UNIVERSITY OF FUKUI

Structure Formation of the Millimeter-Wave Air Breakdown Plasma at 303 GHz

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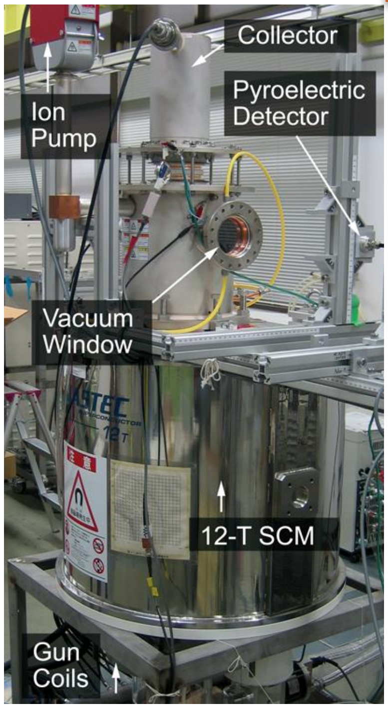
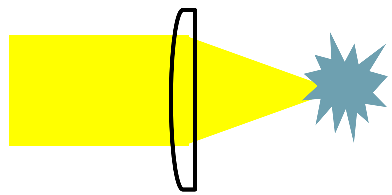
Millimeter-wave discharge generated by a gyrotron



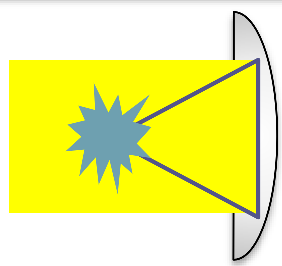
Gyrotron

Focusing beam

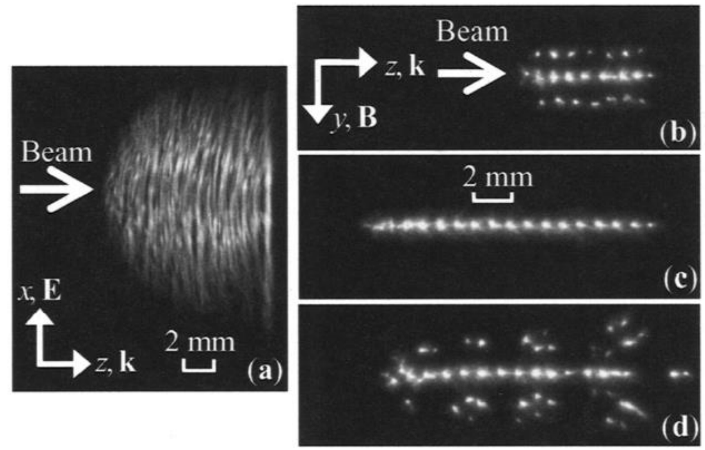


Lens

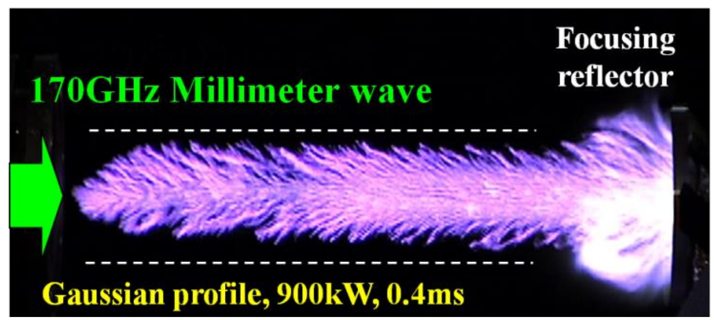
Parallel beam



Parabolic mirror



Hidaka et al.(110 GHz, 1.5 MW, 3 μs)

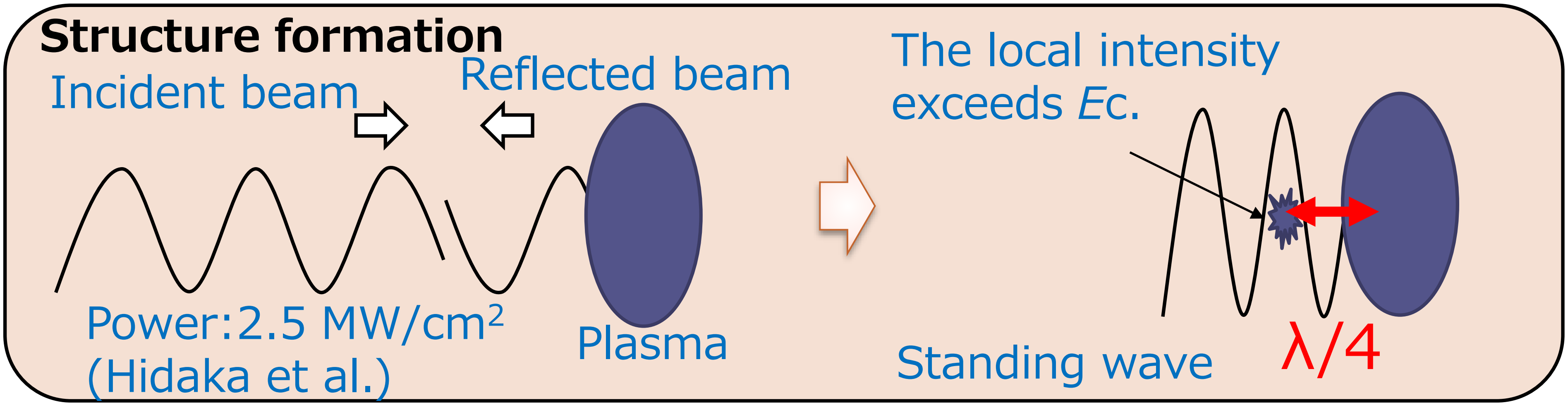


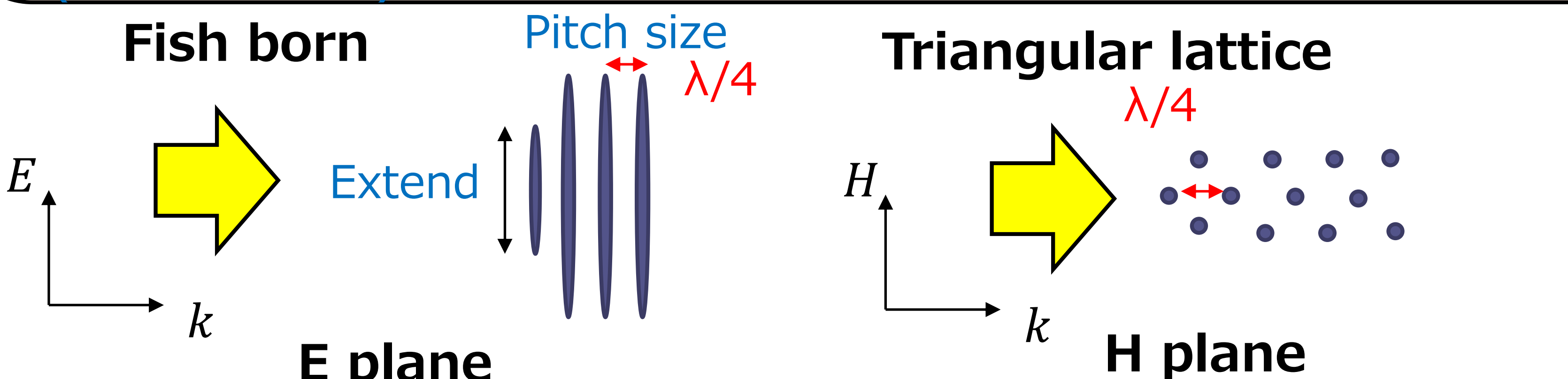
Oda et al.(170 GHz, 0.9 MW, 0.4 ms)

The millimeter wave discharge has a self-organized structure called "Fish born" or "Filament".

Overcritical condition

The beam power density is higher than the critical-intensity of the gas.(Focusing beam) **Hidaka, Temkin et. al., & Bouef et. al**





- Plasma filaments are elongated along the E field due to the Debye shielding and spaced about one quarter wavelength($\lambda/4$).
- Propagation velocity >> sonic velocity.

Subcritical condition

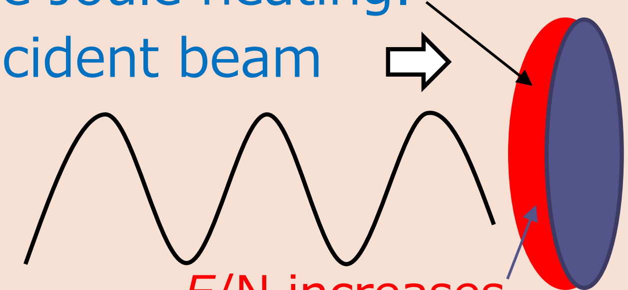
The beam power density is much lower.(Parallel beam)

Khodataev et al. & Takahashi et al.

Structure formation

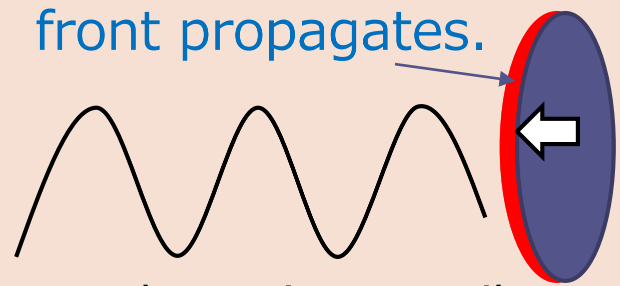
Expansion wave generated by the Joule heating.

Incident beam



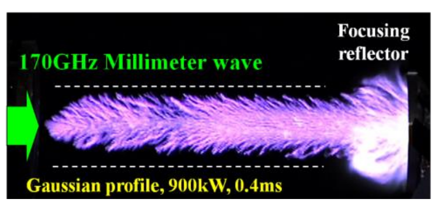
E/N increases.

The ionization front propagates.

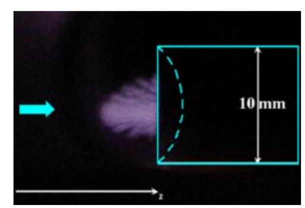


The gas dynamics contributes to the ionization front propagation.

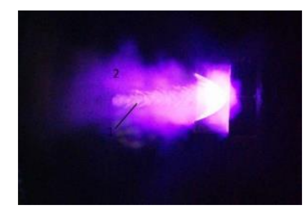
Bogatov et al.(85 GHz)



Oda et al.(170 GHz)



Bratman et al. (550 GHz)



Sidorov et al. (670 GHz)

- Though the discharge shows a self-organized structure, the characteristic size is not λ/4. (0.9 λ was reported by Oda et al.)
- The propagation velocity ～ the sonic velocity.

Motivation of the research

There has been few studies on the millimeter-wave discharge especially for the subcritical condition.

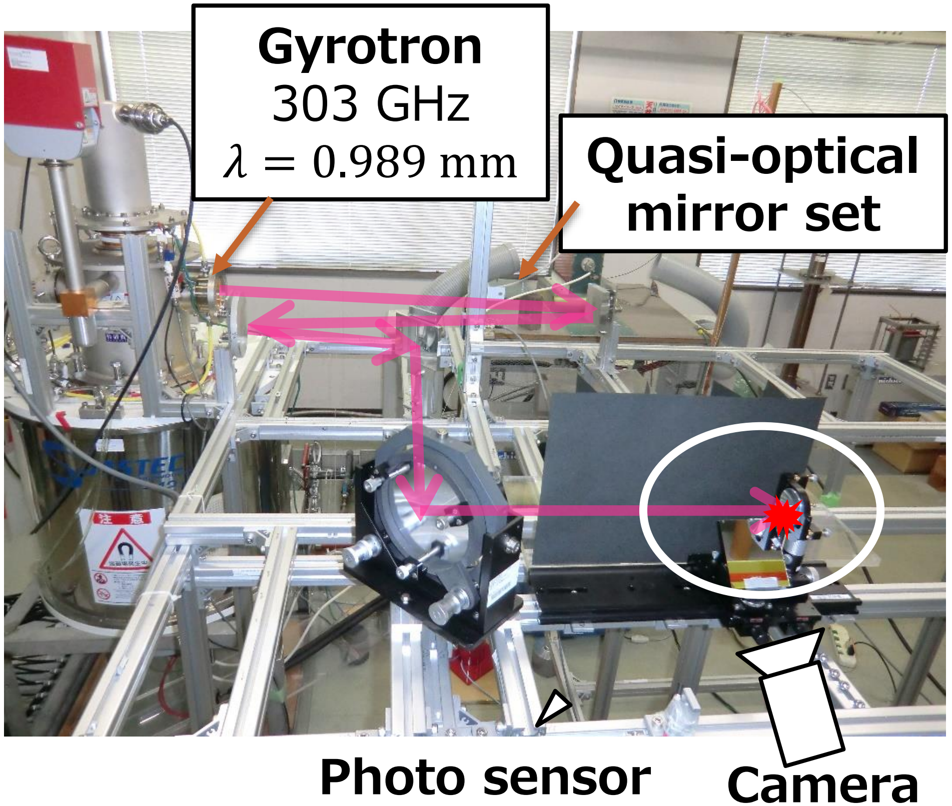
- ✓ The difference of the discharge structure in the H and E planes has never been investigated.
- ✓ The characteristic size and the mechanism of the structure formation have been unclear.

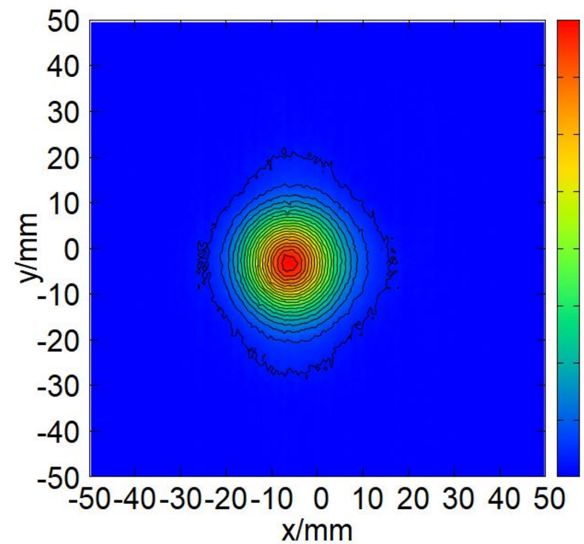
⇩

Experiments in the subcritical condition are necessary.

We observed the millimeter wave discharge at 303 GHz with high spatial and time resolutions using a high-speed shutter camera.

Experimental setup



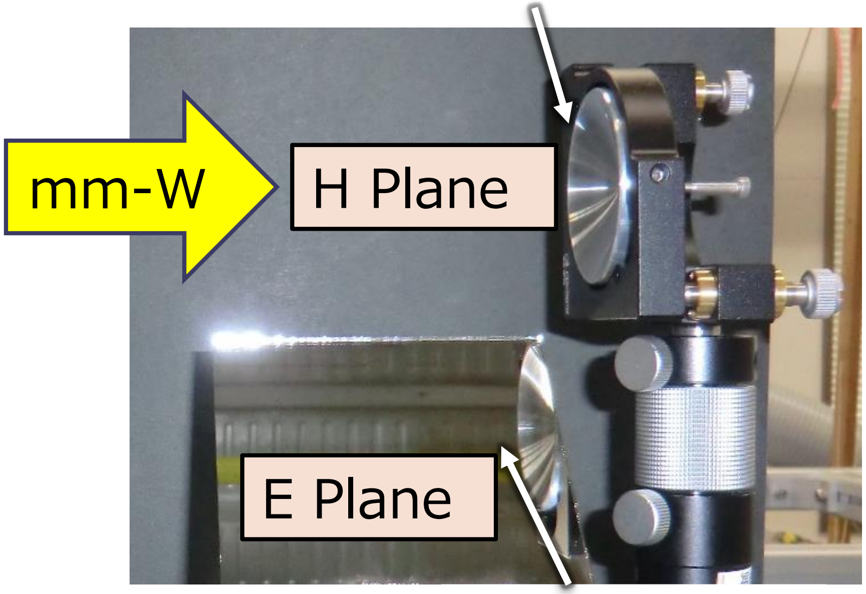


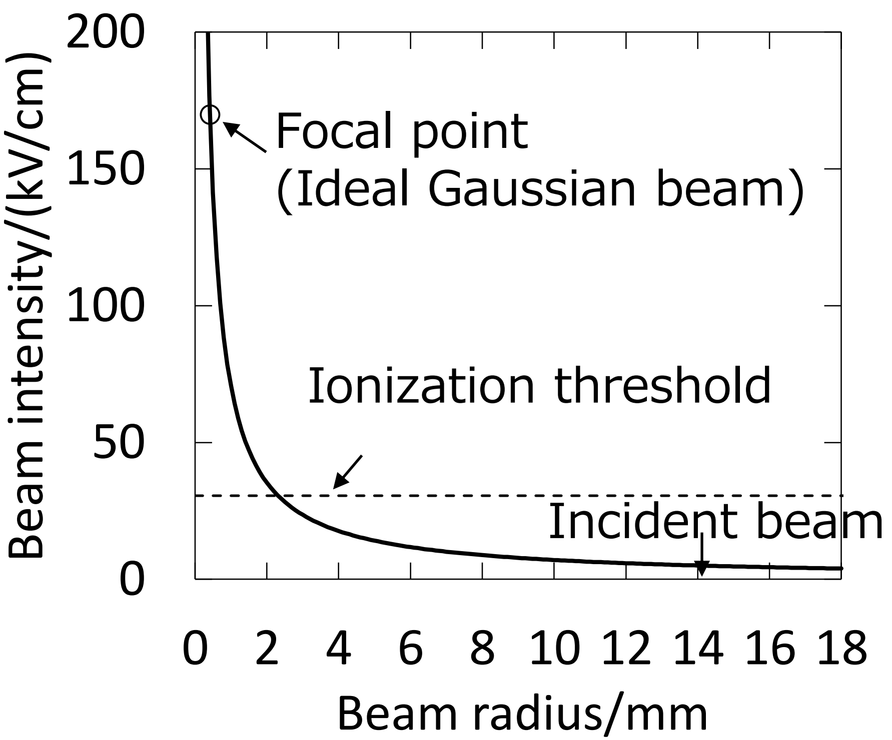
IR image of the incident beam

Spot size : 14 mm
Incident power : 104 kW
Peak power density : 34 kW/cm^2

- A 303 GHz high power gyrotron developed by Research Center for Development of Far-Infrared Region in University of Fukui was used as a beam source.
- The incident beam is modified into an axisymmetric Gaussian beam by quasi-optical mirrors.

Local electric field intensity



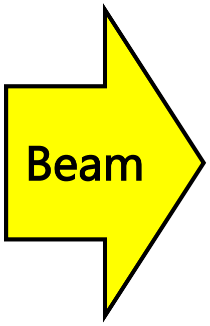


- The critical intensity is 30.5 kV/cm at 303 GHz under atmospheric conditions.
- The beam power density of 34 kW/cm^2 corresponds to intensity of 5.1 kV/cm.
- Assuming ideal Gaussian beam propagation, the beam radius at the focal point was estimated as 0.4 mm and the beam intensity of the reflected beam at the focal point was enhanced to 170 kV/cm.

λ/4 structure at the focal point

Exposure time of the camera: 1 μs

$\lambda = 0.989\ \mathrm{mm}$



- The pitch between each filament was 0.26 λ on average in the E plane.
  (**Typical λ/4 structure**)
- The ionization front propagates toward the parabolic mirror.
- We found that 303 GHz is the highest frequency at which the λ/4 structure can be observed experimentally.

Transition from the overcritical condition

- Filaments in the E plane separate into granular plasma particles.
- The diameter of the particle is about 0.2 λ ~ 0.8 λ.
- The structure in E plane is similar to that in H plane.

Filament formation under the subcritical condition

- New plasma filaments parallel to the incident beam grow in the E-k plane.
- In contrast, in the H-k plane, the plasma keeps a continuous structure and the ionization front forms a vertex at 60 μs.
- Note that filamentary array formation in the H-k plane was numerically predicted at 170 GHz by Takahashi et al.

Pitch between each filament

- The pitch between each filament was estimated as 0.96λ on average. The width of the filament was 0.8λ on average.
- The comb-shaped filamentary array numerically predicted by Nakamura et al. at 170 GHz was confirmed clearly in the experiments for the first time.

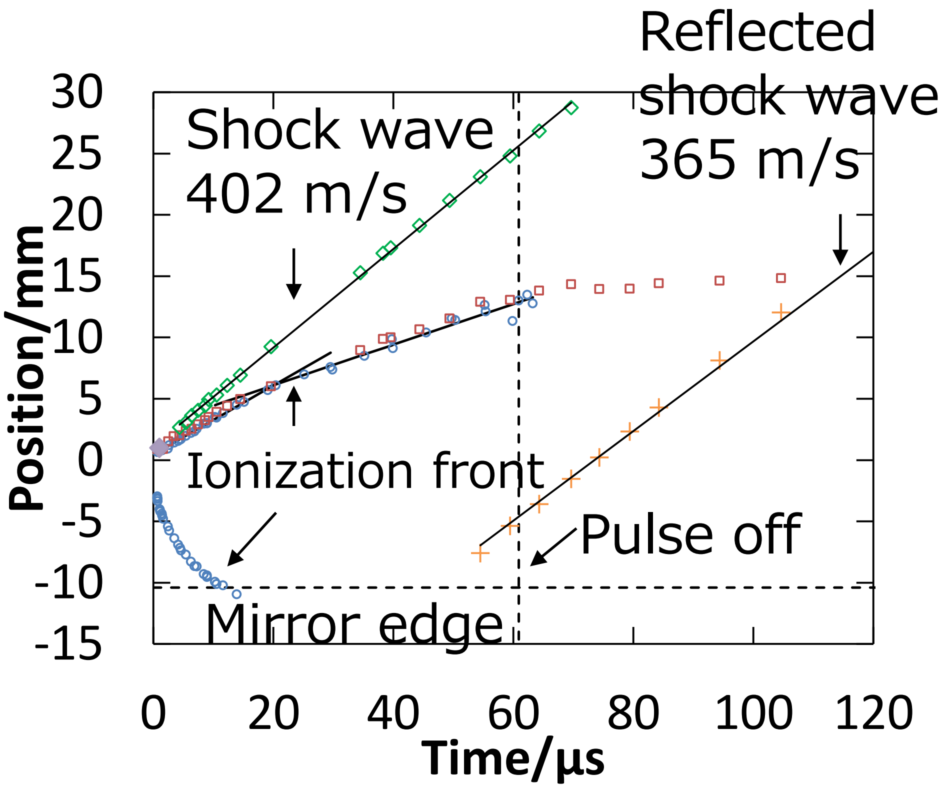
Propagation velocity of the ionization front

- The velocity of the ionization front propagating toward the parabolic mirror decreases gradually from 3.7 km/s to 350 m/s.
- The velocity of the ionization front propagating backward to the incident beam is 280 m/s until ~20 μs and decreases to 170 m/s after 20 μs. At this time, the new comb-shaped filaments parallel to the incident beam begin to grow.

Shadowgraph images

- The shock wave is driven in the subcritical condition.
- The shock wave detached from the ionization front before the comb-shaped filaments formation.

The shock wave propagation velocity and the lateral expansion

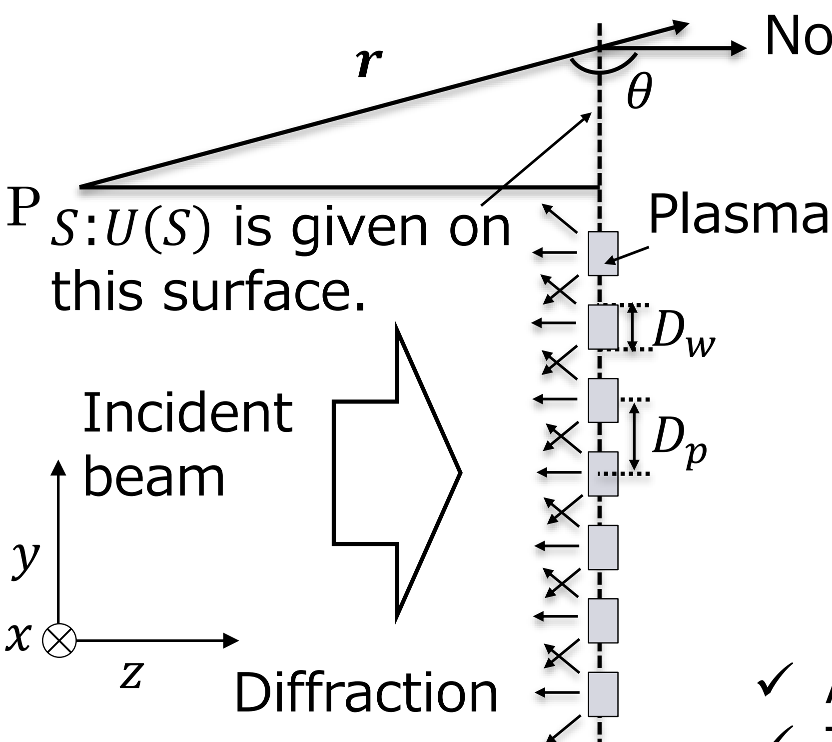


- The shock wave does not interact with the filament formation.
- The tendency of the lateral expansion does not change at 20 μs.

➡ The variation of the ionization front velocity attributes to the filament formation.

A standing wave structure generated by waves diffracted from the plasma surface

The structure formation under subcritical condition depend on the field distribution of the diffraction waves from the plasma surface.

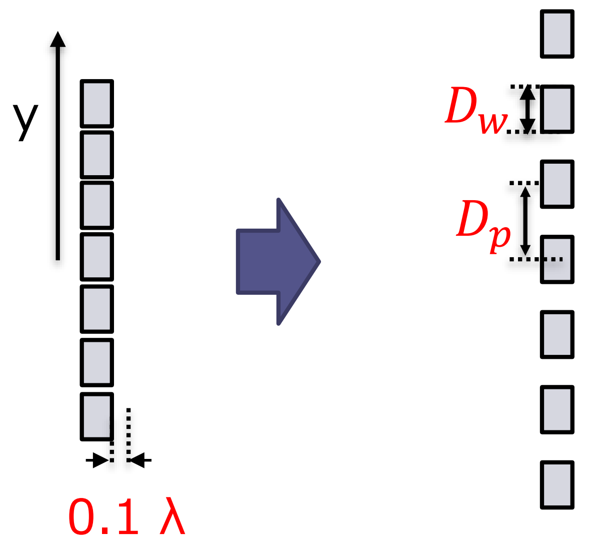


Kirchhoff diffraction formula

$$U(P) = -\frac{1}{4\pi}\oint_S dS \times \left\{U(S)\left(\frac{\exp(ikr)}{r}\right)\left[ik - \left(ik - \frac{1}{r}\right)\cos\theta\right]\right\}$$

- ✓ Assuming the simple plasm distribution.
- ✓ The scalar filed $U(P)$ is calculated by given $U(S)$ on the plasma surface.

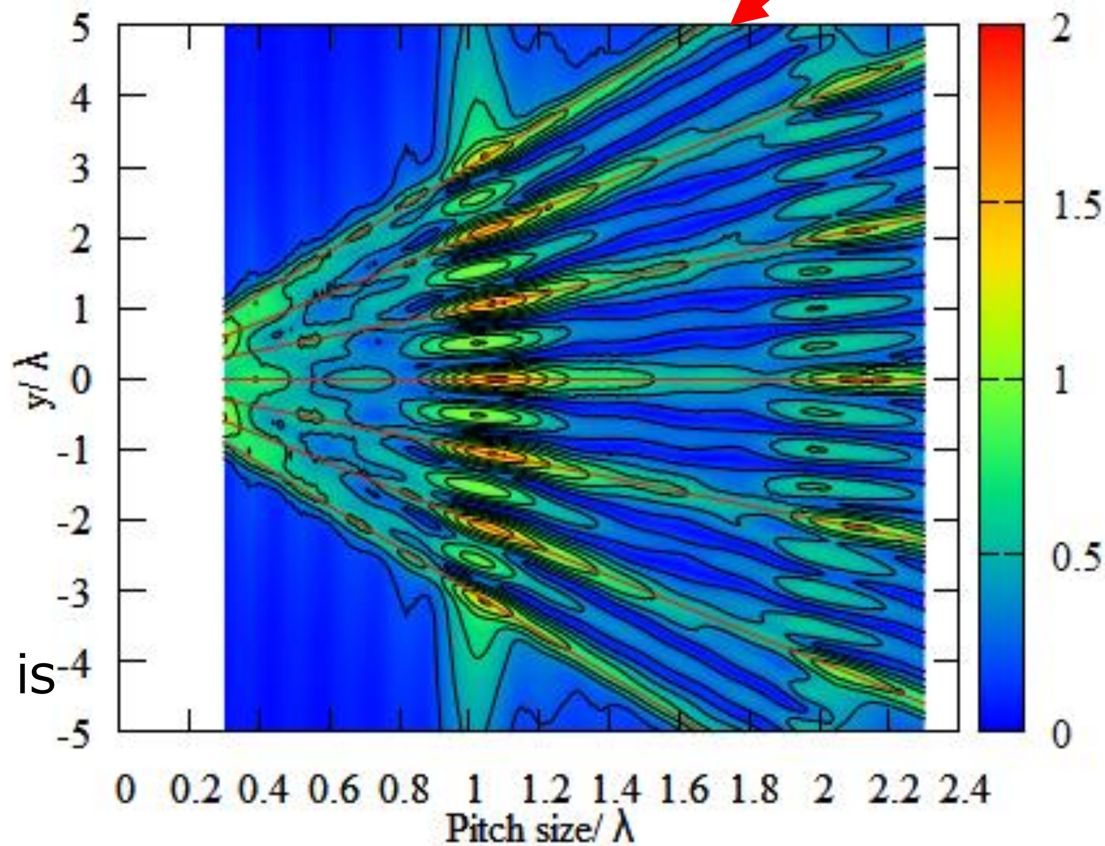
Standing wave formation



The scalar filed at the 0.1 λ away from the plasma surface is calculated varying the pitch D_p

$D_w = 0.3\lambda$

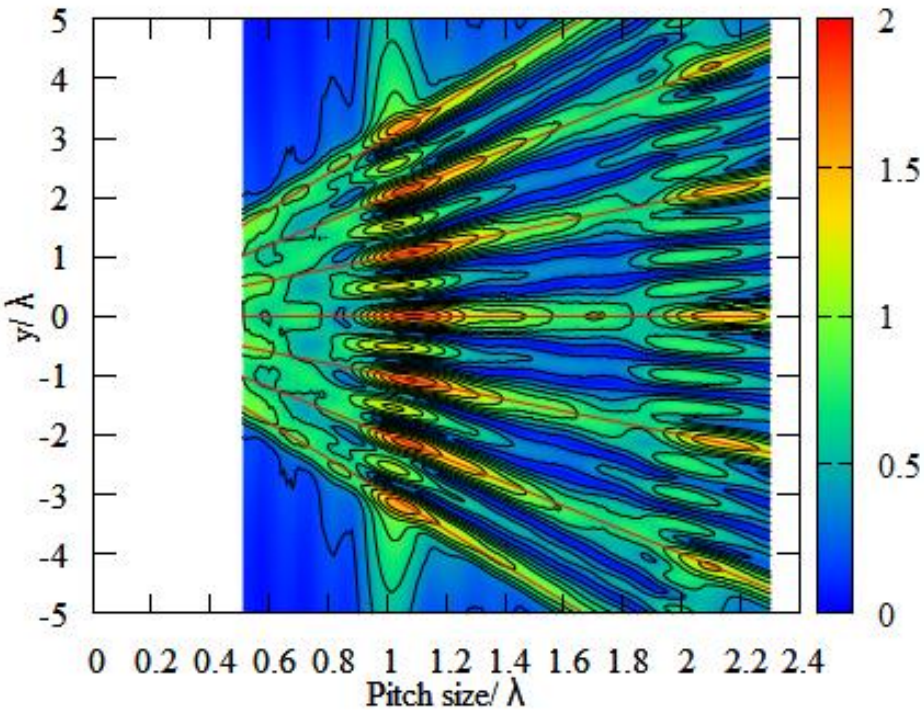
The red line shows plasma position



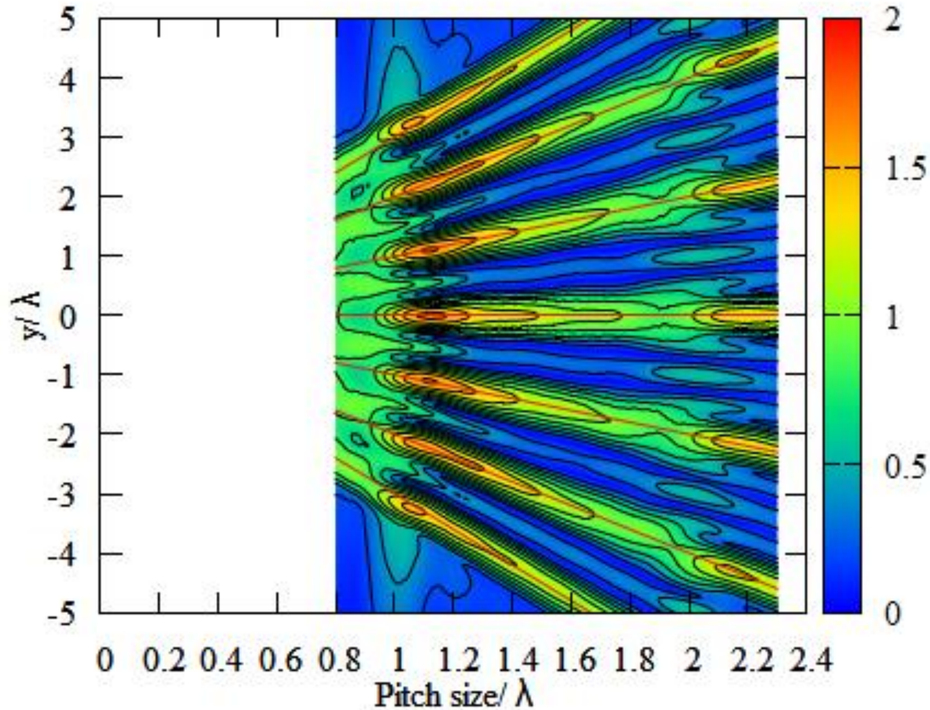
- When the pitch closes to λ, the diffraction wave forms a standing wave.
- The antinode is located at the plasma front. Thus, the ionization front propagates along the antinode.
- The standing wave is generated independently of Dw

Influence of the plasma width D_w

The plasma width D_w varies depending on the beam intensity and the number density of the electron*.



$D_w = 0.5\lambda$



$D_w = 0.8\lambda$

In this scenario, the plasma width D_w does not influence to the pitch.

*B. Chaudhury, J. P. Boeuf, G. Q. Zhu, and O. Pascal, J. Appl. Phys. 110,113306 (2011).

Summary

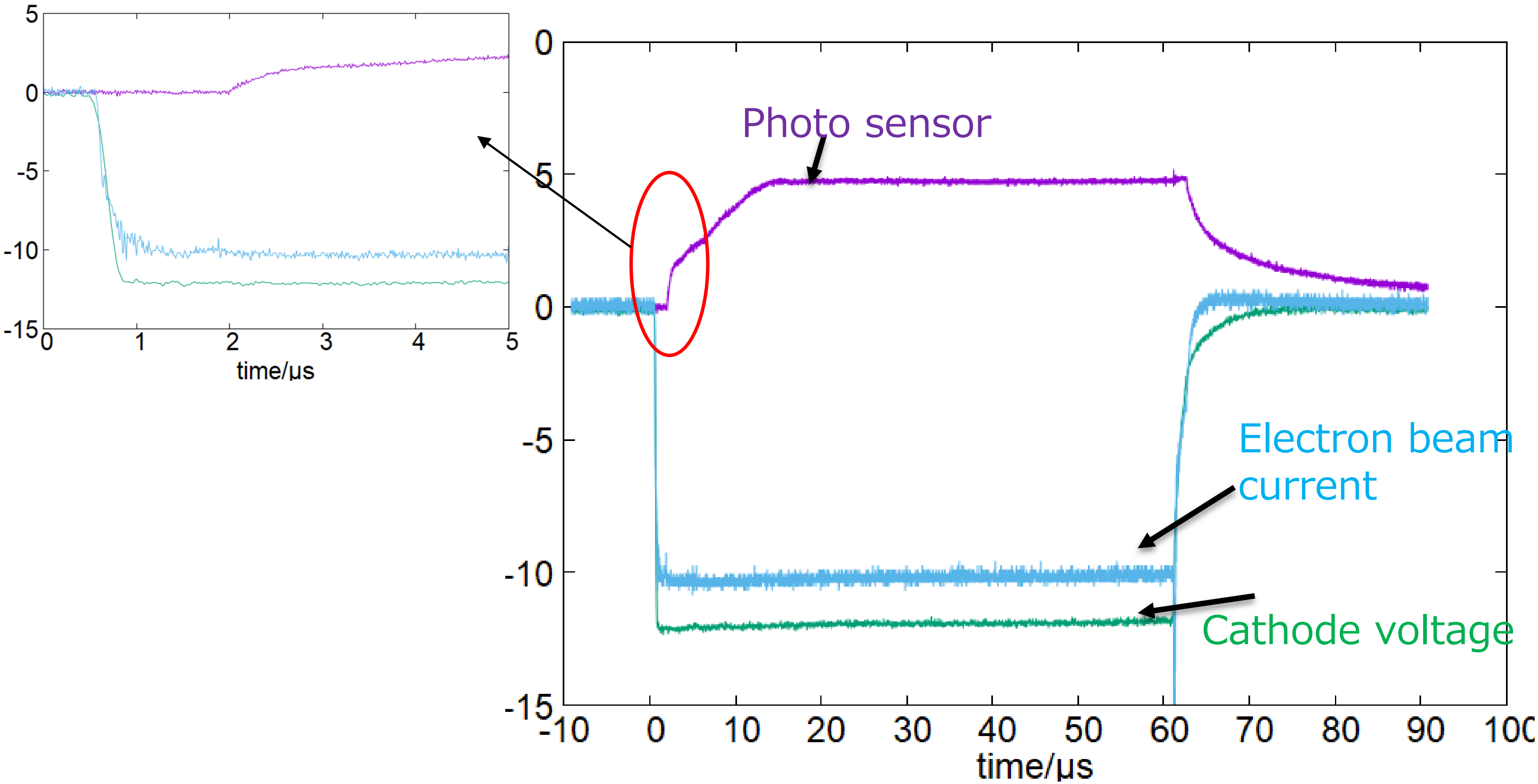
The dynamic transition of the discharge structure from overcritical to subcritical conditions has been observed as a series of images at 303 GHz.

- A numerically predicted comb-shaped filamentary plasma array was clearly confirmed under subcritical condition for the first time.
- The difference in plasma structures in the E-k and the H-k planes under subcritical condition was found. This was not expected in the numerical calculation for 170 GHz.
- This structure is created by a standing wave generated by waves diffracted from the plasma surface.

Thank you for your kind attention!
Any questions?

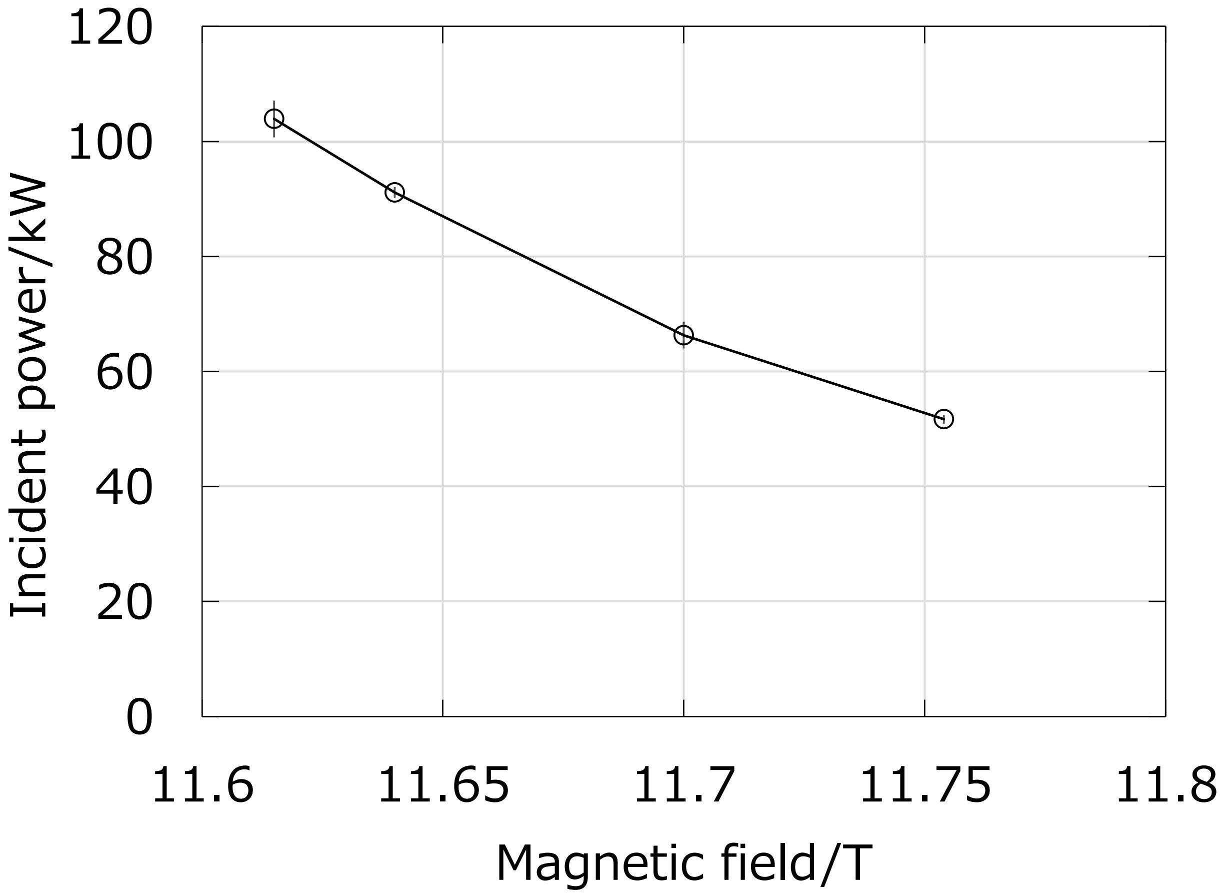
This work was supported by JSPS KAKENHI Grant Number 17K17764.

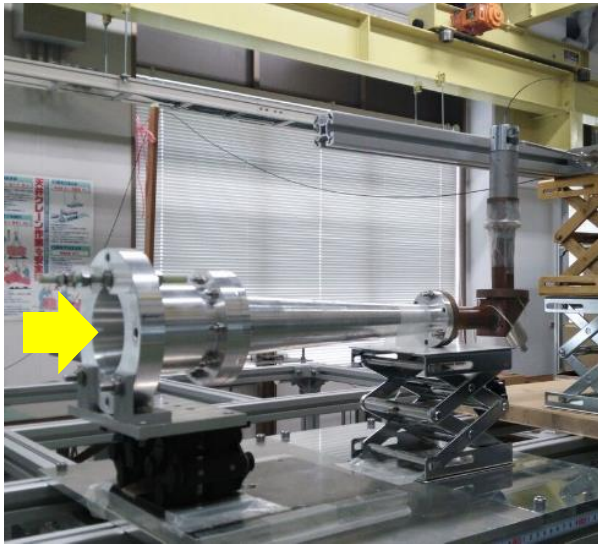
Signals at 303 GHz



The origin of the propagation time was set the signal rise of the Photo sensor

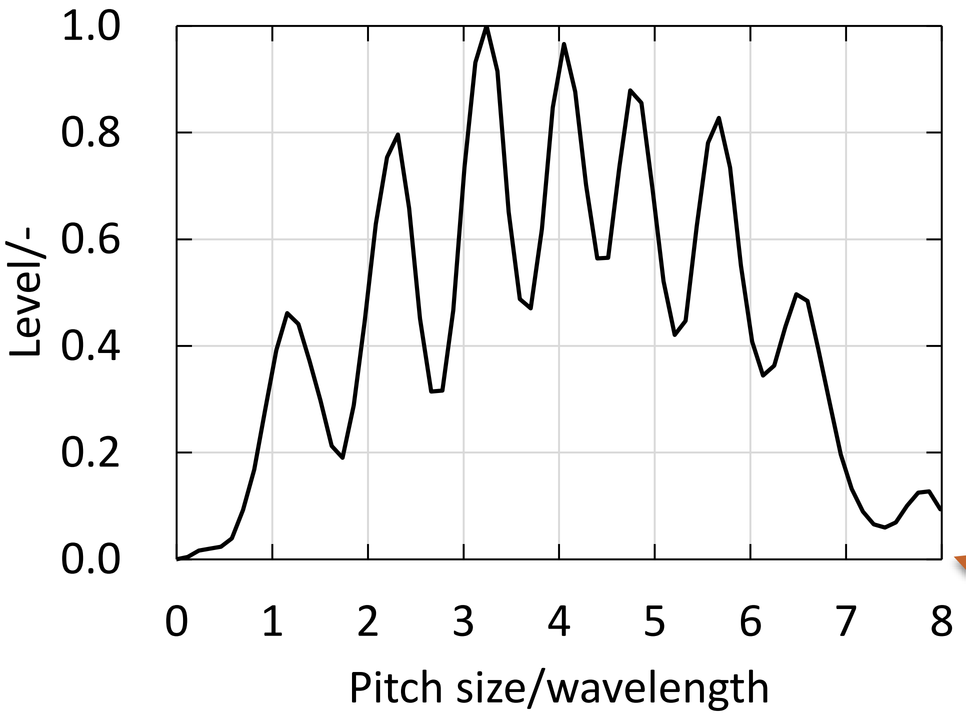
Incident power measurement

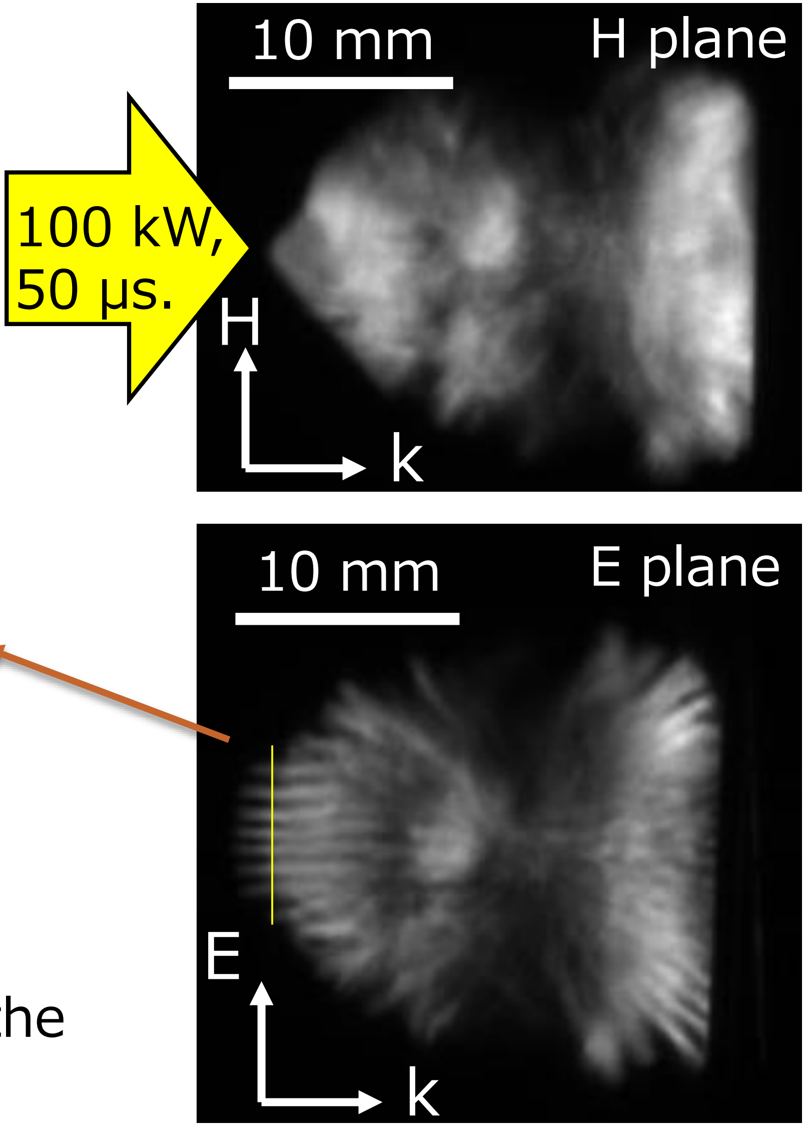




Water dummy load

Time integral images at 303 GHz





- The pitch size was ~0.9 λ as same as 170 GHz in the E plane.
- The structure was different between the H and E plane.

Detonation model

1. Mass conservation

$$\rho_1 u_1 = \rho_2 u_2$$

2. Momentum conservation

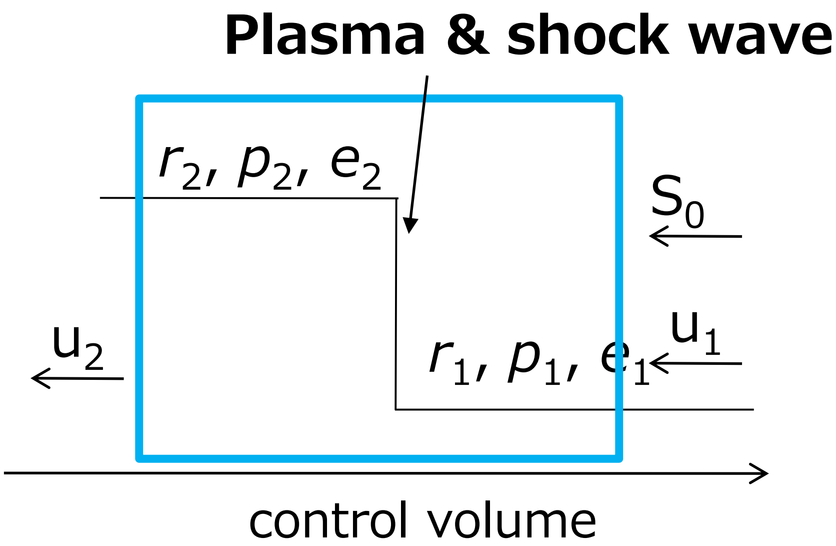
$$p_1 + \rho_1 u_1^2 = p_2 + \rho_2 u_2^2$$

3. Energy conservation

$$C_p T_1 + \frac{1}{2} u_1^2 + q = C_p T_2 + \frac{1}{2} u_2^2$$

4. State equation

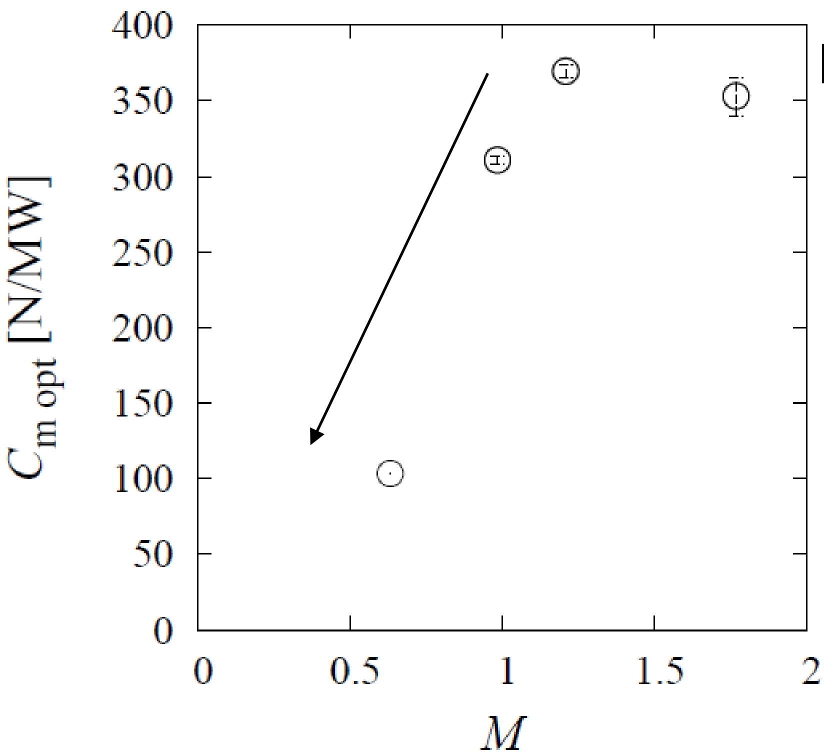
$$p = \rho R T$$



$q = \text{const.}$ **Chemical detonation**

$q = \dfrac{\eta S_{av}}{\rho_1 u_1}$ **Microwave detonation**
One more equation is needed to solve

Cm and efficiency



Engine efficiency

$$\eta = \frac{1}{2}\frac{\dot{m}v_{\mathrm{ex}}^2}{P} = \frac{1}{2}v_{\mathrm{ex}}C_m \approx \frac{1}{2}U_{\mathrm{plasma}}C_m$$

$\dot{m}$: the exhausted mass flow per unit time.

v_{ex} :the exhaust velocity.

P : the incident beam power.