LA-5474-P

PROPOSAL

Proposal for the Construction of a Scylla IV-P Confinement Studies Theta Pinch

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PROPOSAL FOR THE CONSTRUCTION OF A SCYLLA IV-P CONFINEMENT STUDIES THETA PINCH

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W. R. Ellis, Jr., W. B. Riesenfeld, and G. A. Sawyer

ABSTRACT

An experimental linear theta-pinch device, called Scylla IV-P, is proposed to obtain important physical and technological data in support of the LASL high-beta confinement program. The major objective of this experiment will be to perform precise studies of the scaling laws for the growth rates of the most important magnetohydrodynamic modes acting in the Scyllac configuration. These experimental checks of theoretical predictions are expected to play a major role in defining the technological parameters of a Physics Test Reactor based upon the toroidal theta-pinch concept. Auxiliary and secondary goals for the Scylla IV-P device will be finite-ion-gyroradius effects studies, high-field coil development, wall-stabilization experiments, high-density linear theta-pinch studies, and diagnostic development.

I. SCIENTIFIC SCOPE

A. Introduction and Summary

The present proposal sets forth, details, and explains the motivation for a Controlled Thermonuclear Research Experimental System to be known as "Scylla IV-P." By virtue of its scope and the magnitude of the financial and manpower investments required to realize its scientific and technological goals, this system falls in the category of "Major Project" as defined in the memorandum of February 23, 1973, by Robert L. Hirsch, DCTR.

The proposed linear Scylla IV-P device will be a research theta pinch, designed to carry out important missions in support of the high-beta controlled thermonuclear research program at the Los Alamos Scientific Laboratory, leading to a toroidal theta-pinch Physics Test Reactor (PRT). This program has in recent years concentrated its efforts on the research, engineering, and systems design leading to a toroidal theta-pinch fusion reactor. The achievement of toroidal equilibrium for a high-energy theta-pinch plasma column and the stabilization of the most dangerous magnetohydrodynamic modes constitute the confinement research objectives of the Scyllac device, the first major experiment on LASL's path to a toroidal high-beta fusion reactor. The objectives of toroidal equilibrium and mode stabilization pose formidable scientific and technological challenges. The solutions incorporated into the Scyllac design rely to some extent on experimental results obtained on several preceding generations of straight theta pinches, which have produced plasmas with parameters (density, ion temperature, and beta) entirely suitable to Scyllac requirements. Yet to a very large degree the Scyllac design, as well as follow-on experiments now contemplated, leans upon theoretical ideas, concepts, and calculations which are complex, sophisticated, and often unavoidably model dependent. The concept of achieving toroidal equilibrium through the superposition upon the basic theta-pinch field of helical multipole and azimuthal ripple magnetic fields, the concept of suppressing unstable gross displacement motions through wall effects or feedback fields, the appraisal of finite ion-gyration effects in inhibiting higher-harmonic MHD instabilities, all are theoretical ideas falling into this category. In order to maximize the rate of technological progress, and to ensure that scientific results follow in a sound, logical order, it is necessary to provide clear-cut experimental confirmation of these and other key theoretical concepts.

Large confinement devices like Scyllac are too complex and specialized to serve as experimental test beds to confirm or elucidate theoretical cornerstone ideas one at a time, to study each phenomenon in isolation from other interfering phenomena. Instead, we propose the construction and operation of the Scylla IV-P device to carry out precisely this mission. Scylla IV-P will be a straight theta pinch, profiting from existing engineering expertise in this field, and at the same time serving as a relatively simple test bed for the application of the complicated $\ell=1$ and $\ell=0$ magnetic fields which are required by toroidal equilibrium configurations. It is important to note that the stability properties of such a straight system can be adjusted to reproduce those of a high aspect-ratio toroidal system, without incurring the diagnostic, interpretative, and constructional difficulties inherent in the latter. Thus a prime objective of the Scylla IV-P experiment will be to perform a detailed parametric study of the unstable $m=1$ modes as a function of the axial wavenumbers and surface distortion parameters of the auxiliary magnetic fields, and to compare these results with the predictions furnished by several competing theories which differ from each other in the relative ordering of parameters. This research, which is in direct support of the toroidal theta-pinch confinement program, is the primary mission of the Scylla IV-P experiment and will consequently receive immediate emphasis and priority. It is detailed in the "Variable-Epsilon Experiments" section of this proposal.

Other studies of great direct impact on the toroidal theta-pinch program will be measurements of the influence of ion gyration effects in stabilizing $m \geq 2$ MHD modes, and the effect of wall image currents in suppressing $m=1$ modes; quantitative theories on both phenomena exist and need experimental verification. The wall-stabilization phenomenon will be the basis of a recently proposed injection experiment, in which a highly compressed plasma is generated in a conventional straight theta pinch and allowed to stream into a wall-stabilized section with auxiliary equilibrating fields. Since the wall-stabilized sections can be bent into toroidal sectors, the possibility of an interesting new closed confinement configuration is suggested.

Scylla IV-P will also be designed to aid diagnostics development, and to serve as a high-field coil development and application facility. Details are presented in the appropriate section below. In addition, the high-beta program still maintains an interest in the straight, open-ended theta-pinch geometry as a possible back-up fusion reactor candidate, a concept not ruled out if magnetic field intensities and plasma densities can be raised to values much higher than previously investigated. Scylla IV-P will therefore also undertake a program in specifically linear theta-pinch physics in this regime, such as studies of end-loss rates, end-shorting effects, electron thermal conduction losses, mirrors and multiple mirrors, and MHD-stable mode structures characteristic of straight machines. Finally, a recent experimental proposal envisions the creation of a hot, very high-density plasma column through laser-beam heating; if a preliminary experimental assessment of such a heating procedure shows promise, Scylla IV-P could be used to explore the concept in greater depth.

The Scylla IV-P experiment is therefore proposed as an up-to-date scientific and technological test bed for a great portion of the existing LASL high-beta CTR program, as well as a flexible vehicle for testing new concepts. In a rapidly progressing field this last capability is certain to prove of immense value.

B. Variable-Epsilon Experiments

The name "variable epsilon experiment" has come to be applied to all scaling law experiments concerned with establishing experimental growth rates relevant to the Scyllac configuration. Experimentally it is not yet clear whether plasma confinement in the 5-m and 8-m Scyllac sector experiments is terminated due to a loss of stability or a loss of equilibrium or both. Plasma confinement is observed to be terminated by a gross $m=1, k \approx 0$ lateral motion to the walls beginning 6-10 μsec after initiation of the discharge, approximately equal to an Alfvén transit time from the ends to the center of the sector. A final resolution of the stability question will have to await operation of the full torus.

Theoretically, however, the plasma should be unstable to $m=1$ displacements due to bad curvature of the ℓ=1 or ℓ=0 perturbation fields. Different scaling laws for the ℓ=1 and ℓ=0, m=1 instability growth rates can be derived, depending on the particular assumptions of the theoretical model used. Experiments should be capable of distinguishing between the various predicted scaling laws, and such experiments will have first priority in the Scylla IV-P program.

Some preliminary scaling-law experiments[1,2,3] for ℓ=1 and ℓ=0 growth rates have previously been done on the Scylla IV-3 device, prior to its conversion to a staged θ-pinch facility.[4] These preliminary experiments showed the need for a longer machine in order to delay end effects, and carefully controlled experimental conditions, in order to make accurate, quantitative growth-rate measurements possible. The Scylla IV-P experiment has been designed to satisfy these requirements. The experimental results will be reviewed in Sec. I.B.3.

1. The Scyllac ℓ=1,0 Equilibrium. The main purpose of the Scyllac experiment is to create a stable toroidal equilibrium. The Scyllac equilibrium is made of three basic field components, the largest of which is the toroidal (θ-pinch) field of ∿ 50 kG. This field provides the plasma confinement and compression. Superimposed on this B_o field are small ℓ=1 and ℓ=0 field components of approximately equal magnitude, $(B_{\ell=0}/B_o) \approx (B_{\ell=1}/B_o) \approx 0.07$. This combination of fields has been shown capable of providing a toroidal high-β equilibrium for the plasma.[5,6]

a. Surface Distortions δ_1 and δ_o. The first-order plasma distortions about the radius r=a due to the ℓ=1 and ℓ=0 fields are of the form

$$r = a\,[1 + \delta_1 \cos(\theta - hz) + \delta_o \cos hz] \ . \qquad (1)$$

For ha = ε << 1, where h=2π/λ is the ℓ=1,0 wavenumber, the surface distortions are related to the applied fields by

$$\delta_1 = \frac{1}{\varepsilon\,(1-\beta/2)}\ \frac{B_{\ell=1}}{B_o} \qquad (2)$$

$$\delta_o = \frac{1}{2\,(1-\beta)}\ \frac{B_{\ell=0}}{B_o} \ . \qquad (3)$$

For simplicity we have given approximate formulae which are valid for $\varepsilon^2 \ell n\ \varepsilon/2 << 1-\beta$. The singular behavior in Eq. (3) as β approaches unity is illusory and does not occur in the exact but far more complicated expressions. This approximation must always be kept in mind when substituting experimental values, but for the parameter range of greatest experimental interest the expressions (2) and (3) are of satisfactory accuracy. For equal applied fields, $B_{\ell=1} = B_{\ell=0}$, δ_1 is thus larger than δ_o for β values which are not too close to unity. Typical values for the Scyllac experiment are $\delta_1 \sim 1.0$, $\delta_o \sim 0.15$, $\varepsilon \sim 0.20$, and $\beta \sim 0.85$.

2. m=1 Stability. The basic decision to use the ℓ=1,0 equilibrium for Scyllac was the result of both theoretical and experimental studies. Experience with high-β, high-temperature θ pinches[38,39] has shown that, in general, only long wavelength k≈0, m=1 modes are observed experimentally. Based on this observational result, the m=1 stability of high-β helical systems was investigated using sharp boundary theory.[7,8,9] The results are given in the following dispersion relations:

$$\underline{\ell=0}:\ \gamma_o^2 = h^2 V_A^2 \frac{\beta(3-2\beta)(1-\beta)}{(2-\beta)}\ \delta_o^2 \qquad (4)$$

$$\underline{\ell=1}:\ \gamma_1^2 = 0 \qquad (5)$$

$$\underline{\ell\geq 2}:\ \gamma_\ell^2 = h^2 V_A^2 \frac{\beta(2-\beta)}{2}\ \delta_\ell^2\ , \qquad (6)$$

where V_A is the Alfvén speed, $V_A^2 = B_o^2/4\pi\rho_o$. Note that to leading order in ε the ℓ=1 configuration is stable. It should be pointed out that these dispersion relations are based upon an expansion in which both ε and δ are assumed small, with relative ordering $\delta << \varepsilon \leq 1$. Henceforth this ordering will be known as the "old ordering."

Further theoretical studies[10] with diffuse profiles indicate that the vanishing of the leading order destabilizing term for ℓ=1 is not pathological to sharp boundary profiles, but occurs for a wide class of profiles satisfying the very weak condition

$$\frac{1}{B(r)}\ \frac{dB(r)}{dr} > 0\ , \qquad (7)$$

where B(r) is the toroidal (θ-pinch) field.

a. ℓ=1 Growth Rates

(i) Old Ordering. Since the decision to make Scyllac basically an ℓ=1 system, a great deal of effort has been devoted to calculating the higher order terms in the m=1 dispersion relation.[11-13] At present all the relevant terms have not been simultaneously calculated. Nonetheless we can piece together a dispersion relation, keeping in mind that further theoretical work is required. By optimizing the harmonic content, using Weitzner's prescription,[14] the ℓ=1, m=1 dispersion relation for the old ordering is given by

$$\gamma_1^2 = h^2 V_A^2 \left[-\beta^2\left(\frac{a}{b}\right)^4 + \frac{\beta(4-3\beta)(2-\beta)}{8(1-\beta)}\varepsilon^2\right] \delta_1^2 , \quad (8)$$

where a/b is the ratio of plasma to wall radius.

The first term in Eq. (8) is a wall-stabilization term which is very sensitive to a/b. In conventional θ pinches its effect is usually negligible, due to the small a/b values. A main purpose of the staged θ-pinch experiment at LASL is to increase a/b to several tens of percent, in which case wall-stabilization effects should become important.

A possible test of Eq. (8) is proposed in Sec. I. F. of this proposal, which deals with plasma injection experiments to produce high-temperature plasma columns with large a/b ratios.

The second term in Eq. (8) is a weak destabilization term arising from bad ℓ=1 field curvature. Again, the apparent singularity as β approaches unity is an artifact of the approximations used.

(ii) New Ordering. The old ordering of $\delta \ll \varepsilon \gtrsim 1$ is not the best choice for Scyllac since it is numerically violated for the Scyllac parameters $\delta_1 \sim 1$ and $\varepsilon \sim 0.2$. This led Weitzner[13] to devise a new expansion, hereafter referred to as the "new ordering," in which $\varepsilon \ll \delta \le 1$. This ordering yields an ℓ=1 growth rate of different functional dependence than the old ordering:

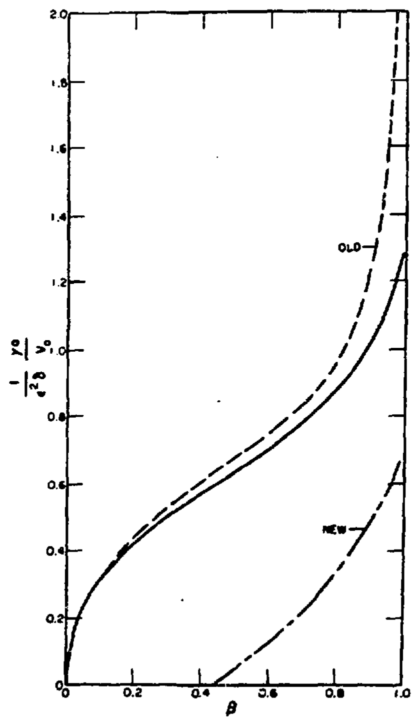
$$\gamma_1^2 = h^2 V_A^2 \left[-\beta\left(\frac{a}{b}\right)^4 + \frac{\beta^5}{32(2-\beta)}\delta_1^2\right] \delta_1^2 . \quad (9)$$

For the Scyllac parameters quoted above, the destabilizing term of Eq. (9) is approximately 1/4 that of Eq. (8).

(iii) Noncircular Cross Sections. Using the new ordering, Weitzner[13,14] has extended the above analysis, which assumes perfectly circular plasma cross sections, to the more general case of slightly elliptical cross sections. This case corresponds to the absence of any ℓ=2 harmonic in the vacuum region (i.e., there is a small ℓ=2 source current in the plasma). Weitzner's analysis shows that the plasma can be m=1 stable by conducting walls located at any finite position.

(iv) Higher Ordering. Freidberg[12] has developed a theory based on the new ordering which carries the ordering one term further in ε^2 and removes the restriction $\delta \le 1$. Thus this theory includes leading and first-order terms in ε^2 and arbitrary δ. The growth rates are calculated numerically.

The results indicate that the higher order corrections to the new ordering dominate in the parameter range of experimental interest. Surprisingly (but conveniently) the ℓ=1 growth rates are very close to those predicted by the old ordering, as shown in Fig. 1.



Growth rate vs. β curve for b/a>4, 0.1<ε<0.2 and 0.2<δ<1.

Fig. 1. Theoretical growth rates for the ℓ=1 instability. The solid curve is from the Freidberg numerical calculation.

The calculation suffers from the deficiency of requiring a circular cross section, which as Weitzner showed, is not the optimum.

(v) Diffuse Profile Calculations. No diffuse profile growth rates have yet been obtained for the $\ell=1$ case, but the problem is currently studied by Freidberg and Berge.

b. $\ell=0$ Growth Rates.

(i) Sharp Boundary Theory. The sharp boundary calculation of Haas and Wesson[15] (1967) assumes $\delta_o << 1$, but does not require knowledge of the relative size of ε and δ, since the growth rate appears in leading order. The resulting calculation of γ_o is therefore valid for both the old and the new ordering:

$$\gamma_o^2 = h^2 V_A^2 \frac{\beta(3-2\beta)}{(2-\beta)} \left[1 - \beta(1 + \frac{a^2}{b^2})\right] \delta_o^2 . \qquad (10)$$

Here we have retained only the most important wall-stabilization term, namely the one which can change the sign of γ_o^2 and hence cause a transition from stability to instability. In conventional θ pinches, $(a/b)^2$ is very small, of order 10^{-2}, and may be neglected, giving

$$\gamma_o^2 = h^2 V_A^2 \frac{\beta(3-2\beta)(1-\beta)}{2-\beta} \delta_o^2 . \qquad (11)$$

Combining this equation with Eq. (3) yields

$$\gamma_0^2 = h^2 V_A^2 \frac{\beta(3-2\beta)}{4(2-\beta)(1-\beta)} \left(\frac{B_{\ell=0}}{B_o}\right)^2 . \qquad (12)$$

As has been remarked above, the unphysical singularity as $\beta \to 1$ disappears both in the more correct ε-dependent result of sharp boundary theory as well as in diffuse profile theories.

(ii) Diffuse Profile Theory.

(1) Analytic Results. A recent calculation by Weitzner[16] treats the stability of the bumpy pinch, also in the $\delta_o << 1$ limit, but for diffuse profiles. The profiles chosen by Weitzner were of Gaussian shape. The resulting dispersion relation is of the form

$$\gamma_o^2 = h^2 V_A^2 \delta_o^2 F(\beta, a/b) . \qquad (13)$$

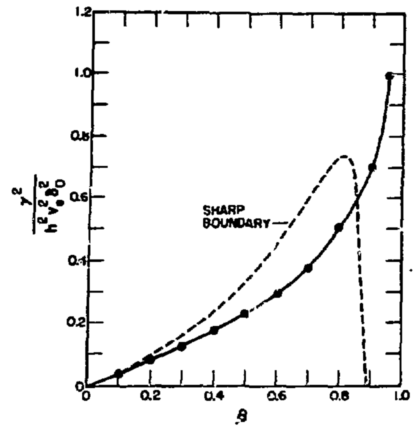


Fig. 2. Growth rates for the $\ell=0$ instability according to three theories, Haas-Wesson (dashed), Weitzner (dots), and Freidberg-Marder (solid), for $b_o/a_o = 2.5$.

The function F (β, a/b) has been tabulated by Weitzner by numerically solving a coupled set of ordinary differential equations.

(2) Numerical Calculations. More recently, Freidberg and Marder[17] have computed diffuse profile $\ell=0$ growth rates numerically for the case of arbitrary δ_o. The profile they chose was the rigid rotor, which is identical to a Gaussian in the limit of low-β, and for high-β is nearly identical even though the functional dependence is different.

The results of these three γ_o calculations are presented graphically in Fig. 2. The Freidberg-Marder theory and the Weitzner analytic theory show excellent agreement over the whole range of β in the small δ_o limit. However, the diffuse theories differ significantly from the sharp-boundary theory at high β, showing neither the wall-stabilization effect predicted by sharp-boundary theory, nor the catastrophe at $\beta = 1$. In both diffuse theories there is no wall stabilization if the plasma extends to the wall, even with exponentially small density. There is a reduction in growth rate as a/b increases, but no transition from instability to stability.

It is for this reason that the wall stabilization term in the sharp boundary growth rate theory is usually dropped when Eq. (10) is used.

3. Variable ϵ Experiments on Scylla IV-3. Two earlier experimental studies[1,2,3] of ℓ=1 and ℓ=0 growth rates will now be briefly reviewed. These experiments were carried out on the 3-meter linear theta-pinch Scylla IV-3. The results were not in complete agreement with sharp boundary instability theory. This is in contrast to the situation with sharp boundary equilibrium theory, which correctly predicts Scyllac equilibrium plasma parameters to within about 10%.

a. Summary of Experimental Results. A series of experiments[1,2] to study the $F_{1,0}$ body force used for the Scyllac equilibrium was conducted on the Scylla IV-3 device in 1971. In these experiments the ℓ=0 field was produced by capacitor-driven feedback coils[18,19] and the ℓ=1 field was produced by square helical grooves or capacitor-driven bifilar windings.[18,19] The resulting fields were not pure ℓ=1 or ℓ=0. The estimated harmonic content was of the order of 30%.[20] Although these experiments were concerned primarily with verifying the theoretical scaling of the $F_{1,0}$ force, some ℓ=1, m=1 growth rate studies were also carried out. The plasma beta was varied by applying a bias magnetic field of a few hundred gauss in the same direction as the main compression field of 42 kG. The corresponding variations in the ℓ=1 growth rate were found to lie somewhere between the predictions of sharp boundary theory for the old ordering [Eq.(8)] and the new ordering [Eq.(9)].

A second series of experiments[3] was carried out on Scylla IV-3 in 1973 to study the effects of variable ϵ (ha) on the growth rates. No beta scaling was done in these experiments. The ℓ=1 field was produced by grooving the inside surface of the compression coil to coincide with a computer-designed ℓ=1 flux surface. This allowed ℓ=1, m=1 growth rates to be studied in a mathematically "exact" ℓ=1 field, of the type used on Scyllac. The ℓ=0, m=1 growth rate was also studied, using another compression coil in which the ℓ=0 field was produced by square annular grooves. The harmonic content in this case was about 15% of the periodic field on axis.[20] These preliminary results indicated an ℓ=1 growth rate approximately 1-2 times larger than predicted by sharp boundary theory [Eq. (8)], and an ℓ=0 growth rate approximately 1-2 times smaller than predicted by sharp boundary theory [Eq. (10)]. The predicted scaling with ϵ was observed in the ℓ=1 growth rate experiments, but the ℓ=0 growth rate experiments were inconclusive in this regard due to the onset of end effects before the instability could become well developed in the longer wavelength case (λ = 90 cm).

4. Lessons for Scylla IV-P. The exploratory studies on Scylla IV-3, while preliminary in nature, have been very valuable in defining problem areas, in both machine operation and plasma diagnostics, which must be overcome for successful growth rate measurements. Some of the conclusions which have been drawn from the Scylla IV-3 experience are:

a. Use of pure ℓ=1 and ℓ=0 fields. Pure fields are needed to match the experiments more closely to the theory, and also to duplicate Scyllac conditions. Techniques have already been developed which allow the machining of computer-generated flux surfaces in the compression coil.

b. Easily changeable compression coils. Numerous front end coil changes will be required in order to vary the wavelength and field strength of the ℓ=1 and ℓ=0 fields.

c. Long machine. In order to delay end effects as long as possible, the machine should be made as long as is consistent with the available bank energy.

d. Control of discharge tube position. In order to measure widely variable growth rates in an Alfvén time, which is essentially fixed by the machine length at 5-10 μsec, the plasma instability motion must be controlled. This is most easily done through the parameter ξ_o, i.e., the initial displacement away from the equilibrium position, by varying the position of the discharge tube with respect to the field axis. Attainment of $k\approx 0$, m=1 motion can be accomplished in the same manner.

e. Extensive diagnostic facilities. In addition to the usual theta-pinch diagnostics (see Sec. I. G.), the variable ϵ studies require some special diagnostic techniques. Tube position must be accurately controlled to within less than 1 mm in both transverse coordinates. Simultaneous luminosity measurements at two axial positions are necessary to measure δ_1 accurately. The ℓ=0 measurements must be made at several axial locations in order to study the plasma bump structure and time-dependent approach to axial pressure equilibrium, and also possible axial variations in the m=1 growth rate (ballooning modes). This involves luminosity measurements of the plasma radius, balanced probe measurements of the excluded flux and beta, and side-on laser interferometry for local density measurements. End-on ruby laser holography will be of somewhat limited value in the $\ell=0$ experiments, due to the presence of the plasma bumps, but in the $\ell=1$ experiments will allow a valuable crosscheck on the plasma radius and helical shift measurements furnished by the luminosity.

In summary, the conclusions from the Scylla IV-3 experience are that quantitative growth rate measurements are possible in a linear machine provided (1) carefully controlled experiments are performed, (2) the machine is long enough (large bank energy) to delay end effects for 5-10 μsec, (3) extensive diagnostics are available, and (4) the machine can accommodate numerous front end changes to vary h and B_ℓ/B_o.

The Scylla IV-P experiment has been specifically designed to satisfy these requirements.

5. Objectives of Variable-ε Scaling Experiments. Future theta-pinch experiments beyond Scyllac will likely be large major-radius devices employing wall stabilization against the destabilizing effects (terms) of bad curvature from the small $\ell=1$ and $\ell=0$ field components required for toroidal equilibrium. In order to design these experiments intelligently, the destabilizing terms for which wall stabilization must be provided need to be known accurately. This would include knowing the scaling of γ_1 and γ_o as a function of the δ_ℓ, field ratio B_ℓ/B_o, and plasma β, as well as any predicted wall stabilizing parameters.

C. Finite-Ion-Gyration Effect Stabilization of MHD Modes.

1. Rationale for Gyro-Stabilization Experiments on Scylla IV-P. Historically, the theoretical analysis of high-beta configurations has been predominantly based upon the plasma model furnished by ideal magnetohydrodynamics (MHD). The need for such a simplification lies in the great complexity of self-consistent high-beta equilibria. Yet the model is clearly incomplete, as follows immediately from the fact that it provides a physically reasonable description for the evolution and growth of only the m=1 mode, the gross lateral displacement motion. For such a mode the MHD theory gives predictions in approximate agreement with experiment. For the modes with higher m-numbers, which describe higher harmonics of azimuthal deformation of the plasma column, ideal MHD theory predicts larger growth rates than for the m=1 mode, yet such instabilities are not observed experimentally. The high-beta theta-pinch experiments with parameters of interest to the CTR program[21,22,23] maintain hot ions which are nearly collisionless and have finite gyro-orbits, and thus it cannot be expected that MHD theory should apply to any but the gross lateral displacement modes in these devices.

Much work has therefore been done to improve the theoretical model by incorporating a physically appropriate description of the $m\geq2$ modes. The improved model[24] treats the ions through the Vlasov equations and the electrons through a fluid equation, and thus retains finite-ion-gyration effects in the description. We summarize the basic results, which not only are physically reasonable but have great potential implications for the future direction of the Scyllac and the toroidal theta-pinch reactor programs.

We define a dimensionless parameter

$$\zeta \equiv (1-\beta)^{1/2}\, a/r_L \qquad (14)$$

which measures finite-ion Larmor radius effects. Here $\beta = 1 - B_{int}^2/B_{vac}^2$, B_{int} and B_{vac} are the internal and vacuum theta-pinch fields, $r_L = (2T_i/m_i\,\omega_c^{\,2})^{1/2}$ is the thermal ion gyroradius for ions of mass m_i, temperature T_i, and gyrofrequency ω_c, and a is the plasma column radius. Furthermore, let γ_m be the MHD growth rate for modes with $m \geq 2$ and let $v_T = (2T_i/m_i)^{1/2}$ be the ion thermal speed. The most interesting ordering of these quantities, which is obeyed by the physical parameters of most hot, high-beta experiments, is given by the inequality

$$\frac{4\gamma_m}{v_T/a} \ll \frac{1}{\zeta} \ll 1. \qquad (15)$$

Under these conditions the finite-gyration-effect stabilization is operative, and the plasma beta is reasonably high. The growth rate γ as given by the improved Vlasov-fluid model then is approximately

$$\frac{\gamma}{\gamma_m} \cong 2\pi^{1/2} \frac{\gamma_m}{v_T/a} \zeta^2 \exp(-\zeta^2) . \qquad (16)$$

Thus for sufficiently large ion Larmor radius the growth rates for unstable MHD modes become drastically reduced. Numerical simulation studies[25] of the same Vlasov-fluid model have corroborated this important conclusion.

In the Scyllac configuration small $\ell=1$ helical magnetic fields are superimposed on a high-beta theta-pinch column. Ideal MHD predicts a growth rate for the m=2 mode given by

$$\gamma_m^2 = (v_A^2/a^2) [\beta^3/2 (2-\beta)] \epsilon^2\delta_1^2 , \qquad (17)$$

where $v_A^2 = B_{vac}^2/4\pi \rho_o$ and the remaining symbols are as previously defined. For target experimental values (B=70 kG, T_i=2 keV, a=0.75 cm, β=0.75, δ_1=0.8 and ϵ=0.14) we find $\tau=1/\gamma_m$=0.3 μsec. This growth time is a third of that for the m=1 mode, but it is not observed experimentally. Since inequality (15) is satisfied by the parameter values, we may apply Eq. (16) and obtain a Vlasov-fluid prediction of the growth time as τ=740 μsec, so that the m=2 mode is effectively stabilized as far as experimental detection is concerned.

Since the right-hand part of inequality (15) is experimentally satisfied under most situations, the condition that the m=2 mode in the Scyllac configuration be effectively stabilized becomes

$$(r_L/a)^2 > [8\beta^2 (1-\beta)/(2-\beta)] \epsilon^2 \delta_1^2 . \qquad (18)$$

Even from a purely scientific standpoint it will be useful and productive for the proposed Scylla IV-P experiment to check these predictions. But the implications for the Scyllac and follow-on programs are even more important if it turns out that wall stabilization is necessary to control the m=1 mode of a toroidal theta pinch. For a toroidal equilibrium obtained through the application of $\ell=1$ and $\ell=0$ fields, the theoretical condition for wall stabilizing the gross m=1, long-wavelength mode is given by[26,27,29,30]

$$\delta_1^2 \left(\frac{a}{b}\right)^4 \geq \frac{(4-3\beta)(2-\beta)}{8\beta(1-\beta)} \epsilon^2\delta_1^2 + \frac{(3-2\beta)(1-\beta)}{\beta(2-\beta)} \delta_o^2 , \qquad (19)$$

where b is the coil radius. The physical basis for the stabilization is the induction of wall image currents in the toroidal direction by the $\ell=1$ dipole currents in the plasma column, and the resultant restoring force on the column.

If these two constraints are combined with the condition for toroidal equilibrium

$$\delta_o\delta_1 = \frac{2}{(3-2\beta)\epsilon hR} \qquad (20)$$

where R is the major toroidal radius and h is the axial wavenumber of the auxiliary fields, then severe limits bracket the allowable values of r_L/a for fixed R. Alternately, to insure safe margins on both the gyration radius stabilization inequality (18) and the wall-stabilization inequality (19), a large value of R may turn out to be necessary to limit the driving force of the instability: the fourth power dependence of a/b in inequality (19) puts a premium on large a/b ratios (a/b $\cong$ 0.4 for implosion-heated "fat" plasma columns), while the value of b cannot be less than a fixed lower limit (of order 10 cm) to allow for the formation of a well-defined magnetic piston and to provide a high-enough load inductance of the implosion-heating coil for efficient energy transfer. Thus the value of a becomes stringently bounded from below. At the same time, since r_L is proportional to $T_i^{1/2} \times B^{-1}$ and thus essentially fixed by the theta-pinch parameters, inequality[18] becomes a contradictory requirement stringently limiting a from above. These considerations are quantitatively evaluated in Ref. (28), where an optimization calculation is performed to minimize the value of R as a function of a/b for given values of β, b, and r_L. For a Scyllac type of experiment with β=0.8, T_i=6 keV, b = 10 cm, δ_1=1, and B=50 kG, a major toroidal radius of about 30 m turns out to be necessary. Furthermore, the minimum permissible R has been shown to scale as $b^{8/3}$.

These considerations explain the need for performing experiments on the Scylla IV-P research device to investigate the theoretical predictions on finite-ion-gyration stabilization effects and the attendant scaling laws. Previous high-energy theta pinches have operated in a regime for which inequality (18) predicts at least marginal m=2 stability. It will be of great interest to change experimental conditions so that this inequality becomes reversed. The ratio r_L/a is not easily influenced, so that the proposed experiment would consist of increasing the value of the right-hand side, by increasing $\epsilon\delta_1$, until threshold for m=2 instability is achieved. Such a threshold would, according to theory, be marked by a dramatic appearance of bifurcations and other deformations in the shape of the plasma column.

We briefly note a final, and more speculative, justification for investigating gyro-stabilization effects on Scylla IV-P. Such stabilization, if sufficiently strong, may also have an effect on the m=1 mode. This surprising conclusion is based on the fact that for the cylindrically nonsymmetric equilibrium under consideration, the normal modes are not single cylindrical harmonics, but consist of a dominant fundamental with coupled sidebands (higher harmonics). Thus the "m=1" mode really has an m=1 fundamental and coupled sidebands with m=2 and higher. The latter, as has been pointed out above, are strongly affected by finite gyration effects. It is speculated that the entire "m=1" structure may therefore be subject to such influence. Results on the Scyllac toroidal sector experiments give plasma lifetimes limited by the onset of end effects. If the m=1 lifetime (which according to MHD theory turns out to be of the same order as the experimental sector end-effect times) proves to be greater than predicted in the Scyllac complete torus experiment, then considerable fuel will be given to this speculation, for which quantitative calculations will be made. Scylla IV-P results bearing on this question would be extremely valuable because the issue of wall-stabilized vs highly compressed plasma columns in toroidal theta-pinch reactors may hinge on these considerations.

2. Gyro-Stabilization Experiments on Scylla IV-P.

a. m=2 Stability Criterion. The m=2 FLR stability condition, Eq.(18), can be tested to see if it correctly predicts the transition from stable to unstable m=2 modes. Damped m=2 motions, manifested as plasma rotations, have been detected in the Scyllac 5-m toroidal sector[31] and Scylla IV-3[32] scaling experiments. For Scyllac parameters $kT_i \sim 1$ keV, $B \sim 50$ kG, $\beta \sim 0.8$, $a \sim 1$ cm, $\epsilon \sim .2$, $\delta_1 \sim 1$, we calculate $r_L = 0.13$ cm for a deuterium ion, and inequality (18) becomes $1.7 \times 10^{-2} > 3.4 \times 10^{-2}$, which fails to be satisfied by a factor of 2. The left side of inequality (18) can be varied experimentally over a wide range through the adjustable parameters β, ϵ, and δ_1. For example, by reducing β by a factor of ~ 3 (by using bias fields during the implosion), the left side of (18) can be reduced by an order of magnitude. Similarly ϵ and δ_1 can be varied over a wide range.

b. m=2 Growth Rates. The Vlasov-fluid model yields a growth rate for the m=2 mode which is given by Eqs. (16) and (17). It is apparent that this growth rate, for which the β, ϵ, and δ_1 dependence is

$$\gamma \sim \frac{\beta^3\,(1-\beta)}{(2-\beta)}\ \epsilon^2\delta_1^2\ \ e^{\beta-1}\ ,$$

may be tested in principle over a wide range of parameter space by varying β, ϵ, and δ_1. Whether the growth rate can be made fast enough for the mode to be detected in a 5-meter machine before end effects set in (observation time 5-10 μsec), even with large initial m=2 perturbations, is a matter which will require careful study.

D. High-Field Coil Development

1. Linear θ Pinch. The basic motivation of high-field coil development is to prepare for a viable linear back-up experiment for the toroidal Scyllac program.

It is widely accepted that the main virtues of the linear θ pinch over other configurations such as the toroidal Scyllac and Tokamak are its simplicity, ease of heating, and its desirable MHD stability properties. The problem with linear theta pinches, of course, is end loss, whereby, without mirrors, particles stream out the ends at essentially the ion thermal velocity. This in turn has led to the conclusion that in order to have sufficient plasma available during the thermonuclear burn time, exceedingly long linear theta pinches would be required. Besides being costly and difficult to site, such devices would produce enormous quantities of power, far in excess of the output of any existing power plants or present requirements.

It can be shown, however, that the use of mirrors is not the best way in which to use the maximum field (B_{max}) obtainable in a θ pinch. The argument goes as follows: if the limiting constraint is that $B \le B_{max}$ everywhere, where B_{max} is the largest magnetic field allowed by strength of materials considerations, then clearly in a θ pinch with mirror ratio R it follows that $B = B_{max}$ in the mirror throat and $B = B_{max}/R$ in the uniform field region. Because of the open ends, the confinement time τ must be less than or equal to τ_{EL}, the particle end loss time. Conventional mirror theory[33-35] predicts that τ_{EL} increases linearly with the mirror ratio; hence $\tau \sim R$. In a θ pinch at fixed temperature, pressure balance requires that n is proportional to B^2; hence $n \sim B^2_{max}/R^2$. Consequently we deduce the Lawson criterion scaling law, $n\tau \sim B^2_{max}/R$. We conclude that a linear θ pinch should operate with no applied mirrors (R=1) and consequently $B = B_{max}$ along the entire plasma column.

For a given nτ in a reactor, i.e., $n\tau = 10^{15}$ cm^{-3} sec, it is clear that the confinement time, and hence the length of the reactor, are both proportional to 1/n. In a reactor at a fixed temperature, therefore, $L \sim 1/B^2$ and $\tau \sim 1/B^2$. For example, at a density of 10^{16} cm^{-3} and a temperature of 10 keV, the required magnetic field is 90 kG, the reactor length is 24 km, and the confinement time is ~ 100 msec. At a field strength of 400 kG, however, the density would be increased to 2×10^{17} cm^{-3}, the required length reduced to only 1.2 km and the required confinement time reduced to 5 msec, i.e., by 95%.

We see that there are compelling reasons for operating a linear θ pinch at the highest possible magnetic field. In addition to cost and length considerations cited above, the reduced confinement time eliminates the pertinence of slowly growing plasma instabilities which might become important on longer time scales.

2. Laser Heating. A second motivation for the development of high-field coils stems from the possibility of using laser radiation to heat a θ-pinch plasma column. Recent studies of long wavelength laser heating by inverse bremsstrahlung in θ-pinch reactors have shown the desirability of operating linear reactors at higher plasma densities than encountered in toroidal θ-pinch reactor designs. The reason for this is the need to make the laser absorption length comparable to the reactor length. For example, at 2×10^{16} cm^{-3} density and 5-keV temperature (the approximate ignition temperature of a D-T system), the absorption length for CO_2 radiation is 60 km, compared to the reactor length of 25 km. Such a reactor, in addition to being excessively long, could probably not be heated to ignition with a CO_2 laser without placing the reactor in a 25-km-long resonant cavity.

At a field strength of 400 kG, however, the plasma density would be increased to 2×10^{17} cm^{-3} (by a factor of 20) and the absorption length decreased to only 140 m (by a factor of 400).

If the option of laser heating is desired as an alternative to magnetically heating a θ-pinch reactor, then operation at field strengths substantially above 100 kG is probably unavoidable.

3. Impedance Matching to the Bank. A development program aimed at high-field coil design will be necessary before reliable operation can be obtained in a single-turn compression coil operated much above 100 kG. Some experience in this direction has been obtained from the linear Scyllac mirror coils (16 cm long) which were made of maraging steel. These coils have been tested to about 250 kG,[36] and routinely operated at 150 kG.[37] However, in order to have a 5 m-long coil operated at 250 kG, the bore cannot exceed a few cm if the magnetic energy storage requirement is not to exceed the capacity of the proposed Scylla IV-P bank. Such a coil, long and with a small bore, has a low load inductance as seen from the bank, and the efficiency of energy transfer is correspondingly poor. In order to match efficiently the coil inductance to the bank, two approaches may be used: (a) an impedance-matching transformer located between the bank and a single-turn load coil; or (b) a multiturn load coil, which would have the required inductance.

Both of these possibilities should be explored on Scylla IV-P, and if feasible, developed in conjunction with an experimental testing program.

4. METS. It is also possible that a high-field coil, once developed, could be tested using a METS power supply, giving direct magnetic-magnetic coupling in the energy transfer system.

E. Linear Θ-Pinch Physics

The high-beta program at Los Alamos continues to maintain an interest in linear θ-pinch experiments as a backup concept to the toroidal Scyllac program. Under the heading of "linear θ-pinch physics" there is a variety of categories in which the physics requires further study before the behavior and scaling of large linear devices can be predicted with confidence. In particular, experiments utilizing the new high-field coil and operating in a density regime of 10^{17} - 10^{18} particles/cm^3 will be breaking new ground for large θ-pinch experiments, and some new physics problems can be anticipated. However, operation in the higher density regime will probably make the plasma diagnostics problem easier (see Section I. G .).

Some of the more important physics problem areas, based on present understanding, are discussed briefly below.

1. Particle End Loss. Particle end loss is probably the single most important problem for linear θ pinches. Previous experiments[38,39,37] have shown the end-loss time scaling as $L/T_i^{\frac{1}{2}}$, where L is the coil length and T_i is the ion temperature, in agreement with theory. Theory has been less successful in predicting the loss rate coefficient, which is β-dependent. For example, a two-dimensional numerical code by Gula[33] and a diffuse-profile analytical theory by Freidberg,[34,35] which was derived from an earlier sharp-boundary model proposed by Morse,[40] both predicted an end-loss time of 16-19 μsec for the linear Scyllac device without mirrors, compared to the experimental value of 11.5 μsec.[37]

The high-field coil is intended to be operated without magnetic mirrors. This should permit end-loss studies to be made in a new and interesting plasma regime.

2. Electron Thermal Conduction. At reactor lengths, axial heat conduction by electrons can become an important source of energy loss from linear θ pinches. As long as the effective velocity of thermal transport is small compared with the electron thermal velocity, electron thermal conduction is independent of density. The electron-ion energy equilibration time, which controls the heating of the electrons, is inversely proportional to density, according to Spitzer,[41] as long as the electron thermal velocity is much larger than that of the ions (which is almost always the case). A recent model by Morse[42] and numerical studies by Gula[33] have treated the electron thermal conduction problem in θ pinches, but so far the only experimental tests of the theory have been indirect, involving electron temperature measurements far from the ends of the coil.[38,37,43] The electron temperature there is only a weak function of the plasma parameters.[42] A better test of the theoretical model will require measurements of electron temperature as a function of axial position and time, $T_e(z,t)$, extending beyond the ends of the compression coil along field lines to the electron thermal attachment point.

From the standpoint of designing future linear experiments, the study of electron thermal conduction is an idea whose time has probably come.

3. Other End Effects. A general subject area which will require further study as θ-pinch plasmas tend to become longer and more energetic is the whole problem area of magnetic line attachment at the ends. In this category we include line-tying, i.e., the stabilizing effect of "freezing-in" magnetic field lines in the tube wall or mass-loading the lines with dense impurity plasmas; end-shorting, whereby the radial electric field which electrostatically contains the plasma ions when the electrons carry the current is shorted out along the discharge tube wall. End-shorting results in a transfer of the diamagnetic current from the electrons to the ions,[44,45] with a concomitant large increase in the angular momentum of the plasma column; the so-called "wobble effect,"[46,39] a long-wavelength, off-axis rotation of limited amplitude, which appears to occur in linear θ pinches of 1-m length or greater, with an onset time approximately equal to an Alfvén transit time from the ends to the middle; and impurity boil-off problems, which are associated with plasma bombardment of the walls as energetic plasma particles are lost from the ends along field lines.

Any of these potential problem areas might be expected to become more severe at the higher density and energy content associated with high-field operation of Scylla IV-P. Since these problem areas all have a common cause, namely the intersection of magnetic field lines with the discharge tube near the ends of the coil, they also have a common solution if the intersection can be removed. Two possible ways in which this might be done are by the use of a shaped discharge tube, with special "end-bubble" chambers which would attempt to parallel a magnetic flux surface, or by the use of some kind of magnetic divertor at the ends, which would bend field lines away from the tube.

The operation of Scylla IV-P in the high-density mode will allow us to address these and other problems which are pertinent to the linear θ-pinch reactor problem.

F. Plasma Injection Experiments to Test Wall Stabilization

1. Plasma Injection. It may be possible to provide a test of wall stabilization without staging[4] by using the "injection" method discussed by Marder and Siemon in Los Alamos Report LA-5399-P and illustrated in Fig. 3. Here 2-meter straight coils act as theta-pinch sources at each end of a central straight section which will be the injected region. After the initial filling of gas, the magnetic field in the central section is slowly raised to its final value. This produces a solenoidal field in the un-ionized gas. After this small-coil field is established, the fields of the main 2-meter coils are quickly brought to the same value, imploding and compressing their plasma columns in a time short compared to the injection time by end loss into the central section. This creates hot, linear theta-pinch plasmas which inject along field lines into the central section. The end sections should be sufficiently long that they continue to inject until a plasma of uniform density, temperature, and radius is established throughout the whole device.

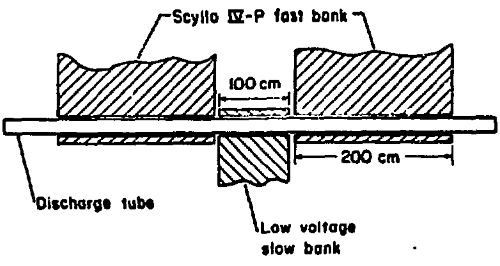


Fig. 3. Proposed injection experiment.

The magnetic field and preionization of the injected region would be separately programmed to permit study of the following questions:

- Does injection take place and lead to a uniform plasma column when the injected region contains a simple solenoidal field constant in time?
- Are instabilities observed during the injection phase due, for example, to self-mirroring in the transition region?
- What are the final plasma parameters (temperature, density, beta, radius) in the injected region?
- Is the preionization state of the injected region important?
- What complications result when the injected region has a reduced discharge tube diameter?

Studies such as these would quickly show the problem areas and feasibility of using a straight theta pinch for injection.

2. Possible Injected Wall-Stabilization Experiment. Presuming injection experiments in the straight geometry are successful, the injection method offers a powerful approach for proving the existence of wall stabilization against m=1 modes in an ℓ=1 helical field configuration.

The injected region of the above experiment could be assembled with a shaped coil to produce a helical ℓ=1 column. The transition might appear something like that shown in Fig. 4. The wall-stabilization criterion according to the original Scyllac ordering is, from Eq. (8),

$$ha \leq \left(\frac{a}{b}\right)^2 f(\beta)$$

where $h = 2\pi/\lambda$, a = plasma radius, b = wall radius,

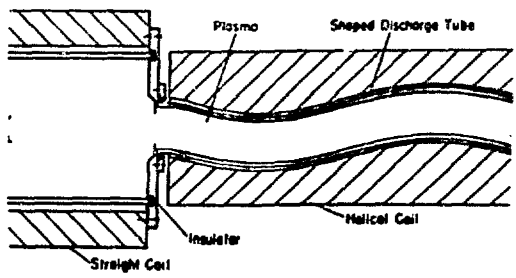


Fig. 4. Transition region of the injection experiment.

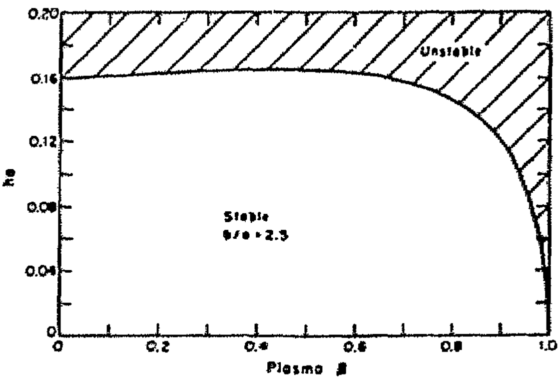


Fig. 5. Wall-stabilization criterion.

and f(β), shown in Fig. 5, is essentially unity. In a straight ℓ=1 equilibrium the m=1 motion can be wall stabilized for any given a/b by making h sufficiently small. By machining two types of coils for the injected region, the ratio a/b can be varied by changing only b of the coil. Using the following reasonable parameters we would demonstrate wall stabilization if the plasma were found stable for small b/a and unstable for large b/a.

	Stabilized	Unstabilized
Wall radius	2.5 cm	6.0 cm
Plasma radius	1 cm	1 cm
b/a	2.5	6
Magnetic field	50 kG	50 kG
Density	3×10^{16} cm^{-3}	3×10^{16} cm^{-3}
Plasma β	0.8	0.8
δ_1	0.5	0.5
$\lambda = 2\pi/h$	50 cm	50 cm
Length of injected region	100 cm	100 cm
γ_{theor}	zero	0.3×10^6 sec^{-1}

Notice that no plasma parameters are changed since it is possible to vary the wall radius in the helical region without affecting the fields created in that region. It is also important to note that a shaped discharge tube is required to create the equilibrium without appreciable density on the wall. This tube (approx. 2.3-cm outer diameter and 100 cm long) would be relatively easy to fabricate because of its small size and the very gentle curvature required by the helical fields being used.

G. Diagnostics and Diagnostics Development

1. Existing Diagnostic Techniques. The plasma measurements to be made on Scylla IV-P will mainly use conventional techniques which have been highly refined on the Scylla and Scyllac theta pinches. The ranges of plasma density and temperature often will be similar to those in Scyllac. The most useful Scyllac diagnostics are listed below. New combinations of these measurements or more simultaneous measurements may aid the ever-evolving interpretation of the data obtained.

a. Magnetic Probes. The measurement of excluded magnetic flux has become a standard ingredient of theta-pinch diagnostics. The flux excluded by the plasma is measured by a differential loop probe technique.[47,48]

b. Luminosity. The measurement of plasma luminosity as a function of radius is made with ten channels of photomultiplier light detectors.[49] This measurement has been perfected to a high degree of sophistication with respect to data analysis using automatic computer data acquisition and reduction to give relative plasma density as a function of radius. The luminosity data, when combined with the magnetic probe data, give plasma beta as a function of radial position across the column.

c. Holographic Interferometry. Holographic interferometry is a technique particularly suitable for theta pinches in which a longitudinal view is available.[50,51] The technique leads to time-resolved mapping of the plasma density. Interferometry has proved a very successful diagnostic tool in previous Los Alamos experiments.

d. Coupled-Cavity Gas Laser Interferometry. The standard coupled-cavity interferometer used so successfully on present theta pinches[48] will be directly applicable to the Scylla IV-P experiment. The measurement yields density information as a function of time.

e. Thomson Scattering. Apparatus for measuring 90° Thomson scattering has been developed recently and is being applied to Scyllac.[48] The same technique will be applicable to Scylla IV-P for making absolute plasma density and electron temperature measurements.

f. Streak Photography. The standard image converter streak cameras will be used on Scylla IV-P for measurement of gross plasma column motion and deformation.

g. Neutron Detectors. Neutron detectors, both fast scintillators and silver activation detectors, are well-developed devices which will be used routinely as they have been in the past for measurement of plasma ion temperature.

Most of the diagnostics for linear theta-pinch experiments at high magnetic fields and large plasma density (10^{17} - 10^{18} particles/cm^3) will be no more difficult than under Scyllac conditions. In some optical experiments (e.g. Thomson scattering) measurements will be easier because there will be more light available. Holographic interferometry, on the other hand, will be more difficult because the high density gradients will tend to refract the light beam out of the column.

2. New Techniques. In addition to the established methods, new diagnostics will be developed either for Scyllac or for the needs of Scylla IV-P itself. The former includes further development of Thomson scattering and the extension of sensitivity, time resolution, and flexibility of both gas laser interferometry and holographic techniques. The laser-heating experiment, in particular, would require development of a wider range of spectral emission measurements, e.g., the detection of turbulence through both infrared and visible light spectroscopy. Such techniques, in turn, may find application in implosion studies.

II. ENGINEERING DESCRIPTION

A. Design Considerations

The proposed new project, Scylla IV-P, is planned as a facility for performing a wide range of different experiments. It is necessary to plan for flexibility and easy conversion from one coil configuration to another.

The capacitor bank energy course is designed to be capable of powering all anticipated experiments with only minor changes. The bank must be capable of approximately matching the electrical parameters of Scyllac in order to make variable-ε scaling experiments meaningful, and it must also be adaptable in the extreme to producing 250-kG fields for high-density θ-pinch experiments. At the same time, the coil must be long enough so that proposed experiments are not dominated by end loss.

We have fixed on a 5-meter-long coil with an energy storage of at least 400 kJ per meter of coil length. This approximately matches the energy density in Scyllac (350 kJ in the 5-meter toroidal sector, and 420 kJ/m in the Scyllac torus, at 60 kV). This requires 600 Scyllac capacitors. More detail on the capacitor bank is given below.

Convenient experimental access is also important since the emphasis will be on accurate measurement of plasma properties. This requirement dictates that the coil be fed from one side only and rules out the capacitor rack arrangement used on the linear Scyllac experiment where the feed was from both sides.

B. Experimental Arrangement.

Space is available for the planned Scylla IV-P experiment in the basement of LASL Building SM 105. The space is popularly known as "The Pit"; it is a room 50-feet square with a 25-foot ceiling. The room was designed as a major experimental area and has existing control room and screen room facilities. In addition it has adequate electric power available. Little or no site preparation will be required.

The planned room layout is shown in Figs. 6a and 6b. The capacitor rack will be placed at the north side of the room on three levels. We plan to change from the capacitor rack construction of Scyllac to a platform construction. Platforms or floors will be built in the room to fill the north side of the room in something akin to a library-stacks configuration. This will make for more convenient access to the bank. The rack construction of Scyllac was dictated by the need for rearrangement of the bank during conversion of Scyllac to the full torus.

The experimental platform or floor will fill the south side of the room and will be placed vertically to line up with the middle capacitor level to minimize lengths of load cable. This arrangement is just as in Scyllac.

The control room, screen room, and power supplies are against the east side of the room.

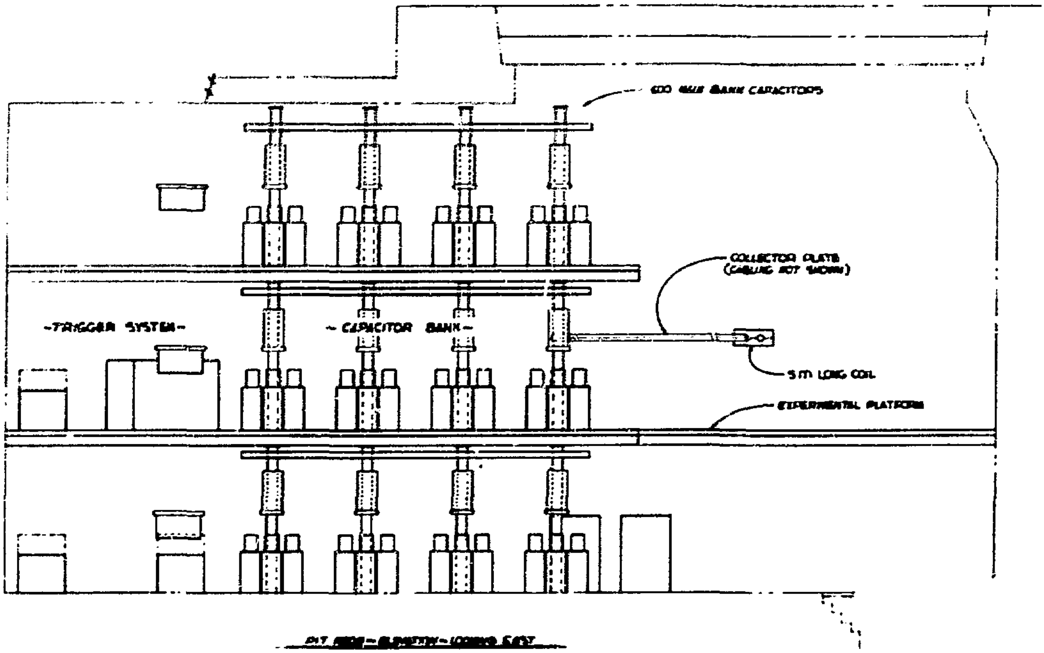


Fig. 6a. Scylla IV-P elevation.

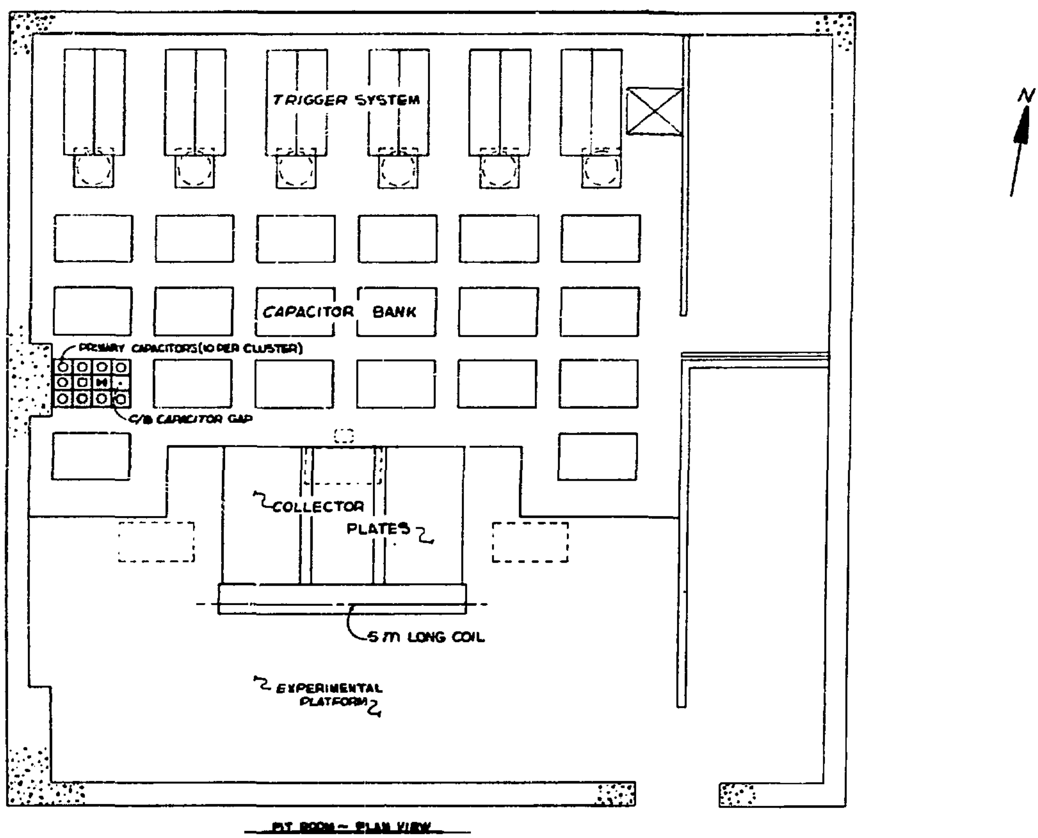


Fig. 6b. Scylla IV-P floor plan.

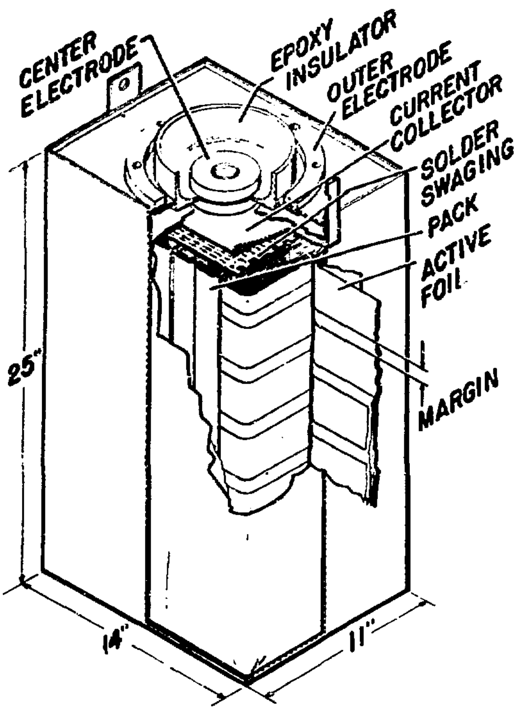


Fig. 7. Scyllac capacitor.

C. The Capacitor Bank.

The capacitor bank electrical design is based on the successful Scyllac design. We plan to use conventional components throughout except perhaps for the energy storage capacitor itself. The major components in the system are described in the following paragraphs.

1. The Capacitor. The primary bank would store 2 MJ at 60 kV, and would consist of 600 1.85-μF, 60-kV capacitors of the Scyllac type (Fig. 7). We can easily use Scyllac capacitors without any development. The bank layout is therefore planned to accommodate 600 capacitor cans. However, advances in capacit... technology now permit higher energy density than was used in the Scyllac capacitor design. We believe that the same capacitor container can be built with 2.5-3 μF at no increase in cost and still retain the necessary reliability. The LASL fusion engineering group (Q-4) plans to undertake negotiations with capacitor manufacturers to develop such a capacitor. If possible we will use the new high-energy density capacitor in Scylla IV-P. We still plan to use 600 capacitors and will thus gain about 50% in energy storage. If development of the new capacitor is delayed we will, of course, use the standard Scyllac capacitor and will still be able to meet our energy storage requirements.

2. The Spark Gap. One spark gap switch will be used for each capacitor, as in Scyllac. The spark gaps will be of the Scyllac type (Fig. 8) with no planned changes. Actual spark gap assembly will be done at LASL, as in the past, and manpower has been allocated for this in the budget projections that follow. Since the spark gap design is conventional, no problems are anticipated. The bank will be crowbarred.

3. Triggering System. The spark gap trigger system is also conventional, copied from Scyllac, and no problems are anticipated. The trigger system incorporates a master-submaster system with considerable energy storage to provide low jitter triggering. We expect about 20-ns jitter as in Scyllac.

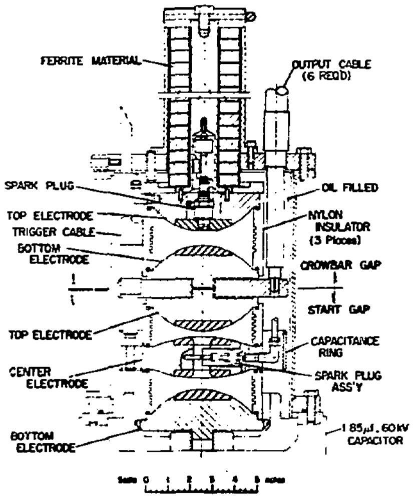


Fig. 8. Scyllac spark gap.

D. Control System and Power Supplies.

The control system and power supplies will be located on the east side of the room as shown in Fig. 6b. The power supplies, placed on two or more levels, will be in the northeast corner.

The control system will be a new design but will be based on successful Scyllac practice. LASL engineers will design and install the system. We definitely plan to include more computer control than is used in Scyllac as well as computer data acquisition.

E. Front End Design.

Several different coils are required for the various experiments proposed here: a) variable ε coils may be grooved coils similar to those used in Scylla IV-3 (Fig. 9) or they may be smooth-bore coils with added helical windings. The helical windings allow for easier changing of pitch and field strength of the ℓ=1 and ℓ=0 fields, but the fields are then not true ℓ=0 and ℓ=1 fields. In any case many field configuration changes will be required. b) The injection experiment requires a small bore coil to create the guide field region with wall stabilization, as well as conventional θ-pinch coils. Separate timing of the banks will be necessary. The construction of these coils will be conventional. c) High-field coils are required for the linear theta-pinch experiments. Multiturn small-bore coils may be necessary in order to match their impedance to the capacitor bank. The multiturn coils will probably be helically wound as shown in Fig. 10. Short sections of multiturn coils will be placed in parallel end-to-end to reach the required length. Multiturn coils for high fields have been used in small sizes by other laboratories, but they have not been used previously in LASL θ-pinch research. We anticipate a development program toward a satisfactory high-field small-bore coil. The mechanical pressure of the magnetic field at 250 kG is about 2500 atmospheres or 40,000 psi.

The scaling of such coils is simple however. The coil inductance is directly proportional to the square of its diameter, d, and to the square of the number of turns, n. Therefore, if the product nd is kept constant the coil inductance is unchanged and the maximum current and its risetime are unchanged. But the B field is directly proportional to n and it will increase with the number of turns.

Table I gives operating parameters for three possible coils, varying from a conventional 1-turn coil to a 3-cm bore 5-turn coil.

Fig. 9. Photograph of the Scylla IV-3 coil.

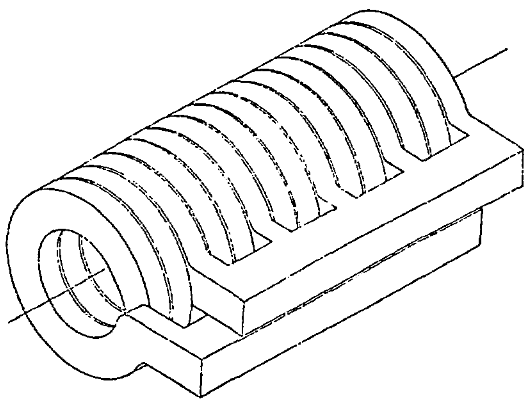


Fig. 10. Proposed multiturn coil for linear Scylla experiments.

TABLE I. PARAMETERS OF SCYLLA IV-P

Parameter	Value		
W_{bank} (60 kV)	2 MJ (3 MJ)		
C	1110 μF		
V_{bank} (operating)	50 kV		
L_{bank}	1.8 nH		
$L_{col\ plates}$	3.8 nH		
Coil length	5 m		
Coil bore	15 cm	5 cm	3 cm
No turns in coil	1	3	5
L_{coil}	21.72 nH	21.72 nH	21.72 nH
L_{total}	72.3 nH	27.3 nH	27.3 nH
α	0.8 nH	0.8 nH	0.8 nH
τ/4	3.9 μsec	3.9 μsec	3.9 μsec
B_{max}	51 kG	150 kG	250 kG

III. TOTAL ESTIMATED COST AND MANPOWER REQUIREMENTS

A. Costs by Fiscal Year

In the following tabulation (Table II) of costs for Scylla IV-P we assume that construction of the experiment is started in FY-74 and that initial construction is completed in FY-75. About 2/3 of the capacitor bank will be installed initially with the money available through FY-75. The bank will be expanded to full energy in FY-76. Total construction cost is estimated at $2.4 M. In FY-77 and following years, the experiment will be in full operation and only costs for normal operation are included.

TABLE II. SCYLLA IV-P COSTS BY FISCAL YEAR

FY-74	Initiate construction	$ 500 K
FY-75	Complete initial construction	1,300 K
FY-76	Increase bank energy	400 K
FY-76	Operation	300 K
FY-77	Operation	300 K

B. Costs by Budget Category

It is planned to construct and operate Scylla IV-P under the confinement-systems budget category. Therefore, all costs given here fall entirely in that category. Construction costs, which include major device fabrication, are given in the next section.

C. Construction Costs

The costs for construction are listed in the tables that follow. Materials and contract services, covered in Tables III and IV, come under major device fabrication. LASL design and assembly work (Table V) will be covered under normal operating funds. Costs in Tables III - VI are total costs summed over three fiscal years, FY-74-76.

TABLE III. MATERIAL COSTS FOR SCYLLA IV-P (MDF)

Item	Cost
Capacitors	$365 K
Spark gaps	285
Collector plate and coils	160
Cables	200
Trigger system	90
Charge system	35
Control system	20
Structural	50
Discharge tubes	25
Vacuum system	20
TOTAL MATERIAL	$1250 K

TABLE IV. CONTRACT LABOR FOR INSTALLATION OF THE EXPERIMENT (MDF)

Item	Cost
Structural	$ 20 K
Capacitor installation	15
Capacitor cabling	75
Air system	40
Charge system	25
Trigger system	65
Support crafts, utility modifications	25
TOTAL INSTALLATION	$265 K

TABLE V. DESIGN AND ASSEMBLY BY LASL PERSONNEL, INCLUDING INDIRECT COSTS

Design and drafting	$ 65 K
Electrical engineering	100
Spark gap assembly	55
Assembly of bank components	55
Component testing	13
Control system	40
Front end design and assembly	80
TOTAL LASL WORK	$408 K

TABLE VI. CAPITAL EQUIPMENT REQUIREMENTS

Computerized spark gap monitor	$ 45 K
Oscilloscopes	48
Main bank power supply	16
Vacuum pumps	10
Streak cameras	50
Air compressor	5
Computer control system	100
TOTAL CAPITAL EQUIPMENT	$274 K

Costs for construction are summarized in Table VII, listed by budget category.

TABLE VII. SUMMARY OF SCYLLA IV-P CONSTRUCTION COSTS

1. Major device fabrication :	
Material	$1250 K
Contract labor	265
2. Operating funds, including overhead:	
LASL manpower	$ 408 K
3. Contingency @ 15% :	$ 288 K
Total construction cost	$2211 K
4. Capital equipment:	$ 274 K

D. Operating Costs of the Experiment, FY-76

The cost of operating the Scylla IV-P experiment after construction is complete is given in Table VIII. We propose to staff the experiment with an operating crew consisting of one engineer, one physicist, and four technicians. In addition to the permanent operating crew, various experimental physicists and their supporting technicians will perform measurements on the facility. We estimate one experimental physicist and one technician will be required on the average.

TABLE VIII. OPERATING COSTS PER YEAR INCLUDING OVERHEAD

Operating crew	
1 Engineer	$ 55 K
1 Physicist	55
4 Technicians	110
Experimental support	
1 Physicist	55
1 Technician	25
TOTAL OPERATING COSTS, PER YEAR	$300 K

IV. MILESTONES

The Scylla IV-P device is intended to be a flexible research experiment whose major goals lie in program-directed, scientific and engineering areas. The primary immediate emphasis will be placed on accomplishing the research objectives outlined in Section I, with highest priority given to the "variable-epsilon" scaling experiments which are expected to have immediate impact on the toroidal theta-pinch PTR program.

Beyond the research objectives of Section I there will certainly arise the need and opportunity for further investigations prompted by a rapidly changing and developing high-beta confinement program. Scylla IV-P is therefore envisioned to be open-ended in its research scope as well as in its physical geometry.

Major milestones and time schedules for the immediate portion of the experiment are suggested as follows:

Approval to initiate construction:	January 1974
Completion of initial construction:	April 1975
First results on "variable-epsilon" scaling experiments:	August 1975

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