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BREAKDOWN IN THE PRETEXT TOKAMAK

by

JAY F. BENESCH

JUNE 1981

MASTER

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BREAKDOWN IN THE PRETEXT TOKAMAK

by

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DISSERTATION

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The University of Texas at Austin

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Breakdown in the PRETEXT Tokamak

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We discuss our experimental investigation of the breakdown phase in the PRETEXT tokamak, and the implications of our results for larger machines.

PRETEXT is a moderate sized machine designed for studies in tokamak start-up. Its basic parameters are: $B_T = 10$ kG, $I_p = 60$ kA, $R_0 = .53$ m, $a = .15$ m, pulse length 50 ms, $T_e = 200$ eV, $n_e = 10^{13}$ cm⁻³, and $Z_{eff} \leq 2$. The design of the machine is discussed, with emphasis on those elements of the design which make it particularly suitable for studying start-up. Its operation is then briefly discussed by reference to a typical shot.

We present the first data on the application of ion cyclotron resonance RF power to preionization in tokamaks. We applied 0.3-3 kW at 12 MHz to hydrogen and obtained a visible discharge, but found no scaling of breakdown voltage with any parameter we were able to vary. A possible explanation for this, which implies that higher RF power would have been much more effective, is discussed.

Finally, we present our investigation of the dV/dt dependence of breakdown voltage in PRETEXT, a phenomenon also seen in JFT-2. The breakdown is discussed in terms of the physics of Townsend discharges. Among the implications of this work are:

1. Volume ionization by ions must be included in any model of breakdown in tokamaks.
2. Low dV/dt in the application of the loop voltage during breakdown is desirable for physics, as well as engineering, reasons.
3. The limiter need not participate in the breakdown.

1. T. Sometani & N. Fujisawa, Plasma Physics 20, 1101 (1978)

Table of Contents

List of Tables	vii
List of Figures	viii
Chapter One - Motivation and Physics	1
I-A Background	1
I-B Preionization	7
Chapter Two - The Machine	15
II-A Vacuum System	15
II-B Toroidal Field System	18
II-C Poloidal Field System	22
II-D Ohmic Heating Power Supply	27
II-E Vertical Field Power Supply	31
II-F Decoupling Transformer	32
II-G Operating Characteristics	33
Chapter Three - ICRF Preionization	35
Chapter Four - Influences on Breakdown Voltage	43
References	63

List of Tables

PRETEXT Parameters	65
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Diagnostics	65
-------------	----

List of Figures

1. Diagnostic Access on PRETEXT	66
2. Toroidal Field Power Supply	67
3. Toroidal Field vs Time	67
4. HF Coil Field	68
5. VF Coil Field	69
6. OH Coil Field	70
7. Total External Field Seen by Plasma	71
8. Total Poloidal Magnetic Field	71
9. Stray Vertical Field of OH Coil	72
10. Ohmic Heating Power Supply	73
11. Primary Current, Secondary Voltage vs Time	73
12. Typical PRETEXT Shot	74
13. ICRF Initiated Discharge	77
14. Raw Data Sample - Breakdown Time and Voltage	78
15. Raw Data Sample - Unloaded Loop Voltage	79
16. Effect of Frequency on Breakdown Voltage	80
17. Effect of Bias Vertical Field on Breakdown	81
18. As 17, but with better Radial Field Setting	82
19. Effect of Limiter Bias on Breakdown Voltage	83
20. Effect of Working Gas on Breakdown	84
21. Effect of Pressure on Breakdown	85

Chapter One - Motivation and Physics

I-A Background

Following Papoular,¹ we will divide the start of a tokamak discharge into three phases: breakdown, plasma formation and current rise. In the first of these electron neutral collisions dominate the physics, so the Townsend avalanche and gaseous electronics provide the framework for the examination of this phase. When the number of free electrons is such that the electron-ion collision frequency is higher than the electron-neutral collision frequency, plasma effects become dominant because of the longer range involved in electromagnetic interactions, and the resistivity may be viewed as depending only on the plasma temperature and density. This happens when the electron density reaches about 10% of the original neutral density, and marks the start of the plasma formation phase. Since we are concerned about the resistivity of the plasma this collision frequency condition is appropriate for judging plasma effects, rather than the usual Debye sphere condition. Finally, after the plasma is substantially ionized, the current rise phase begins. The

distinction between the second and third phases is harder to make than that between the first and second, as it is a function of the amount of ohmic heating power available at the time - the division of the loop voltage between resistive and inductive components is not easy to model or measure. On the other hand, the toroidal current is so small during the first phase that inductive effects are negligible. The experimental work to be discussed herein deals only with the first of these phases, but the reasons for doing it are tied to all three, and so will be presented next.

The physics in a Townsend avalanche is dominated by the ratio E/p^2 . Most gaseous electronics research is done in linear discharges with flat plate electrodes and no magnetic field. Plate separation is generally one to ten millimeters, voltages range from .1 to a few kV, and pressure from .1 to 10 torr. The data available therefore covers well the E/p range 10-1000. Luckily, tokamaks are generally run towards the high end of this range. Unluckily, the electric field is of the order of 10V/m, and the pressure .1 millitorr, so both E and p have been reduced three orders of magnitude from the conditions under which all the data available has been taken. Things should scale, but....

Since the E/p range in which tokamaks have been successfully operated is rather limited, and the pressure is fixed to a narrow range by the need to avoid the production of runaway electrons, E is also restricted to a narrow range. The loop voltage required, on the other hand, will grow linearly with major radius. Where a medium sized machine like PLT ($R=1m$) requires a loop voltage of 60V during startup, TFTR ($R=2.7m$) will require about 150V,³ and a reactor will require 300-500V. While these voltages seem low, recall that these are secondary voltages, and that the primaries contain from forty to a hundred or more turns. These voltages then become serious in the primary, which is what the power supply has to drive. Further, these voltages are frequently obtained by biasing the primary with a negative current to a limit determined by mechanical (air core) or saturation (iron core) effects, making a resistor across the primary, and then breaking the bias supply out of the circuit. This breaking switch is a severe technical and financial problem. One must break a current of about 100 kA and then hold off the inductive kick of 30kV or more. One reactor study⁴ estimates that a solid state switch for this function would include 6400 SCRs and cost over \$10M. Further, the primary is stressed severely and so more prone to mechanical or

insulation failure than other coil systems, like the toroidal field system. More cost is involved in beefing it up. Finally, it would be nice to be able to use superconducting ohmic heating coils to lower the cost of operating the power plant - but superconducting coils cannot withstand the stresses involved in the dI/dt required to produce a loop voltage of 300-500V.

As mentioned above, there is a limit on the current which may be run through the ohmic heating transformer. This is in fact a limit on magnetic field, rather than current. In an air core transformer the field is limited by the ability of the materials in the coil to resist the deforming forces due to the magnetic fields. The iron in an iron core transformer will saturate if the applied fields are too high, changing the stray fields drastically, and therefore affecting the plasma significantly. This limitation is commonly expressed in terms of volt-seconds, as it is then easy to relate to the secondary. An ohmically heated tokamak discharge typically runs at a loop voltage of 2-3 V during the current plateau. Volt-second loss during startup is more than one tenth of the total volt-second consumption of a discharge, in PLT⁵. In discharges with large amounts of additional heating from neutral beams, the loop

voltage can drop as low as 0.1 V ⁶. In this case the volt-second loss during startup, $0.3\text{--}0.4 \text{ V-s}$ in PLT, is equivalent to shortening the discharge plateau by 3-4 seconds.

Atomic physics also plays a large role in tokamak startup, as one starts with a neutral gas H_2 , goes through a period where five species, H , H_2 , H^+ , H_2^+ , and e^- , are important, and finish up with a fully ionized plasma. It takes about 100 eV to fully ionize an H_2 molecule. One must provide the molecular ionization energy, 15.4 eV; the dissociation energy for this ion, roughly 10 eV; and the ionization energy of the remaining H atom, 13.6 eV. The products of each of these collisions will generally come off in excited states and radiate away some energy before colliding again. The heavy ions and electrons will generally have some kinetic energy after each collision, and this must be provided as well, so that while 39 eV is the absolute minimum of energy required, 100 eV is a better typical number. Enough energy to ionize all the molecules in what will be the plasma volume must be provided in a time less than the particle confinement time, for otherwise one will not get to full ionization. Further, until a toroidal current and flux surfaces are established, particles will drift to the walls in the toroidal field, knocking

junk off the walls and cooling the discharge. One cannot establish a toroidal current of sufficient magnitude to produce flux surfaces, given the inevitable stray fields in a practical device, until the plasma formation phase is well underway. One therefore inevitably gets impurity influx during and after the breakdown phase. Uping the voltage would help in getting through this phase more quickly, but the voltage is already higher than is comfortable. The power requirement described is often termed the radiation barrier, as the impurities coming off the wall, predominately carbon and oxygen, cool the plasma by line radiation unless the power input is such that they, as well as the hydrogen, can be brought to high ionization states quickly. An electron temperature of at least 50 eV in most of the plasma volume is needed for this.

It therefore behooves us to examine in more detail the startup of tokamak discharges, in the hope that with a better understanding of the physics involved we may lower the peak electric field applied, the rate at which it is applied (dV/dt) and the volt-second consumption during this period of the discharge. Lowering volt-second consumption during startup allows one to lengthen the plateau time, and it is in the plateau that power, and

money, would be made. Lowering E and dV/dt would make much easier the task of the fusion reactor designer, by enlarging his option space for trade-offs, and would lower system costs as well. These must be done while maintaining or decreasing the duration of start-up, so as not to increase impurity content, as that would make the radiation barrier higher.

I-B Pre-ionization

Methods for reducing the duration of the breakdown phase, and therefore volt-second consumption, are generally termed preionization. This is due to the role they play in the Townsend avalanche. In a standard linear discharge with electrodes, the current gain in the avalanche is given as a function of the distance from the anode, d ; the number of ionizations per centimeter, Townsend's first ionization coefficient α ; and the efficiency of a secondary source of electrons, $\gamma \ll 1$. The current gain is then $e^{\alpha d} / (1 - \gamma e^{\alpha d})$. The current grows exponentially until $\gamma e^{\alpha d}$ becomes close to 1, at which point the expression blows up and the current is limited primarily by external circuitry constraints, rather than

physics. One can speak as easily of the doubling time characteristic of the exponential growth phase as the doubling distance, or of the number of generations required to go from a single seed electron to the point at which the denominator above vanishes. Obviously, if one starts with more than a single electron, the number of generations and the time required will decrease. The provision of a substantial number of seed electrons is termed preionization.

The methods of preionization used in tokamaks are almost as numerous as tokamaks, so we will discuss only the main ones here. These range in sophistication from providing a small amount of UV with an ion gauge to 100kW of electron cyclotron RF power.

The simplest scheme for preionization is that used on Alcator-A. This machine has a standard Bayard-Alpert gauge for monitoring pressure on a long stalk which extends outside the toroidal field. Breakdown occurs iff the gauge is on. This is obviously due to photoionization, as no particles can possibly get into the plasma volume from the gauge location.

TFR 400 also used UV photoionization, but with a dedicated source which provided an ionized fraction 10^{-6} in about 1/30th of the torus volume. In this machine there was a time lag of roughly 0.4 ms

between application of the loop voltage and an electron density measureable with a microwave interferometer.¹

At the next level of complexity is the breakdown oscillator. A ringing discharge of frequency 2-50 kHz is imposed on the ohmic heating coil, or another coil of similar geometry but lower inductance. Five to ten cycles are generally sufficient to produce a visible discharge. This is typically accomplished by ringing a capacitor into the primary of an air core transformer whose secondary is in series with the ohmic heating coil. This has been used successfully on several of the small tokamaks built by R.J. Taylor,⁷ but proved to be incompatible with the solid state switchgear used on PRETEXT. It seems to work well on smaller machines using mechanical or arc switchgear. The high voltages required to swing even a small current at this frequency on larger machines seems to eliminate it from consideration for future devices.

FT-1 and TEXT use a single negative voltage spike, of duration one and forty milliseconds respectively, for preionization. This works well on TEXT, allowing the main discharge to go forward with loop voltages as low as 12V, probably due to the extremely low stray fields attained on this machine.⁹

The standard method of preionization on PRETEXT, as well as on the machines at General Atomic,¹⁰ is the supply of a small current of electrons at energies of 40-60 V from a filament in the shadow of the limiter. The filament is positioned so that it is protected but the electrons from it will have drifted below the limiter before completing an orbit. In PRETEXT the emission current is generally 1 mA, which is sufficient to provide a visible cylinder of plasma at R_0 when the toroidal field is fired. We have made no attempt to measure the characteristics of this plasma. The downward drift of these electrons is governed by the stray vertical field due to misalignments in the toroidal field coils. This was measured with an electron beam in a DC field of 0.7 kG to be about one part in four hundred. The measurements described in Chapter Three were made with a dc radial field of 7 G, a toroidal field of 8 kG, and without a bias vertical field during breakdown to compensate for the stray field described. In doing the research recounted in Chapter Four, it became clear that such a bias field was necessary, so it was added.

A means of preionization which is currently the subject of much research is the use of electron cyclotron radio frequency (ECRF) power. The ECRF resonance frequency is 28GHz/T, so the wavelengths

involved are one centimeter or less. This may be introduced into the vacuum vessel via waveguide, which is quite convenient.

There was quite a bit of work done in the period 1970-1975 involving the application of small amounts of ECRF power to smaller machines with fields less than 1 T, in the centimeter band.¹¹ It proved quite useful, but there were no sources available suitable for attempting the same thing in the subsequent higher field machines until quite recently, and it is still impossible to get significant amounts of power at any frequency above 35 GHz, or 1.25 T. A comparison of the effectiveness of ECRF and of a negative voltage spike for preionization was recently made in FT-1. The two methods proved equally effective in this test, which is unfortunate as ECRF is so much more difficult technically. Still, the ECRF pulse in this experiment was only two microseconds long, so no equilibrium was reached.

ECRF preionization became a topic of much interest after the recent theoretical work of Peng, Borowski and Kammash¹² showed that it should be possible to actually get through the radiation barrier via the application of sufficient amounts of ECRF, something much more desirable than mere preionization. There have been several

experimental attempts made to check this prediction during the last year. Two of these have been published in preprint;^{13, 14} the details of the others will emerge when the proceedings of the 4th Topical Conference on RF Heating of Plasmas, Feb. 1981, are published later this year.

The results of Gilgenbach et al on the results of ECRF preionization in ISX are best summarized simply by quoting their abstract:

Preionization experiments have been performed on a tokamak by injecting about 80 kW of microwave power at 35 GHz for up to 15 ms. Microwave absorption occurs at the electron cyclotron and upper hybrid resonance frequencies as predicted by theory. Preionization causes substantial (40%) reductions in loop voltage during the initial phase of the tokamak shot. Flux (volt-second) savings with preionization are about 30% in the first 2ms or about 2% of the total flux expenditure in a tokamak shot. The plasma current starts 200 μ s earlier and rises 1.4 times more rapidly in the preionized case. Electron densities of $5 \times 10^{12} \text{ cm}^{-3}$ can be sustained with only a toroidal magnetic field during microwave injection. The bulk electron temperature in the preionized plasma is about 10 eV although there are indications of higher electron temperatures (50 eV) in the upper hybrid resonance layer. During the early stages of ohmic heating the preionization is effective in decreasing the peak of the radiated power.¹³

These results were somewhat disappointing because of the low temperature reached in the bulk plasma - the radiation barrier was penetrated only in the vicinity of the resonance layer, if there. It would therefore require an array of ECRF sources at different frequencies, and therefore different resonance radii, to get through the radiation barrier in most of the plasma volume before the application of the ohmic heating field. This is clearly impractical, because the cost of such an array of sources would be enormous, as would the array.

The paper by Ohkubo et al,¹⁴ reporting work done on the JIPP T-II stellerator, is somewhat more encouraging. They were able to obtain discharges subsequent to preionization with loop voltages as low as 8V, which I believe to be a record for ohmic discharges. This is probably due to the excellent electron confinement, even during the preionization phase, which is characteristic of the existence of flux surfaces, externally produced in stellerators. Thus these results augur well only for stellerators, as tokamaks do not have flux surfaces until well into the plasma formation phase, and therefore after the loop voltage has been applied.

These results indicate that ECRF is not the panacea Peng et al¹² suggested it would be, and that getting through the radiation barrier via the injection of ECRF power would be an exceedingly expensive undertaking, if the sources become available at all. It is therefore somewhat strange that the other vacuum resonance available, the ion cyclotron, has been heretofore ignored. As the ion mass is at least 1840 times the electron mass, the ion cyclotron resonance frequency is no more than 1/1840-th of the electron cyclotron. High power RF sources are easily obtainable at frequencies suitable for the toroidal fields of any of the tokamaks operating or foreseeable. Perhaps this neglect is due to the general conditioning of plasma physicists in the view that the electrons do all the moving. In any event, we have applied small amounts of ion cyclotron radio frequency power (ICRF) power to the PRETEXT tokamak, and will report on the results of our experiments in Chapter Three. Before doing this, however, we must discuss the design and the operating regime of the tokamak itself.

Chapter Two - The Machine

The basic parameters provided me in June 1976 for this tokamak were: major radius 50 cm, minor radius 15 cm, toroidal field one Tesla, pulse length 50 ms and maximum plasma current consistent with MHD stability. This section of the thesis will describe the design, construction and operation of the PRETEXT tokamak. It will conclude with a discussion as to how well the machine meets the brief above. The diagnostic outputs for a typical shot will be displayed.

II-A Vacuum System

The desire for good diagnostic access and spatially resolved spectroscopic scans dominated the design of the torus. There are a total of 42 ports, with an area of 3577 cm^2 . These include four 8" conflats, five 4.5" conflats, five 2.75" conflats and sixteen 2.125" conflats. There are also four port boxes with large, racetrack shaped ports. The top and bottom ports are 6x22 cm, clear area 125 cm^2 . The large outside ports are 12x35 cm, clear area 394 cm^2 . One of these port boxes will be dedicated to Thomson scattering, the other three to spectroscopy at various wavelengths. Figure 1 is a

scale drawing of the PRETEXT vacuum vessel showing the viewing area of each port and the diagnostic assignments to those ports in November 1979.

The vacuum vessel is divided into four symmetric quadrants with four voltage breaks. The voltage breaks are bridged with 10 KOhm resistors. Without these resistors the loop voltage did not divide evenly among the quadrants as they have not the same capacitance because of the varying diagnostics attached to each. The voltage breaks are oversized Viton O-rings shielded from contact with the plasma by a labyrinth. The vacuum seals on the port boxes are adapted from a design by Hawryluk¹⁵ and will accept either elastomers or wire O-rings. Currently the elastomers are installed. The base pressure of the basic vacuum vessel is 6×10^{-8} torr. With all diagnostics installed the base pressure is an order of magnitude greater. Most of this pressure is due to water, as we do not bake the vessel.

The circular portion of the vacuum vessel is made from 304L stainless steel petrochemical process 90° bends. The port boxes are welded from 304L stainless steel plate, 1.43 cm thick. After leak checking as quadrants, the vessel was chemically cleaned with the

Diversity process before assembly. Some time after operation began, much of the vessel was accidentally plated with aluminum and brass. This was removed with a nitric acid wash in situ, as far as possible. Some of the deterioration of our vacuum conditions is due to loading of the sputtered material remaining. All observable leaks since the original assembly have been in elastomer seals. We do not use vacuum grease on the elastomers, except on sliding seals for probes. The latter are double O-ring, differentially pumped feedthroughs.

We are using a Sargent-Welch 3133 Turbo-Torr vertical shaft turbo-molecular pump backed by a 50cfm two-stage mechanical pump. The top flange of the pump is 35 cm below the torus centerline. The system is conductivity limited to a pumping time constant of about one second. The turbo pump sees a pulsed magnetic field of approximately 300G due to the ohmic and vertical field coils. This should not be a problem.¹⁶ We do not have a gate valve above the turbo pump. This means that the entire vessel must be brought up to at least one torr, and preferably atmospheric pressure, any time the turbo is shut off, in order to prevent backstreaming of the turbo pump oil. The vapor pressure of the turbo oil is much higher than we expected. Had we known this, a gate valve would have been installed.

There is an interlock on the foreline of the turbo which will close a valve at the backing port of the pump if a set pressure is exceeded. This is to prevent the turbo from ever seeing a reverse pressure ratio greater than its own compression ratio, as this is fatal to the pump. Accidents above the turbo can do little damage to it if it is screened from large, hard objects. We have accidentally popped a 1.5" inlet gate valve open with the turbo at full speed without damaging the pump.

We are using a Granville-Phillips 270-004 controller with an ETI 8140 nude gauge to monitor vacuum pressure. An attempt to build a fast Schulz- Phelps gauge controller for use in monitoring gas puffing proved unsuccessful. This gauge was later calibrated for absolute pressure in hydrogen by reference to a capacitive manometer. The hydrogen pressures quoted herein are so derived. Nitrogen pressures are simply read from the Bayard-Alpert gauge.

II-B Toroidal Field System

At the beginning of this project we had on hand a 500 kJ capacitor bank, in the form of 160 10 kV, 60 μ F capacitors. This was to form the basis of the toroidal field supply. Given this energy

and the following constraints: toroidal field one Tesla, ripple less than 3%, $R_0=50$ cm, $a=15$ cm, and 100 s repetition rate, design of the vacuum vessel and TF coil system proceeded simultaneously. The code used to model the TF coils was written from the documentation of MAFCO, a code available at MFECC. In order to minimize cost and maximize L/R time, it was decided to wind the TF coils from .5" x 2" solid copper bar and rely on air cooling. The coils have an L/R time of .25 s at room temperature and .18s at peak temperature, which occurs after eight hours of running at full field. Our runs have always been less than six hours, and heating in the coils has not been a problem. The measured coefficient of heat transfer by convection is $7.5 \times 10^{-4} \text{ W/cm}^2 \text{ } ^\circ\text{C}$.

There are sixteen toroidal field coils, with inner bore 22", outer diameter 32" and nine turns each. These are not wound as an Archimedean spiral, but rather bent at a given spot to jump from one turn to the next. The current return is then brought from the inside to the outside of the coil at this spot, to form a dipole in the radial direction, lowering stray field due to the current transfer from turn to turn. Current transfers from coil to coil are done in .5" x 3" bus. These provide one net turn in the toroidal direction,

which must be balanced to reduce stray fields. The compensating turn is made in the form of two 15kV, 500MCM copper cables which are clamped to either side of the 3" bus. This provides a very good dipole whose field drops off with a scale length of about 5cm.

Figure 2 is a schematic of the basic TF power supply. It differs from those of most capacitor driven tokamaks in having a power crowbar, rather than simply allowing the field to L/R decay.

C_1 consists of twenty groups of eight 10kV capacitors. Each of these groups is switched by a 7703 ignitron. The output of the ignitron goes through a .4 ohm, 40 μ H isolation coil made of #3 nichrome, and then to a collection bus. The nichrome resistor isolates each group of eight caps from the other nineteen. If a cap fails, only the other seven in its group dump into it directly. Most of the energy of the other nineteen banks is dissipated in the nichrome before it can get to the sick cap. This minimizes the chance of an explosion or fire, at a cost of about 3% of the top field possible without the nichrome resistors.

C_2 consists of 64 groups of ten 3100 μ F, 450V electrolytic capacitors. Each group is connected to the output bus via a 300 A, 1000 V_{RR} diode, represented here by D_1 . D_2 is six 2800 A, 500 V_{RR}

diodes in parallel. A small 600V gas surge protector is connected across points A and B. It acts to protect the electrolytic bank and its associated diodes from destruction if the switches S_2 or S_3 close while the 10 kV bank is still charged to more than 480 V. It dies in the process, but is much easier and cheaper to repair or replace than the caps and diodes.

S_1 is the twenty 7703 ignitrons mentioned in the paragraph before last. S_2 is two 37207 ignitrons, and S_3 is a mechanical switch designed for this project by Paul Wildi. S_2 provides the timing accuracy required to trigger the crowbar bank just when the current from the 10 kV bank is at its peak, and S_3 eliminates the power loss in the ignitron arcs. Further, the 37207 ignitrons are designed to transfer only 300 coulombs each, and the electrolytic bank holds up to 1250 C. The ignitrons can handle this alone, even though it is twice their rating, given the long pulse length, but their life is drastically shortened. The presence of the mechanical switch helps here too.

The switching sequence which produces figure 3 is as follows: S_1 and S_3 are triggered simultaneously. S_1 closes immediately, S_3 after a delay of about 14 ms. S_2 is triggered at 6.9ms, and closes

immediately. S_3 assumes the burden of TF current some 7ms after S_2 closes. This provides a much greater margin of safety than is required by S_3 's jitter of 1ms.

This power crowbar configuration provides a field of 10 kG $\pm 5\%$ for 60 ms.

II-C Poloidal Field System

The poloidal field coils on PRETEXT were located with the aid of a program written by George Cardwell of the FRC staff for the design of TEXT. This program provides values of the vertical field along the midplane of the machine as a function of major radius for the plasma current, the images of the plasma current in the iron core, the ohmic heating coils, the vertical and radial field coils and the total vertical field. It can also provide plots of these fields. Such plots are shown in Figures 4-8.

The major constraint on the placement of the PF coils was the desire to keep all radial and vertical chords of the plasma free of obstructions to observation. Beyond this, we had the usual MHD constraints on the vertical field profile. Finally, we had an additional, and most serious, constraint on the OH coils. Since we

had decided to use an iron center post without return yoke as the basis of our ohmic heating transformer, the current in the OH coils must change as a function of time in order to maintain a constant plasma current, as in an air core transformer, though the derivative need not be as large as in that case due to the better coupling provided by the iron. Still, the changing primary current produces a changing stray field which can be of considerable size. This would put a significant strain on whatever vertical field supply is used, and so is to be avoided. The OH coils were therefore located so as to give minimum stray vertical field along the midplane. The final results of this long search for optimal position are shown in Figure 6. In figure 9 we compare the numerical predictions of the code for the vertical field along the midplane with measured fields in the four port boxes. The agreement with theory is remarkable, especially in view of the fact that each coil package provides a field of some 200G in the plasma volume. We did not expect to obtain a vector sum of the fields of the four coil packages this close to zero throughout the plasma volume. The vertical field of the OH coils is less than 2% of the equilibrium vertical field on the midplane, and less than 4% throughout the plasma volume. This is well within the

capabilities of our vertical and radial field supplies. Indeed, we can basically ignore it.

The choice of an iron core was due in large part to a desire to obtain some experience with iron core tokamaks before TEXT came into operation. It also provides cost benefits, as some $2/3$ of the equilibrium vertical field is provided by images of the plasma current in the iron core. The exact portion of the required VF provided is a function of the plasma current profile, and so is difficult to ascertain exactly, and impossible to measure directly. All this makes position control more difficult than in air core machines, but still makes things cheaper, as power supply requirements are lowered considerably. According to a French study,¹⁷ the ratios of costs for an iron core tokamak with return yoke, an iron core without return yoke, and an air core are 1 : 1.36 : 1.55. We chose the middle way.

About $2/3$ of the volt-seconds in the core go into LI, and about $1/3$ into maintaining the plasma current once we have it. This latter part would be much reduced by the addition of the return yoke. We can run in a saturated center-post mode by upgrading the VF and HF

supplies if higher plasma currents prove desirable, but have not seen the need as yet.

Once the OH coils were located in space, the choice of number of turns and conductor size remained to be made. The code cited above also produced values for all the self and mutual inductances in the system. The interaction between these numbers and our rough ideas on the OH VF and HF power supplies led to the following: 120 turns in the OH coil, 56 inside and 64 outside the major radius, divided evenly above and below the midplane. We decided that 2/0 square copper magnet wire was the largest we could easily wind with the tools available in house. Plywood mandrels of appropriate diameter were turned, and the coils then wound in double pancakes on a large turntable. To reduce tooling, we used the same mandrels to wind the VF and HF coils as well. This resulted in very little compromise on the latter two fields, as may be seen in Figures 4 and 5. These coils were wound as single pancakes, as there are only four turns in each coil pack.

We have had significant dielectric problems with our OH coils. The first coils were wound with Nomex insulated copper, and then potted for us by Westinghouse. There was no penetration of the

epoxy into the coil- the paper was completely dry inside the outer edge. These failed over time, causing much delay. Subsequent coils were insulated with fiberglass of various types over Nomex, or over bare copper, and vacuum impregnated with various epoxies in house. Our current procedure, developed after 18 months of trials, is as follows. Half lap bare copper wire with 1.5" wide, 16 x 17 weave, volan treated fiberglass tape while winding the copper onto the mandrel. After completing each double pancake, band it with stainless steel and remove it from the mandrel. Band with epoxy soaked fiberglass tape. Once this has hardened, remove the steel bands. Solder two such double pancakes together to form one OH coil. Half lap this entire coil in glass tape. Place the coil in a mold inside a vacuum tank. Heat the coil to 70 °C, while evacuating the tank. At the same time, heat the two components of Scotchcast 235 or 237 to 60°C and then mix them. Pour into another vacuum tank and heat to 70°C while outgassing the epoxy. Transfer the epoxy under vacuum into the coil mold in the first tank. When the epoxy has filled the coil, bring the large tank up to atmosphere. This will drive the epoxy more deeply into the coil. Repeat the last three instructions until no more epoxy will penetrate the coil. Bring the

large tank to atmosphere, and heat the coil to 90°C. Hold at this temperature for 3-4 hours, by which time the epoxy should have set into a firm gel. Increase the coil temperature to 120°C for two hours for the final cure.

All this was technology we had no intention of or desire to learn. These dielectric failures have caused close to a year's delay in our experimental work. The VF and HF coils were done as a wet lay-up job in house originally, and have given no problems as yet.

II-D Ohmic Heating Power Supply

The basic ohmic heating power supply is shown in figures 10 and 11. Much of the work on this supply was done by Steve Eckstrand, but it is impossible to delineate specific contributions on the portion of it I will describe. In this section, therefore, "we" is not editorial, but rather refers to Steve and myself.

There is one novel feature on this supply: there is no breaking switch per se. In a normal OH circuit, the transformer is biased with one power supply, here C_1 . When the discharge is to begin, a resistor is made across the OH coil and the bias supply is broken out of the circuit, producing a voltage spike followed by an

L/R decay. The plasma current is initiated by the spike, and rises thereafter because of the loop voltage induced by the L/R decay in the primary. A high voltage capacitor bank comes in as the primary current crosses zero, and brings the plasma current up to its plateau value. The breaking switch required to remove the bias supply from the circuit, while not hard to make for small machines, becomes an increasing problem as the energy in the OH circuit grows. For reactors, the cost of this switch may be as much as 20% of the cost of the entire OH supply.

In our scheme, the $S_3 - C_2$ combination performs the functions of the breaking switch, L/R decay, and high voltage cap bank described above. We ring the energy from the inductor (OH coil) into C_2 and then back into the inductor. This provides a sinusoidal voltage instead of one which begins with a sharp spike. This allows us to compare various preionization schemes handily, as we can arrange the initial vertical and radial fields so that there is no breakdown without preionization, yet a good discharge with it. Alternatively, the initial fields may be optimized for breakdown, which involves nulling the stray fields due to the TF coil misalignments, in which case the discharge will begin with no formal

preionization, albeit at a higher voltage and later time in the half wave. By changing C_2 we can vary the period over which the startup takes place, allowing us to check for time dependence in this process. We have run with $C_2 = 250, 500$ and $1750 \mu\text{F}$, giving periods of 7, 10, and 19 ms for the half-wave.

As indicated above, C_1 biases the iron core. This takes 41ms. At 40ms, the solenoid driving VB, a vacuum interrupter, is energized. It takes 2ms for the interrupter to open. At 41ms S_3 is triggered. As the left loop has much lower inductance than the right, C_2 attempts to drive a clockwise current in this loop, thereby turning off SCR's 1&2. We now have only one loop in the circuit, with a virtually empty capacitor and a fully charged inductor. The energy from the inductor rings into C_2 and then back into the inductor. The dI/dt in the inductor during this half cycle is high enough to initiate the discharge and bring the plasma current to the desired value. S_4 , which has been protected from the high voltage in C_2 by D_4 and D_5 , each of which is rated at 4kV, is now triggered to hold the plasma current at the desired value for the remainder of the discharge - the current plateau. Meanwhile, back at 42ms, the vacuum interrupter has opened. The SCR's in this leg had already been

commutated off by S_3 and C_2 , so no current was flowing in this leg and therefore no arc was drawn when the interrupter opened. The voltage on C_2 at 42 ms is under 1500V, while S_1 and S_2 are rated at 1000V each. Were VB not to open, the SCR's in series with it would fail due to overvoltage. The presence of the vacuum interrupter allows us to use 1 kV SCR's in place of 4 kV SCR's. The lower voltage components are much more rugged than the others, and the system is much more reliable in this mode than it was without the breaker and with the 4 kV SCR's. Further, a failure is much cheaper in this mode than in the other, as two of the low voltage units cost less than one of the high voltage. The combination of SCR's and a vacuum interrupter produces a switch with very nice current carrying and voltage hold-off characteristics at a low cost. Further, jitter is much lower than for an interrupter alone.

Up to five modules of the C_3, S_4, D_6, D_7 type may be placed in parallel behind D_4 and D_5 . These are then triggered in sequence, with each bank first commutating off the previous and then acting to sustain or raise the plasma current. At least a second bank is necessary for heavy gas puffing, as otherwise the current channel

constricts too much as the edge is cooled by the incoming gas, and the plasma disrupts.

II-E Vertical Field Power Supply

As was mentioned above in section B, images of the plasma current in the iron provide about $2/3$ of the vertical field required for stability. When the machine was originally designed, a much flatter current profile than exists was assumed. With this flat profile, the images in the iron would have provided 90% of the VF required. A power supply sufficient to provide 1 kA into the VF coil was therefore built - a big linear amplifier with 100 transistors in parallel emitter-follower arrangement as the output stage. This proved inadequate for the current profile as achieved, with its higher requirements for external, supplementary field. Attempts to scale the transistor array up produced many dead transistors. Several of the modules described in the last paragraph of the preceeding section were therefore pressed into use as a VF supply, though this gave us poor control of radial plasma position. The center of the current channel typically moves about a cm during a discharge. Vertical stability is quite good, and a dc power supply

suffices to null the stray field from the TF coil, keeping the discharge centered.

II-F Decoupling Transformer

The final subsystem to be discussed in this design section is the decoupling transformer. The OH and VF coils of a tokamak are always coupled inductively. In our case, the mutual inductance is about 160 μH . The rapidly changing current in the OH coil during the plasma initiation and current rise phase will therefore induce a substantial voltage in the VF coil, which the VF power supply must then buck out. This would increase the cost of the VF supply considerably, as volts cost more than amps in this business. One therefore builds another transformer with the same mutual inductance as occurs between the OH and VF coils on the machine, but connected so that this mutual inductance is opposite in sign to the first. The self inductance in the windings of this transformer can be much lower than those in the coils on the machine, as one has no other constraints and so can couple the two tightly. By using a decoupling transformer one is trading self-inductance in each of two, now

independent, systems for mutual inductance between them. It is much easier to handle two independent systems than one large coupled one.

Our decoupling transformer is a pair of coaxial solenoids wound of 3/0 cable. It adds 5% to the inductance of the OH circuit, and 20% to the inductance of the VF circuit.

II-G Operating Characteristics

In Table 1 we list the basic parameters of PRETEXT, and in Table 2 the diagnostics which have been installed on it at one time or another. Many of the latter have been moved down to TEXT. The predictions in Table 1 were made in May 1978; the "Achieved 5/81" column gives our best values of these parameters to date. As is usual, not all of these were obtained on the same discharge. For instance, high density discharges are colder than 200 eV, and run to lower plasma currents, as we have a fixed amount of ohmic heating power available. We have met all of the requirements in our original brief, as given in the first paragraph of this chapter, except for plasma current. This could probably be met for short discharges with the system as is, or for the entire 50 ms if a feedback system on vertical field is installed, as we are not using the OH power supply

to full capacity. In the course of the breakdown studies described in the last chapter of this thesis we advanced our current record by over 20%, and still hope to reach 80 kA some day.

In figure 12 we graph the outputs of the diagnostics in use on shot 11, 2 April 1981, which we have designated our typical shot. This shot was taken with 8 kG toroidal field, hydrogen fill pressure 2×10^{-4} torr, 3.5 G radial field, 12G vertical field during breakdown, and that displayed on channel 14 thereafter. The diagnostics were triggered at the same time as the vacuum interrupter in the OH power supply. Breakdown occurs about 3.2 ms after the trigger.

Chapter Three - ICRF Pre-Ionization

We will now discuss the use of the ion cyclotron resonance as a means of preionization in the PRETEXT tokamak, and its applicability to other machines. The first section of this chapter will discuss preionization in general and the particular suitability of the PRETEXT tokamak for studies thereof. The second will describe the particular experiments done on ICRF preionization. The third will cover an exceedingly crude model of the physics involved and the implications thereof. Our conclusions follow.

Pre-ionization is generally required in tokamaks to insure reproducible discharges. The techniques used range from turning on an ion gauge to applying 100kW of ECRF. Effective preionization will often reduce volt-second consumption during startup to some extent, but these gains are rarely major in comparison to the total expenditure during a long discharge. There is a second goal available, however, which would represent a major savings : getting through the radiation barrier throughout the plasma volume before the application of the ohmic heating field. Gilgenbach et al¹³ have shown this to be possible in a narrow region around the resonance

layer with the application of 100kW of ECRF in ISX. Several such supplies at different frequencies to match the different toroidal fields at various major radii would be needed to burn through everywhere. Such a setup would be bulky and expensive even at the frequencies of interest in ISX, and might be prohibitive at the higher frequencies needed on larger machines with higher toroidal fields.

Examination of the other vacuum resonance available, the ion cyclotron, is therefore of interest. Commercial sources are readily available in the frequency range of interest. Indeed, if ICRH becomes a standard feature on tokamaks, there is no reason the source used could not be turned on earlier in the discharge sequence. Again, several sources matched to different radii might be necessary to get through the radiation barrier everywhere.

PRETEXT is highly suitable for the study of preionization because of the shape of its ohmic heating pulse during the current formation and rise phase: half a period of a sine wave rather than the usual LC or L/R decay, with their high initial loop voltages. With no preionization, breakdown occurs at a loop voltage of about 15V (5V/m) under standard conditions. It is possible to arrange the

initial horizontal and vertical fields such that no breakdown occurs without preionization, yet reasonable discharges are obtained with it. Thus the effects of the preionization technique may be studied independently of other variables. We discuss below our use of small amounts of ICRF power for this purpose.

The antenna used in this work was originally installed for the Alfvén wave heating research being done on PRETEXT.¹⁸ It is a D-shaped loop which encloses the plasma poloidally; the straight vertical member is outside the vacuum vessel. This antenna has a resistance of about .5 ohms at 12 MHz, the frequency used in this work. It is therefore necessary to match the 50 ohm transmitter output with the antenna via a capacitive divider. We typically get 75% of the transmitter power through the match box. The transmitter provides 0.3-3.2kW at 12 MHz. The powers cited here and below are those measured at the transmitter output. Attempts were made to measure the antenna power with a current transformer, but the Q of the circuit proved very sensitive to the exact orientation of the transformer, so it was removed.

In figure 13 we show a discharge initiated with 300W ICRF. The toroidal field is 8 kG, the filling pressure 1.6×10^{-4} torr of H₂. As mentioned above, we apply the toroidal E field in the form $V \cos \omega t$. On this shot, $V=3.4\text{V/m}$, and $\omega=50$ (half period of 20ms). The avalanche begins at $E=2.8\text{V/m}$, and takes roughly 3 ms to proceed to full ionization, a time consistent with the recent theoretical results of Kubarev et al.¹⁹ Following this shot the RF power was gradually increased to the maximum available over a series of ten shots. No change in the breakdown was observed. We then dropped back down to 300W and did a breakdown voltage vs pressure scan, over the range $1-3 \times 10^{-4}$ torr. A standard curve ensued, with the minimum at the original filling pressure, as expected. Returning to 1.6×10^{-4} torr, we did a toroidal field scan over the range 5.5-9 kG. All shots with the resonance inside the limiter appeared identical.

We will now look at the interaction between a single proton and the ion cyclotron wave. It is impossible to do a power balance even for a single particle as almost none of the cross-sections required have been measured in the energy range of interest. The only ones located were those for charge exchange, ionization, and Lyman α emission. The last two are nearly equal, but the first is

always at least an order of magnitude bigger than either of the others. It will obviously be the dominant loss channel at high proton energies, so we will balance only charge exchange against ionization. Still, the proton must pass through energy regimes where a wide variety of elastic and inelastic processes will provide significant loss channels. Unfortunately, even the total elastic and inelastic scattering cross-sections are unavailable in this energy range. The estimates given below will therefore be optimistic; how optimistic we cannot say.

In a circle of radius a , with current $I e^{i\omega t}$, the induced $E(r) = \frac{1}{c} \omega \frac{4I}{c} \frac{a}{r} [K(r/a) - E(r/a)]$. At $r = a = 16\text{cm}$, $[] = 0.74$, and, $E(\text{v/cm}) = .23 I(\text{A})$ at 12 MHz. Our antenna is somewhat longer than such a circle, so we will take $E = 0.2 I$. The $[]$ falls to 0.37(50%) at $r/a = .22$. As the resistance of the antenna is .5 ohm, the power is then $I^2/4$.

300 W $\rightarrow$ 30A peak $\rightarrow$ 6V/cm at the antenna

3.2kW $\rightarrow$ 110A peak $\rightarrow$ 22V/cm at the antenna

100kW $\rightarrow$ 630A peak $\rightarrow$ 130V/cm at the antenna

$v = n\sigma v = 7 \times 10^{12} \sigma 10^6 / T_1$ at 2×10^{-4} torr

N = number of cycles of 12 MHz between charge exchange collisions

$$N = \frac{12 \times 10^6}{v} = \frac{1.7 \times 10^{-12}}{\sigma \sqrt{T_i}} \quad (1)$$

$$T_i = k_B \frac{e^2 E^2}{8 m_p} t^2 = 8.3 \times 10^{-4} E^2 N^2 \quad (2)$$

At 5 keV, $\sigma(c-x) = 8.5 \times 10^{-16} \text{ cm}^2$.²³ Plugging this into (1) and substituting in (2), we get $T_i \approx 7 \text{ keV}$ for 100 kW. These are single particle energies, not temperatures, but we will use T_i anyway. At this energy the charge exchange cross section is ten times the ionization cross-section, but we are putting in enough energy to ionize all the molecules available in less than a quarter millisecond, so it should be possible to get to full ionization in and around the resonant layer, if not throughout the volume. In a larger machine, $a \gg 100 \text{ cm}$, multiple charge exchanges will lead to ionization at substantial distances from the resonant layer.

If we do the same calculations for 3.2 kW, we get $T_i \approx 1.5 \text{ keV}$, but the ICRF does not supply enough energy to get to full ionization even in the resonance region. At this energy the charge exchange cross-section is twenty times that for ionization, so the losses are greater than at higher power levels. It is probably for this reason

that we saw no scaling with applied power in the range we had available.

The work described in the chapter following provides a couple of other possibilities for the lack of any scaling. These measurements were taken with 7 G radial field and no vertical field during breakdown. This combination of fields was found in the course of the work which follows to be rather poor for breakdown. Stray field effects may therefore have masked other physics which would have given rise to scaling with power, location of resonance, etc. On the other hand, the lack of scaling may be due to the effect of the quadrupole component of the OH field during breakdown, which would tend to localize the breakdown in the center regardless of where the initial preionization occurred. At the time this work was done no bottom port was available for spectroscopic scans which would have localized the breakdown in major radius. While one is available at this writing, the antenna configuration in use for the Alfvén experiments has changed enough to preclude repeating this work with the original set-up. I eagerly await the retuning mentioned in the next to last paragraph.

The energy estimates made here are obviously not valid once plasma effects become important. Still, at 100 kW we would be providing 4 keV per molecule per millisecond in the resonance region. If the confinement times are comparable to those in ISX with ECRF, the ICRF should do almost as well even with the charge exchange losses, and at a much more convenient frequency.

We have shown experimentally that it is possible to initiate a tokamak discharge with ICRF preionization. Estimates made indicate that 100kW of ICRF will provide a fully ionized warm plasma in the resonance layer. The high power transmitter used in the Alfvén wave studies will soon be retuned to 5.6 MHz, at which time it may be possible to repeat these studies at higher power levels by working in deuterium.

While this work is crude, it indicates that it would be worthwhile to check on the effectiveness of ICRF preionization on those larger machines which already have high power sources installed for ICRH.

Chapter Four - Influences on Breakdown Voltage

In this chapter we will discuss our investigation of a curious dependence of breakdown voltage on the derivative of the applied voltage at the time of breakdown. This phenomena was first seen on JFT-2,²⁰ which applies a voltage of similar shape to ours: half a sine wave. They were unable to explain the phenomenon, and changed only one parameter, pressure, in their investigations. When we happened on the same effect, some time before learning of the JFT-2 reference, we became annoyed at the intransigence of what seems to be such a simple problem, and so have investigated it in greater detail.

We define breakdown voltage as that voltage at which the secondary first departs from a pure sine wave, i.e., that voltage at which the primary is first loaded by the plasma. We determine the time at which this occurs by looking at the plasma current and H β light with much greater amplifications than usual and seeing when they first depart from zero. These are more sensitive indicators than the loop voltage itself, as they allow for greater amplification easily. The cursor function in TOAD, the data acquisition program

used, then allows us to determine the loop voltage at this time. The machine is then fired without toroidal field to obtain the amplitude of the unloaded loop voltage; with this and the breakdown time we can compute the derivative of the applied voltage at the instant before breakdown. An example of the raw data may be seen in figures 14 and 15. The initial negative slope on the plasma current signal is due to drift in the analog integrator, which is set for an output of 0.2V/kA. Full scale on figure 14 is 0.1 V, or 500 A.

We first noted this effect while doing the ICRF breakdown experiments described earlier. Noting that the ISX results¹³ indicated an RF pulse of roughly 10 ms was needed to obtain an equilibrium plasma, we decided to increase C_2 in the ohmic heating supply to lengthen the time available at low loop voltages for an ICRF pulse. We changed C_2 from 500 μ F to 1750 μ F, decreasing the frequency of the applied sine wave from 50 to 27 Hz. We were happy to see that the breakdown voltage with the larger capacitance was lower than those previously obtained, but unhappy to discover that this had nothing to do with the preionization method used. We decided to investigate this strange dependence on the frequency of the applied voltage.

Our first step was to take a breakdown voltage vs pressure curve with our standard 500 μ F capacitor. This curve, along with a second taken with half the capacitance, is shown in figure 16. The couple of points taken with the 1750 μ F capacitance are also shown. Note that the interval between the two full curves is larger than that between the lower curve and the couple of points taken at 1750 μ F. These curves resemble those taken in linear gas discharges, but are not comparable as we cannot define an electrode distance in a tokamak, and the gas discharge results are all given in terms of voltage vs (pressure x distance). Nonetheless we have also included in figure 16 the line on which the minimum of the V vs pd curve for hydrogen lies. While we changed C_2 in taking this data, we did not change the charging voltage on C_1 , and therefore maintained a constant flux swing in the transformer.

We subsequently realized we could obtain a range in dV/dt more easily by varying the charging voltage on C_1 , and all the data which follows was taken in this fashion, as was the JFT-2 data.

As discussed in chapter one, this phase of a tokamak discharge resembles a Townsend avalanche.² There are many physical processes which may effect the course of a Townsend discharge.²¹ Among

these, the ones which may be relevant to this experiment are: gas ionization by electrons emitted from the filament in the shadow of the limiter; gas ionization by (secondary) electrons from the gas; gas ionization by ions; fast neutral formation via charge exchange, and perhaps subsequent Penning ionization; gas ionization by fast neutrals; photoionization; gas ionization by electrons or ions produced by electron, ion, or neutral collisions with the wall or limiter; particle drifts in the toroidal field; and the effects of the stray fields due to toroidal field coil misalignment. The first cannot be the cause of the effect under investigation, as all tests were made with the same filament emission current and bias voltage. Photoionization in the volume may be eliminated in view of the small cross-sections. The photoelectric effect might contribute at the walls, but there can be no time delay of this magnitude associated with it, so that may be eliminated as well. We cannot directly examine the effects within the volume of ions and neutrals independently, but we can learn something about their joint effects by changing the gas. Finally, there is so little plasma density at this time that single particle orbits are not disturbed by plasma effects, hence ions and electrons will interact primarily with the

limiter, rather than the walls, as there is no way a particle can follow a field line to the wall without running into the limiter first. We must now examine experimentally as best we can those processes listed above which have not been eliminated.

The first process checked was basic particle drift. All particle drift velocities in a tokamak go as $1/B$, so we varied the toroidal field to check on these. It was varied from 5.5 to 9 kG, while maintaining all other conditions the same. The breakdown voltage increased by 4% as the field was changed 65%, so that particle drifts are probably not a cause of the time dependence. The 4% change may be explained by the fact that the DC power supply which is used to null the stray radial field produced by the TF coil was left at 7G, the setting thought appropriate for 8kG, throughout the run. Note that stray field effects will change linearly with the toroidal field, being purely geometric, and so are not eliminated by this test.

Examination of the effect of stray fields is clearly next on the agenda. These have a significant effect, as may be seen in figure 17. These runs were taken with our standard conditions : 8 kG toroidal field, 7 G radial compensating field, 2×10^{-4} torr filling

pressure in hydrogen. The upper line was taken with no compensation for vertical error fields due to toroidal coil misalignments; the lower with 5 G. Linear regression gives values for these lines of $V = .92 \text{ dV/dt} + 8.0$ and $V = .62 \text{ dV/dt} + 8.0$ respectively. The units here are volts and volts/ms. The correlation coefficient for each of the lines is 0.98. Several runs were taken with similar parameters. The slopes without vertical field varied from 0.92 to 0.94. With vertical field the range was 0.62 to 0.66. These runs were spread over several weeks, a period which encompassed one major vacuum accident and several vacuum system changes. We therefore feel that we are justified in using two significant figures. The variations might be ascribable totally to the 5% ripple in the vertical field provided by the rectified three phase power supply used, or to the similar amount of ripple in the dc radial field, which is supplied by a rectified single phase supply filtered with 0.11 F output capacitance.

The values for the compensating vertical and radial fields cited above are those which produce the "lowest" breakdown voltage. These were obtained by varying each alone, with the other set at zero, to find the field which minimized the breakdown voltage, and

then varying the combination of fields around the point in parameter space so defined to obtain a good local minimum. I specify local minimum here because Thomson scattering measurements later determined that the radial field determined by the procedure above was too high, causing the plasma to be centered above the midplane. We therefore reduced it until the plasma was reasonably centered, as determined from our sine coil, and proceeded to vary the applied vertical field until a new minimum in breakdown voltage was reached. This minimum turned out to be lower than that previously found, though it was not a minimum for either field alone, or even close to them. The independent minima were: radial field 7-8 G, vertical 5-6 G. The new minimum turned out to be: radial field 3.5 G, vertical 9-12 G. It follows that the procedure described first above, which is the standard one for determining compensating fields for use during breakdown,²⁰ does not produce a true minimum in breakdown voltage. While we have not searched enough of the two-parameter space available to make a firm statement, the fields which minimize breakdown voltage also seem to minimize the dV/dt dependence being studied. The dependence is not eliminated, however, so some physics remains to be explained.

With the new setting for radial field it was necessary to repeat the measurements of dependence on vertical field. In figure 18 we show runs taken at three vertical fields : 5 G, 8.5 G and 12 G. The dependence is again strong, with the highest field providing the lowest slope. The dependence of breakdown voltage on initial vertical field continues to drop, but very slowly, for fields above 12 G. It drops only about 3%, at our standard C_1 charging voltage, during the change from 8.5 to 12 G; the slope drops rather more than this.

We next investigated the possibility of this effect being due to ionization by ions or neutrals in the volume. This is an attractive hypothesis because the time required for an ion to accelerate to the minimum energy necessary for an ionizing collision with a neutral is about .2ms with a loop voltage of 9V. The hypothesis was tested by changing the working gas to deuterium, which would require 40% more time to get up to the necessary energy. These runs were taken with 3.5 G radial field and 8.5 G vertical field. Linear regression on all the hydrogen data taken with these fields gives the line $V = 0.53 \text{ dV/dt} + 7.0 \text{ V}$. The line for deuterium is derived from four runs taken 18-20 March 1981, and is fit by $V = 0.63$

$dV/dt + 6.7$ V. All of the numbers given immediately above are accurate to $\pm 5\%$. The ratio of the slopes of the hydrogen and deuterium lines is 1.2 - not the square root of the mass ratio as one would hope, but still significantly greater than 1. This indicates that ion motion plays a major role in the effect under study, though other physics may enter. In particular, we may still not have arrived at the optimal set of compensating fields, in which case some of the effect of ion mass will be masked. Indeed, in earlier experiments done with the combination 7 G radial and 6 G vertical, the independent minima, the ratio of slopes obtained was 1.1, rather than 1.2 as above.

We have not as yet addressed the possibility of electron or ion interaction with the limiter as a source of electrons. In particular, the energy required of an impinging ion for electron production is very low, only a few eV. The ion would be accelerated towards the metal by the work function potential, so that is not a lower limit. It follows that an ion would have to make less than half a turn around the machine to be effective in this mode. Since the energy is much lower than that required for volume ionization, the effect of the change in ion mass would be less evident, and might

explain the results above. In any event, there is a direct test of limiter interaction available, given some jury-rigging of the machine.

The possibility of limiter interaction causing the time dependence shown may be checked by biasing the limiter with respect to the vacuum vessel, thereby increasing or decreasing the ion and electron currents to it. In figure 19 we present the results of this experiment, done with a 15 cm radius annular limiter made of stainless steel, as were all the other experiments described here. The limiter was isolated from the vacuum vessel on 1.5 cm long standoffs of glass loaded teflon in the direction parallel to the toroidal field. The gap between the limiter and the port box wall across the field was about 0.3 cm. The limiter was then connected to a high current vacuum feedthrough on the bottom of that port box. The bias voltage was supplied by a 0.11 F electrolytic capacitor bank connected to a charging supply. The current drawn by the limiter was not monitored during the shot.

We see in figure 19 that there was little effect on breakdown over the entire range of voltages used. The breakdown voltage increased by perhaps 4% as the limiter voltage was raised from 0 to

100V with respect to the vessel, and decreased a similar amount over the range 0 to -100V. It is impossible to predict the ion or electron energy at the time of breakdown with any accuracy, as should be clear from the discussion in the the chapter on ICRF breakdown. Still, I would expect most ions or electrons hitting the limiter to have less than 100 eV, and therefore to bounce from the potentials applied. Further, any secondary electron due to ion impact will have less than 100eV, and so will be captured when a positive bias is imposed. The negative bias would encourage both ion bombardment and secondary electron emission, on the other hand. These effects may account for the slight changes in breakdown voltage measured, but the overall result is not consistent with the hypothesis of particle interaction with the limiter as a major source of electrons. It is consistent with the notion that volume ionization by ions figures significantly in the breakdown, as increasing the limiter bias will only constrict the channel through which a low energy ion may pass, not bar them altogether from completing multiple circuits around the machine. It is possible to write an analytic expression for the electric field parallel to the toroidal field in the plane of the limiter as a function of minor radius, but the integral equation

resulting is not one I am competent to solve numerically. In any event, it is intuitively clear that quite large voltages must be applied to the limiter, given the images provided by the vacuum vessel wall, to interdict most of the cross section for passage by ions. These results are consistent with the JFT-2A result²² : "Next, we describe the measurement of charged particle flux to the wall. One of the shells is used as a collecting electrode. It was found that a large d.c. bias voltage on the shell prevents the initiation of the Tokamak discharge." The bias voltages used covered the range -200 to +300 V. I would therefore assume that "large" implies voltages above 100V. Since the shell biased has significant toroidal extent, it will be more effective than a limiter in constricting the portion of the cross section through which a low energy ion may pass. These results are therefore consistent with the hypothesis advanced.

Having at this point settled on the hypothesis of breakdown via ionization by ion collisions with neutrals in the volume as being the most promising, we attempted to examine it further. We decided to add a third gas to our set to give a greater spread in masses : nitrogen. Nitrogen is diatomic like hydrogen, and has a molecular ionization potential only 1% higher. Its chemistry is also similar.

The results of this test, run at 3.5 G radial field, 12 G vertical field, and 8 kG toroidal field, are given in figure 20. The ratio of slopes $H_2:D_2:N_2$ is 1 : 1.3 : 2.3. There is clearly a mass dependence, but it is not so strong as the square root of the mass ratio. Note that the difference in branching ratio for dissociative ionization vs molecular ionization lowers the effective mass ratio for $N_2:H_2$ to 50:2 from 56:2. The branching ratio may also affect things more indirectly. Dissociative ionization by electron impact has a cross-section 6% of the total ionization cross-section in hydrogen, and 22% in nitrogen. The resulting monatomic ions have much lower charge exchange cross-sections with the diatomic gas than do the molecular ions, and so have a better chance at participating in a "chain reaction" leading to exponential current growth. The difference in the cross-section ratios probably will lead to different ion population ratios during breakdown, and so alter how it proceeds. Stray field dependence, vacuum and surface conditions, and inaccuracy in matching absolute filling pressures may also contribute to depressing the ratios of slopes from a pure velocity dependence. The cross-section for ionization by electrons for nitrogen is roughly four times that of hydrogen; I haven't found an ionization

cross-section for ionization of nitrogen by singly ionized nitrogen. If the latter is similar to the former in its relationship to the hydrogen cross-section, this would help account for the lowering of the ratio.

Surface conditions do have some effect on breakdown voltage, albeit a fairly small one. A crude test of this was made by comparing the breakdown voltage before and after opening the machine to air. The "before" result was 11.3 V, taken after one night's pumping and four hours of Taylor discharge cleaning. The "after" result was taken five hours after the machine was opened to float the limiter, at a time when the base pressure was roughly twice normal. It was 12.8 V, roughly 13% higher than "before".

A completely different hypothesis has been suggested by K. Gentle. He suggests that I am simply seeing the time delay required for getting to perhaps 1% ionization from 0.001%, roughly ten generations. If the drift velocity of electrons is independent of gas and dependent only on E/p , then one can obtain doubling times for H_2 and N_2 from their α 's. At $E/p = 150$, $\alpha(H_2)$ is twice $\alpha(N_2)$. This agrees fairly well with the ratio of slopes obtained at 12 G VF, 2.3, but does not agree with the ratio at 8.6 G VF, 1.5, or that at

15 G VF, which is roughly 4. For all these bias vertical fields an electron should produce at least a few pairs while drifting downward a distance $a = \text{limiter radius}$. I am therefore reluctant to believe that this is a substantial part of the physics in play. A much more definitive test of all this could be made in a stellerator, where the confinement is excellent throughout start-up, and stray fields due to TF coil misalignment will have much smaller effects than in a tokamak.

We conclude that volume ionization by ions, and perhaps neutrals, plays a dominant role in the breakdown in PRETEXT. Once the Townsend discharge is established electrons will predominate, of course, but the time dependences seen cannot be due to electron effects. Surface condition and limiter bias seem to affect the value of the breakdown voltage but not the time dependence.

For completeness, we then repeated the experiment done on JFT-2,²⁰ to check the pressure dependence of the effect. In figure 21 we see that it is indeed pressure dependent, something not clear from the JFT-2 data. There is obviously not a simple dependence between the changes in pressure and those in either the slopes or intercepts of these lines. The intercepts are at least monotonically

increasing, as one would expect, but the slopes vary in a fashion we are at a loss to explain. The minimum at intermediate pressures recalls the curves shown in figure 16, with minima in breakdown voltage vs pressure at similar values of the pressure. It is not clear how all this relates to our hypothesis.

Recall that the path in velocity space of a secondary electron, much less an ion, is not something which is easy to predict, as the differential scattering cross-sections for elastic collision change rapidly in the energy region 1-10 V, as do the differential cross-sections for rotational and vibrational excitation. Differential cross sections for events involving excitation and radiative decay are hard to find in this regime. All of the possible collisions would have to be included in the model, because all types of collisions have similar cross-section in this energy range. It is the first few collisions that will determine whether or not an electron gets up to 15 V, the ionization energy for hydrogen, in a reasonable amount of time. It could hit a (figurative) wall somewhere, as is often a problem in laser discharges. Perhaps the simplest model for the electron is two dimensional Brownian motion under an applied force, with the mean

passage time being the number desired. Unfortunately, no significant work has been done in this area of Brownian motion - it seems that the problem of Brownian motion with applied drift in 2D is the hardest approachable at this time. One could put all the collision cross-section information available into a big Monte Carlo code and run it a few thousand times to get a mean passage time, but that would be at least another dissertation-length project, and so will not be attempted. What's more, such a model would not include the heavy particle effects which have been shown important, but for which few if any cross-sections are known in the energy range of interest - another good reason for stopping here.

The following conclusions may be drawn from the work described above:

1. The standard technique for minimizing stray field effects during breakdown, minimizing the effects of radial and vertical fields independently, ²⁰ is not optimal. This would not be noticed in a machine with feedback supplies for both radial and vertical fields, as the fields would change to keep the plasma centered after a current existed. Our discovery is therefore dependent on

our use of a DC supply for the compensating radial field. It would be interesting to check machines with feedback systems to see if the radial field used during breakdown is automatically lowered or raised once the current begins to rise. This is something easily, but typically not, monitored - or at least not reported. In any event, the technique described here, minimizing the slope of the V vs dV/dt curve, provides for better breakdown than the standard one.

2. It is possible to obtain good tokamak discharges in which the limiter plays no significant role during the breakdown phase. It will therefore not be necessary to start the discharge in large new machines near the limiter, allow them to grow there for a while, and then move them into the center of the vessel, as had been feared. This desirable result may be due to the fact that the OH field in PRETEXT is a distinct quadrupole, as opposed to the higher order multipole typical in more expensive devices. Recent results in PDX²⁴ support this hypothesis, as they got better breakdowns with an initial quadrupole than with the original octopole. The quadrupole would tend to discourage

avalanches except at small minor radius. A quadrupole is much cheaper to build, and easier to fit into the 3-D jigsaw puzzle which is a tokamak, so we can have our cake and eat it too.

3. Volume ionization by ions plays a significant role in tokamak breakdown, and must be included in models thereof. Recent experimental and theoretical work in linear discharges suggests this is true even there.²¹

4. The application of loop voltage with low dV/dt is desirable. This would allow one to increase the conductivity of the vacuum chamber, thereby mitigating the effects of disruptions on external systems. It also allows the easy application of superconducting ohmic heating coils to tokamaks. Both of these conclusions should gladden the hearts of reactor designers.

5. Toroidal systems allow for many investigations in gaseous electronics in a regions of parameter space very different from those available classically.² For instance, it should be possible to measure Townsend's first and second ionization coefficients in

such a system with a scheme similar to the one used. The only major change required would a be change in the Rogowski coil sensitivity and in its processing chain to allow detection of sub-ampere currents, where our system is optimized for measuring tens of kiloamps. Toroidal systems could also provide lab models which match most ionospheric parameters well; the principle exception being magnetic field. There is a very large room behind the door we have shown to be open.

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Table 1: PRETEXT Parameters

	<u>Projected 1978</u>	<u>Achieved 5/81</u>
Vessel major radius, R_0	53.3 cm	
Limiter radius a	15 cm	
Aspect ratio	3.5	
Toroidal Field on axis	10 kG	9.5 kG, but 8 kG typical
Plasma current	80 kA	60 kA @ 8 kG
Chord average electron density	10^{13} cm ⁻³	3×10^{13} cm ⁻³
Mean electron temperature	400 eV	200 eV
Pulse length	50 ms	60 ms
System base pressure	10^{-8} torr	10^{-7} torr
Interval between shots	100 s	
Vessel inner radius	17.4 cm	
Vessel material	SS304L	
Volume of vessel and diagnostics	500 L	
Pumping speed at vessel	500 L/s	
TF coils	16, circular, copper, air cooled	
TF coil dimensions	IR 27.6 cm, OR 41.3 cm, width 5cm, 9 turns	
TF ripple	1%	
OH transformer	iron core, air return	
Flux swing in core	.16 V-s	
OH coil	120 turns, L=22 mH	
VF coil	16 turns, 5.6 G/100A at R_0 in midplane	
HF coil	16 turns, 8.8 G/100A at R_0 in midplane	

Table 2: Diagnostics

1. Zebra stripe interferometer - 4 mm and 2 mm
2. 90° Thomson scattering
3. Optical spectroscopy
4. Position loops and coils, Mirnov loops
5. Cyclotron emission
6. X-ray pulse height analyzer
7. VUV, grazing incidence spectrometers
8. soft x-ray detectors

Figure 1 - Diagnostic Access on PRETEXT

FIGURE 2 - TOROIDAL FIELD
POWER SUPPLY

FIGURE 3 - TOROIDAL FIELD VS TIME

FIGURE 4 - HF COIL FIELD

OVERALL

DETAIL

FIGURE 5 - VF COIL FIELD

OVERALL

DETAIL

FIGURE 6 - OH COIL FIELD

OVERALL

DETAIL

**FIGURE 7 - TOTAL EXTERNAL
FIELD SEEN BY PLASMA**

**FIGURE 8 - TOTAL POLOIDAL
MAGNETIC FIELD**

Figure 9 - Stray Vertical Field of OH Coil
Theory and Experiment

Figure 10 - Ohmic Heating Power Supply

FIGURE 11

PRIMARY CURRENT, SECONDARY VOLTAGE VS TIME

02-APR-81 SHOT: 11

FIGURE 12a

02-APR-81 SHOT: 11

FIGURE 12b

02-APR-81 SHOT: 11

FIGURE 12c

FIGURE 13

FIGURE 14

FIGURE 15

Figure 16 - Effect of Frequency on Breakdown Voltage

Figure 17 - Effect of Bias Vertical Field on Breakdown

Figure 18 - Effect of Vertical Field on Breakdown, Better Radial Field Setting

Figure 19 - Effect of Limiter Bias Voltage on Breakdown Voltage

Figure 20 - Effect of Working Gas on Breakdown

Figure 21 - Effect of Pressure on Breakdown