JFT-2M

Plasma Breakdown Analysis in JFT-2M without the Use of Center Solenoid

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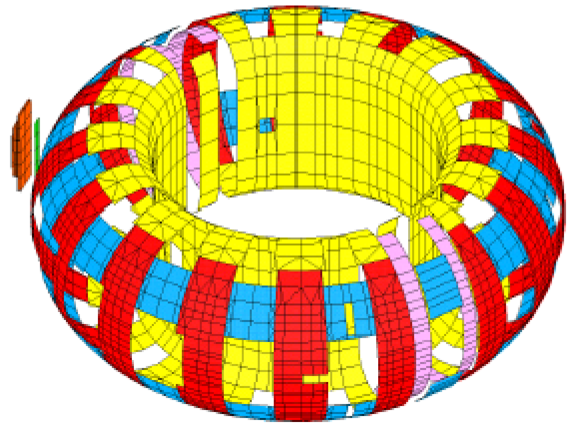
Introduction

In order to demonstrate compatibility between the low activation ferritic steel (such as F82H) and plasma, JFT-2M performed the Advanced Material Tokamak EXperiment (AMTEX) program.



Thickness of FPs
■: 10.5mm, ■: 8mm,
■, ■: 6mm

- Measurements of permeability in a perpendicular direction of magnetic field
- Measurements of a breakdown characteristic (required loop voltage and neutral gas pressure) with the ferritic steel.
- A numerical investigation of the breakdown characteristic

Measurement of F82H Magnetization

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- **In order to evaluate the equivalent permeability in a poloidal direction under a toroidal field,** magnetization of the ferritic steel is measured.

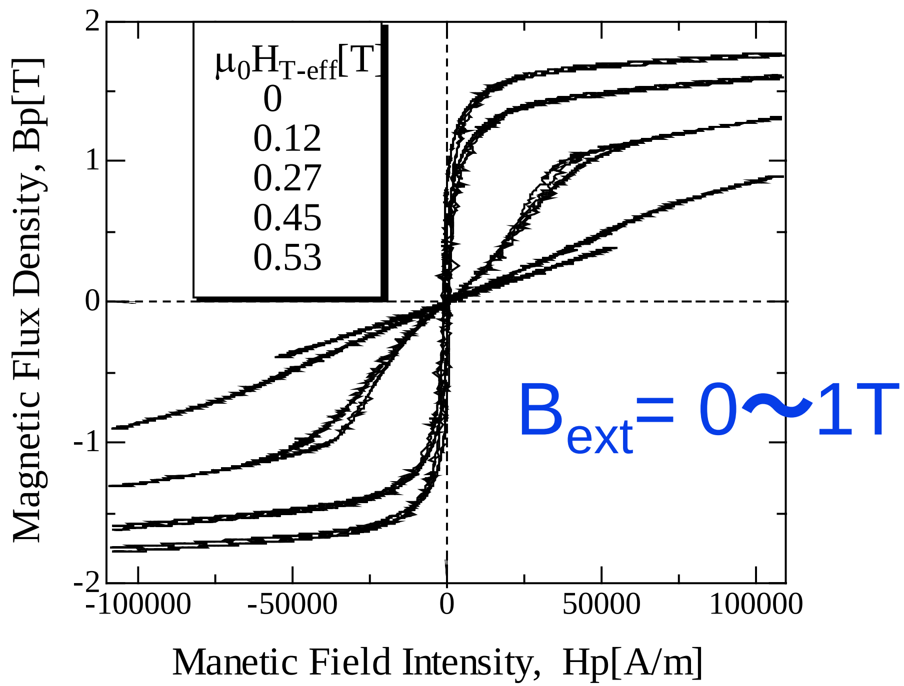
$$\boldsymbol{B} = \mu_0 \boldsymbol{H} + \boldsymbol{M}$$

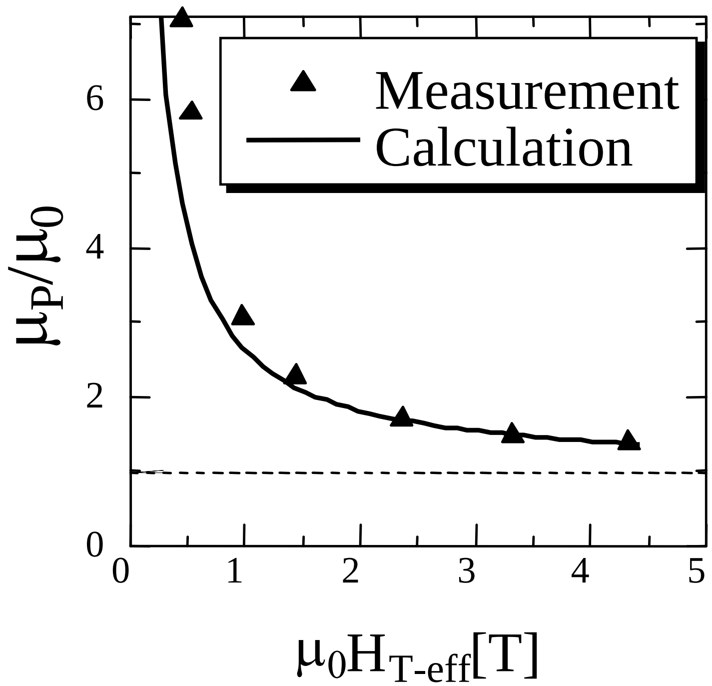
$$B_p = \left(\mu_0 + \frac{|\boldsymbol{M}(\boldsymbol{H})|}{|\boldsymbol{H}|}\right) H_p$$

Tokamak	Coil
Toroidal Field	Vertical Field(<5T)
Poloidal Field	Toroidal Field

Equivalent permeability μ_p

Measurement of Magnetization (Results)





- It was found that the **equivalent permeability** μ_p in the poloidal direction follows the theory.

Breakdown Experiment

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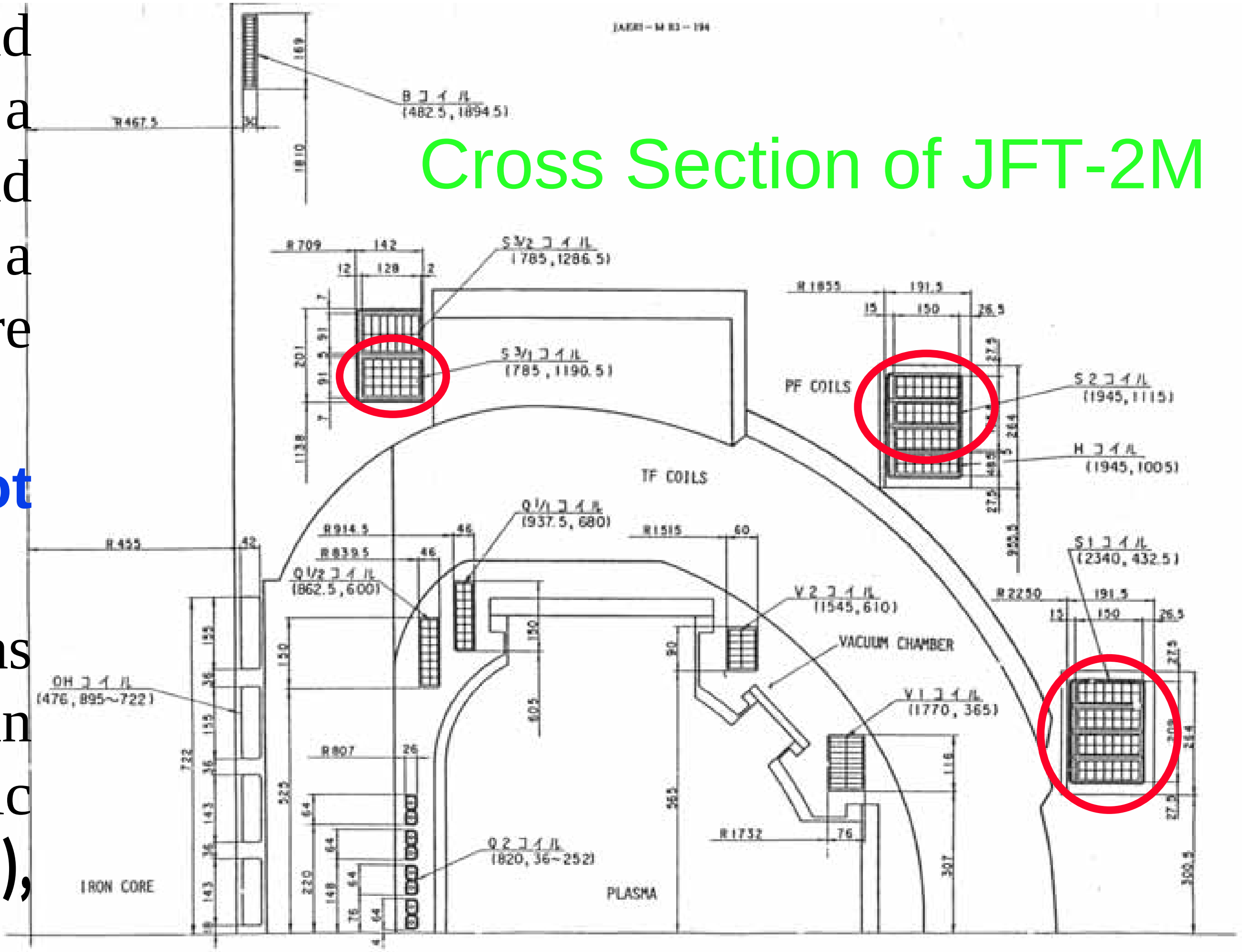
- Using only TF coils and **S coils**, relations of a neutral gas pressure and a required voltage for a breakdown were measured.
- **OH coil does not work !!**
- Toroidal field was changed to check an effect of the ferritic steel. (μ_{eff}=2.2(1.6T), 4.3(0.6T), 7.5(0.3T))



Cross Section of JFT-2M

第2.2-1図 JFT-2M ポロイダル断面図

Breakdown Experiment (Results)

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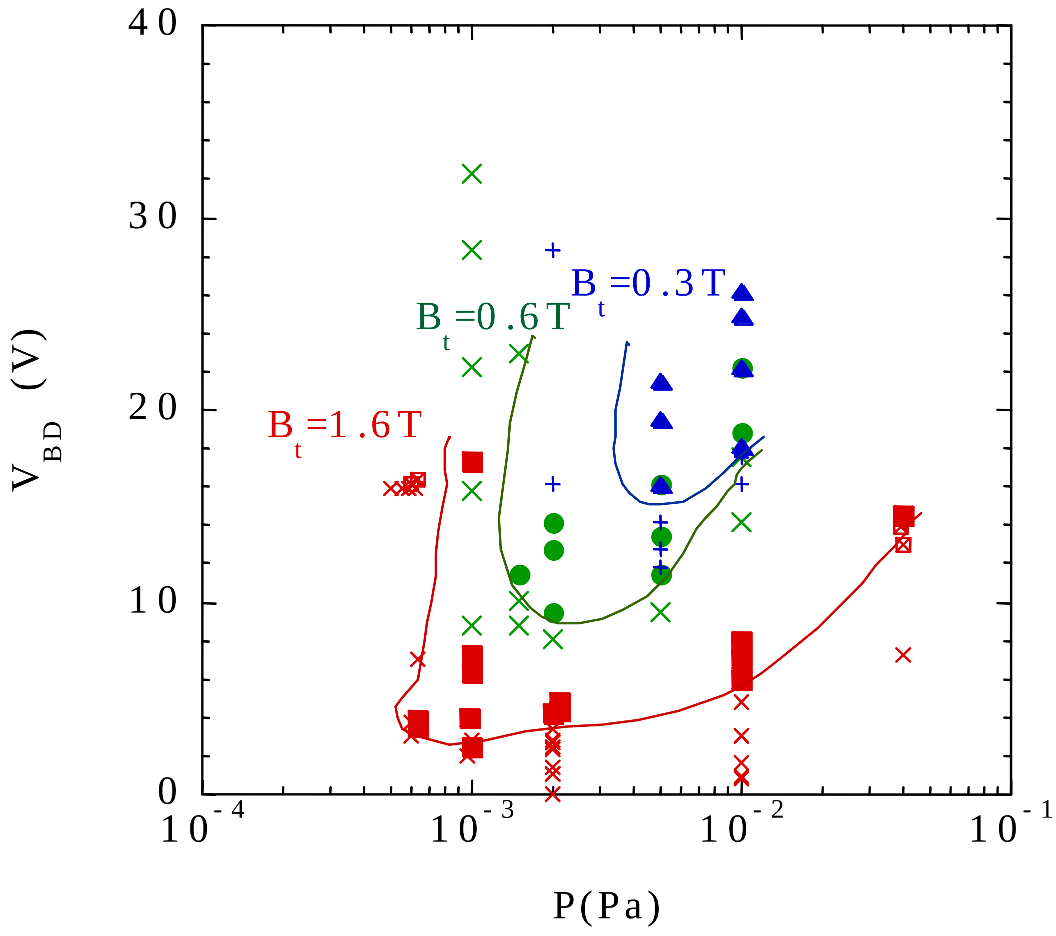
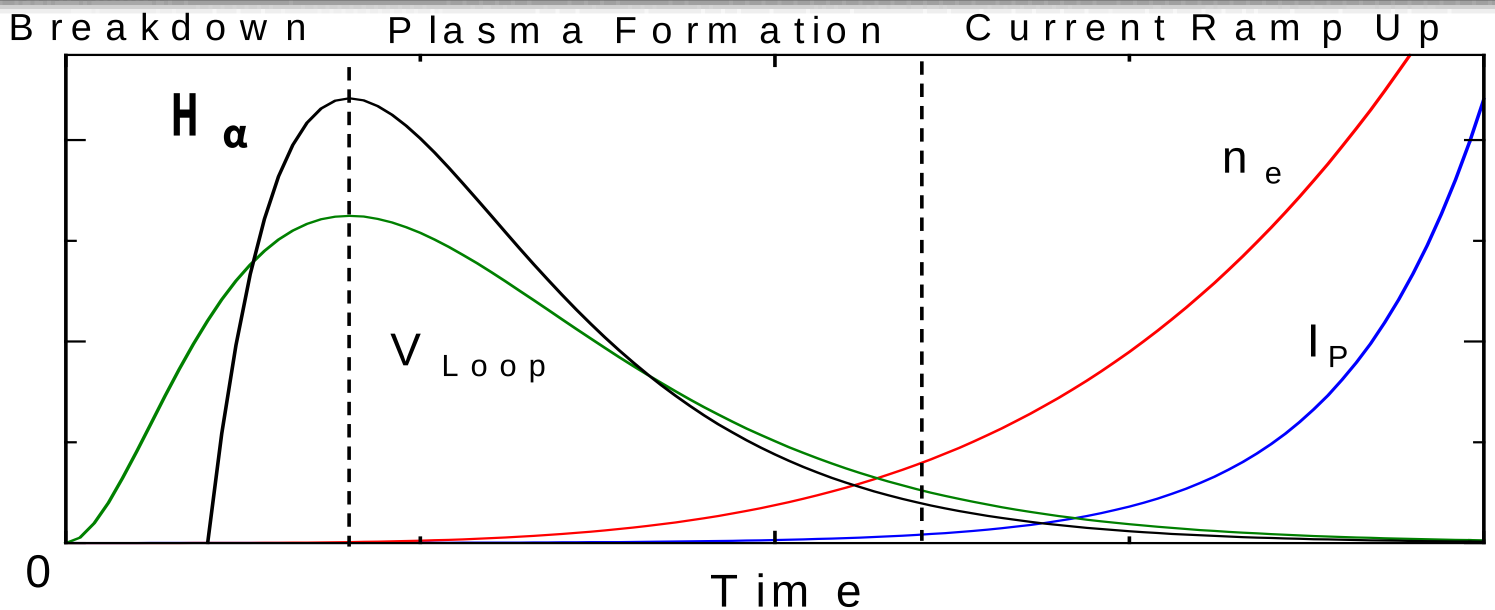
- Breakdown characteristics were measured aginst the toroidal field strengths of 1.6T , 0.6T, 0.3T. Succeeded and failed cases are marked with ■ and ✕ , respectively.
- The minimum neutral gas pressure required for breakdown exists. Under the pressure, the required voltage increases abruptly or a breakdown does not occur. This result qualitatively agrees with the experiments of JFT-2 and a conventional breakdown theory.



Breakdown and Plasma Formation



- ◆ ***Breakdown***
  - **Electron-neutral gas collisions are dominant (Avalanche model by Townsend)** ☆ionization<0.1
- ◆ ***Plasma Formation***
  - **Electron-Ion collisions have to be considered including the thermal motion of electrons**
  - **Electromagnetic field by plasma current is negligible**

Simulation

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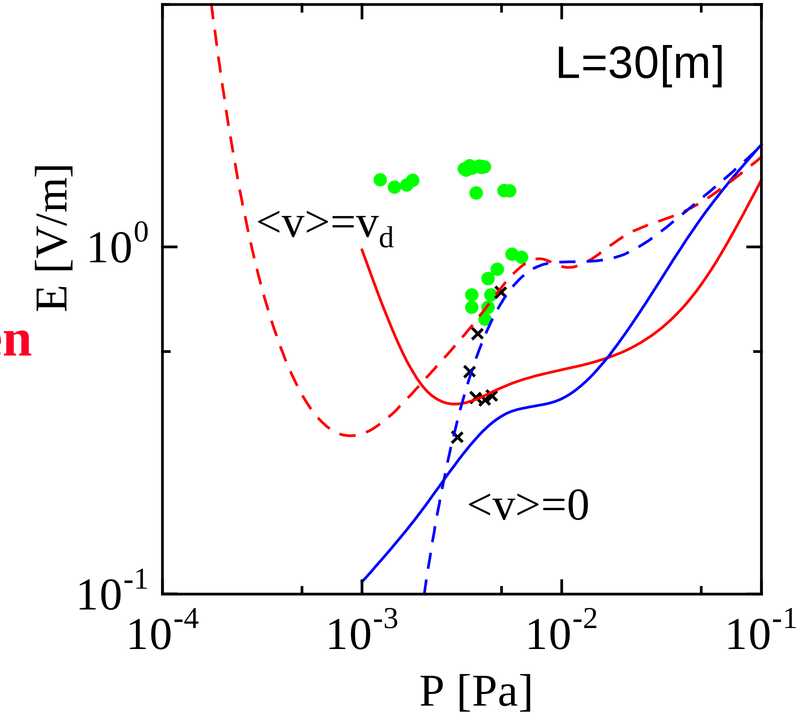
◆Collision Ionization Model

- **Elementary** collision **processes are considered.**
- Electron-neutral gas collisions are dominant (**when ionization >0.1, breakdown is succeeded.**)
- Electron-Ion collisions are included
- Electromagnetic field by plasma current is negligible



Application for JT-60U

◆A insulation in the toroidal direction is introduced.

◆An effect of iron core is included by a modification of inductance.

Basic Equations

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

$$\alpha = \frac{\nu_I}{\mathrm{v}_d}$$ **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**

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

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

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

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

$$\frac{3}{2} k_B T_e = W_e - \frac{1}{2} m \mathrm{v}_d^2$$

Shifted Maxwellian

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

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

Elementary Process

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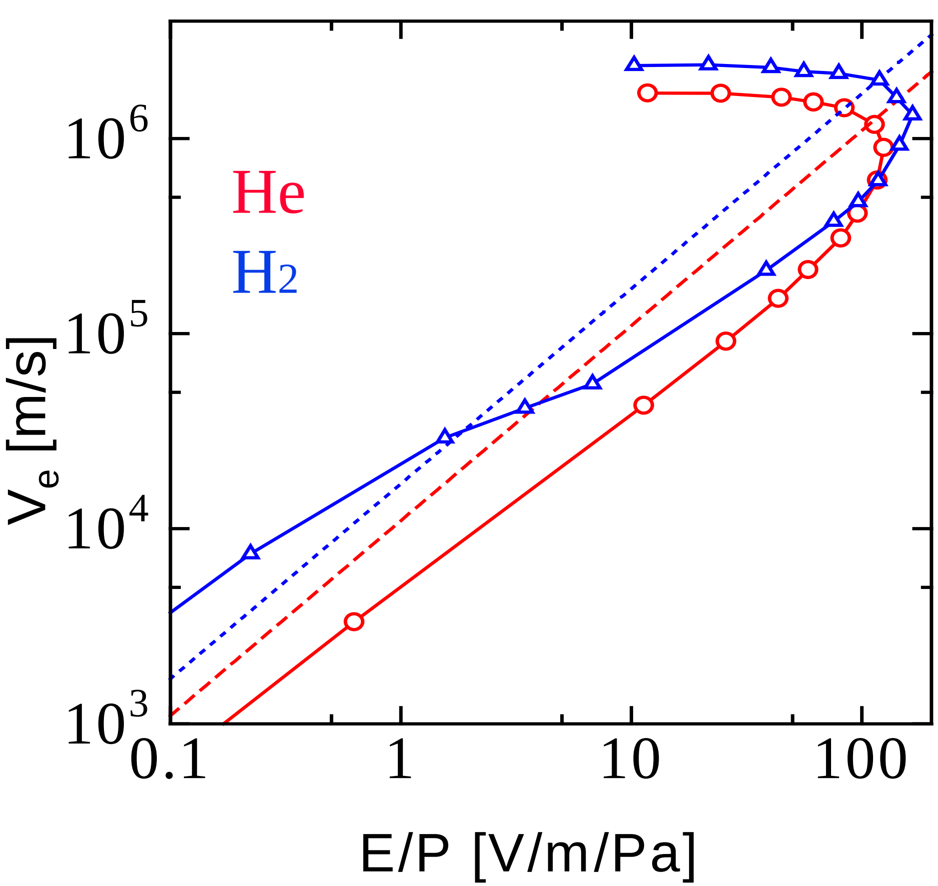
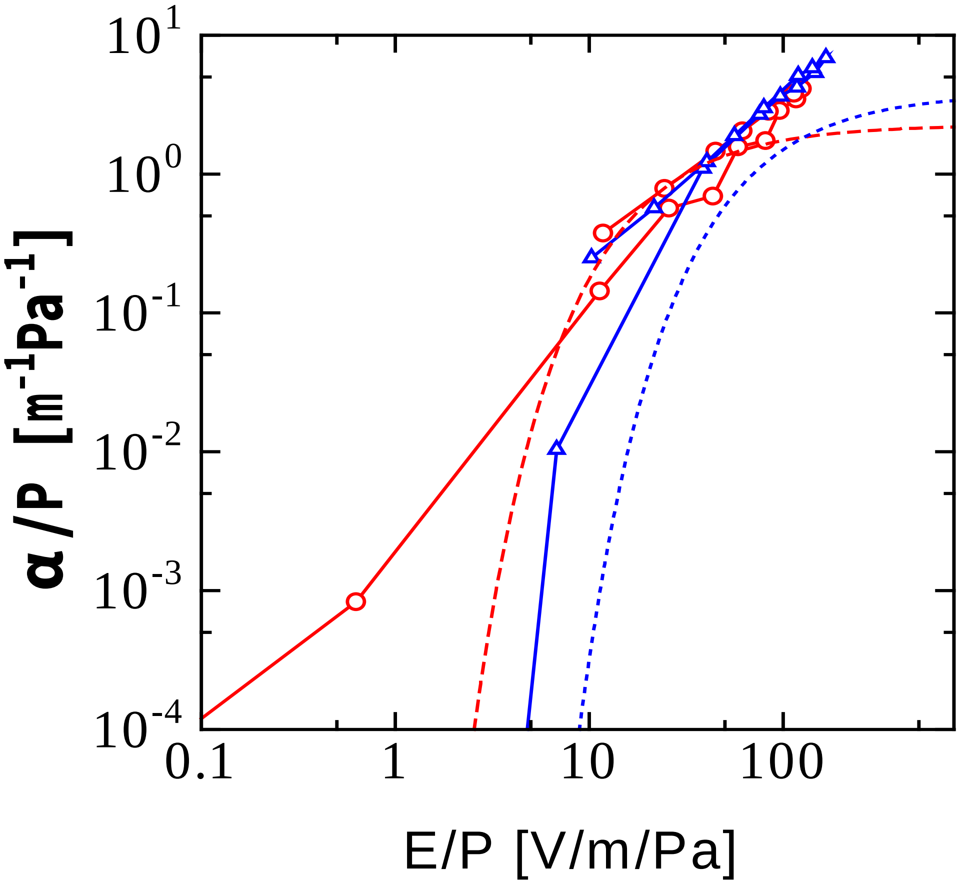
Table 1: Elementary processes in hydrogen plasmas

				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

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

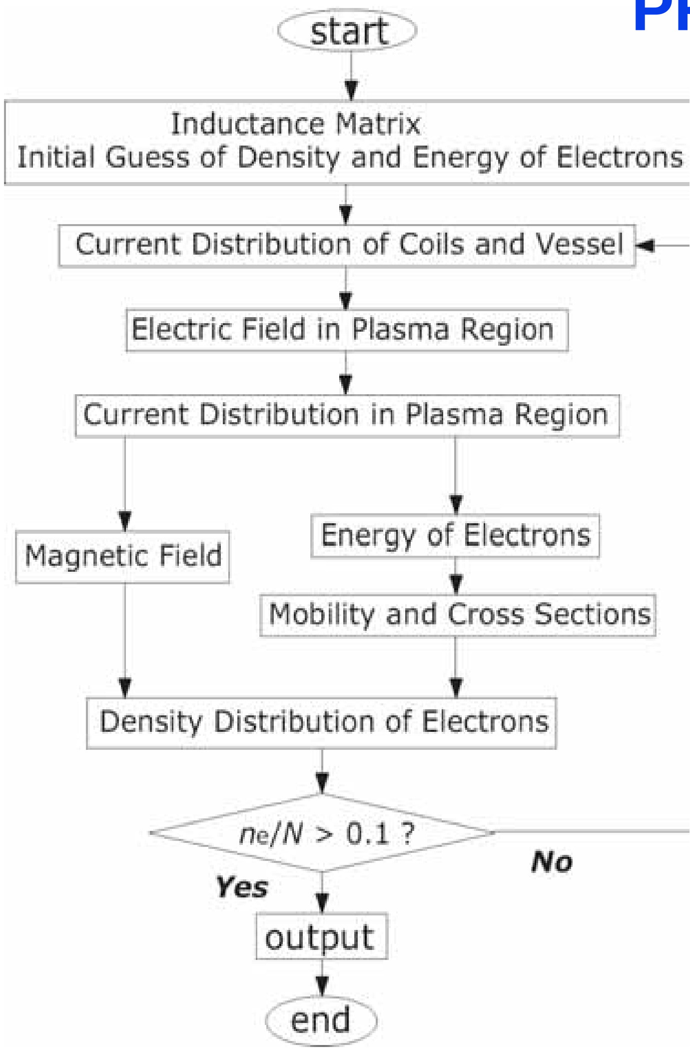


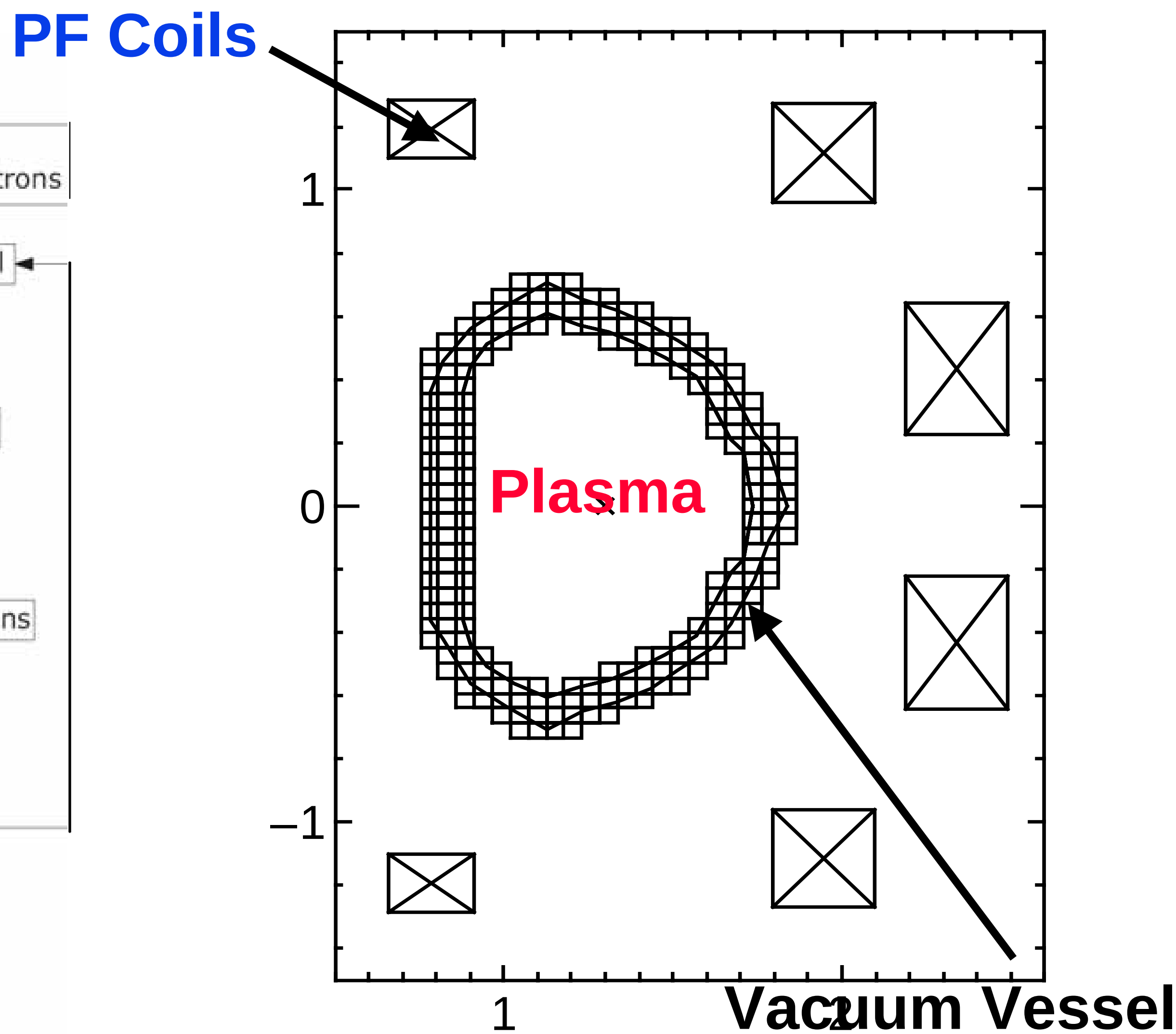


Solid Lines: Static Model

Dashed Lines: Experiments with electrodes

2-D Simulation Code

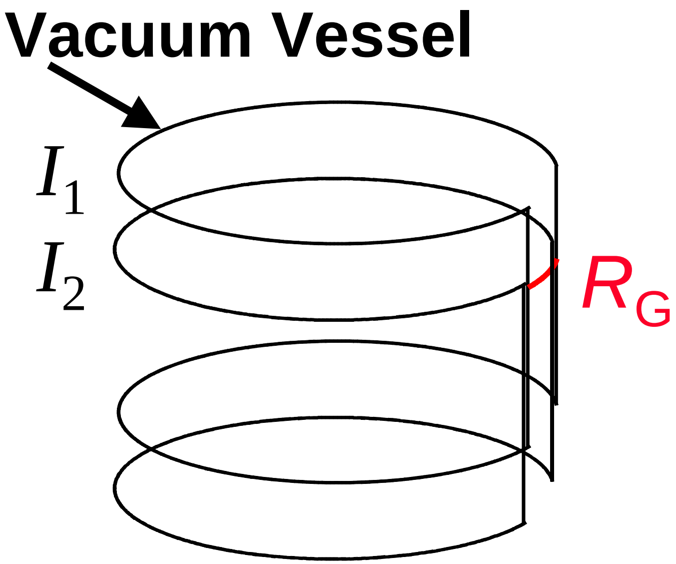




Insulation in the toroidal direction

- JFT-2M obtains a loop resistance by a toroidal insulation.

- In order to simulate the toroidal insulation, a gap resistance R_G is inserted among coils which simulate a vacuum vessel.



$$I_G = \sum_n I_n$$

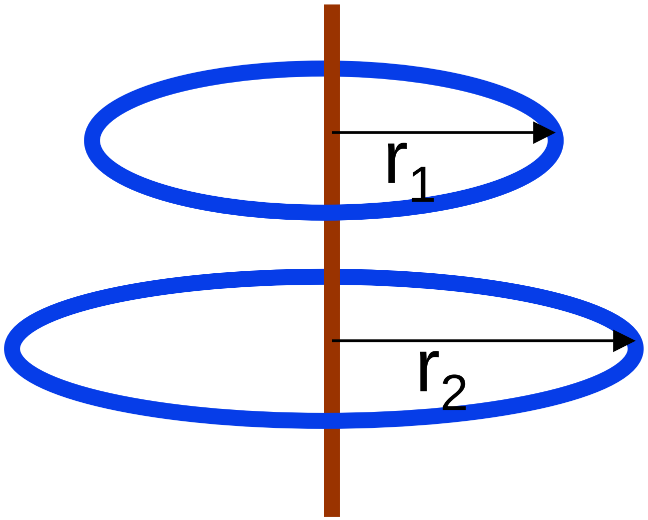
$$V_V = R_G I_G$$

Effect of Iron Core

- An iron core scarcely affects a poloidal field in a vacuum vessel.

- It is assumed that a **iron core**, which is sufficiently fine and long, exists on the Z axis.

- A inductance is modified to include a magnetic flux in the iron core.

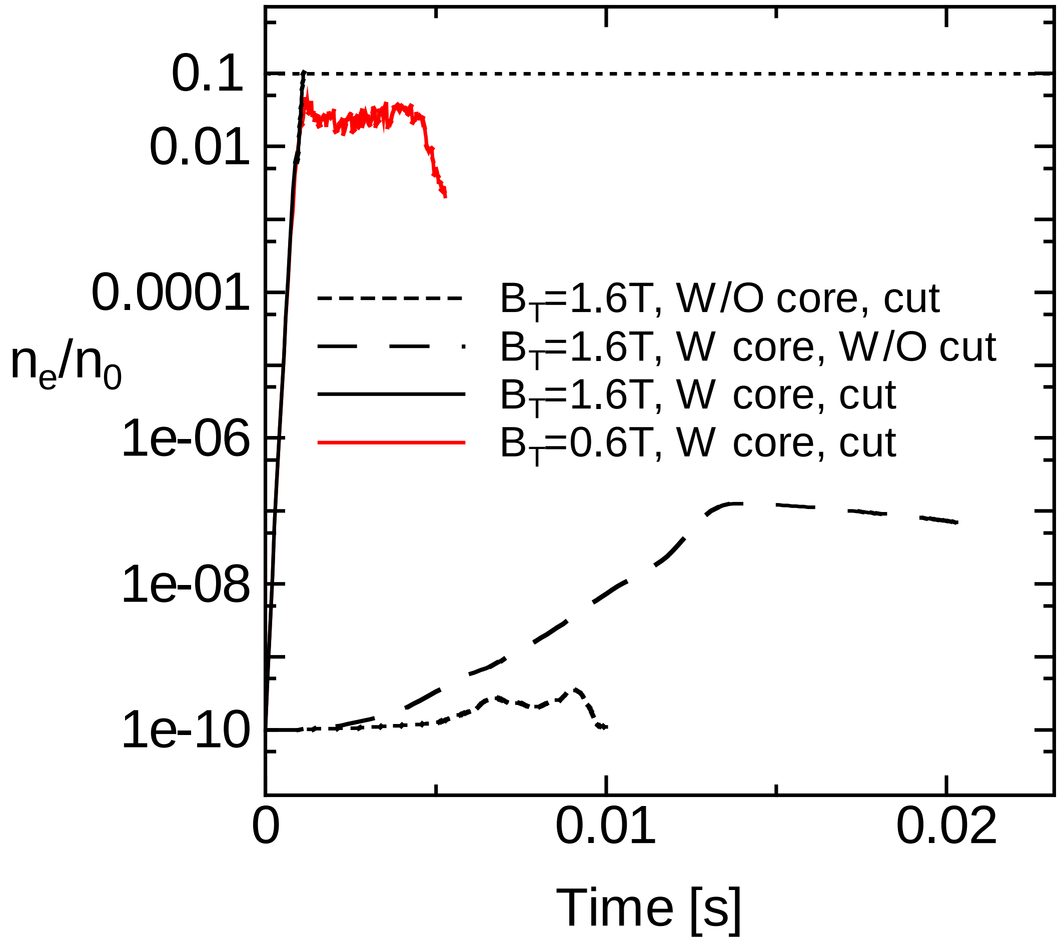


$$\Delta M(r_1, r_2) = \frac{\mu_0 \chi_m}{2} \frac{\pi a^3}{r_1 r_2}$$

a: **the radius of the iron core,** χ_m: relative permeability

Results of Simulations

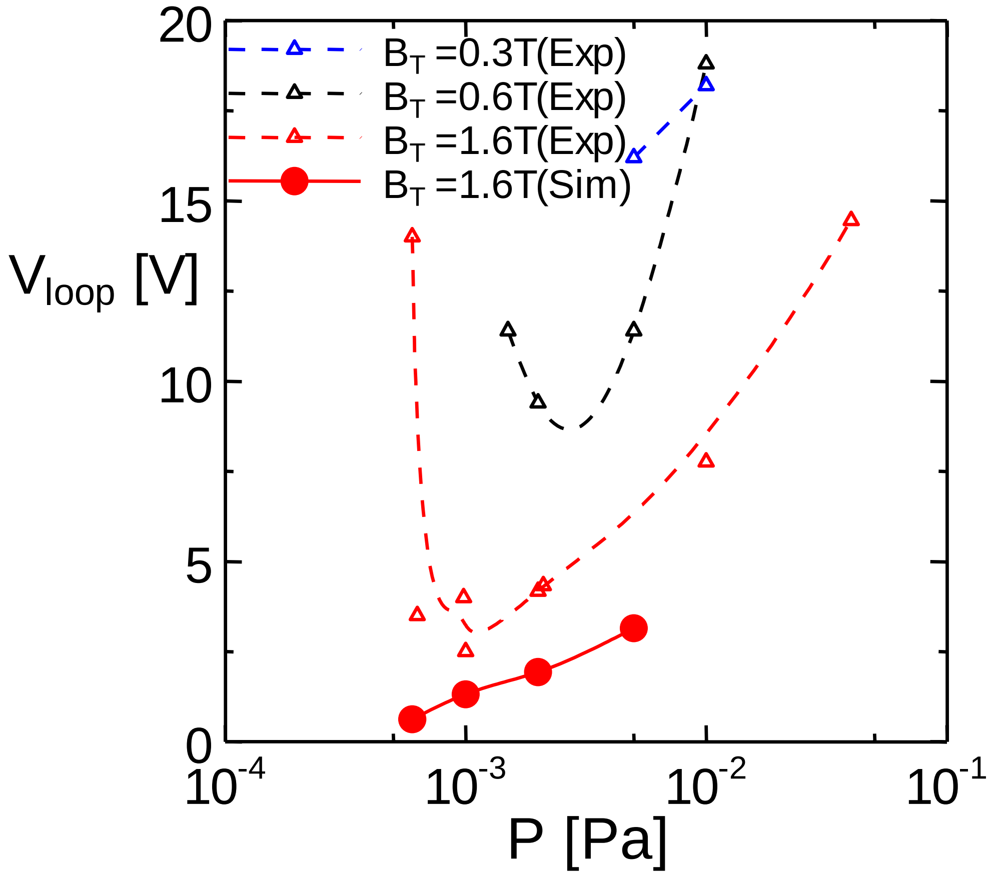
- Using the 2D-simulation code with the modifications for JFT-2M without the ferritic steel, time evolutions of ionization are computed.
- Effects of the toroidal gap and the iron core are investigated.



The iron core and toroidal gap are required for the breakdown.

Results of Simulations (2)

- Using the modified simulation code, we calculated the relations of breakdown voltages and gas pressures.
- Comparing the simulation with the experiments, the range of neutral gas pressure for the breakdown is narrow, and the voltages become low. Effects of toroidal field has not yet obtained.



It is needed that more detail investigation of calculation results and a modification of a simulation model.

Configurations at Breakdown

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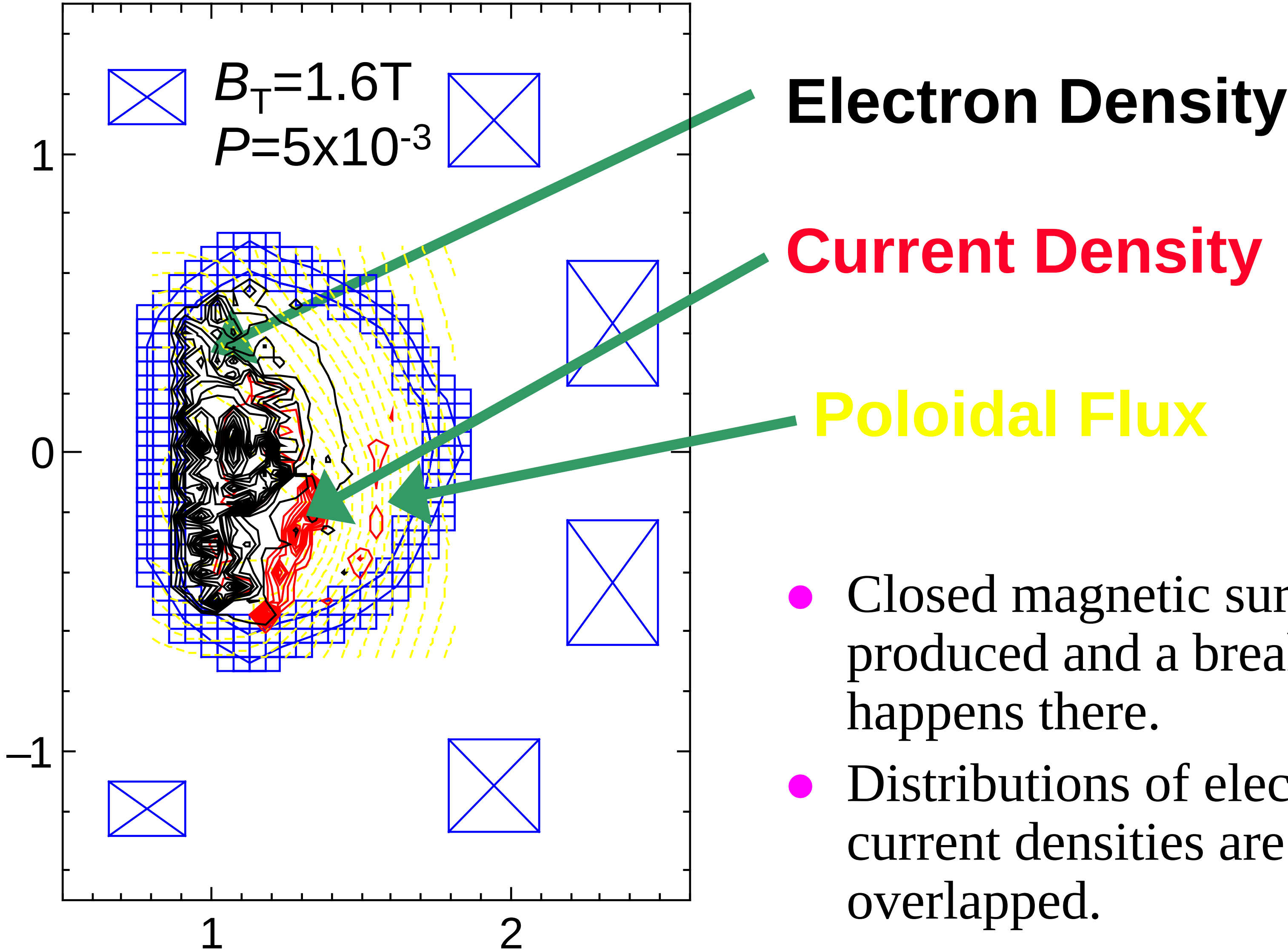

- Closed magnetic surfaces are produced and a breakdown happens there.
- Distributions of electron and current densities are not overlapped.

Time Evolution in Breakdown Failure

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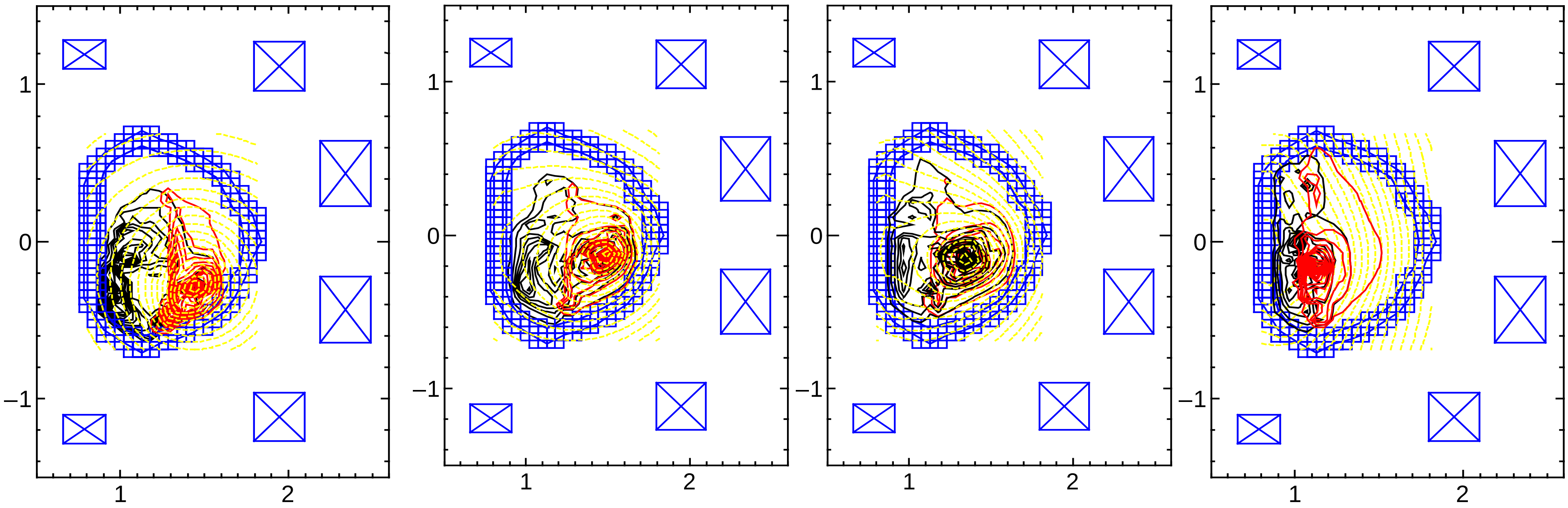
B_T=1.6T P=5x10^{-3}Pa

t =1.06x10^{-3} ms t =1.12x10^{-3} ms t =1.18x10^{-3} ms t =1.24x10^{-3} ms



- A breakdown was failed in spite of the production of closed magnetic surfaces.

Conclusion

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- The equivalent permeability in the poloidal direction was measured.
  - The usual theory is confirmed.
- Breakdown characteristics (voltage and pressure) were experimentally investigated.
  - Dependences on the toroidal fields (B_T=1.6T, 0.6T, 0.3T) are obtained.
  - Breakdown voltage decreases with the toroidal field strength.
- Modifying the simulation code for JFT-2M, computation results are compared with the experiments.
  - The toroidal gap and the iron core are required for the breakdown.
  - Quantitative agreements between the experiments and the simulation are not obtained. More modification of the code is needed.