ENERGY SYSTEM FOR THE
GENERATION OF DIVERTOR MAGNETIC
FIELDS IN THE PDX FUSION
RESEARCH DEVICE

BY

N. M. TURITZIN

PLASMA PHYSICS
LABORATORY

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

PRINCETON UNIVERSITY
PRINCETON, NEW JERSEY

This work was supported by U. S. Energy Research and Development Administration Contract E(11-1)-3073. Reproduction, translation, publication, use and disposal, in whole or in part, by or for the United States Government is permitted.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

Printed in the United States of America.

Available from
National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151

Price: Printed Copy \$ * ; Microfiche \$1.45

<u>*Pages</u>	<u>NTIS Selling Price</u>
1-50	\$ 4.00
51-150	5.45
151-325	7.60
326-500	10.60
501-1000	13.60

ENERGY SYSTEM FOR THE GENERATION OF
DIVERTOR MAGNETIC FIELDS
IN THE PDX FUSION RESEARCH DEVICE*

N. M. Turitzin
Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08540

ABSTRACT

One of the major problems encountered in the development of Tokamak type fusion reactors is the presence of impurities in the plasma. The PDX device is designed to study the operation of poloidal magnetic field divertors and consequent magnetic limiters for controlling and reducing the amount of impurities.

A system of coils placed at specific locations produces a required field configuration for the poloidal divertor. This paper describes the system of energy supplies required and the interrelations of field coil currents during plasma current initiation, growth and steady state.

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

*Presented at the Sixth Symposium on Engineering Problems of Fusion Research, Nov. 18-21, 1975, San Diego, CA.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED *leg*

1. INTRODUCTION

Impurities content of plasma will assume a greater and greater importance as fusion devices increase in size on the way to the energy producing reactor. To function properly the thermonuclear reactor will require the achievement of high temperatures in a clean plasma. The presence of large impurities levels would affect in a large measure plasma ignition.¹

The primary purpose of the PDX machine is to produce a device capable of generating a plasma with a reduced amount of impurities, to control these impurities using a poloidal magnetic field divertor, and to study the behavior of an expanding magnetic limiter. The magnetic limiter will eliminate metallic contamination and its expanding feature will reduce plasma skin-effect, making current distribution more uniform throughout plasma cross-section.

2. MAGNETIC REQUIREMENTS

Studies made indicated that the desired magnetic fields can be produced by three sets of interconnected coils placed at certain locations inside and outside the vacuum vessel.² These coils have been designed with electrical parameters and ampere turns shown below:³

	L milli- henries	R milli- ohms	NI KA turns
Divertor Field Coils (DF)	2.4	31.8	2520
Nulling Field Coils (NF)	0.122	2.2	157.5
Centering Field Coils (CF)	1.48	17.4	2520

Their physical locations for the upper portion of the vessel are shown in Fig. 1. Identical symmetrical coils are also located at the lower portion.

Each set of coils must be supplied with current having a predetermined amplitude versus time relation which is different from any other set.

Divertor field coils direct the outer plasma layer into gettered regions on top and bottom of the vacuum chamber where plasma is neutralized and neutral particles are pumped out.

Nulling field coils create, on the horizontal axis of the machine, a favorable condition for the initial occurrence of plasma and provide a stable plasma configuration during the early stages of plasma formation and expansion.

Centering field coils shape the plasma into a rectangular cross section and prevent plasma from becoming unstable.

Under the influence of these coils the plasma will assume a steady state configuration illustrated in Fig. 2, which shows the full size model cross-section of the PDX vacuum vessel and coil system.

In order to build up to this final stable plasma shape the coils must be supplied with currents shown in Fig. 3.

The Divertor Field Coils are powered with a constant current, I_{DF} , in order to generate a constant field for the entire duration of the experiment.

The Nulling Field Coils carry a maximum current, I_{NF} , at the start of the experiment, causing plasma to strike at the correct location. This current then decreases to zero in approximately 20 milliseconds during plasma formation.

The Centering Field Coils require zero current, I_{CF} , at the start and an increasing current as the plasma is formed and the ohmic heating current rises. This current reaches the full value of divertor field current close to the end of the ohmic heating current rise.

These considerations posed the engineering problem of designing an electrical system capable of generating the current requirements with the correct time relationship.

3. ELECTRICAL NETWORK

Fig. 4 shows a simplified basic diagram of the network synthesized to satisfy the magnetic requirements. The DF and CF coils are connected in series and energized from a constant voltage dc supply, while the CF and NF coils are driven from a switched capacitor bank charged to a voltage of opposite polarity from a constant voltage rectifier.

The system is designed to operate at a maximum of 21,000 amperes with a projected operating current of 17,500 amperes. The extra capacity provides some flexibility in experimental use.

Circuit operational sequence starts before $t = 0$, the start of the experiment. Events occurring prior to this time have no bearing on the experimental data taken, as there is no plasma in the machine.

The excitation of the generator field is increased until the current in the DF-CF circuit reaches the desired value at $t = 0$. During this time the capacitor bank is charged to a voltage of opposite polarity.

At $t = -20$ milliseconds the switch in series with the

capacitor bank is closed and the bank discharges through the series connected NF-CF coils. The bank capacitance value chosen, in conjunction with the series inductance of the NF-CT coils, results in a one-half oscillatory period of 40 milliseconds. The charged bank voltage is set so that a current equal and opposite to the DF current is produced at the peak of the sine wave. When the current decreases to zero the switch opens and interrupts the current flow. The current behavior generated by this circuit is shown in Fig. 5.

It is evident that the shapes of currents versus time produced by this electrical network fulfill the magnetic requirements for the duration of the experimental time. The DF current is constant, the CF current, a combination of generator and capacitor currents is zero at $t = 0$ and rises to full value of DF current at the end of 20 milliseconds. The NF current starts at full value and decreases to zero in the same time.

4. EQUIPMENT DESCRIPTION

A more detailed electrical elementary diagram showing the actual equipment used appears in Fig. 6.

Constant Voltage Supply

The DF-CF circuit resistance is such that approximately 1250 volts are required to establish a current of 21,000 amperes. As each of the generators available is rated at 750 volts DC, 22,000 amperes, two in series are used. These generators are separately excited and can be programmed for a desired pulse shape with one second flattop at a rate of three pulses per minute, a

rate which greatly exceeds the projected machine pulse rate of one pulse every two minutes.

The entire circuit operates ungrounded. A ground detector is connected across the output of the two generators; it operates to actuate an alarm when the circuit balance to ground is disturbed by a fault. Transients arising during pulsing are absorbed by series R-C circuits connected across the generators.

Each generator is connected to the load through two sets of breakers. In opening the circuit, fast breakers open first and allow current to flow through a resistance in series with a second set of breakers. A summing relay detects the fact that both fast breakers have opened and actuates the resistor breakers. These breakers are provided with back contacts which make before the main contacts break and establish a path for the coils to dissipate their stored energy. The mechanical switches are arranged to depend upon the previous breaker actions before disconnecting and grounding the coils.

Capacitor Bank Supply

The capacitor bank has a rating of 1.6 megajoules at 10 kV. It is divided into ten racks, each of 3200 microfarads with a charging vacuum switch, output ignitron switch, and grounding system. The firing of individual ignitron switches can be inhibited, providing means to select easily the value of total capacitance required for any particular experiment.

The capacitor bank is charged from a three phase voltage doubler rectifier, a circuit particularly suitable for capacitor charging. A voltage divider across one bank senses the capacitor voltage, compares it with the preset desired value and automatically

actuates a network which opens the charging switches. Small voltage transducers connected to voltmeters indicate the voltages across each capacitor bank.

To compensate for the jitter in ignitron firing and prevent one fast firing ignitron from shorting out the other units, load equalizing transformers are connected in the outputs of all ignitrons. Each consists of a laminated iron core with four turns of copper strips for the primary and the same number for the secondary, capable of carrying the repeated pulse current. The transformers are so connected that each primary winding is in the output of its own ignitron, while each secondary winding is in the output of the neighboring ignitron. The polarities are such that current in one winding induces approximately 500 volts positive in the output of the other ignitron for approximately 15 microseconds before the core becomes saturated. This maintains a positive voltage on the slower firing ignitron and allows it to establish current conduction.

Since the current discharge is a half sine wave, the voltage across the capacitor is a half cosine wave. At the end of the discharge, the bank is charged to a reverse positive voltage. One could recover the stored energy by reversing the polarity of the capacitor bank and supply the energy lost during the pulse from the rectifier before pulsing again. This method presents a very complex and expensive design problem.

Another method considered was to "reverse ring" the capacitor bank into a separate coil using the second half period of the current sine wave and recover the energy in the capacitors with correct polarity. It was estimated that only 60% of the original

energy could be recovered, a coil with one megajoule of stored energy would be required, and additional switching and current blocking would be necessary.

The method selected was to dissipate the energy in the discharge resistors. Each capacitor rack already had a resistor in series with a vacuum switch for normal capacitor discharge use. The wattage of these resistors was increased to provide for the additional duty.

Compensating Transformer

The voltage pulse from the capacitor bank distributes itself across circuit elements proportionately to their inductances, and thus part of it appears across the generators' terminals. To eliminate this sudden voltage change, a compensating transformer with a proper turn ratio and mutual inductance was installed in series with the generator. It was so connected as to induce a voltage opposite to that resulting from the capacitor pulse.

Blocking Diode

The frequency of the capacitor discharge current is 12.5 Hz., which is low enough to extinguish the ignitron switch and to prevent current conduction in the opposite direction. There exists, however, a possibility that one or more ignitrons may short out. The current flowing in the wrong direction in NF-CF coils will then add to the DF-CF generator current and put an excessive stress on the coils' supporting structure. To take care of this eventuality, a blocking diode was installed in series with the capacitor supply line.

This diode consists of paralleled strings of series-connected diodes capable of carrying the normal operating pulse. An attempt

was made to secure a diode assembly which could withstand a short circuit current. It was discovered, however, that this would result in a prohibitively costly unit with an exorbitant size and weight. A decision was made to let the diodes be destroyed and replace them with spare units after a short circuit, an occurrence which was assumed to possess a very low probability.

Crowbar

An ignitron tube crowbar is connected across the NF-CF circuit. An electronic device detects a reverse current in the NF-CF loop and generates a pulse which fires the crowbar. This provides an additional safeguard against overstressing the machine structure.

A resistor connected in series with the crowbar makes the circuit critically damped. This same crowbar can be used for experimental purposes by firing it through a timer at the proper instant.

Machine Disconnect Switches

It is essential that all power be disconnected when the machine is accessible to personnel.

The generators are connected through two position disconnecting switches which ground machine leads when the generator circuit is open, thereby connecting DF, CF, and NF coils to ground.

A three pole, three position switch is installed in the DF, CF, and NF coils circuit. In its closed position it connects the supply from the capacitor bank to the coil circuit. In its mid-position it opens the leads from the capacitor supply and the CF coil connection, to prevent plasma induced current from circulating in the DF-CF network when this circuit is not used, such as when discharge cleaning is in progress. In its third position it grounds

the leads from the capacitor bank. The switches are so interlocked that they go to ground automatically when the machine is disabled.

5. PARALLEL COIL OPERATION

One half of the DF, CF and NF coils are located on the top of the machine and another half at the bottom. For normal operation the corresponding halves are connected in series. These connections can be easily modified so that coils above the horizontal midplane of the machine can be reconnected in parallel with homologous coils below the midplane.

Since each half of the coils can carry the same current of 21,000 amperes as before, the total machine current now becomes 42,000 amperes. To provide this, the two generators are put in parallel.

Similarly since the inductance of the parallel arrangement is one quarter of the previous value, while the capacitance remains the same, the impedance of the circuit is one half of the previous value. The peak capacitor current for the same voltage will now be twice what is used to be or 42,000 amperes. The electrical system is, therefore, easily adaptable to the parallel coil operation.

This parallel connection will provide stabilization, when necessary, for vertical plasma motion in a manner similar to a copper shell. That is, when plasma moves away from its equilibrium position, it induces currents of opposite polarity in the upper and lower coils. With a series connection these currents cancel each other and with a parallel connection they help each other and

produce a circulating current in the loop generating a restoring magnetic force which moves plasma back towards its equilibrium position.

6. CONCLUSION

This paper has described an electrical energy system for the PDX machine magnetic poloidal divertor.

This system helps to make the PDX machine a versatile device for experimental studies. It will aid in establishing the essential features of poloidal divertors and the properties of magnetic limiters. The machine will provide facilities for the study of impurities control techniques in large high temperature Tokamaks and, thereby, supply important answers to the problems confronted by the designers of future energy producing fusion reactors.

ACKNOWLEDGMENT

This work was supported by the U.S. Energy Research and Development Administration, Contract E(11-1)-3073.

REFERENCES

1. Meade, D. M., et al., "The Effects of Impurities and Magnetic Divertors on High-Temperature Tokamaks," MATT-1079 (1974).
2. Brown, D. I., Christensen, U. R., "The Magnetic Design of the PDX Poloidal Coil System," presented at the Sixth Symposium on Engineering Problems of Fusion Research, Nov. 18-21, 1975, San Diego, CA.
3. Dahlgren, F., Heitzenroeder, P. J., "PDX Machine Poloidal Field Coils," presented at the Sixth Symposium on Engineering Problems of Fusion Research, Nov. 18-21, 1975, San Diego, CA.

PDX POLOIDAL COIL SYSTEM LAYOUT

Fig. 1. Location of Divertor DF, CF and NF Coils Within PDX Poloidal Coil System.

756134

Fig. 2. Full Scale Section of PDX Vacuum Vessel and Coil System Showing Steady-State Plasma Configuration. 753967

Fig. 3. Current Requirements for DF, CF and NF Coils
of PDX Divertor.

754620

Fig. 4. Basic Electrical Network of PDX Divertor: 754E21

Fig. 5. Current Shapes in DF, CF and NF Coils Generated by PDX Divertor Network.

756137

754622
Fig. 6. Elementary Electrical Diagram of PDX Divertor Circuit.