NUMERICAL STUDY ON CURRENT DRIVE OPERATIONS IN A TOKAMAK

A MASTER'S THESIS

in

Electrical and Electronics Engineering

Middle East Technical University

By

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Sept.1990

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NUMERICAL STUDY ON CURRENT DRIVE OPERATIONS IN A TOKAMAK

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97 Pages, Sept-1990

ABSTRACT

The aim of this thesis is numerically studying the transition from the pulsed state to the steady state in a tokamak by using a model circuit for the current drive operations. The problem of shutting off the primary circuit without reducing plasma current is analysed for the case of air core transformer in a medium-sized tokamak. It is observed that, after shutting off the primary circuit plasma current is continued in steady state or quasi-steady state phase by the current drive operation.

Keywords : Tokamak, Confinement, Current Drive, Plasma, Modelling, Heating

Science Codes: 608.02.01, 622.01.02

BİR TOKAMAK'TA AKIM SURME ISLEMLERININ

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97 Sayfa, Eylül-1990

ÖZET

Bu tezin amacı, bir tokamak'ta akım sürme işleminin bir model devre kullanılarak darbeli halden sürekli hale geçisini sayısal olarak incelemektir. Orta boyutlu bir tokamak'ta hava çekirdekli transformatorun birincil devresini plazma akımını azaltmaksızın açma sorunu incelenmektedir. Birincil devre açıldıktan sonra, akım sürme işlemi ile plazma akımının sürekli halde veya kısmi sürekli halde devam ettirildiği gözlenmektedir.

Anahtar sözcükler: Tokámak, Hapisleme, Akım Sürme, Plazma Modelleme, Isitma

Bilim Sayısal Kodları: 608.02.01, 622.01.02

ACKNOWLEDGEMENT

I would like to express my deep gratitude to Prof.Dr. *Sadrettin Sinman* for his friendly supervision and helpful comments. I wish to thank ASELSAN A.Ş. for providing proper working conditions for the completion of this thesis.

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LIST OF ABBREVIATIONS

OH :	Ohmic Heating
TF :	Toroidal Field
EF :	Equilibrium Field
ECRH :	Electron Cyclotron Resonance Heating
ICF :	Inertial Confinement Fusion
MCF :	Magnetic Confinement Fusion
TFTR :	Tokamak Fusion Test Reactor
JET :	Joint European Tokamak
JT-60 :	Japanese Tokamak

CHAPTER 1

INTRODUCTION

Nowadays, studies on nuclear fusion are continued at research and development level especially in Soviet Union, United States, Western Europe and Japan. According to these research and development studies it is seen that Tokamak type fusion reactors approach to the commercial reactor domain. Some of the great tokamak reactors [17] are TFTR in USA, JET in England, T-20 in Soviet Union and JT-60 in Japan. Obviously these studies require high level of engineering and technology.

There are several problems to be solved if tokamak reactors are to operate at steady state. Most important of them is called current drive operation.

For the exploration of the possibility of steady-state tokamak operation, non-Ohmic current drive methods are currently under active study. Methods using lower hybrid waves [14,15,16], neutral beam injection [11,12], and radio frequency waves [22] have been demonstrated experimentally. Usually, in reactor size tokamaks Ohmic transformers first establish the plasma current, then maintained by a non Ohmic driver; this is the scheme currently employed. For genuine steady-state tokamak operation, the primary circuit of the Ohmic transformer should be disconnected or opened.

In this thesis, the result of numerical analysis of a model circuit, which includes the primary circuit, the plasma current and driving current source is presented. In particular,the problem of shutting off the primary circuit without a reduction in plasma current in a medium-sized tokamak is examined.

In the first section, general information about the nuclear fusion and confinement system were reviewed.
In the second section, after giving the necessary information on the tokamak concept, plasma heating systems were presented. In the third section, current drive operations were examined. Lastly, for current drive operations on a tokamak, a model circuit were numerically analyzed by using initial condition solution type of pSpice simulator by using a PS computer.

CHAPTER 2

A REVIEW OF NUCLEAR FUSION [1,2,18,29]

2.1. General Information

Fusion reaction is a nuclear reaction between light atomic nuclei as a result of which a heavier nucleus [18] is formed and large quantity of nuclear energy is released.

A possible alternative and successor to the fast breeder reactor is a system in which useable energy results from the fusion of light nuclides such as deuterium (D), tritium (T), helium-3, and lithium. Deuterium exists abundantly in nature; for example, it comprises 0.015 atom percent of the hydrogen in sea water [2]. This amount of deuterium could supply enough energy for $4*10^9$Q. The deuterium is not muldistributed. The fusion process itself does not leave long-lived radioactive products, and problem of radioactive-waste disposal is much less serious than that for fission reactors. However, this immense reserve of nuclear energy is not yet useable; in fact controlled fusion is still in the stage of basic research, altough fusion energy was released in an uncontrolled, explosive manner by the hydrogen bomb in 1951. [1,2]

Nuclear reactions of interest for fusion reactors are as follows [1]:

(1) $D + D \longrightarrow T\ (1.01\ MeV) + p\ (3.03\ MeV)$

(2)	D + D	$\longrightarrow$	He^{3}(0.82 MeV) + n (2.45 MeV)
(3)	D + T	$\longrightarrow$	He^{4}(3.52 MeV) + n (14.06 MeV)
(4)	D + He^{3}	$\longrightarrow$	He^{4}(3.67 MeV) + p (14.67 MeV)
(5)	Li^{6}+ n	$\longrightarrow$	T + He^{4} + 4.8 MeV
(6)	Li^{7}+ n	$\longrightarrow$	T + He^{4} + n - 2.5 MeV

A binding energy per nucleon is smaller in very light or very heavy nuclides and largest in the [1] nuclides with atomic mass numbers around 60. Therefore, large amount of the energy can be released when the light nuclides are fused. The cross sections of the reactions (1)+(2), (3), and (4) are shown in Figs. 2.1 and 2.2.

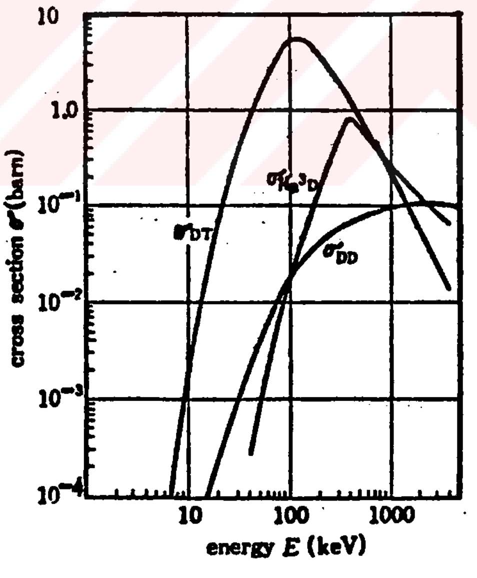


Fig.2.1 Fusion cross sections plotted against the kinetic energy of relative motion. σDD is the sum of the cross sections of reaction (1) and (2). One barn is 10^{-24} cm^{2}.

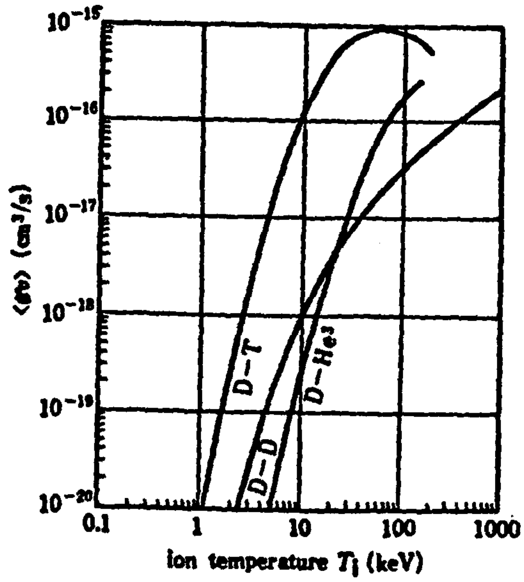


Fig.2.2 The expected value of $\langle \sigma v \rangle$ when the ions obey the Maxwell distribution at the temperature Ti $\langle \sigma v \rangle_{DD}$ is the sum of the cross section of reactions (1) and (2).

The D-T reaction has the largest cross section of those shown, and the amount of released energy is also largest. Taking account of the difficulties of the plasma confinement, the D-T reaction should be one undertaken in the first steges, altough D-D reactors should be aimed at ultimately. For a D-D reactor, a lithium blanket surrounding the plasma moderates the fast neutrons, converting their kinetic energy to heat. Furthermore, the lithium blanket breeds tritium due to the reaction (5) and (6). Figure 2.3 shows an example of electric power plant based upon such a controlled fusion reactor [29]. Lithium at high temperature comes out from the blanket, gives up its heat to liquid potassium in a heat exchanger; a potassium turbine generates the electric power. The potassium-turbine exhaust, itself at a high temperature, is circulated in a second heat exchanger to generate steam for a steam-turbine generator.

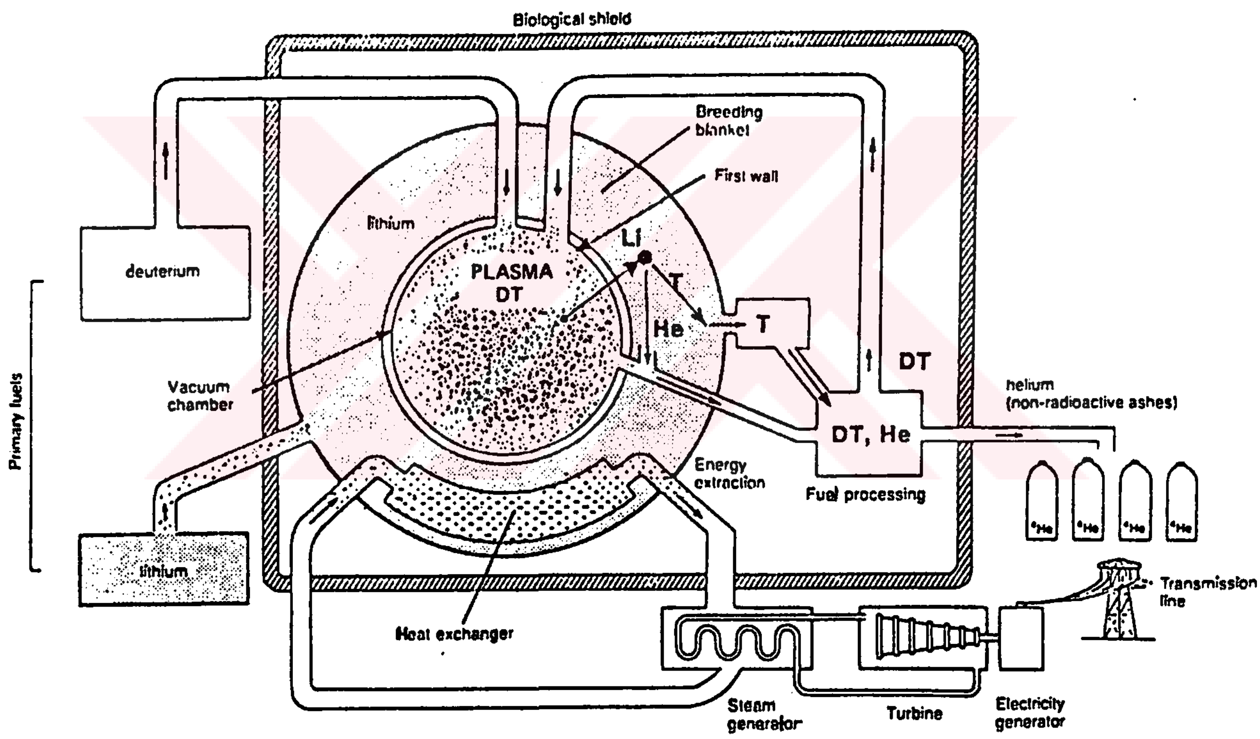


Fig.2.3 An electric power plant based upon a D-T fusion reactor.

The technologies concerning potassium heat exchangers and turbines are the same as those reqiured for similar components used in fission breeder reactors. Abundances of Li^6 and Li^7 are 7.5% and 92.5% respectively [1]. Reactions between lithium and neutrons are endotermic (-1.97 MeV) on the avarage. Since D-T reaction releases 17.58 MeV, a lithium atom may be considered as a 15.6 MeV energy source. The world reserve of lithium is estimated to be $(8-9)*10^6$ tones; this is equivalent to about 1700 Q . It should be noted that the lithium content of seas, of total volume of $1.37*10^9$ km^3, is 0.17 g/m^3 (while the uranium content is 0.003 g/m^3), and that it is possible to extract this lithium from the sea water [1].

In otherwords, the primary fuels for D-T reactors (deuterium and lithium) are so abundant in nature that, practically speaking, D-T fusion is an inexhaustible energy source for global energy requirements. Indeed, deuterium is present in all water (one D atom out of 6700 H atoms) and lithium is widely distributed throughout the earth crust at rather low mean concantrations (30 ppm by weight), with known deposits of lithium at higher concentrations (up to 4%) around the world. Moreower, the concentration lithium in the ocean is about 0.2 ppm. Fusion will consume very small quantities of these fuels, 0.5-5 tonnes per GW, depending on the efficiency of using the natural lithium (the estimated resources of lithium available on land can supply D-T reactors for several hundred years) [5].

The environmental disturbance of extracting lithium from brines and deuterium from water is small. The provision of other materials specific to fusion reactors appears to pose no special difficulty and to have no impact on the environment.

The primary fuels and direct end product of fusion -the inert gas helium- are neither toxic nor radioactive; they do not produce atmospheric pollution nor do they contribute to greenhouse effect. The fusion reactors contain neither uranium and plutonium nor their fission products. Criticality accidents are impossible. However, D-T fusion reactors will have a radioactive inventory arising from the intermediate fuel (tritium) and from the radioactive material parasitically produced by fusion neutron activation of parts of the reactor structure [29].

2.2. CONFINEMENT SYSTEM

At present the major research effort in the area of controlled nuclear fusion is focused on the confinement of hot plasmas by means of strong magnetic fields. The study of magnetic confinement and inertial confinement systems, different approaches toward the controlled nuclear fusion process are being actively investigated. If a very hot and dense plasma could be produced within a very short time, it might be possible to complete the nuclear fusion reaction, satisfy the Lawson criterion (Appendix B) before the plasma starts [2,5] expanding and large quantity of energy is released. When this energy is transposed into temperatures, it represents an extremely high value, of the order of several tens of millions of degrees. At temperatures the particles move at extremely high velocities (several thousand km/s) and if no precautions were taken they would quickly escape without having collided with another particle to give rise to a fusion reaction and therefore without having produced energy [5].

2.2.1. INERTIAL CONFINEMENT

The simplest solution consists in creating a medium which is so dense that a particle has practically no chance of escaping without meeting another [2]. According to that idea of an ICF reactor is illustrated in Fig. 2.2.1.

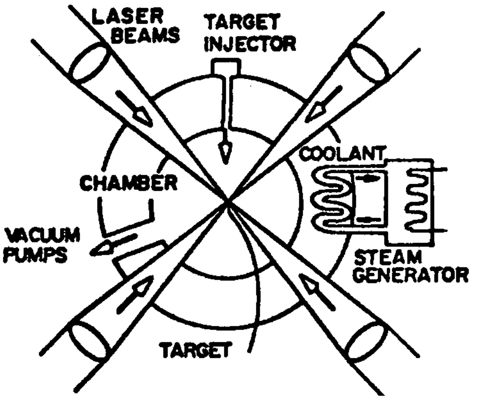


Fig.2.2.1 The general idea of an ICF reactor (simplified for clarity).

A small target pelled several mm in diameter is injected into the chamber. As it passes through the center of the chamber, it is compressed and ignited by powerful laser beams or ion beams, producing a small thermonuclear explosion. Vacuum pumps remove gases and debris between explosions. New pellets are injected and ignited about 1-10 times/s [2]. Heat from the thermonuclear explosions is deposited in the chamber walls and extracted by coolant to generate steam, which used to drive turbine -generators (not shown in the figure) for production of electricity.

Status of ICF technology:

Compression of D-T pellets up to 600 times solid density has been demonstrated. In other experiments, 10^{13} fusion reactions have been produced, representing a fusion energy of 0.2% of the energy of the driver pulse of the 10 kJ laser. From the experiments it is concluded that a 100 kJ blue laser is required for break-even (fusion energy = laser energy). The ICF experiments and the computational data support projections about the feasibility of achieving ignition and high energy gain [29].

2.2.2. MAGNETIC CONFINEMENT

The idea of magnetic confinement of high temperature plasma can be expresed in general terms by the magnetohydrodynamic equation [13]

$$\underline{j} * \underline{B} = \underline{\nabla} p + \frac{D(\rho v)}{Dt}, \qquad (3)$$

where j is current density, B is magnetic field and p, ρ, and v are the plasma pressure, density and velocity respectively. Scaler pressure gradients can be contained magnetically only normal to the lines of force. The purpose of magnetic pressure is to force the particles to remain in a confined space. The idea of a material container has to be abondoned, since in striking the walls the hot particles would quickly loose their energy [19]. Advantage is taken of the fact that at these high temperature atoms are ionized and the charged particles execute a helical motion in a magnetic field. If the magnetic field closed on itself, e.g., in the form of a torus as seen in Fig.2.2.2, the particles are trapped.

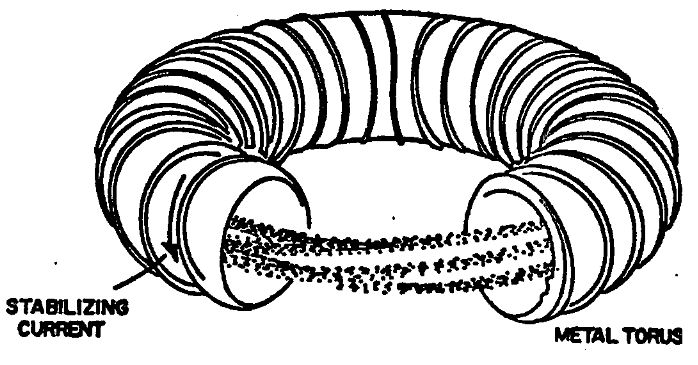


Fig.2.2.2. Helical motion of charged particles in a torus

The best-known of the torus-shaped configurations obtained in this way is called Tokamak: in this device the lines of force are slightly twisted by the addition of a toroidal current in the plasma. Owing to certain parasitic phenomena, the particles eventually escape from the trap after a certain length of time called the particles *confinement time*. In a fairly dense medium, collisions are frequent and the confinement time can be short; on the other hand, if the medium is not very dense, collisions are rare and the particle should remain confined for longer times.

Lawson was the first to give in detail the values which had to be reached in order to obtain a [13] positive energy balance. Fig.2.2.3 is illustrative of the condition needed for net fusion energy production rather than a hard-and-fast rule. In real apparatus the density, temperature and power loss all vary with position: the global energy confinement time is defined as the total thermal energy in the plasma required to sustain that energy in a steady-state. The actual fuel temperatures required for D-T reactions are $T > 10$ keV 10^{8} K. The required confinement time τ is given approximately by the "Lawson Criterion" $n\tau > 10^{20}$ $m^{-3}s$, where n is the plasma ion density (ions/m^{-3}). If $n = 10^{20}$ m^{-3}, then the required confinement time is about 1s [2].

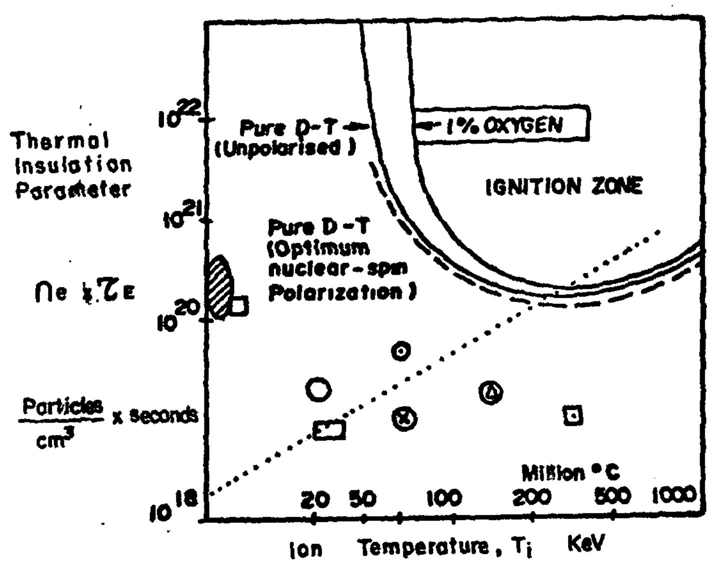


Figure 2.2.3. Ignition conditions for a uniform D-T plasma (from Pease 1987, Micklich and Jassby 1984). Experimental Points from Bitter 1987, Goldston 1986, Yoshikava 1986, Rebut 1986.

JET (ohmic)
JET (X-point operation)
JET (best temperature)
TFTR (ohmic with pellet injection)
TFTR (best temperature)
JT-60 (neutral beam heating)
D-3-D (ohmic)
Nova laser compression

Status of MCF technology:

Progress in technology (such as for superconducting magnets) is good and, on the basis of current experience with components, there is no doubt that technical solutions for the design and construction of an experimental tokamak reactor will be available, provided sufficient activity is conducted. For the technology of a demonstration or prototype power reactor, considerable development efforts are still required.

Several breeding blanket concepts are under study, as is the development of advanced, low activation materials. Such materials appear to be necessary for the full exploitation of the environmental potential of fusion power. The materials for an experimental reactor are already available.

The safety and environmental impact of fusion reactors are important issues which are being studied intensively. The favourable characteristics of fusion systems may constitute the major appeal of fusion as an energy system [29].

CHAPTER 3

TOKAMAK SYSTEM

3.1. INTRODUCTION [2,29,34,35]

Tokamak is one of the most promising magnetic confinement system which has been developed.

The tokamak configuration consists of a toroidal vacuum vessel containing a plasma with surrounding field coils. The combination of the magnetic field created by outer windings and the current that flows in the plasma are specific features of the tokamak configuration.

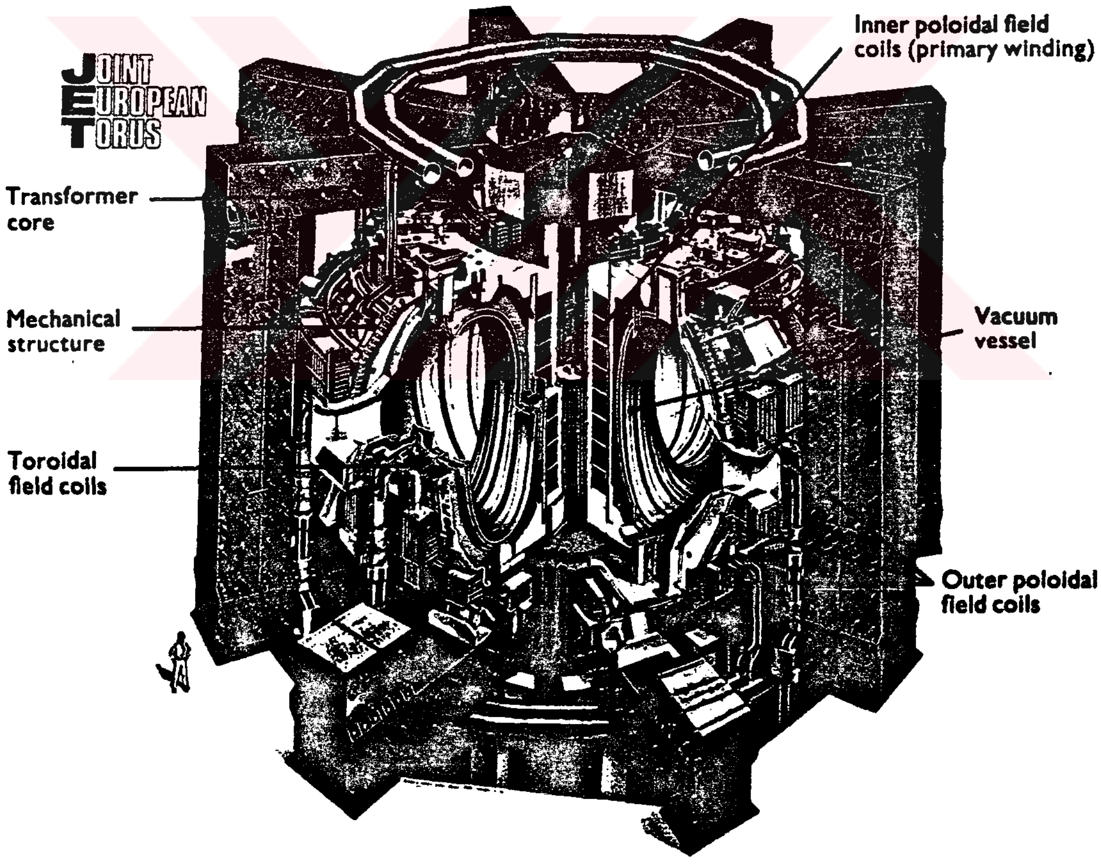


Fig.3.1 Diagram of the JET tokamak [35]

In present tokamak machines, the current in the plasma is produced by induction and the plasma performs the secondary function of a transformer coupled magnetically to the outer primary windings. The higher intensity magnetic field in the toroidal direction, to several teslas, is created by coils placed outside the vacuum vessel. A lower intensity magnetic field is created by the current flowing in the plasma ring. The resulting field forms a lattice of "lines of force" generating toroidal surfaces, which sustain the plasma by applying a pressure of about one hundred atmospheres [34]. Some auxiliary magnetic fields are also provided to keep the plasma properly centered within the vacuum vessel. The various field components, which are not longitudinal to the torus centerline, constitute the poloidal field.

The plasma heated by the current flowing through it containes approximately 10^{14} particles per cubic centimeter, about one hundred thousand times less than a gas under atmospheric pressure [34]. The temperatures attained are measured in tens of millions of degrees. Under these conditions the pressure of the plasma reaches several atmospheres, which is far below the magnetic confinement pressure.

Several additional devices are required in conjunction with this basic configuration. It became evident that the current heating the plasma would not be sufficient to achieve the required temperatures. Radio frequency (RF) waves and fast particle injection heating systems were consequently added. Temperatures of over one hundred million degrees were thus achieved [34].

Magnetic confinement of a magnetic field can affect the motion of individual plasma particles (nuclei and electrons) more strongly than interparticle collisions do, so that the fusion reaction can occur. As a result, closed confinement configurations are toroidal and helical shaped [2.29].

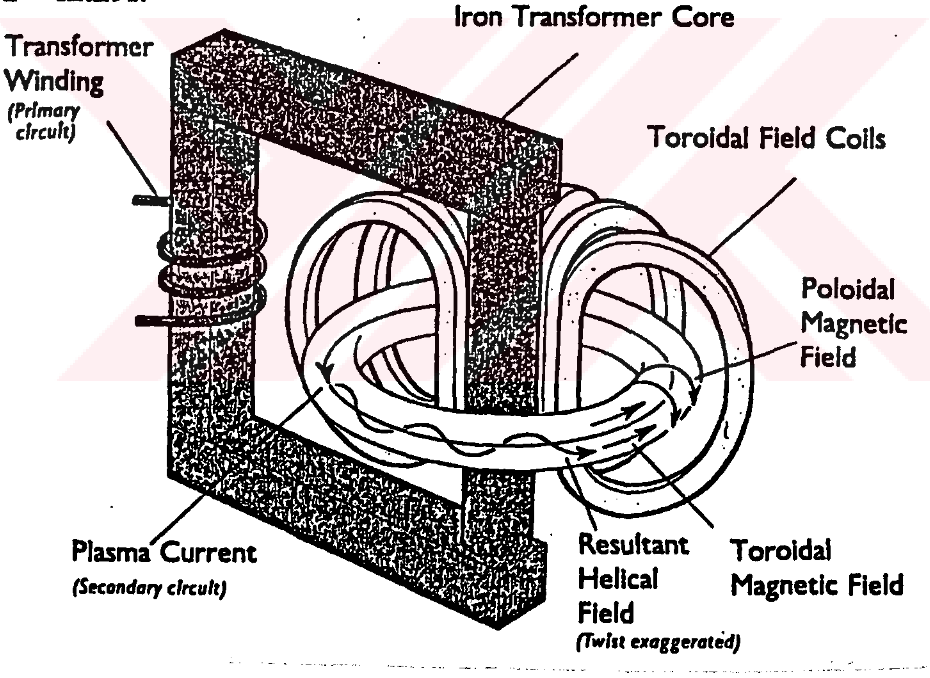


Fig.3.2 Tokamak Magnetic field configuration

To provide toroidal plasma equilibrium and stability, the magnetic field lines have to pass around and around both the short (poloidal) way and long (toroidal) way to form magnetic surfaces.

In the tokamak seen in Fig.3.2, the poloidal magnetic field component is produced by a toroidal current flowing in the plasma itself, with the result that the magnetic configuration can be axisymmetric. In practice, this is the case when the toroidal field, in which the plasma is embedded, is produced by currents flowing in a sufficiently large number of uniformly distributed (poloidal) coils encircling the plasma torus, called toroidal field coils. The positioning of the plasma and shaping of its poloidal cross-section are achieved by a set of circular horizontal coils which are coaxial with the vertical axis of symmetry of the tokamak. The toroidal plasma current is usually transiently induced by transformer action (where the plasma plays the role of the secondary circuit). However, in a reduced parameter space, this current can be produced and maintained in steady state by injecting appropriate elctromagnetic waves or neutral beams into the plasma (current drive). In addition, as in any magnetically confined toroidal plasma, a steady state toroidal current can be created and maintained by the particle and energy transport across the magnetic surfaces the 'bootstrap' current [29].

3.2. GENERAL CONSIDERATION [2,29]

The main figure of merit used to assess the approach to ignition is the ratio of the fusion power released by D-T reactions to the power lost from the plasma. At ignition relevant temperatures, in a pure 50% D-50% T plasma, this ratio is proportional to the triple product $n\tau T$, where n is the number of nuclei per cubic metre of fusion fuel, T is its temperature in keV (1 keV is equivalent to about ten million degrees Celsius) and τ is the energy confinement time in seconds. The minimum value of $n\tau T$ necessary for ignition is about 5×10^{21} m^{-3}.s.keV at a temperature of about 15 keV. In the best cases it is less than a factor of ten away from ignition and is close to break-even. Moreover, in several tokamak experiments, the value of T exceeded the requirement by a factor of two or so. Information on a large variety of phenomena which have been discovered has been gained from improved diagnostics and has enabled improved modelling of plasma behaviour, supplemented by semi-emprical scaling relation-ships. In fusion, as in otherfields, fundamental studies on basic processes and possible improvements continue.

3.3. SYSTEM COMPONENTS [2,31]

The plasma is produced in a toroidal vacuum vessel (torus), usually made of steel. The first wall of liner have electrical resistance in toroidal direction to avoid drawing large currents into the vacuum vessel during the plasma current initiation phase. The outer magnetic surface is defined not by the wall, leaving a gap of typically 1-5 cm. In early tokamaks the limiters were commonly made of refractory metals such as tungsten or molybdenum. However, small amounts of metal impurities in the plasma lead to radiation losses. Today lighter elements such as carbon are often used to overcome this problem [31].

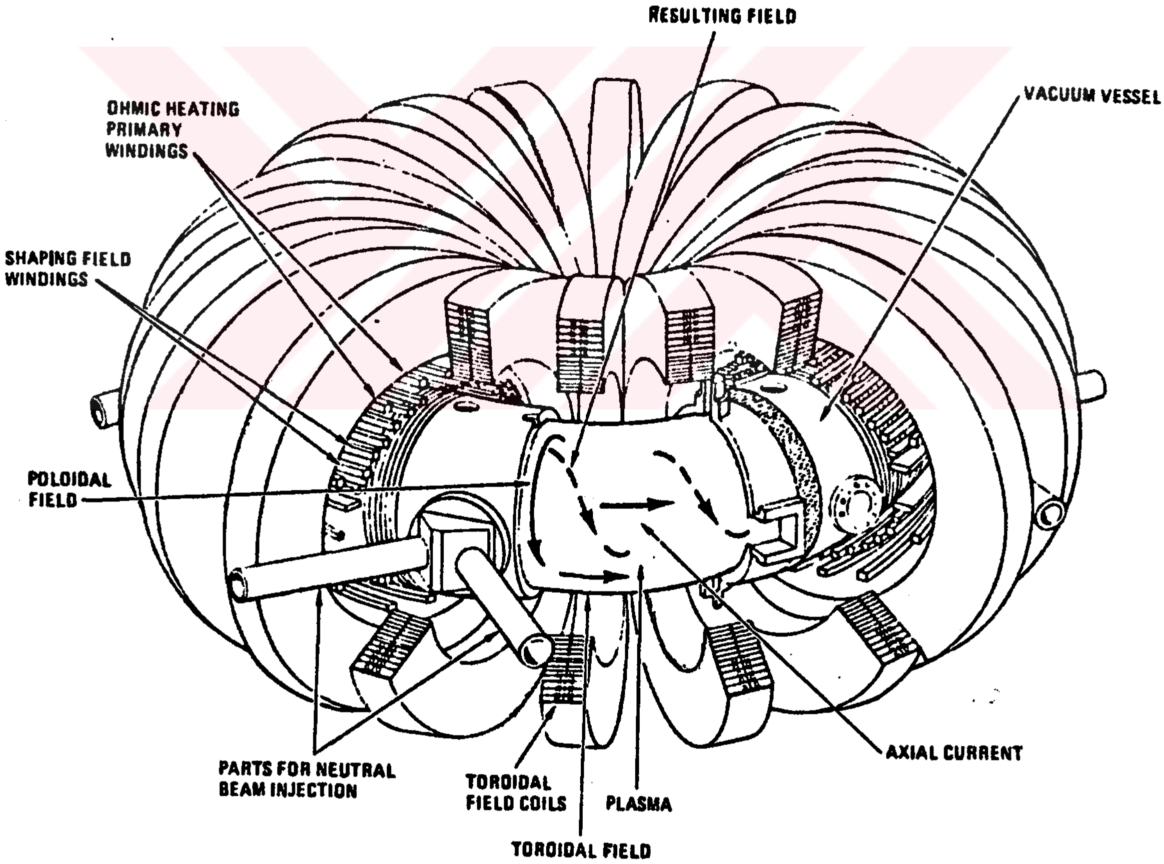


Fig.3.3. Basic components of a tokamak. Some tokamaks also have an iron transformer core improve magnetic coupling between theprimary ohmic heating windings and the plasmacurrent.

In most present-day-tokamaks the magnetic field is produced by water-cooled copper coils. However, superconducting coils and magnets technology have been developed, they will be the most expensive componenets required for a fusion reactor. So far, superconducting magnets have been built for laboratory size tokamaks [29]. The magnetic field has in essence two componenets: toroidal field and poloidal field. Toroidal field is produced by a set of toroidal coils wound around the plasma and directed the long way around the plasma. In present experiments this field has values around 0.1-10 T [32]. Charged particles are not confined for long by a toroidal field which decreases inversely withthe major radius. The particles drift vertically up or down, depending on their charge. To obtain proper confinement, a second field is added, which is directed the short way around the plasma. This poloidal field counteracts the vertical drift and prevents vertical charge separation. Hence magnetic confinement is provided by contribution of poloidal and toroidal fields, and the resultant field in the vacuum vessel is in helical form.

The poloidal magnetic field is produced by a current induced in the toroidal direction in the plasma by the transformer action of a set of poloidal coils mounted coaxially with the plasma. In some tokamaks an iron core is used to improve the coupling between the coils and the plasma. This field is established by a combination of several coil systems. Mainly these coils system are ohmic heating coils and positioning coils such as equilibrium field (EF) coils and divertor coils. In some designs external or divertor coils are used such as variable-curvature field and horizontal field [2,33]. Another componenet of the poloidal field is produced by liner (B_l). Liner has a greater electrical resistance compared to plasma in toroidal direction to avoid drawing large currents at plasma initiation phase. During start-up it is heated by a separate supply. For example at Textor a power of 200 kW is required to heat the liner up to a temperature of about 600°C [2]. According to above discussion the poloidal field can be given,

$$B_p = B_{liner} + B_{E(position)} + B_{ext.\,coil} \qquad (3.1)$$

hence the resultant field in the vacuum vessel is summation of poloidal and toroidal fields in helical form.

3.4. HEATING

In order to raise the temperature of a plasma, it is necessary to inject energy while holding the energy dissipation to a minimum. Definition of heating rate is H as the energy absorbed by a unit volume of plasma [1] in unit, and τ_E is the energy confinement time. Then the change of plasma temperature over time is given by

$$\frac{d(nT)}{dt} = \frac{2}{3} H - \frac{nT}{\tau_E} \qquad (3.2)$$

n	:	Density
T	:	Plasma temperature
$\frac{nT}{\tau_E}$	:	Energy loss rate

$$nT = \frac{2}{3} H \tau_E \qquad (3.3)$$

A wide range of heating methods have been explored, and many now have been tested at the multi-megawatt level. One may say that broadly speaking, they are understood and usually they work.

3.4.1. JOULE (OHMIC) HEATING

When an electric field E is applied to a plasma, the plasma electrons are accelerated, i.e, their kinetic energies are increased. These kinetic energies are thermalized by means of collisions with the plasma ions [1,6]. This is the mechanism of joule or ohmic heating. The heating rate for joule heating is given by

$$j \cdot E = \eta \cdot j^2 = E^2 / \eta \qquad (3.4)$$

$$\eta = \frac{m_e \cdot \nu_{ei}}{n_e \cdot e^2} \quad 2 * 10^{-9} * Z \ln \Lambda \, (T_e)^{-3/2} \qquad (3.5)$$

where j is the current density, η is the resistivity of the plasma.

$$T_e : \text{keV} , \qquad \ln \Lambda = \frac{1}{\sin \frac{\chi_{min}}{2}} \qquad (3.6)$$

The resistivity decreases as the electron temperature increases and heating rate decreases.

$$H = j \cdot E = \eta \cdot j^2 = E^2 / \eta \qquad (3.7)$$

Lawson's condition cannot be realized by joule heating alone in the tokamak configuration. Further heating is necessary in order to realize a practical reactor. However, the cost of joule heating is much less than that of other methods and the heating rate can be measured relatively easily [1,6]; so, even though it is insufficient of itself, joule heating is frequently used in toroidal devices.

3.4.2. NEUTRAL BEAM HEATING

High-energy neutral particle beams can be injected into plasmas across strong magnetic fields. The neutral particles are converted to high-energy ions by means of charge exchange with plasma ions or ionisation. The high-energy ions running through the plasma are slowed down by Coulomb collisions with the plasma ions and electrons and the beam energy is therefore transferred to the plasma. This methods called heating by fast neutral beam injection [1,11].

The heating is independent of the magnetic field strength, but as the plasma gets more dense and hot, the penetration of the neutral beams can be achieved only at rather high energies, where the neutralization of positive ions offer a solution, but have not so far been used because large-scale negative ion sources are now being developed. The slowing down of the ions has been exhaustively studied and appears to be entirely due to collisions (Caltanei 1985) [11,12].

The method has the merit that all the complexity is outside the plasma region; and that the high energy ions contribute to the fusion reaction rate. The record value of temperatures and of thermonuclear fusion output of 10 kWatts in deuterium have been achieved with neutral beam heating. Current drive can also be obtained when the particles are directed: up to about 750 kA is obtained in TFTR [23].

3.4.3. RF HEATING [2,16,21,22]

Most common form of ion cyclotron resonance heating nowadays uses a frequency tuned to the cyclotron frequency of a minority ion species, an effect discovered accidentally. (Yoshikawa et al 1965). The minority species are accelerated to quite high energies >100 keV and the charged particles in slowing down, tend to heat the electrons.

Generators with unit sizes of 200 kW at frequencies up to 100 GHz are now available to researchers especially in Russia. Generally speaking, effiencies in the 50% range are found. About 10 keV is reached in Tokamaks (Razumova 1987).

Up to 2 MA of poloidal current has been driven in JT-60 by 3 MW of such r.f. power; the process can be regarded as a travelling wave accelerator induced in the plasma (Yoshino 1987).

3.4.4. ALFA (α) PARTICLE HEATING [2,21]

The method ultimately sought in a reacting plasma is to sustain the temperature against losses, and to heat the cold fresh fuel by the power of the 3.5 MeV α-particles from D-T reactions. Direct simulation of this heating has not yet been reported. The experience of up to 10 MWatts of Neutral Beam injection at about 100 keV suggest that the α-particle power eventually required (100MW - 1000MW) will not necessarily be accompanied by deleterious effects. Indeed, because the α-particles is small compared to the plasma radius (i.e. $I\phi$ > 3MA).

In current Tokamaks, the velocity of the neutral beam ions is less than the Alfven velocity, i.e. the velocity of the α-particles will exceed the Alfven velocity, and in principle give Cerenkov radiation. Some velocity distributions will give rise to instabilities. The slowing down of the high velocity reaction products of fusion is now the subject of direct study.

However the real test will come only when deuterium and tritium mixtures are put into JET or TFTR to yield macroscopic heating levels from the α-particles.

CHAPTER 4

CURRENT DRIVE OPERATIONS

4.1. INTRODUCTION

There are several problems to be solved if tokamak reactors are to operate at steady-state (or with very long pulses):

.current drive

.burn control

.plasma purity

.fueling

The aim of this chapter isto introduce current drive operations and advantages of them.

4.2. MAGNETIC INDUCTION [2]

According to Faraday's law

$$2\pi rE = -A(dB/dt),$$

so the induction of a toroidal electric field E (to drive the plasma current) requires a changing magnetic field [2] dB/dt, which in turn requires a changing current in the ohmic heating (OH) coils. Thus, the inductive current drive ceases when the ohmic heating coils reach maximum current. The pulse length can be maximized by running the coils from negative current to positive current, as illustrated in Fig.4.1.

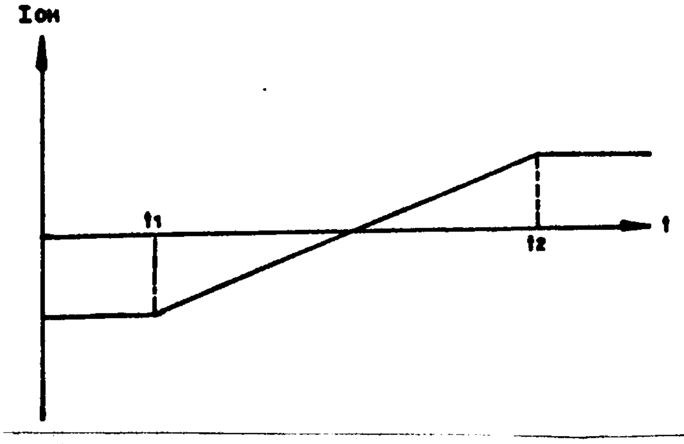


Fig.4.1. Ohmic heating coil current vs.time. The pulse length is (t_2-t_1).

The poloidal magnetic field is established by a combination of several coil system:

Ohmic Heating (OH) coils provide enough Volt-second of induction to develop a stronge plasma current.

Equilibrium Field (EF) coils (also called vertical field coils) control the plasma shape and position.

Divertor coils are used in some designs to direct the outer magnetic surfaces away to another chamber, so that the outer layers of plasma can be scraped off, neutralized, and pumped away, in order to maintain plasma purity.

During initial operation, the ohmic heating coils will drive a plasma current of 2.5 MA with a flat-top (constant-current) period of 1 second. The EF coils will produce an equilibrium field up to 0.42 T. The flat-top time may be extended to 3 seconds by use of additional power supplies.

For obtimum performance, the OH coils should lie on a single flux surface or else be connected in parallel.

Coil system interactions can be minimized by making the total EF coil current equal to the total OH coil current, and by minimizing the mutual inductance between the coil systems.

Placement of EF coils outside the TF coils simplifies coil winding and maintenance, but requires higher EF coil currents and loses the stabilizing effect of closely fitting coils. The OH and EF coils must be protected against voltage spikes and electromagnetic forces induced by plasma disruptions.

The use of an iron-core transformer, as in Fig.4.2, decreases the energy required to drive the OH coils and reduces stray magnetic fields. However, in high-field devices saturation of the iron diminishes the energy

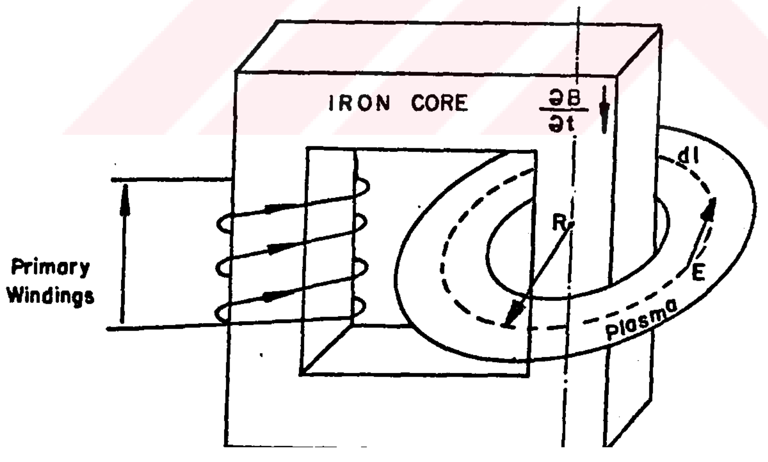


Fig.4.2. Electric field induced in plasma by changing magnetic induction in transformer.

savings, complicates the electrical behavior of the system and causes field errors. The presence of iron core reduces access space on the inside of the torus and reduces plasma stability against radial displacements.

The voltage $\phi = 2\pi rE$ required from the OH coil system is determined by the electric field needed to start the discharge and drive the desired current. The maximum OH coil current limits the Volt-second (magnetic flux) capacity, hence the pulse length. Breakdown is usually initiated by microwave heating or ultraviolet radiation. ECRH is useful to reduce the loop voltage which the OH coils must provide. For example, in ISX-B the inductive componenet of the loop voltage ($LdI/dt+I_R$) stayed constant at 16V, but the resistive component decreased from 27V to 9V with ECRH preionisation. Usually the discharge is initiated at low pressure, with cold gas added later to build up the density after the current is large enough for plasma confinement.

It is possible to operate Tokamaks at steady-state, if a means of current drive other than magnetic induction can be provided. Steady state operation would have the following advantages:

* steady power output, without thermal energy storage
* reduced complexity of OH coil system
* avoidance of pulsed coil stresses and fatigue
* avoidance of thermal cycling of metarials and associated thermal stress fatigue problems
* avoidance of repeated energy losses during startup.

There are several ideas for steady-state current drive, including the bootstrap current, neutral-beam driven currents, and rf current drive.

4.3. BOOTSTRAP CURRENT [2]

The bootstrap current is induced by outward diffusion of plasma particles, so it is not compatible with edge fueling by cold neutral gas. If fresh fuel could be continuously supplied to the plasma core, however, the bootstrap current might be able to sustain plasma confinement, or at least to reduce the required OH power. A selective counter-current loss of some alpha particles, combined with banana orbit effects, may act as a "seed current" for the bootstrap current.

4.4. NEUTRAL-BEAM-DRIVEN CURRENT [2,9,12]

When a neutral beam is injected and trapped, the resultant flowing ions constitute an electrical current.

Beam ions colliding with background electrons will impart momentum to the electrons, tending to drag them along with the beam, and the resulting electronic current opposes the beam ion current. The electrons will also be retarded by friction with back ground plasma ions. When the frictional forces are in balance, the electronic current cancels the beam ion current. However, impurities and trapped electrons can increase the friction of streming electrons with back-fully cancel the beam ion current. The net current density is approximately

$$J_{net} = J_{beam} \left[1 - 1/Zeff + (1.5/Zeff).(1 + 0.7/Zeff).(r/R)^{1/2} \right] \quad (4.1)$$

where

$$J_{beam} = 2\pi r.e \int d^3 \vec{v}\, f_{beam}\, v_{11} \,. \quad (4.2)$$

High neutral beam energies and powers may be required to attain satisfactory penetration.

4.5. ELECTRON-BEAM-DRIVEN-CURRENT [2]

Relativistic electron beams can be injected into a torus along $\vec{B}_t$ using vertical drift to carry them away from the electron gun. Calculations indicate that large currents could be sustained in tokamaks by repeated bursts of electrons from a pulsed gun. Beams with pulse lengths up to 20 transit times (around the torus) have been injected into a torus with trapping effiencies on the order of 60%. The main problems to be solved are:

* beam energy transport into the chamber without introducing impruties
* injection and trapping
* pulse repetation rate and lifetime of beam generator.

4.6. RF CURRENT DRIVE [2,14,15]

Travelling waves have time-avaraged energy densities W_{rf} and momenta $\vec{p}$ related by the expression

$$\vec{p} = (\vec{k}/w)W_{rf} \tag{4.3}$$

where $\vec{k}$ and w are the wave propagation vector and angular frequency. Wave momentum is transferred to electrons and collisionally dissipated at a rate

$$\dot{p} = nmu_e \nu \tag{4.4}$$

where the dot represents a time derivative, n is the electron density, m is the electron mass, u_e is the avarage electron flow velocity, and ν is the momentum-transfer collision frequency. The current density

$$J = neu = (e/m\nu)\dot{p} = (e/m\nu)(k/w)\dot{W} \quad . \tag{4.5}$$

Since the wave phase velocity is $V_\Phi = w/k$, then the ratio of current density to the rf power dissipated is can be simply written as,

$$J/\dot{W} = e/m\nu V \quad . \tag{4.6}$$

This ratio is a figure of merit for rf current drive schemes.

If the rf power is transferred to electrons at $V_e \sim V_\Phi$ and dissipated by electron-ion collisions with momentum-transfer collision frequency ν_e, then

$$J/\dot{W}_{rf} = \begin{cases} (e/m\nu_e V_{te})\; C_1 (V_\Phi/V_{te})^2 & \text{if} \quad V_\Phi > V_{te} \quad (1) \\ (e/m\nu_e V_{te})\; C_2 (V_{te}/V_\Phi) & \text{if} \quad V_\Phi < V_{te} \quad (2) \end{cases} \tag{4.7}$$

where the electron thermal velocity $V_{te} \equiv (k\ Te/m)^{\frac{1}{2}}$. The constants $C_1 = 0.2$ and $C_2 = 1$ are determined by Fokker-Plank codes describing collisional dissipation of wave energy. For the high-phase-velocity case (4.7, Eq.(1)) the resonant electrons will have high velocities $V_e \sim V_\Phi \gg V_{te}$, and therefore low collision frequencies, since $\nu_e \propto 1/V_e^3$. These low collision frequencies will tend to make the ratio $J/\dot{W}_{rf}$ large, as desired.

For the low-phase-velocity case $V_\Phi \ll V_{te}$, the ratio (V_{te}/V_Φ) appearing in the Eq.(2) of (4.7) tends to make $J/\dot{W}_{rf}$ large, but trapped particle effects may invalidate this equation. Assuming the poloidal beta $\beta \simeq R/a$, that $Z \simeq 1$, and that the fusion reaction rate parameter $\langle\sigma v\rangle_{DT} \propto T^2$, the ratio of required rf power to fusion power is estimated to be

$$\frac{P_{rf}}{P_F} = \begin{cases} \dfrac{2.5 \times 10^{10}}{(\bar{n}\ a\ R_o)^{1/2}\ (V_\Phi/c)^2\ \bar{T}^{3/2}} & \text{if } V_\Phi > V_{te} \\[2ex] \dfrac{2.8 \times 10^{12} (V_\Phi/V_{te})}{(\bar{n}\ a\ R_o)^{1/2}\ \bar{T}^{5/2}} & \text{if } V_\Phi < V_{te} \end{cases} \tag{4.8}$$

where $\bar{T}$ is the avarage plasma temperature (keV), $\bar{n}$ is the avarage density (m^{-3}) and c is the speed of light. In order to keep the recirculating power fraction low, large, hot plasmas are desirable. If $\bar{n} = 10^{20} m^{-3}$, $\bar{T} = 20$ keV, a=1.2 m

R_o= 6 m, and V_{Φ}/c = 0.5, then P_{rf}/p_F =0.04 . For this same case, if V_{Φ}/V_{te}= 0.3 , then P_{rf}/P_F = 0.02 .

CHAPTER 5

MODEL AND NUMERICAL SCHEME FOR CURRENT DRIVE OPERATION

5.1. MODEL [20,21,24,26]

The model circuit is shown in Fig.5.1, which includes the primary circuit, the plasma and driving current source. The driving current source is applied externally, parallel to the plasma resistance. The idealized driving current source can be used for any of the current drive methods which are mentioned in chapter 4.

This model is applicable to both the constant and the time-warying current source, and can also be used in the air core and iron core transformer case. It is assumed that the plasma inductance remains constant, i.e, the plasma current profile does not vary with time.

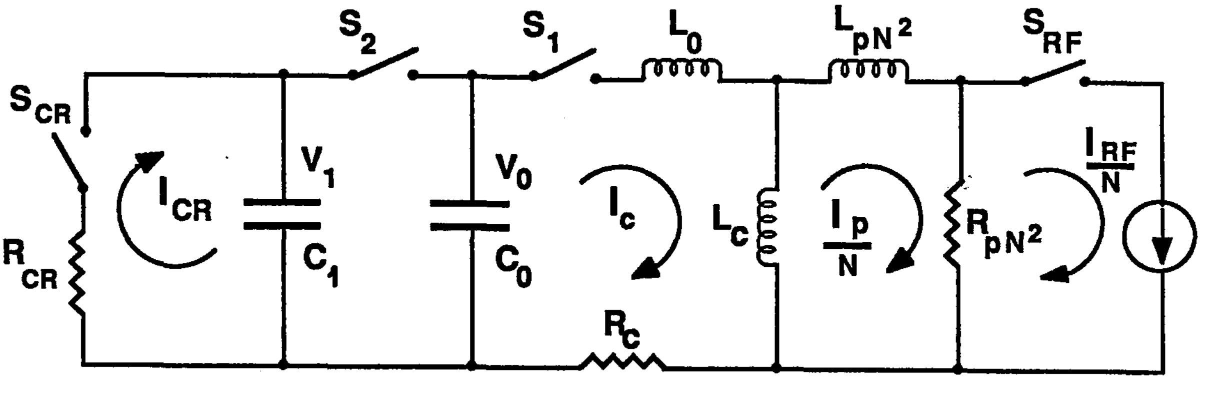


Fig.5.1. Model circuit for current drive operations. The switches are closed in order: S_1, S_2, S_{CR} and S_{RF}.

where I_P is the total plasma current, I_{RF} is the driving current, I_C is the primary coil current, I_{CR} is the crowbar current. The other symbols are explained in Table I the parameters of STOR-II [24] as an example of parameters of medium-sized tokamaks.

Similar equivalent circuit of the plasma and driving current source has been used in experiments reported in Ref. [20] and [21].

5.2. NUMERICAL SCHEME [25,26,27,28]

The equivalent circuit in the current drive phase after crowbar may be described by the following set of equations:

$$L_p \frac{dI_p}{dt} + R_p (I_p - I_{RF}) = M \frac{dI_M}{dt} \tag{5.1}$$

$$L_o \frac{dI_c}{dt} + R_c I_c + M \frac{dI_M}{dt} = V_c - \frac{1}{C_o + C_1} \int_{t_{RF}}^{t} (I_c - I_{CR})\, dt \tag{5.2}$$

$$V_s - \frac{1}{C_o + C_1} \int_{t_{RF}}^{t} (I_c - I_{CR})\, dt + R_{CR} I_{CR} = 0 \tag{5.3}$$

where I_p is the total plasma current, I_{RF} is the driving current, I_c is the primary coil current, I_{CR} is the crowbar current, I_M is the magnetizing current given by

$$I_M = I_c - I_p/N \tag{5.4}$$

V_s is the voltage of the capacitor at $t = t_{RF}$, and M is the mutual inductance given by $M = L_c/N$ .The other symbols are explained in Table 1.

The loop voltage of the plasma may be given by

$$V_L = M \frac{dI_M}{dt} = L_p \frac{dI_p}{dt} + R_p (I_p - I_{RF}) \qquad (5.5)$$

If above equations are drived and collected,a state equation matrix can be obtained as fo lows:

$$L_p \frac{dI_p}{dt} + R_p (I_p - I_{RF}) = \frac{L_c}{N} \frac{d}{dt} (I_c - I_p/N) \qquad (5.6)$$

$$(L_p + \frac{L_c}{N^2}) \frac{dI_p}{dt} = - R_p (I_p - I_{RF}) + \frac{L_c}{N} \frac{dI_c}{dt} \qquad (5.7)$$

$$\frac{dI_p}{dt} = - \frac{R_p}{L_p + \frac{L_c}{N^2}} (I_p - I_{RF}) + \frac{L_c}{NL_p + \frac{L_c}{N}} \frac{dI_c}{dt} \qquad (5.8)$$

$$(L_o + \frac{L_c}{N}) \frac{dI_c}{dt} = - R_c I_c + \frac{L_c}{N^2} \frac{dI_p}{dt} - R_{CR} I_{CR} \qquad (5.9)$$

$$\frac{dI_c}{dt} = - \frac{R_c}{L_o + \frac{L_c}{N}} I_c + \frac{L_c}{N^2 L_o + NL_c} \frac{dI_p}{dt} - \frac{R_{CR}}{L_o + \frac{L_c}{N}} \qquad (5.10)$$

Eqs. (5.8) and (5.10) can be brought to a matrix form:

$$\begin{bmatrix} 1 & -\frac{L_c}{NL_p + \frac{L_c}{N}} \\ -\frac{L_c}{N^2 L_o + NL_c} & 1 \end{bmatrix} \begin{bmatrix} \frac{dI_p}{dt} \\ \frac{dI_c}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{R_p}{L_p + \frac{L_c}{N^2}} & 0 \\ 0 & -\frac{R_c}{L_o + \frac{L_c}{N}} \end{bmatrix} \begin{bmatrix} I_p \\ I_c \end{bmatrix} + \begin{bmatrix} \frac{R_p}{L_p + \frac{L_c}{N^2}} & 0 \\ 0 & -\frac{R_{CR}}{L_o + \frac{L_c}{N}} \end{bmatrix} \begin{bmatrix} I_{RF} \\ I_{CR} \end{bmatrix}$$

In solving the above equations or the state equations matrix it can be used pSpice simulator (Appen.E, algorithm and the program outputs) and the parameters of STOR-II [24] as an example of parameters of medium-sized tokamaks.

TABLE 1

PARAMETERS OF STOR-II TOKAMAK

Major radius	R_o = 70 cm
Minor radius	a = 15 cm
Toroidal field	B_T = 10 kG
Plasma inductance	L_p = 1.86 μH
Plasma resistance	R_{p1} = 300 μohm (current rise phase)
	R_{p2} = 60 μohm (quasi-steady-state phase)
Plasma decay time	$L_p/R_{p2} \simeq$ 31 ms
Self-inductance of the OH coil	L_c = 0.897 mH
External inductance	L_o = 4 mH
External resistance	R_c = 10 mohm
Turn number of the OH coil	N = 74 turns
Crowbar resistance	R_{CR} = 2 mohm
First capacitance	C_o = 10 mF
Second capacitance	C_1 = 150 mF
First charging voltage	V_o = 10 kV
Second charging voltage	V_1 = 2.45 kV

CHAPTER 6

RESULTS OF COMPUTATIONAL EXPERIMENTS

6.1. CASE I

In the firt case, model circuit is made up for plasma and primary circuit.

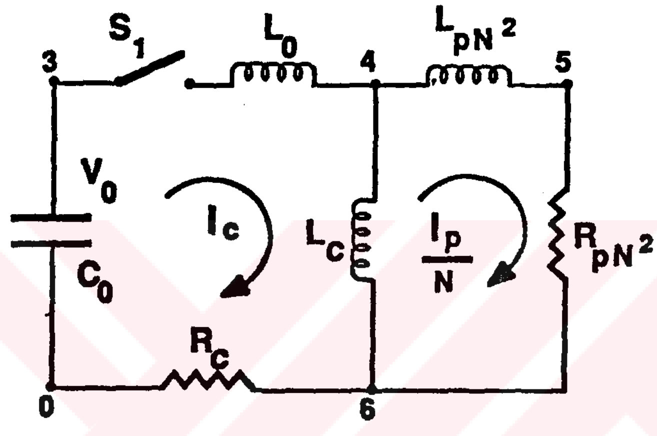
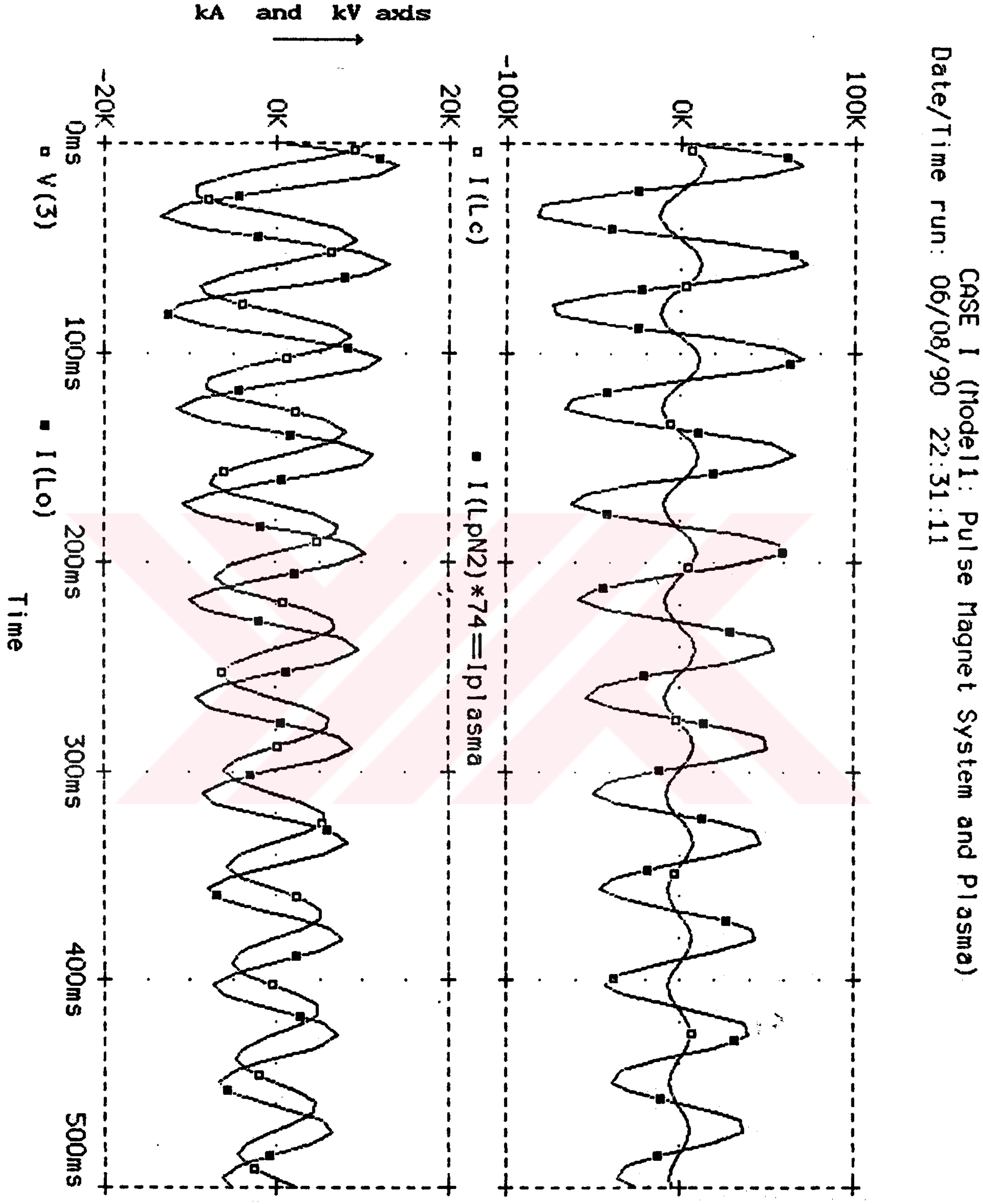


Fig.5.2 First model circuit which represents the plasma and primary circuit.

In this model circuit left part works as a pulse magnet system (Appendix C). When S_1 is closed at t=0, analysis results: V(3) voltage on node 3, I_{Lo}, I_{Lc}, $I(LpN^2)*74=I_{plasma}$ currents are shown on Fig.5.3 by using initial condition Vo=10 kV. (Components on the circuit are represented on Table.1.)

All currents and voltages on the RLC circuit behave as damped sinusoidal oscillations shown on Fig.5.3.



CASE I (Model1: Pulse Magnet System and Plasma)
Date/Time run: 06/08/90 22:31:11
kA and kV axis
100K
0K
-100K
20K
0K
-20K
0ms
100ms
200ms
300ms
400ms
500ms
I(Lc)
I(LpN2)*74=Iplasma
V(3)
I(Lo)
Time

Fig.5.3

6.2. CASE II

In that case, model circuit includes crowbar switch (Appendix C). It is desired to have the coil L_o current I_{Lo} rise up to a maximum value, then stay nearly constant at that value closing the S_{CR} crowbar switch at t=11.2 ms ($I_{Lo\ max}$ instant) instead of oscillating with the damped sinusoid wave form.

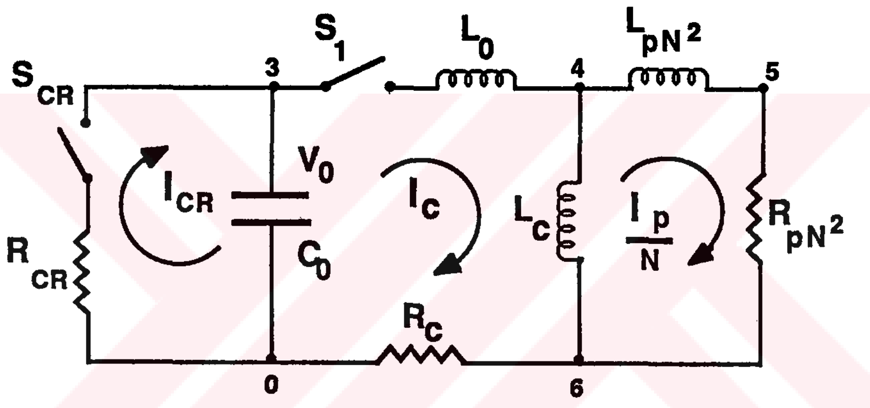


Fig.5.4 Second model circuit, plasma and primary circuit with crowbar.

at t=11.2 ms initial conditions are:

$V_{C_o}(0) = -288$ V

$I_{L_o}(0) = 14.12$ kA

$I_{L_c}(0) = 13.69$ kA

$I_{LpN2}(0) = 421$ A

Initial conditions are determined by transient analysis program output (see Case II transient analysis result at 0.00 ms in Appendix E).

In Fig.5.5 after crowbaring and without driving current, I_{plasma} current decreases slightly from 32 kA, V_{plasma} (loop voltage) from 10 kV. The primary current I_{Lo} or (I_c) and capacitor voltage V(3) in the primary circuit are also shown in Fig.5.5 at 50 ms time scale.

Fig.5.6 shows same outputs at 500 ms time scale. In this figure it can be seen that I_{plasma} current reaches to zero in very short time (approx. 55 ms).

Capacitor voltage V(3) and crowbar current $I_{R_{CR}}$ variations are illustrated in Fig.5.7 at 250 μs time scale in 5.8 at 500 ms time scale.

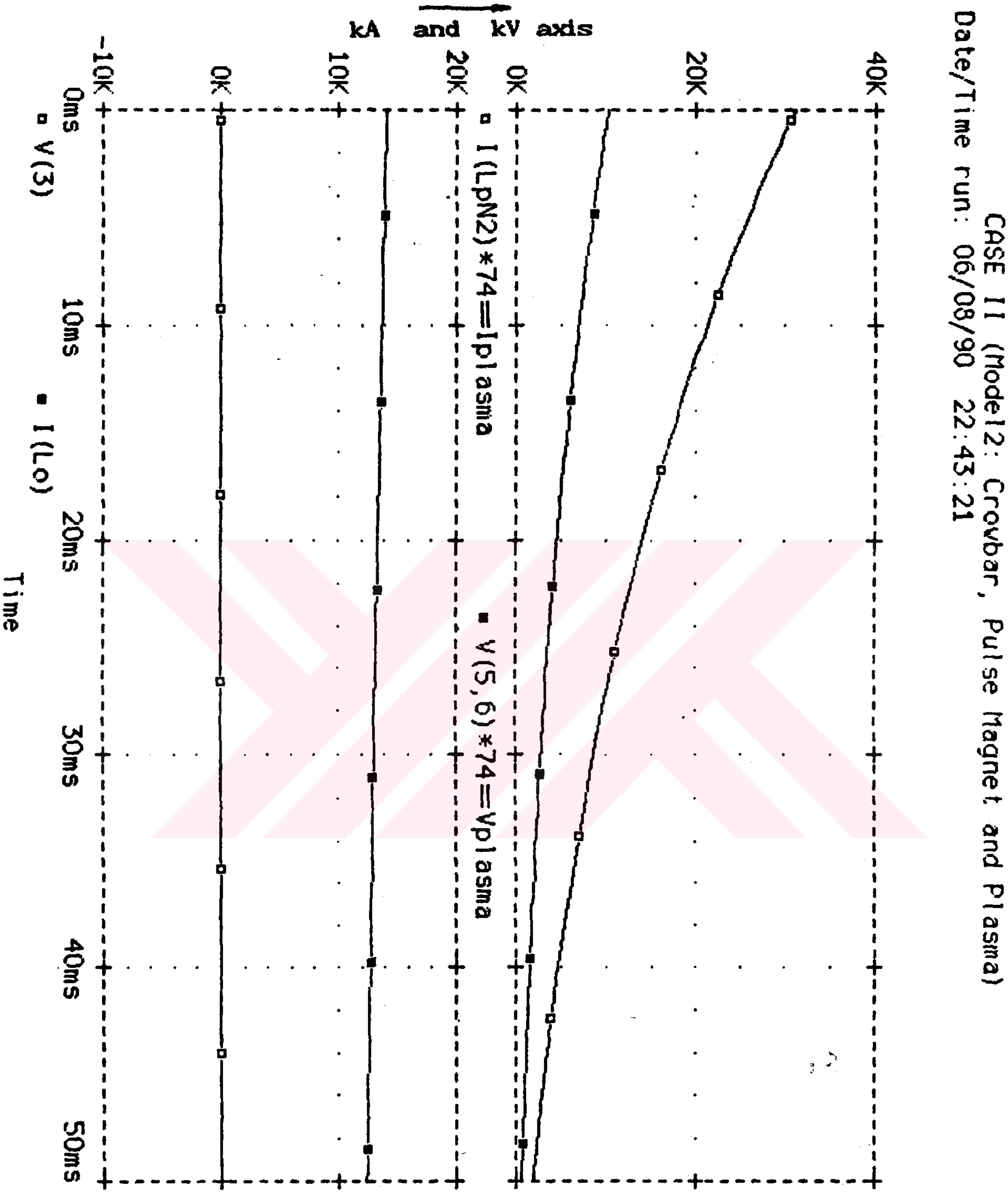

CASE II (Model2: Crowbar, Pulse Magnet and Plasma)
Date/Time run: 06/08/90 22:43:21
kA and kV axis
40K
20K
0K
20K
10K
0K
-10K
0ms
10ms
20ms
30ms
40ms
50ms
Time
I(LpN2)*74=Iplasma
V(5,6)*74=Vplasma
V(3)
I(Lo)

Fig. 5.5

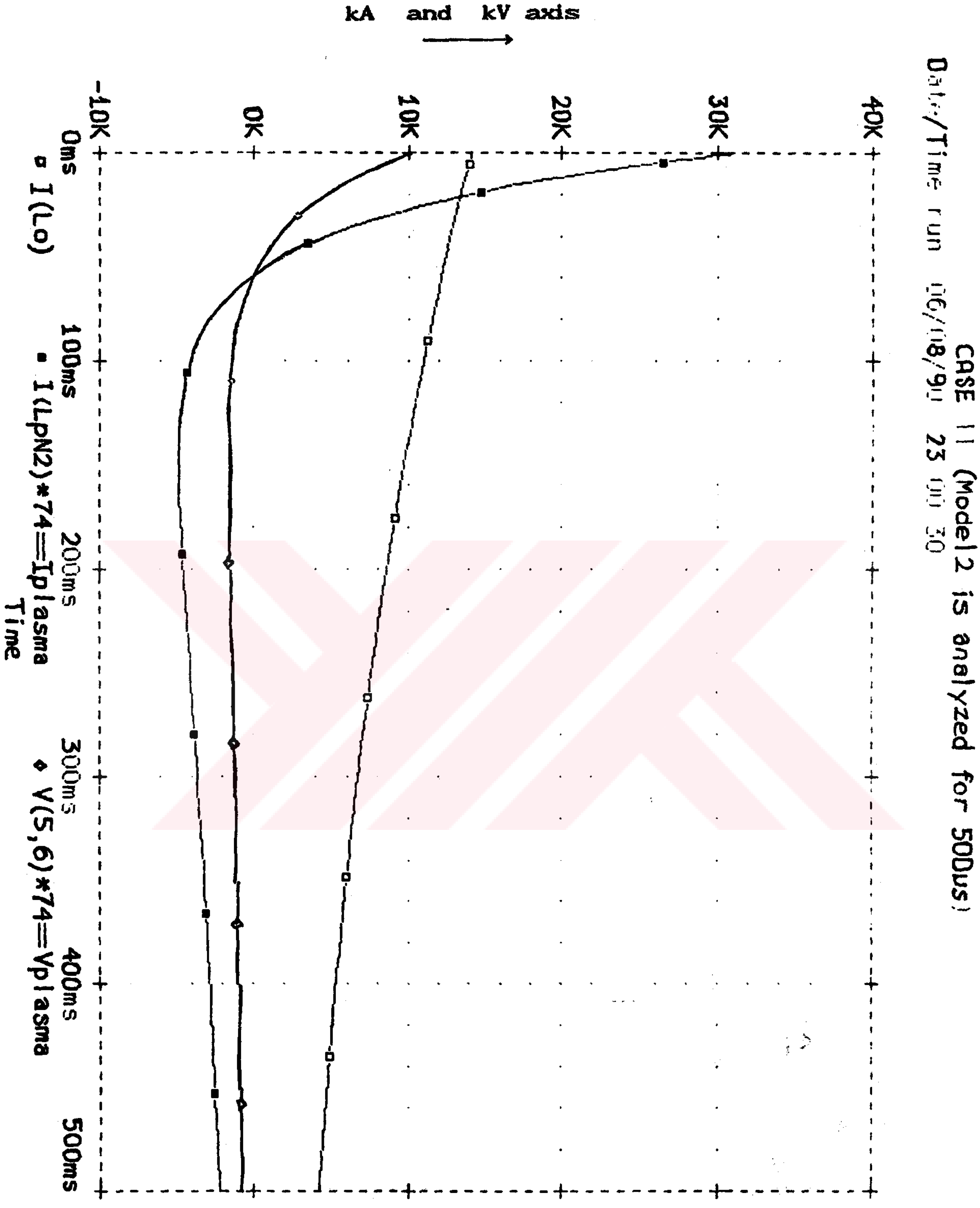

CASE II (Model2 is analyzed for 500us)
kA and kV axis
40K
30K
20K
10K
0K
-10K
0ms
100ms
200ms
300ms
400ms
500ms
Time
I(Lo)
I(LpN2)*74=Iplasma
V(5,6)*74=Vplasma

Fig.5.6

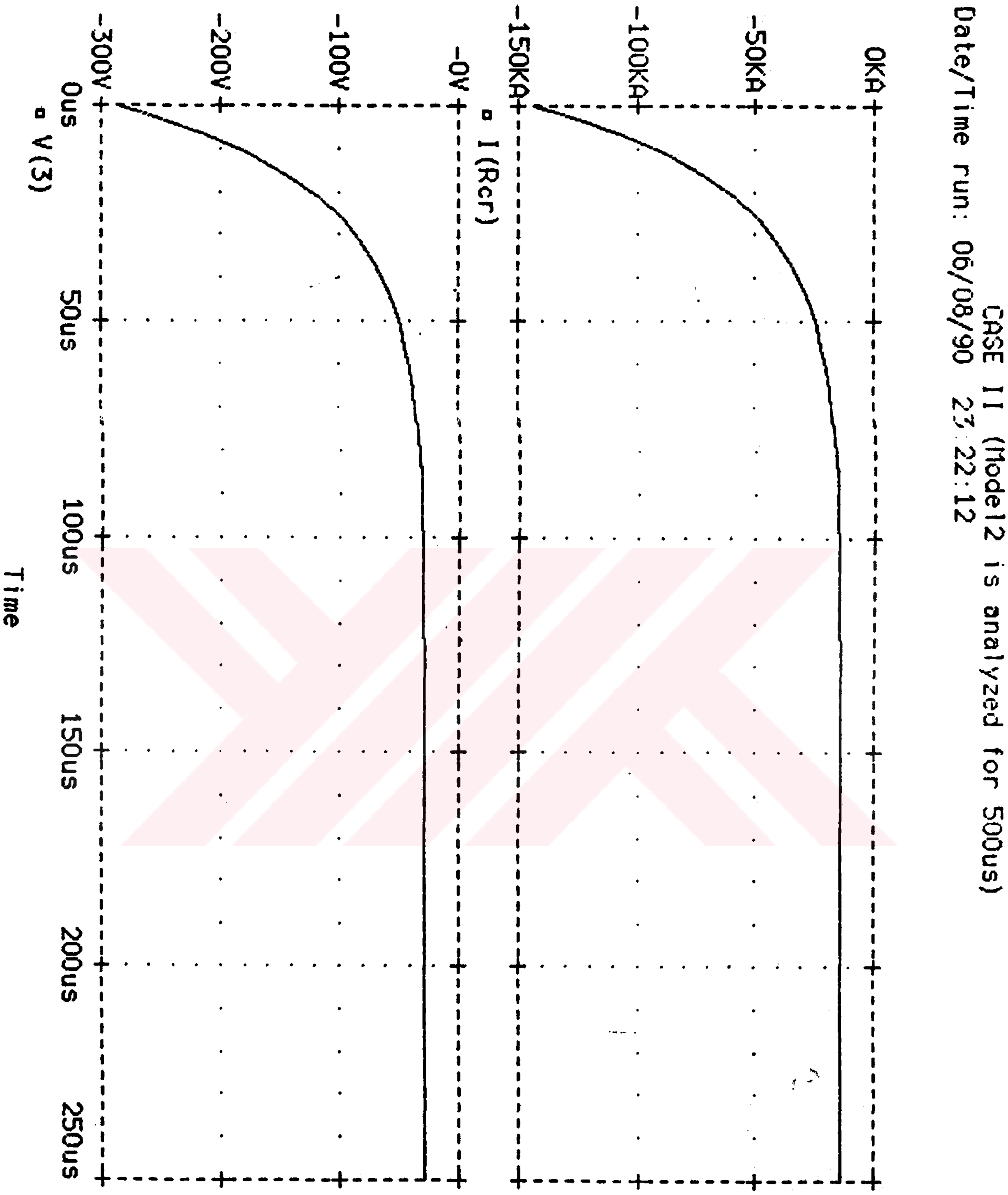
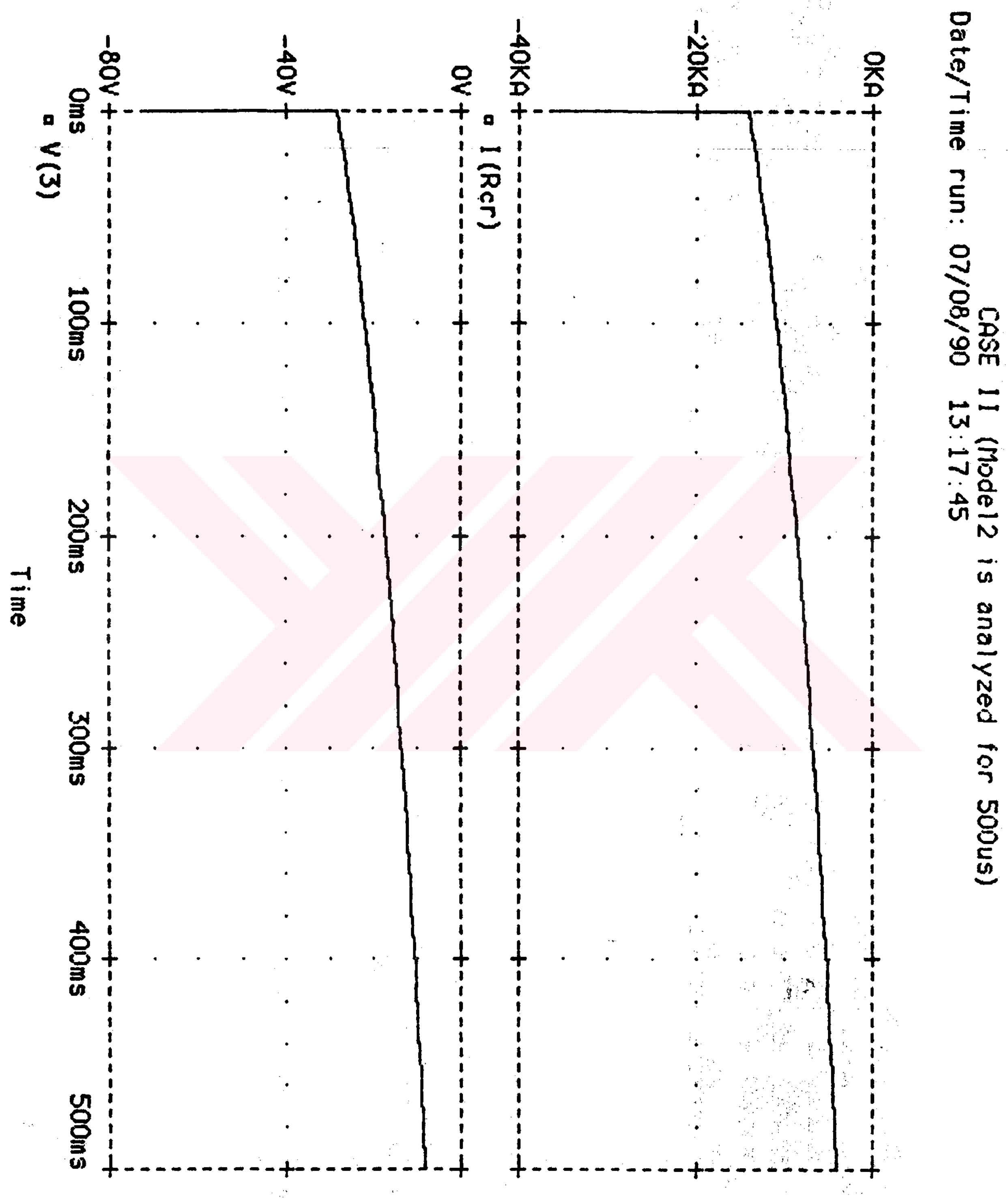

CASE II (Model2 is analyzed for 500us)
Date/Time run: 06/08/90 23:22:12
0KA
-50KA
-100KA
-150KA
I(Rcr)
-0V
-100V
-200V
-300V
V(3)
0us
50us
100us
150us
200us
250us
Time

Fig.5.7



CASE II (Model2 is analyzed for 500us)
Date/Time run: 07/08/90 13:17:45
0KA
-20KA
-40KA
I(Rcr)
0V
-40V
-80V
V(3)
0ms
100ms
200ms
300ms
400ms
500ms
Time

Fig.5.8

6.3. CASE III

In this case, model circuit is made up as seen in Fig.5.9.

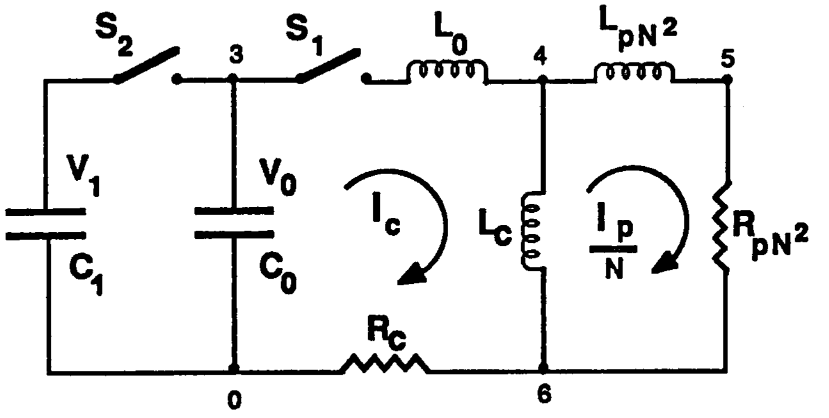


Fig 5.9. Third model circuit

After S_1 is closed, C_1 is applied to the circuit by closing the S_2 at t=9.2 ms, for increasing the discharge capacity and damped oscillation period.

at t=9.2 ms initial conditions are;

$Vc_o(0) = 2.45$ kV

$IL_o(0) = 13.82$ kA

$IL_c(0) = 12.85$ kA

$IL_{pN2}(0) = 953.4$ A

As seen in Fig.5.10, sinusoidal damping period is increased by adding capacitor C_1. Therefore decay time of plasma current becomes more than Case I.

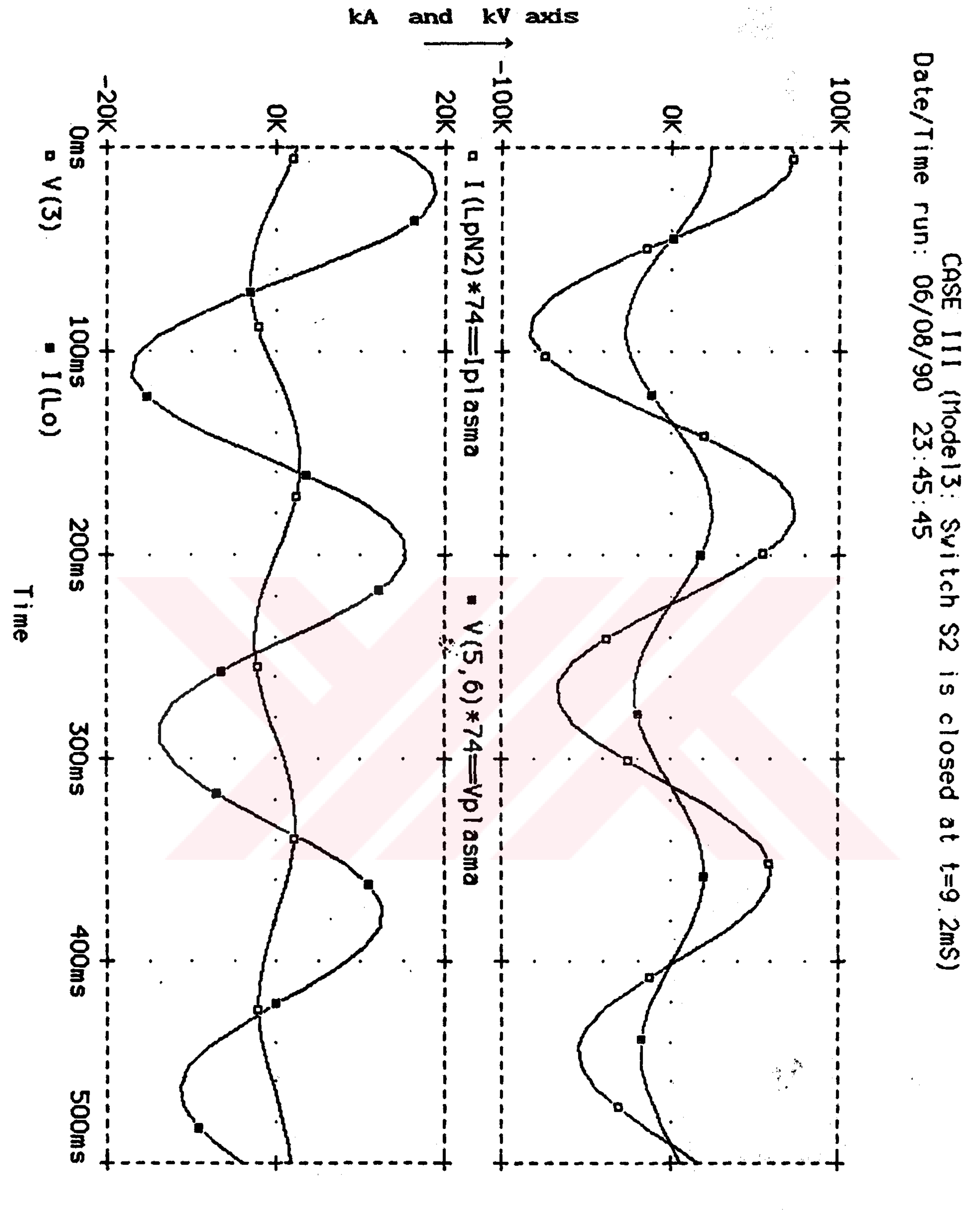

CASE III (Model3: Switch S2 is closed at t=9.2mS)
Date/Time run: 06/08/90 23:45:45
kA and kV axis
100K
0K
-100K
20K
0K
-20K
0ms
100ms
200ms
300ms
400ms
500ms
Time
I(LpN2)*74=Iplasma
V(5,6)*74=Vplasma
V(3)
I(Lo)

Fig.5.10

6.4. CASE IV

In this case model circuit is same as the Case II except C_1 capacitor.

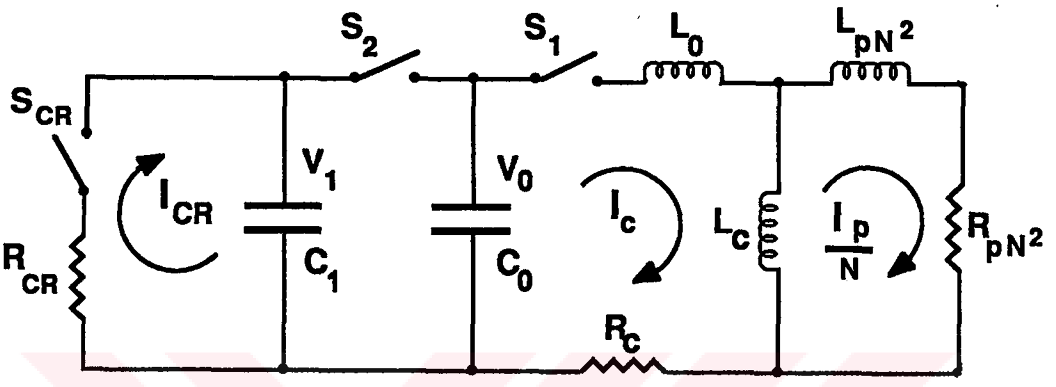


Fig.5.11 Fourth model circuit

S_{CR} crowbar switch is closed at t=11.2 ms. At this instant I_{Lo} stay nearly constant at that value, instead of oscillating with the damped sinusoid wave form.

at t=11.2 ms initial conditions are:

$Vc_o(0) = -18.57$ V

$IL_o(0) = 13.78$ kA

$IL_c(0) = 12.88$ kA

$IL_{pN2}(0) = 896.7$ A

$Vc_1(0) = -18.57$ V

In that case, plasma current starts to decrease from approx. 80 kA as seen from Fig.5.12 and reaches to zero at 85 ms. This difference results from the Case II is obtained by adding C_1 at 9.2 ms. Vplasma voltage as for decreases slightly from 25 kV because of bigger plasma current.

Fig.5.13 shows V(3) capacitors voltage, I_{Lo} primary coil current and $I_{(RpN2)}$ or I_p/N current and and V(5,6) voltage variations.

Fig.5.14 illustrates V(3) capacitors voltage and $I_{R_{CR}}$ crowbar current in this case.

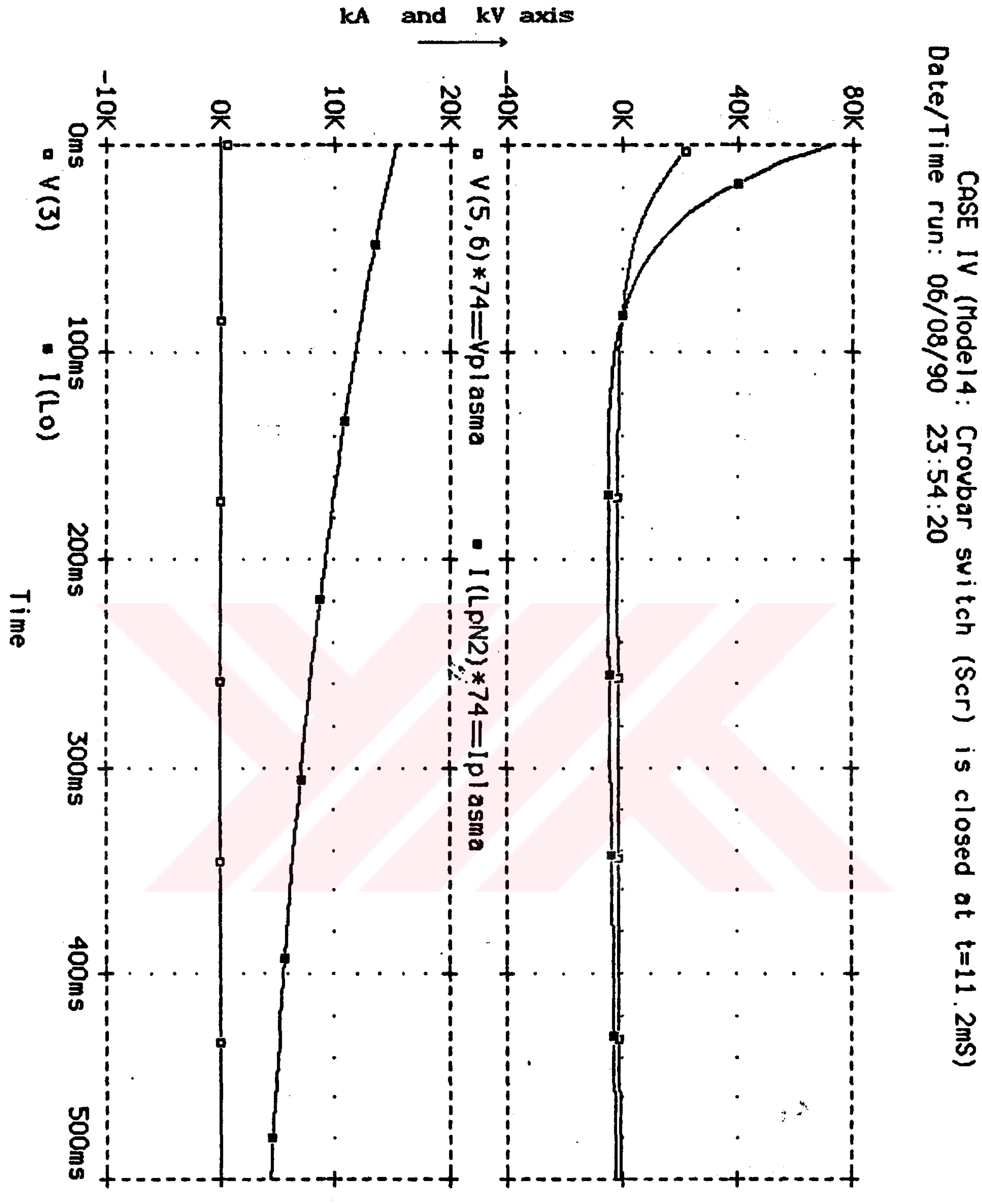

CASE IV (Model4: Crowbar switch (Scr) is closed at t=11.2mS)
Date/Time run: 06/08/90 23:54:20
80K
40K
0K
-40K
20K
10K
0K
-10K
kA and kV axis
V(5,6)*74=Vplasma
I(LpN2)*74=Iplasma
V(3)
I(Lo)
0ms
100ms
200ms
300ms
400ms
500ms
Time

Fig.5.12

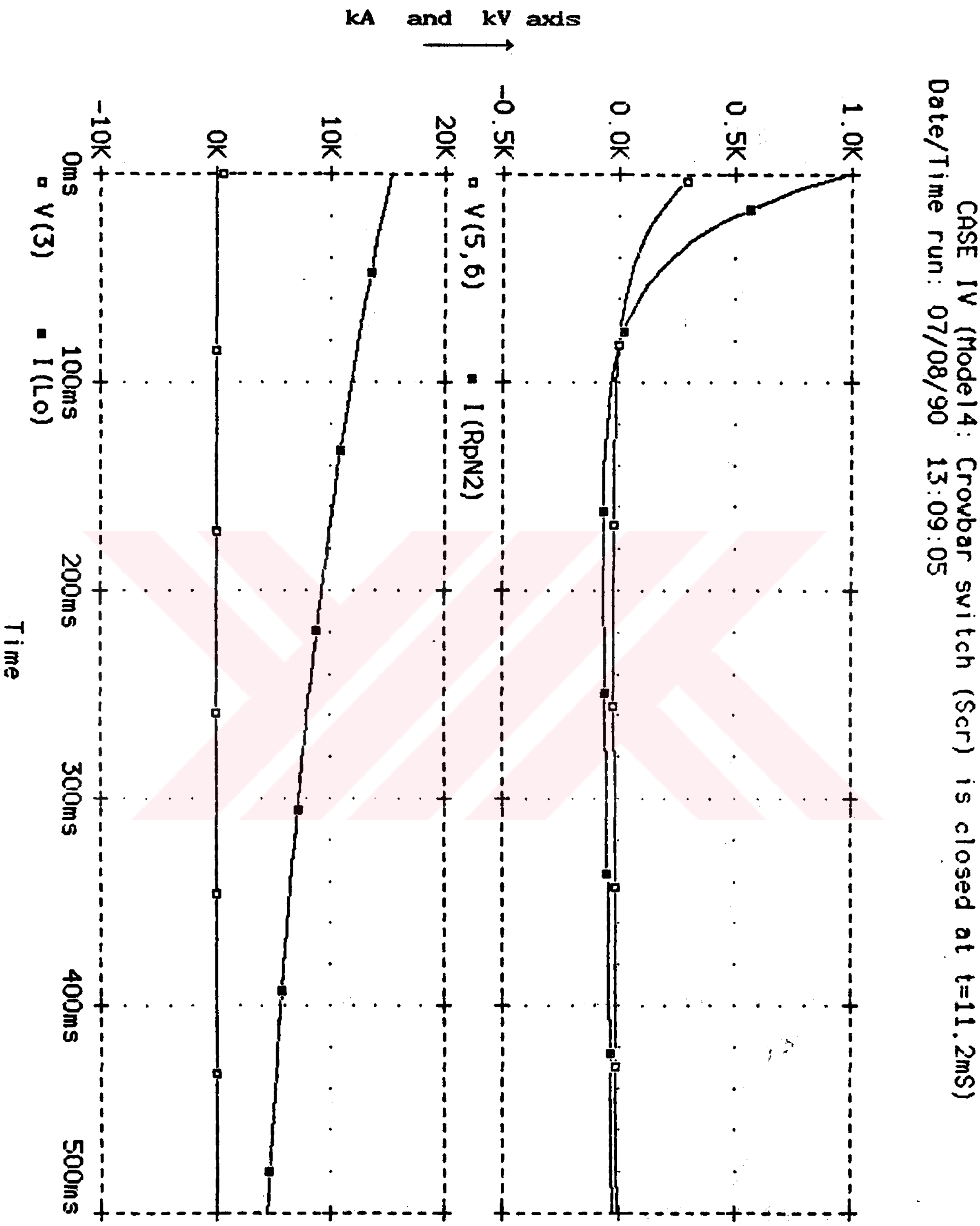

CASE IV (Model4: Crowbar switch (Scr) is closed at t=11.2mS)
Date/Time run: 07/08/90 13:09:05
kA and kV axis
1.0K
0.5K
0.0K
-0.5K
20K
10K
0K
-10K
0ms
100ms
200ms
300ms
400ms
500ms
Time
V(5,6)
I(RpN2)
V(3)
I(Lo)

Fig.5.13

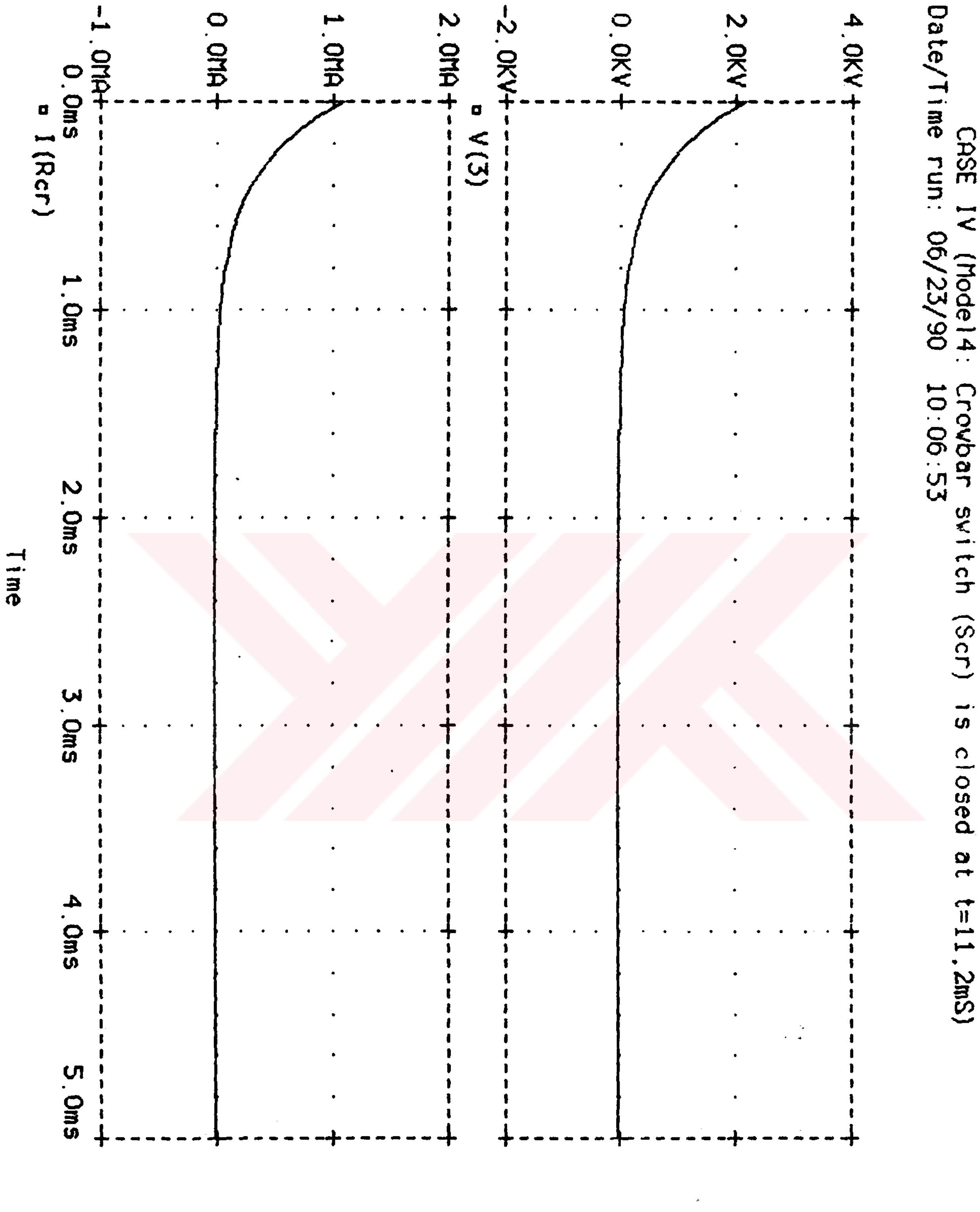

CASE IV (Model4: Crowbar switch (Scr) is closed at t=11.2mS)
Date/Time run: 06/23/90 10:06:53
4.0KV
2.0KV
0.0KV
-2.0KV
V(3)
2.0MA
1.0MA
0.0MA
-1.0MA
I(Rcr)
0.0ms
1.0ms
2.0ms
3.0ms
4.0ms
5.0ms
Time

Fig.5.14

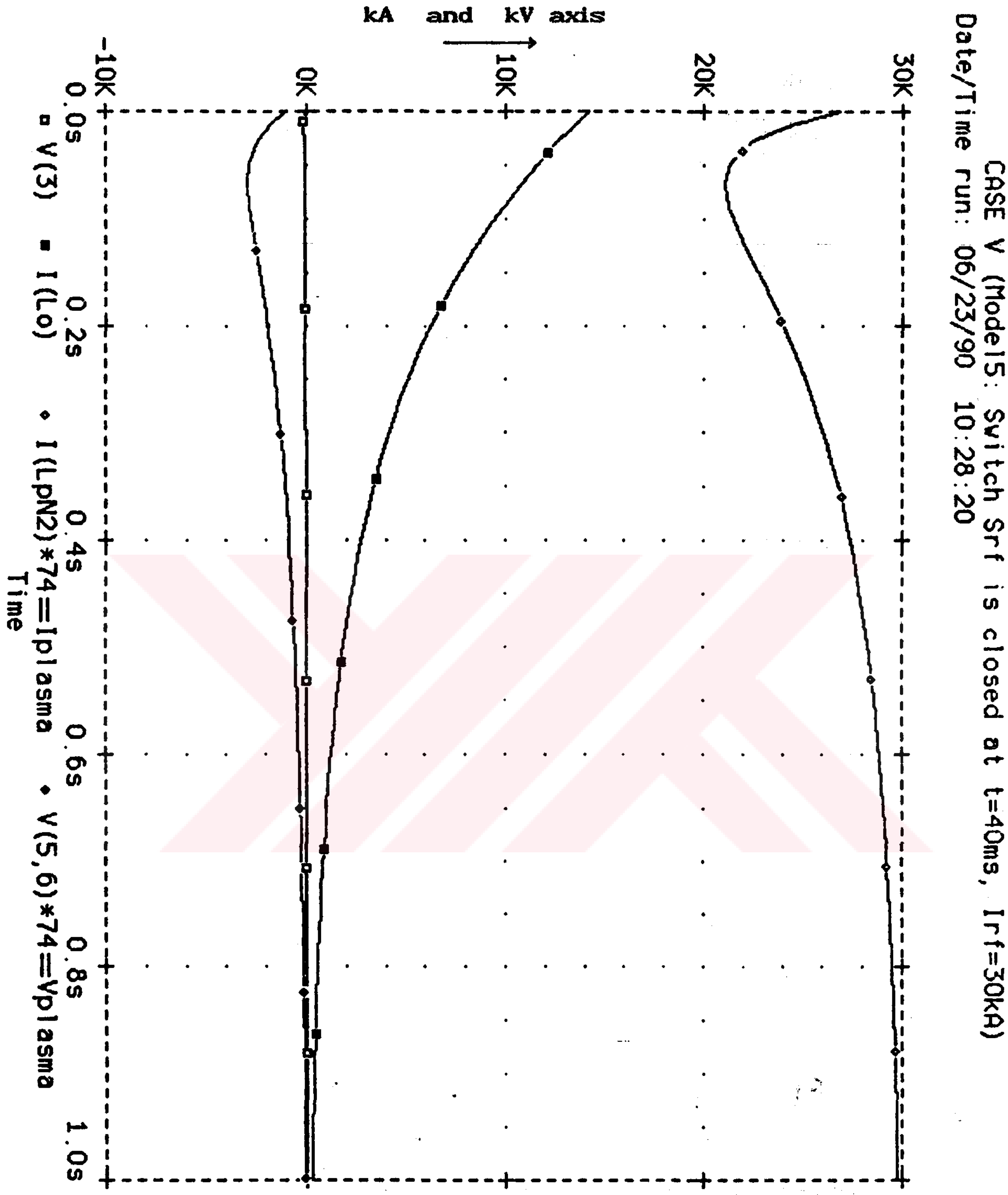

CASE V (Model5: Switch Srf is closed at t=40ms, Irf=30kA)
Date/Time run: 06/23/90 10:28:20
kA and kV axis
30K
20K
10K
0K
-10K
0.0s
0.2s
0.4s
0.6s
0.8s
1.0s
Time
▫ V(3) ▪ I(Lo) ◆ I(LpN2)*74=Iplasma ◆ V(5,6)*74=Vplasma

Fig.16

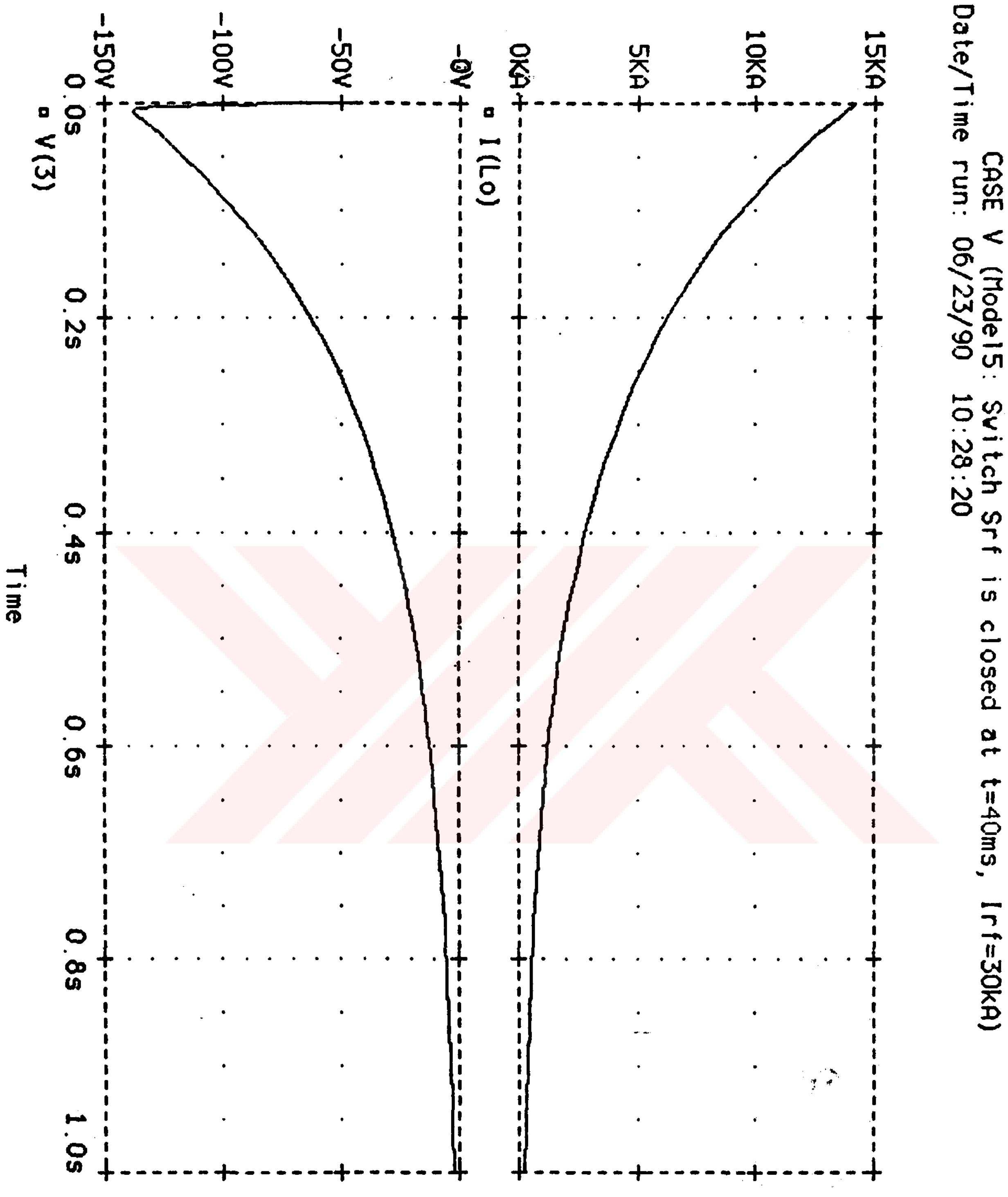

CASE V (Model5: Switch Srf is closed at t=40ms, Irf=30KA)
Date/Time run: 06/23/90 10:28:20
15KA
10KA
5KA
0KA
-0V
-50V
-100V
-150V
▫ I(Lo)
▫ V(3)
0.0s
0.2s
0.4s
0.6s
0.8s
1.0s
Time

Fig.5.17

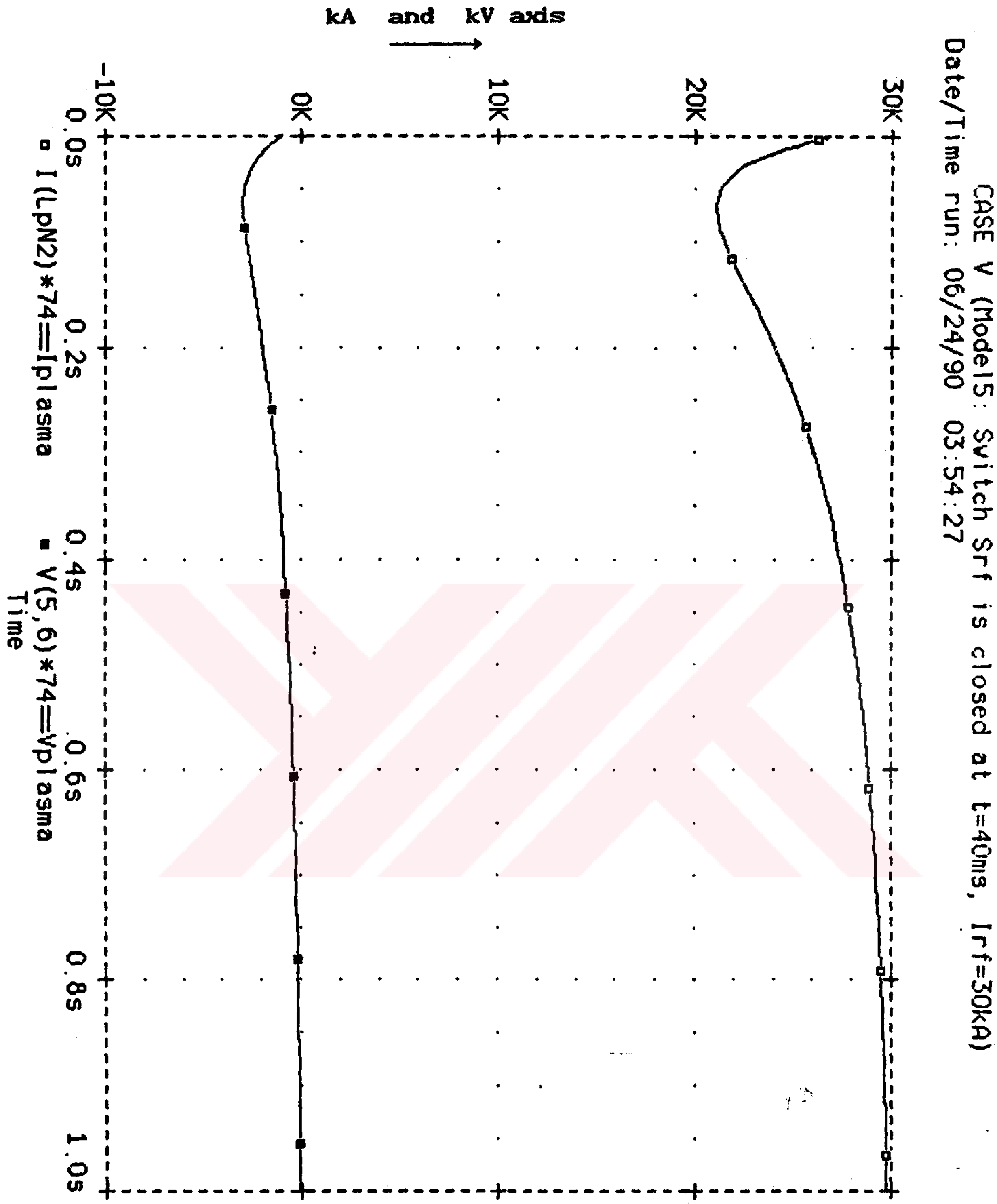

CASE V (Model5: Switch Srf is closed at t=40ms, Irf=30kA)
Date/Time run: 06/24/90 03:54:27
kA and kV axis
30K
20K
10K
0K
-10K
0.0s
0.2s
0.4s
0.6s
0.8s
1.0s
▫ I(LpN2)*74=Iplasma
▪ V(5,6)*74=Vplasma
Time

Fig.5.18

CHAPTER 7

CONCLUSION

Nowadays we learn, How to bring the tokamaks to reactor domain using numerical scheme to evaluate the experimental data obtained from implemented and developed scaled teory of tokamaks. From that consideration we presented physical event with electrical engineering discipline modestly.

- It is seen from chapter 5 and 6 that, it is possible to operate tokamak steady state, if a means of current drive other than magnetic induction can be provided.

- Such a study of a computational experiment and numerical scheme provide so many advantages by using modelling methods to give greater understanding and insight into the behavior of the physical system. Time, money and effort have been saved by using these tecniques.

- From now on it is very easy to investigate and analyze current drive operations in different tokamaks by using their parameters and pSpice simulator program.

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APPENDICES

APPENDIX A

ENERGY SOURCES AND FUSION [29]

Energy supply is vital and, in the long run, an uncertain issue, given the growth of the world population. Depending on the degree and rate of levelling out the extremely uneven global distribution of primary energy consumption over the various economies and depending on the extent of success in enhancing the efficiency of energy end use worldwide, the total energy needs may well increase enormously.

Whatever quantity of energy will be necessary in the future, the criterion of quality will become most important: Energy must be produced in a manner that is not only economically but also environmentally acceptable, even if what is and will be environmentally acceptable is a moving target that is a difficult to define. Every source of energy appears to have its own economic, health and environmental costs and risks. Reliance on fossil fuels, apart from problems linked with global or local availability, carries the risk of global warming (the greenhouse effect) and acidification, which is now perceived with acuteness both by the public and governments. A possible large scale use of the renewable energy sources (sunlight, biomass, etc.) depends on local conditions and seems to be confronted with high costs and substantial environmental consequences. Nuclear power from fission reactor is facing concerns regarding safety, accidental radioactive releases, waste disposel and proliferation of nuclear material. The degree of concern in these areas will most probably be lower in the case of nuclear power from a future fusion power source (typically referred to as a 'fusion reactor'), for which, however, it is too early to tell whether eventually it will be economically competitive.

Against the background of recent experience, the need for the development of diverse and widely accessible long term sources of energy is perceived more and more acutely. These energy sources should show promise of being not only technologically feasible but also acceptable from the economic, safety and environmental points of view. Fusion has the potential of becoming one of these sources.

Developing a completely new source of enrgy such as fusion is a formidable scientific and technological challenge which spans several human generations. Yet the continuity in, and the magnitude of, the progress achived so far on the way to a fusion reactor are impressive and augur well.

Fusion power plants offer the prospects of problems to solve and it will be many years before the development of fusion power is complete.

APPENDIX B

B. THE LAWSON CRITERION

In order to sustain fusion reaction, the deterium-tritium mixture must be heated to an extremely high temperature. The reaction rate for a mixture of two types of ions with respective densities n_D and n_T is determined by the following equation:

$$\frac{dn}{dt} = n_D . n_T \langle \sigma v \rangle_{DT} \tag{B.1}$$

where $\langle \sigma v \rangle_{DT}$ is an average value for the energy distribution assumed to conform to Maxwell's distribution, which varies rapidly depending on temperature and expresses the probability of occurrence of fusion reaction. If Q is the energy produced by a fusion reaction, the energy released per unit volume and per second is:

$$\frac{dF}{dt} = (n^2/4) \langle \sigma v \rangle_{DT} .Q \tag{B.2}$$

assuming $n_D = n_T = n/2$.

To heat the plasma to the required temperature T, 3/2 nkT must be supplied. If τ_E is the energy confinement time in the plasma, the power input required to maintain temperature T is:

$$\frac{dP}{dt} = \tau_E^{-1} . (3/2)\ nkT \tag{B.3}$$

The energy released in this way and the power input (nkT) can only be recovered with an efficiency ρ. Ultimately, the amount of energy recovered will exceed the power input if

$$n\tau_E > (6/Q).(kT/\langle\sigma v\rangle).(1-\rho)/\rho \qquad (B.4)$$

The is the Lawson criterion.

According to the temperature, $kT/\langle\sigma v\rangle$ passes through a minimum of about 27 keV for the D-T reaction and 50 keV for the D-D reaction.

For a D-T reaction at 27 keV, the result is: $n\tau$ 10^{14} $cm^{-3}s$. For a D-D reaction at 27 keV, the result is: $n\tau$ $5.10^{15} cm^{-3}s$.

APPENDIX C

C. PULSED MAGNET SYSTEM AND CROWBAR [2]

The term *pulsed magnets* means that current is supplied from a pulsed power source. Pulsed magnet systems consist of energy storage devices, switches, current tranmission lines, and coils.

A simple RLC circuit, representing a pulsed magnet system, is illustrated in Fig.C.1. The capacitor C is charged up to a voltage V_0 with the switch S_1 open, and then S_1 is closed at $t = 0$. The problem is to determine the current I in the circuit as a function of time.

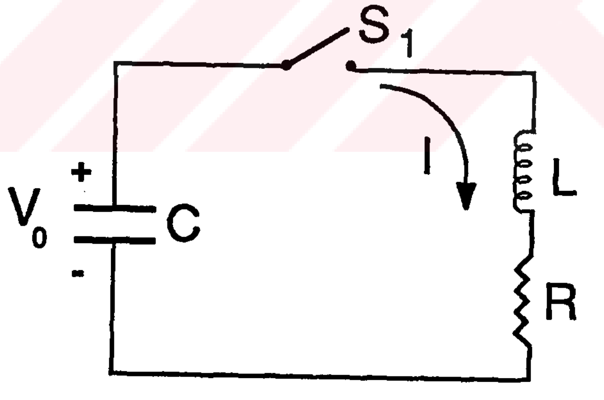

Fig.C.1. Simple RLC circuit. Here R represents the total resistance of all the elements in the circuit, such as the capasitor, switch transmission lines, headers, and magnet coil, and L represents the total inductance of all the circuit elements.

If q is the charge on the capacitor, then the voltage acrossthe capacitor is q/C, the voltage drops across the resistance R is R(dq/dt), and the voltage drop across the inductance L is $L(d^2q/dt^2)$, assuming L to be a constant. (In an actual circuit, L will vary, because of phenomena such as plasma diamagnetism. However, a good estimate of the current can be obtained assuming L to be constant.) By Kirchoff's low, The sum of the voltages around the circuit is zero, and

$$L(d^2q/dt^2) + R(dq/dt) + q/C = 0 \qquad (C.1)$$

The initial conditions are $q = CV_o$ and $dq/dt = 0$. This linear, homogeneous, second-order differential equation can be solved by using the operator notation $D = (d/dt)$, for which

$$(LD^2 + RD + 1/C)q = 0 \quad . \qquad (C.2)$$

The roots of this quadratic equation are

$$D = -a \pm i\omega \qquad (C.3)$$

where $a = R/2L$ and and $\omega = [(1/LC)-a^2]^{1/2}$ .For pulsed magnet circuits, the resistance is kept low, so the quantity in bracets is positive, and the solution is oscillatory. The general solution is therefore

$$q(t) = A\ e^{-at+i\omega t} + A\ e^{-at-i\omega t} \qquad (C.4)$$

which may also be expressed in terms of trigonometric function as

$$q(t) = A_3e^{-at}\cos\omega t + A_4e^{-at}\sin\omega t \quad . \qquad (C.5)$$

From the initial condition $q(0) = CV_o$, it is found that $A_3 = CV_o$. From the other initial condition, $(dq/dt)_{t=o} = 0$, it is found that $A_4 = aA_3/\omega$. The current as a function of time is found from the relation $I(t) = -dq/dt$. The resulting expressions for charge and current are

$$q(t) = CV_o e \quad (\cos\omega t + (a/\omega)\sin\omega t) \tag{C.6}$$

$$I(t) = (V /\omega L)\, e^{-at} \sin\omega t \ . \tag{C.7}$$

Thus $I(t)$ is a damped sinusoid, as illustrated in Fig.C.2. The maximum current and the time t_{max} when the current is maximum are found by setting $dI/dt = 0$, which gives

$$t_{max} = (1/\omega)\mathrm{Arctan}(\omega/a) \tag{C.8}$$

$$I_{max} = (V_o/\omega L)\exp(-at_{max})\sin(\omega t_{max}) \ . \tag{C.9}$$

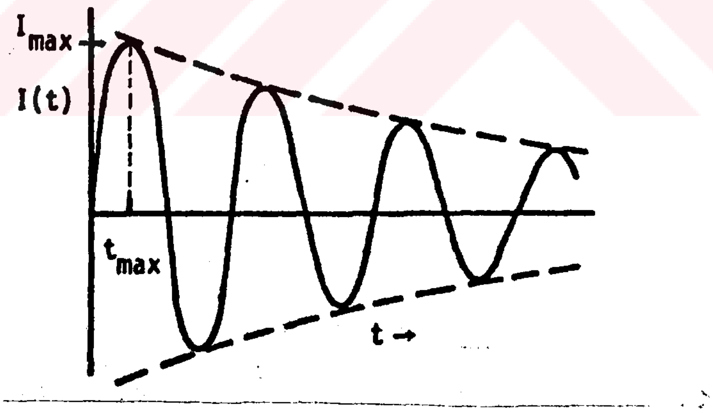

Fig.C.2. Damped sinusoidal oscillation of current in an undercritically damped RLC circuit.

If R,L,C, and V_o are known, then t_{max} and I_{max} can be predicted. Conversely, if R and L are unknown, they can be calculated from measured values of t_{max} and I_{max}.

Usually it is desired to have the coil current rise up to a maximum value, then stay nearly constant at that value, instead of oscillating with the damped sinusoid wave form of Fig.C.2.

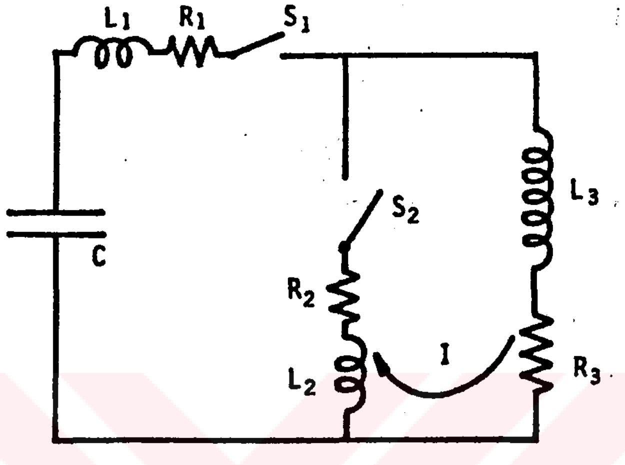

Fig.C.3. A crowbar switch. In this circuit R_1 and L_1 represent the combined resistance and inductance of the capacitor, switch S_1 and other elements of the C-S_1 circuit R_2 and L_2 represent the resistance and inductance of the S_2 circuit (the crowbar switch circuit), and R_3 and L represent the combined resistance and inductance of the load circuit, including coil, header, transmission lines, etc.

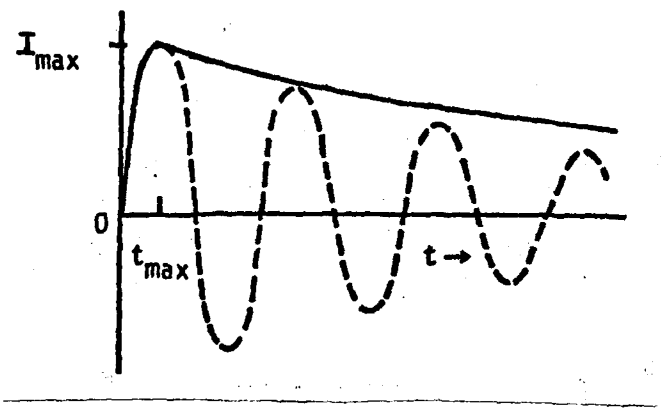

Fig.C.4. Waveform of a crovbarred circuit. The dashed curve represents the damped sinusoid which would occur if the circuit were not crowbarred. There will be some ripples (not shown here on the decay current, due to interaction of energy stored in L2 and L3. The ripples may be deleterious in some experiments.

If a second switch S_2 is added to the circuit, as shown in Fig.C.3, it can be closed when I=Imax, effectively short-circuiting coil L_3 at maximum current. Then the coil current gradually decays from its peak value with a time constant $[(L_2 + L_3)/(R_2 + R_3)]^{1/2}$, as shown in Fig.C.4. The switch S_2 is called *crowbar*.

APPENDIX D

SPICE 2: A COMPUTER PROGRAM TO SIMULATE ELECTRONIC CIRCUITS [28]

D.1.1. DESCRIPTION OF SPICE AND PSPICE

SPICE is a digital computer program that simulates the electrical performance of electronic circuits. This program will determine the quiescent operating point of the circuit, the time domain responce of the circuit, or the small-signal frequency-domain response of the circuit. SPICE contains models for the common circuit components and is capable of simulating most elctronic circuits.

The SPICE input syntax is a free-format style that does not require that data be entered in fixed column locations. The program supplies reasonable default values for circuit parameters that are not specified and performs a considerable amount of error checking to insure that the circuit has been entered correctly. At the beginning user needs specify a minimal number of circuit parameters and simulation controls to obtain reasonable simulation results.

PSPICE is member of the SPICE family of circuit simulators. The programs in this family come from the SPICE 2 circuit simulation program. PSPICE uses the same algorithms as SPICE 2 and also conforms to the SPICE 2 format for input and output files.

PSPICE will run on an IBM-PC competable, XT or AT with 640 kilobytes of memory. The floting-point co-processor (8087 or 80287) is necessary. Either the monocrhome or color display and any printer may be used.

D.1.2. CIRCUIT DESCRIPTION IN PSPICE

The program input defines the circuit to be simulated on an element by element basis. The types of circuit elements that presently are included in the PSPICE component library. Each element in the circuit is defined by an element card that contains the element name, the nodes that the element is connected to and the values of the parameters that define the electrical characteristics of the element.

The first card in the deck is the title card; the contents of this card are printed as the heading for the various sections of the PSPICE output. The last card in the deck is the ".END" card, which serves only signfy the end of the input deck. Except for the title card and .END card, the order of the cards is of no importance to the program. Each circuit element in the circuit is represented in the input by one line, which does not begin with "." .

APPENDIX E

ALGORITHM AND PSPICE PROGRAM LISTING

a) ALGORITHM

Since the switches are closed in different times and the initial conditions of capacitor and inductors will be determined, the whole model circuit is analyzed in five cases. In each state initial conditions determined by transient analysis results when the switch in order not closed yet. With these values and componenets connection nodes can be created a input file. Then this file is compiled by pSpice compilier. During this operation, circuit and components are introduced and if there are errors these are found then .PRINT and .PLOT cards operate and analysis results are obtained.

b) PSpice Program Listing

```
**** 08/08/90 ********* PSpice 4.00 ********* 14:51:34 ********

CASE I (Model1: Pulse Magnet System and Plasma)

****  CIRCUIT DESCRIPTION  ************************************

 .OPT ACCT  NOPAGE RELTOL=.001       ;relative tolerance for
                                      aproximation
 .WIDTH OUT=80                        ;page with 80 character
                                      (or 132 character)
 .TEMP 20                             ;circuit is analysed at 20C

 .TRAN/OP 5mS 50mS UIC             ;transient obtion, sampling
                                    period 5mS, analysis period
                                    50mS, using initial condition
 Co   3  0  10mF IC=10kV         ;Co capacitor connection between
                                 nodes 3 and 0, initial cond.10kV
 Lo   3 4 4mH

 Lc   4 6 0.897mH

 Rc   6 0 0.010

 LpN2 4 5 0.010185H

 RpN2 5 6 0.32856

 .PRINT  TRAN V(3)  I(Lo)  I(LpN2)  V(5,6)

 .PROBE                             ;Probe card runs, analysis
                                     results can be plotted
 .END

 *** TEMPERATURE-ADJUSTED VALUES    TEMPERATURE = 20.000 DEG C

 *** TRANSIENT ANALYSIS             TEMPERATURE = 20.000 DEG C
```

TIME	V(3)	I(Lo)	(Iplasma/74) *********** I(LpN2)	Vplasma/74 ********** V(5,6)
0.000E+00	1.000E+04	6.065E-04	5.462E-04	1.795E-04
5.000E-03	7.522E+03	9.400E+03	7.043E+02	2.314E+02
1.000E-02	1.402E+03	1.406E+04	9.526E+02	3.130E+02
1.500E-02	-5.333E+03	1.177E+04	6.425E+02	2.111E+02
2.000E-02	-9.369E+03	3.728E+03	-5.466E+01	-1.796E+01
2.500E-02	-8.759E+03	-6.044E+03	-7.816E+02	-2.568E+02
3.000E-02	-3.861E+03	-1.273E+04	-1.172E+03	-3.852E+02
3.500E-02	2.870E+03	-1.309E+04	-1.031E+03	-3.389E+02
4.000E-02	8.108E+03	-7.018E+03	-4.280E+02	-1.406E+02
4.500E-02	9.302E+03	2.419E+03	3.419E+02	1.123E+02
5.000E-02	5.928E+03	1.057E+04	9.054E+02	2.975E+02

JOB CONCLUDED

**** JOB STATISTICS SUMMARY

NUNODS	NCNODS	NUMNOD	NUMEL	DIODES	BJTS	JFETS	MFETS	GASFE
5	5	5	6	0	0	0	0	

NDIGITAL	NSTOP	NTTAR	NTTBR	NTTOV	IFILL	IOPS	PERSPA
0	8	20	26	1	6	50	59.375

NUMTTP	NUMRTP	NUMNIT	DIGTP	DIGEVT	DIGEVL	MEMUSE
57	0	171	0	0	0	8334

	SECONDS	ITERATIONS
MATRIX SOLUTION	1.01	2
MATRIX LOAD	.88	
READIN	1.98	
SETUP	.17	
DC SWEEP	0.00	0
BIAS POINT	0.00	0
AC and NOISE	0.00	0
TRANSIENT ANALYSIS	6.15	171
OUTPUT	.27	
OVERHEAD	2.86	
TOTAL JOB TIME	11.43	

```
***** 08/08/90 ********* PSpice 4.00 ********* 16:07:49 *****

CASE II (Model2: Crowbar, Pulse Magnet and Plasma)

****   CIRCUIT DESCRIPTION   ********************************

.OPT ACCT NOMOD NOPAGE RELTOL=0.001
.WIDTH OUT=80
.TEMP 20
.TRAN/OP 1mS 50mS UIC
Co  3 0 10mF IC=-288V
Lo  3 4 4mH  IC=14.12kA
Lc  4 6 0.897mH IC=13.69kA
LpN2 4 5 10.18536mH IC=421A
Rc  6 0 0.010
RpN2 5 6 0.32856
Rcr 3 0 0.002
.PRINT  TRAN V(3),I(Lo),I(LpN2),V(5,6)
.PROBE
.END

***  TRANSIENT ANALYSIS       TEMPERATURE = 20.000 DEG C
```

TIME	V(3)	I(Lo)	Iplasma/74 ************ I(LpN2)	Vplasma/74 *********** V(5,6)
0.000E+00	-2.803E+02	1.412E+04	4.216E+02	1.385E+02
1.000E-03	-2.816E+01	1.408E+04	4.062E+02	1.335E+02
2.000E-03	-2.809E+01	1.404E+04	3.914E+02	1.286E+02
3.000E-03	-2.801E+01	1.401E+04	3.771E+02	1.239E+02
4.000E-03	-2.794E+01	1.397E+04	3.631E+02	1.193E+02
5.000E-03	-2.787E+01	1.393E+04	3.496E+02	1.149E+02
6.000E-03	-2.779E+01	1.390E+04	3.365E+02	1.105E+02
7.000E-03	-2.772E+01	1.386E+04	3.237E+02	1.064E+02
8.000E-03	-2.765E+01	1.382E+04	3.114E+02	1.023E+02
9.000E-03	-2.758E+01	1.379E+04	2.994E+02	9.837E+01

1.000E-02	-2.750E+01	1.375E+04	2.878E+02	9.456E+01
1.100E-02	-2.743E+01	1.372E+04	2.765E+02	9.086E+01
1.200E-02	-2.736E+01	1.368E+04	2.656E+02	8.728E+01
1.300E-02	-2.729E+01	1.364E+04	2.550E+02	8.380E+01
1.400E-02	-2.722E+01	1.361E+04	2.448E+02	8.042E+01
1.500E-02	-2.715E+01	1.357E+04	2.348E+02	7.715E+01
1.600E-02	-2.708E+01	1.354E+04	2.252E+02	7.398E+01
1.700E-02	-2.701E+01	1.350E+04	2.158E+02	7.091E+01
1.800E-02	-2.694E+01	1.347E+04	2.067E+02	6.793E+01
1.900E-02	-2.687E+01	1.344E+04	1.979E+02	6.504E+01
2.000E-02	-2.680E+01	1.340E+04	1.894E+02	6.223E+01
2.100E-02	-2.673E+01	1.337E+04	1.811E+02	5.952E+01
2.200E-02	-2.667E+01	1.333E+04	1.731E+02	5.688E+01
2.300E-02	-2.660E+01	1.330E+04	1.654E+02	5.433E+01
2.400E-02	-2.653E+01	1.326E+04	1.578E+02	5.185E+01
2.500E-02	-2.646E+01	1.323E+04	1.505E+02	4.945E+01
2.600E-02	-2.640E+01	1.320E+04	1.434E+02	4.712E+01
2.700E-02	-2.633E+01	1.316E+04	1.366E+02	4.487E+01
2.800E-02	-2.626E+01	1.313E+04	1.299E+02	4.268E+01
2.900E-02	-2.619E+01	1.310E+04	1.235E+02	4.056E+01
3.000E-02	-2.613E+01	1.306E+04	1.172E+02	3.851E+01
3.100E-02	-2.606E+01	1.303E+04	1.111E+02	3.651E+01
3.200E-02	-2.600E+01	1.300E+04	1.053E+02	3.458E+01
3.300E-02	-2.593E+01	1.296E+04	9.956E+01	3.271E+01
3.400E-02	-2.586E+01	1.293E+04	9.404E+01	3.090E+01
3.500E-02	-2.580E+01	1.290E+04	8.869E+01	2.914E+01
3.600E-02	-2.573E+01	1.287E+04	8.351E+01	2.744E+01
3.700E-02	-2.567E+01	1.283E+04	7.848E+01	2.579E+01
3.800E-02	-2.561E+01	1.280E+04	7.361E+01	2.419E+01
3.900E-02	-2.554E+01	1.277E+04	6.890E+01	2.264E+01
4.000E-02	-2.548E+01	1.274E+04	6.432E+01	2.113E+01
4.100E-02	-2.541E+01	1.271E+04	5.989E+01	1.968E+01
4.200E-02	-2.535E+01	1.267E+04	5.560E+01	1.827E+01
4.300E-02	-2.529E+01	1.264E+04	5.144E+01	1.690E+01
4.400E-02	-2.522E+01	1.261E+04	4.741E+01	1.558E+01
4.500E-02	-2.516E+01	1.258E+04	4.351E+01	1.430E+01
4.600E-02	-2.510E+01	1.255E+04	3.973E+01	1.305E+01
4.700E-02	-2.503E+01	1.252E+04	3.606E+01	1.185E+01
4.800E-02	-2.497E+01	1.248E+04	3.251E+01	1.068E+01
4.900E-02	-2.491E+01	1.245E+04	2.908E+01	9.554E+00
5.000E-02	-2.485E+01	1.242E+04	2.574E+01	8.455E+00

JOB CONCLUDED

**** JOB STATISTICS SUMMARY

NUNODS	NCNODS	NUMNOD	NUMEL	DIODES	BJTS	JFETS	MFETS	GASFET
5	5	5	7	0	0	0	0	

NDIGITAL	NSTOP	NTTAR	NTTBR	NTTOV	IFILL	IOPS	PERSPA
0	8	20	26	2	6	50	59.375

NUMTTP	NUMRTP	NUMNIT	DIGTP	DIGEVT	DIGEVL	MEMUSE
65	1	195	0	0	0	8402

	SECONDS	ITERATIONS
MATRIX SOLUTION	1.16	2
MATRIX LOAD	.99	
READIN	2.04	
SETUP	.17	
DC SWEEP	0.00	0
BIAS POINT	0.00	0
AC and NOISE	0.00	0
TRANSIENT ANALYSIS	6.75	195
OUTPUT	.77	
OVERHEAD	2.63	
TOTAL JOB TIME	12.36	

```
**** 08/08/90 **** PSpice 4.00  ***** 17:19:23 *******

CASE II (Model2 is analyzed for 500us)

****   CIRCUIT DESCRIPTION   **************************

 .OPT ACCT NOMOD NOPAGE RELTOL=0.001

 .WIDTH OUT=80

 .TEMP 20

 .TRAN/OP 10uS 500uS UIC

 Co   3 0 10mF IC=-288V

 Lo   3 4 4mH  IC=14.12kA

 Lc   4 6 0.897mH IC=13.69kA

 LpN2 4 5 10.18536mH IC=421A

 Rc   6 0 0.010

 RpN2 5 6 0.32856

 Rcr 3 0 0.002

 .PRINT  TRAN  V(3) I(Lo) I(LpN2) V(5,6)

 .PROBE

 .END
```

```
****  TRANSIENT ANALYSIS        TEMPERATURE = 20.000 DEG C
```

			Iplasma/74	Vplasma/74
			**********	**********
TIME	V(3)	I(Lo)	I(LpN2)	V(5,6)
0.000E+00	-2.880E+02	1.412E+04	4.216E+02	1.385E+02
1.000E-05	-1.875E+02	1.412E+04	4.214E+02	1.385E+02
2.000E-05	-1.252E+02	1.412E+04	4.212E+02	1.384E+02
3.000E-05	-8.620E+01	1.412E+04	4.211E+02	1.383E+02
4.000E-05	-6.284E+01	1.412E+04	4.209E+02	1.383E+02
5.000E-05	-4.889E+01	1.412E+04	4.207E+02	1.382E+02
6.000E-05	-4.056E+01	1.412E+04	4.206E+02	1.382E+02
7.000E-05	-3.559E+01	1.411E+04	4.204E+02	1.381E+02
8.000E-05	-3.262E+01	1.411E+04	4.203E+02	1.381E+02

9.000E-05	-3.085E+01	1.411E+04	4.201E+02	1.380E+02
1.000E-04	-2.979E+01	1.411E+04	4.200E+02	1.380E+02
1.100E-04	-2.916E+01	1.411E+04	4.198E+02	1.379E+02
1.200E-04	-2.878E+01	1.411E+04	4.197E+02	1.379E+02
1.300E-04	-2.856E+01	1.411E+04	4.195E+02	1.378E+02
1.400E-04	-2.842E+01	1.411E+04	4.193E+02	1.378E+02
1.500E-04	-2.834E+01	1.411E+04	4.192E+02	1.377E+02
1.600E-04	-2.830E+01	1.411E+04	4.190E+02	1.377E+02
1.700E-04	-2.827E+01	1.411E+04	4.189E+02	1.376E+02
1.800E-04	-2.825E+01	1.411E+04	4.187E+02	1.376E+02
1.900E-04	-2.824E+01	1.411E+04	4.186E+02	1.375E+02
2.000E-04	-2.823E+01	1.411E+04	4.184E+02	1.375E+02
2.100E-04	-2.823E+01	1.411E+04	4.183E+02	1.374E+02
2.200E-04	-2.822E+01	1.411E+04	4.181E+02	1.374E+02
2.300E-04	-2.822E+01	1.411E+04	4.180E+02	1.373E+02
2.400E-04	-2.822E+01	1.411E+04	4.178E+02	1.373E+02
2.500E-04	-2.822E+01	1.411E+04	4.177E+02	1.372E+02
2.600E-04	-2.822E+01	1.411E+04	4.175E+02	1.372E+02
2.700E-04	-2.822E+01	1.411E+04	4.173E+02	1.371E+02
2.800E-04	-2.822E+01	1.411E+04	4.172E+02	1.371E+02
2.900E-04	-2.821E+01	1.411E+04	4.170E+02	1.370E+02
3.000E-04	-2.821E+01	1.411E+04	4.169E+02	1.370E+02
3.100E-04	-2.821E+01	1.411E+04	4.167E+02	1.369E+02
3.200E-04	-2.821E+01	1.411E+04	4.166E+02	1.369E+02
3.300E-04	-2.821E+01	1.411E+04	4.164E+02	1.368E+02
3.400E-04	-2.821E+01	1.410E+04	4.163E+02	1.368E+02
3.500E-04	-2.821E+01	1.410E+04	4.161E+02	1.367E+02
3.600E-04	-2.821E+01	1.410E+04	4.160E+02	1.367E+02
3.700E-04	-2.821E+01	1.410E+04	4.158E+02	1.366E+02
3.800E-04	-2.821E+01	1.410E+04	4.157E+02	1.366E+02
3.900E-04	-2.821E+01	1.410E+04	4.155E+02	1.365E+02
4.000E-04	-2.821E+01	1.410E+04	4.153E+02	1.365E+02
4.100E-04	-2.821E+01	1.410E+04	4.152E+02	1.364E+02
4.200E-04	-2.820E+01	1.410E+04	4.150E+02	1.364E+02
4.300E-04	-2.820E+01	1.410E+04	4.149E+02	1.363E+02
4.400E-04	-2.820E+01	1.410E+04	4.147E+02	1.363E+02
4.500E-04	-2.820E+01	1.410E+04	4.146E+02	1.362E+02
4.600E-04	-2.820E+01	1.410E+04	4.144E+02	1.362E+02
4.700E-04	-2.820E+01	1.410E+04	4.143E+02	1.361E+02
4.800E-04	-2.820E+01	1.410E+04	4.141E+02	1.361E+02
4.900E-04	-2.820E+01	1.410E+04	4.140E+02	1.360E+02
5.000E-04	-2.820E+01	1.410E+04	4.138E+02	1.360E+02

JOB CONCLUDED

**** JOB STATISTICS SUMMARY

NUNODS	NCNODS	NUMNOD	NUMEL	DIODES	BJTS	JFETS	MFETS	GASFE
5	5	5	7	0	0	0	0	

NDIGITAL	NSTOP	NTTAR	NTTBR	NTTOV	IFILL	IOPS	PERSPA
0	8	20	26	2	6	50	59.375

NUMTTP	NUMRTP	NUMNIT	DIGTP	DIGEVT	DIGEVL	MEMUSE
57	0	171	0	0	0	8402

	SECONDS	ITERATIONS
MATRIX SOLUTION	1.16	2
MATRIX LOAD	.93	
READIN	2.14	
SETUP	.22	
DC SWEEP	0.00	0
BIAS POINT	0.00	0
AC and NOISE	0.00	0
TRANSIENT ANALYSIS	6.04	171
OUTPUT	.82	
OVERHEAD	2.86	
TOTAL JOB TIME	12.08	

```
**** 09/8/90 ******* PSpice 4.00 ******* 19:45:04 *******

   CASE III (Model3: Switch S2 is closed at t=9.2mS)

 ****   CIRCUIT DESCRIPTION   ********************************

  .OPT ACCT NOMOD NOPAGE RELTOL=0.001

  .WIDTH OUT=80

  .TEMP 20

  .TRAN/OP 5mS 500mS UIC

  Co   3 0 10mF IC=2.45kV

  Lo   3 4 4mH  IC=13.82kA

  Lc   4 6 0.897mH IC=12.85kA

  LpN2 4 5 10.18536mH IC=953.4A

  Rc   6 0 0.010

  RpN2 5 6 0.32856

  C1   3 0 150mF IC=2.45kV

  .PRINT TRAN V(3) I(Lo) I(LpN2) V(5,6)

  .PROBE

  .END

 ****  TRANSIENT ANALYSIS          TEMPERATURE = 20.000 DEG C
```

TIME	V(3)	I(Lo)	Iplasma/74 ********** I(LpN2)	Vplasma/74 ********** V(5,6)
0.000E+00	2.450E+03	1.382E+04	9.545E+02	3.136E+02
5.000E-03	1.981E+03	1.591E+04	9.800E+02	3.220E+02
1.000E-02	1.454E+03	1.741E+04	9.579E+02	3.147E+02
1.500E-02	8.967E+02	1.833E+04	8.977E+02	2.949E+02
2.000E-02	3.187E+02	1.870E+04	8.034E+02	2.640E+02
2.500E-02	-2.532E+02	1.857E+04	6.835E+02	2.246E+02
3.000E-02	-8.175E+02	1.777E+04	5.311E+02	1.745E+02
3.500E-02	-1.346E+03	1.652E+04	3.636E+02	1.195E+02
4.000E-02	-1.828E+03	1.468E+04	1.768E+02	5.809E+01
4.500E-02	-2.249E+03	1.250E+04	-1.352E+01	-4.441E+00
5.000E-02	-2.592E+03	9.863E+03	-2.083E+02	-6.845E+01

5.500E-02	-2.857E+03	7.030E+03	-3.952E+02	-1.298E+02
6.000E-02	-3.021E+03	3.943E+03	-5.720E+02	-1.879E+02
6.500E-02	-3.101E+03	8.268E+02	-7.308E+02	-2.401E+02
7.000E-02	-3.071E+03	-2.327E+03	-8.667E+02	-2.848E+02
7.500E-02	-2.960E+03	-5.339E+03	-9.773E+02	-3.211E+02
8.000E-02	-2.744E+03	-8.170E+03	-1.056E+03	-3.468E+02
8.500E-02	-2.460E+03	-1.071E+04	-1.105E+03	-3.629E+02
9.000E-02	-2.088E+03	-1.288E+04	-1.116E+03	-3.667E+02
9.500E-02	-1.669E+03	-1.465E+04	-1.098E+03	-3.608E+02
1.000E-01	-1.191E+03	-1.591E+04	-1.042E+03	-3.425E+02
1.050E-01	-6.927E+02	-1.671E+04	-9.604E+02	-3.156E+02
1.100E-01	-1.686E+02	-1.692E+04	-8.453E+02	-2.777E+02
1.150E-01	3.468E+02	-1.667E+04	-7.107E+02	-2.335E+02
1.200E-01	8.514E+02	-1.584E+04	-5.513E+02	-1.811E+02
1.250E-01	1.320E+03	-1.459E+04	-3.814E+02	-1.253E+02
1.300E-01	1.744E+03	-1.284E+04	-1.980E+02	-6.504E+01
1.350E-01	2.110E+03	-1.078E+04	-1.406E+01	-4.619E+00
1.400E-01	2.403E+03	-8.332E+03	1.705E+02	5.602E+01
1.450E-01	2.624E+03	-5.725E+03	3.457E+02	1.136E+02
1.500E-01	2.753E+03	-2.909E+03	5.089E+02	1.672E+02
1.550E-01	2.804E+03	-8.619E+01	6.543E+02	2.150E+02
1.600E-01	2.757E+03	2.747E+03	7.768E+02	2.552E+02
1.650E-01	2.637E+03	5.436E+03	8.752E+02	2.875E+02
1.700E-01	2.424E+03	7.940E+03	9.429E+02	3.098E+02
1.750E-01	2.151E+03	1.017E+04	9.835E+02	3.231E+02
1.800E-01	1.801E+03	1.204E+04	9.895E+02	3.251E+02
1.850E-01	1.412E+03	1.355E+04	9.687E+02	3.183E+02
1.900E-01	9.721E+02	1.458E+04	9.136E+02	3.002E+02
1.950E-01	5.170E+02	1.519E+04	8.353E+02	2.744E+02
2.000E-01	4.259E+01	1.527E+04	7.273E+02	2.390E+02
2.050E-01	-4.211E+02	1.494E+04	6.024E+02	1.979E+02
2.100E-01	-8.712E+02	1.408E+04	4.560E+02	1.498E+02
2.150E-01	-1.287E+03	1.286E+04	3.009E+02	9.887E+01
2.200E-01	-1.658E+03	1.118E+04	1.348E+02	4.430E+01
2.250E-01	-1.975E+03	9.252E+03	-3.072E+01	-1.009E+01
2.300E-01	-2.223E+03	6.989E+03	-1.956E+02	-6.428E+01
2.350E-01	-2.406E+03	4.595E+03	-3.512E+02	-1.154E+02
2.400E-01	-2.504E+03	2.032E+03	-4.948E+02	-1.626E+02
2.450E-01	-2.532E+03	-5.206E+02	-6.214E+02	-2.042E+02
2.500E-01	-2.471E+03	-3.062E+03	-7.266E+02	-2.387E+02
2.550E-01	-2.346E+03	-5.457E+03	-8.095E+02	-2.660E+02
2.600E-01	-2.137E+03	-7.666E+03	-8.642E+02	-2.839E+02
2.650E-01	-1.876E+03	-9.613E+03	-8.942E+02	-2.938E+02
2.700E-01	-1.548E+03	-1.123E+04	-8.928E+02	-2.933E+02
2.750E-01	-1.187E+03	-1.250E+04	-8.675E+02	-2.850E+02
2.800E-01	-7.833E+02	-1.333E+04	-8.115E+02	-2.666E+02
2.850E-01	-3.685E+02	-1.379E+04	-7.351E+02	-2.415E+02
2.900E-01	6.035E+01	-1.376E+04	-6.326E+02	-2.079E+02
2.950E-01	4.768E+02	-1.336E+04	-5.157E+02	-1.694E+02
3.000E-01	8.776E+02	-1.249E+04	-3.803E+02	-1.250E+02
3.050E-01	1.245E+03	-1.130E+04	-2.381E+02	-7.823E+01
3.100E-01	1.569E+03	-9.717E+03	-8.714E+01	-2.863E+01
3.150E-01	1.843E+03	-7.909E+03	6.239E+01	2.050E+01
3.200E-01	2.052E+03	-5.819E+03	2.101E+02	6.903E+01
3.250E-01	2.201E+03	-3.624E+03	3.485E+02	1.145E+02

3.300E-01	2.274E+03	-1.296E+03	4.749E+02	1.560E+02
3.350E-01	2.283E+03	1.009E+03	5.854E+02	1.923E+02
3.400E-01	2.211E+03	3.284E+03	6.755E+02	2.220E+02
3.450E-01	2.082E+03	5.413E+03	7.452E+02	2.449E+02
3.500E-01	1.880E+03	7.358E+03	7.889E+02	2.592E+02
3.550E-01	1.631E+03	9.055E+03	8.102E+02	2.662E+02
3.600E-01	1.325E+03	1.044E+04	8.031E+02	2.639E+02
3.650E-01	9.908E+02	1.151E+04	7.745E+02	2.545E+02
3.700E-01	6.209E+02	1.217E+04	7.186E+02	2.361E+02
3.750E-01	2.434E+02	1.249E+04	6.447E+02	2.118E+02
3.800E-01	-1.435E+02	1.237E+04	5.479E+02	1.800E+02
3.850E-01	-5.169E+02	1.193E+04	4.389E+02	1.442E+02
3.900E-01	-8.730E+02	1.106E+04	3.141E+02	1.032E+02
3.950E-01	-1.197E+03	9.911E+03	1.839E+02	6.043E+01
4.000E-01	-1.479E+03	8.414E+03	4.699E+01	1.544E+01
4.050E-01	-1.715E+03	6.728E+03	-8.778E+01	-2.884E+01
4.100E-01	-1.890E+03	4.801E+03	-2.198E+02	-7.222E+01
4.150E-01	-2.011E+03	2.793E+03	-3.426E+02	-1.126E+02
4.200E-01	-2.061E+03	6.818E+02	-4.537E+02	-1.491E+02
4.250E-01	-2.054E+03	-1.395E+03	-5.497E+02	-1.806E+02
4.300E-01	-1.975E+03	-3.428E+03	-6.267E+02	-2.059E+02
4.350E-01	-1.845E+03	-5.318E+03	-6.848E+02	-2.250E+02
4.400E-01	-1.649E+03	-7.025E+03	-7.190E+02	-2.362E+02
4.450E-01	-1.414E+03	-8.501E+03	-7.330E+02	-2.408E+02
4.500E-01	-1.129E+03	-9.681E+03	-7.212E+02	-2.370E+02
4.550E-01	-8.200E+02	-1.057E+04	-6.903E+02	-2.268E+02
4.600E-01	-4.817E+02	-1.109E+04	-6.350E+02	-2.086E+02
4.650E-01	-1.389E+02	-1.130E+04	-5.640E+02	-1.853E+02
4.700E-01	2.096E+02	-1.111E+04	-4.730E+02	-1.554E+02
4.750E-01	5.438E+02	-1.063E+04	-3.715E+02	-1.220E+02
4.800E-01	8.597E+02	-9.768E+03	-2.567E+02	-8.433E+01
4.850E-01	1.145E+03	-8.668E+03	-1.378E+02	-4.528E+01
4.900E-01	1.390E+03	-7.260E+03	-1.380E+01	-4.534E+00
4.950E-01	1.599E+03	-5.702E+03	1.087E+02	3.571E+01
5.000E-01	1.761E+03	-3.952E+03	2.292E+02	7.531E+01

JOB CONCLUDED

**** JOB STATISTICS SUMMARY

NUNODS	NCNODS	NUMNOD	NUMEL	DIODES	BJTS	JFETS	MFETS	GASFETS
5	5	5	7	0	0	0	0	0

NDIGITAL	NSTOP	NTTAR	NTTBR	NTTOV	IFILL	IOPS	PERSPA
0	8	20	26	3	6	50	59.375

NUMTTP	NUMRTP	NUMNIT	DIGTP	DIGEVT	DIGEVL	MEMUSE
57	0	171	0	0	0	8470

	SECONDS	ITERATIONS
MATRIX SOLUTION	1.48	2
MATRIX LOAD	.33	
READIN	2.09	
SETUP	.22	
DC SWEEP	0.00	0
BIAS POINT	0.00	0
AC and NOISE	0.00	0
TRANSIENT ANALYSIS	6.15	171
OUTPUT	1.43	
OVERHEAD	2.74	
TOTAL JOB TIME	12.63	

**** 09/08/90 ******* PSpice 4.00 ******* 21:27:45 *******

CASE IV (Model4: Crowbar switch (Scr) is closed at t=11.2mS)

**** CIRCUIT DESCRIPTION ********************************

```
.OPT ACCT NOMOD NOPAGE RELTOL=0.001
.WIDTH OUT=80
.TEMP 20
.tran/op 5mS 500mS UIC
Co   3 0 10mF IC=2.175kV
Lo   3 4 4mH  IC=15.16kA
Lc   4 6 0.897mH IC=14.19kA
LpN2 4 5 10.18536mH IC=976A
Rc   6 0 0.010
RpN2 5 6 0.32856
Ci   3 0 150mF IC=2.175kV
Rcr 3 0 0.002
.probe
.print tran V(3) I(Lo) I(LpN2) V(5,6)
.END
```

**** TRANSIENT ANALYSIS   TEMPERATURE = 20.000 DEG C

			Iplasma/74 **********	Vplasma/74 **********
TIME	V(3)	I(Lo)	I(LpN2)	V(5,6)
0.000E+00	2.121E+03	1.516E+04	9.759E+02	3.206E+02
5.000E-03	-3.021E+01	1.509E+04	8.355E+02	2.745E+02
1.000E-02	-2.980E+01	1.489E+04	7.068E+02	2.322E+02
1.500E-02	-2.940E+01	1.469E+04	5.973E+02	1.962E+02
2.000E-02	-2.900E+01	1.449E+04	5.000E+02	1.643E+02
2.500E-02	-2.862E+01	1.430E+04	4.156E+02	1.366E+02
3.000E-02	-2.824E+01	1.411E+04	3.439E+02	1.130E+02
3.500E-02	-2.788E+01	1.393E+04	2.819E+02	9.261E+01

4.000E-02	-2.752E+01	1.375E+04	2.293E+02	7.534E+01
4.500E-02	-2.717E+01	1.357E+04	1.838E+02	6.039E+01
5.000E-02	-2.682E+01	1.340E+04	1.453E+02	4.775E+01
5.500E-02	-2.648E+01	1.323E+04	1.121E+02	3.682E+01
6.000E-02	-2.615E+01	1.306E+04	8.399E+01	2.760E+01
6.500E-02	-2.582E+01	1.290E+04	5.975E+01	1.963E+01
7.000E-02	-2.550E+01	1.274E+04	3.931E+01	1.292E+01
7.500E-02	-2.518E+01	1.258E+04	2.171E+01	7.134E+00
8.000E-02	-2.487E+01	1.243E+04	6.917E+00	2.273E+00
8.500E-02	-2.456E+01	1.227E+04	-5.793E+00	-1.903E+00
9.000E-02	-2.426E+01	1.212E+04	-1.644E+01	-5.401E+00
9.500E-02	-2.396E+01	1.197E+04	-2.555E+01	-8.395E+00
1.000E-01	-2.367E+01	1.182E+04	-3.314E+01	-1.089E+01
1.050E-01	-2.338E+01	1.168E+04	-3.961E+01	-1.301E+01
1.100E-01	-2.309E+01	1.154E+04	-4.495E+01	-1.477E+01
1.150E-01	-2.281E+01	1.139E+04	-4.947E+01	-1.625E+01
1.200E-01	-2.253E+01	1.125E+04	-5.316E+01	-1.747E+01
1.250E-01	-2.225E+01	1.112E+04	-5.625E+01	-1.848E+01
1.300E-01	-2.198E+01	1.098E+04	-5.874E+01	-1.930E+01
1.350E-01	-2.171E+01	1.085E+04	-6.077E+01	-1.997E+01
1.400E-01	-2.145E+01	1.071E+04	-6.237E+01	-2.049E+01
1.450E-01	-2.118E+01	1.058E+04	-6.364E+01	-2.091E+01
1.500E-01	-2.093E+01	1.045E+04	-6.459E+01	-2.122E+01
1.550E-01	-2.067E+01	1.033E+04	-6.530E+01	-2.146E+01
1.600E-01	-2.042E+01	1.020E+04	-6.578E+01	-2.161E+01
1.650E-01	-2.017E+01	1.008E+04	-6.609E+01	-2.171E+01
1.700E-01	-1.992E+01	9.954E+03	-6.622E+01	-2.176E+01
1.750E-01	-1.968E+01	9.833E+03	-6.623E+01	-2.176E+01
1.800E-01	-1.944E+01	9.713E+03	-6.611E+01	-2.172E+01
1.850E-01	-1.921E+01	9.595E+03	-6.591E+01	-2.166E+01
1.900E-01	-1.897E+01	9.478E+03	-6.562E+01	-2.156E+01
1.950E-01	-1.874E+01	9.363E+03	-6.526E+01	-2.144E+01
2.000E-01	-1.851E+01	9.249E+03	-6.484E+01	-2.131E+01
2.050E-01	-1.829E+01	9.136E+03	-6.438E+01	-2.115E+01
2.100E-01	-1.806E+01	9.025E+03	-6.388E+01	-2.099E+01
2.150E-01	-1.784E+01	8.915E+03	-6.334E+01	-2.081E+01
2.200E-01	-1.763E+01	8.807E+03	-6.277E+01	-2.062E+01
2.250E-01	-1.741E+01	8.700E+03	-6.219E+01	-2.043E+01
2.300E-01	-1.720E+01	8.594E+03	-6.158E+01	-2.023E+01
2.350E-01	-1.699E+01	8.489E+03	-6.096E+01	-2.003E+01
2.400E-01	-1.679E+01	8.386E+03	-6.033E+01	-1.982E+01
2.450E-01	-1.658E+01	8.284E+03	-5.970E+01	-1.961E+01
2.500E-01	-1.638E+01	8.183E+03	-5.905E+01	-1.940E+01
2.550E-01	-1.618E+01	8.084E+03	-5.840E+01	-1.919E+01
2.600E-01	-1.598E+01	7.985E+03	-5.775E+01	-1.898E+01
2.650E-01	-1.579E+01	7.888E+03	-5.710E+01	-1.876E+01
2.700E-01	-1.560E+01	7.792E+03	-5.645E+01	-1.855E+01
2.750E-01	-1.541E+01	7.697E+03	-5.581E+01	-1.834E+01
2.800E-01	-1.522E+01	7.604E+03	-5.516E+01	-1.812E+01
2.850E-01	-1.503E+01	7.511E+03	-5.452E+01	-1.791E+01
2.900E-01	-1.485E+01	7.420E+03	-5.388E+01	-1.770E+01
2.950E-01	-1.467E+01	7.330E+03	-5.324E+01	-1.749E+01
3.000E-01	-1.449E+01	7.241E+03	-5.261E+01	-1.729E+01
3.050E-01	-1.432E+01	7.152E+03	-5.199E+01	-1.708E+01
3.100E-01	-1.414E+01	7.065E+03	-5.137E+01	-1.688E+01

3.150E-01	-1.397E+01	6.979E+03	-5.076E+01	-1.668E+01
3.200E-01	-1.380E+01	6.895E+03	-5.015E+01	-1.648E+01
3.250E-01	-1.363E+01	6.811E+03	-4.955E+01	-1.628E+01
3.300E-01	-1.347E+01	6.728E+03	-4.895E+01	-1.608E+01
3.350E-01	-1.330E+01	6.646E+03	-4.836E+01	-1.589E+01
3.400E-01	-1.314E+01	6.565E+03	-4.778E+01	-1.570E+01
3.450E-01	-1.298E+01	6.485E+03	-4.720E+01	-1.551E+01
3.500E-01	-1.282E+01	6.406E+03	-4.663E+01	-1.532E+01
3.550E-01	-1.267E+01	6.329E+03	-4.607E+01	-1.514E+01
3.600E-01	-1.251E+01	6.252E+03	-4.551E+01	-1.495E+01
3.650E-01	-1.236E+01	6.176E+03	-4.496E+01	-1.477E+01
3.700E-01	-1.221E+01	6.100E+03	-4.442E+01	-1.459E+01
3.750E-01	-1.206E+01	6.026E+03	-4.388E+01	-1.442E+01
3.800E-01	-1.192E+01	5.953E+03	-4.335E+01	-1.424E+01
3.850E-01	-1.177E+01	5.880E+03	-4.282E+01	-1.407E+01
3.900E-01	-1.163E+01	5.809E+03	-4.230E+01	-1.390E+01
3.950E-01	-1.149E+01	5.738E+03	-4.179E+01	-1.373E+01
4.000E-01	-1.135E+01	5.668E+03	-4.128E+01	-1.356E+01
4.050E-01	-1.121E+01	5.600E+03	-4.078E+01	-1.340E+01
4.100E-01	-1.107E+01	5.531E+03	-4.028E+01	-1.324E+01
4.150E-01	-1.094E+01	5.464E+03	-3.979E+01	-1.307E+01
4.200E-01	-1.080E+01	5.398E+03	-3.931E+01	-1.292E+01
4.250E-01	-1.067E+01	5.332E+03	-3.883E+01	-1.276E+01
4.300E-01	-1.054E+01	5.267E+03	-3.836E+01	-1.260E+01
4.350E-01	-1.041E+01	5.203E+03	-3.789E+01	-1.245E+01
4.400E-01	-1.029E+01	5.140E+03	-3.743E+01	-1.230E+01
4.450E-01	-1.016E+01	5.077E+03	-3.698E+01	-1.215E+01
4.500E-01	-1.004E+01	5.016E+03	-3.653E+01	-1.200E+01
4.550E-01	-9.917E+00	4.955E+03	-3.608E+01	-1.186E+01
4.600E-01	-9.796E+00	4.894E+03	-3.565E+01	-1.171E+01
4.650E-01	-9.677E+00	4.835E+03	-3.521E+01	-1.157E+01
4.700E-01	-9.559E+00	4.776E+03	-3.478E+01	-1.143E+01
4.750E-01	-9.443E+00	4.718E+03	-3.436E+01	-1.129E+01
4.800E-01	-9.328E+00	4.660E+03	-3.394E+01	-1.115E+01
4.850E-01	-9.215E+00	4.604E+03	-3.353E+01	-1.102E+01
4.900E-01	-9.103E+00	4.548E+03	-3.312E+01	-1.088E+01
4.950E-01	-8.992E+00	4.492E+03	-3.272E+01	-1.075E+01
5.000E-01	-8.882E+00	4.438E+03	-3.232E+01	-1.062E+01

JOB CONCLUDED

**** JOB STATISTICS SUMMARY

NUNODS	NCNODS	NUMNOD	NUMEL	DIODES	BJTS	JFETS	MFETS	GASFE
5	5	5	8	0	0	0	0	

NDIGITAL	NSTOP	NTTAR	NTTBR	NTTOV	IFILL	IOPS	PERSPA
0	8	20	26	4	6	50	59.375

NUMTTP	NUMRTP	NUMNIT	DIGTP	DIGEVT	DIGEVL	MEMUSE
75	7	232	0	0	0	8538

	SECONDS	ITERATIONS
MATRIX SOLUTION	1.33	2
MATRIX LOAD	1.44	
READIN	2.09	
SETUP	.22	
DC SWEEP	0.00	0
BIAS POINT	0.00	0
AC and NOISE	0.00	0
TRANSIENT ANALYSIS	7.74	232
OUTPUT	1.37	
OVERHEAD	2.92	
TOTAL JOB TIME	14.34	

```
***** 10/08/90 ******* PSpice 4.00 1988 ****** 17:46:15 ******

 CASE V (Model5: Switch Srf is closed at t=40ms, Irf=30kA)

****   CIRCUIT DESCRIPTION   ********************************

 .OPT ACCT  NOPAGE RELTOL=.001

 .WIDTH OUT=80

 .TEMP 20

 .TRAN/OP 50mS 1S UIC

 Co    3 0 10mF IC=-28.31V

 Lo    3 4 4mH  IC=14.18kA

 Lc    4 6 0.897mH IC=13.8kA

 Rc    6 0 0.010

 LpN2 4 5 0.010185H IC=362A

 RpN2 5 6 0.32856

 Rcr   3 0 10m

 C1    3 0 150mF IC=-28.31V

 Irf/N  5 6 405.4A

 .PRINT  TRAN V(3) I(Lo) I(LpN2) V(5,6)

 .PROBE

 .END

*** TEMPERATURE-ADJUSTED VALUES      TEMPERATURE = 20.000 DEG C

*** TRANSIENT ANALYSIS               TEMPERATURE = 20.000 DEG C

                                        Iplasma/74  Vplasma/74
                                        **********  **********
TIME          V(3)          I(Lo)        I(LpN2)      V(5,6)

 0.000E+00  -2.972E+01    1.418E+04    3.632E+02  -1.385E+01
 5.000E-02  -1.165E+02    1.157E+04    2.872E+02  -3.883E+01
```

1.000E-01	-9.494E+01	9.432E+03	2.900E+02	-3.791E+01
1.500E-01	-7.733E+01	7.682E+03	3.073E+02	-3.224E+01
2.000E-01	-6.305E+01	6.264E+03	3.246E+02	-2.655E+01
2.500E-01	-5.136E+01	5.103E+03	3.394E+02	-2.169E+01
3.000E-01	-4.188E+01	4.161E+03	3.515E+02	-1.769E+01
3.500E-01	-3.412E+01	3.390E+03	3.615E+02	-1.442E+01
4.000E-01	-2.782E+01	2.764E+03	3.696E+02	-1.176E+01
4.500E-01	-2.266E+01	2.252E+03	3.763E+02	-9.576E+00
5.000E-01	-1.848E+01	1.836E+03	3.816E+02	-7.809E+00
5.500E-01	-1.505E+01	1.496E+03	3.860E+02	-6.361E+00
6.000E-01	-1.228E+01	1.220E+03	3.896E+02	-5.187E+00
6.500E-01	-1.000E+01	9.934E+02	3.925E+02	-4.225E+00
7.000E-01	-8.154E+00	8.101E+02	3.949E+02	-3.445E+00
7.500E-01	-6.642E+00	6.599E+02	3.969E+02	-2.807E+00
8.000E-01	-5.416E+00	5.381E+02	3.984E+02	-2.289E+00
8.500E-01	-4.412E+00	4.383E+02	3.997E+02	-1.864E+00
9.000E-01	-3.598E+00	3.574E+02	4.008E+02	-1.520E+00
9.500E-01	-2.931E+00	2.912E+02	4.016E+02	-1.238E+00
1.000E+00	-2.388E+00	2.372E+02	4.023E+02	-1.009E+00

JOB CONCLUDED

**** JOB STATISTICS SUMMARY

NUNODS	NCNODS	NUMNOD	NUMEL	DIODES	BJTS	JFETS	MFETS	GASFET
5	5	5	9	0	0	0	0	0

NDIGITAL	NSTOP	NTTAR	NTTBR	NTTOV	IFILL	IOPS	PERSPA
0	8	20	26	8	6	50	59.375

NUMTTP	NUMRTP	NUMNIT	DIGTP	DIGEVT	DIGEVL	MEMUSE
59	0	177	0	0	0	8656

	SECONDS	ITERATIONS
MATRIX SOLUTION	1.26	2
MATRIX LOAD	1.12	
READIN	2.14	
SETUP	.22	
DC SWEEP	0.00	0

BIAS POINT	0.00	0
AC and NOISE	0.00	0
TRANSIENT ANALYSIS	6.54	177
OUTPUT	.38	
OVERHEAD	3.02	
TOTAL JOB TIME	12.30	