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Plasma Initiation in the KAERIT Tokamak

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KAERIT 토카막의 플라즈마 생성 실험

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Abstract

Experiments on the hydrogen gas breakdown for plasma initiation in the KAERIT tokamak are described. The influence of the applied loop voltage, toroidal magnetic field, gas filling pressure, error magnetic field, and preionization is studied. It is concluded that the magnitude of the error field is the most important factor for successful discharge initiation. The gas breakdown voltage becomes minumum when the external compensating field most effectively corrects the net error field. Even though preionization effect is not prominent, it is exhibited more easily in the case of worse confinement. Discharge initiation conditions experimentally determined are compared with those calcuated from a theoretical model. Some other unknown physical processes maintain the operation range somewhat narrower than predicted by the present theoretical model. However, this model is adequate for the breakdown phase of tokamaks.

요 약

KAERIT 토카막 장치의 플라즈마 생성을 위한 수소기체 방전실험에 관해 기술하였다. 이 실험에서는 일주전압, 토로이달 자장, 충전기체 압력, 오차자장 및 예비전리 등이 방전시작에 미치는 영향이 연구되었다. 오차자장은 방전에 가장 큰 영향을 미치는 인자로서 방전전압이 최소가 되는 것은 결국 오차자장 성분을 가장 잘 상쇄시켰을 때였다. 예비전리의 효과는 전반적으로 두드러지지는 않았지만 밀폐 성능이 나쁠수록 상대적으로 크게 나타났다. 실험적으로 구해진 방전시작조건은 이론적인 모델의 계산결과와 비교하였다. 실험에서의 방전영역이 이론적인 계산결과에 비해 줄어드는 경향을 보이고 있는 것은 고려되지 않은 다른 인자에 기인하는 것으로 판단되지만 토카막의 방전시작단계를 다루기에는 이 모델로도 충분하다.

1. Introduction

The approaches to overcome the endloss and the macroscopic plasma instabilities, whcih had been encountered by the linear pinch, were to bend the linear pinch into a torus and to stiffen the plasma with a strong toroidal magnetic field. Closed field-line magnetic confinement systems have a favorable trend in experimental achievements, and especially tokamaks now occupy the major position in fusion research worldwide. The basic tokamak configuration consits of an intense toroidal magnetic field together with a weak poloidal field generated by a toroidally directed plasma current which can be induced by transformer action. The joule dissipation associated with this current heats the plasma to temperature of about 1 KeV.

The operation of tokamak is divided into four typical time phases; startup, plasma buildup(and heating), plasma maintenance and plasma shutdown[1] As well as being important factor in the design of the poloidal field system, the startup phase also has a strong influence on the development of denstiy and current profiles, and the influx of impurities into the plasma. A detailed understanding of the plasma behaviours during this phase is therefore essential for determination of operating parameters which will ensure successful and efficient initiation of the discharge. The tokamak startup is divided into three parts; gas breakdown (or plasma initiation), plasma formation and current rise[2] By transformer action loop voltage is applied to a nearly neutral filling gas at the beginning of the breakdown phase. Usually a large voltage spike and consequently a large poloidal field power supply should be required. A breakdown with a high loop voltage will consume a lot of poloidal field transformer flux, otherwise that would permit longer tokamak pulse length. There is, therefore, a good reason to explore possible techniques for tokamak startup with a reduced loop voltage.

In the previous investigations of the startup process in a tokamak, various models for the ionization of the neutral gas have been developed and the influence of parameters such as initial filling pressure, impurity concentration, loop voltage, preionization and magnetic configuration has been studied theoretically and experimentally in some detail[3)-7)]. Because comparatively little is known about the complex atomic processes occurring in this period of transition between neutral gas and plasma, the results of such investigations have a variety of restrictions in the practical application for a specific tokamak device.

This paper will describe the startup experiment in the KAERIT tokamak with particular emphasis on the breakdown phase. The parametric dependance of the hydrogen gas breakdown is investigated to find the various physical requirements for optimal discharge of the KAERIT tokamak.

2. Experimental configuration

The KAERIT tokamak is an iron core device with a major radius(R) of 27cm, and aminor radius(a) of 5 cm. There is no limiter. The total available magnetic flux of the iron core transformer is 0.11 Wb. This tokamak is designed to operate in a toroidal field of 1~4 T range, but the present breakdown experiment has been carrided out with a toroidal field of maximum 0.44 T because of a limited capacity of the power supply.

A whole view of the machine is shown in figure 1. The toroidal vacuum chamber is constructed with four 77° long radius elbows made of stainless steel 304L. There are four boxes located at 90° intervals. These componets are then joined together with sealing and insulating hardware to close the vacuum chamber and to provide two voltage breaks in the toroidal direction. To minimize the variation in the toroidal field, the access angle of the port box is determined to be comparable with a gap of approximately 13° between the toroidal windings. The base pressure is 7×10^{-8} torr. The toroidal magnet is composed of 28 windings of 13 turns each with a conductor crossection of $21\times7\text{mm}^2$. Glass fiber reinforced epoxy is used to provide insulation between conductors. The overall shape of the winding closely approximates a

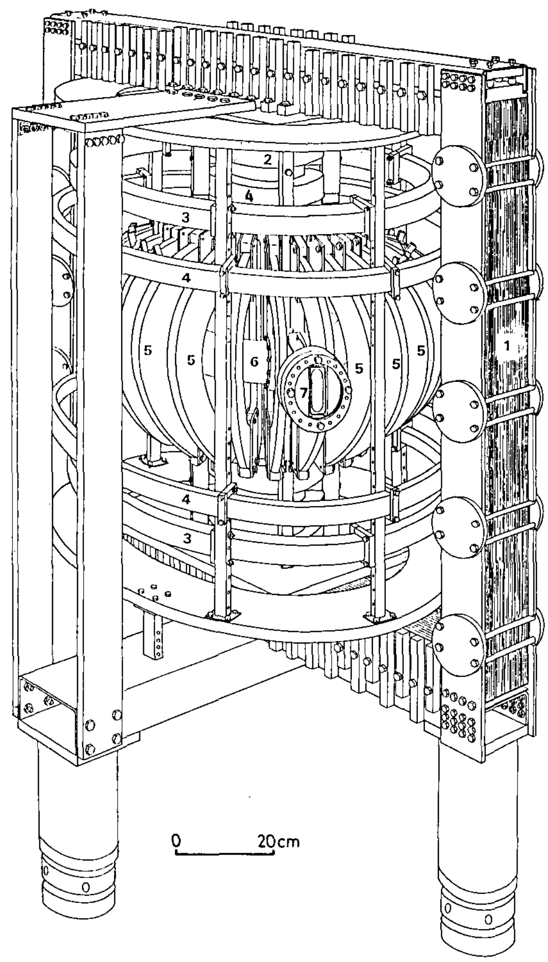

Fig.1. Whole View of the KAERIT Tokamak, [1] Iron Core, [2] Ohmic Heating Coil, [3] Equilibrium Field Coil, [4] Compensation Field Coil, [5] Toroidal Field Coil, [6] Torus Vacuum Chamber, [7] Vacuum/Dignostic Port.

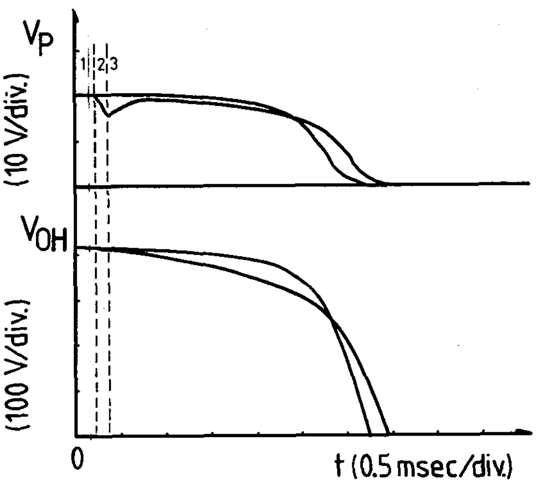

Fig.2. Primary and Secondary Voltages, with(lower) and Without(upper) Plasma; 1.Breakdown, 2. Plasma Formation, 3.Current Rise.

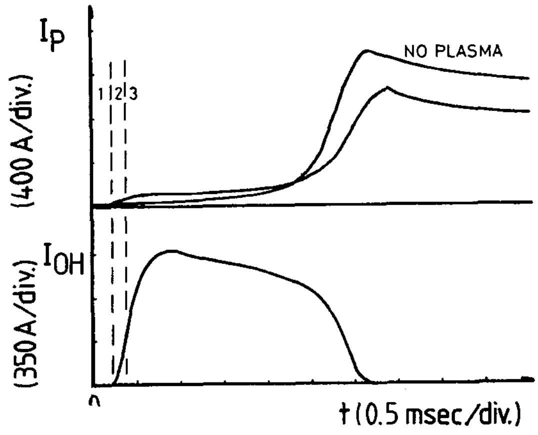

Fig.3. Primary and Secondary Currents, with and without Plasma Current (also Reference to the Description of fig.2).

constant tension D. The coil is energized from a DC power supply which can providea maximum 1600, A for about 1 second to the loda of 57.2 mΩ and 6.4.mH.

The ohmic heating magnet consists of two 10-turn coils located at top and bottom of the center iron core. The stray field due to ohmic heating coils at the plasma center is 12.5 G per coil current of 1 KA, and the coil is energized from a capacitor bank of 2400 μF at maximum 5KV (30 KJ), Which is switched by a high current SCR, and passively crowbarred at current maximum by a diode. The self inductance and the resistance are respectively maximum 22 mH and 2.37 mΩ. The equilibrium field coil has four windings. This coil is wound inside the ohmic heating transformer loop, and there should be minimal mutual inductance between them. The measured value of the mutual inductance is maximum 99 μH. Decay index of the equilibrium field is in the range of 0.1～0.9 at the plasma region, and the unit field induction is 0.15 G/A. The field requisite for equilibrium is about 140 G for a plasma current of 10 KA. About 3/4 of

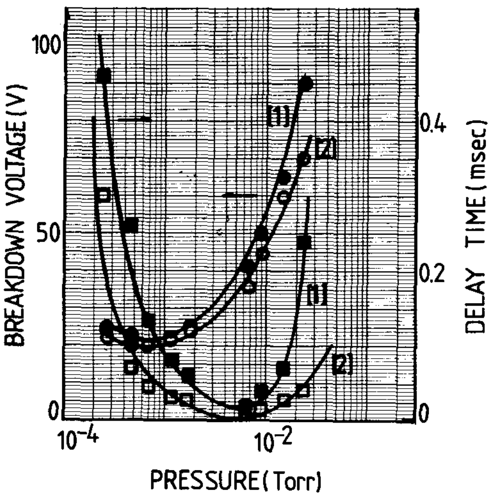

Fig.4. Breakdown Voltage and Breakdown Delay(when Applied Voltage is 100V) Versus Gas Filling Pressure with a Hot Filament[1] and an ExB[2] Preionization at Error Field of 30 G.

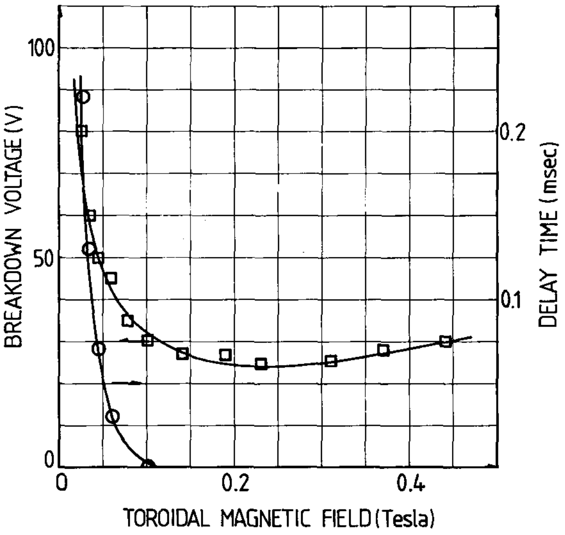

Fig.5. Effect of Toroidal Magnetic Field on Breakdown Voltage and Breakdown Delay (when Applied Voltage is 120 V) at p=5×10^{-3} torr.

the equilibrium field is supplied by the images of the plasma current in the iron core. Two types of preionization were used; a hot filament in the shadow of the chamber wall and an ExB drift source. At the inital time t = 0 the toroidal field and the error compensation field were fired. 500~600 msec later the ohmic heating field was fired, and after a presetting delay the equilibrium field was pulsed.

Operating pressure was varied from 5×10^{-5} to 5×10^{-2} torr, which was adjusted by steady state pressure equilibrium between the gas injection from a precision niddle valve and the exhaust with a 510 ml/s turbomolecular pumping system.

3. Toroidal discharge experiments

KAERIT has relied on slightly assisted or unassisted inductive breakdown to accomplish its discharge. A typical development of primary coil voltage(V_{OH}), primary coil current(I_{OH}), plasma loop voltage(V_P) and plasma current (I_P) are shown in figures 2 and 3, which illustrate well three phases of standard tokamak startup. KAERIT discharge experiments may be classified into three stages according to the physical conditions of the machine. In the first stage the stray error field, mainly due to misalignments of the toroidal magnet, was very high, and the ExB preionization source was used. To analyze the breakdown characteristics we display, as shown in figure 4, plosts of breakdown voltage(V_B) and breakdown delay(τ_B) versus gas filling pressure (p) for two different amounts of preionization, even if quantitative estimate of preionization effect has not been performed. Breakdown voltage and delay versus toroidal field(B) are also shown in figure 5. Breakdown delay is taken as that time at which the secondary loop voltage first departs from its vacuum value. Just at the breakdown voltae, ideally, delay should be infinite. Due to statistical scatter, however, one development leads to an observable breakdown and the other dies out with nearly equal probabilities. Figures 4 and 5 show the general characteristics of toroidal breakdown experiments. There exists an optimum pressure according to a minimum breakdown voltage. Breakdown voltage and time lag decrease as toroidal magnetic field increases up to about 0.3 T, while the decreasing rate gradually falls off to zero. Hence there may be a threshold toroidal field for steld breakdown.

The trend of slight increase in the breakdown voltage above this threshold value is a specific nature of the KAERIT, which may be due to the trouble with the mechanical structure of the toroidal magnet. The relation between the filling pressure and delay, as shown in figure 4, looks somewhat unusual in comparison with the plot of breakdown voltage versus filling pressure. What makes the delay minimum does not coincide with what makes the breakdown voltage minimum. However, this behaviour is in agreement with theory which predicts that the time lag is an explicit function of the breakdown voltage as well as the gas filling pressure [8]. A simple theory on the gaseous electronics in toroidal geometry predicts an error field(B_{err}) of 30 G, which is about 0.7 % of the toroidal field.

Likely sources of such a field error include the primary windings, transformer, toroidal field coil misalign - ent and various bus bars. some of these would be axisymmetric or nearly so. If such errors are responsible for major particle losses, correction fields would improve the breakdown characteristics[9]. For the purpose of simulation of field errors, we made use of the equilibrium field coil set, which was not used for its own function in the breakdown experiments. The coils could produce a vertical or a horizontal correction field. The direction and magnitude of the correction field were changed, while loop voltage and plasma current were mointored. A minimum in delay occurrs at a horizontal field of 15G at plasma center as shown in figure 6, which gives the curves of delay and breakdown voltage versus applied stray field. Either the applied correction field accidentally cancells a main error field or it compensates for the toroidal drifts during startup. The simulation coil used here could not produce enough correction field to perfectly cancel the total error field.

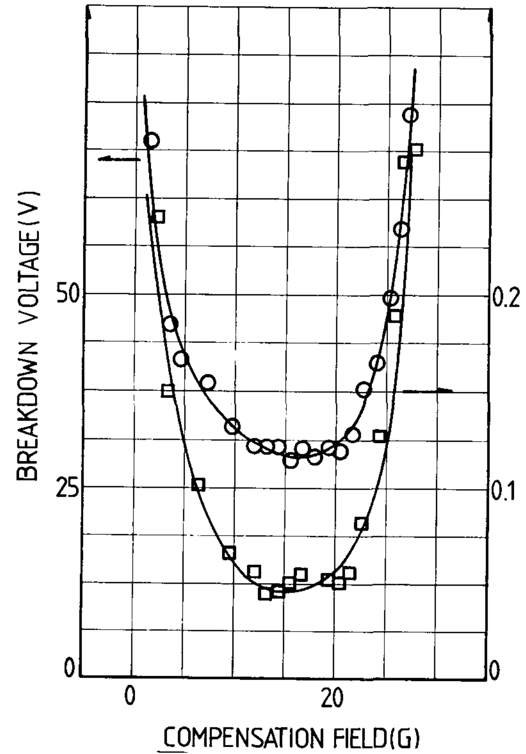

Fig.6. Effect of Compensation Field on Breakdown Voltage and Breakdown Delay(when Applied Voltage is 20V) at $P=5\times10^{-3}$ torr.

Figure 7 gives the result of the breakdown experiments following compensation of error field. This plot indicates considerable reduction of the breakdown voltage and extension of the operation regime in contrast with the previous experiments in the first stage. We could estimate error field at 13 G, which was still 0.3 % of the toroidal field. It was concluded that the

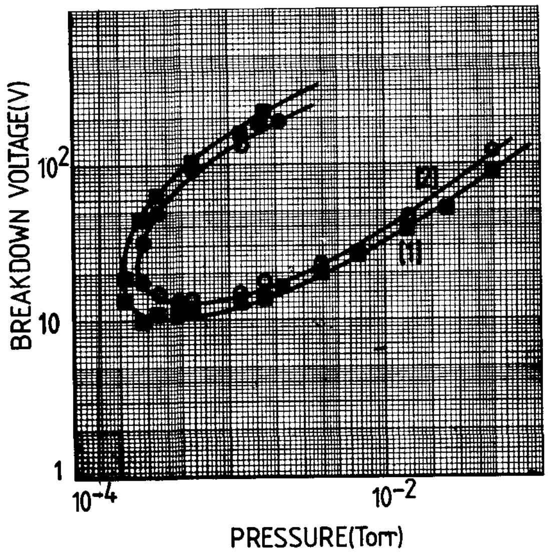

Fig.7. Relations between Breakdown Voltage and Gas Filling Pressure with [1] and without [2] Preionization (a Hot Filament) at Error Field of 13G.

radical correction could be possible only by remounting the toroidal magnet wintings. After that, error field reduced to about 6 G and the minimum breakdown loop voltage decreased to about 5 V. Figure 8 shows the results from the final breakdown experiments, after compensating error field with a correction field of 4.5 5 G. The minimum breakdown loop voltage is about 3 V. The remaining error field is evaluated to be about 5 G, which indicates that the error compensation is not properly fulfilled. A stray field due to toroidal magnet is not a major constituent anymore. It is easily established by the fact that the reversal of the primary current raises the minimum breakdown voltage nearly double. The phenomena of the failure of breakdown at high loop voltage, one of the characteristic features of toroidal discharge, will be discussed in the next section.

In the breakdown phase the departure from neutrality is a few seed electrons, due to cosmic rays or a preionization source. In a simple theory the breakdown conidtion is independent of the amount of preionization, and determined by the comptietion between the generation and the loss of electrons. But it is found that practically the amount of preionization influences on the startup characteristics through the reduction of delay and breakdown voltage, which might result from the increase of conductivity, reduction of impurity influx, suppresion of runaway electrons, and earlier formation of a current channel. In figures 4, 7 and 8, the effect of preionization on the KAFRIT startup may be recognized. The influence of preionization is exhibited more easily in the worse confinement.

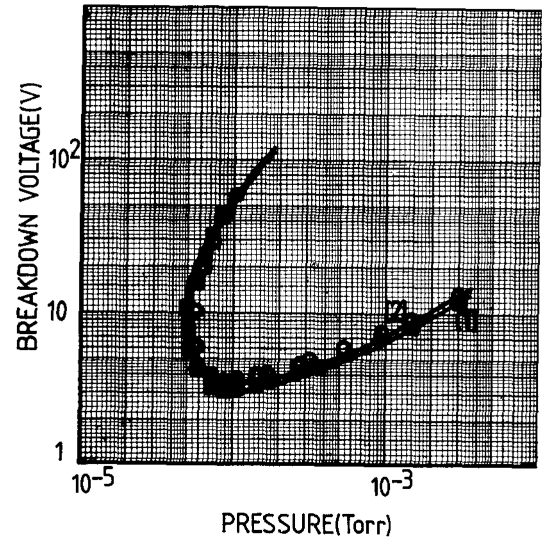

Fig.8. Relations between Breakdown Voltage and Gas Filling Pressure with [1] and wihout [2] Preionization (a hot filament) at Error Field of 5 G.

4. Theoretical considerations

As previously reported by one of the authors10), tokamak discharge is controlled by electron diffusion, and breakdown may be treated as a competition of ionization and losses of electrons. This breakdown theory is based on the zero-dimensional time independent model. Even if this model treats the problem more roughly than a two-dimensional time dependent one, it adequatedly provides a fast and useful evaluation of the breakdown condition. The ionization rate and the various loss rates used in this model are given by the equations as follows 7),11);

$$\text{Ionization}: \nu_{\text{ion}} = a \times V_d \quad (1)$$

$$\text{Error field loss}: \nu_{\text{err}} = \frac{V_d \delta}{a} \quad (2)$$

$$\text{Diffusion loss}: \nu_{\text{dif}} = \frac{6.74 \times 10^{-2} p T_e}{a^2 B^2} \quad (3)$$

$$\text{Drift loss}: \nu_{\text{dr}} = \frac{(1.5 T_e + 5.69 \times 10^{-12} V_d^{12})}{aRB}$$

$$\text{Bohm loss}: \nu_{B} = \frac{T_e}{4a^2 B} \quad (5)$$

where Townsend 1st ionization coefficient $\alpha = 5.1 \times 10^2 pe^{-138.8P/E}$, electron drift velocity $V_d = 3.9 \times 10^3$ E/P, error ratio $\delta = B_{err}/B$, electron temperature $T_e = 0.225 (E/P)^{2/3}$, and electric field $E = V_P / 2\pi R$. All quantities are in MKS units except T_e expressed in eV, p in torr, and E in V/cm.

Derivations of these equations are based upon the fact that electron-neutral, collision is dominant and rotational transform is small in the breakdown phase.

The avalanche will develop if the ionization rate exceeds the total loss rate given by the sum of all presented loss terms. In figure 9 several $V_B - p$ curves calculated for different values of error field and toroidal field are shown. The unique characteristics of a toroidal discharge. for example extremely low breakdown voltage, wide range of operating pressure, and an upper limit of breakdown voltage above which discharge does not take place anymore, are well exhibited in figure 9. As toroidal field increases or error field decreases, lower limit (upper limit) of the breakdown voltage monotonically falls down (goes up) at a fixed gas filling pressure. The failure of breakdown at too high an applied volage is asscribed to the toroidal drift of electrons, which varies in proportion to the square of the loop voltage. Experimental lower limit of the breakdown voltage is well predicted by proper assumption of the magnitude of the stray error field. But there is considerable disagreement between the calculated and observed upper limits of the breakdown voltage. The discrepancy results from possibly the net poloidal field due to stray toroidal current induced by secondary loop voltage.

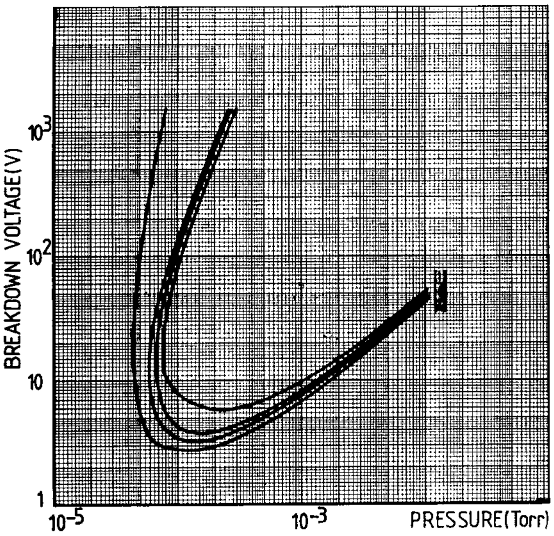

Fig.9. Breakdown Voltage Versus Gas Filling Pressure, Obtained Theoretically;

A theoretical model that adequately reproduces the characteristics of the discharges has been developed. An ion dominated dischage is not treated by this mode. Some other physical processes, for example error field

5. Summary and conclusions

The KAERIT tokamak is an iron core device with a major radius of 27 cm and a minor radius of 5cm. The influence of the applied loop voltage, toroidal magnetic field, gas filling pressure, error field and preionization in the breakdown phase of the KAERIT tokamak is studied with the inductive discharges. It is concluded that the magnitude of the error field is critically important. The breakdown voltage becomes minumum when the external compensating field most effectively cancells the net stray error field. Because toroidal field may be the principal source of error field, an accurate alignment of toroidal magnet is essential. The minimum breakdown voltage is about 3 V at filling pressure of 9×10^{-5} torr with a hot filament preionization source. The remaining error field is about 5 G. due to stray toroidal current, maintain the operating range somewhat narrower than predicted by the present model. However, this model is adequate for the breakdown phase of tokamaks.

Acknowledgements

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