LA-11175-MS

UC-20f

Issued: December 1

LA--11175-MS

DE88 005074

Passive Equilibrium Studies on ZT-P

M. M. Pickrell

W. A. Reass

MASTER

Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

PASSIVE EQUILIBRIUM STUDIES ON ZT-P

by

M. M. Pickrell and W. A. Reass

ABSTRACT

The poloidal field system of ZT-P was modified by the addition of a transformer, which coupled the magnetizing and equilibrium circuits. ZT-P is a small, air core, Reversed Field Pinch, operated at the Los Alamos National Laboratory. It is used as test bed for the much larger ZT-H, RFP experiment, now under construction at LANL. Planned experiments include size scaling measurements and determining the effect of low time constant shell operation. ZT-P has had an entirely passive equilibrium system, which did not provide a well centered equilibrium, although a tolerable equilibrium was realized by removing half of the equilibrium coil set. The transformer was added to the poloidal field system to adjust the equilibrium current for a centered plasma, while using the entire coil set. It also had the effect of reducing the dependence of the equilibrium on the plasma resistance. Stable, well centered discharges were achieved over a broad range of plasma currents. The improved equilibrium also lowered the loop voltage and extended the discharge lifetime. These experiments also investigated the unique problems of equilibrium systems on air core RFP devices.

The passive equilibrium control studies on ZT-P have had two separate, but related objectives. The first requirement was the need to obtain proper equilibrium on ZT-P so that machine could pursue its experimental agenda: scaling and transport studies mean little without a well centered plasma. The second objective was to develop an understanding of the problems associated with passive equilibrium in air core Reversed Field Pinches. This effort focussed on ZT-P, which is a small, air core RFP, that provided a natural test bed for investigating these problems before committing to the design of a much larger and more expensive machine.

A transformer was designed and incorporated in the poloidal field circuit to measure how well a strictly passive system could achieve a stable, centered equilibrium. It was designed using the

same computer codes which were originally used to design ZT-P, and which had been modified to reflect the actual machine operation. These codes are accurate representations of the behavior of ZT-P, and demonstrated computationally that a transformer could modify the circuit behavior sufficiently that a well centered, stable equilibrium could be achieved. The transformer was built, tested, and successfully used on ZT-P.

ZT-P [1] is a prototype of the larger ZT-H [2,3] machine, and includes many of the design changes from ZT-40M [4,5,6,7,8,9,10], which ZT-H will incorporate. The original equilibrium system for ZT-P was explicitly designed for operation with feedback equilibrium power supplies. The passive system was designed to provide more vertical field than necessary so the feedback supplies would only operate in a unipolar mode to reduce the equilibrium field. Unfortunately the plasma position processor for the amplifier feedback system has not been completed. The vertical field circuit was seriously over driven, and no centered equilibrium was possible. A tolerable equilibrium was obtained by removing half of the vertical field coils. [5,1,4]

I. GENERAL EQUILIBRIUM REQUIREMENTS

The principal requirement of any equilibrium system is that it provide the precise vertical field necessary to balance the outward pressure of the plasma column and maintain radial equilibrium. The requisite vertical field can be calculated from the Shafranov formulation of MHD, or from ordinary force balance: [11,12]

$$B_v = I_p \left(\frac{\mu_o}{4\pi R} \right) \left[\beta_{pol} + \frac{\ell_i}{2} + \ln \left(\frac{8R}{a} \right) - \frac{3}{2} \right] \quad (1)$$

The value inside the brackets is nearly constant. Only the poloidal beta and normalized internal inductance vary with the plasma conditions, and the total variation is small. [13,14,6] The dominant term is the plasma current which must be matched by the equilibrium coil current according to the condition:

$$B_v = I_p \times constant \quad (2)$$

where the *constant* is chosen so the equilibrium field is specified by equation 1 for nominal values of internal inductance and poloidal β .

On most toroidal plasma machines, including tokamaks and RFPs, equilibrium can be achieved with active feedback control or with a combination of active and passive systems. [12,10,6,15,16,17,3] Many tokamaks use purely active systems. A purely active system is possible on the RFP, however passive equilibrium is important for economic reasons. Power from the equilibrium power supply is far more expensive than from the magnetizing supply, perhaps by as much as a factor of 10, because the equilibrium system requires a faster time response and lower ripple voltage. Each kilowatt effectively transferred from the equilibrium system to the magnetizing system represents about \$ 90 saved.

The economics reasons are more critical for the RFP than for a tokamak because of the relative strengths of the confining fields. In a tokamak, the toroidal field is much stronger than the poloidal field, and is the dominant contribution to the cost of the magnetic system. Conversely, on the RFP the poloidal and toroidal fields are comparable, and the poloidal field costs more to generate. [11,13,14,18,19] Although no passive system is expected to maintain equilibrium under all plasma conditions, it can provide most of the equilibrium power and relieve the burden on the

external equilibrium supplies. Because the poloidal field is the dominant magnetic field in the RFP, the savings for the equilibrium power system can be considerable.

II. THE EQUILIBRIUM PROBLEM ON AIR CORE RFPS

The equilibrium problem for RFPs and tokamaks is similar, but is more complicated on air core RFPS because of the intrinsically high impedance of the RFP plasma. For equivalent plasma conditions (current and density), the loop voltage of the RFP can be an order of magnitude higher than on a tokamak. This impedance is reflected back through the magnetic coupling between the plasma and the poloidal field coil sets, and changes the network response of the system.

The air core design is desirable on RFPs because it reduces field errors induced by the presence of the iron. These field errors are thought to seriously affect energy confinement in the RFP. [4,20,21,22,9,23,24,25,6,14,17] For ZT-H and ZT-P the choice was made to improve the field errors at the cost of more difficult magnetic engineering.

On an iron core RFP, for example ZT-40M [8], the difficulty is alleviated by the large coupling between the poloidal field system and the plasma. A single poloidal field coil set provides both the ohmic drive and the equilibrium field. These coils are placed very close to the vacuum chamber so they provide an equilibrium field with the proper index. The close location of the coils and the presence of the iron cores tightly couples the poloidal coil system and the plasma, which forces the plasma current to closely follow the poloidal field current. Equilibrium is maintained because the vertical field depends directly on the poloidal field current. The coupling is sufficiently tight that the equilibrium is insensitive to changes in plasma resistance and plasma current risetime. The feedback equilibrium power supply only has to accommodate changes in radial position due to changes in poloidal beta, internal inductance, and the resistance of the windings.

The poloidal field circuits of both a tokamak and an iron core RFP are also primarily inductive on time scales of interest. For the tokamak the plasma resistance is low, and the reflected impedance is mostly the plasma inductance, which is also small compared to the magnetizing inductance. In the case of the iron core RFP, because the magnetic coupling is large the system is also mostly inductive except for very fast transients. Both systems depend primarily on the inductance of the poloidal field coil set, which is invariant. Both systems are linear, time invariant, and standard circuit analysis techniques can be used. Also, because the impedances scale the same way, the ratio of the plasma to equilibrium currents remains constant with frequency. The equilibrium system response is therefore independent of the plasma risetime, the plasma resistance, or the discharge duration.

Conversely, the air core RFP does not have such tight coupling. Other constraints, such as providing diagnostic and maintenance access, can force the poloidal field coils away from the plasma, further reducing the coupling. [2,3] Because of the high plasma impedance and the relatively low magnetic coupling, the poloidal field network response is complicated, and a passive equilibrium may be difficult to achieve. For time scales of interest, the reflected plasma resistance and the magnetizing reactances of the air core RFP are more nearly comparable. The circuit response is explicitly dependent on the plasma resistance, which varies. None of the previous simplifying assumptions applies to the air core RFP: it is not linear, it is not time invariant, and it is not frequency independent.

As an example, consider the effective impedance of a general equilibrium - plasma system, (one that applies to tokamaks, air core RFPS, and iron core RFPS). The equilibrium system

response will depend directly on the effective impedance of the equilibrium field coil set which depends on the equilibrium coil inductances and the reflected plasma impedance. Ignoring the coupling to the magnetizing system for the moment, this impedance is readily calculated from a network analysis:

$$Z_I = L_E s \frac{(1 - k_1^2) L_E s + \frac{L_E R_p}{L_p}}{L_E s + \frac{L_E R_p}{L_p}} \quad (3)$$

where

Z_I is the input impedance of the equilibrium system,
 L_E is the self inductance of the equilibrium coil set,
 $s = 2\pi i f$, is the frequency,
 k_1 is the coupling coefficient,
 L_p is the plasma total inductance, and
 R_p is the plasma resistance.

There are two natural time constants for this system:

$$S_0 = \frac{R_p}{L_p} \quad (4)$$

$$S_1 = \frac{R_p}{(1 - k_1^2) L_p} = \frac{S_0}{(1 - k_1^2)}$$

In the specific cases where either an iron core is used and the coupling coefficient, k_1 , is large, or the plasma resistance R_p is low, as in a tokamak, the equilibrium impedance appears inductive. In both cases the machines operate in regimes where the reflected plasma impedance is small, and the equations can be approximated by terms containing the plasma impedance. The network response is linear, time invariant, and the impedance scales linearly with frequency, (i.e. it is inductive). In the tokamak case, $\frac{R_p}{L_p} \ll s$, $k_1 \ll 1$ and equation 3 simplifies to:

$$Z_I = L_E s \frac{(1 - k_1^2) L_E s}{L_E s} = (1 - k_1^2) L_E s \quad (5)$$

which depends only on the equilibrium coil set inductance.

Conversely, in the case of the iron core RFP, $\frac{R_p}{L_p} \geq s$ but $k_1 \sim 1$, and equation 3 simplifies to:

$$Z_I = L_E s \frac{\frac{L_E R_p}{L_p}}{L_E s + \frac{L_E R_p}{L_p}} = L_E s \frac{\frac{R_p}{L_p}}{s + \frac{R_p}{L_p}} \sim L_E s \quad (6)$$

which also depends only on the equilibrium coil set inductance. Both simplifications assume time scales for operation that are typical for toroidal experiments: the plasma current risetime for tokamaks is on the order of several hundred milliseconds, 100 milliseconds for large air core RFPs, and 1 millisecond for iron core RFPs. The air core RFP could move into the tokamak regime simply by operating on faster time scales.

The air core RFP differs from other toroidal machines because equation 3 cannot be simplified by dropping all the terms containing the plasma impedance. The equilibrium system impedance

Fig. 1: Bode plot showing the frequency response for the poloidal field system. $|Z|$ is the magnitude of the impedance of the equilibrium system. All impedances are normalized to 1 and all frequencies to the “natural” frequency: $S_0 = R_p/L_p$.

strongly depends on the plasma impedance, because the plasma resistance is high *and* the coupling coefficient is low. The network response is both resistive and inductive over the frequency ranges for normal operation, and there is a time dependent parametric change. The network response is neither linear nor time independent.

Figure 1 sketches the magnitude of the equilibrium system impedance as a function of frequency normalized to the time constant S_0 . The regions of operation for tokamaks, iron core RFPs, and air core RFPs are shown. This diagram is only schematic: because of the parametric change of plasma impedance the Laplace transform cannot be applied properly for the air core RFP case.

The nonlinear effects and the complexity of the circuit behavior make the design of an equilibrium system more difficult for the air core RFP. The problem is aggravated because the equilibrium system must maintain plasma position over the entire discharge duration, and by several other conditions which must also be satisfied:

1. The equilibrium and magnetizing systems should be completely decoupled because their current wave-forms are completely different.
2. The equilibrium field should maintain circular flux surfaces, unless deliberately distorted into some other shape for physics reasons.

3. The equilibrium field should be indexed (have curvature), in order to maintain vertical position.
4. None of the equilibrium coil currents should cross zero. Otherwise bipolar feedback supplies are required, which are 4 times as expensive as unipolar supplies of the same rating.
5. The coupling between the magnetizing system and the plasma should be high, so that the ohmic drive system is as efficient as possible.
6. The magnetizing flux must not penetrate the plasma column, otherwise the ohmic drive system will distort the equilibrium.
7. The coils must be placed to provide adequate diagnostic and maintenance access to the machine.
8. Non-axisymmetric field errors should be minimized as much as possible.
9. The peak equilibrium coil currents should be nearly the same, so identical supplies can be purchased. Economies of scale may then reduce supply costs.

III. THE ANTI-TRANSFORMER SOLUTION

The objectives for the passive equilibrium studies on ZT-P were to determine whether a passive system could be designed for an air core RFP which would achieve a centered equilibrium. The concept was to introduce another degree of freedom into the poloidal field system design, which might allow a solution satisfying all of the conditions. One of the most critical design issues was the coupling between the magnetizing and equilibrium components of the poloidal field system, so we chose to add a transformer to couple these two systems. A circuit schematic is shown in figure 2. The transformer is colloquially termed the anti-transformer because it couples the equilibrium and magnetizing systems with opposite polarity.

There are two principle benefits to including a coupling transformer in the poloidal field system design, which apply equally to ZT-P and ZT-H:

- It increases the dynamic range of the equilibrium system, by allowing the system to be trimmed. Because the transformer is external to the front end, it can have numerous taps which are accessible. These taps permit the equilibrium system to adapt to plasma operating conditions other than those for which the system was nominally designed. Variations of plasma behavior, risetime, or current, can be absorbed in the anti-transformer, and not by the equilibrium power supply. This change may allow an increase in the dynamic range of the equilibrium system while reducing the equilibrium power supply cost.
- It may allow a better optimization of the poloidal field coil design, by allowing another degree of freedom. If no coupling transformer is used, the poloidal coil system must be designed such that the magnetizing and equilibrium coils are completely decoupled. The anti-transformer releases this constraint by providing the necessary decoupling between the two systems. The other aspects of the coil design can then be adjusted to optimize only the remaining parameters, perhaps allowing a better optimum.

Fig. 2: A schematic of the ZT-P poloidal field system, modified with the anti-transformer.

The concept of the anti-transformer was borrowed from the Alcator tokamaks [12] where it was used to fully decouple the equilibrium and magnetizing systems. The decoupling diminished the voltage transients to levels below the damage threshold of the thyristor supplies. Because there was no net coupling from the equilibrium system to the rest of the poloidal field coils, the equilibrium coils appeared as an independent inductor, which could be driven by a simple feedback system.

IV. ANTI-TRANSFORMER DESIGN AND CIRCUIT SIMULATIONS

The transformers for both ZT-P and ZT-H were designed so the equilibrium current would closely match the field required for a centered equilibrium, as specified in equation 2. The design was done using the same computer simulations used for the original development of the ZT-P and ZT-H poloidal field systems. [3,2,26] In the simulations, the anti-transformer was connected between the magnetizing and equilibrium circuits and the coupling, inductance, and turns ratio were adjusted to optimize the plasma position.

Computer simulations were used because of the nonlinear nature of the circuit and because the simulations had already been developed for the designs of ZT-P and ZT-H. The addition of

Fig. 3: Circuit simulations for ZT-P. Note that equilibrium current and vertical field closely match the required current and field with the anti-transformer, but do not when there is no anti-transformer.

the anti-transformer was a relatively minor modification.

The results of the simulations for ZT-P are shown in figure 3. This plot shows the required and actual equilibrium coil currents for both of the ZT-P equilibrium circuits. The top pair show the results without the anti-transformer and the bottom pair with the anti-transformer. With the proper coil inductance, coupling coefficient, and turns ratio, the equilibrium circuit currents were nearly identical to those required for a centered equilibrium.

A similar set of computer simulations was also done on an existing ZT-H poloidal field system design. The results of these simulations are shown in figure 4.

Both sets of simulations show that the anti-transformer does improve the match between the actual and the required equilibrium currents. In the case of ZT-H, the power requirement for the feedback power supplies was considerably reduced. In the case of ZT-P, the equilibrium coil currents were much closer to ideal with the coupling transformer than without it, and proper equilibrium was maintained with the original coil set. ZT-P should have a sufficiently stable and centered position to pursue normal operations without feedback supplies, although these supplies will be added for other studies.

V. EXPERIMENTAL RESULTS

The computer results were tested by building and installing the anti-transformer on ZT-P. The requirements for the anti-transformer were a 2.5:1 turns ratio, a total magnetizing inductance

Fig. 4: Circuit simulations for ZT-H. Note that equilibrium currents closely match the required currents with the anti-transformer, but do not when there is no anti-transformer. The outermost flux surface deviation is correspondingly reduced and some additional volt-seconds are obtained.

Fig. 5: Early experimental equilibrium results for ZT-P. Two shots are plotted: with and without the anti-transformer, but all other conditions are nominally the same. Note that equilibrium remains constant and nearly centered with the anti-transformer for most of the discharge duration.

of 200 microhenries, and a coupling coefficient of $k \geq 0.9$. An air core design was employed to eliminate the hysteresis from an iron core, which would change the frequency response of the network. The transformer was also designed to withstand the magnetic stresses from current imbalances up to 50 kA. Large current imbalances are anticipated because of the “anti” nature of the transformer: its purpose is to reduce the equilibrium currents, which have the same polarity as the magnetizing current.

The anti-transformer was wound on a 2 foot diameter, spiral grooved, PVC pipe. The windings were made with RG17/14 high voltage coax cable and consisted of 4 sets of 5 turns each. The outer braids of each winding set were connected in parallel to form the transformer primary. The secondary winding was configured from the center conductors and could be connected to obtain 4 different turns ratios, from 1:1 to 1:4, in integer steps. The “ideal” turns ratio of 2.5:1 was not available, and we found experimentally that a ratio of 1:3 was a little too high and a ratio of 1:2 was a little too low for optimum operation.

Roughly a thousand discharges were fired using the anti-transformer, over a two month period. Some of the early experimental results are shown in figure 5, which shows two typical discharges: one with and the other without the anti-transformer. The plasma current and radial position are plotted for both discharges. The anti-transformer plasma is more closely centered, and consequently continues for a longer time. Discharges have subsequently been achieved on ZT-P that have a longer duration and better equilibrium than any on record.

The ZT-P results also demonstrated the improved dynamic range provided by the anti-transformer. Deviations from the original computer predictions were easily accommodated by adjusting taps on the transformer. The best choice of coil taps on the transformer also varied

Fig. 6: Scaling of plasma loop resistance with current. Discharges with and without the anti-transformer are plotted. The scaling of resistance with current seems the same, but the resistance is much lower with the anti-transformer.

somewhat depending on plasma conditions. The circuit could be adjusted for the entire range of plasma currents run.

Another result of both simulations and the early experimental results, not readily apparent in figures 3 and 5, is that the network became less sensitive to changes in plasma resistance. Changes in operating conditions during parameter scaling did affect plasma resistance, but did not as strongly affect plasma equilibrium compared to the original circuit.

The corrected plasma equilibrium also reduced the plasma resistance, as might be expected. Discharges taken with the anti-transformer are compared to scaling runs prior to its installation in figure 6. The improved equilibrium achieved with the anti-transformer has reduced the loop voltage compared to similar discharges without it, although, the relative scaling of resistance with current appears the same for both cases.

The experimental results on ZT-P with the anti-transformer achieved longer discharges, a stable centered equilibrium, and lower loop voltages. The results were obtained with an entirely

passive system. The anti-transformer experiments were successful on ZT-P, and similar designs should be considered for other air core RFP experiments.

ACKNOWLEDGEMENTS

The authors wish to express their appreciation to R. Gribble, L. C. Burkhardt, and J. A. Phillips. R. Gribble developed the magnetic design codes which were used for the computer simulations of the anti-transformer on both ZT-P and ZT-H. He also ran the ZT-H simulation. J. Phillips reduced the loop voltage data and plotted figure 6. L. C. Burkhardt operated ZT-P during the anti-transformer tests.

VI. REFERENCES

- [1] Kurt F. Schoenberg, C. J. Buchenauer, L. C. Burkhardt, L. D. Caudill, R. S. Dike, T. Dominguez, J. N. Downing, P. R. Forman, J. A. Garcia, A. J. Giger, R. F. Gribble, A. Haberstich, C. F. Hammer, L. J. Iko, J. C. Ingraham, R. W. Kewish, P. L. Klinger, T. W. Linton, E. M. Little, J. G. Melton, T. L. Peterson, W. A. Reass, N. L. Salazar, J. D. Sandoval, J. S. Sandoval, A. E. Schofield, J. D. Smith, E. K. Spanos, P. G. Weber, R. W. Wilkins, and G. A. Wurden. *ZT-P: An Advanced Air-Core Reversed Field Pinch Prototype*. Technical Report LA-10593-MS, Los Alamos National Laboratory, January 1986.
- [2] Philip Thullen and Kurt F. Schoenberg. *ZT-H Reversed-Field Pinch Experiment*. Technical Document LA-UR-84-2601, Los Alamos National Laboratory, 1984.
- [3] K. F. Schoenberg, R. F. Gribble, T. W. Linton, and W. R. Reass. *Poloidal Field System Design for the ZT-40U Reversed Field Pinch*. Technical Document LA-UR-83-3476, Los Alamos National Laboratory, 1983.
- [4] K. F. Schoenberg, G. A. Wurden, P. G. Weber, J. C. Ingraham, C. P. Munson, D. A. Baker, C. J. Buchenauer, L. C. Burkhardt, T. E. Cayton, J. N. DiMarco, J. N. Downing, R. M. Erickson, P. R. Forman, A. Haberstich, R. B. Howell, F. C. Jahoda, R. S. Massey, G. Miller, R. W. Moses, R. A. Nebel, J. A. Phillips, M. M. Pickrell, A. E. Schofield, R. G. Watt, D. M. Weldon, and K. Werley. Reversed field pinch experiments in ZT-40M and ZT-P. In *Plasma Physics and Controlled Nuclear Fusion Research, 1986*, pages 423-432, IAEA, Vienna, 1987. Volume II (Kyoto Conference), 1986.
- [5] K. F. Schoenberg, J. C. Ingraham, R. Ellis, P. G. Weber, J. N. Downing, C. P. Munson, C. A. Wurden, D. A. Baker, C. J. Buchenauer, L. C. Burkhardt, T. E. Cayton, R. E. Chrien, J. N. DiMarco, P. R. Forman, R. F. Gribble, R. B. Howell, G. Miller, R. W. Moses, R. A. Nebel, J. A. Phillips, M. M. Pickrell, W. A. Reass, A. E. Schofield, and D. M. Weldon. Reversed field pinch experiments in ZT-40M and ZT-P. In *14th European Conference on Controlled Fusion and Plasma Physics*, page , European Physical Society, European Physical Society, Madrid, June 1987. LA-UR-87-1616.
- [6] R. S. Massey, C. J. Buchenauer, L. C. Burkhardt, A. R. Jacobson, J. G. Melton, G. Miller, R. W. Moses, K. F. Schoenberg, and R. G. Watt. *Preliminary Equilibrium and Field Error Studies on ZT-40M*. Technical Report LA-9567-MS, Los Alamos National Laboratory, 1983.
- [7] R. S. Massey, R. G. Watt, P. G. Weber, G. A. Wurden, D. A. Baker, C. J. Buchenauer, L. C. Burkhardt, T. Cayton, J. N. DiMarco, J. N. Downing, R. M. Erickson, R. F. Gribble, A. Haberstich, R. B. Howell, J. C. Ingraham, E. M. Little, G. Miller, C. P. Munson, J. A. Phillips, M. M. Pickrell, K. F. Schoenberg, A. E. Schofield, and D. M. Weldon. Status of the ZT-40M RFP experimental program. *Fusion Technology*, 8:1571-1581, July 1985.
- [8] D. A. Baker, M. D. Bausman, C. J. Buchenauer, L. C. Burkhardt, G. Chandler, J. N. DiMarco, J. N. Downing, P. R. Forman, R. F. Gribble, A. Haberstich, R. B. Howell, J. C. Ingraham, A. R. Jacobson, F. C. Jahoda, K. A. Klare, E. M. Little, L. W. Mann, R. S. Massey, J. Melton, G. Miller, R. Moses, J. A. Phillips, A. E. Schofield, K. F. Schoenberg, K. S. Thomas, R. G. Watt, P. G. Weber, and R. Wilkins. Performance of the ZT-40M

- reversed-field pinch with an Inconel liner. In *Plasma Physics and Controlled Nuclear Fusion Research, 1982*, pages 587–595, IAEA, Vienna, 1983. Volume I (Baltimore Conference), 1982.
- [9] D. A. Baker, C. J. Buchenauer, L. C. Burkhardt, E. J. Caramana, J. N. DiMarco, J. N. Downing, R. M. Erickson, R. F. Gribble, A. Haberstick, R. B. Howell, J. C. Ingraham, A. R. Jacobson, K. A. Klare, E. M. Little, R. S. Massey, J. G. Melton, G. Miller, R. W. Moses, C. P. Munson, J. A. Phillips, M. M. Pickrell, R. A. Nebel, A. E. Schofield, K. F. Schoenberg, R. G. Watt, P. G. Weber, D. M. Weldon, K. A. Werley, R. W. Wilkins, and G. A. Wurden. Experimental and theoretical studies of the ZT-40M reversed field pinch. In *Plasma Physics and Controlled Nuclear Fusion Research, 1984*, pages 439–447, IAEA, Vienna, 1985. (Proc. 10th Int. Conf. London, 1984), Vol. 2.
 - [10] R. S. Massey, C. J. Buchenauer, G. Miller, and G. Barnes. *Preliminary Results from ZT-40M using Active Feedback for Equilibrium Control*. Technical Report LA-9809-MS, Los Alamos National Laboratory, July 1983.
 - [11] J. P. Freidberg. Ideal magnetohydrodynamic theory of magnetic fusion systems. *Reviews of Modern Physics*, 54(3):801–901, 1982.
 - [12] M. M. Pickrell. *Radial Equilibrium of Toroidal Plasmas*. Technical Report, Massachusetts Institute of Technology, 1976. Undergraduate Thesis.
 - [13] D. A. Baker, L. W. Mann, and K. F. Schoenberg. *Equilibrium Poloidal Field Distributions in Reversed Field Pinch Toroidal Discharges*. Technical Report LA-9162-MS, Los Alamos National Laboratory, 1982.
 - [14] H. A. B. Bodin and A. A. Newton. Reversed-field-pinch research. *Nuclear Fusion*, 20(10):1255–1324, 1980.
 - [15] R. Stambaugh, S. Adcock, R. Callis, J. deGrassie, J. Luxon, P. Rock, J. Wesley, S. Seki, M. Shimada, and H. Yokomizo. *Plasma Equilibrium Control in Doublet III*. Technical Report GA-A16049, General Atomic Company, 1980.
 - [16] T. Shimada, Y. Hirano, Y. Yagi, A. A. Newton, and K. Ogawa. Results from the reversed field pinch experiment TPE-1RM15 with programmed vertical field. In *Eleventh International Conference on Plasma Physics and Controlled Nuclear Fusion Research*, page , International Atomic Energy Agency, International Atomic Energy Agency, Kyoto, Japan, November 1986. Volume II (Kyoto Conference), 1986.
 - [17] B. Alper, V. Antoni, M. K. Bevir, H. A. B. Bodin, C. A. Bunting, P. G. Carolan, J. Cunnane, D. E. Evans, A. R. Field, S. J. Gee, C. G. Gimblett, R. Hayden, T. R. Jarboe, P. Kirby, A. Manley, A. A. Newton, P. G. Noonan, A. Patel, R. S. Pease, M. G. Rusbridge, K. P. Schneider, D. P. Storey, H. Y. W. Tsui, S. Whitfield, and P. D. Wilcock. Results from HBTX with improved confinement. In *Eleventh International Conference on Plasma Physics and Controlled Nuclear Fusion Research*, International Atomic Energy Agency, International Atomic Energy Agency, Kyoto, Japan, November 1986. Volume II (Kyoto Conference), 1986.
 - [18] D. A. Baker and W. E. Quinn. The reversed-field pinch. *Fusion*, 1(A):437–475, 1981.

- [19] H. A. Bodin, R. A. Krakowski, and S. Ortolani. The reversed field pinch: from experiment to reactor. *Fusion Technology*, 10(3):307–353, 1986.
- [20] R. G. Watt and R. A. Nebel. Sawteeth, magnetic disturbances, and magnetic flux regeneration in the reversed-field pinch. *Physics of Fluids*, 26(5):1168–1170, 1983.
- [21] R. G. Watt and E. M. Little. RFP energy evolution and containment in the presence of giant sawteeth. *Physics of Fluids*, 27(4):784–786, 1984.
- [22] D. A. Baker. The role of magnetic reconnection phenomena in the reversed-field pinch. In *Magnetic Reconnection in Space and Laboratory Plasmas*, pages 332–340, American Geophysical Union, Washington D.C., 1984.
- [23] R. B. Howell and H. F. Vogel. Magnetic field perturbations due to a hole in a conducting wall on the ZT-40M reversed-field pinch. *Journal of Applied Physics*, 56(7):2017–2022, 1985.
- [24] R. B. Howell, J. C. Ingraham, G. A. Wurden, P. G. Weber, and C. J. Buchenauer. Asymmetric magnetic flux generation, $m=1$ activity and edge phenomena on a reversed field pinch. *Physics of Fluids*, 30(6):1828–1838, 1987.
- [25] G. Miller. A model of energy confinement in the reversed field pinch. *Plasma Physics and Controlled Nuclear Fusion*, 26(9):119–1125, 1984.
- [26] K. F. Schoenberg, R. F. Gribble, and J. A. Phillips. Zero-dimensional simulations of reversed-field pinch experiments. *Nuclear Fusion*, 22(11):1433–1441, 1982.