IW-FIRT2019

Development of a 600 kW Gyrotron for Microwave Rocket Researches

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4) Plasma Research Center, University of Tsukuba

Contents

1. **High-power gyrotron application for beamed energy propulsion “Microwave Rocket”**

2. **94 GHz, 600 kW gyrotron development at the University of Tokyo**

3. **Future research of air breakdown plasma using UT-gyrotron**

4. **Summary**

Space transportation
“ BEP (Beamed Energy Propulsion) ”

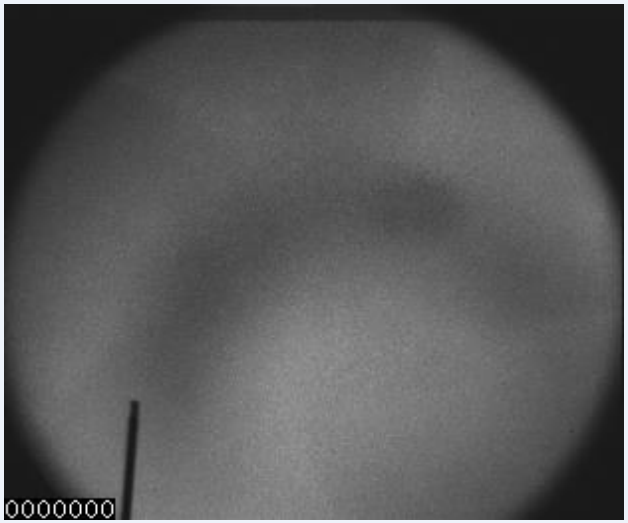
Artist image of BEP

Launch demonstration,
1 MW mm-W, 109 g to 2 m, 2009

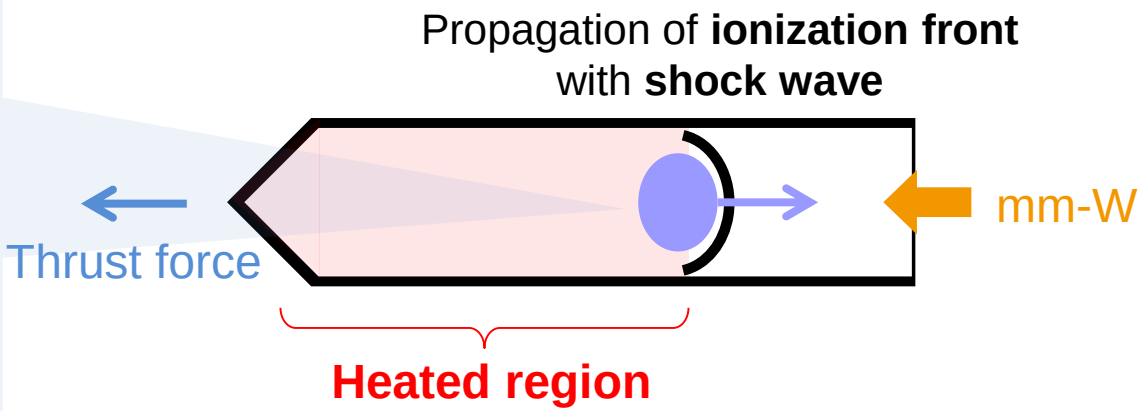
Air-breathing	No onboard propellant	High payload ratio
Beam from ground	Reusable	Amortizable
Pulse detonation engine (PDE)	Simple structure	Low manufacturing cost

Low launch cost

Thrust generation using air breakdown plasma induced by high-power mm-W

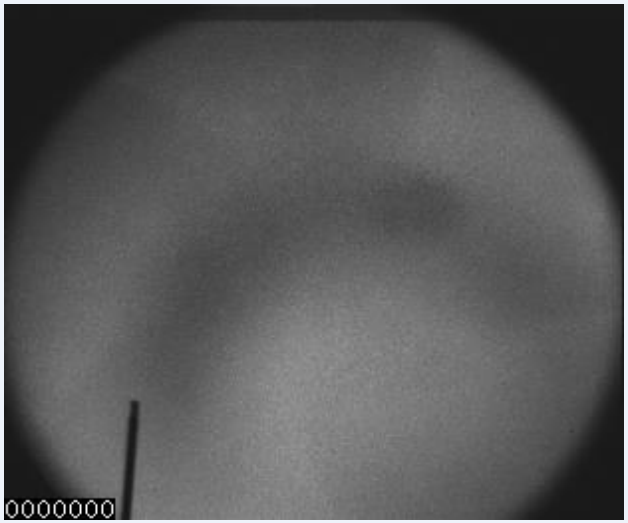


Shadow graph of propagating ionization front and shock wave



- Air inside a cylindrical tube (thruster) is heated and pressure is drastically increased. Pressure difference between inside and outside makes thrust force.

Thrust generation using air breakdown plasma induced by high-power mm-W



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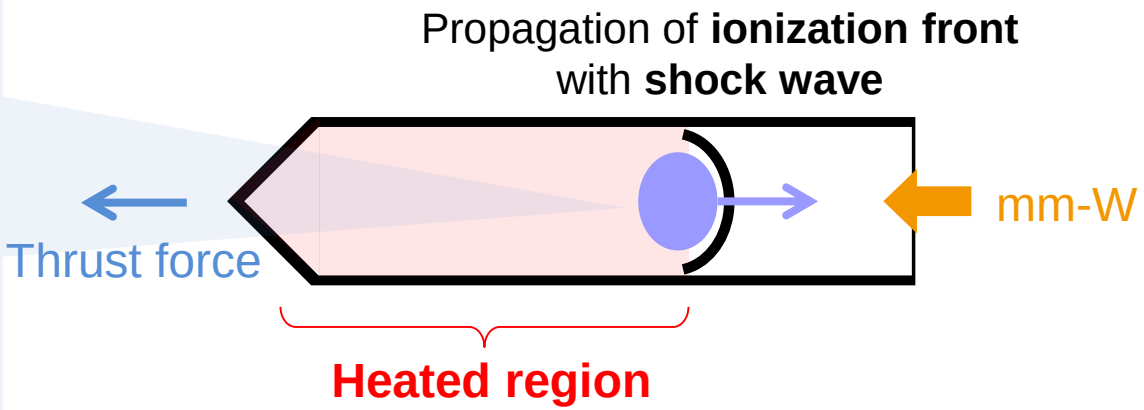


$$E\,[\mathrm{J/m^3}] = \frac{S_{\mathrm{beam}}\,[\mathrm{W/m^2}]}{U_{\mathrm{ioniz}}\,[\mathrm{m/s}]}$$

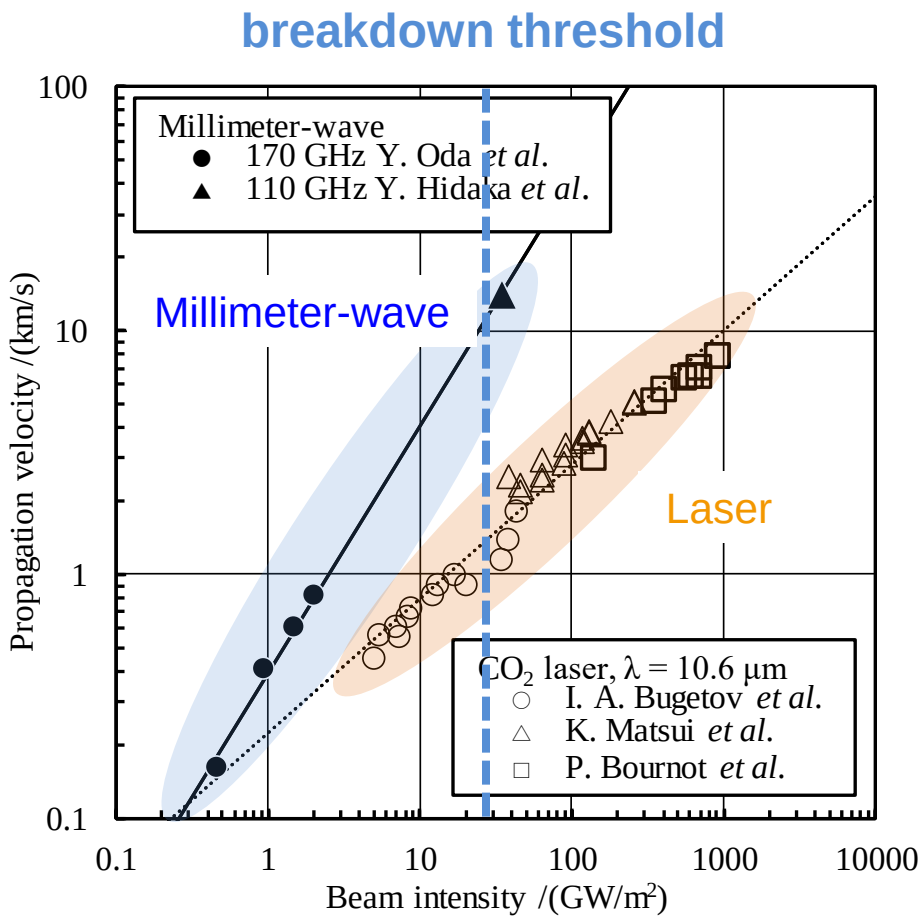
← Beam intensity

← Propagation velocity

- The smaller propagation velocity is for a certain beam intensity, the more energy air can obtain.

→ **In order to estimate thrust performance, modeling of ionization front propagation velocity is needed.**

Ionization front propagation velocity of Laser and mm-W



Measured propagation velocity of ionization front.

■ **Problem in numerical calculation**

Once breakdown occurs, discharge front propagated at much lower intensity than breakdown threshold.

↓

It's necessary to investigate mm-W discharge in detail.

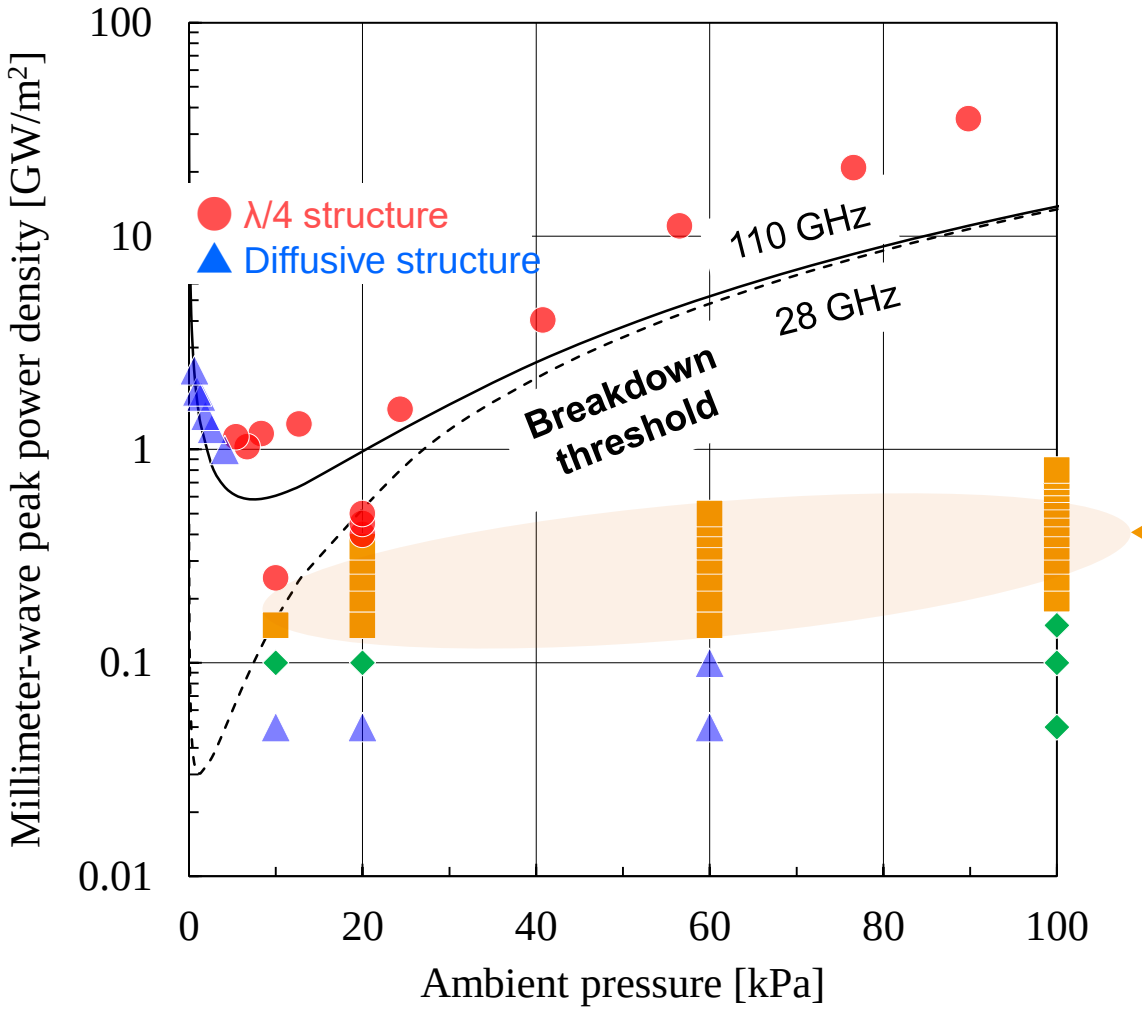
↓

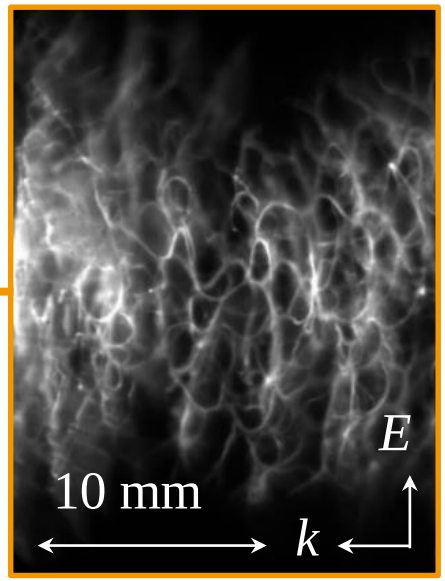
Collaborative research at Plasma Research Center, 28 GHz gyrotron

Prof. Kariya
Prof. Minami

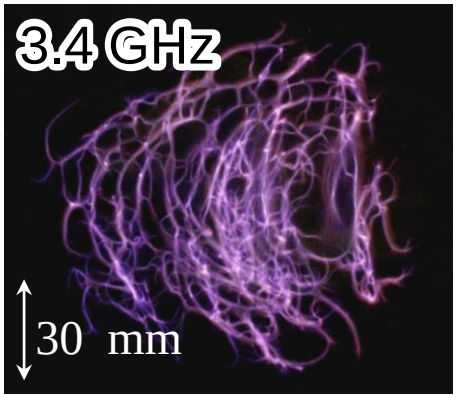
筑波大学 University of Tsukuba

Observed plasma structures in 28 GHz



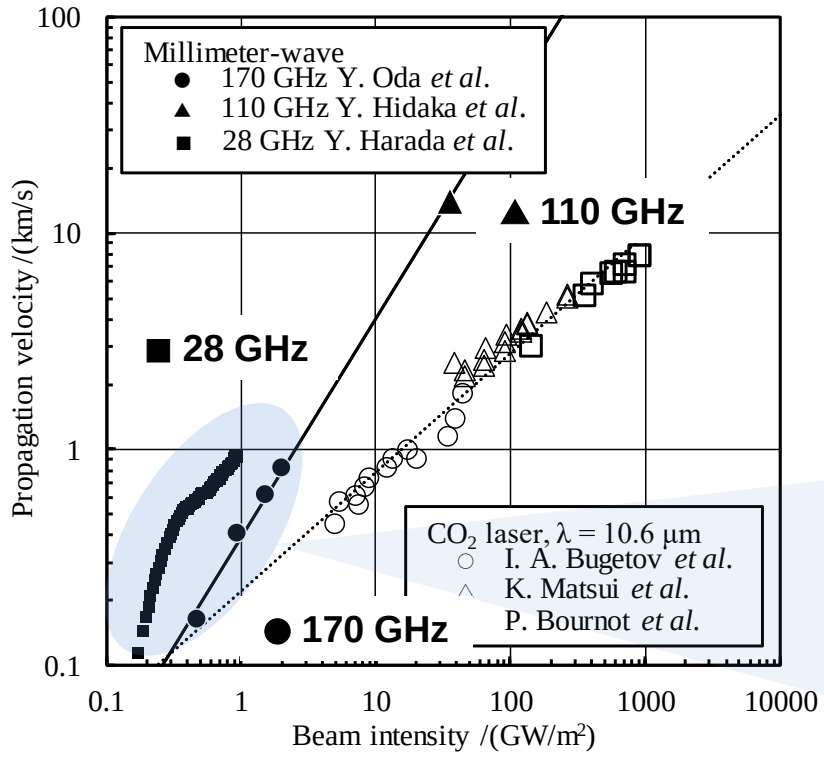


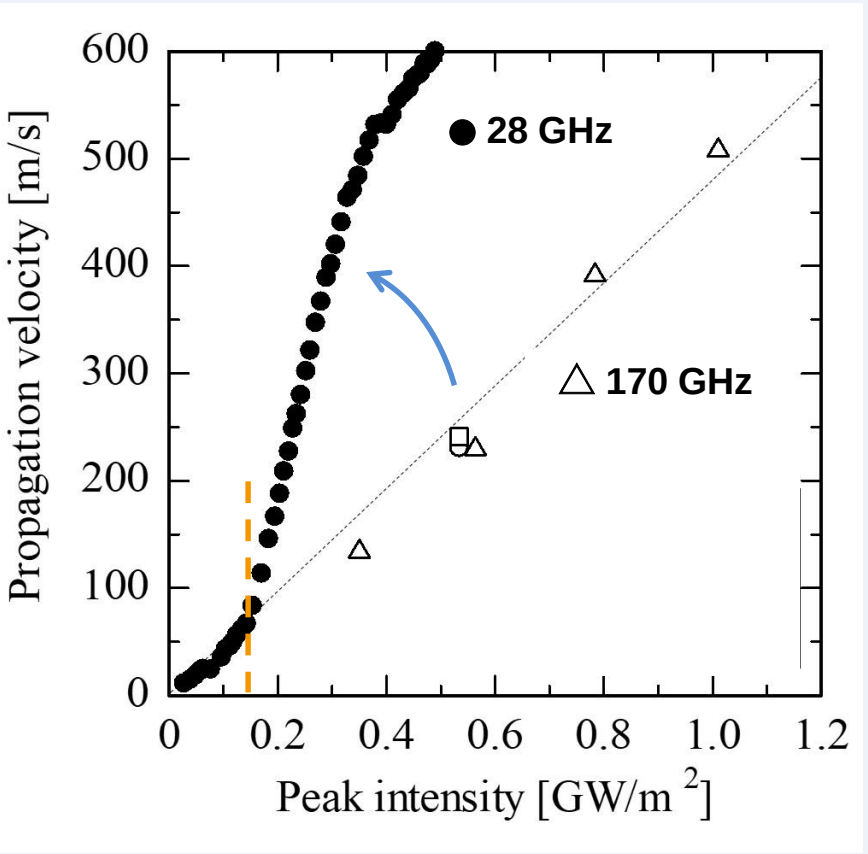
Similar



110 GHz: A. M. Cook et al., Phys. Plasmas, **18**:100704, 2011.
28 GHz: K. Tabata et al., IRMMW-THz, 2018.

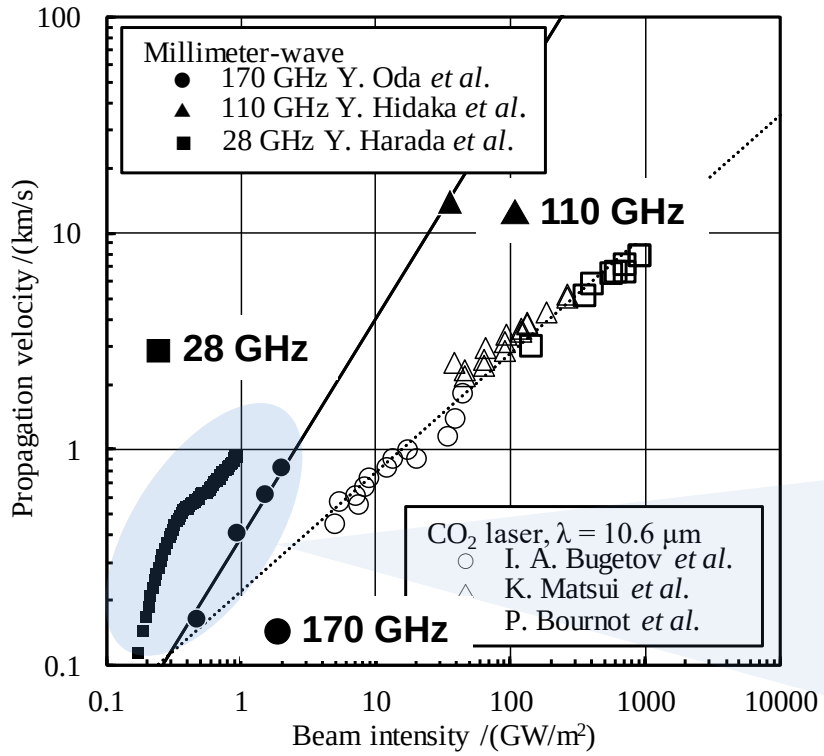
Propagation velocity of 28 GHz is higher than that of mm-W frequencies.

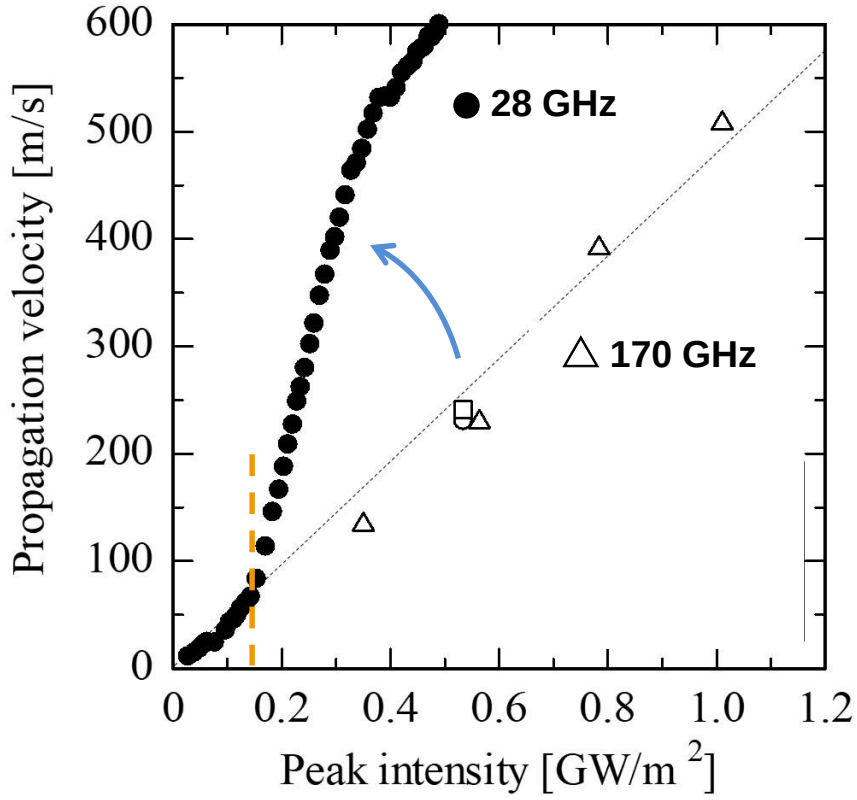




Measured 28 GHz propagation velocity has a different tendency from mm-W over 0.2 GW/m^2.

Propagation velocity of 28 GHz is higher than that of mm-W frequencies.





As a next step, we'd like to conduct experiments using a 100 GHz band gyrotron for Microwave Rocket researches.

Gyrotron development and its specification

Thanks to cooperation of 4 research institutes, developing a new gyrotron became possible.

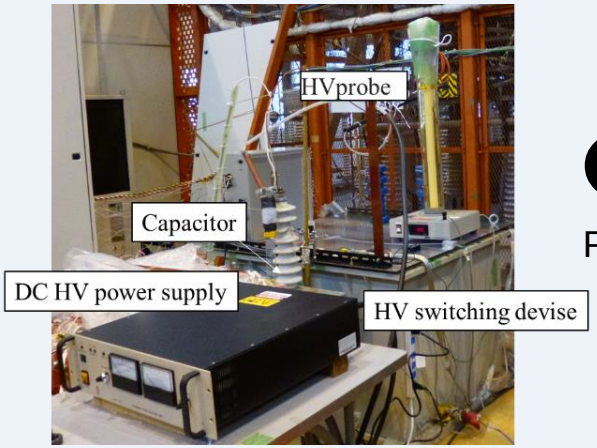
Collaboration

- The University of Tokyo
- University of Fukui
- QST
- University of Tsukuba

Specification

Frequency	**94 GHz**
Maximum output power	**600 kW**
Operation	Single pulse operation
Pulse width	~ 100 μs
Beam profile	Gaussian profile

UT gyrotron concept – demountable-type gyrotron



Switching test QST

❷ Annular electron beam, **25 A**

❸ Power Supply

Collector

mm-W Beam, **$TE_{10,5}$ → Gaussian**

Mode Convertor

Sapphire Window

Capacitor

❶ 8T SC-Magnet,

3.696 T for 94 GHz
(MAX 230 GHz, 1st harmonic oscillation)

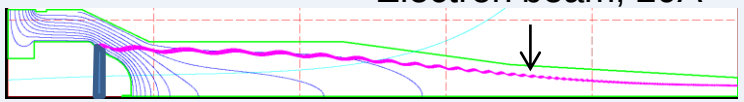
Multi-stage IGBT Switch,
IGBT element: SKM150GB17E4

Cavity resonator

Gun coil

❷ Electron Gun (Cathode) , **Diode, 80 kV**

Electron beam, 20A



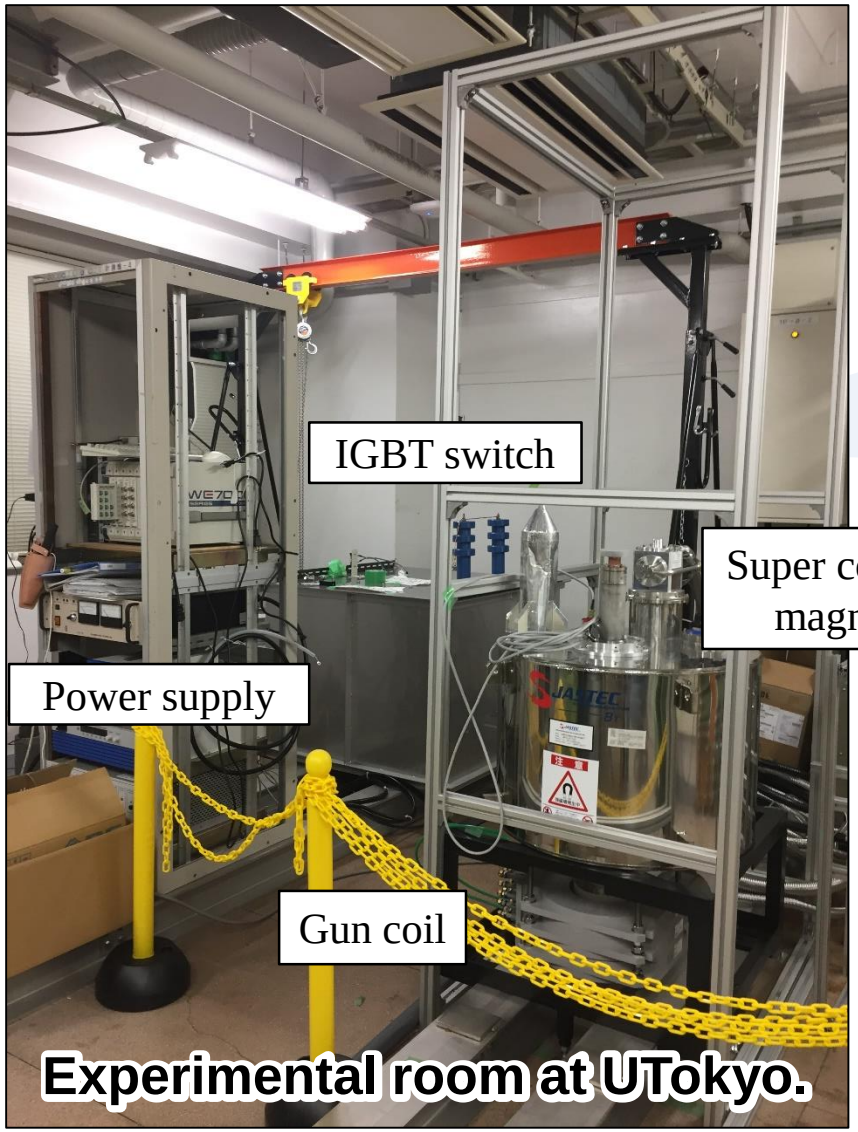
Cavity

Electron Gun

Calculated electron trajectory using a EGUN.

By Dr. Fukunari UNIVERSITY OF FUKUI Research Center for Development of Far-Infrared Region

Photograph of experimental room



IGBT switch

- Gyrotron components other than cavity and mode converter was already developed.
- By the end of next year, first operation of the gyrotron will be carried out.

Future research of air breakdown plasma utilizing a UT-Gyrotron

Previous works – measured parameters using a 28 GHz gyrotron

Former slides

- Propagation velocity of ionization front
- Plasma structures

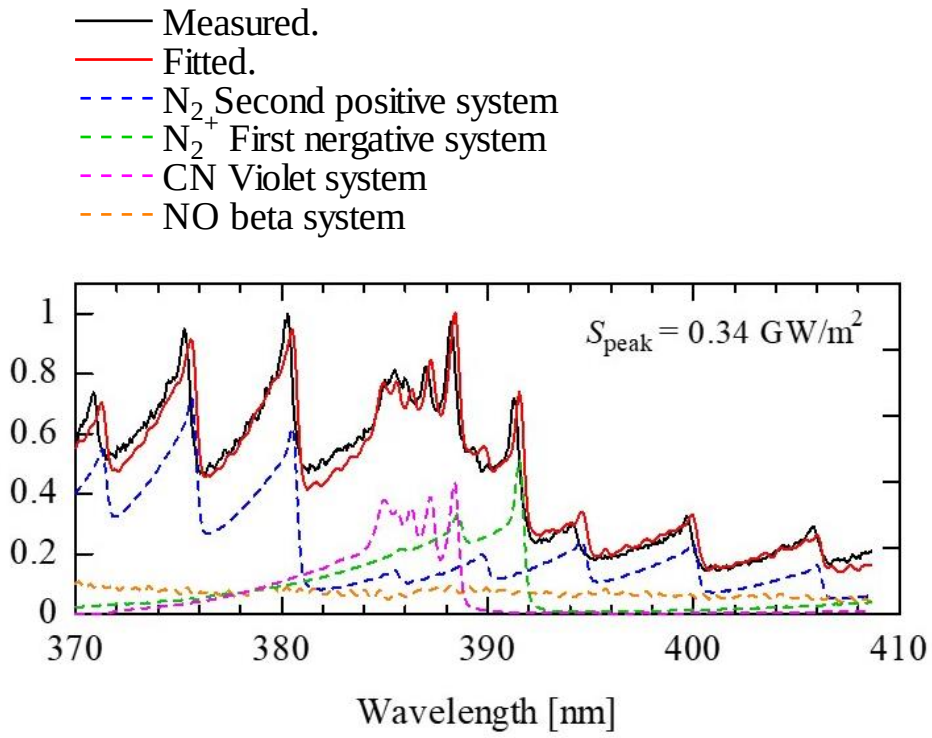
→ **Similar to microwave discharge**

- Excited temperatures of neutral particles were measured using optical emission spectroscopy.

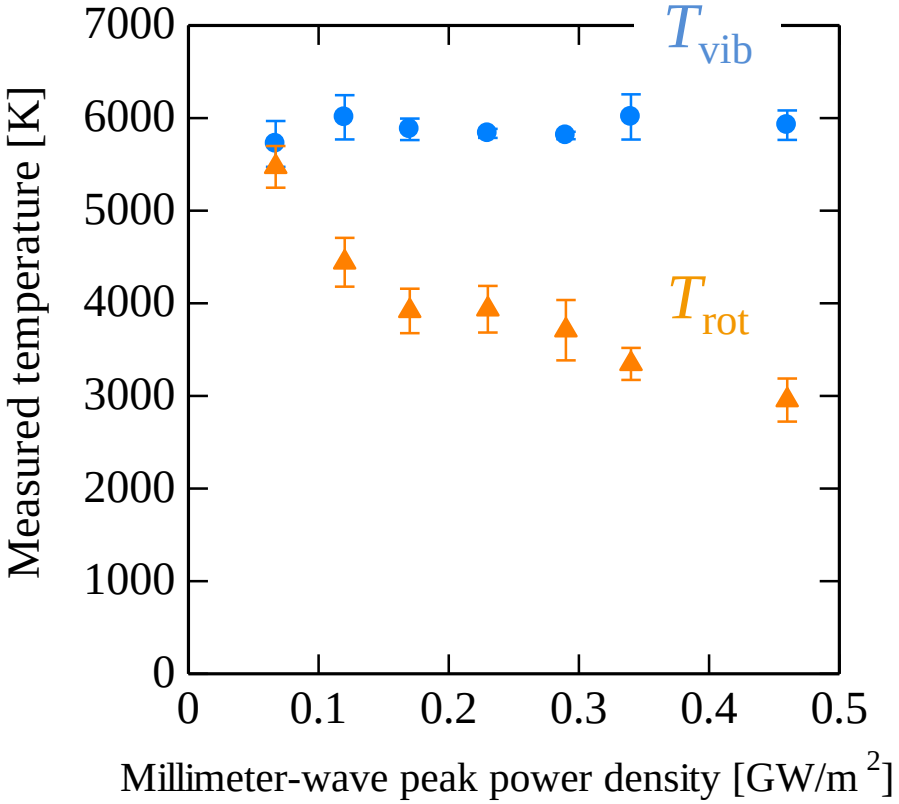
→ **Discharge mechanism below breakdown threshold** is becoming apparent. However, it's not been well understood.

→ **Future research will be carried out in detail using the UT gyrotron.**

Measured temperatures in 28 GHz



Measured emission spectrum and fitting result.

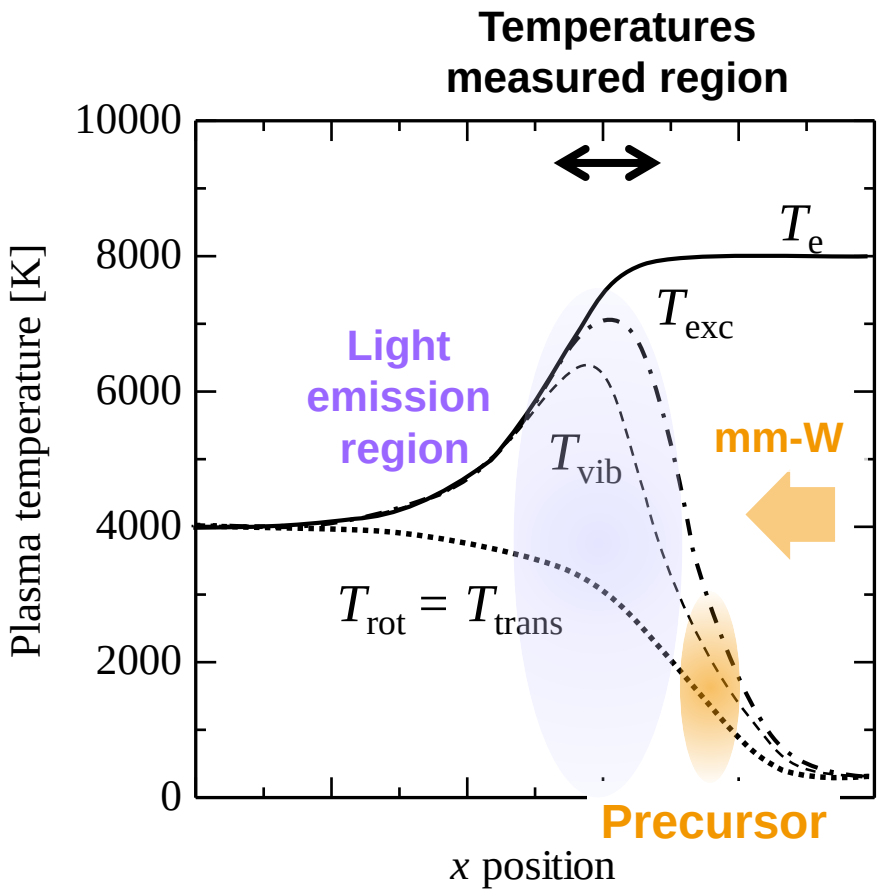


Measured T_{vib} and T_{rot} of N_2 in bulk plasma region.

K. Tabata, thesis for master degree, the University of Tokyo, 2019.

Predicted thermal structure in 28 GHz

Example: S_{beam} = 0.45 GW/m^2, Velocity = 550 m/s



Predicted thermal discharge in mm-W discharge.

In non-thermal plasma generated by external electric field,

$$T_e > T_{exc} > T_{vib}$$

↓

Neutral particles will be electronically excited.

↓

Discharge is possible in precursor by cumulative ionization from an excited state?

Summary

- Microwave Rocket utilizes air breakdown plasma using mm-W for its thrust generation.
- 94 GHz, 600 kW gyrotron is being developed at the University of Tokyo for Microwave Rocket researches.
- Air breakdown below breakdown threshold will be investigated in detail using the UT-gyrotron and numerical modeling of propagation velocity is supposed to be constructed.

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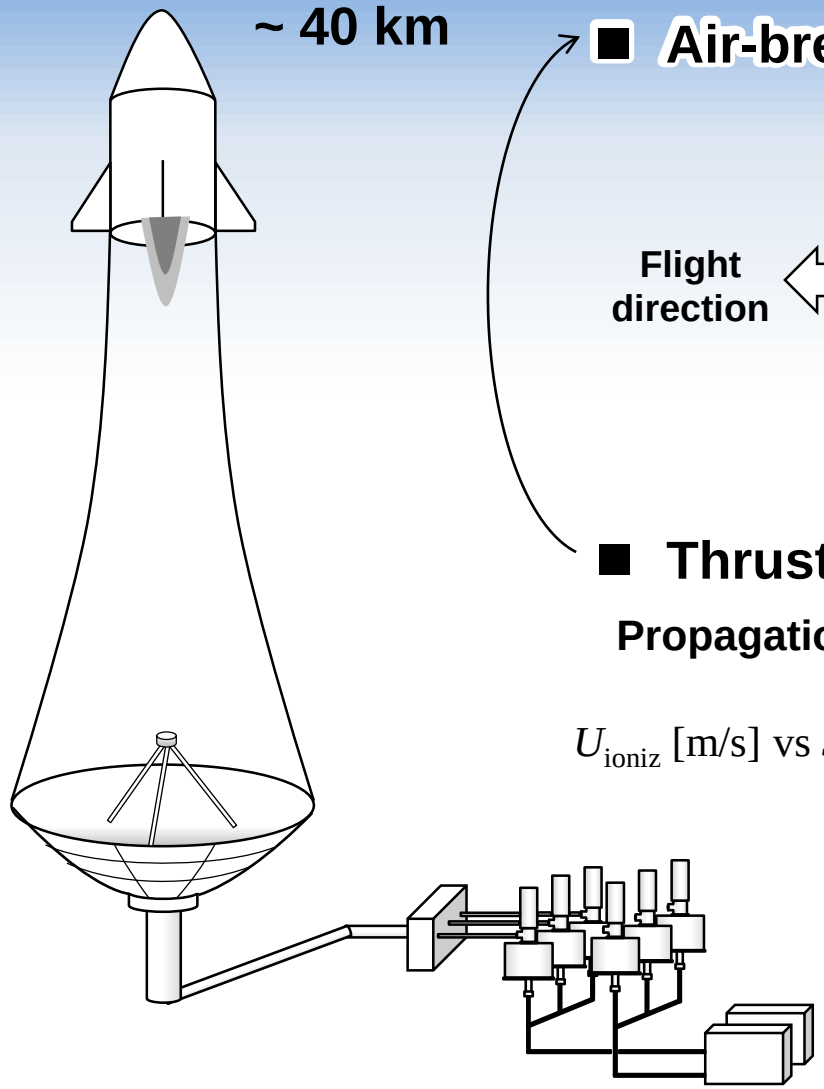
⇨ **Flight simulation of Microwave Rocket**

Flight simulation of Microwave Rocket

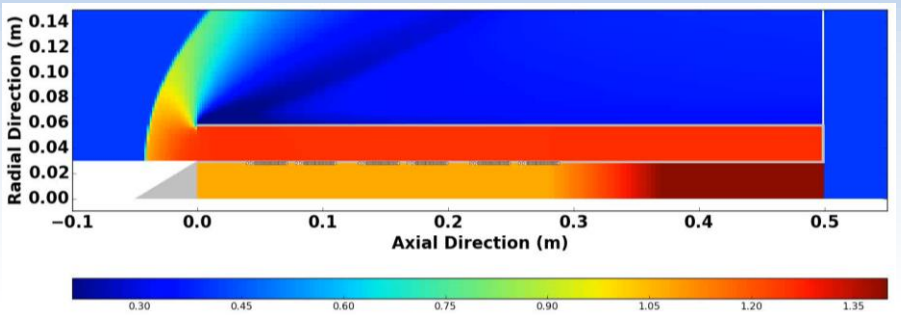


~ 40 km

1 GW class beam station

■ Air-breathing phase

Flight direction



Low density — High density

■ Thrust generation phase

Propagation velocity

$U_{\mathrm{ioniz}}\,[\mathrm{m/s}]$ vs $S_{\mathrm{beam}}\,[\mathrm{W/m^2}]$

Thrust force

$$E\,[\mathrm{J/m^3}] = \frac{S_{\mathrm{beam}}\,[\mathrm{W/m^2}]}{U_{\mathrm{ioniz}}\,[\mathrm{m/s}]}$$

Energy that air obtains

Thank you for your attention!
Give me any questions or comments.

Acknowledgements

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- Thank you for the collaborative research of Research Center for Development of Far-Infrared Region (Univ. of Fukui), QST and Plasma Research Center (Univ. of Tsukuba)