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PREIONIZATION STUDIES IN ZT-40M

by

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ABSTRACT

A study of preionization techniques has been performed in ZT-40M at Los Alamos National Laboratory. The results of this study and the techniques routinely utilized to preionize the plasma in this device are presented. A simple theoretical model involving drift motion of the electrons in the inhomogeneous toroidal field B_ϕ present during breakdown is examined. This model is shown to offer a conceptual explanation for the breakdown limits in ZT-40M. This simple theory appears to indicate that the preionization system produces photoelectrons locally at the wall as opposed to acting as a volume source of electrons.

I. INTRODUCTION

In the present generation of metallic vacuum vessel Reverse Field Pinches (RFP's), the behavior of the plasma current decay ($\dot{I}_\phi$) as a function of fill pressure (P_0) may be used as an indicator of the best operating regime.¹ A study in the ZT-40M device at Los Alamos National Laboratory of the behavior of $\dot{I}_\phi$ vs P_0 has been an integral component in the definition of the proper fill pressure for maximum plasma temperature and lifetime. To cover the possible operating regimes completely so that one does not miss the best operating point, it is necessary to create the plasma with fill pressures as low as 1 mtorr. With a 250 μ s I_ϕ risetime, pressures below 1.8 mtorr are inaccessible without creating a preionized plasma prior to application of the toroidal voltage (E_ϕ). At lower pressures, E_ϕ/P_0 is too large for the breakdown to occur spontaneously and one must aid the breakdown with a source of preionization. This report will cover the techniques used routinely on ZT-40M for this purpose, as well as other techniques investigated. A simple

theoretical model will be presented in an effort to explain the capabilities and limitations of the present approach to preionization in ZT-40M.

II. APPARATUS

A commonly used technique for creating a low level of preionization in a plasma containment device is the exposure of the neutral fill gas (D_2 in ZT-40M) to an intense source of ultraviolet radiation. On ZT-40M this technique is used in a manner that is simple to accomplish and that uses inexpensive, commercially available light sources. A Vivitar 215 commercial electronic photoflash unit with its amber plastic filter removed is positioned to illuminate the plasma through a 2-in.-diam. quartz window. The combination of a Xenon flash tube in the Vivitar unit and quartz window material permits the UV portion of the spectrum from the flash unit to reach the fill gas with relatively little attenuation (transmission of the quartz is reasonably flat between 200-700 nm).

Such units are used to preionize some portion of the fill gas at up to four points toroidally around ZT-40M. The units are all powered by a common battery pack and triggered simultaneously by the thyristor circuit shown in Fig. 1. The trigger circuit is powered by the flash unit itself and is used

Fig. 1.
Thyristor circuits used to actuate the Vivitar 215 strobe lights.

to short one end of the flash tube and an associated tickler coil from about 80 V to ground, causing the tube to fire. The duration of the light pulse is approximately 0.5 ms and is positioned in time so that the application of the toroidal drive voltage (E_ϕ) occurs during the decay of the light pulse. A typical time history of the UV portion of the pulse (viewed through a Corning 7-54 optical filter which transmits light at wavelengths below 400 nm) is shown in Fig. 2. The trigger circuit and flash unit combination has a timing jitter of less than 10 μ s. It was found experimentally that the flash units had a tendency to fire by themselves when used with a trigger circuit containing no bypass (storage) capacitor and a large gate resistor. This was presumably caused by noise on the anode of the SCR, which coupled through the Miller capacitance to the gate and caused the unit to fire. Insertion of the anode capacitor and a low resistance shunt to ground on the gate eliminated the problem resulting in the circuit shown in Fig. 1.

This system, usually containing either 3 or 4 photoflash units, is now used routinely every shot on ZT-40M. The battery pack, consisting of two 2F2H Burgess 3-V batteries in parallel, has powered the system of four lamps for more than 1,000 shots and has just recently been replaced. The effects of the

Fig. 2.
Typical time history of a flash discharge (intensity increases downward).

preionization system on the breakdown limit (lowest attainable P_0) will be discussed in the next section.

In an effort to extend the breakdown limit below that obtainable with the four strobes, a second preionization source was also experimented with. This second source was a nude high-vacuum ionization gauge inserted in one of the tubulations connected to ZT-40M's metal liner. The purpose of the structure was to replace the electrons created using photoionization from one of the four strobes by electrons emitted thermionically from the hot filament of the ionization gauge. This source was capable of being biased up to 535 V negative with respect to the metal liner. This technique was used here in an attempt to gain access to the fill pressure regime below 1 mtorr. The results are discussed in the next section, but in general at moderate bias voltages (~ 180 V) the results, using this source in conjunction with three strobes, were similar to those obtained with four photoionization sources.

III. EXPERIMENTAL RESULTS

The breakdown process in the plasma under the influence of the applied field E_ϕ takes a finite amount of time. In ZT-40M at high pressures (> 3 mtorr), the breakdown takes a minimum of 15-20 μ s. This delay between application of E_ϕ and the beginning of the toroidal current in the plasma is directly observable as a momentary hesitation in the current rise, as viewed by a Rogowski probe viewing $\langle B_\theta \rangle$ at the wall outside the liner. For the first 15-20 μ s, all the current is carried in the liner (~ 30 kA at 15 kV charge on the E_ϕ bank). At later times (> 20 μ s) the plasma begins to conduct and the current rises sharply to the 200-kA level in 250 μ s. The delay between the liner current and plasma current is clearly seen in the trace of I_ϕ shown in Fig. 3. To quantize the preionization process, this time delay was measured at constant E_ϕ for a variety of fill pressures and several different source configurations. As one approaches the limiting value of P_0 , below which breakdown will fail, this delay, in the space of approximately 0.1 mtorr, will go from low values (15-25 μ s) to the limiting value allowed by the nonbreakdown protection circuit on ZT-40M (150 μ s). In this way the breakdown limit may be established as that fill pressure at which the ionization lag time has increased to values above 40-50 μ s.

Fig. 3.

Typical plasma current initiation showing ionization lag time (shaded portion).

Fig. 4.

Ionization lag times measured in ZT-40M as a function of initial fill pressure.

Measurements of the ionization lag time are shown in Fig. 4. In order to present the data in the clearest possible manner, only the data with one to three strobes positioned at 0° , 90° , and 180° from the north pump stand and the best results with three strobes and the filament (bias at -180 V) are shown. Other data with the filament produced breakdown limits at higher P_0 levels, presumably because with no bias voltage or with too large bias voltage (-535 V), the thermionic electrons do not get out into the breakdown volume. The lower limit with four sources is in the vicinity of 1 mtorr regardless of the source type. It is believed that this is an effect of the position of the nearest neighbor source and that the only improvement will come from much larger numbers of sources distributed evenly throughout the machine.

IV. THEORY

In an effort to understand the limits and capabilities of the breakdown in ZT-40M, an extremely simplified model may be invoked. This theory must be composed of two parts, an examination of the local breakdown physics and an examination of the process throughout the entire torus. In an effort to provide a complete theoretical package in one location, both aspects of the problem are discussed here in some detail. The two aspects of the problem will be considered in sequence.

The problem is that of a neutral gas background in which low ionization levels are created by the applied E_ϕ . Because during the breakdown phase the current I_ϕ in the plasma is small but the toroidal field B_ϕ is large, the plasma created by the breakdown process exists in a simple torus that is incapable of sustaining an MHD or single-particle equilibrium.² The loss of equilibrium is caused by the drift motion of the charged particles due to the curvature (drift velocity proportional to $v_\perp^2$) and gradient (drift velocity proportional to $v_\perp^2$) of the toroidal field.

The problem of loss of equilibrium of a motionless, thermal plasma due to drift motion in the presence of a uniform magnetic field under the force of gravity has been solved by Longmire.³ With replacement of the gravitational force g in this analysis by the centrifugal force $v_\perp^2/R$ the same solution may be made to apply to the loss of equilibrium of a plasma in a torus in the absence of an external accelerating toroidal electric field.³ Hirano⁴ has used this solution with ion temperatures estimated from measured x-ray spectra

during breakdown to estimate the drift velocity in a fast risetime, small cross-section torus.

In the presence of a toroidal electric field, the problem changes because the electrons become the dominant species. Longmire's solution must be modified to reflect the fact that the velocity distribution functions (particularly for the electrons) now have a preferred direction and cannot be considered to be even remotely thermal. Such a modification is outlined here. In the case of ZT-40M, the initial process of the instability is caused by the acceleration of the created electrons along E_ϕ , which results in a cross-field drift dominated by the curvature term for the electrons (rather than the ions as in Longmire's analysis) because $v_{||,e} \gg v_{\perp,e}, v_{||,i}, v_{\perp,i}$. This drift is charge dependent and results in a charge separation and resulting vertical electric field E_z , which produces a drift in the major radial direction for all charged species. This latter drift is the dominant motion and results in rapid loss of plasma to the wall in a simple torus. In the following, a coordinate system in which ϕ is the toroidal coordinate, θ is a poloidal coordinate, and z is the vertical coordinate is used. One may write down expressions for the dominant velocities in the problem⁵ given in MKS units.

Velocity due to the driving field E_ϕ :

$$\vec{v}_{||} = \frac{-q_\alpha \vec{E}_\phi}{m_\alpha} \tau_1, \quad ,$$

where τ_1 is the time between randomizing collisions, q_α is the charge of species α , m_α is the mass of species α , and $\vec{E}_\phi$ is the toroidal applied field.

Curvature drift velocity:

$$\vec{v}_{D,(\vec{B} \cdot \nabla)\vec{B}} = \frac{m_\alpha}{q_\alpha} v_{||}^2 \frac{\vec{B} \times (\vec{B} \cdot \nabla)\vec{B}}{B^4}$$

$$|\vec{v}_{D,(\vec{B} \cdot \nabla)\vec{B}}| \approx \frac{m_\alpha v_{||}^2}{q_\alpha} \frac{1}{RB_\phi} \quad . \quad (1)$$

$\vec{E} \times \vec{B}$ drift velocity:

$$\vec{w}_D, \vec{E}_z \times \vec{B}_\phi = \frac{\vec{E}_z \times \vec{B}_\phi}{B_\phi^2},$$

where the third expression is the approximate value of the curvature drift velocity for a simple torus of major radius R and toroidal field B_ϕ . The vertical electric field induced ($\vec{E}_z$) is given (for the one-dimensional problem with electron density n_e) by

$$\vec{E}_z = \frac{-n_e e \hat{z}}{\epsilon_0} = \frac{-n_e e}{\epsilon_0} \vec{v}_z \tau_2, \quad (2)$$

where $\vec{v}_z$ is the velocity along the $\hat{z}$ direction $[\vec{v}_D, (\vec{B} \cdot \nabla)\vec{B}]$ and τ_2 is the time during which $\vec{v}_z$ acts. In this case the n_e is that electron density generated locally caused by the breakdown process and thus is time dependent. The electron density at any time is created by the ionization process in the applied field, corrected by whatever fluid motion occurs (here caused by the drift motion induced by B_ϕ). The controlling equation is the mass conservation equation of the two-fluid MHD theory, neglecting cross-field diffusion,

$$\frac{\partial n_e}{\partial t} + n_e \nabla \cdot \vec{u} = S(\vec{r}, t), \quad (3)$$

where S is the electron source term, here given by⁶

$$S(\vec{r}, t) = u \alpha n_e \quad (4)$$

and $\vec{u}$ is the electron fluid velocity. The coefficient α is the Townsend coefficient given by the expression

$$\alpha = 510 P_0 \text{ (torr)} \exp \{-1.388 \times 10^4 P_0 \text{ (torr)} / E_\phi \text{ (V/m)}\}.$$

The ions travel with the electrons due to the induced $\vec{E}_z \times \vec{B}_\phi$ drift, which is mass independent, but contribute nothing (except for a collision term) to the breakdown process which involves only electron-impact ionization of the neutral background. The electron-ion collision term, which does not appear explicitly in this simple model, does contribute to one of the time scales in the problem (the time τ_1 to be defined later). Using the above drifts in place of the fluid velocity perpendicular to $\vec{E}_\phi$ and $\vec{v}_\parallel$ in place of $\vec{u}$ along $\vec{E}_\phi$, we may write the controlling equation

$$\frac{\partial n_e}{\partial t} = -v_\parallel \alpha n_e - n_e \nabla_\perp \cdot \vec{v}_D. \quad (5)$$

This equation could be solved numerically, along with the time-dependent momentum equation that generates the velocities, but such an analysis is beyond the scope of this report.

In keeping with the simplistic model invoked here, let us define some average quantities $\langle v_\parallel \rangle$, $\langle v_\perp \rangle (\vec{B} \cdot \nabla) \vec{B}$, $\langle E_\perp \rangle$, and $\langle v_\perp \rangle \langle \vec{E}_\perp \rangle \times \vec{B}_\phi$ in the following manner.

$$\langle v_\parallel \rangle = - \frac{e E_\phi}{m_e} \tau_1,$$

$$\langle v_\perp \rangle (\vec{B} \cdot \nabla) \vec{B} = - \frac{m_e \langle v_\parallel \rangle^2}{e} \frac{1}{RB_\phi},$$

$$\langle E_\perp \rangle = - \frac{en_e}{\epsilon_0} \tau_2 \langle v_\perp \rangle (\vec{B} \cdot \nabla) \vec{B}, \text{ and} \quad (6)$$

$$\langle v_\perp \rangle \langle \vec{E}_\perp \rangle \times \vec{B}_\phi = \frac{|\langle \vec{E}_\perp \rangle \times \vec{B}_\phi|}{B_\phi^2} = \frac{|\langle \vec{E}_\perp \rangle|}{B_\phi}.$$

The times τ_1 , τ_2 are characteristic times in the problem representing how long $\vec{E}_\phi$ may accelerate electrons before a collision randomizes their directed velocity, and how long the $(\vec{B} \cdot \nabla)\vec{B}$ drift can act to create charge separation before saturation occurs, respectively. We may approximate the mass conservation equation (noting $\partial/\partial z \approx 0$) by

$$\frac{\partial n_e}{\partial t} \approx - \langle v_{\parallel} \rangle n_e - \frac{n_e}{R} \langle v_{\perp} \rangle \langle \vec{E}_{\perp} \rangle \times \vec{B}_\phi, \quad (7)$$

which may be rewritten in general as

$$\frac{\partial n_e}{\partial t} = \frac{e E_\phi}{m_e} \tau_1 n_e \left\{ \alpha - \frac{en_e}{\epsilon_0} \frac{1}{(RB_\phi)^2} E_\phi \tau_1 \tau_2 \right\}. \quad (8)$$

Written in this manner, we may conclude that convection dominated breakdown cannot occur unless the right side is positive; that is, the breakdown occurs when

$$\alpha > \frac{en_e}{\epsilon_0} \frac{1}{(RB_\phi)^2} E_\phi \tau_1 \tau_2. \quad (9)$$

The above equations represent the microscopic part of the breakdown picture and include the effects of the Townsend avalanche caused by E_ϕ and the convection out of the region due to drifts. If this convection occurs faster than the ionization, the process will quench locally and breakdown will not occur (Eq. 9).

There is also a second part to the process. Because the total current I_ϕ in the plasma must go completely around the torus, an electron cascade originating at one point in the torus must eventually reconnect with itself after a full toroidal revolution or with the source region of another electron cascade in the torus to make a complete charge-carrying ring. If this global

cascade reconnection is defeated because the cascade from one region drifts out and contacts the wall before it can combine with other cascades to complete the ring of charge carriers, the breakdown, while occurring locally, will have difficulty sustaining itself. This limit may also be expressed in terms of the drifts. If the major radial drift, acting over the time necessary for electrons to get from one source region to another, produces a larger major radial displacement than the diameter of the torus, no breakdown can occur. This process again is time dependent, but we may estimate the limit in terms of average $\langle v_D \rangle$ and $\langle v_{\parallel} \rangle$ as

$$\langle v_D, \vec{E}_z \times \vec{B}_\phi \rangle \cdot \frac{d}{\langle v_{\parallel} \rangle} \leq a, \quad (10)$$

where d is the largest distance between sources and a is the minor radius of the torus. In terms of the previously defined quantities, this may be written as

$$\frac{en_e}{\epsilon_0 R B_\phi^2} E_\phi \tau_1 \tau_2 \leq a/d \quad (11)$$

for breakdown to occur in this global sense.

One may evaluate these two breakdown limits in terms of E_ϕ/P_0 and P_0 to define where each is important, but to do so one must finally define τ_1 and τ_2 . The characteristic time τ_1 is the time it takes to disturb a freely accelerating electron from its path via collisions, either with neutrals or ions. The effective time for disturbing a freely accelerating electron is some hybrid between electron-ion and electron-neutral collision times. The electron-neutral collision time is given by the expression⁷

$$\tau_{e-n} = 3.57 \times 10^{-7} / \sigma n_n T_e^{1/2}. \quad (12)$$

The units of the parameters are m^{-3} for the neutral density n_n and eV for the

plasma temperature T_e . The cross section σ is approximately $1.21 \times 10^{-20} \text{ m}^2$ and corresponds to a hard-sphere model of the neutral atom. There are numerous expressions for the electron-ion collision time, all of the form

$$\tau_{e-i} = \text{constant} \cdot T_e^{3/2} / n_e, \quad (13)$$

where n_e is electron density in m^{-3} . The constant varies from 9.18×10^9 for many small-angle scattering processes accumulating into a 90° deflection up to 1.49×10^{12} for a single 90° coulomb collision. Because of the uncertainty in what atomic processes are involved in the detailed breakdown, as well as the fact that these values for τ_{e-i} bracket the value of τ_{e-n} in a 7 eV, $3.5 \times 10^{19} \text{ m}^{-3}$ electron density plasma at 50% ionization, we will use the τ_{e-n} expression as an approximation for τ_i . This expression is in reasonable agreement with that value computed for τ_i if one uses the experimental value of $\langle v_{\parallel} \rangle$ quoted in Ref. 6. For an average temperature of 7 eV ($\sim 1/2$ the ionization potential) and 50% ionization of a 1-mtorr fill of D_2 , Eq. (12) yields $\tau_i \approx 318 \text{ ns}$. The 50% figure used here is higher than is usually used in breakdown studies, but the dependence on ionization is fairly weak and the high figure is used because the equilibrium loss is an MHD effect. The effect of lowering the assumed level will be discussed later.

To estimate τ_2 , note that the field $\langle E_{\perp} \rangle$ produced by the curvature drift can only be as large as the energy that creates it will allow; that is,

$$\epsilon_0 \frac{\langle E_{\perp} \rangle^2}{2} \leq \frac{n_e m_e}{2} \langle v_{\perp} \rangle^2 (\vec{B} \cdot \nabla) \vec{B}. \quad (14)$$

Substituting the expression for $\langle E_{\perp} \rangle$ from Eq. (6) we arrive at

$$\tau_2 \leq \left[\frac{\epsilon_0 m_e}{2 n_e e^2} \right]^{1/2}, \quad (15)$$

which is on the order of 1 ps for 50% ionization of a 1-mtorr D_2 fill pressure.

Putting the above expressions for τ_1 and τ_2 into Eqs. (9) and (11), one may solve for representative curves of P_o , critical vs $(E_\phi/P_o)_{\text{critical}}$ for the two limits, assuming that breakdown (and completion of a charge carrying ring) is considered to occur if more than 50% ionization takes place; that is, if $n_e \approx 0.5 n_o$. Such a set of curves is shown in Fig. 5. The three curves labeled with symbols are for the distance d associated with 1, 3, or 4 pre-ionization sources in the ZT-40M discharge with a typical toroidal voltage of 1900 V, which is similar to the voltage around a single toroidal loop for 200-kA operation prior to breakdown. The solid curve with a pronounced minimum is the breakdown limit imposed on the plasma due to the convection term in Eq. (3). The vertical solid curve is the diffusion limit imposed locally by the requirement that $v_{\text{ionization}} = \langle v_p \rangle \alpha > D_1/a^2 = v_{\text{diffusion}}$.⁸ All curves are calculated assuming a volume preionization so that $a = 0.2$ m. The dashed curves show the result for four preionization sources with an assumed preionized layer of only $a = 0.01$ m near the wall, as might result from photoelectron emission rather than photoionization of the source gas. As before, the vertical curve (dashed) is the diffusion limit. The operating region of ZT-40M is shown in the dotted area. It should be noted that if a 10% ionization is used instead of 50%, the source dependent limit of P_o only changes by a factor of 2. The local quenching limit changes by a larger amount but is still orders of magnitude from experimental conditions.

The actual response of ZT-40M (in the theory) to changes in E/P is not obvious when displayed, as in Fig. 5, because E/P and P are not independent variables. If one examines the theoretical breakdown limit for constant E_ϕ as a function of d , he finds that P_{critical} increases as d goes up. As is clear from Fig. 5, the operating breakdown region for ZT-40M is several orders of magnitude inside the theoretical limits imposed by the source thickness a . If a source region of only $a = 0.01$ m width is assumed (as might be expected for photoelectron emission from the liner), the breakdown limits observed are much closer to the theoretical limit. It is believed by the authors that the preionization is in fact a surface effect and that a source region on the order of 0.01 m in width is indicated. The theoretical critical pressure at constant E_ϕ for three source region widths (0.01, 0.0075, 0.005 m) is plotted as a function of d in Fig. 6. All regions above a particular curve are

Fig. 5.

Breakdown limits predicted by the simple theory evaluated at 50% ionization. The curves labeled with symbols correspond to various numbers of sources in the case of ZT-40M ($\square$ = 4 sources, Δ = 3 sources, $\circ$ = 1 source). Also included are the limits due to diffusion and local quenching via the major radial drift. The dashed curves represent calculations where the source was assumed to be only 1 cm wide rather than the 20-cm width assumed for a volume preionization source.

accessible theoretically. Also included in Fig. 6 are three experimental points that have an apparent dependence on d , which is weaker than

Fig. 6.

Breakdown limit as a function of distance between sources for constant E_{ϕ} . The solid curves are for three different assumed source widths ($o = 3$ cm, $\Delta = 2$ cm, $\square = 1$ cm). The dashed curve shows the theoretical effect of doubling the initial toroidal field (for a source width of 1 cm). Also shown are the breakdown limits observed in ZT-40M for 190-kA operation.

theoretically expected. The dashed curve in Fig. 6 shows the breakdown limit predicted by the theory when twice as large an initial toroidal field B_{ϕ} is

present (0.26 T compared to the experimental 0.13 T, for a source width of 0.01 m).

V. CONCLUSIONS

The experimental data for breakdown in ZT-40M appear to have a dependence on the number of ionization sources (up to four) present. A simple theory has been presented that is qualitatively consistent with the observation but is quantitatively quite far off. One possible explanation for the numerical disagreement has been presented that indicates the preionization source may be of very limited extent (0.01 m) and is believed by the authors to account for the discrepancy. This theory indicates that further gains in the breakdown limit created by additional sources must be associated with decreasing distance from source to source, which is difficult beyond four sources for reasons of access to the discharge. Hidden in the formulation of the problem, however, is another dependence, $P_o, \text{critical} \propto E_\phi^2/B_\phi^4$, which is much more easily controlled than is the source separation, as shown in Fig. 6. A previous theory (Ref. 6), which only included the preliminary curvature and gradient B drifts and did not include the more dominant $\vec{E}_z \times \vec{B}_\phi$ drift that results from them, shows a weaker E_ϕ/B_ϕ dependence than this. If the theory presented here is correct, further gains in ZT-40M's operating regime, if needed, may be obtainable by increasing the initial toroidal field or decreasing the loop voltage. If it is desired to probe the regions of fill pressure below the present 1-mtorr limit, the first tests should be conducted by varying B_ϕ to values considerably higher than the present 0.13 T used for the majority of discharges to date. (Lowering E_ϕ would also be effective but requires an additional low voltage preionization bank.) Initial observations at lower B_ϕ show substantial increases in P_o consistent with the inverse B_ϕ dependence of both theories, but neither seems to be correct in the exponent. The actual dependence seems weaker than either theory implies, but because many uncontrollable variables change along with B_ϕ , absolute answers are difficult to achieve. The same statement may be applied in the case of the observed dependence of P_o on d which is weaker than the d^2 dependence the simple theory predicts. Because the plasma appears able to control the B_ϕ field once it is fully conducting, it is possible much higher initial fields may be applied to aid breakdown without harmful effects on plasma performance.

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