Role of Photon-Carrying Exited-Neutral-Particles on Ionization Front Propagating in Millimeter-Wave with Under-Critical Intensity

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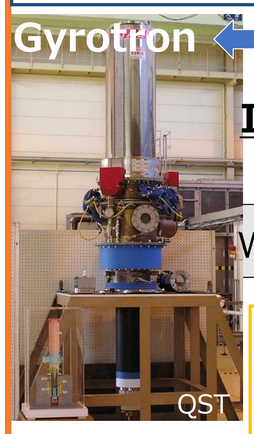
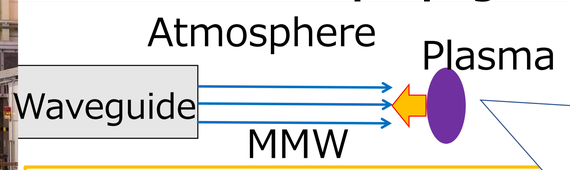
1.Background



High power millimeter wave (MMW) oscillator

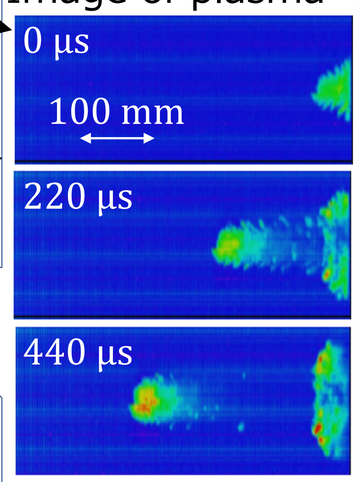
Ionization front propagation



Ionization front propagates from seed plasmoid toward the beam source.

Wavelength $\lambda = 1.76$ mm

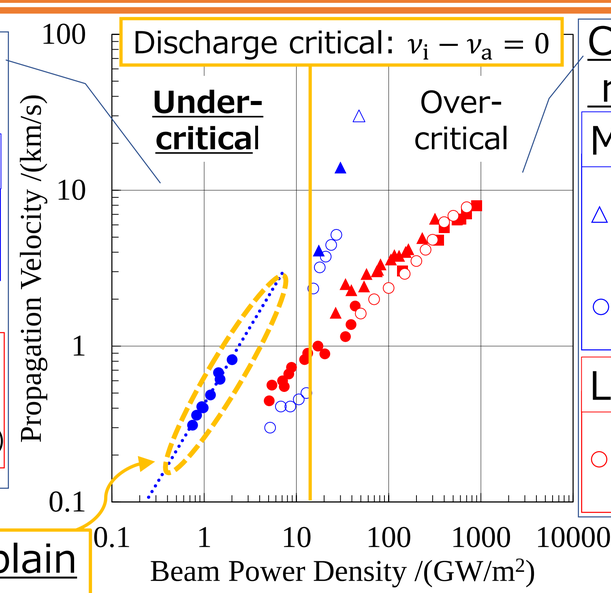
Image of plasma[1)]



Experimental results

Millimeter-wave
- Oda et al.[2)]
- Hidaka et al.[3)]

Laser
- Bufetov et al.[4)]
- Matsui et al.[5)]
- Bournot et al.[6)]



Computational results

Millimeter-wave
- Electron collision model[7)]
- Gas expansion model[8)]

Laser
- Gas compression model[9)]

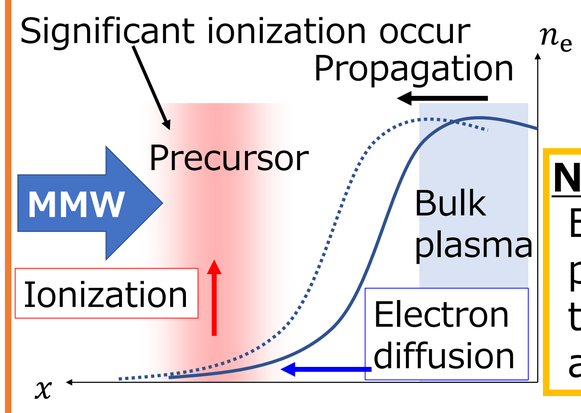
Propagation velocity of ionization front

No model can explain the propagation in this region.

Objective

Make a new model that can explain the ionization front propagation in the under-critical millimeter- wave.

2.Concept of New Model

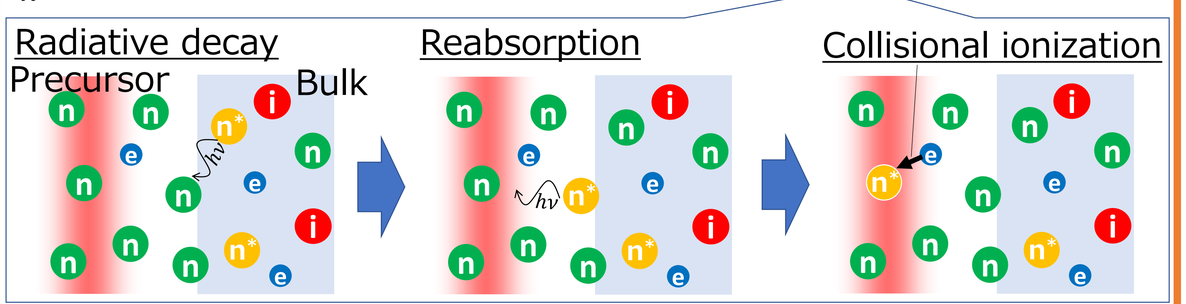


Ionization at the precursor region is important

That was under estimated in the previous models

New Hypothesis

Electronically excited neutral particles are carried by photons to the precursor region and induce ionization.



Assumption

- Nitrogen is the main component.
- Effects of collisions between heavy particles are negligibly small.
- Electron energy and vibrational excitation energy obey Boltzmann distribution.
- Electronically excited species except ground state obey Boltzmann distribution at bulk temperature.

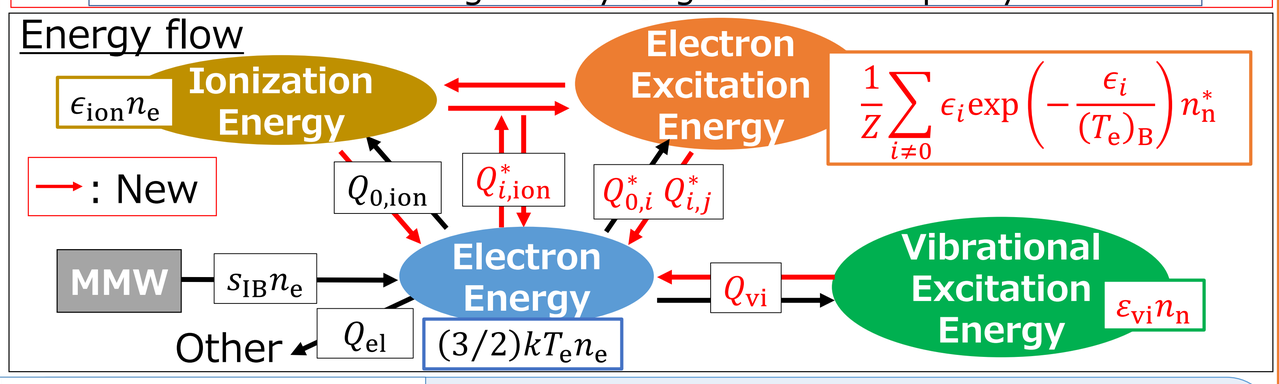
For number density of electronically excited species i

$$n_{n,i}^* = \frac{1}{Z}\exp\left(-\frac{\epsilon_i}{(T_e)_{bulk}}\right) n_n^* \qquad Z \equiv \sum_{i\neq 0} \epsilon_i \exp\left(-\frac{\epsilon_i}{(T_e)_B}\right) \qquad n_n^* \equiv \sum_n n_{n,i}^*$$

$(T_e)_{bulk}$: Electron temperature T_e at the bulk

* Degeneracy is ignored for simplicity

Energy flow



3.Basic Equations

Red: Equation added in this study
Orange: Equation changed in this study

Solve MMW

Maxwell's eq.

$$\nabla \times \boldsymbol{E} = -\mu_0 \frac{\partial \boldsymbol{H}}{\partial t}$$

$$\nabla \times \boldsymbol{H} = \varepsilon_0 \frac{\partial \boldsymbol{E}}{\partial t} + \boldsymbol{J}_e$$

Motion eq. of electrons

$$\frac{d\boldsymbol{J}_e}{dt} = \frac{e^2 n_e}{m_e}\boldsymbol{E} - \nu_m \boldsymbol{J}_e$$

Solve time evolution

Diffusion eq. of electrons

$$\frac{\partial n_e}{\partial t} - D_{eff}\nabla^2 n_e = f_i n_e$$

Diffusion eq. of exited species

$$\frac{\partial n_n^*}{\partial t} - D_{ex}\nabla^2 n_n^* = S^*$$

Vibrational excitation energy conservation eq.

$$n_h \frac{\partial T_{vi}}{\partial t} = Q_{vi}$$

Solve energy balance

Electron energy conservation eq.

$$\frac{3}{2} n_e k T_e \left(\nu_i + n_e {}^2 r_{3B}\right) = s_{IB} n_e - Q_{0,ion} - Q_{0,i}^* - Q_{i,ion}^* - Q_{i,j}^* - Q_{vi} - Q_{el}$$

Excitation energy conservation eq. ⇒ $Q_{i,j}^* = \frac{1}{Z}\sum_{n\neq 0} \epsilon_n \exp\left(-\frac{\epsilon_n}{(T_e)_B}\right) S^* - Q_{0,i}^* - Q_{i,ion}^*$

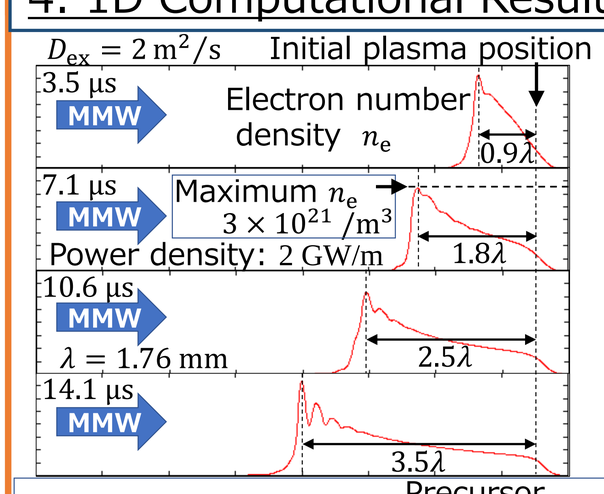
Optically thick assumption

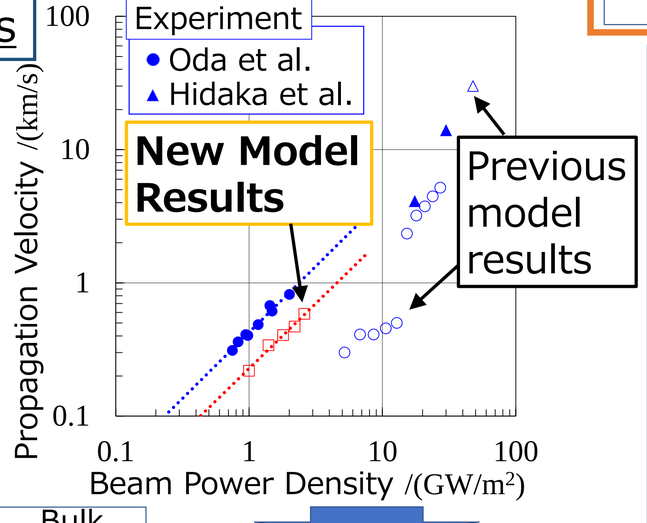
$$D_{ex} = \frac{1}{3}\frac{l_r^2}{\tau_r} \quad \sim 1\ \mathrm{m^2/s}$$

$\tau_r \sim 10^{-10}$ s : Radiative decay time scale of excited species

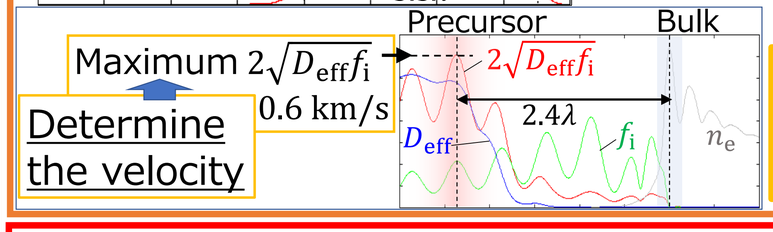
$l_r \sim 10^{-5}$ m : Mean free path of photon

4. 1D Computational Results





Computational velocities were 50% to 60% of experimental value



Allocation of incident beam energy

Radiative energy flux from excited neutral particles are 2.4% at maximum

Breakdown of absorption
- Vibrational excitation 86%
- Electron excitation & Ionization 10%

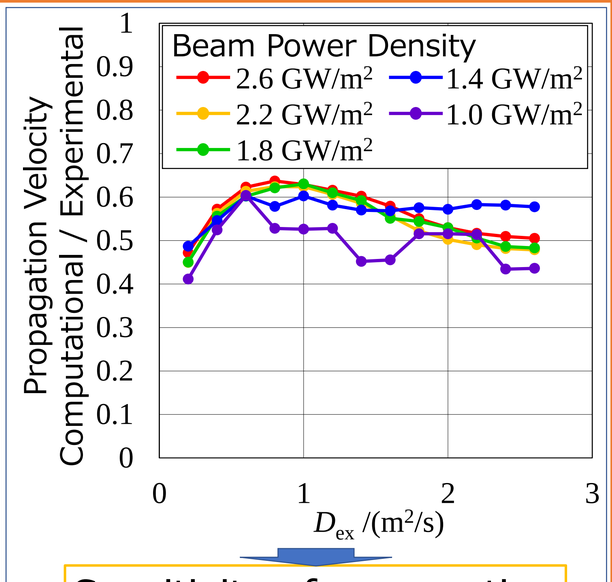
Absorption 96%

Incident beam Energy 100 %

Reflection 4%

Transmission 0%

Ionization front



Sensitivity of propagation velocity to D_{ex} is low

Conclusion

- New propagation mechanism considering **excited neutral particles** and **photon excitations** was proposed.
- This propagation mechanism was simply modeled using optically thick approximation and 1D computation was conducted.
- The trend of computational propagation velocity shows good agreement with that of experiment.

Reference

1) Y. Oda et al., *Journal of Applied Physics* 100, 113307 (2006).
2) Y. Oda et al., *Japanese Journal of Applied Physics* 48, 116001 (2009).
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4) I. A. Bufetov et al., *JETP Lett.* 39, 258 (1987).
5) K. Matsui et al., *Vacuum*, 171(2016).
6) P. Bournot et al., *Acta Astronautica* 6, 257 (1979).
7) J. P. Boeuf et al., *Physical Review Letter* 104, 015002 (2010).
8) M. Takahashi et al., *AIP Advances* 7, 055206 (2017).
9) H. Katsurayama et al., *Frontier of Applied Plasma Technology* 7(2), 83 (2014).