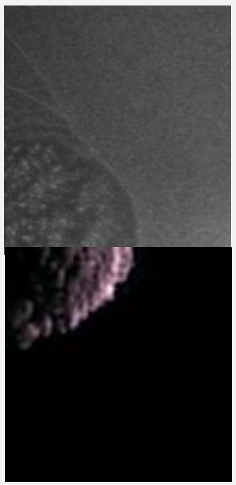
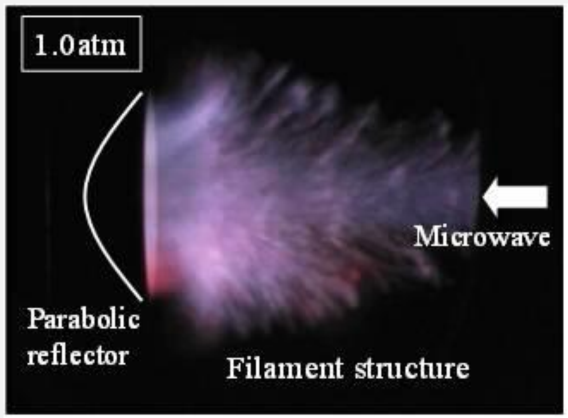
*- The 26th Annual Meeting of IAPS /*
*The 6th Workshop on Discharge Induced in High-Energy Electromagnetic Beam -*

# Visualization of 170 GHz Millimeter-Wave Discharge in Atmosphere



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# Beamed-Energy Propulsion (BEP)

## *Energy conversion*

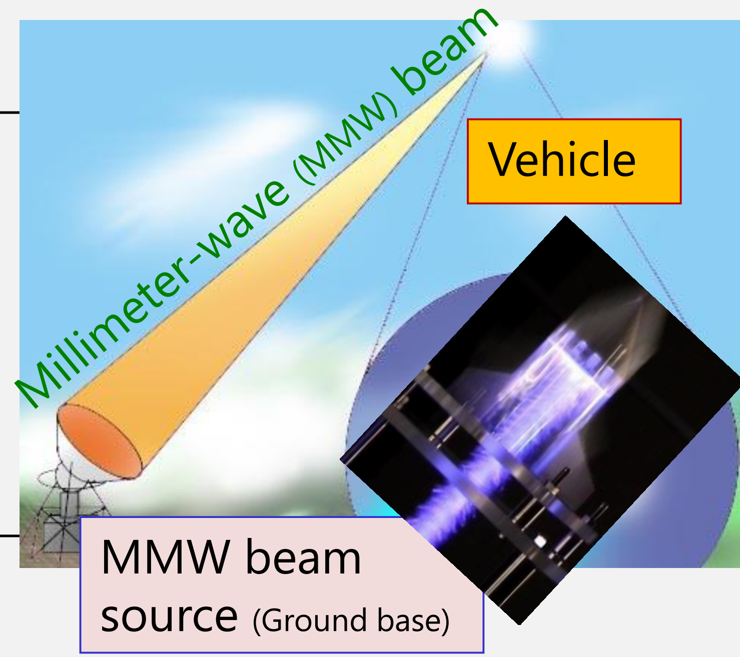
Electric energy ⇨ (Beam source) ⇨ E-M wave beam ⇨ (Thruster) ⇨ Thrust

Remote power supply from ground base

*Electric energy, Remote control, Reusable base*

Energy conversion on-board

from millimeter-wave (MMW) to thrust




## *Attractive point*

Electric control

Remote power supply

⇨ Universal transportation

# Advantages of Detonation-type BEP

| | Laser (CW/RP) | **Microwave** (CW/**RP**) |
|---|---|---|
| Thermal | CW: Laser-sustained plasma | CW: Microwave thermal rocket |
| Ablation | RP: Laser ablation | |
| **Detonation** | RP: Laser detonation | RP: **Microwave Rocket (MR)** |

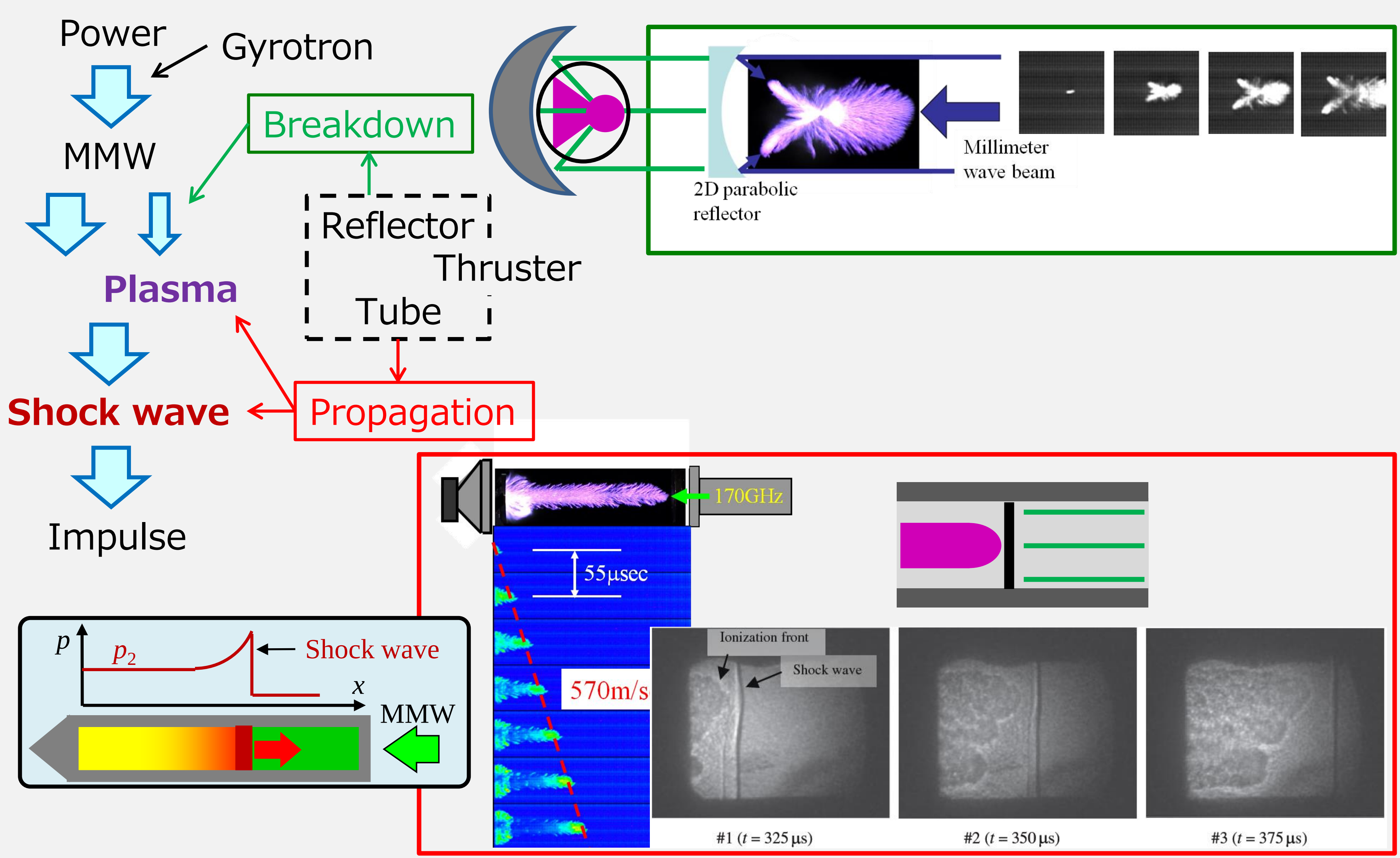
*Beam source: gyrotrons*
*Vehicle: beam-focus reflector + tube + beam receiver*

Air-breathing (ambient propellant feed)

## *Advantages as a future* ***low-cost launcher***

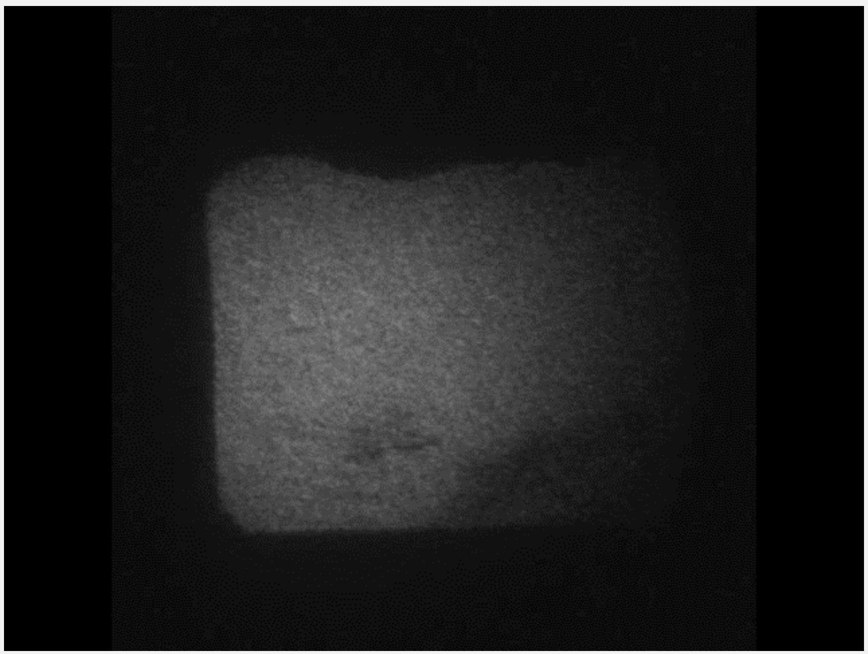
| | | |
|---|---|---|
| **Air breathing** system | **No propellant** is needed in dense atmosphere | High payload ratio |
| Pulsed-**detonation** operation | No turbo pump leads **simple** vehicle structure | One-time use of simple/cheap vehicles |
| Beam source **on the ground** | **Reused**/easy-maintained expensive/complex system | Cost reimbursement |

# Energy conversion of Microwave Rocket

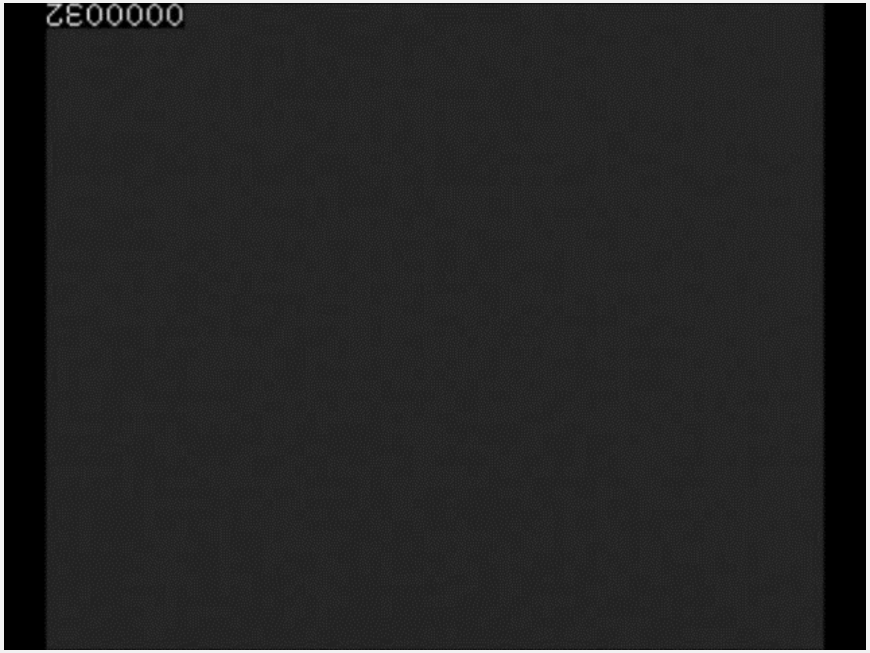


# Millimeter-wave discharge and Shock wave

Structural change of millimeter-wave (mmw) discharge plasma is studying under different mmw power density conditions.

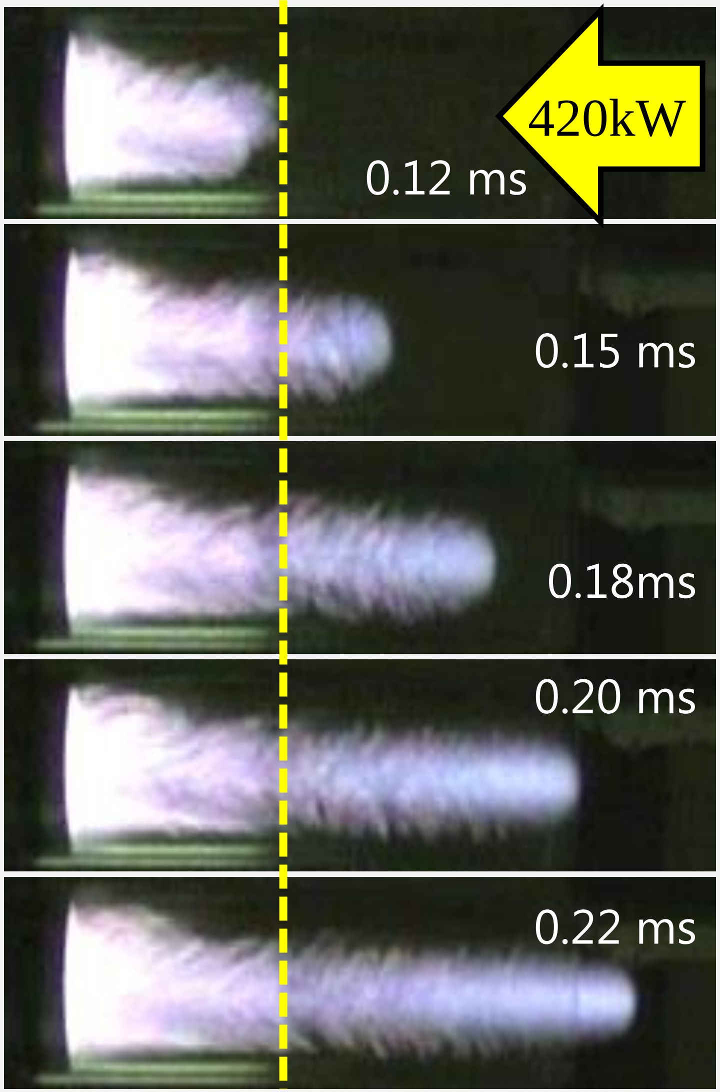


Low power density

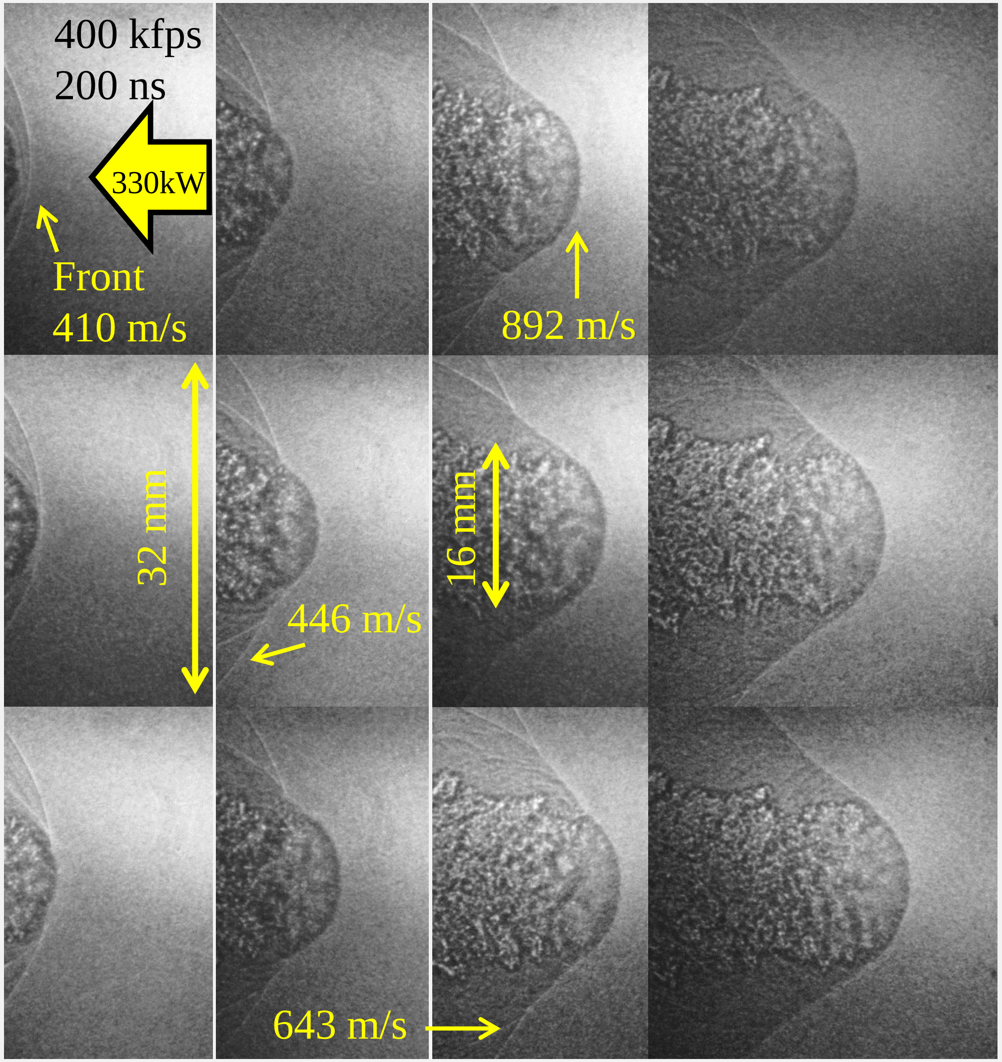



High power density

# Plasma and Shadowgraph images (IAPS 2017)




Exposed images




Shadowgraph images

# Visualization of 170GHz Discharge in Atmosphere

- **IAPS 2019 : Shadowgraph imaging at focal area**

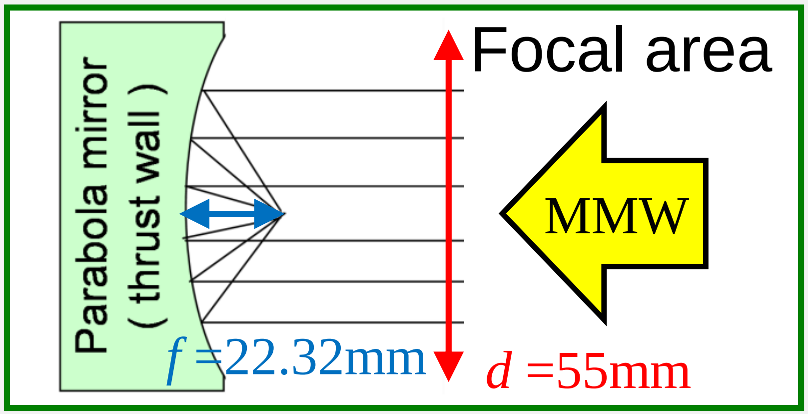
Objectives : **Observe mmw discharge at high power density condition and Measure shock wave velocity**

- Recent presentations
  - IAPS 2018 : Low ambient pressure
    - Plasma image, Pressure
      -> Performance saturation with filamentary structure
  - **IAPS 2017 : High power density beam**
    - **Shadowgraph, Pressure -> Plateau pressure saturation**
  - IAPS 2016 : Beam profile conversion
    - Plasma image, Pressure -> Impulse enhancement

# Exp. Setups

**Ionizer**

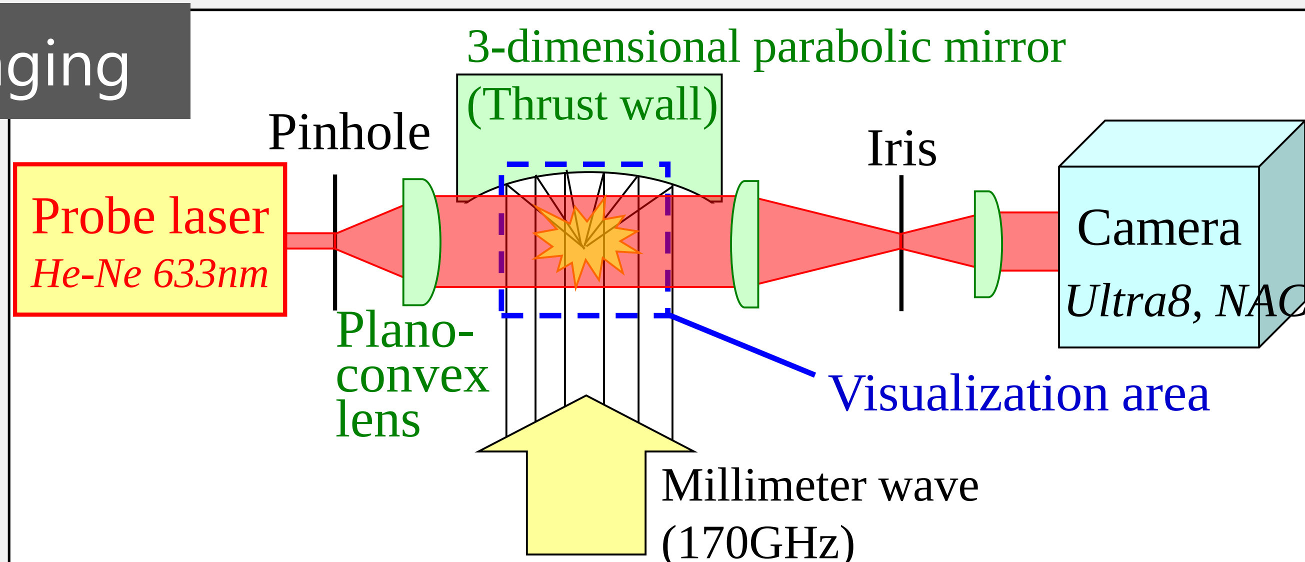
Parabolic reflector (aluminum)



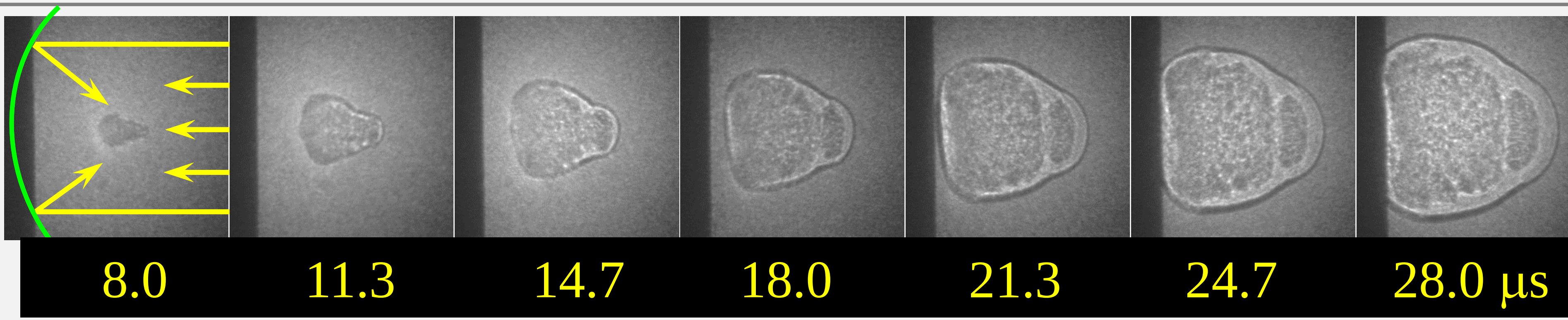

| Incident beam | |
|---|---|
| Beam source | 170 GHz gyrotron (wavelength: 1.76 mm) |
| Beam power | 150 – 600 kW, variable (constant during a pulse) |
| Pulse duration | 0.1 – 0.5 ms, variable |
| Beam pattern | Gaussian-like ($HE_{11}$ mode) |
| Beam radius | 20.4 mm at spot size |

## Shadowgraph imaging

Fluid density
↓
Refractive index
↓
Darkness



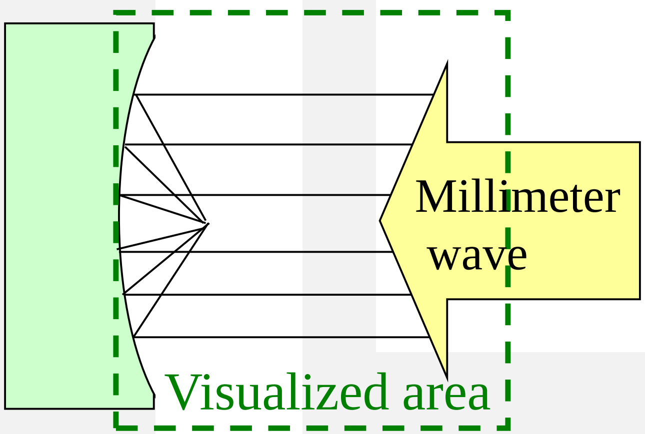
# Results : Shadowgraph images

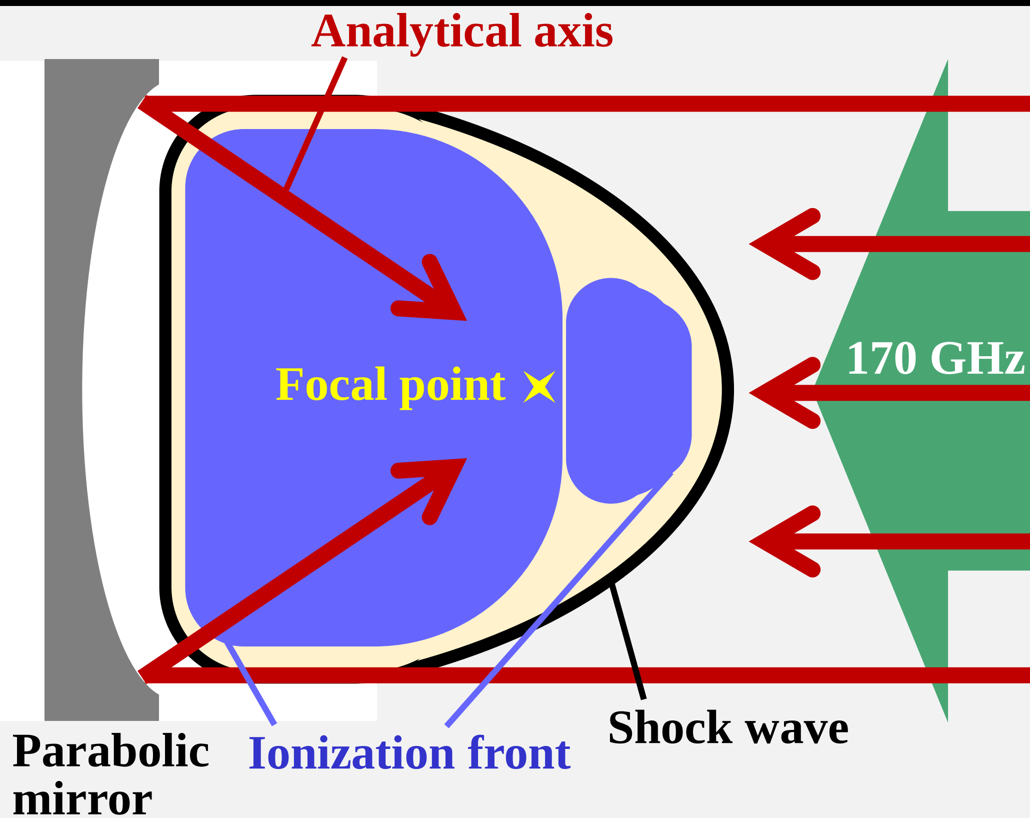



air, 1atm

power : 598kW

3D parabola
(thrust wall)



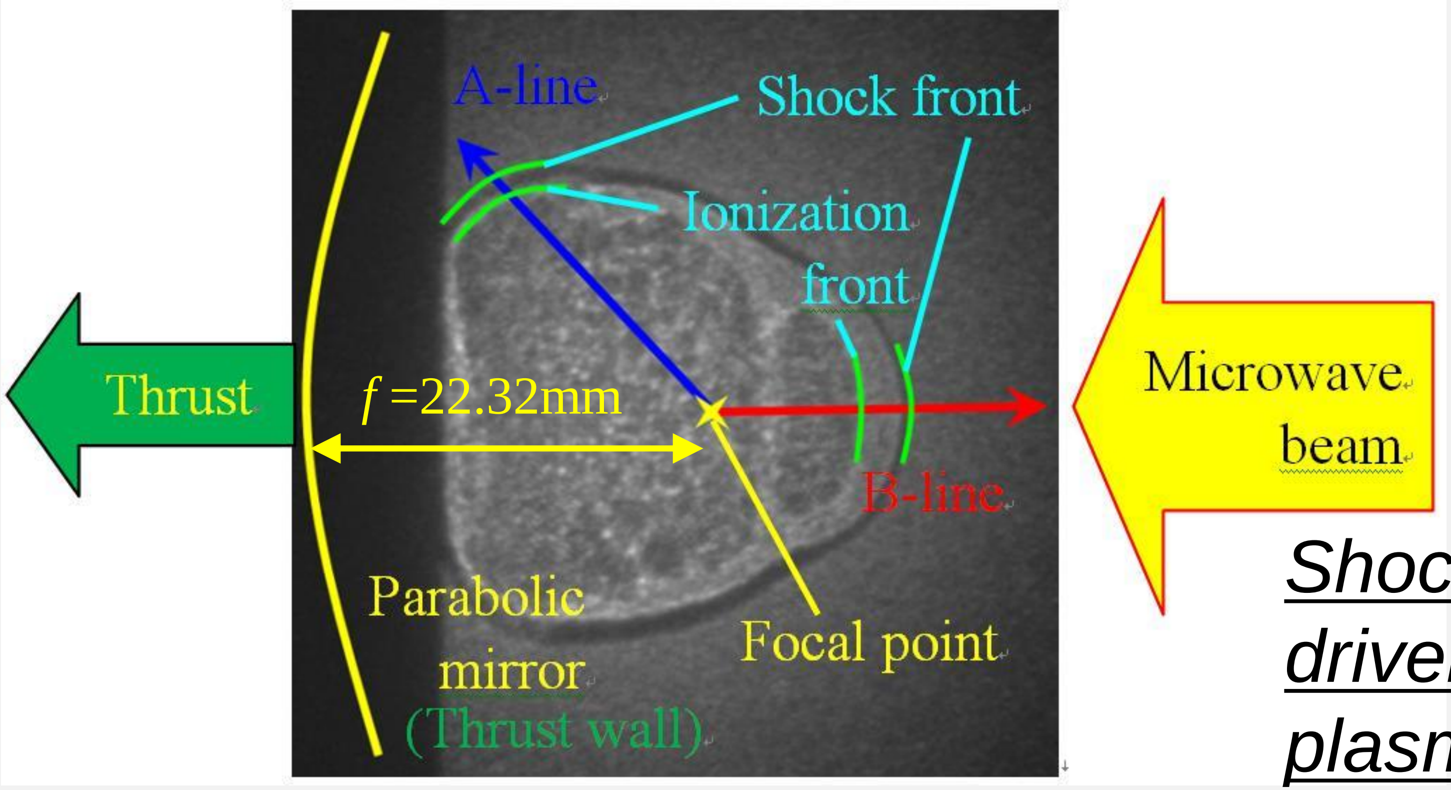
# Non-spherical shape of the shock wave

*A-line (focused)*

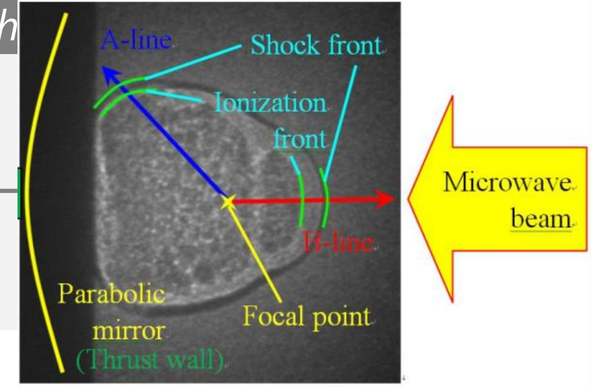
Local power density decreases along A-line.

*B-line (main beam)*

Local power density is almost constant on B-line.

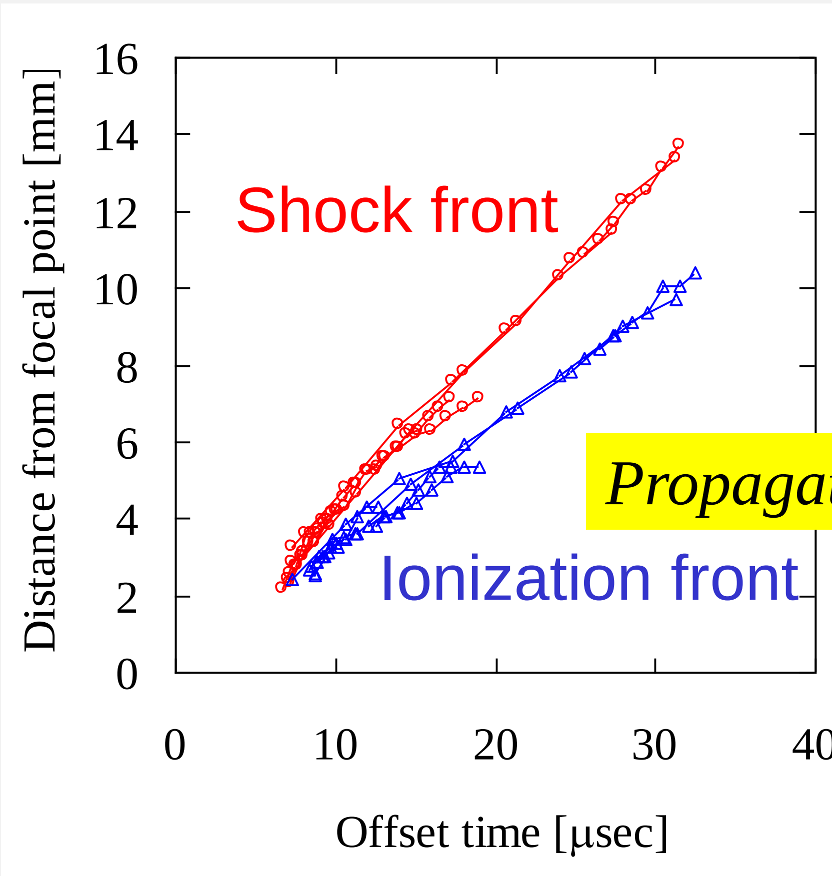



***<u>Shock wave is driven by the plasma front</u>***



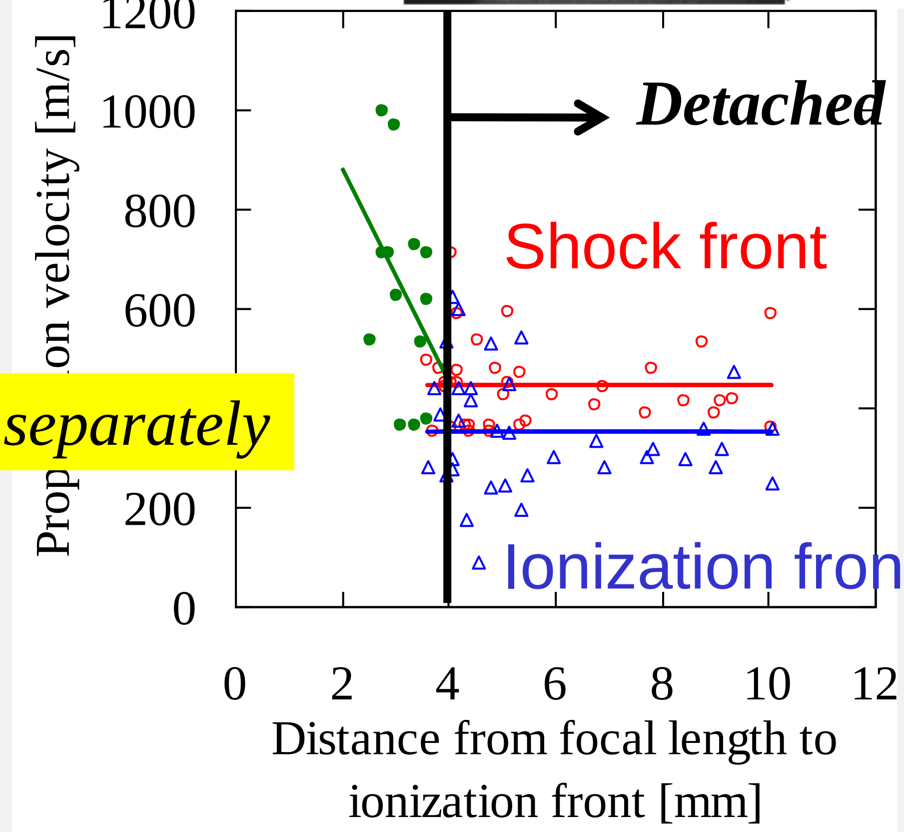

# With constant local power density

## *On the B-line (main beam)*



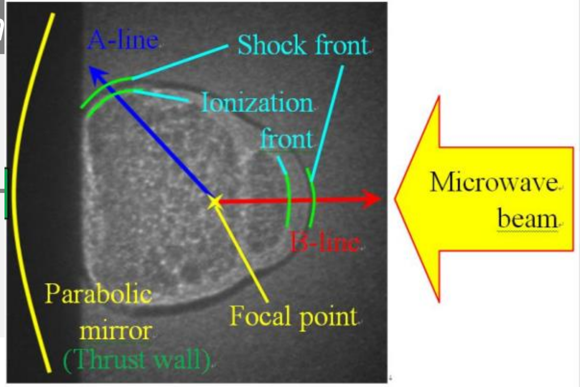

Distance from focal point

*Propagate separately*

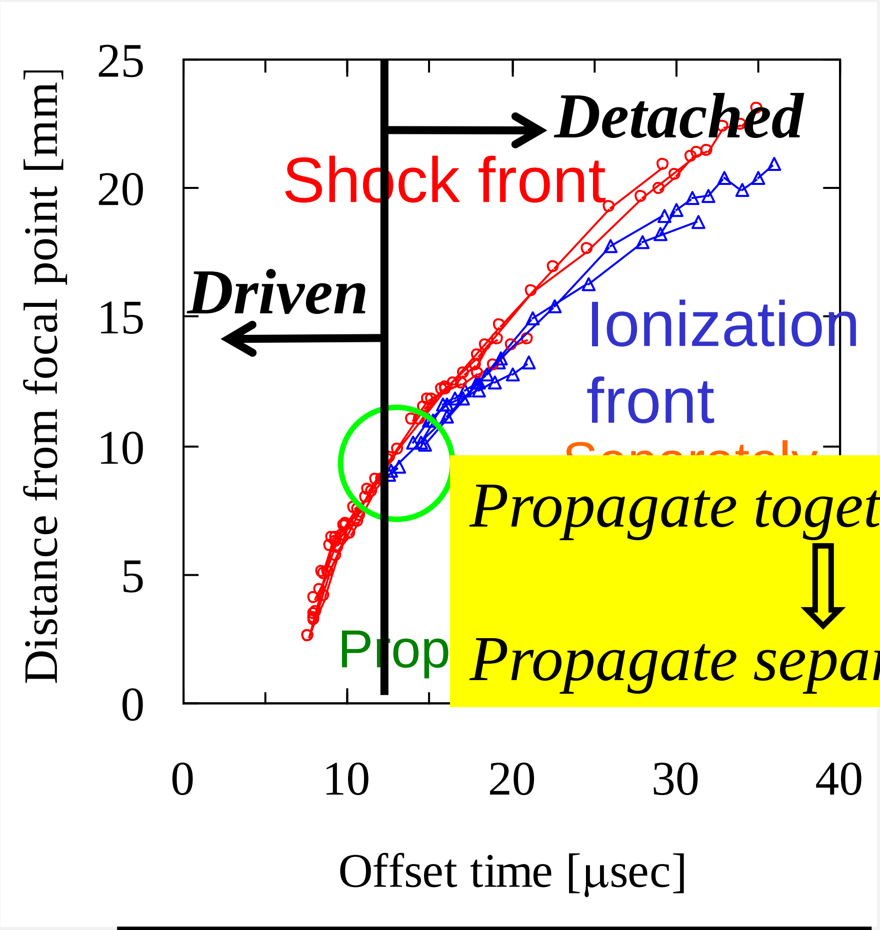



Propagating velocity under the distance

# With decrease of local power density




## *On the A-line (focused)*

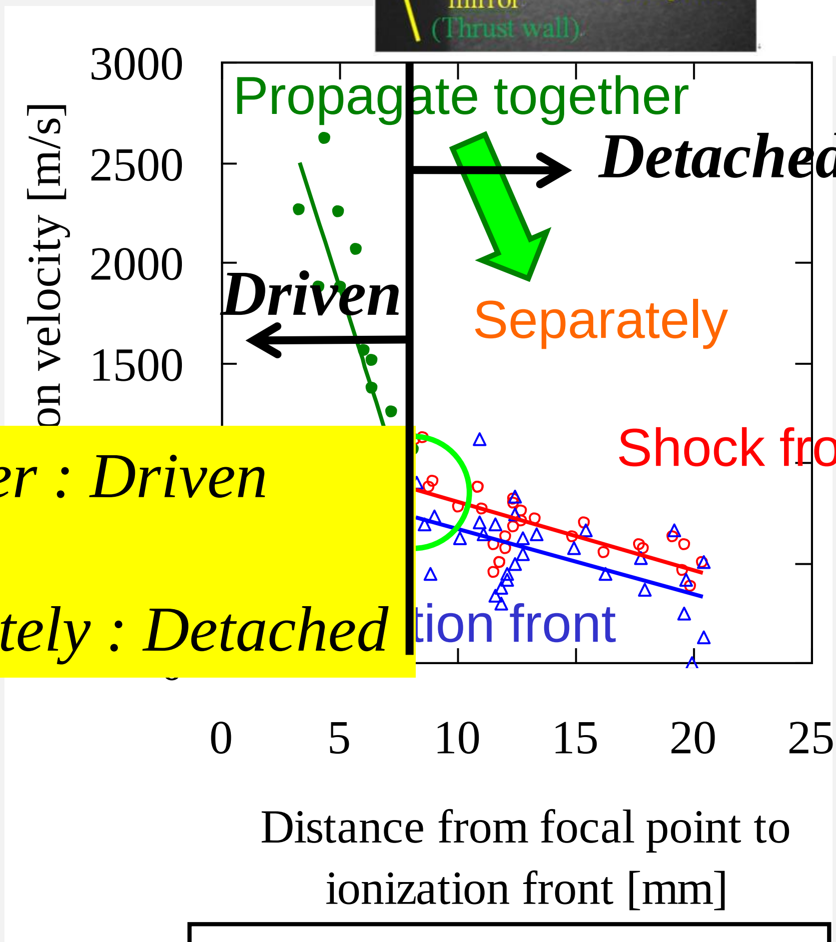



Distance from focal point

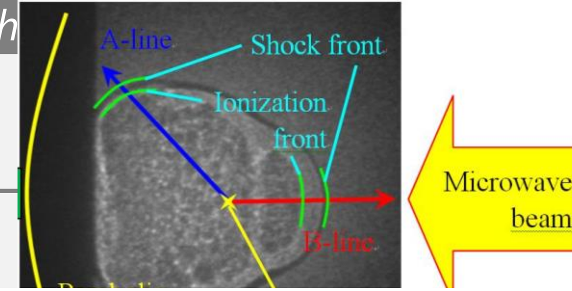
*Propagate together : Driven*

⇓

*Propagate separately : Detached*

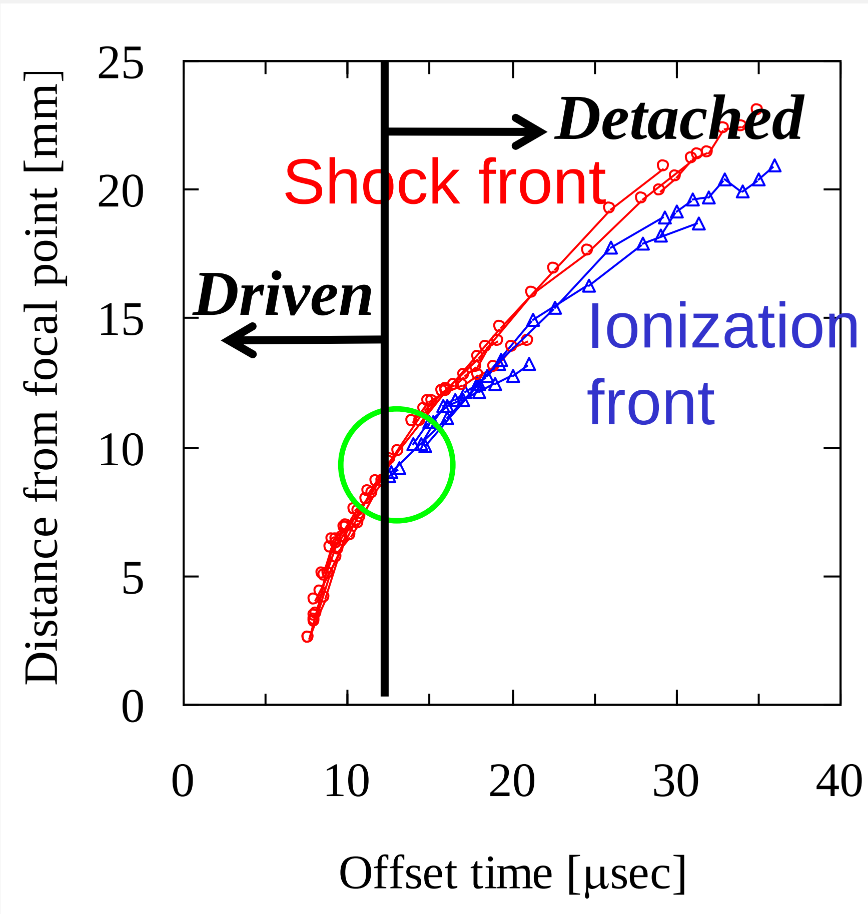



Propagating velocity under the distance

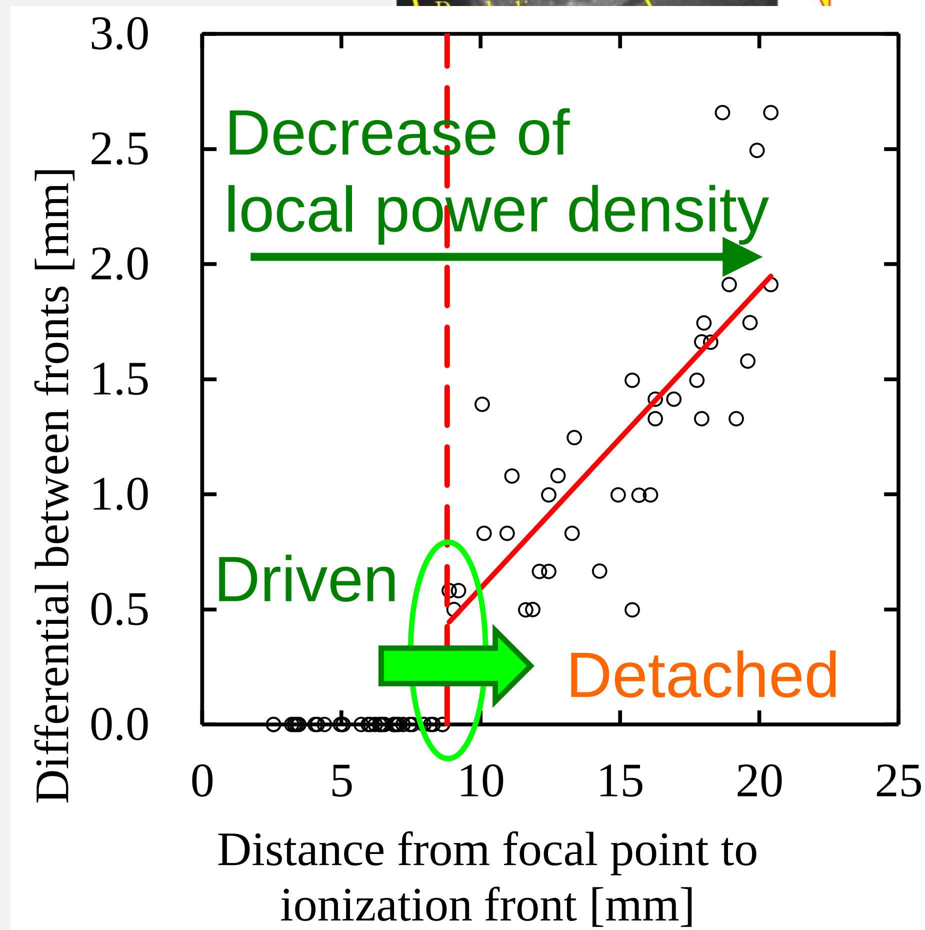



# Transition from Driven to Detached

## *On the A-line (focused)*

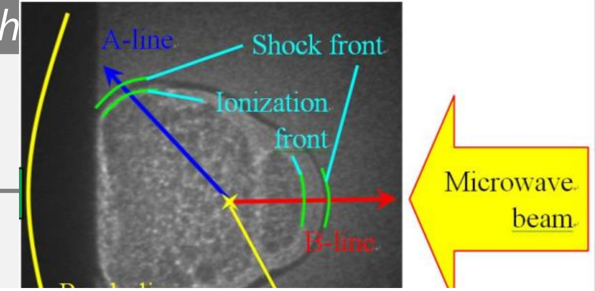



Distance from focal point

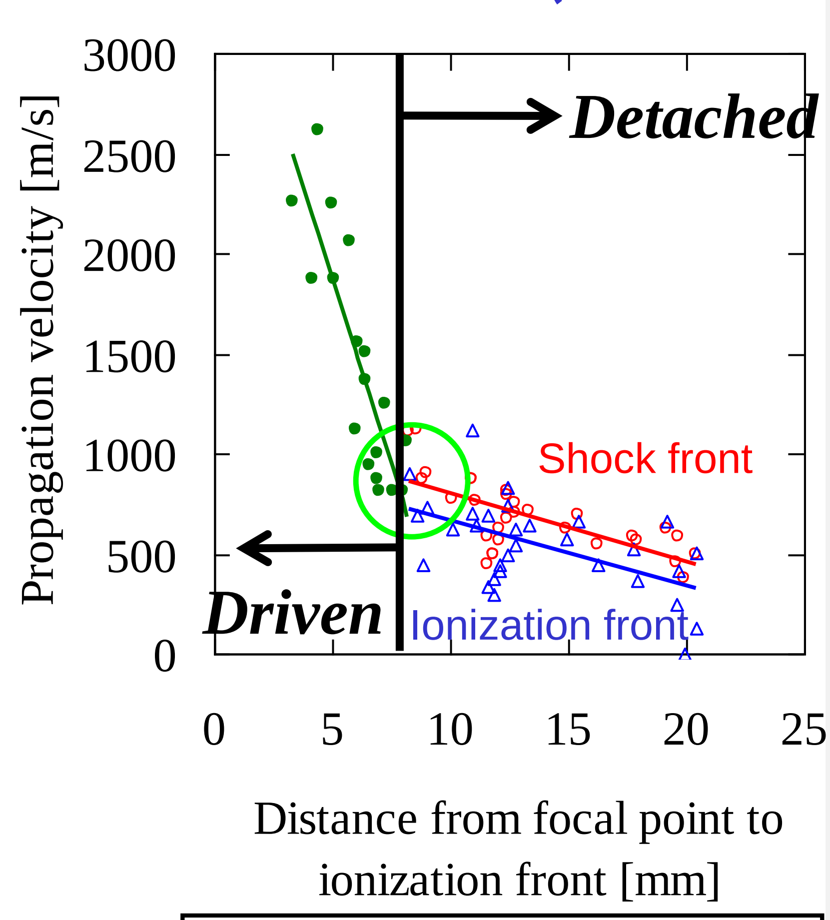


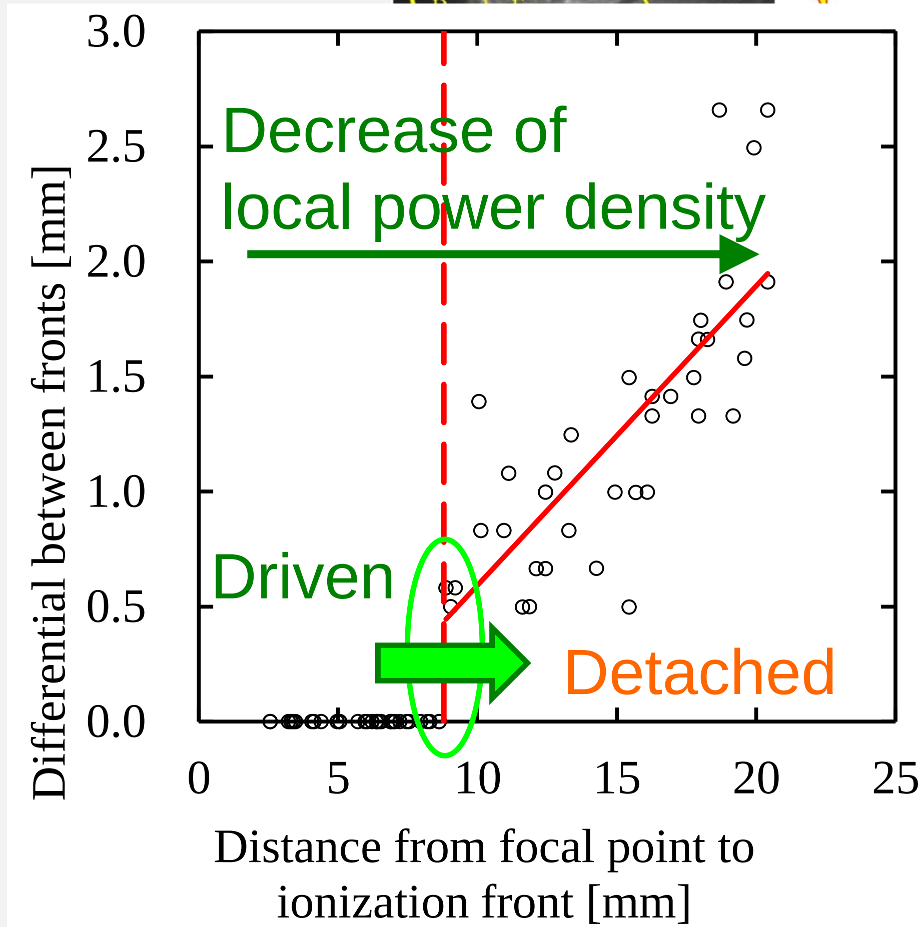

Differential between two fronts under the distance

# Propagating velocity at transition




## *On the A-line (focused)*

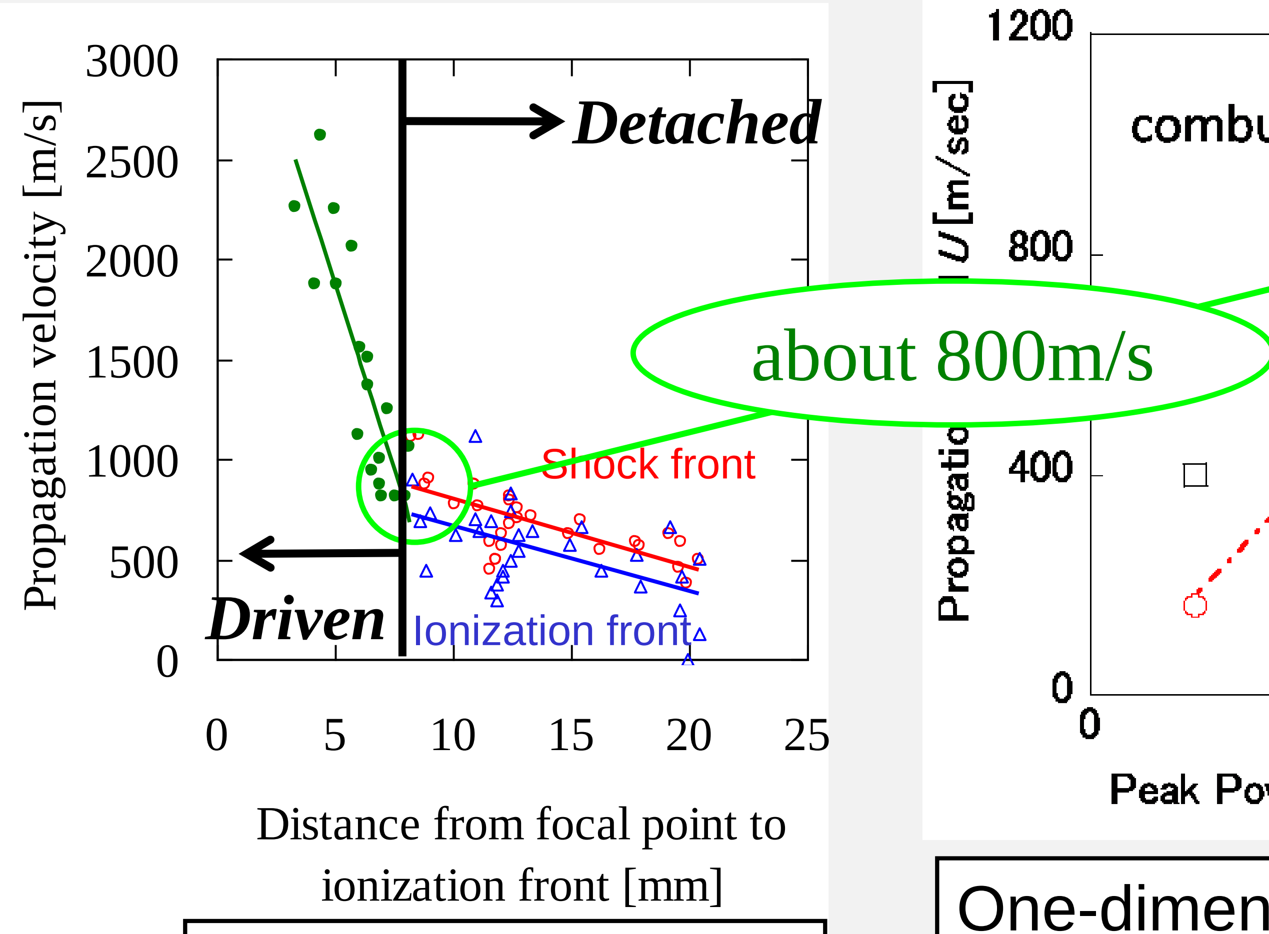


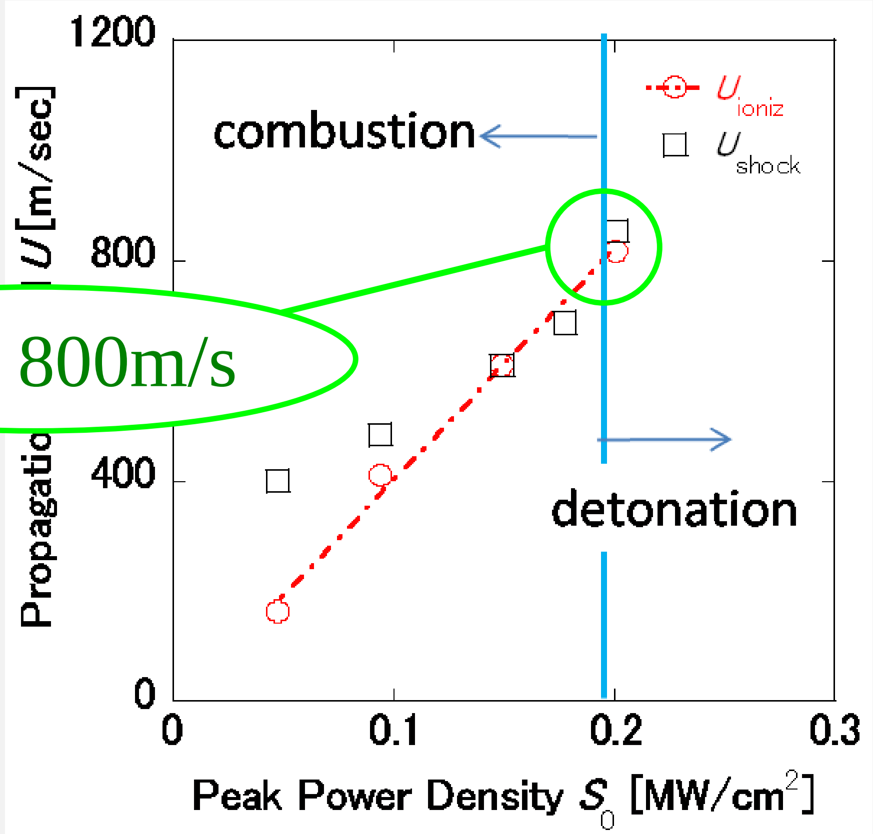

Propagation velocity under the distance

Differential between two fronts under the distance

# Agreement with one-dimensional simulation




Propagation velocity under the distance




One-dimensional experiments and calculations(Shimada *et al.*)

# Summary

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- **Atmospheric MMW discharge** caused by **170GHz gyrotron** was observed **at focal area** by **Shadowgraph imaging**.
- Propagating shape of shock wave was not spherical, but dependent on the shape of the heated plasma front which absorbs mmw beam energy.
- Transition from **Driven structure** to **Detached structure** was observed due to the decrement of the local power density.
- **Propagating velocity** of the shock wave was about **800m/s at the transition**, which agrees with computational study of one-dimensional propagating model.

Thank you for your kind attention!