Breakdown Analysis of Tokamak by Collisional Ionization Model

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Background and Objective

Investigation of breakdown phenomena
in the strong magnetic field with toroidal configuration

- Collisional Ionization ← Cross Section Data
- Influence of Error Fields by Eddy Currents

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Axisymmetric Code

- Maxwellian
- Shifted-Maxwellian

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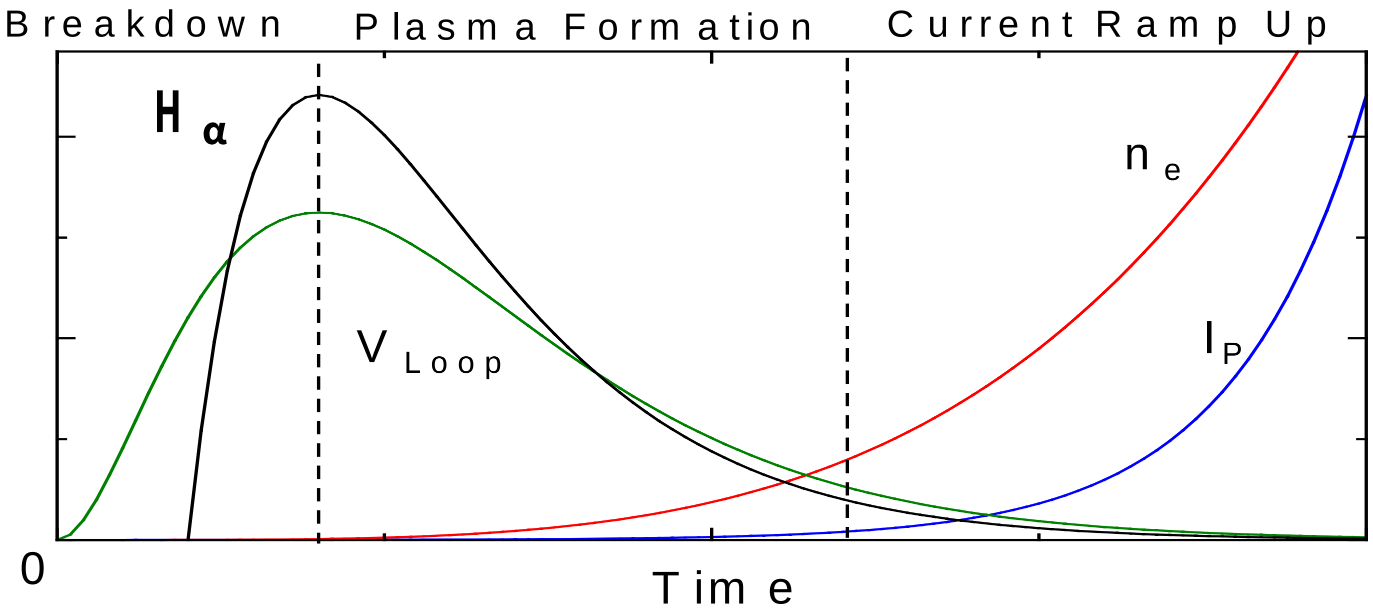
Breakdown Condition → Reduction of Power Supply

The maximum voltage occurs at the breakdown phase.

Breakdown and Plasma Formation



- *Breakdown*
  - Electron-neutral gas collisions are dominant (Avalanche model by Townsend)
- *Plasma Formation*
  - Electron-Ion collisions have to be considered including the thermal motion of electrons
  - Electromagnetic field by plasma current is negligible

Elementary Process

Table 1: Elementary processes in hydrogen plasmas

				Δw
1	$e+H$	$\rightarrow$	$2e+H^+$	13.6eV
2	$e+H$	$\rightarrow$	$e+H^*$	10.2eV
3	$e+H_2$	$\rightarrow$	$2e+H_2^+$	15.4eV
4	$e+H_2$	$\rightarrow$	$e+2H$	10.0eV
5	$e+H_2$	$\rightarrow$	$e+H+H^*$	14.9eV
6	$e+H_2$	$\rightarrow$	$e+H_2^{v1}$	0.5eV
7	$e+H_2$	$\rightarrow$	$e+H_2^{v2}$	1.0eV
8	$e+H_2$	$\rightarrow$	$e+H_2^b$	11.37eV
9	$e+H_2$	$\rightarrow$	$e+H_2^c$	11.7eV
10	$e+H_2^+$	$\rightarrow$	$2e+2H^+$	14.7eV
11	$e+H_2^+$	$\rightarrow$	$e+H+H^+$	2.4eV
12	$e+H_2^+$	$\rightarrow$	$e+H^*+H^+$	14.0eV
13	$e+H_2^+$	$\rightarrow$	$H+H^*$	0eV
14	$e+H_2$	$\rightarrow$	$e+H_2$	0eV
15	$e+H$	$\rightarrow$	$e+H$	0eV
16	$e+H_2^+$	$\rightarrow$	$e+H_2^+$	0eV
17	$e+H^+$	$\rightarrow$	$e+H^+$	0eV

Table 1: Elementary processes in helium plasmas

				Δw
1	$e+He$	$\rightarrow$	$2e+He^+$	24.6eV
2	$e+He^+$	$\rightarrow$	$2e+He^{2+}$	54.4eV
3	$e+He$	$\rightarrow$	$e+He^{1s2s1s}$	20eV
4	$e+He^{1s2s1s}$	$\rightarrow$	$2e+He^+$	4eV
5	$e+He$	$\rightarrow$	$e+He^{1s2p1p}$	20eV
6	$e+He^{1s2p1p}$	$\rightarrow$	$2e+He^+$	3.5eV
7	$e+He$	$\rightarrow$	$e+He^{1s2s3s}$	20eV
8	$e+He^{1s2s3s}$	$\rightarrow$	$2e+He^+$	5eV
9	$e+He$	$\rightarrow$	$e+He^{1s2p3p}$	20eV
10	$e+He^{1s2p3p}$	$\rightarrow$	$2e+He^+$	3.8eV
11	$e+He^{1s2s3s}$	$\rightarrow$	$e+He^{1s2s1s}$	0.8eV
12	$e+He^{1s2s3s}$	$\rightarrow$	$e+He^{1s2s1p}$	1.3eV
13	$e+He^{1s2s1s}$	$\rightarrow$	$e+He^{1s2p3p}$	0.35eV
14	$e+He^{1s2p3p}$	$\rightarrow$	$e+He^{1s2p1p}$	0.25eV
15	$e+He^{1s2s1s}$	$\rightarrow$	$e+He^{1s2p1p}$	0.6eV
16	$e+He^{1s2s3s}$	$\rightarrow$	$e+He^{1s2p3p}$	1.1eV
17	$e+He$	$\rightarrow$	$e+He$	0eV

Basic Equations

$$\frac{\partial n_e}{\partial t} + \nabla \cdot (n_e \mathbf{v}_d) = \alpha \mathbf{v}_d n_e$$

$$\alpha = \frac{\nu_I}{v_d}$$ Townsend Coefficient

$$e\mu \mathbf{v}_d = e(\boldsymbol{E} + \mathbf{v}_d \times \boldsymbol{B})$$ Drift Approximation

$$\mu = \frac{e}{m_e \nu_p}$$ Mobility

$$\frac{\partial \psi}{\partial t} + \oint \boldsymbol{E} \cdot d\boldsymbol{l} = V$$

$$E = \eta j = \frac{1}{e n_e \mu} j$$

$$\psi(x) = \int G(x, x') j_\varphi(x') d^2 x'$$

$$\frac{\partial n_e W_e}{\partial t} + \nabla \cdot (n_e W_e \mathbf{v}_d) = \boldsymbol{j} \cdot \boldsymbol{E} - n_e \sum_i \nu_i \Delta W_i$$

$$\frac{3}{2} k_B T_e = W_e - \frac{1}{2} m v_d^2$$

Shifted Maxwellian

$$\nu_i = n_{\text{target}} < \sigma_i \mathbf{v} > (T_e, v_d)$$

$$\nu_p = \sum_{i=\text{elastic}} \nu_i + \sum_{i \neq \text{elastic}} \frac{\Delta W_i}{W_e} \nu_i + \nu_I$$

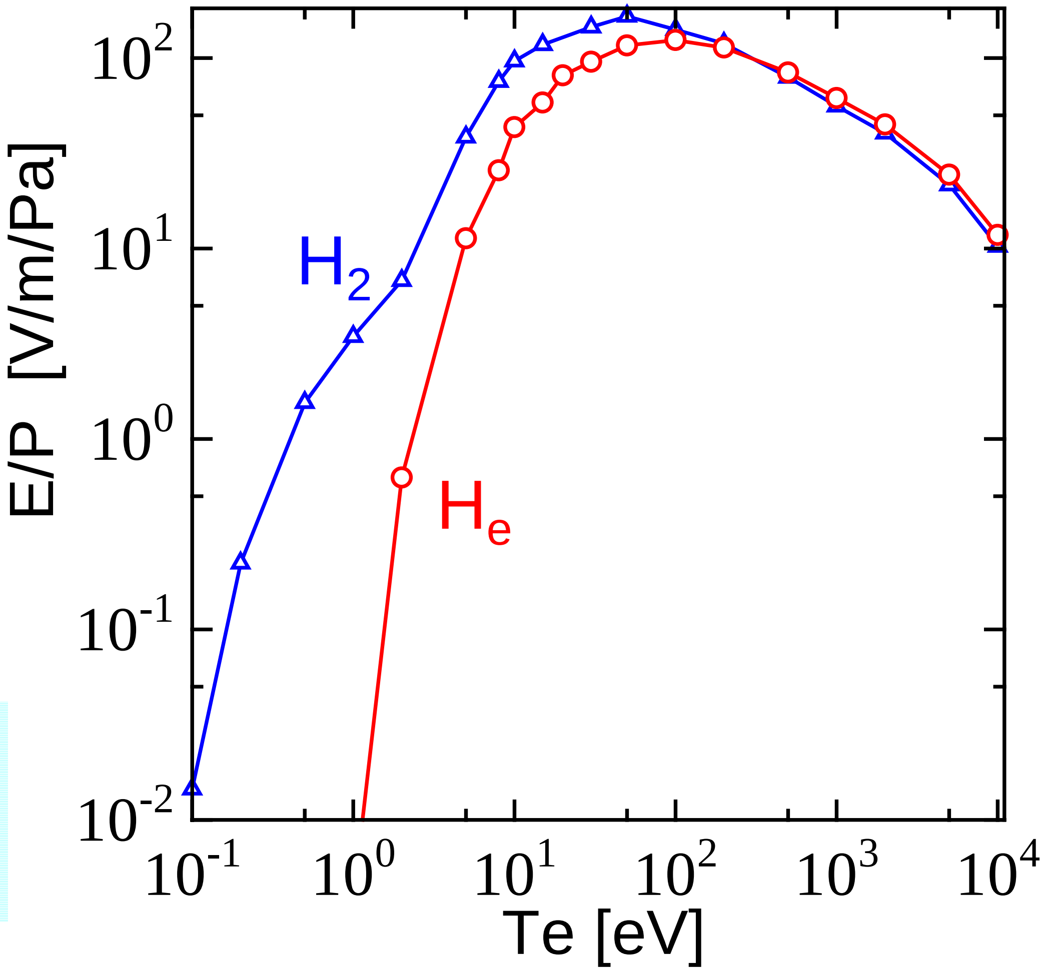
Static Model

It is assumed the energy of electrons is stationary.

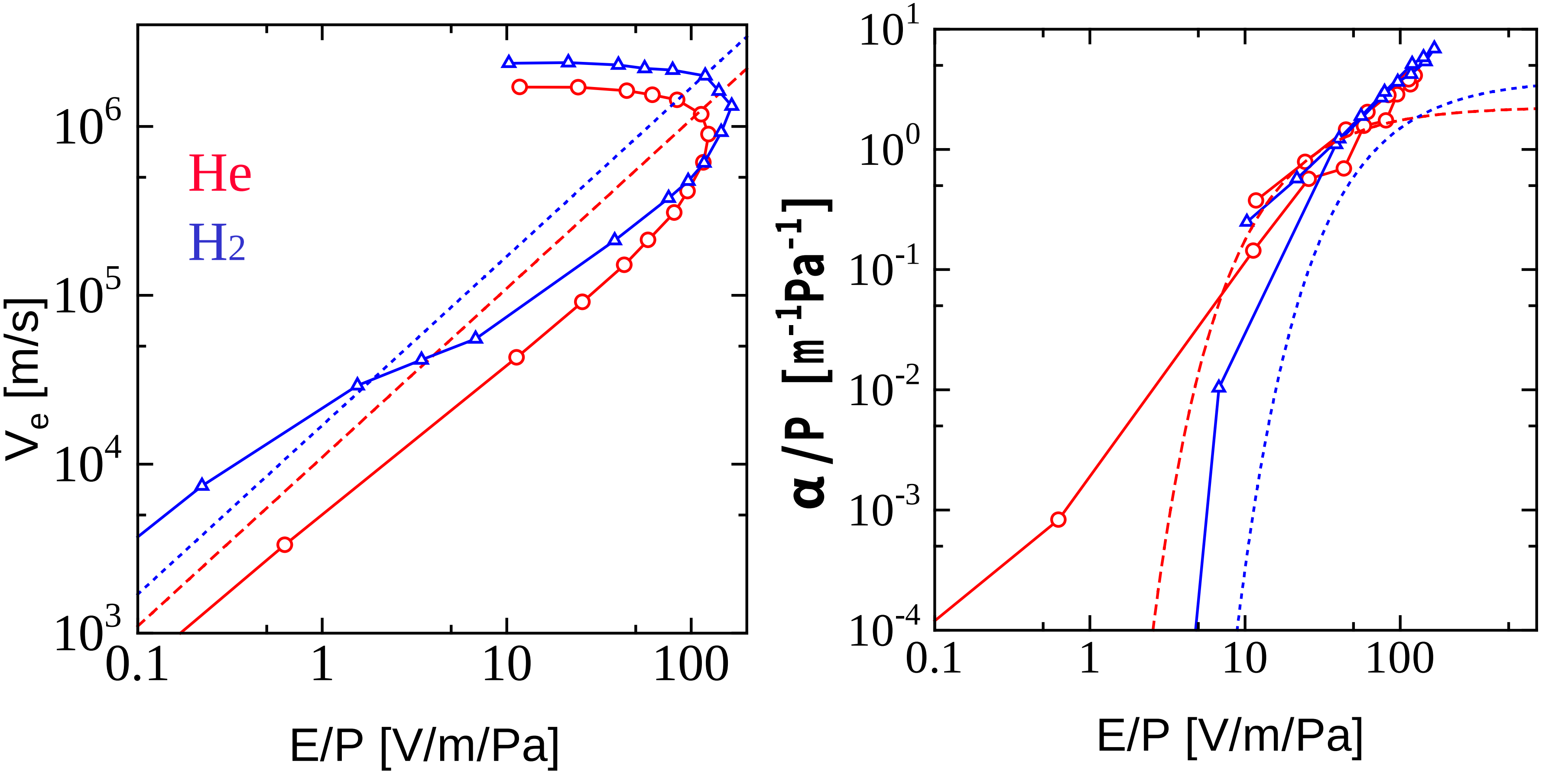
$$v_d = \mu E = \frac{e}{\nu_p m} E$$

$$\boldsymbol{j} \cdot \boldsymbol{E} = n_e \sum_i \nu_i \Delta W_i$$

$$E^2 = \frac{m}{e^2} \nu_p \sum_i \nu_i \Delta W_i$$



Dependence of *V*e, α on *E/P* in Static Model

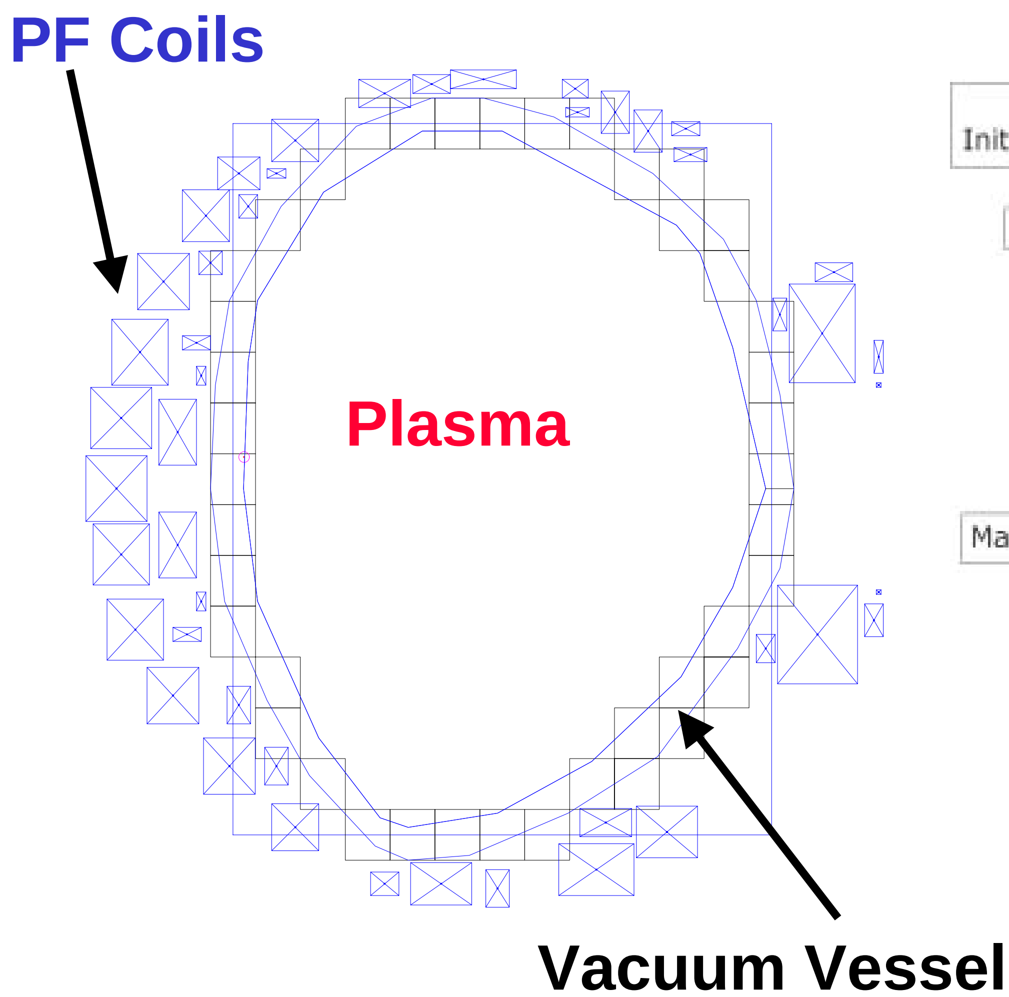


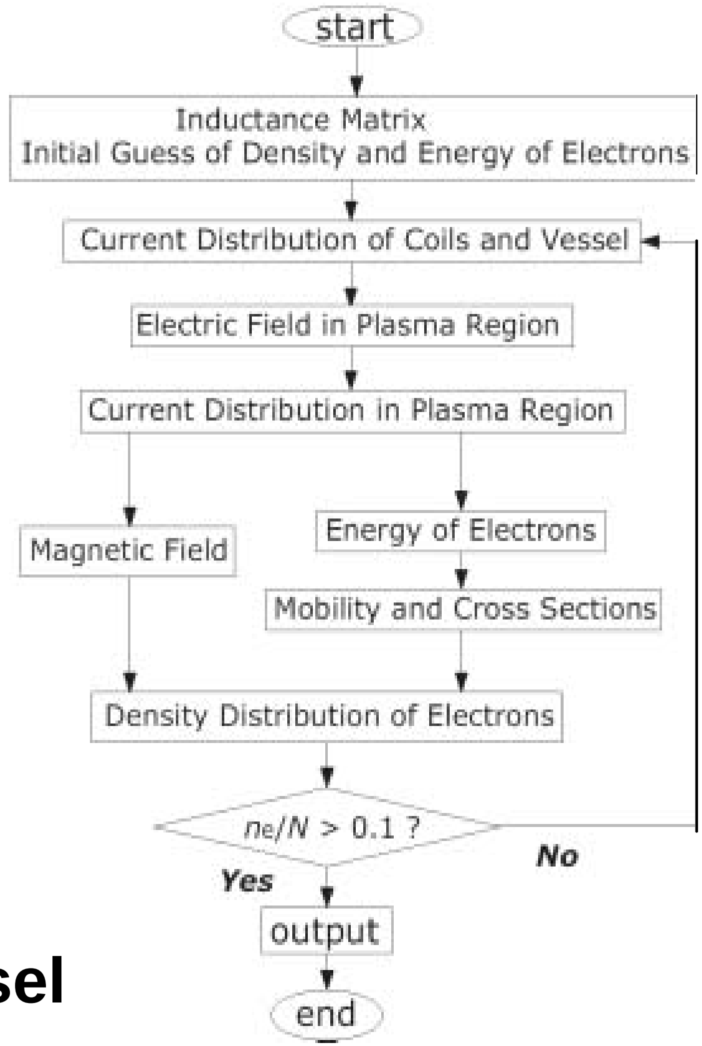
Solid Lines: Static Model

Dashed Lines: Experiments by electrodes

Numerical Model

Full 2D-Simulation without Static Model

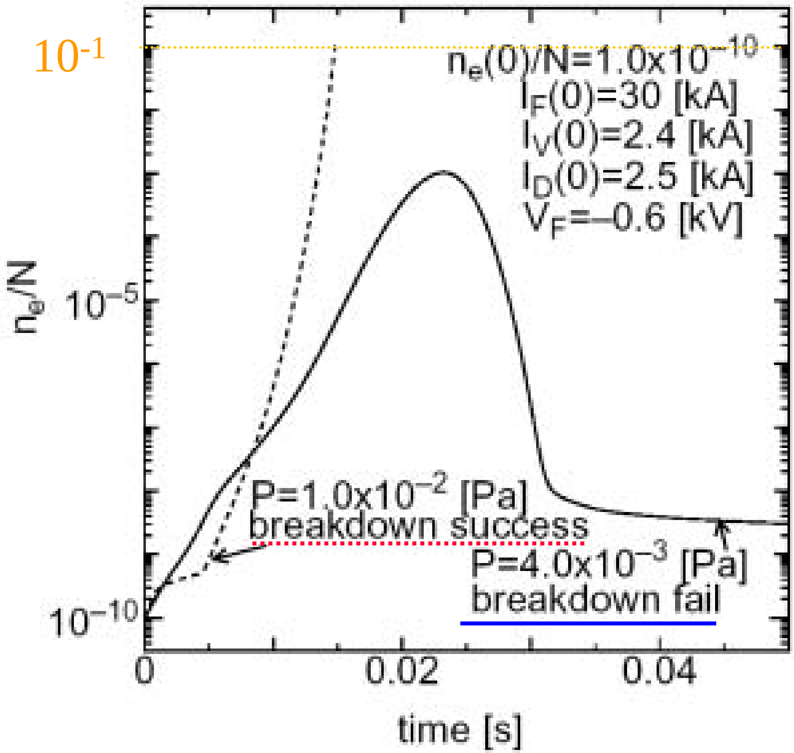




Parameters and Time Evolution

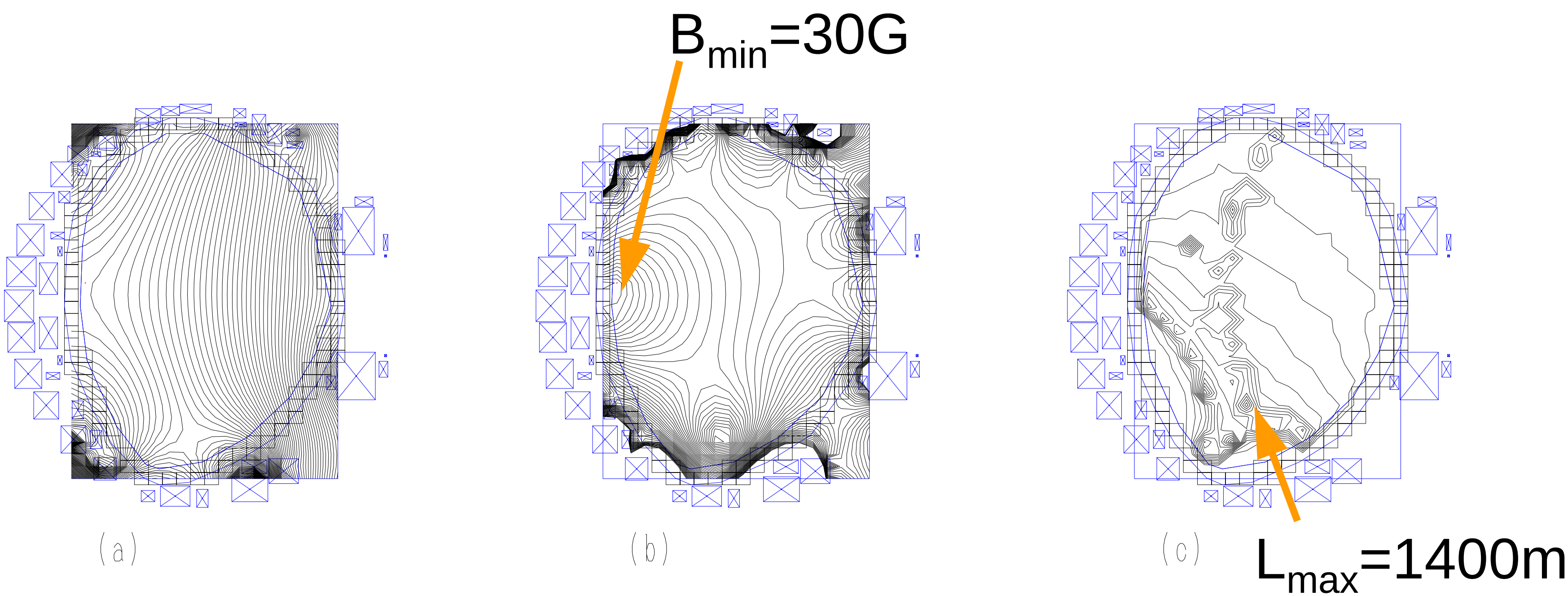
Parameters	Values
Toroidl Field at Center of Vessel	3.0 T
Major Radius of Vessel	3.32 m
Minor Radius of Vessel	1.7 m
Temperature of Neutral Gas	423 K
Resistance of Vessel	$1.60 \times 10^{-4}\ \Omega$
Decay Time of Current in Vessel	15 ms

determined from JT-60U



Breakdown condition is assumed to be **ionization degree > 0.1**

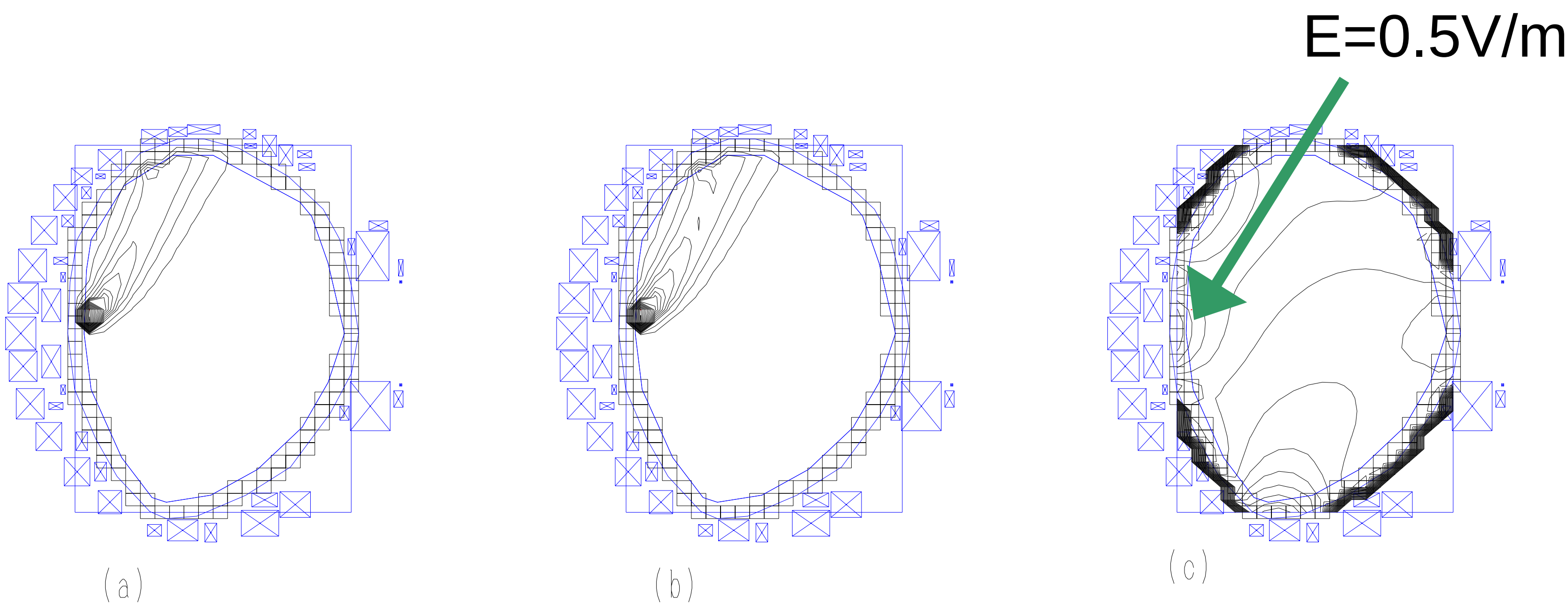
Magnetic Configurations at Breakdown



Poloidal Flux   Poloidal Field   Connection Length

The direction of electrons on the cross section is upward.

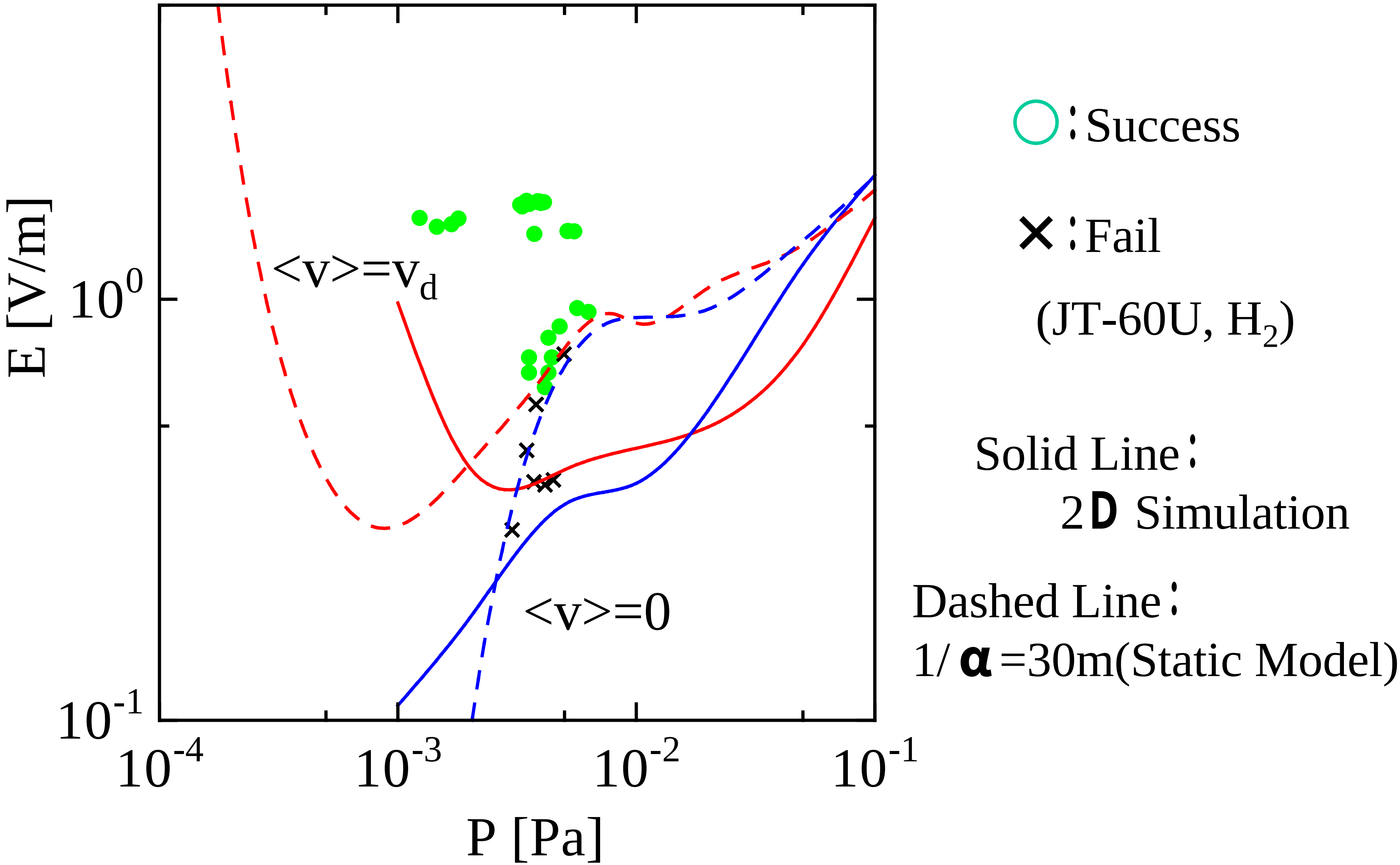
Configurations at Breakdown



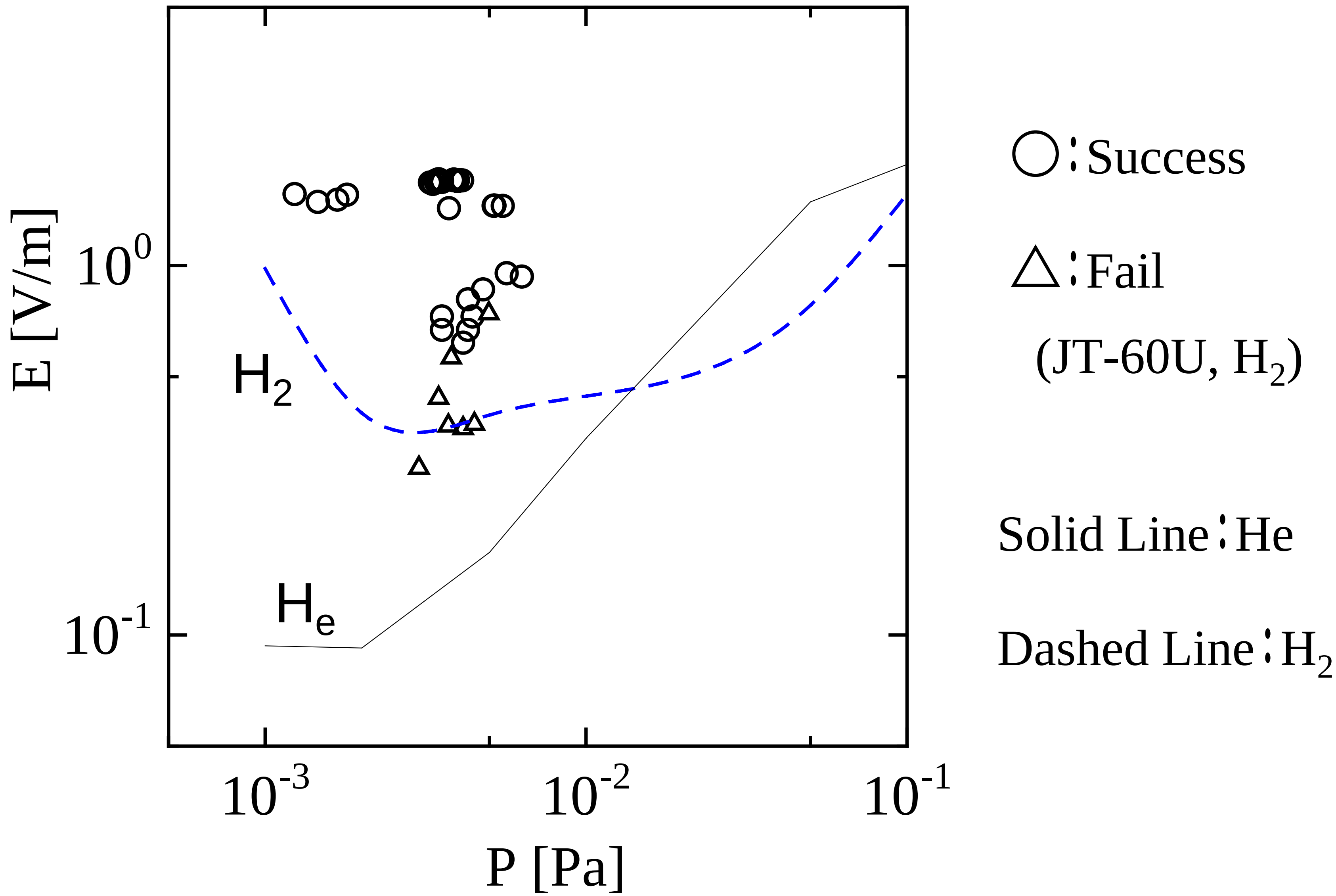
Electron Density   Current Density   Electric Field

The direction of electrons on the cross section is upward.

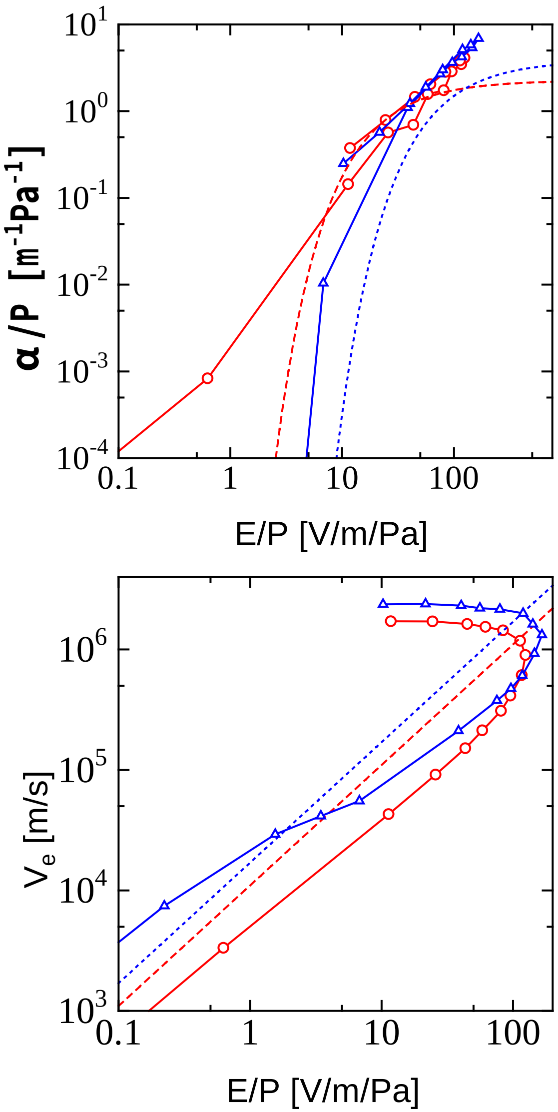
Breakdown Boundary (H_2)

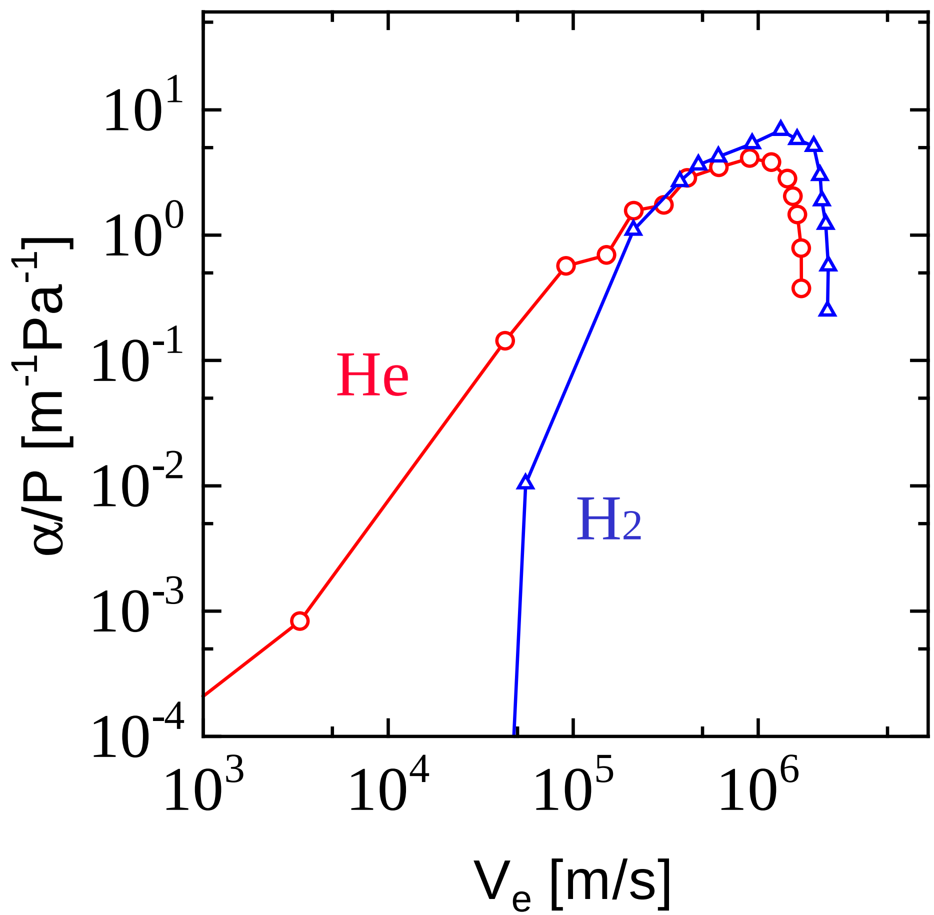


Breakdown Boundary (H_2, He)



Relations of *V*e and α in static model





In the low velocity,

He has larger α than that of H_2

Conclusions

- We made a 2D breakdown code which includes all electromagnetic fields and cross sections depending on the electron energy.
- Qualitative agreements between simulations and experiments in JT-60U were obtained by the use of shifted-Maxwellian distribution.
- The breakdown voltage of helium was calculated to be lower than that of hydrogen. It is qualitatively explained by the static model.

Dependence to Initial Ionization Degree