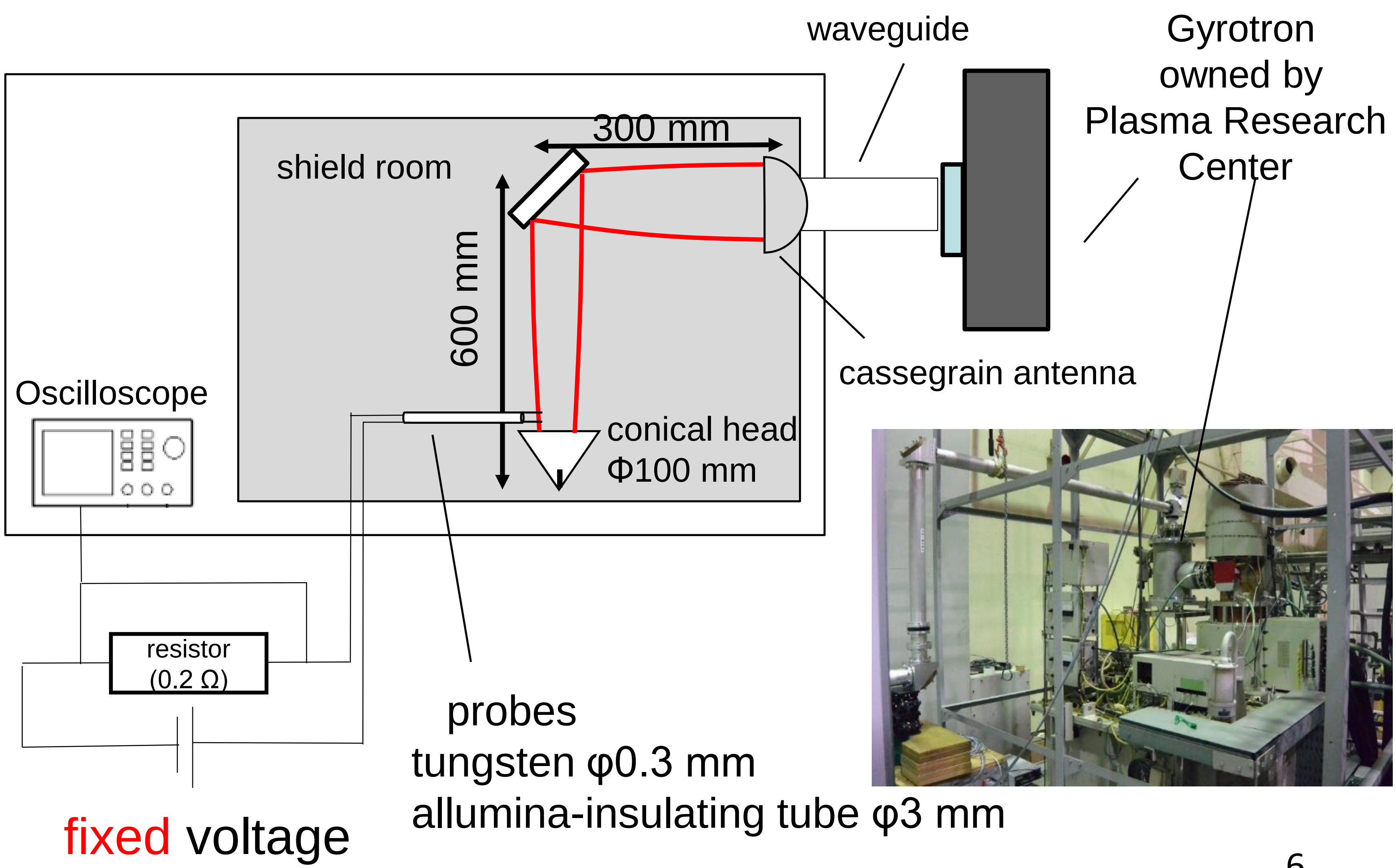


input signal

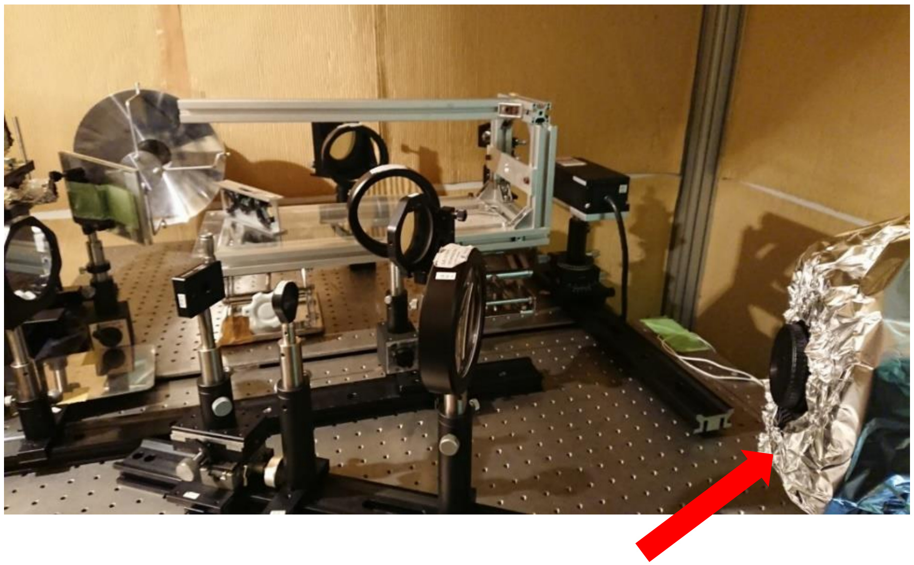
identical *IV* characteristics

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



Experimental conditions



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

gyrotron

Frequency	28 GHz
Wavelength	10.7 mm
Power	350 kW
Duration	8 ms
Mode	linearly polarized gaussian beam
Beam waist	20.3 mm

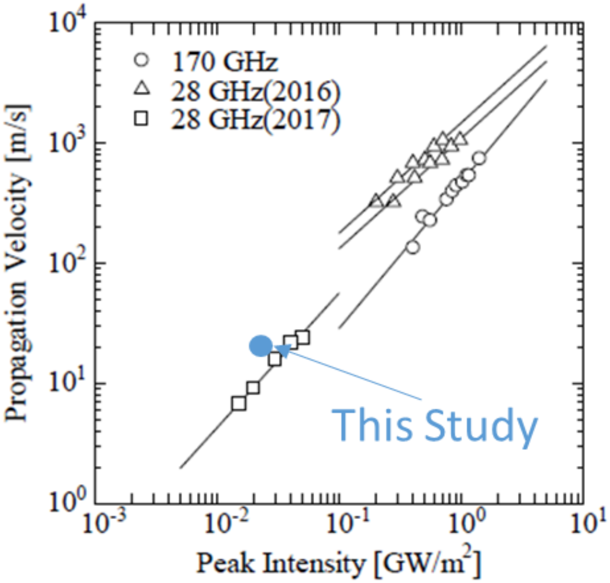
Bias voltage

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

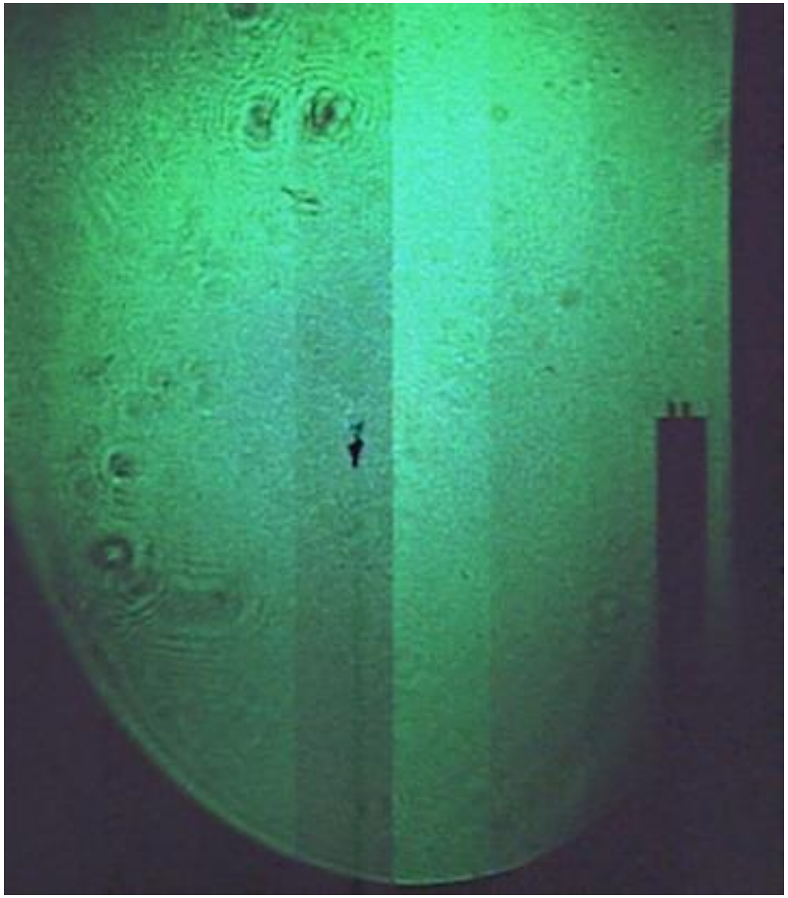
Peak intensity 17 MW/m²
measured with rectenna



There are different structures between wave front and other section.

Y. Harada, Y. Nakamura, K. Komurasaki, R. Minami, T. Kariya, T. Imai, K. Shimamura, M. Fukunari, Structural Change of Plasma at Various Ambient Pressures in 28 GHz Millimeter-Wave Discharges, Frontier of Applied Plasma Technology 10, 7 (2017)

Schlieren method



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

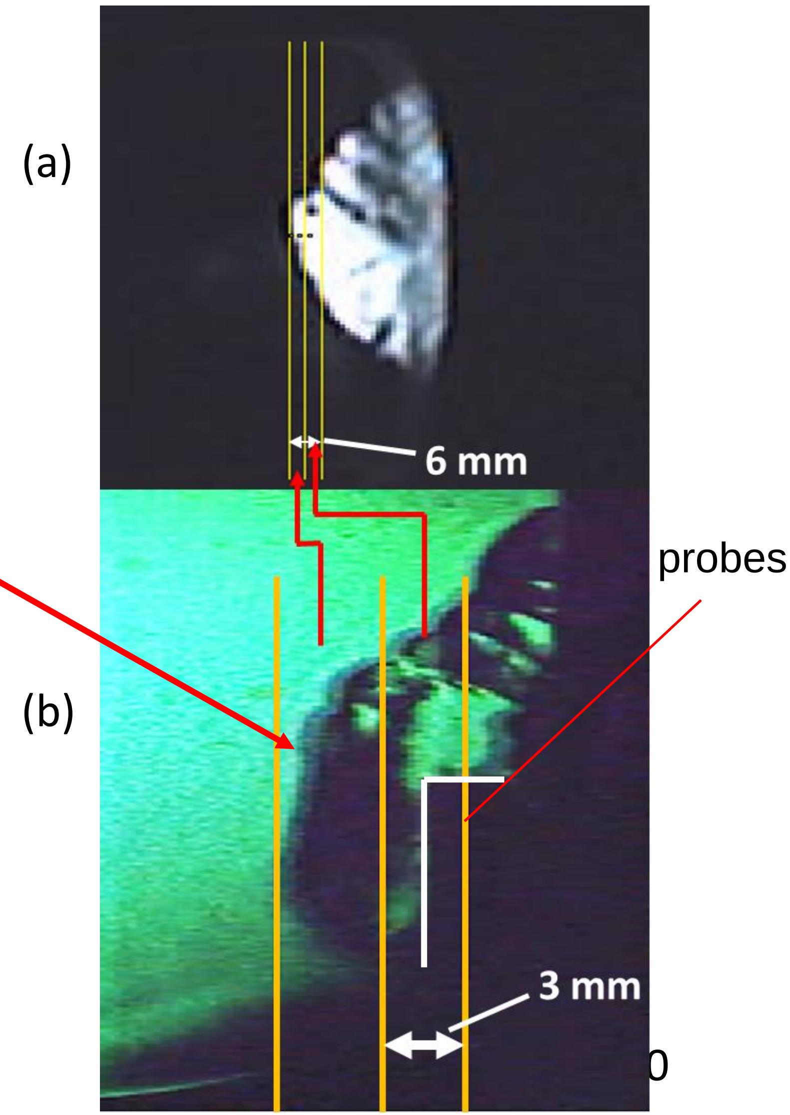
- As shown in the movie, density of heavy particles varies at not only wave front.
- At the wave front gradient is larger than at any other point.

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.



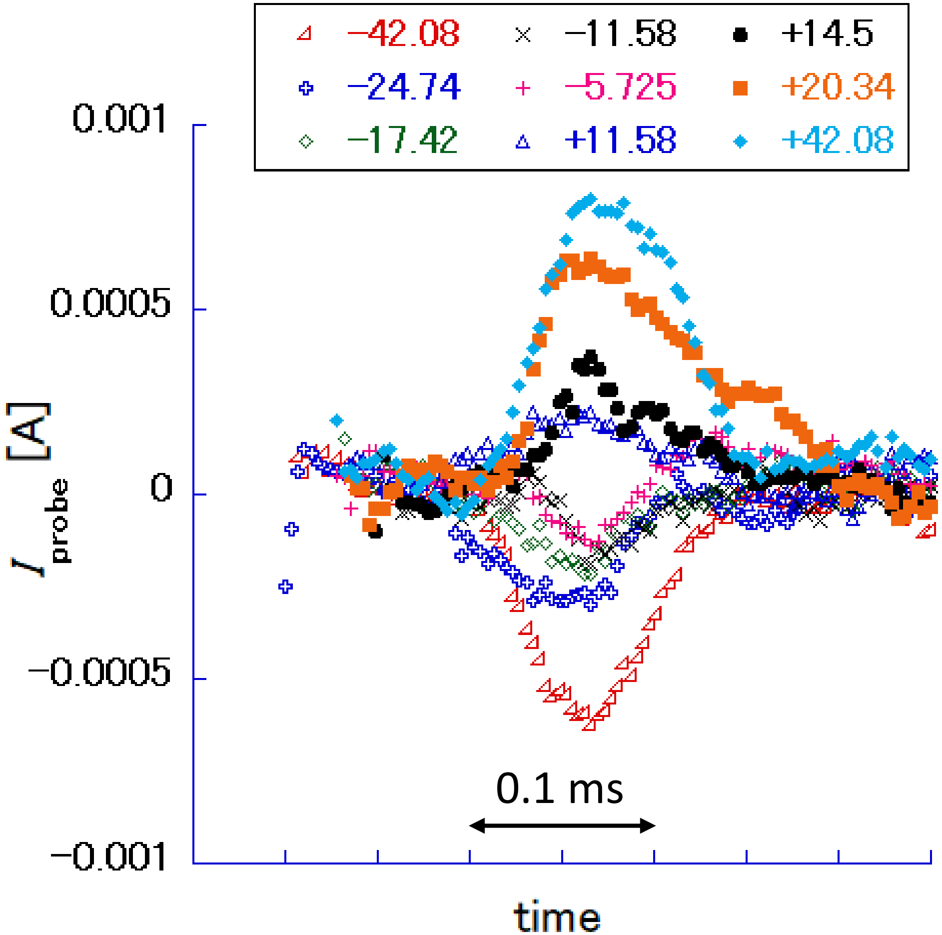
Probe current from -42 V to +42 V

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

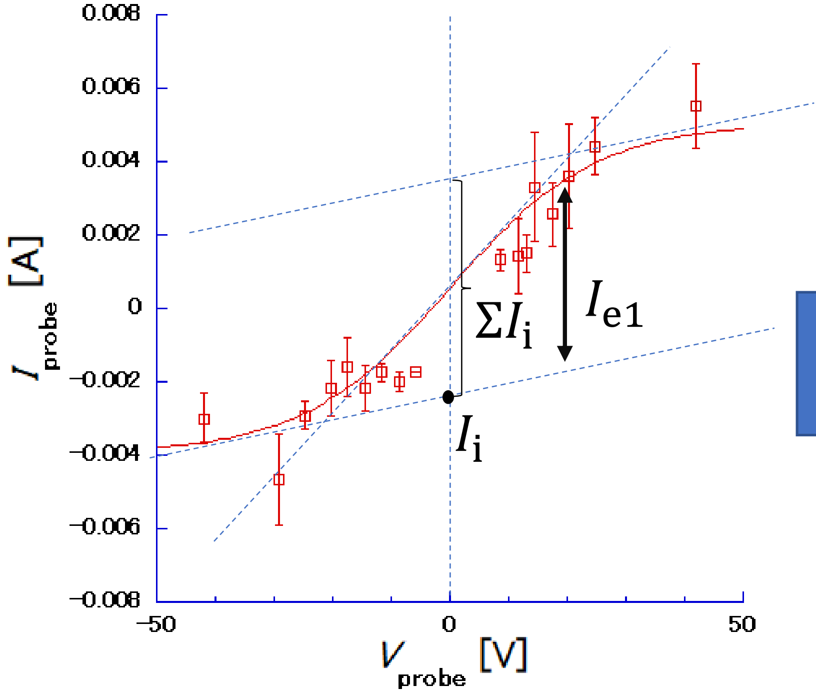
Each time axis is arranged on the basis of the peak values after smooth fitting by Kaleidagraph.

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

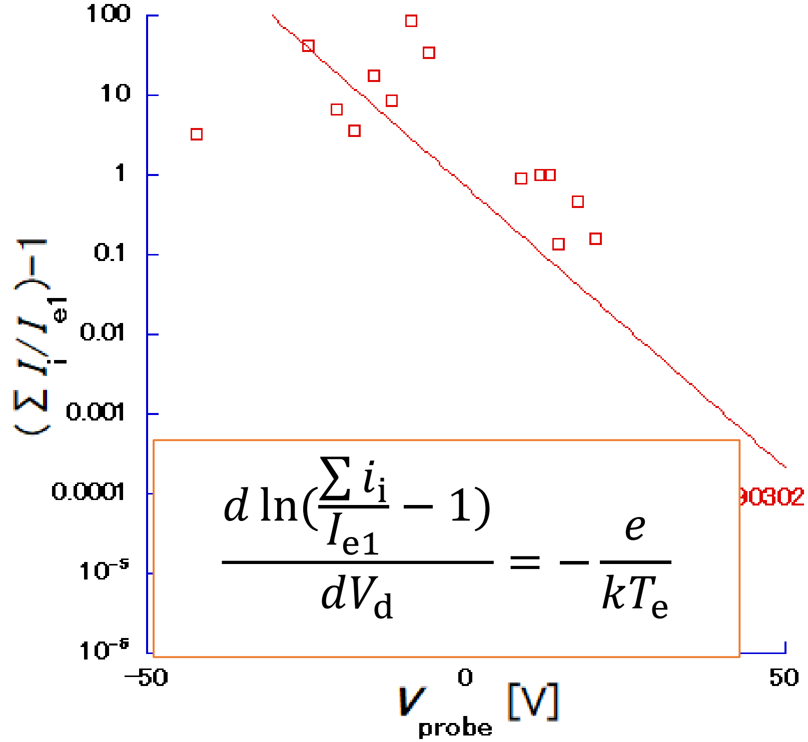
plot *IV* characteristics at some time points extracting in vertical direction



T_e and N_e from *IV* curve



Example of *IV* characteristics



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

Left side is slope of the right graph. → T_e is calculated 71500 K

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

→ N_e is calculated 0.9×10^{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 1.2×10^{21} $/\mathrm{m}^3$ (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 0.9×10^{19} $/\mathrm{m}^3$ 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

$$\frac{d\ln\left(\frac{\sum i_{\mathrm{i}}}{I_{\mathrm{e1}}}-1\right)}{dV_{\mathrm{d}}}=-\frac{e}{kT_{\mathrm{e}}}$$

$$I_{\mathrm{i}}=\kappa N_{\mathrm{e}}eS\sqrt{\frac{kT_{\mathrm{e}}}{m_{\mathrm{i}}}}$$

In this case,

$$\kappa = 0.61$$

k[J/K]:Boltzmann's constant

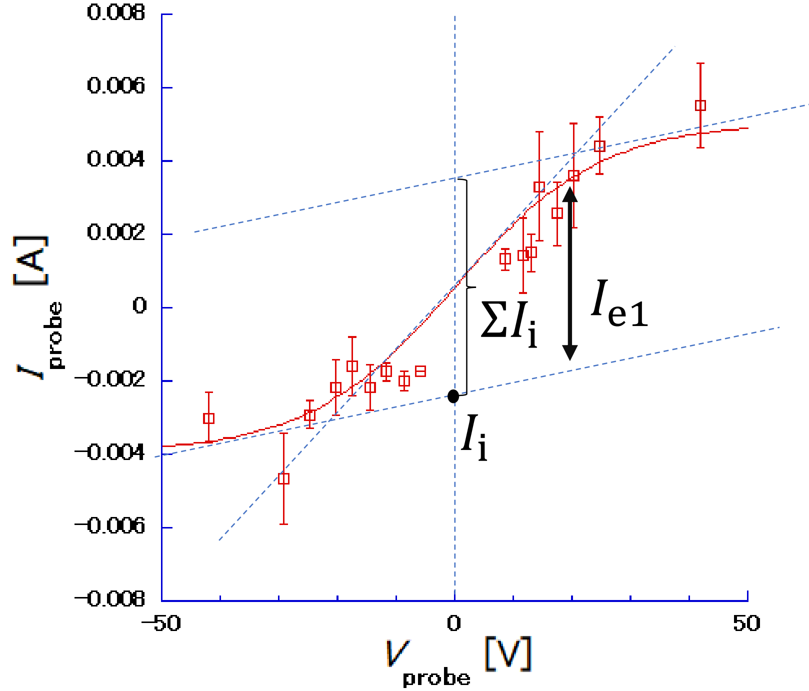
T_{e}[K]:electron temperature

e[C]:elementary charge

N_{e}[/m³]:electron number density

S[m²]:surface area of probe

m_{i}[kg]:ion's mass

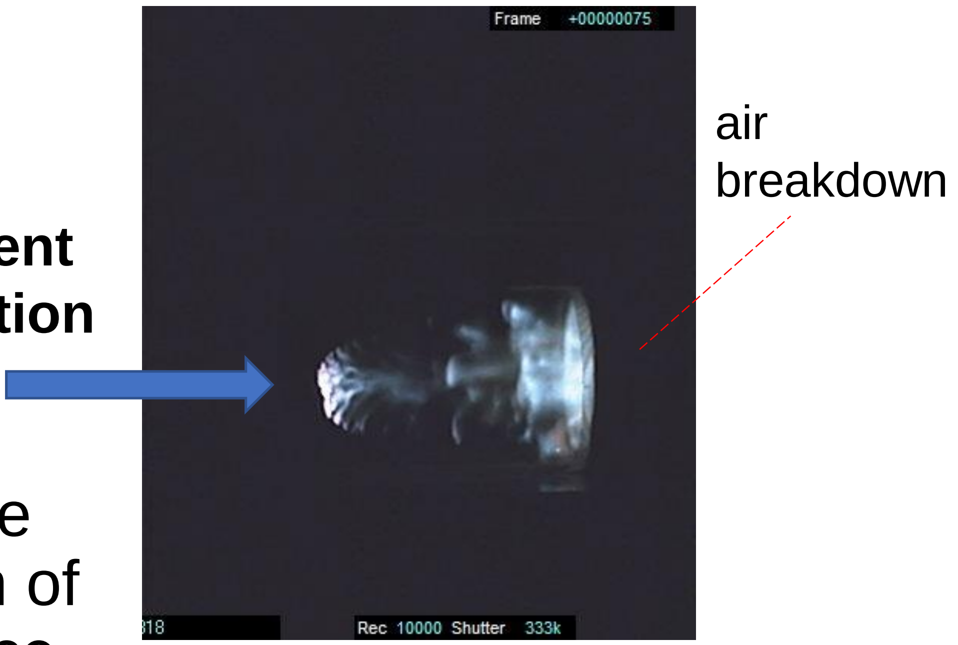


Example of *IV* characteristics

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.

Beaming Energy propulsion

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

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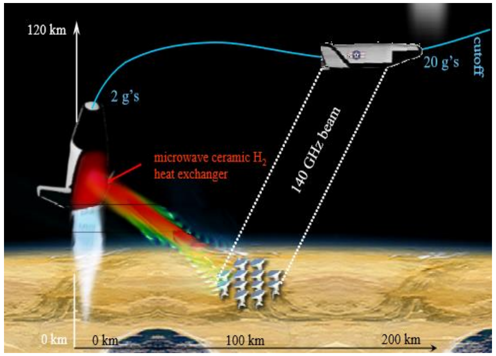
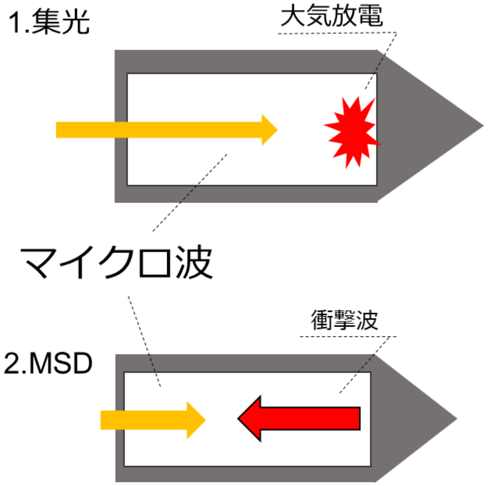


THE MICROWAVE THERMAL THRUSTER AND ITS APPLICATION TO THE LAUNCH PROBLEM,Parkin,2006

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



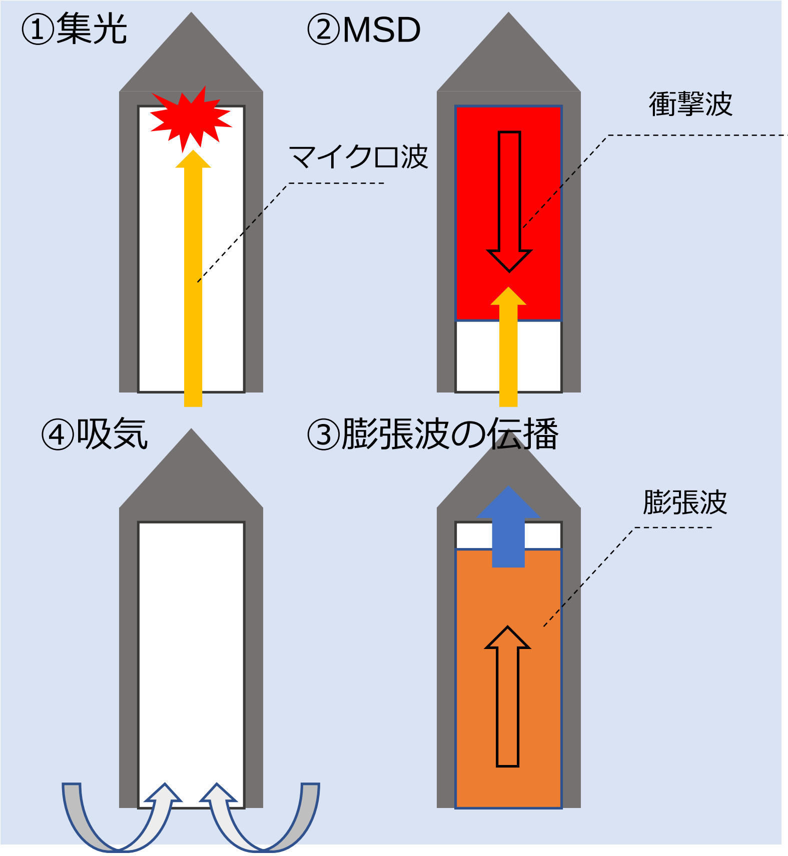
先行研究

1.円筒状の機体に照射し、頭頂部で集光する。

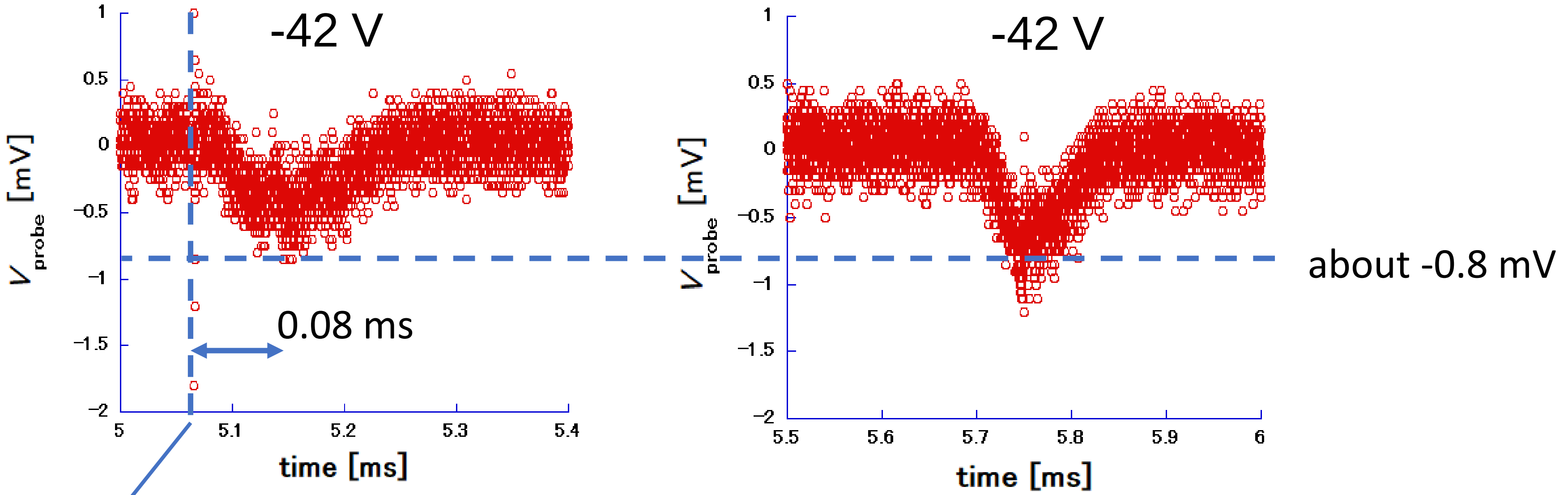
2.プラズマの電離波面が衝撃波を伴って伝播する。(MSD)

3.衝撃波排気後、膨張波が機体内に伝播する。

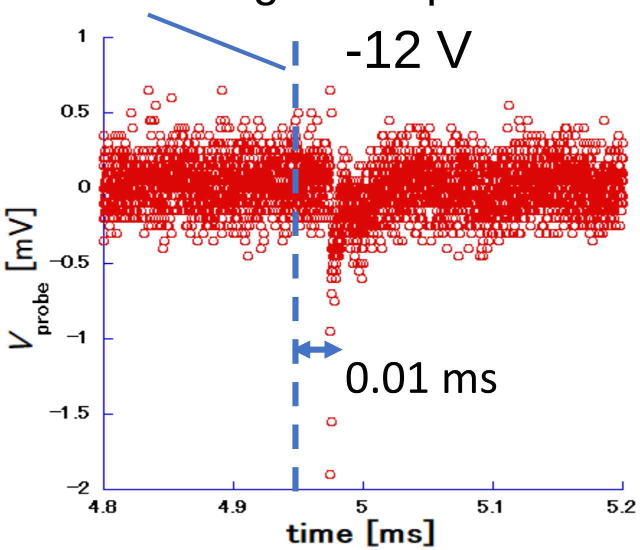
4.吸気して、再びマイクロ波を照射する。



Output data

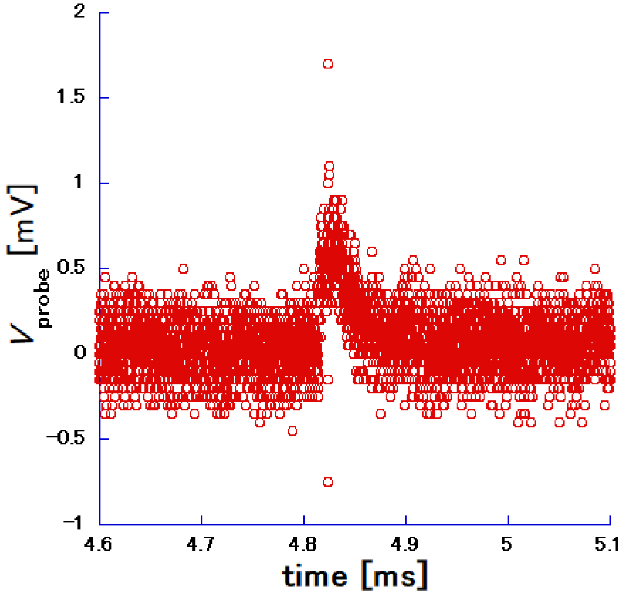


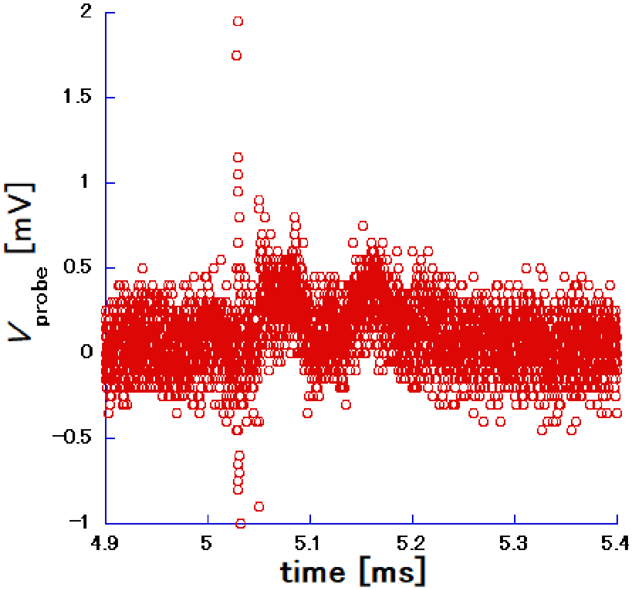
the time thought that plasma arrived at probes



- 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



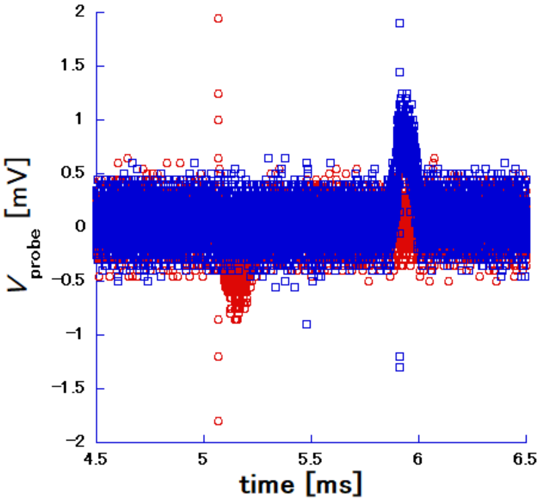


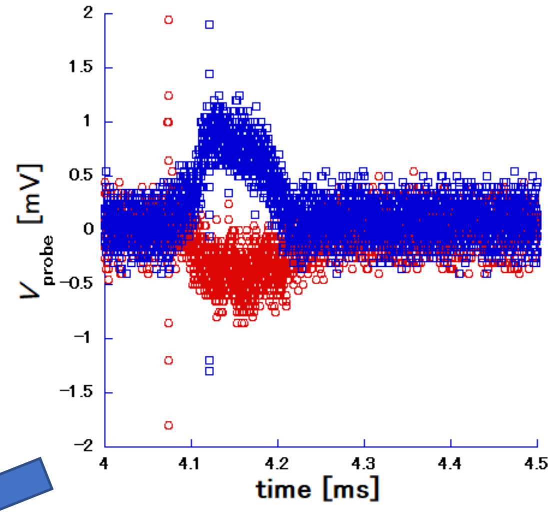
Both figures are under the same bias voltage(+15 V).

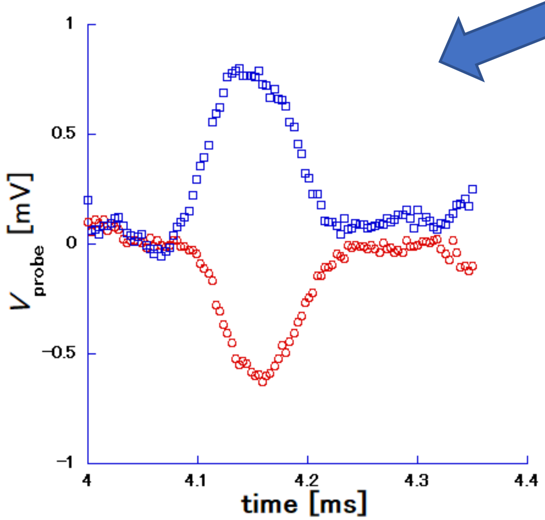
- Output voltage is as small as noise signal.
- Even if bias voltage is the same, that of probes doesn't show the same values.
- Also, the time thought that plasma generates is different every shot.

Arrangement

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



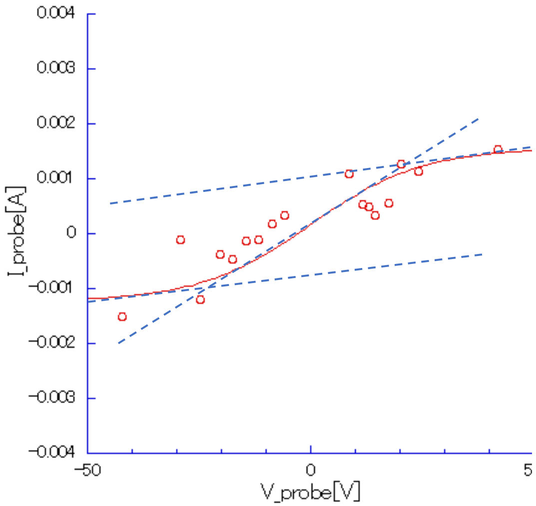




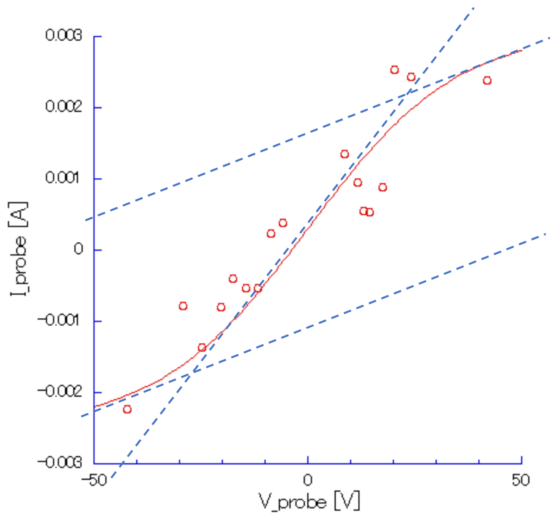
Stineman function

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

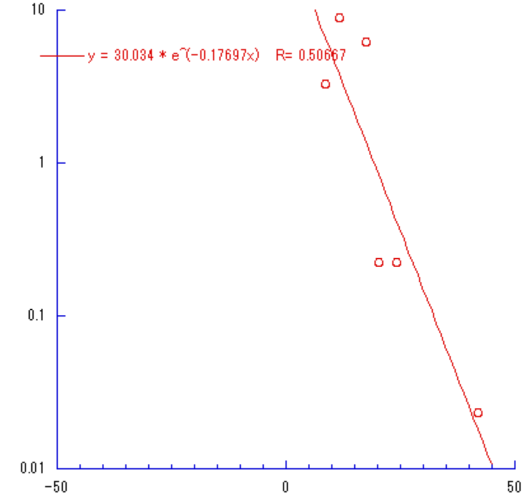
Calculation



4.1272ms

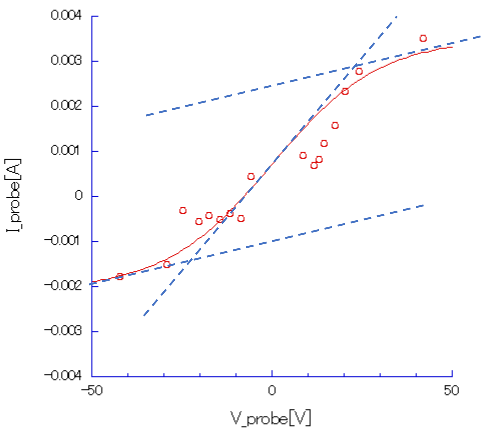


4.1378ms

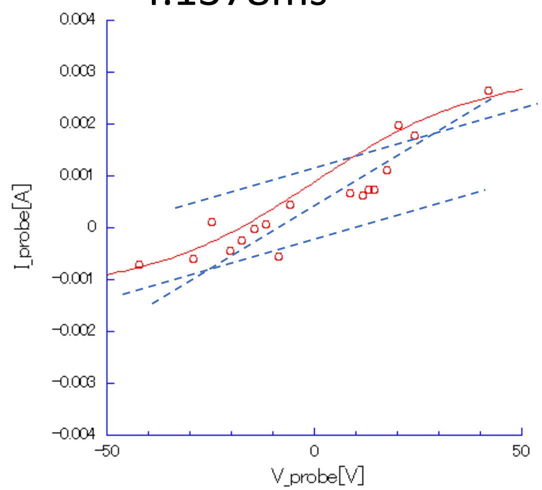


4.1378ms

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



4.1979ms

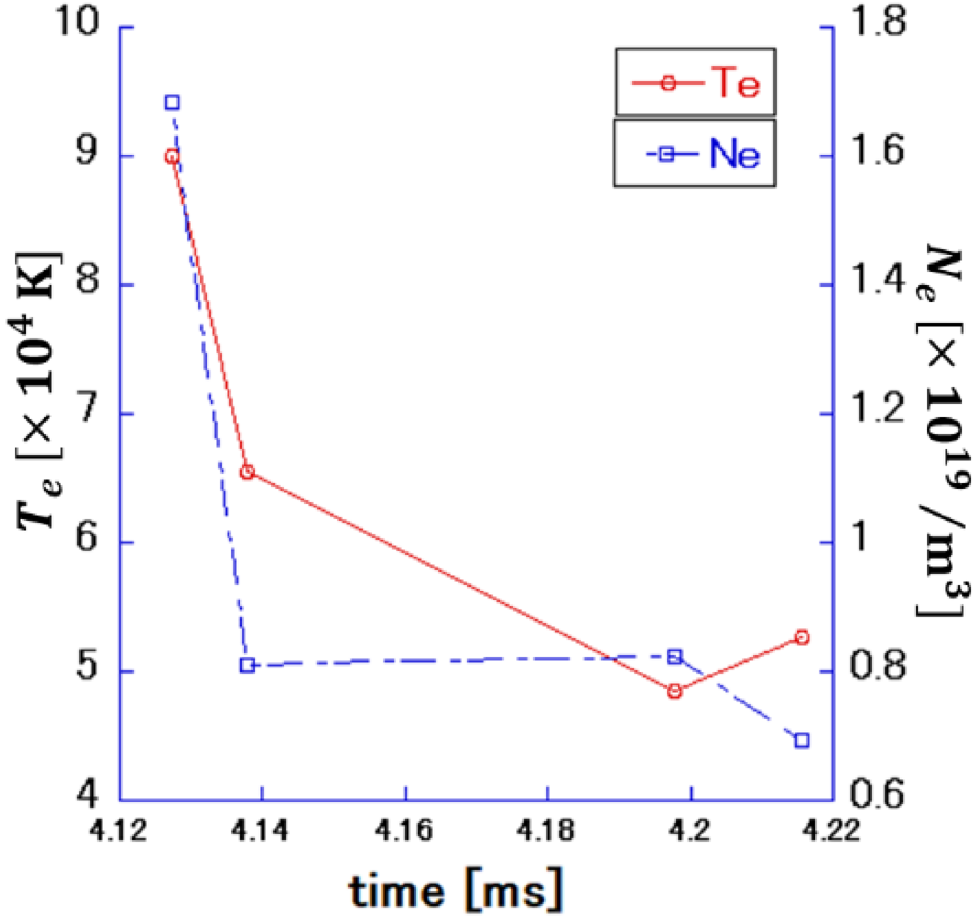


4.2156ms

Calculation

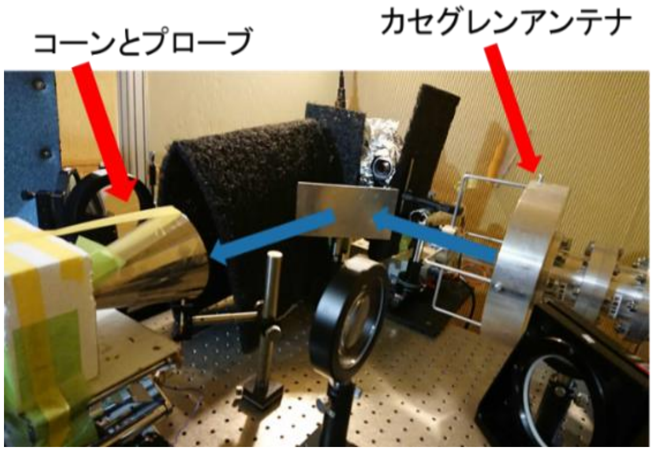
calculated T_e and N_e at some points

- T_e varies from 90,000 K to 50,000 K.
- N_e has the same tendency of T_e and varies from 1.6×10^{19} /m³ to 0.8×10^{19} /m³.

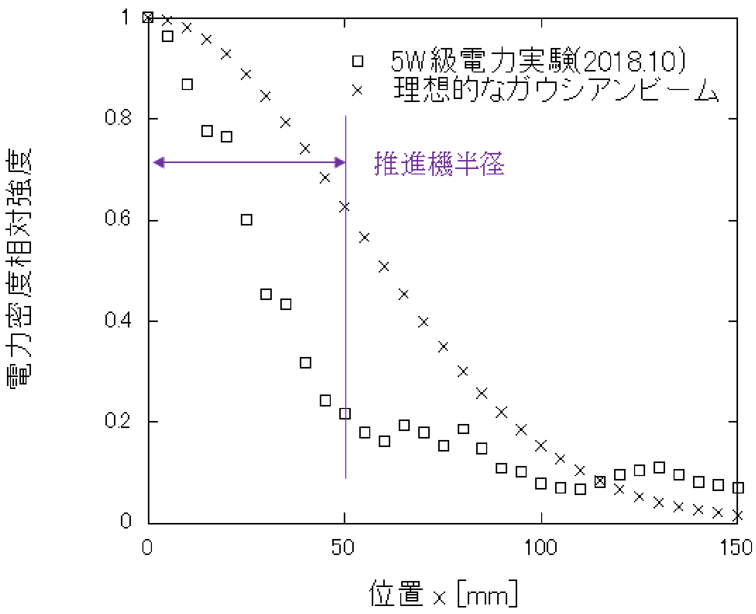


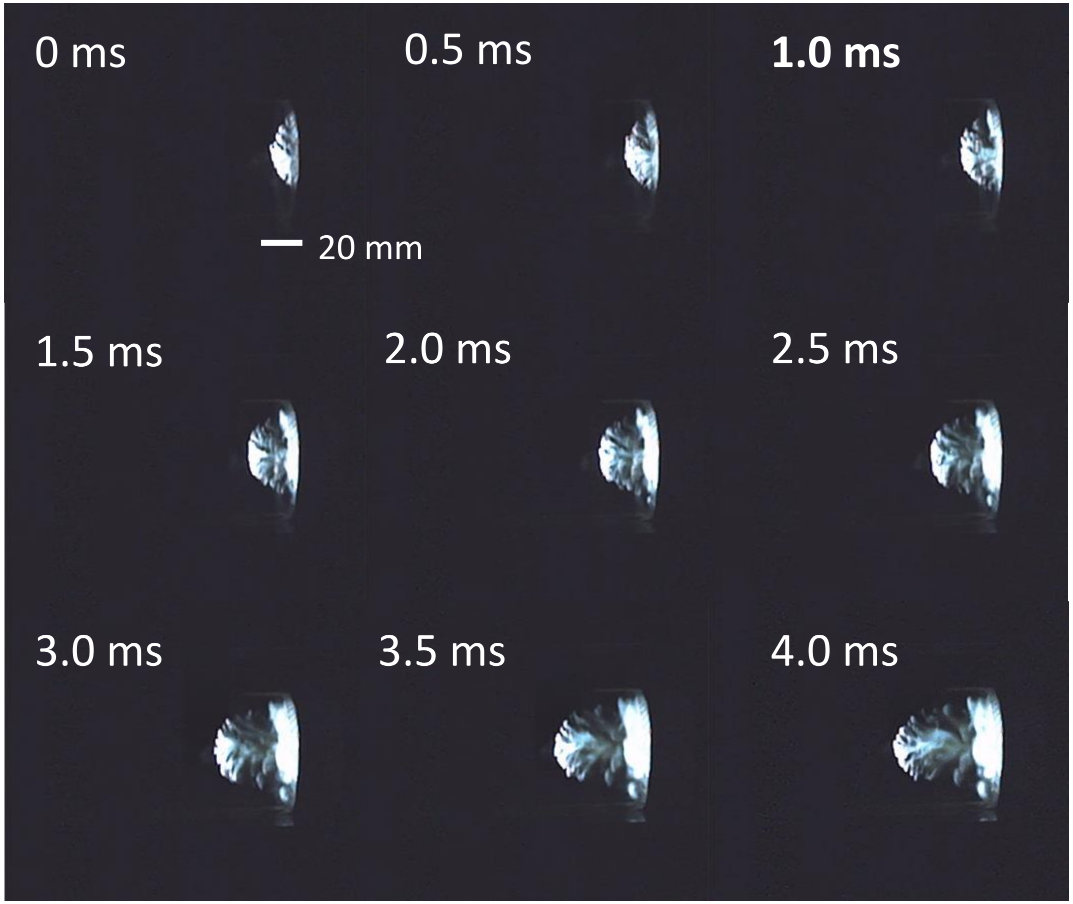
The temperature is thought too high.

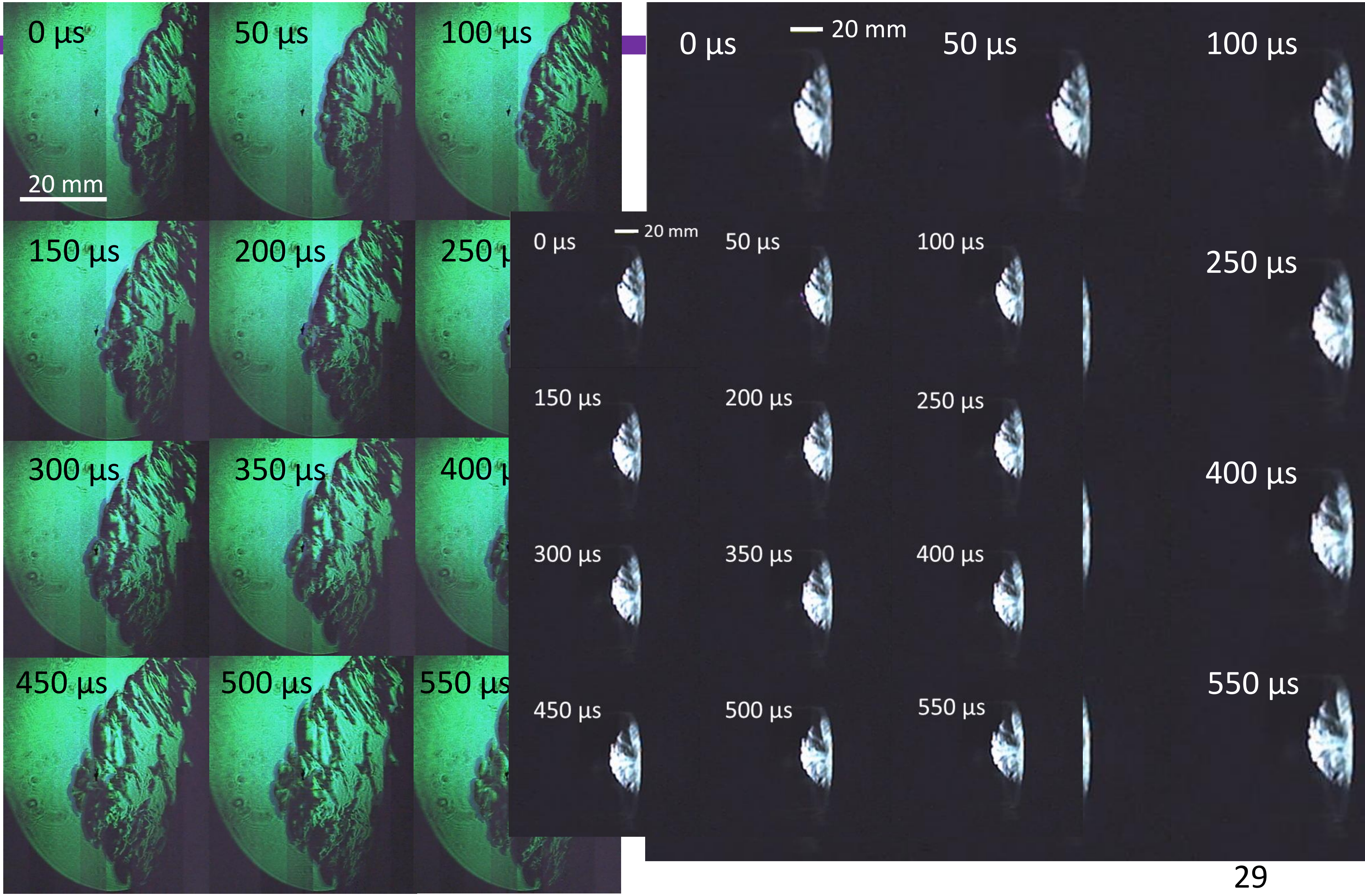
And error gets big on the process of calculation.

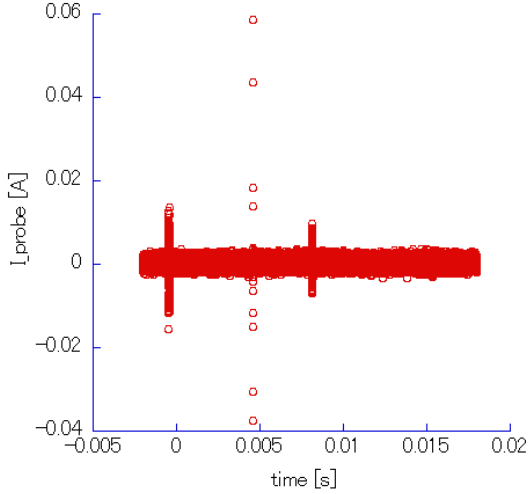

コーンとプローブ
カセグレンアンテナ

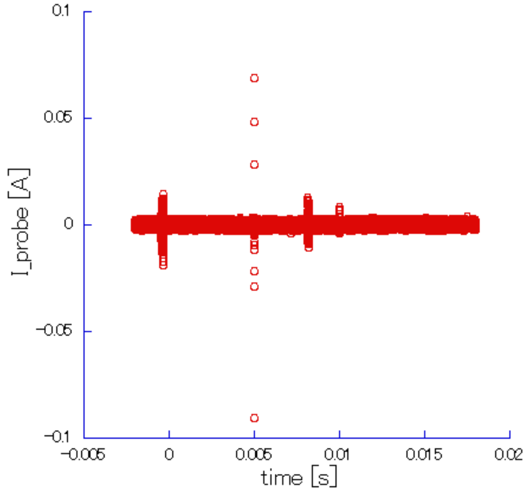
実験系

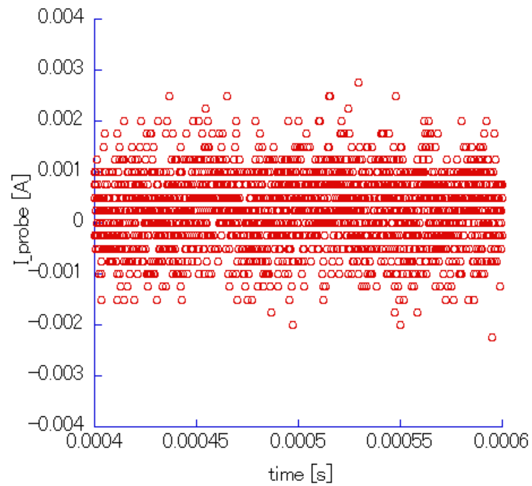

5W級電力実験(2018.10)
理想的なガウシアンビーム
推進機半径
電力密度相対強度
位置 x [mm]
1
0.8
0.6
0.4
0.2
0
0
50
100
150

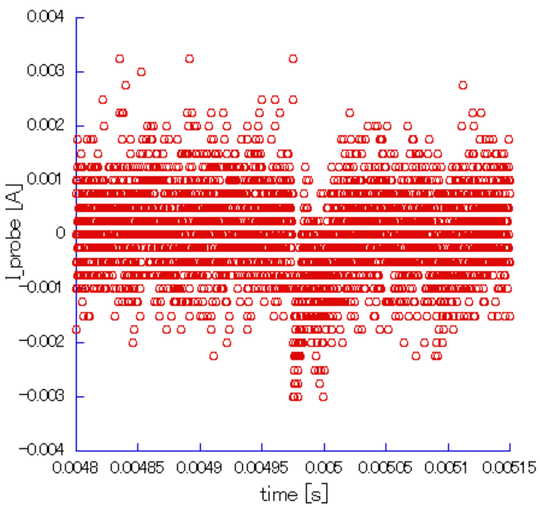

0 ms
0.5 ms
1.0 ms
20 mm
1.5 ms
2.0 ms
2.5 ms
3.0 ms
3.5 ms
4.0 ms

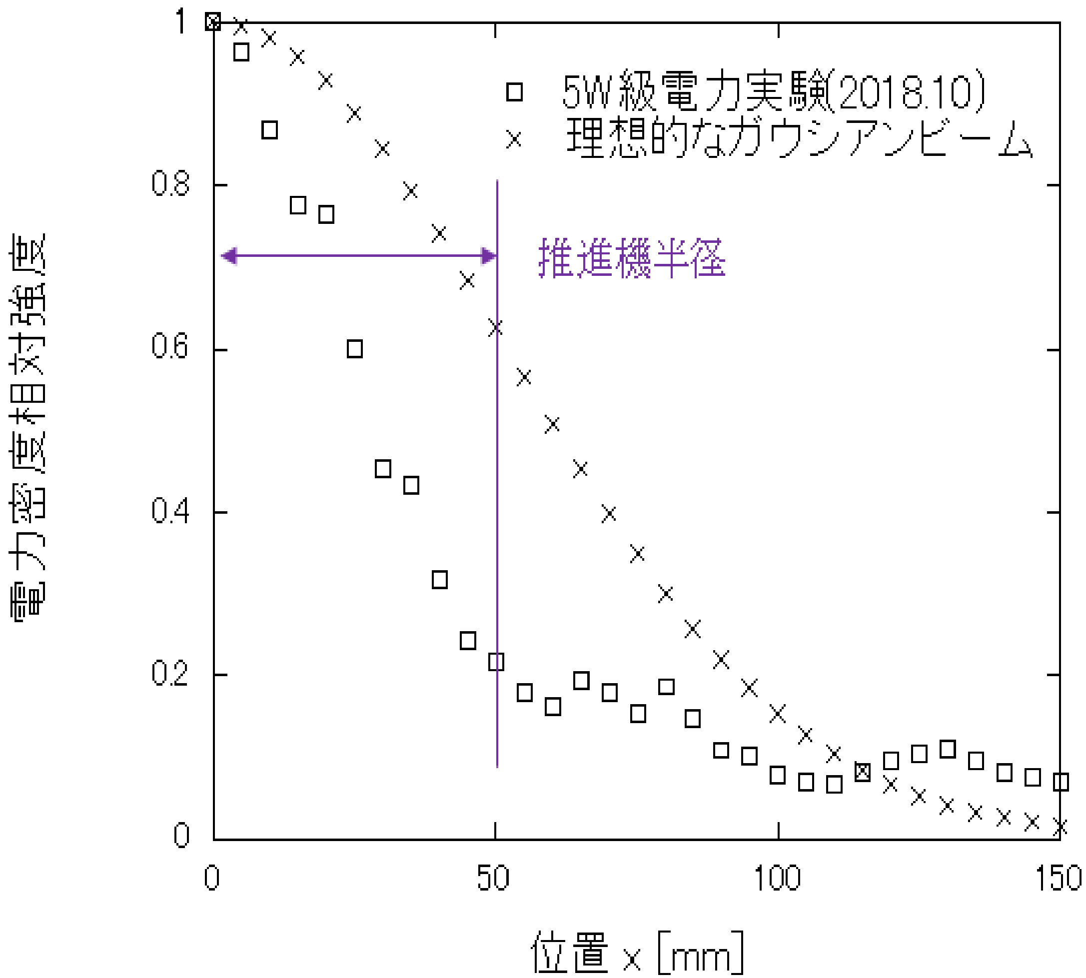

0 µs
50 µs
100 µs
20 mm
150 µs
200 µs
300 µs
350 µs
450 µs
500 µs
550 µs
0 µs
20 mm
50 µs
100 µs
250 µs
400 µs
550 µs
0 µs
20 mm
50 µs
100 µs
150 µs
200 µs
250 µs
300 µs
350 µs
400 µs
450 µs
500 µs
550 µs


0.06
0.04
0.02
0
−0.02
−0.04
−0.005
0
0.005
0.01
0.015
0.02
I_probe [A]
time [s]


0.1
0.05
0
−0.05
−0.1
−0.005
0
0.005
0.01
0.015
0.02
I_probe [A]
time [s]

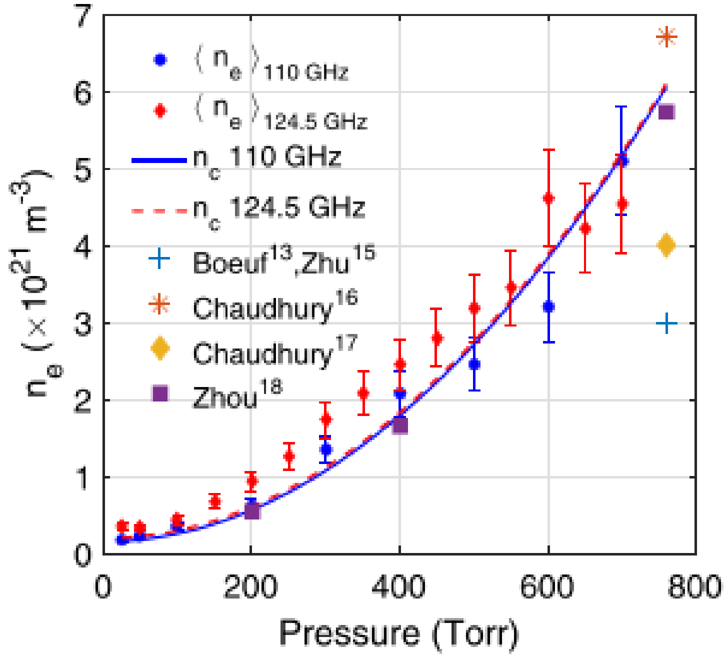

0.004
0.003
0.002
0.001
0
−0.001
−0.002
−0.003
−0.004
0.0004
0.00045
0.0005
0.00055
0.0006
I_probe [A]
time [s]


0.004
0.003
0.002
0.001
0
−0.001
−0.002
−0.003
−0.004
0.0048
0.00485
0.0049
0.00495
0.005
0.00505
0.0051
0.00515
I_probe [A]
time [s]



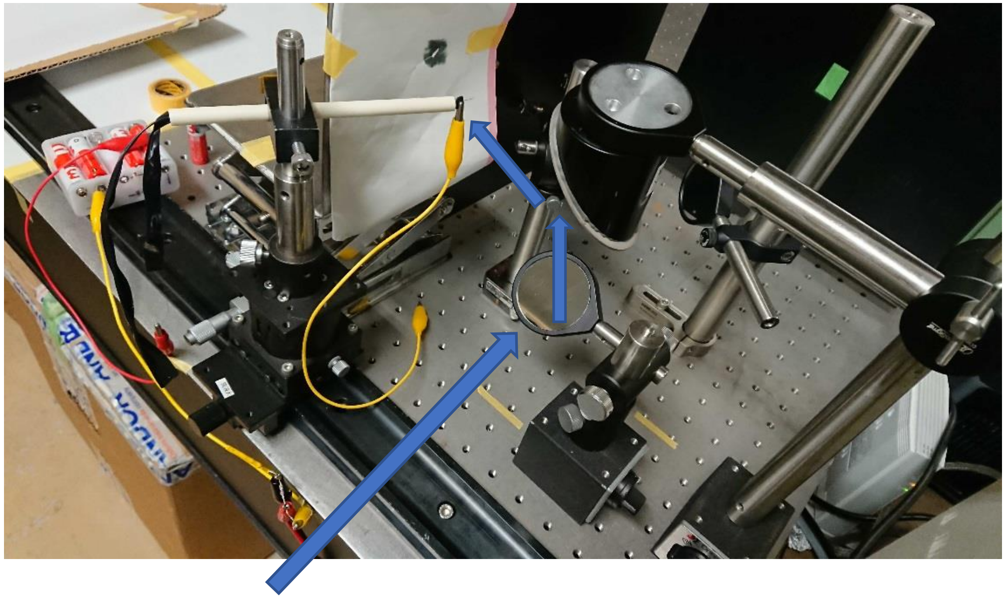
電力密度相対強度
1
0.8
0.6
0.4
0.2
0
0
50
100
150
5W級電力実験(2018.10)
理想的なガウシアンビーム
推進機半径
位置 x [mm]

- N_e は大気圧で10^{21}m^{-3}の範囲内であり、周波数によって変化する。

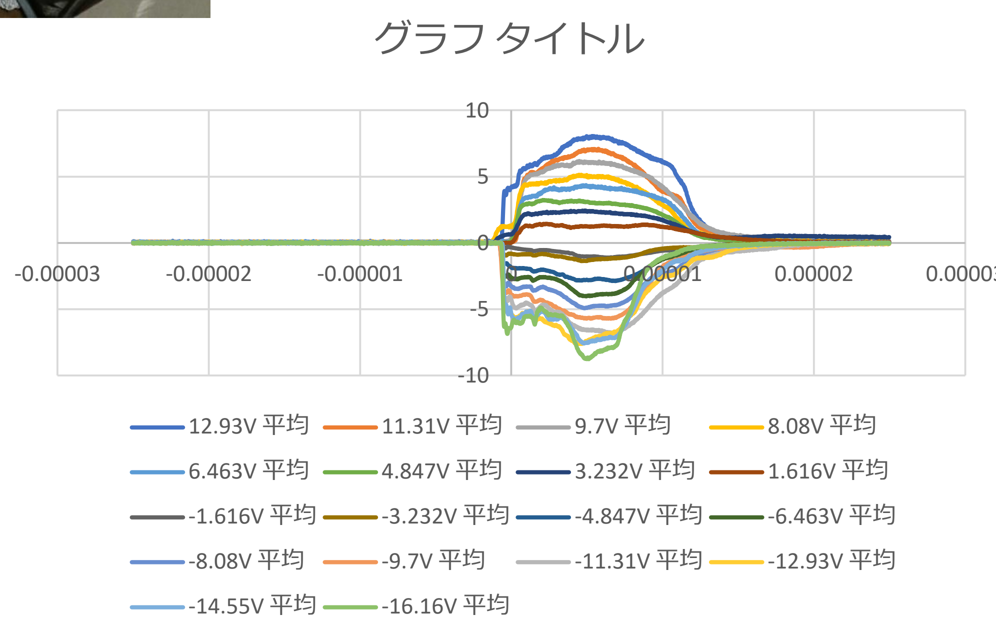


Schaub 2016 Physics of Plasmas 23, 083512

予備実験



レーザー入射方向



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。

t=50μsec

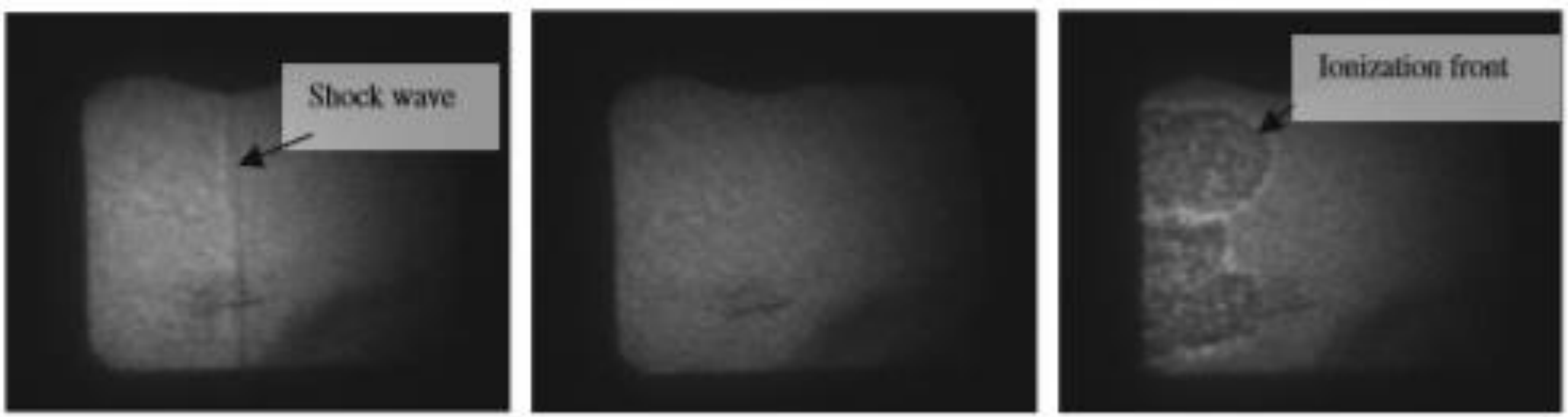
プラズマの伝播速度

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



#1 ($t = 467$ μs)　#4 ($t = 533$ μs)　#7 ($t = 600$ μs)

プラズマの伝播速度

また、

気圧→小
周波数→小

⇩

伝播速度→大