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Proposal

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**Proposal for the
ZT-40 Reversed-Field Z-Pinch Experiment**

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CONTENTS

ABSTRACT	1
I. INTRODUCTION	1
II. SCIENTIFIC SCOPE	3
A. <u>General Philosophy</u>	3
1. Methods of RFP Plasma-Field Production	3
3. Containment	3
B. <u>Rationale for the Experiment</u>	4
1. Reactor Potential	4
2. Scaling to be Demonstrated	4
3. Limits on Temperature	5
a. Impurity Radiation	5
b. MHD Stability	8
C. <u>Specific Objectives of ZT-40</u>	8
1. Confinement Time	8
2. Temperature	8
3. Operating Parameters	9
4. Modes of Operation	9
5. Sheath Scaling	9
D. <u>Diagnostics and Data Handling</u>	10
III. THE STATUS OF Z-PINCH THEORY	10
A. <u>Ideal MHD Stability Theory</u>	10
1. Sharp Boundary Model	10
2. Diffuse Boundary Theory	12
3. Toroidal Calculations	13
B. <u>Nonideal MHD Stability Theory</u>	15
C. <u>Plasma Dynamics</u>	16
1. Numerical Analysis	16
2. Analytic Work	16
a. Self-Reversal	16
b. Global Energy and Pressure Balance	17
D. <u>Microinstability Theory</u>	17
IV. SUMMARY OF RFP EXPERIMENTS	18
A. <u>United Kingdom</u>	18
1. HBTX I	18
2. ZETA	19
3. HBTX II	19

B.	<u>Italy - ETA BETA</u>	19
C.	<u>Japan</u>	20
1.	ETL-TPE-I	20
2.	STP-I	20
D.	<u>LASL Experiments</u>	20
1.	ZT-I	20
2.	ZT-S	21
V.	ENGINEERING	21
A.	<u>Introduction</u>	21
B.	<u>Layout</u>	21
C.	<u>Machine Features</u>	22
D.	<u>Energy Systems</u>	22
E.	<u>Control and Trigger Systems</u>	27
F.	<u>Vacuum Systems</u>	27
1.	Discharge Tubes	27
2.	Vacuum Requirements	28
G.	<u>Development Program</u>	29
VI.	ESTIMATED COST AND MANPOWER REQUIREMENTS	30
A.	<u>Costs by Budget Category</u>	31
B.	<u>Construction Costs</u>	31
C.	<u>Operating Cost in FY-79.</u>	35
VII.	MILESTONES	35
	REFERENCES	36

PROPOSAL FOR THE ZT-40 REVERSED-FIELD Z-PINCH EXPERIMENT

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ABSTRACT

A next-generation, toroidal, reversed-field Z-pinch experiment to be constructed at LASL is proposed. On the basis of encouraging ZT-I and ZT-S experimental results, a larger device with a 40-cm bore and a 114-cm major radius is proposed, to extend the confinement time by about an order of magnitude. The new experiment will explore the physics of programming reversed-field pinches in a size range unexplored by previous reversed-field pinch experiments. Model reversed-field pinch reactor calculations show that, if stability is assumed, small fusion reactors are possible if the pinch current density is high. A basic aim will be to delineate the plasma and current density ranges in which stable reversed-field pinches can be produced. Improved vacuum techniques will be used to overcome the radiation losses that probably kept electron temperatures low in the earlier, smaller experiments.

I. INTRODUCTION

This is a proposal for a next-generation LASL, reversed-field, Z-pinch experiment. The approach is based on theoretical prediction of MHD stable equilibrium in reversed-field Z pinches (RFP). The improved stability of toroidal Z pinches operated with a reversed toroidal field outside the plasma column has been demonstrated at several laboratories.¹⁻⁴ The ZT-I and ZT-S experiments at LASL show that nonideal effects of plasma resistivity limit the

lifetime of stable configurations and indicate that a toroidal pinch of larger minor diameter and higher electron temperatures should remain stable longer.

The experiment is designed to shed light on plasma scaling and on programming of the fields needed to achieve the desired plasma-field configurations as the size increases. The phenomenon of automatic field reversal will be explored, but not relied upon, over the regime allowed by the experiment. The experiment will also yield design information for a larger ZT-II feasibility experiment that should take the Z-pinch concept to $nt = 10^{13}$ - 10^{14} .

The concept and design of the next generation experiment have been encouraged by the Review Panel on the Reversed-Field Z-Pinch Program. About its potential as a fusion reactor, the panel noted that:

"An RFP reactor has potential economic and technological merits which make it worthy of consideration independently of the success or failure of any other reactor program. However, in the context of the requirements of the present DCTR objectives, the primary argument for the development of an RFP reactor resides in the possibility that the beta required for optimal neutron wall loading may not be achievable in tokamaks of acceptable size. If this situation, in fact, evolves, the RFP reactor may have a substantial lower capital cost than a comparable tokamak and could turn out to be our major candidate for a toroidal reactor."⁵

This proposal begins with a discussion of the general philosophy and rationale of the reversed-field Z-pinch approach. The scientific objectives are then delineated, and the proposed diagnostics are outlined. A design for an experiment, designated ZT-40, with a 40-cm-bore vacuum chamber is summarized. This size gives a projected order of magnitude greater confinement time than the present LASL ZT-S and is a next step within the constraints of laboratory space, projected manpower, and anticipated LASL funding for FY-77 and 78. It will allow development of the system engineering experience and testing needed for large Z pinches and will feed directly into the design of a later, large ZT-II device. The proposal concludes with a schedule of cost estimates, manpower requirements, and construction milestones.

II. SCIENTIFIC SCOPE

A. General Philosophy

The reversed-field Z pinch differs basically from its near relatives, the tokamak, belt pinch, and screw pinch, in that it is designed to operate above the Kruskal-Shafranov limit and owes its predicted MHD stability to the wall and shear stabilization of special plasma-field profiles. Grossly unstable modes are excluded by the outer bounding conductor, located so that the unstable eigenmodes cannot fit across a minor diameter of the torus. The localized modes are excluded by the strongly sheared magnetic field. The bounding conductor also helps to stabilize tearing modes that might otherwise appear in a resistive plasma.

1. Methods of RFP Plasma-Field Production. A key experimental question about an RFP thermonuclear containment scheme involves the plasma set-up phase. What is the best technique for producing the desired high-beta reversed-field configuration? This question bears on factors such as pinch formation time, initial heating mechanisms, the impurity radiation barrier, and losses from wall contact and other mechanisms. Three methods for producing reversed-field configurations have been proposed: (1) programming a reversed toroidal field during pinch formation, (2) operating so that the field self-reverses automatically after the plasma goes through an initial unstable phase, and (3) inducing a reversed field by applying a rotating transverse field whose rotation frequency lies between the ion and electron gyrofrequencies.⁶ Method (1) has been explored at LASL and Culham, method (2) is a basis for a proposed large experiment, RFX, at Culham, and method (3) is in the study and planning stages at Flinders University of Southern Australia.

2. Containment. Once the plasma and field profiles have been produced, a central question is how resistance and other nonideal processes affect field profile maintenance. Field diffusion and localized heating may cause stable field configurations to evolve toward unstable ones. The issue is to what extent the resistivity in the plasma is anomalous and how it scales with temperature, plasma density, and current density.

Idealized engineering calculations show that a RFP reactor can be brought to ignition temperatures by classical ohmic heating alone.^{7,8} In reality, the

magnitude of the actual losses determines whether other heating mechanisms (compression heating, RF heating, magnetoacoustic heating, neutral beam injection, etc.) also are required. This next experiment should permit delineation of these issues to provide sensible input to the large ZT-II, a more definitive but less flexible device.

B. Rationale for the Experiment

1. Reactor Potential. The RFP is an alternative to the tokamak approach to a fusion reactor. It has the following potential advantages: (1) no small aspect ratio requirements, which simplifies the engineering design and provides possible escape from trapped particle instabilities, (2) possible smaller reactor design, (3) MHD stability at high beta ($\sim 30-40\%$) which allows economic use of the field and attainment of optimal neutron wall loading, (4) no superconducting coil requirement, (5) possible ignition by ohmic heating, (6) moderate field strength requirements, which simplify structural design, and (7) possible lower contamination if successful programming keeps plasma from the wall during compression and burn.

Reactor engineering calculations predict burn times as low as 160 ms and Q_E values of 6 (Q_E = electrical energy out/recirculated energy) with acceptable wall loading (2 MW/m^2). Conceptually, given high current densities, small (75-MWe) reactor designs are feasible.⁹ It should be emphasized, however, that the minimal reactor size depends critically on the limitations imposed on particle and current density by the physics of stable containment which must be determined by experiments.

2. Scaling to be Demonstrated. A chief aim will be to extend the confinement time scaling from the ZT-I and ZT-S results. The physics that controls confinement time scaling with size determines minimum reactor size. The higher the current and plasma densities, consistent with containment, the shorter the burn time and smaller the reactor size can be. One aim of future experiments will be to determine the optimum scaling of confinement time, current density, and plasma density with size. Recent work⁸ on a reactor model has given designs ranging from a 4-m bore for a current density at the present 20-MA/m^2 experimental level to a 1-m bore for 160 MA/m^2 with Q_E values

of 6. See Fig. 1. Thus, one is motivated to demonstrate confinement time scaling for as high a current density as plasma containment physics will allow.

3. Limits on Temperature.

a. Impurity Radiation. Electron temperatures measured in ZT-I and ZT-S were small, 15 eV. Associated high resistivity may be responsible for loss of favorable profiles as the fields diffuse into the plasma. One possibility is that the devices may have been operating below, and were being limited in temperature by, the so-called radiation barrier. There may be enough impurity so that too much energy is emitted in line radiation to allow the electron temperature to rise beyond a certain limit. To avoid such a limitation, the next experiment is designed to include a clean vacuum system and an effective method of discharge cleaning.

Figure 2a demonstrates the radiation barrier effect. The temperature as a function of time is shown for several oxygen impurity levels. The simple model¹⁰ used in these calculations assumes certain uniform current density and electron density values. Only radiation losses are included, and the heating is assumed to be governed by classical ohmic resistivity using the plasma's effective Z . Classical relaxation between ions and electrons also is included. These curves show the temperature-clamping effect (to about 15-eV) of impurity radiation losses when the impurity level exceeds a critical value. The ohmic heating at this level cannot burn through the highly radiative ionization states of the impurity atoms. Figure 2b shows how 100-eV initial ion temperature assists in burning through the radiation barrier.

The operating regions allowed on the basis of this classical ohmic heating model are shown in Fig. 3. The region above and to the left of any given impurity curve represents the range of n_e and total current density J in which the electron temperature rises from 2 eV to above 20 eV, showing that the ~ 15 -eV barrier has been penetrated within 50 μ s. The calculations predict that, for this simple model with ohmic heating for 200 μ s and a $\sim 0.1\%$ impurity level, T_e should range from 200 eV for $n_e = 10^{15} \text{ cm}^{-3}$ to 100 eV for $5 \times 10^{15} \text{ cm}^{-3}$ for total current densities of 3 kA/cm² with no initial ion heating. The calculations predict that at $J = 3 \text{ kA/cm}^2$ an initial ion heating of ~ 60 eV will allow barrier penetration at 10^{15} - 10^{16} cm^{-3} density. Calculations made using a hybrid code developed by Sgro and Nielson at LASL predict initial compressional

Fig. 1
Reversed-field Z-pinch reactor sizes.

Fig. 2(a).

Ion temperature ($T_i \approx T_e$) vs time for 0.000, 0.001, 0.00175, 0.002, 0.0025, and 0.005 fractional oxygen impurity (FI), $5 \times 10^{15} \text{ cm}^{-3}$ plasma density, 3-kA/cm^2 current density, 0-eV initial ion temperature, and 2-eV initial electron temperature (from preionization). The results were obtained with the IMPRAD computer code.

Fig. 2(b).

Ion temperature ($T_i \approx T_e$) vs time for 0.000, 0.002, 0.003, and 0.005 fractional oxygen impurity (FI), $5 \times 10^{15} \text{ cm}^{-3}$ plasma density, 3-kA/cm^2 current density, and 100-eV initial ion temperature. These results were obtained with the IMPRAD computer code. The assumed initial ion temperature would be generated during Z pinch formation and compression.

ion heating of 100-200 eV in ZT-40 with a 600-kA toroidal current rising in 2.5 μ s. Probably barrier penetration will be made easier by anomalously high resistivity during the early phase of pinch formation. Also, during pinch formation, current sheaths with very high current densities may exist.

The experimental results listed in Table I indicate that 0.1% impurity should be attainable. The carbon impurity should be essentially eliminated in ZT-40 by excluding organics that were present in ZT-I and ZT-S. Further improvement should result from the quadrupled volume-to-surface ratio between ZT-40 and ZT-I.

TABLE I

IMPURITY MEASUREMENTS

<u>Machine</u>	Fractional Impurity	<u>Impurity</u>	Uncompressed Plasma	Uncompressed Impurity
	<u>Measured</u>		<u>Density</u>	<u>Density</u>
Scylla IV ^a	0.00065	0	$2 \times 10^{15} \text{ cm}^{-3}$	$1 \times 10^{12} \text{ cm}^{-3}$
ISAR II ^b	0.0018	C, O, N	2.8×10^{15}	5×10^{12}
ZT-I ^c	0.004	C, O	2×10^{15}	8×10^{12}

^aF. Jahoda, Private communication. Result determined from soft x-ray measurements of O VII and O VIII. Possible residual cold ion influx not included.

^bW. Engelhardt, W. Köppendörfer, M. Munich, and J. Sommer, "Absolute Measurement of Radiation Losses from a Theta Pinch Plasma in the Wavelength Region from 10 to 200 Angstroms," Proc. 4th Eur. Conf. on Contr. Fusion and Plasma Physics, Rome, (1970) p. 50.

^cHowell and Karr, ZT-I Progress Reports, 1975.

b. MHD Stability. Another important temperature consideration is that MHD theory predicts upper beta limits consistent with stability. For the straight cylindrical approximation, the poloidal beta can be defined as the ratio of average plasma pressure to poloidal field pressure at the wall. Theoretical work¹¹ shows that for MHD stability, poloidal beta should be $\lesssim 0.5$. This condition limits the average temperature T for given values of electron number density n_e , mean axial current density J_z and plasma radius a. This condition can be written as

$$T(\text{eV}) \leq 2.45 \times 10^9 J_z^2 a^2 / n_e ,$$

where J_z is in A/cm², n_e in cm⁻³ and a in cm. Thus, for a given plasma radius, the allowable mean temperature for MHD stability depends critically on the electron and current densities. If one uses $J_z = 2 \text{ kA/cm}^2$ and a pinch ratio $a/r_{\text{wall}} = 2$, this condition limits T in ZT-40 to $\sim 100 \text{ eV}$ and $\sim 1 \text{ keV}$ for $n_e = 10^{16}$ and 10^{15} cm^{-3} , respectively.

C. Specific Objectives of ZT-40

1. Confinement Time. The prime ZT-40 objective is to extend the programmed RFP confinement time approximately an order of magnitude beyond present ZT-S results. Assuming that the stable time is controlled by the field diffusion time $\tau_d = a^2/D$ and the diffusion coefficient D is unchanged, ZT-40's projected confinement time is 150-200 μs . As the field diffusion coefficient is proportional to the plasma resistivity, still more confinement time could result from the expected higher T_e values if the plasma resistivity behaves classically with a $T_e^{-3/2}$ dependence.

2. Temperatures. A second objective is to operate with clean enough vacuum so that impurities will not limit the electron temperature. Ohmic heating will be studied as a potential reactor heating mechanism, and its effects on stability also will be studied. Projected temperatures depend upon J and n_e values that are assumed to be compatible with setting up the desired MHD stable profiles. From the considerations in Sec. II-B-3 for containment times of $\sim 200\text{-}\mu\text{s}$ and $n_e = (1-5) \times 10^{15} \text{ cm}^{-3}$, $T_i = T_e$ values of 100-200 eV are

projected. Higher temperatures can be obtained if stable operation at lower densities proves possible in the larger experiment.

3. Operating Parameters. A third objective is to determine the current density J and electron density n_e that are compatible with setting up of stable configurations. This involves determination of the plasma conductivity behavior as a function of n_e , J , current risetime, and plasma compression ratio. A parameter of interest is $\alpha \equiv v(\text{drift})/v(\text{thermal}) \propto J/(n_e T^{1/2})$ which may control onset of microinstabilities. Another objective will be to see if upper limits on α (or other pertinent parameters) are needed to keep diffusion and anomalous transport within acceptable bounds.

4. Modes of Operation. A design objective will be to make the current and its rate of rise flexible enough to allow exploration of at least the following RFP operation modes to determine their relative merits.

- (a) Pinches formed in the presence of a toroidal bias field, produced from a slow capacitor bank, with subsequent field programming.
- (b) Operation with an initial toroidal bias field established by a single fast bank that can reverse the toroidal field in about the same time as the main current. (This mode is studied in ETA BETA at the University of Padua.)
- (c) Operation with self-field reversal. (The risetime versatility should allow examination of possible favorable RFP configuration production by self-reversal. The self-reversal mode is considered at Culham as a slow risetime experiment. Self-reversal and other slow startup methods may be studied in the ~ 100 -to 1 -ms risetime regime using power crowbar system of ZT-40).

5. Sheath Scaling. Scaling of the current sheath thickness among the different bore Z-pinch devices will be studied, as will the field diffusion rates as a function of operating parameters. These items are important both in setting up stable profiles and in sustaining them for long times.

D. Diagnostics and Data Handling

The diagnostics and data handling techniques developed for the ZT-I and ZT-S devices will be used for the proposed experiment. Methods and equipment will be expanded and improved wherever possible, and new diagnostics will be developed to complement those now in use. Table II summarizes parameters to be measured and diagnostics to be used. Data retrieval and processing methods are indicated. The table also shows whether a particular diagnostic is already in use and available, to be developed during machine construction, or planned for later use, depending upon availability of funds and manpower.

III. THE STATUS OF Z-PINCH THEORY

A. Ideal MHD Stability Theory

Application of ideal MHD theory to Z pinches has an extensive history and has been developed to a mature state.

1. Sharp Boundary Model. The first application of a normal mode analysis¹² to a pinch discharge was for a cylindrical plasma with a sharp boundary which carried the longitudinal current in an infinitely thin layer. There was no axial magnetic field. The analysis proceeded with study of perturbations of the form

$$\vec{\xi} = \vec{\xi}(r)\exp(im\theta + ikz + \gamma t) \quad .$$

The system immediately proved unstable for $m = 0$ and 1 . Further analysis¹³ showed that this simple, sharp boundary pinch was unstable for all azimuthal mode numbers m .

These calculations were extended further by sharp boundary model analyses that allowed axial field both inside and outside the plasma¹⁴⁻¹⁶ and had a conducting wall around the pinch. Complete stability was then possible using the sharp boundary model. The results showed that the pinch could be stabilized for $m = 0$ and $m = 2$ modes by axial field alone, but the conducting wall was essential to stabilize the $m = 1$ mode. For compression ratios above five, the thin-skin-current model is never totally stable.

TABLE II. DIAGNOSTICS

Experimental Parameter to be Measured	Diagnostic Name	Available on ZT-1/S or other LASL Experiments	Under Development	Highly Desirable but Currently Unavailable	Comments	Proposed Data- Handling Technique
1. Electron temperature (T_e)	(a) Thomson scattering	x			(a) Spatially resolved Thomson scattering now being developed for Scylla IV-P	(a) Gated integrator, A/D conversion, computer processing
	(b) Differential x-ray absorption	x				(b) A/D transient recorder, computer processing
2. Plasma den- sity (n)	(a) Coupled cavity HeNe laser inter- ferometer, single chord	x				(a) Fast A/D, computer
	(b) Multiple beam coupled cavity		x		(b) Needs phase sensi- tive detector development	(b) Computer processing
3. Plasma motion	(a) Streak cameras	x			(a) Visible spectrum only	(a) Photographic film
	(b) Luminosity	x			(b) Visible spectrum only A/D, computer	(b) A/D, computer
	(c) Sine-cosine fourier coils	x				
4. Ion tempera- ture (T_i)	(a) Doppler visible line-broadening	x			(a) Large T_i makes this difficult	(a) A/D, computer
	(b) Small angle CO ₂ laser scattering			x		
	(c) Neutral particle detectors			x		
	(d) X-ray spectroscopy			x	(d) Easily feasible, given enough space	(d) Film or photoelectric detection A/D, computer
5. Growth rate and k of instabilities	Sine-cosine four coil	x				
6. Magnetic fields	Plasma probes	x			May perturb plasma too much, particularly at late time	A/D, computer
7. Energy loss	(a) Broad band radiation detector		x			(a) A/D, computer
	(b) uv spectroscopy	x				(b) Film or photoelectric detection
8. Plasma impurities	Spectroscopy	x				
9. Neutron emission	(a) Integrated neutron counters	x				(a) Scalars
	(b) Time resolved neutron detectors	x				(b) Oscilloscopes
10. Toroidal magnetic flux	Flux loops	x				A/D, computer
11. Toroidal current	Rogowski loops	x				A/D, computer

2. Diffuse Boundary Theory. Because very sharp boundary pinches are not observed in practice, the stability of straight plasma columns with diffuse current profiles must be studied. Suydam¹⁷ derived a necessary condition for stability of a diffuse linear pinch. For stability, the diffuse equilibrium must satisfy

$$(r/4\mu^2)(d\mu/dr)^2 + (8\pi/B_z^2)(dp/dr) > 0, \mu \equiv B_\theta/(rB_z) ,$$

at all radii r . Wherever this condition is not satisfied, the pinch is unstable to perturbations sufficiently localized along the helical field lines.

A comprehensive study by Newcomb¹⁹ gives necessary and sufficient conditions for linear diffuse pinch stability. He shows that a pinch is stable at all m and k values if, and only if, it is stable for $m = 0$, $k \rightarrow 0$, and $m = 1$ at all k values. This result greatly reduces the work needed to test a given equilibrium for stability. Application of Newcomb's criterion involves solving the Euler-Lagrange equation in each region between the singular points in the differential equation. In practice, these equations are solved numerically by computer. Other applications of necessary and/or sufficient conditions¹⁹⁻²¹ generally involve numerical methods. Newcomb's work has been used directly to examine how current layer thickness affects stability.²² By use of a particular profile, this study showed that the maximum sheath thickness for stability depended on the plasma compression. It was concluded that, for the profile studied, a stabilized pinch can be stable even with a fairly diffuse skin at 20-30% beta, if the plasma compression is not too great. More recently stable profiles having $\sim 40\%$ beta values have been found with the current totally permeating the plasma.^{11,23,24}

Finding stable profiles involves some trial and error. In practice, the final stability check is made numerically. This checking has been done by (1) numerically solving Euler-Lagrange equations to apply the Newcomb criterion, (2) solving the eigenvalue equation from the equation of motion, and (3) checking a discretized quadratic form δW of the energy principle to see if it is positive definite, corresponding to stability. The second method's advantage is that it yields growth rates and eigenfrequencies of the normal modes at the price of

extra computing time. Three sample profiles that have been found stable are shown in Fig. 4.

Robinson¹¹ has pointed out the importance of radial distribution of the pitch parameter $P = rB_z/B_\theta$ in controlling diffuse linear pinch stability. In particular, to get a stable configuration, one must avoid a minimum in the pitch vs radius because, at such a position, the shear stabilization effect vanishes and an unstable perturbation that makes δW negative can be demonstrated explicitly. To avoid a minimum, the pitch must fall monotonically from the pinch axis. If there is a vacuum field region outside the pinch, the fields in that region are $B_z = \text{const}$, $B_\theta \propto 1/r$, so the pitch varies as $B_z r^2$. If B_z and B_θ are positive everywhere, a pitch minimum must exist because the pitch is decreasing inside but increasing outside the pinch. An RFP avoids this behavior, by reversing the sign of B_z at an appropriate radius so that the pitch continues to fall outside the pinch. Thus, MHD stability requires a field reversal in the outer region of a Z pinch that has a vacuum field region between the plasma and the wall.

If one is willing to operate with plasma pressure gradients and current extending to the walls of the discharge tube, the stable high-beta equilibrium configurations need not have the reversed axial field. Such operation leads to plasma cooling, wall bombardment, and impurities release, so it should be avoided if possible. The reversed-field region acts as a buffer between the plasma column and the walls, and lack of such a region would probably lead to use of limiters as in tokamaks.

3. Toroidal Calculations. MHD stability calculations have been extended to toroidal configurations²⁵ by using an iterative code to determine the toroidal equilibrium configuration. A large discretized quadratic form of δW for the equilibrium is obtained by using double Fourier expansion, in the toroidal and poloidal field directions, and finite differencing normal to the flux surfaces. The resulting quadratic form is tested to see whether it is positive definite, corresponding to stability. Because such calculations must involve a finite resolution owing to their discrete nature, the stability of very localized modes is checked by applying the Mercier criterion²⁶ (the toroidal analog of the Suydam criterion) numerically to the calculated equilibrium. The latest work²⁷ indicates that for the reversed-field pinch configuration there is an optimum aspect ratio that gives the greatest margin of

Fig. 3.
Current density and plasma density at which ohmic heating (assuming Spitzer resistivity with Z_{eff}) will "burn" through the radiation barrier formed by oxygen impurity in the percentages indicated on each curve. Values of n_e and j above each curve must be used to avoid limiting the plasma temperature by radiation. The results were obtained using a modified IMPRAD 3 computer code.

Fig. 4.
Sample MHD stable pressure and field profiles of a linear pinch showing the location of the conducting wall (arrow) for stability as a function of increasing pressure.

stability for the localized modes. Moreover, for hollow pressure profiles, a toroidal equilibrium can be Mercier stable at a small aspect ratio although it is unstable at a large aspect ratio.²⁸

Toroidal calculations generally indicate that for the large aspect ratios used in the LASL experiments, the toroidal effects on the reversed-field Z pinch are small and application of the linear pinch stability theory is a very good approximation. This fact saves much computer time in testing experimentally obtained plasma-field profiles for theoretical MHD stability.

B. Nonideal MHD Stability Theory

The straight reversed-field pinch configuration's resistive instabilities have been studied numerically using a time-dependent code that solves the linearized equations of motion.^{29,30} The equations solved included compressibility, finite resistivity, viscosity, and thermal conductivity. The $m = 1$ mode growth rates were found to be largest. The unstable resistive tearing mode can occur in a configuration that is stable according to ideal MHD. These unstable modes vanish as the wall is moved closer to the pinched plasma column.

The effect of a finite resistivity wall around a screw pinch stabilized by force-free currents in the outer region has been studied.³¹ As one might expect, slowly growing modes are found which are not present with a perfectly conducting wall. Given the usual high plasma density in the pinch, these growth rates can be slow enough not to be a limiting factor in thermonuclear applications, if the equilibrium parameters are chosen carefully. Limitations do arise if the plasma density is reduced.

The physics of sharp-boundary pinch instabilities has been analyzed using the Vlasov-fluid model, assuming an ordering especially applicable to the study of stabilized Z pinches.³² The instabilities are assumed to have a wavelength comparable to or less than the pinch radius and an azimuthal mode number m greater than zero. A Maxwellian equilibrium ion distribution function is chosen and the ratio of ion Larmor radius to pinch radius is assumed to be small but nonvanishing. With these assumptions, the equations of the Vlasov-fluid pinch differ from those of an ideal magnetohydrodynamic pinch in at least two crucial aspects, a frequency-dependent compressibility function and a magnetoviscosity term that can induce finite-Larmor-radius stabilization. The marginal stability domain of the Vlasov-fluid pinch is shown to be identical to that of the ideal magnetohydrodynamic pinch, in agreement with Freidberg's results.³³ Even if

finite Larmor-radius effects are ignored, the Vlasov-fluid growth rate to ideal magnetohydrodynamic growth rate ratio is less than unity in all cases studied. When β is finite, this ratio must approach zero as marginal stability is approached. Further, for unstable modes with $m > 1$, finite Larmor-radius stabilization effects in the Vlasov-fluid model can be significant when $\beta |\omega/kv_{th}| \gg 1$ and $|\omega/kv_{th}| \ll 1$, where v_{th} is the ion thermal speed. In contrast, these effects are insignificant in a magnetohydrodynamic model even when a magnetoviscosity term is included.

The Vlasov-fluid model always predicts better pinch stability (lower growth rates) than does ideal MHD. Application of this model to a diffuse RFP is planned.

C. Plasma Dynamics

1. Numerical Analysis. At LASL, time-dependent, one-dimensional computer code results are being compared with experimental results. A. Haberstich and R. B. Howell have used a fluid code that includes effects of anisotropic electrical resistivity, heat conduction, and an impurity radiation loss term. The postimplosion phase of ZT-I can be approximated by an electrical resistivity that increases by two orders of magnitude from the discharge axis to the discharge tube wall. Comparison with measured electron temperatures indicates that this resistivity value is nearly classical at the center and possibly larger than classical in the outer region at the pinch. Energy loss can be accounted for by enhanced heat transport to the wall or by impurity radiation, assuming approximately 1% oxygen and 1% carbon impurity content. For the same problem, T. Sgro and C. Nielson use a hybrid code that treats the ions as particles and the electrons as fluid. The computed ion temperatures are a factor of 2 to 4 lower than those measured in the ZT-I experiments, and the computed electron temperatures are higher than those from measurements of the radial electron temperature profile. Because of this high calculated T_e , the code must include an enhanced resistivity to match the magnetic field profiles. The field diffusion during the early pinch phases has been matched well.

2. Analytic Work. Two important theoretical results concern the setup phase of a reversed-field pinch:

a. Self-Reversal. Taylor³⁴ has made a theoretical study of self-reversal of the outer toroidal field, observed in many toroidal Z-pinch

experiments. Assuming Woltjer's volume integral invariant³⁵ $\int \vec{A} \cdot \vec{B} d\tau$ ($\vec{A}$ = vector potential, $\vec{B}$ = magnetic field) and toroidal flux conservation Taylor has shown that the lowest magnetic energy state of a plasma column inside a perfectly conducting cylindrical shell has a force-free configuration with a reversed toroidal field for $\theta = 1.2$. (θ = poloidal field at wall/average toroidal field.) He predicts that, given some dissipation, the pinch will naturally relax toward this state of minimum magnetic energy. This naturally occurring field reversal is to be exploited in the Culham RFX experiment. S. Ortolani and G. Rostagni have made related analyses of a sharp boundary model using toroidal flux conservation and beta and θ as constant parameters.³⁶ Their model also gives reversed field lowest energy states.

b. Global Energy and Pressure Balance. The following theorem³⁷ has been obtained from global pressure and energy balance: If a cylindrically symmetric stabilized pinch is driven by a current that rises to its final value very rapidly compared to the compression and flux diffusion times, static equilibrium cannot be achieved after the azimuthal field has diffused to a uniform current distribution unless losses or plasma pressure at the wall are present. This theorem points up the importance of the loss mechanisms during pinch formation if diffusion leads to a state of uniform current in the pinched column. If the currents rise too fast and the losses are too small during field diffusion, the plasma pressure becomes too high for the poloidal field to contain. If the pinch maintains a relatively thin skin, this difficulty need not arise.

D. Microinstability Theory

Microturbulence may produce anomalous diffusion away from the desired MHD stable profiles. If such a production could be verified experimentally, relevant microinstability theory would furnish one of the scaling laws needed to guide design of future experiments to reduce this unwanted effect.

The Z pinch microinstability theory has proceeded along the following lines. An equilibrium model of the postimplosion phase has been constructed in which the ions carry no current. The resulting electron drift velocity, with components both along and across the (total) magnetic field, is a source of free energy for driving various microinstabilities. Many well-known microinstabilities have then been surveyed to see which might occur in this

environment.³⁸ Two candidates, the current-driven whistler³⁹ and the lower hybrid drift modes,⁴⁰ have been found to have fast growth rates.

The present theory of the current-driven whistler has recently been found invalid for RFP conditions.⁴¹ The unstable wavelengths are never short compared to the plasma column radius, so the theory, which ignores field and plasma density gradients, is invalid. There is no longer any theoretical reason to consider this instability dangerous for the postimplosion phase of an RFP.

We are left, then, with the lower hybrid drift instability. Numerical particle simulations⁴² suggest that ion trapping in the potential wells of the drift wave is the instability saturation mechanism. The ion trapping leads to the anomalous resistivity formula⁴³

$$\eta = (\pi^{3/2})^9 (\pi/2)^{1/2} (V_{Di}/V_{thi})^8 (\omega_{ce}/\omega_{pe})^2 / \omega_{LH}, \text{ (Gaussian units)}$$

where V_{Di} is the diamagnetic ion drift velocity, V_{thi} the ion thermal speed, ω_{ce} the electron gyrofrequency, ω_{pe} the plasma frequency, and ω_{LH} the lower hybrid frequency. For parameters that correspond to the present range of experiments, this formula predicts about one tenth of classical resistivity in the main body of the pinch. It appears then that the lower hybrid drift instability should be important only in the outer low-density regions. Furthermore, Krall's recent work⁴⁴ indicates that shear stabilization of this instability should be effective over a major part of the pinch radius. Thus, there are no known strong candidates that predict fast field diffusion into the interior of the pinched plasma column.

IV. SUMMARY OF RFP EXPERIMENTS

A. United Kingdom

1. HBTX I. (Culham Laboratory). Parameters: $a = 6.5$ cm, $R = 1$ m, quartz vacuum vessel, nominal filling pressure = 40 mtorr D_2 , and current = 40-110 kA.

Stable high-beta reversed-field configurations were set up without wall contact using fast programming. At 40-kA toroidal currents, fully stable plasma was observed and the lifetime was stated to be governed by classical field

diffusion. Stability required the total toroidal flux to be positive, as theory requires. Temperature was constant for $\sim 20 \mu\text{s}$, and energy containment time was $\sim 15 \mu\text{s}$. Theoretical and experimental predictions agreed quantitatively. The experiments demonstrated that resistive tearing modes can be stabilized by locating the conducting wall a little closer to the pinch than is required for ideal MHD stability, in agreement with resistive MHD theory. At higher currents, the temperature increased as I^2 up to 110 eV at 150 kA.

2. ZETA. (Harwell). Parameters: $a = 50 \text{ cm}$, $R = 150 \text{ cm}$, thin metal first wall, $n = 10^{14} \text{ cm}^{-3}$, and nominal current = 500 kA.

Recent interest at Culham has revived analysis of old ZETA experimental data, particularly self-reversal. Under special conditions, ZETA showed an interesting quiescence beginning about 2 ms into the discharge and lasting for another 2-3 ms. It was subsequently shown that quiescence occurred only when both the toroidal magnetic and electric fields on the outermost part of the discharge were reversed. The electron temperature increased by ohmic heating to $\sim 150 \text{ eV}$, and the beta values were about 0.1. The energy containment times became much longer during the quiescent state and were estimated to be 3-10 ms.

3. HBTX II. Culham Laboratory is planning a large, slow machine, RFX, with $a = 60 \text{ cm}$, $R = 180 \text{ cm}$, stainless steel liner, $n = 10^{14} \text{ cm}^{-3}$, $I = 700 \text{ kA}$, risetime = 1.5-10 ms, and decay time = 10-20 ms. They plan to exploit self-generation of the reversed field and to tailor the plasma-field profiles by slow field programming. A prime objective is to obtain energy confinement times of tens of milliseconds.

B. Italy

ETA BETA. (University of Padua). Parameters: $a = 5 \text{ cm}$, $R = 40 \text{ cm}$, quartz torus, filling pressure 20-80 mtorr H_2 , $I = 30\text{-}150 \text{ kA}$, and risetime = $\sim 1 \mu\text{s}$.

Stable configurations are found, at 40 mtorr, for currents up to 60 kA. These plasmas are characterized by very low compression ratios (~ 1.5). The plasma lifetime is limited by field diffusion consistent with classical transport coefficients. At higher currents, the plasma shows instabilities followed by quiet decay and the plasma lifetime is limited by the primary circuit current decay. A new 24-cm-bore experiment, ETA BETA II, is planned.

C. Japan

1. ETL-TPE-1. (Electrotechnical Institute Tokyo). Parameters: $a = 5$ cm, $R = 40$ cm, Pyrex torus, filling pressure = 30-50 mtorr He, and nominal current = ~ 80 kA.

This machine has been run as both a screw pinch and a RFP. Thomson scattering indicates I_e values of ~ 20 eV which drop in ~ 20 μ s, indicating loss of stability at that time. Poloidal beta is reported to be ~ 0.6 . The very diffuse pinch makes the plasma column very difficult to define using streak pictures.

2. STP-I. (Nagoya University). Parameters: $a = 4$ cm, $R = 12$ cm, quartz torus, nominal filling pressure = 20-30 mtorr D_2 , and current = ~ 50 kA.

Preliminary RFP operation studies show that reversed-field programming definitely improves plasma stability. The experiment has power crowbars on both circuits and shows much less toroidal flux loss when they are used. As in ETL-TPE-1, the streak pictures of the pinch are very diffuse. The machine has been run primarily as a high-beta tokamak.

D. LASL Experiments

1. ZT-I. Parameters: $a = 5$ cm, $R = 37$ cm, high-purity sectorized alumina torus, current = 30-200 kA, and filling pressure = 10-100 mtorr D_2 .

The ZT-I experiment was initially designed to operate at high toroidal electric field, ~ 1 kV/cm, and rapid rise rates, $\dot{I} \approx 1.4 \times 10^{12}$ A/s. This operation, accomplished by using inductive energy storage with fuse interrupters, gave ~ 1 -keV ion temperatures. Reversed-field programming was slow compared to the pinch current risetime, and the reversed-field region remained a thin annulus near the wall. Although completely stable MHD profiles were not obtained, reversed-field operation improved the stability, as evidenced by streak pictures and magnetic probe data. ZT-I was operated under derated conditions, without fuses, with I values of 40-70 kA and $\dot{I}$ of up to 10^{11} A/s. These longer times made field programming easier. The ion temperatures were an order of magnitude lower than those from the fuse mode of operation. Field profiles with favorable stability characteristics were obtained. A plasma column that struck the wall in 3 to 4 μ s with no reversed field, struck it in 10-15 μ s with reversed-field programming. Magnetic probe data showed that the

poloidal and toroidal flux surfaces diffused at different rates. As the field diffusion proceeded, the loss of trapped toroidal flux, and the increasing poloidal beta caused the initially favorable profile to be lost eventually.

2. ZT-S. Parameters: $a = 7.7$ cm, $R = 40$ cm, high-purity sectored alumina torus, filling pressure = 10-100 mtorr D_2 , and current = 30-140 kA.

This experiment's prime purpose is to examine confinement time scaling from the smaller bore ZT-I experiment. At low-current, 30-kA, operation, confinement times are as long as 40 μ s. Given 40- to 60-kA currents, the plasma column persists for 18-25 μ s. At high densities, streaks up to 30-40 μ s long are obtained at 60- to 80-kA current. The electron temperature measured by Thomson scattering rises to ~ 15 eV and persists for ~ 20 μ s, considerably longer than in ZT-I. The increased tube bore does lead to longer stable times that seem to result from the increased diffusion time $\tau_d = a^2/D$, due to the larger plasma radius.

V. ENGINEERING

A. Introduction

The ZT-40 design will involve the basic engineering concepts embodied in ZT-I and ZT-S. Although the machine will be designed to operate at 50 kV, it will use the 60-kV components and technology developed for the Scyllac and Staged Theta-Pinch experiments to give improved reliability. The one unique feature of ZT-40 will be a power-crowbar system that will extend the current out to several hundred microseconds with only a 10% droop for the first 200 μ s. The initial experiments will use a passive crowbar system while the power-crowbar system is being developed.

B. Layout

The experiment will be located in the SM-105 experimental area, on a 465-m² dedicated floor space. Figure 5 shows the general layout. The machine will be about 3.4 m above floor level, surrounded by a roughly circular, experiment platform about 2.7 m high. Cable headers with their crowbar switches are located below the platform. The principal energy system is in the four capacitors racks on the left and right of the circular platform. Cables from the capacitors and

start gap switches go into the crowbar switch headers, and output cables from these headers go down to mix headers at platform level. The output cables from the mix headers go to machine headers.

This layout affords physical access to the machine, minimizes the average cable lengths to the banks, and provides access to critical components. The area under the platform will be used for the power crowbar and vacuum systems.

C. Machine Features

The principal features of the machine are shown in Figs. 6-8 and listed in Table III. Figure 9 shows the toroidal coordinate system on which the nomenclature is based. The 40-cm-i.d. discharge tube is located inside the 45-cm-bore Z-current aluminum primary (with less than 2-cm clearance to ensure good inductive coupling.) The discharge tube will have 24 vacuum pumpout ports. The 2-cm-thick aluminum primary is divided into 12 segments and split on the horizontal plane to allow penetration of the B_z toroidal flux. Each segment of the primary is essentially connected to the entire 50-kV I_z capacitor bank by cables and a mix header. In essence, one of the 126 cables in each Z-current header will go to each capacitor in the I_z bank. There are theta current coils around the primary; they are initially considered simple extensions of the cables from the I_θ capacitor bank. The cable will be wound around the primary with its outer braid peeled back and connected to the end of the final turn. There are 12 split, iron-core segments, one in each sector. Each will weigh about 1.5 tons. These cores are like those on ZT-S and well within transformer manufacturers' capabilities. A 15-ton crane is available to handle all heavy equipment.

D. Energy Systems

The principal ZT-40 energy system without the power crowbar will store about 3 MJ at the 50-kV rated operating voltage. The power crowbar system will store approximately 3 MJ of additional energy to extend the current for 200 μ s with a $\leq 10\%$ droop. The principal system will consist of four individual capacitor banks: the $I_\theta(B_z)$ toroidal, bias field bank; the preionization (PI) bank, the $I_z(B_\theta)$ poloidal field bank, and the $I_{\theta R}(B_{zR})$ reverse toroidal field bank. The bank parameters are given in Table IV.

Fig. 5.
General ZT-40 layout.

Fig. 6.
Schematic of ZT-40 experiment.

Fig. 7.
Top view of ZT-40 torus showing magnet-
ic core arrangement.

Fig. 8.
Cross section of ZT-40 torus showing
the toroidal current feed arrangement.

TABLE III

ZT-40 MACHINE PARAMETERS

Discharge tube inner radius	20 cm
Major radius	114 cm
Aspect ratio	5.2
Plasma current	600 kA
Z-current feed points	12
Iron cores	12
Total Z-current cables	1512
Total θ -current cables	1728

TABLE IV

CAPACITOR BANK PARAMETERS

	I_{θ} (BIAS) <u>BANK</u>	PI <u>BANK</u>	$I_{\theta R}$ (REVERSE) <u>BANK</u>	I_z <u>BANK</u>
V(kV)	10	20	50	50
C(μ F)	30 000	1125	528	448
W(kJ)	1500	225	660	560
$I_{MAX.}$ (MA)				
(total)	3.4	2.0	6.0	7.2
(per sector)	0.28	0.17	0.5	0.6
$\tau/4$ (μ s)	75	15	2.5-30	2.5-30

Simplified circuits and waveforms are shown in Fig. 10, and Fig. 11 shows the sequence of current-field applications for programmed reverse-field pinch

formation. The 10-kV bank in the I_θ circuit is fired first to establish a toroidal bias field. It rises in about 75 μ s and is crowbarred at peak current. The risetime is controlled by the isolating inductor L_i .

About 30 μ s before peak bias field, the 20-kV PI bank is fired to produce a small toroidal current to preionize the plasma. The PI bank is designed to operate in either polarity as determined by the physics requirements. The PI current completes one-half cycle and is crowbarred off. The inductor L_i in this circuit isolates the PI bank from the rest of the system.

When the toroidal bias field is established and the plasma preionized, the main I_z bank and the fast $I_{\theta R}$ reverse field bank are fired nearly simultaneously. The I_z current driven in the "primary" shell of the torus induces a "secondary" toroidal current in the preionized plasma. The poloidal field (B_θ) of this plasma current pinches the plasma, sweeping up and compressing plasma and toroidal bias field. The fast-bank $I_{\theta R}$ current reverses the I_θ current around the torus and produces a reverse toroidal field (B_{zR}) on the outside of the imploding, magnetized, toroidal plasma. Both I_z and $I_{\theta R}$ are designed to peak at a minimum of about 2.5 μ s. The I_z and $I_{\theta R}$ circuits are shown with power crowbar banks (PCBs) in series with the crowbar switches. In the initial phase of the experimental program, these PCB capacitors will be shorted out. Currents in the I_z and $I_{\theta R}$ circuits will then decay with an L/R of ~ 100 μ s. Later, when the PCB circuit and its components are fully developed, the PCB system will be added to keep the crowbarred current essentially constant for 200 μ s.

Most components to be used in ZT-40 are identical to those in Scyllac and Scylla IV-P, including high-voltage capacitors and the low-inductance coaxial load cable. Figure 12 shows the 60-kV capacitor for the 50-kV $I_{\theta R}$ and I_z banks and the 10-kV capacitor for the I_θ bias bank. Both are expected to exceed 200 000 shots in the ZT-40 application. About five hundred 60-kV capacitors and two hundred 10-kV capacitors are required. The preionization bank will use about seventy-five 20-kV capacitors on hand from previous experiments.

The 50-kV banks will be switched on by using the field distortion start gap shown in Fig. 13. This gap, developed for Z-pinch devices that require a large operating voltage range, is in service in ZT-S. It is operated reliably at 12-60 kV by simply varying the dry air pressure in it from about 1 to 2 atm. The jitter is less than 20 ns over this range, given a 100-kV trigger pulse. The gap has been tested to over 10 000 shots at currents exceeding those in the ZT-40.

ZT-40 COORDINATE SYSTEM

Fig. 9.
ZT-40 Coordinate system.

I_y (B_z TOROIDAL) CIRCUIT

I_x (B POLOIDAL) CIRCUIT

Fig. 10.
ZT-40 circuits and waveforms.

Fig. 11.
Current programming to produce
reversed-field profiles.

Fig. 12.
ZT-40 capacitors.

experiment without deterioration. It has low inductance and is economical to build and maintain. About 500 will be used.

E. Control and Trigger Systems

The ZT-40 experiment will be controlled by a computer system similar to that for the Scylla IV-P linear θ -pinch experiment. ZT-40 probably will use a Prime-400 computer and a standard CAMAC branch highway for interfacing. This system will also be used for data acquisition and processing.

The trigger system for the various capacitor banks will be similar to those in other operating experiments. Ignitrons in the bias and preionization banks will be triggered by circuits like those in ZT-S. The more critical 50-kV spark gaps in the $I_{\theta R}$ and I_z banks will be triggered by high-voltage trigger circuits like those in the Scyllac and Staged Theta-Pinch systems. These trigger circuits generate 100-kV pulses that rise at 2-3 kV/ns and will trigger the spark gaps with less than 20 n. jitter.

F. Vacuum Systems

1. Discharge Tubes. One type of plasma discharge tube being considered is 99.8% Al_2O_3 ceramic cast as segments that are chords of the major diameter circumference. The segments will be precision ground on the outside and inside with lap joints on each end. They will be joined together by a glass frit compound that must be fired to seal the joint. The entire torus will be made in two or three sections and finally sealed with O-rings at these joints. The sections are necessary because there are no furnaces in this country that can accommodate the complete torus. However, there is some possibility of getting a complete torus from Japan. The cost of a finished ceramic torus is estimated to be \$24-30K.

Another possible discharge tube is of fused or transparent quartz. Such a tube could be made without joints. Manufacture of a transparent, toroidal quartz tube involves problems, but it is possible to make a torus of angular sectors (like the ceramic ones), which are then fused together. The cost is approximately \$35K per torus, and delivery takes about 10 months from Hamburg, Germany. Amersil can make a fused quartz tube (opaque) in 120° sectors with fired-in transparent sections for diagnostic viewing for \$8K to \$10K and deliver it in 6-8 months, or a fused quartz torus can be made in France for \$15K and delivered in 7-8 months.

The manufactured dimensions of quartz tori of the size we need are unpredictable. In fused quartz, the wall thickness will vary between 6 and 12 mm, the thin sections being on the inside of the major radius of the geometry. Tolerances on the major radius may be as high as ± 8 mm. Clear quartz tori are made with better tolerances than fused quartz ones, but, in either case, the torus may have to be undersize, relative to ceramic, to accommodate the larger tolerances.

An all-metal discharge tube is also being considered for the slower risetime ($> 10 \mu s$) applications. Extensive development is required for such a torus, but conceptually it could be a thin, stainless-steel bellows. The bellows would be at right angles to the conventional design in that the convolutions or pleats would be parallel to the major circumference. A second all-metal tube design would involve anodized, tapered washers, like the one developed for ZT-I.⁴⁵

2. Vacuum Requirements. Influx of impurities from the walls in plasma containment experiments can cause large power losses from the plasma and seriously reduce the temperature attained. In the ZT devices, impurity sources include contaminants in the gas, outgassing of the walls during the gas filling process before the discharge, and desorption from the walls during pinch formation. Further desorption by photons, sputtering of wall material, and release of chemisorbed atoms by charge exchange neutrals may release additional impurities that should be expected to reach the compressed pinch surface in a few tens of microseconds after the pinch is formed and heated. Additional later influx may result from diffusing ions and electrons striking the walls and from wall heating. A major objective in the vacuum effort is to minimize impurity influx by reducing the amount of gas adhering to the walls. This is to be done by using surface-cleaning techniques such as bakeout ($100^{\circ}C$) and low-frequency discharge cleaning.

Some experimental measurements of the impurity content of pinch devices are summarized in Table I. From these measurements, the estimated initial fractional impurity in ZT-40 at a compressed density of $5 \times 10^{15} \text{ cm}^{-3}$ would be ≤ 0.001 .

The vacuum system itself will consist of a drum manifold with 12 arms extending out to the 12 pump ports on the underside of the torus. The 12 diagnostic ports on top of the torus can also be pumped. Pumping will be done

by a turbomolecular pump with provisions for addition of LN_2 cryopumps and titanium sublimation pumps. The design base pressure is 10^{-8} mtorr. Vacuum system and gas injection system operation will be fully automated and included in the computer control system.

G. Development Program

The concentric, multichannel crowbar spark gap shown in Fig. 14 is being developed for the passive crowbar switch application and, hopefully, also to serve as the power crowbar switch. We are confident that this switch will be satisfactory as the passive crowbar. About 130 of these concentric crowbar gaps will mount directly into a cable-header system where they will be accessible for maintenance. In this location, they should require little modification when the PCB is added.

As emphasized before, the principal technological problem facing the ZT-40 experiment is the power crowbar system. At least two solutions, an electrolytic capacitor bank and a transformer-coupled capacitor bank, will be studied extensively.

The power crowbar circuit is used to replace the energy dissipated in the crowbarred load circuit for the times of interest (200 μs). An electrolytic capacitor bank is well suited for this application, if the voltage drop around the circuit is within the voltage range of electrolytic capacitors, which is 450 V maximum. In the PCB application, however, the capacitors must pass the full load current, which is ~ 3.5 MA in the $I_{\theta R}$ circuit. One problem is that each electrolytic capacitor can carry only ~ 1000 A in this application before the internal IR-drop becomes too large a fraction of the electrolytic bank's 450-V charge voltage. Connecting two capacitors in series requires twice the energy and is unacceptable for economic and space reasons.

Although the electrolytic capacitor bank is a possible solution, it must be studied and evaluated carefully before it is adopted. A modest electrolytic PCB is being built for performance evaluation.

Our preferred PCB option is use of a low-leakage transformer powered by a conventional 10-kV capacitor bank, because it gives a wide range of slow operation risetimes. Kei-Ichi Hirano of Nagoya University in Japan has developed such a transformer, and it is built commercially by Nissen Electric Company, Ltd., in Japan. Hirano is a consultant to the CTR Division and has discussed the principles of his transformer with us. Unfortunately, the

Fig. 13.
Field distortion start gap.

Fig. 14.
Concentric crowbar spark gap.

commercially available design is not suitable for our exact application, so we are studying designs that could be built "in-house." A low-leakage transformer will be built and evaluated within the next year.

Other PCB options include a 3- to 5-kV pulse-forming network (PFN) line and an inductive storage circuit. Every approach has certain advantages and disadvantages, and no scheme will be ignored without careful study and evaluation. The PCB problem has the highest priority in the engineering group development section, and we are confident that a suitable solution will be developed and installed within a year after ZT-40 begins operation.

VI. ESTIMATED COST AND MANPOWER REQUIREMENTS

Table V which shows costs by fiscal year, assumes that construction of ZT-40 begins in FY-77 and will be completed in FY-79. A few components necessary for initial construction are being purchased in FY-76. The experiment will be built with a passive crowbar and completed in FY-78. A power crowbar system will be added in FY-79. The LASL FY-77 budget and financial plan are firm, and only \$1230K are available for ZT-40 construction in that fiscal year. An additional \$250K must be provided in FY-77 to complete the first phase of this experiment by FY-78.

TABLE V

ZT-40 COSTS BY FISCAL YEAR

FY-76	Initial Critical Components Procurement	\$ 250K
FY-77	Initial Construction	1480K ^a
FY-78	Construction Completion without Power Crowbar System	810K
FY-79	Power-Crowbar System Procurement and Installation	<u>700K</u>
		\$3240K

^a\$1230K available from LASL FY-77 financial plan. \$250K
more required to meet schedule.

A. Costs by Budget Category

ZT-40 is to be constructed and operated under the Confinement Systems category, so all costs given here fall entirely in that category.

B. Construction Costs

Construction costs are listed in the following tables. Material and contract services costs, shown in Tables VI and VII, come under Major Device Fabrication (MDF). The design assembly costs shown in Table VIII are covered by normal operating costs. Capital equipment costs are shown in Table IX.

TABLE VI

MATERIAL COSTS FOR ZT-40 (MDF)

Capacitors	\$ 200K
Cable System	100
Structure	60
Iron Cores	280
Machine Components	225
Charging System	50
Trigger System	165
Switches	260
Control System	35
Ceramic Torus	50
Vacuum System	25
Power Crowbar System	<u>600</u>
	\$2050K

TABLE VII

CONTRACT LABOR FOR ASSEMBLY AND INSTALLATION

Laboratory Utility Modifications	\$ 175K
Component Assembly	100
Structural Installation	100
Charge and Trigger System Installation	50
Cable Installation	150
General Craft Support	<u>50</u>
	\$ 625K

TABLE VIII

COSTS OF DESIGN AND ASSEMBLY BY LASL PERSONNEL
(INCLUDING INDIRECT COSTS IN FY-77 AND FY-78)

Mechanical Engineering and Drafting	\$ 430K
Electrical Engineering	245
Component Assembly and Testing	110
Bank Assembly	475
Control System	240
Machine Assembly	255
	\$1755K

TABLE IX

ZT-40 CAPITAL EQUIPMENT COSTS

Compressor and Dryer	\$ 20K
Water Chiller	25
Vacuum System	20
Power Supplies	50
Computer	125
Screen Room	30
Air Conditioner	15
Pulser System	50
Data Acquisition Channels	50
Streak Camera	35
	\$420K

Table IX summarizes all construction costs. The 15% contingency is adequate for the present design. The 8% escalation is shown for materials only, because most of the contract labor and assembly will be costed in FY-77, and these costs are known. The cost of materials to be purchased in FY-77 also can be estimated accurately. Thus the \$165K escalation applies mostly to FY-78 and FY-79.

TABLE X

SUMMARY OF ZT-40 CONSTRUCTION COSTS

1. Major Device Fabrication (MDF)	
Material	\$2050K
Contract Labor	625K
2. Contingency--15%	400K
3. Material Escalation--8%	<u>165K</u>
Subtotal	\$3240K
4. Operating Funds, (Including LASL Manpower Overhead)	\$1755K
5. Total Construction Cost	\$4955K
6. Capital Equipment	\$ 420K

TABLE XI

OPERATING COST PER YEAR, INCLUDING OVERHEAD

Operating Crew

1	Physicist	\$ 73K
1	Engineer	72K
4	Technicians	146K

Experimental Team

8	Physicists	587K
10	Technicians	<u>365K</u>
	Total	\$ 1243K

C. Operating Cost in FY-79

The cost of operating the ZT-40 experiment in FY-79 is shown in Table XI. The cost of adding the power crowbar system in FY 79 was shown in Table V, so it is not included. The operating crew will consist of a principal physicist, one engineer, and four technicians. Various physicists and supporting technicians also will perform measurements.

VII. MILESTONES

The ZT-40 experiment is a significant step in investigation of toroidal Z pinches' reactor potential. The device's initial construction with a passive crowbar will limit the maximum plasma confinement time. However, the preionization requirements and the plasma formation characteristics can be studied in the passive crowbar mode of operation. The power crowbar system will be added as soon as it is developed and funds are available.

The first milestone after approval is plasma physics in FY-78. We emphasize that a critical \$250K in FY-77 is not available in known financial plans. The FY-78 milestone can be met only if adequate funds are available in FY-77 and FY-78. Assuming adequate funding on schedule, the principal milestones are as follows.

Approval to start construction	December 1976
Initial plasma physics with passive crowbar	July 1979
Plasma physics with power crowbar	June 1980

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