Visualization of 170 GHz Millimeter-Wave Discharge in Atmosphere

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Beamed-Energy Propulsion (BEP)

**Energy conversion**

Electric energy $\rightarrow$ E-M wave beam $\rightarrow$ 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 $\rightarrow$ Universal transportation
## Advantages of Detonation-type BEP

<table>
<thead>
<tr>
<th></th>
<th>Laser (CW/RP)</th>
<th>Microwave (CW/RP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal</td>
<td>CW: Laser-sustained plasma</td>
<td>CW: Microwave thermal rocket</td>
</tr>
<tr>
<td>Ablation</td>
<td>RP: Laser ablation</td>
<td></td>
</tr>
<tr>
<td><strong>Detonation</strong></td>
<td>RP: Laser detonation</td>
<td>RP: <strong>Microwave Rocket (MR)</strong></td>
</tr>
</tbody>
</table>

- **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

- **Power** → **Gyrotron** → **Breakdown** → **Plasma** → **Shock wave** → **Impulse**

- **MMW** → **Reflector** → **Thruster** → **Tube** → **Propagation**

- **170GHz**

- **55μsec**

- **570m/s**

- **Ionization front**

- **2D parabolic reflector**

- **Millimeter wave beam**

- "Visualization of 170 GHz Millimeter-Wave Discharge in Atmosphere" by T. Yamaguchi
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
Exposed images

400 kfps
Front
410 m/s
32 mm

330 kW
200 ns

446 m/s
643 m/s

420 kW
0.12 ms

892 m/s
16 mm

Shadowgraph images

0.15 ms
0.18 ms
0.20 ms
0.22 ms

“Visualization of 170 GHz Millimeter-Wave Discharge in Atmosphere” by T.Yamaguchi

Mar. 09, 2019
IAPS Meeting 2019 / Workshop on HEMEB in Okinawa
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)

<table>
<thead>
<tr>
<th>Focal area</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f = 22.32 \text{mm} )</td>
</tr>
<tr>
<td>( d = 55 \text{mm} )</td>
</tr>
</tbody>
</table>

**Incident beam**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam source</td>
<td>170 GHz gyrotron (wavelength: 1.76 mm)</td>
</tr>
<tr>
<td>Beam power</td>
<td>150 – 600 kW, variable (constant during a pulse)</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>0.1 – 0.5 ms, variable</td>
</tr>
<tr>
<td>Beam pattern</td>
<td>Gaussian-like (HE(_{11}) mode)</td>
</tr>
<tr>
<td>Beam radius</td>
<td>20.4 mm at spot size</td>
</tr>
</tbody>
</table>

**Shadowgraph imaging**

- Fluid density ↓
- Refractive index ↓
- Darkness ↓

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**Inlet**

- **Pinhole**
- **Plano-convex lens**
- **Iris**
- **Camera**
  - Ultra8, NAC

**Visualization area**

- **Millimeter wave (170GHz)**
- **Probe laser**
  - He-Ne 633nm

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Mar. 09, 2019

IAPS Meeting 2019 / Workshop on HEMEB in Okinawa
Results: Shadowgraph images

air, 1 atm
power: 598 kW

3D parabola (thrust wall)

Visualized area

Millimeter wave

Parabolic mirror

Focal point

Ionization front

Shock wave

Analytical axis

170 GHz

Mar. 09, 2019

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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.

Shock wave is driven by the plasma front
With constant local power density

On the B-line (main beam)

Shock front

Ionization front

Propagate separately

Distance from focal point [mm]

Offset time [μsec]

Shock front

Ionization front

Detached

Propagating velocity under the distance
With decrease of local power density

On the A-line (focused)

**Detached**

**Driven**

Propagate together : Driven

Propagate separately : Detached

Distance from focal point

Offset time [μsec]

Distance from focal point to ionization front [mm]

Propagating velocity under the distance
Transition from Driven to Detached

On the A-line (focused)

Distance from focal point [mm]

Offset time [μsec]

Distance from focal point

Differential between two fronts under the distance

Shock front

Detached

Driven

Ionization front

Decrease of local power density

Distance from focal point to ionization front [mm]

Differential between fronts [mm]

0 5 10 15 20 25
Offset time [msec]

0 5 10 15 20 25
Distance from focal point to ionization front [mm]

Decrease of local power density

Detached

Driven
Propagating velocity at transition

On the A-line (focused)

Propagation velocity under the distance

Decrease of local power density

Differential between two fronts under the distance
Agreement with one-dimensional simulation

Propagation velocity [m/s]

Distance from focal point to ionization front [mm]

Detached
Driven

about 800m/s

Peak Power Density $S_0$ [MW/cm$^2$]

Combustion
Detonation

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

- Atmospheric MMW discharge caused by 170 GHz 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!