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

by

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SUPPLEMENT TO LASL REPORT LA-5474-P:
PROPOSAL FOR THE CONSTRUCTION OF A SCYLLA IV-P
CONFINEMENT STUDIES THETA PINCH

by

W. R. Ellis, J. P. Freidberg, and W. E. Quinn

ABSTRACT

A 2-MJ, 5-meter-long linear theta-pinch experimental facility, called Scylla IV-P, has been proposed to obtain important physical and technological data in support of the LASL high-beta confinement program. The original proposal is contained in Los Alamos Scientific Laboratory report LA-5474-P (Dec. 1973).

This report is intended to supplement LA-5474-P. It contains additional new information on the numerical values of the $m = 1$ and $m = 2$ growth rates expected in Scylla IV-P, and has expanded, updated timetables for the machine design, construction, and operational schedules.

I. INTRODUCTION

This report is an addendum to Los Alamos Scientific Laboratory report LA-5474-P "Proposal For the Construction of a Scylla IV-P Confinement Studies Theta Pinch." The additional information contained herein is presented at the request of the Scylla IV-P Review Panel.

The following subjects are addressed: plasma parameters and numerical values of the growth rates ($m = 1$ and $m = 2$ modes); the measurements required of the diagnostics; design, construction, and experimental schedules; clarification of the personnel requirement, personnel availability, and effects of personnel assignments to Scylla IV-P on the overall LASL CTR program; and scheduling priorities of the various proposed experiments.

The construction schedule has been accelerated from the one given in LA-5474-P to allow for the completion of construction and checkout by April 1975, when the first plasma experiments are due to begin. We are proposing to increase the operating staff by the addition of a BS/MS physicist (a new hire in FY-75), and the operating costs have accordingly been revised.

II. VARIABLE-EPSILON EXPERIMENTS

By "variable-epsilon experiments" we mean scaling experiments concerned with measuring growth rates and plasma distortions relevant to the Scyllac configuration. Experimentally it is not yet clear whether plasma confinement in Scyllac is limited by a loss of equilibrium or a loss of stability, or both.^{1,2} Theoretically, however, $m = 1$ instabilities are predicted when either $k = 1$ or $k = 0$ fields are added to a straight theta pinch, and such instabilities have been observed and measured on the linear 3-meter theta-pinch Scylla IV-3.³⁻⁷

Future toroidal theta-pinch experiments beyond Scyllac are likely to be large major radius devices employing wall stabilization against the destabilizing effects of bad curvature from the small $k = 1$ and $k = 0$ equilibrium fields. In order to design these experiments with confidence, the destabilizing effects for which wall stabilization must be provided need to be known accurately. The magnitudes of the plasma surface distortions also need to be known accurately since shaped discharge tubes are a possibility for next-generation experiments.

We propose a detailed parametric study of the $m = 1$ growth rates γ and plasma surface distortions

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δ_2 to be carried out in a systematic series of experiments on Scylla IV-P. The end product of such a study will be a set of empirical curves which show the parametric variation of γ_k and δ_2 as functions of the various experimental variables. These are discussed below.

In addition to empirical design data, the variable-epsilon scaling experiments will allow critical comparisons to be made between various competing theories for the growth rates. This should lead to a better understanding of the strengths and limitations of the theoretical models used.

A. $\ell = 1$ Scaling Experiments

According to sharp-boundary theory,⁸⁻¹⁰ the $\ell = 1$ configuration is neutrally stable in leading order in ϵ ($\epsilon = ha$, where $h = 2\pi/\lambda$ is the axial wave-number and a is the unperturbed plasma radius), but unstable in higher order. Two competing theories have been formulated analytically.

1. Old Ordering. According to sharp-boundary theory for the "old ordering" ($\delta_1 \ll \epsilon < 1$), the $\ell = 1$, $m = 1$ growth rate is given by¹¹

$$\gamma_1^2 = h^2 v_A^2 \left[\frac{\beta(4-3\beta)(2-\beta)}{8(1-\beta)} \right] \epsilon^2 \delta_1^2 \quad (1)$$

where $v_A = B_0/(4\pi p)^{1/2}$ is the Alfvén speed and δ_1 is the normalized helical plasma distortion,

$$\delta_1 = \frac{1}{\epsilon(1-\beta/2)} \left(\frac{B_{\ell=1}}{B_0} \right) \quad (2)$$

If we assume that the plasma particle number density is equal to the filling density (n_0) multiplied by the compression ratio (an assumption verified by many previous experiments on Scylla IV-3),⁷ then the column mass density is given by

$$\rho_0 = m_i n_i = m_i n_0 \left(\frac{R_t}{a} \right)^2 \quad (3)$$

where $m_i = 3.34 \times 10^{-24}$ g is the mass of a deuterium ion and R_t is the tube radius. The filling density (at 20° C) is related to the filling pressure by

$$n_0 = 7 \times 10^{13} P(\text{mtorr}) \text{ cm}^{-3} \quad (4)$$

where a factor of 2 has been included for molecular dissociation. Combining Eqs. (1) - (4) yields the

$\ell = 1$ growth rate in terms of experimentally measurable quantities:

$$\gamma_1 = \frac{4.09 \times 10^7}{\sqrt{P}} \frac{B_0 a}{\lambda R_t} \left[\frac{\beta(4-3\beta)(2-\beta)}{(1-\beta)(1-\beta/2)^2} \right]^{1/2} \left(\frac{B_{\ell=1}}{B_0} \right) \quad (5)$$

(γ_1 in sec^{-1} for B_0 in kG, a , λ , and R_t in cm, and P in mtorr.)

In terms of the $\ell = 1$ wavelength and field strength, Eq. (5) predicts that γ_1 scales as $\frac{1}{\lambda} (B_{\ell=1}/B_0)$. In any given experiment, these quantities are determined by the experimenter. For example, Fig. 1 shows two computer-designed $\ell = 1$ coils which were used during preliminary $\ell = 1$ scaling experiments on Scylla IV-3.⁷ The inside surfaces of these coils are machined to be exact $\ell = 1$ surfaces, producing essentially "pure" $\ell = 1$ fields. Pure fields are required to (1) duplicate Scyllac conditions, and (2) allow experimental comparisons with theory. In the case of the two coils shown, the wavelengths and field strengths were chosen to keep the quantity $\frac{1}{\lambda} (B_{\ell=1}/B_0)$ equal to a constant.

Typical parameter values for the Scyllac experiment are $B_0 = 50$ kG, $a = 1.0$ cm, $\lambda = 42$ cm, $R_t = 4.4$ cm, $P = 15$ mtorr, $\beta = 0.8$, and $(B_{\ell=1}/B_0) = 0.06$. Substituting these numbers into Eq. (5) yields $\gamma_1 = 0.79 \times 10^6 \text{ sec}^{-1}$ on the old ordering theory.

The old ordering is not necessarily the correct ordering to use for Scyllac, however. Substituting our parameter values shows that for Scyllac $\epsilon = 0.15$ and $\delta_1 = 0.67$, which fails to satisfy the $\delta_1 \ll \epsilon \leq 1$ criterion.

This fact led Weitzner¹² to devise a new expansion, hereafter referred to as the "new ordering."

2. New Ordering. According to sharp-boundary theory with the "new ordering" ($\epsilon \ll \delta_1 \leq 1$), the $\ell = 1$, $m = 1$ growth rate is given by¹¹

$$\gamma_1^2 = h^2 v_A^2 \left[\frac{\beta^5}{32(2-\beta)} \right] \delta_1^4 \quad (6)$$

which, following the procedures outlined above, can be written in terms of experimental quantities as:

$$\gamma_1 = \frac{5.18 \times 10^5}{\sqrt{P}} \frac{B_0 \lambda}{a R_t} \left[\frac{\beta^5}{(2-\beta)(1-\beta/2)^4} \right]^{1/2} \left(\frac{B_{\ell=1}}{B_0} \right)^2 \quad (7)$$

[same units as Eq. (5)]. Since this equation predicts that γ_1 scales as $\lambda (B_{\lambda=1}/B_0)^2$ in terms of the wavelength and field strength of the $\lambda = 1$ field, the theoretical growth rate for coil B in Fig. 1 is eight times larger than the growth rate for coil A. Under the old ordering, of course, the two growth rates should theoretically be equal. By means of parameter variations such as these, the experimenter can derive empirical scaling laws and determine which theory, if any, best fits the data.

Substituting the Scyllac parameters used above, we calculate $\gamma_1 = 0.33 \times 10^6 \text{ sec}^{-1}$ on the new ordering, which is about a factor of 2.4 smaller than the old ordering theory would predict.

Typical parameters for the $\lambda = 1$ experiments are given in Table I.

TABLE I
TYPICAL PARAMETERS FOR SCYLLA IV-P $\lambda = 1$ SCALING EXPERIMENTS

$B_{\lambda=1}$ B_0	λ	B_0	P	R_t	b	a	n	T_e	T_i	β	δ_1	Old Ordering γ_1	New Ordering γ_1
(cm)	(cm)	(kG)	(mtorr)	(cm)	(cm)	(cm)	(cm ⁻³)	(keV)	(keV)			(sec ⁻¹)	(sec ⁻¹)
0.06	42	50	15	4.4	6.0	1.0	2×10^{16}	0.6	2.5	0.8	0.67	0.79×10^6	0.33×10^6
0.06	21	50	15	4.4	6.0	1.0	2×10^{16}	0.6	2.5	0.8	0.33	1.58×10^6	0.17×10^6
0.03	42	50	15	4.4	6.0	1.0	2×10^{16}	0.6	2.5	0.8	0.33	0.40×10^6	$.084 \times 10^6$
0.03	21	50	15	4.4	6.0	1.0	2×10^{16}	0.6	2.5	0.8	0.17	0.79×10^6	$.042 \times 10^6$

A

B

Fig. 1. Computer-designed $\lambda = 1$ coils used on Scylla IV-3.

$$A. \quad \lambda = 15 \text{ cm}, \quad \left(\frac{B_{\lambda=1}}{B_0} \right) = 0.03$$

$$B. \quad \lambda = 30 \text{ cm}, \quad \left(\frac{B_{\lambda=1}}{B_0} \right) = 0.06$$

B. $\lambda = 0$ Scaling Experiments

According to sharp-boundary theory,¹³ the $\lambda = 0$ configuration is unstable in leading order. We therefore do not require knowledge of the relative size of ϵ and δ_0 . In order to keep γ_0 relatively small, however, i.e., of the same order of magnitude as γ_1 it is necessary to have $\delta_0 \ll \delta_1$. The maximum value of δ_0 is unity, corresponding to a completely "pinched-off" column. If we make the reasonable assumption $\delta_0 \ll 1$ we obtain the following result for γ_0 , valid for both the old and the new ordering:

$$\gamma_0^2 = h^2 v_A^2 \frac{\beta(3-2\beta)}{(2-\beta)} \left[1 - \beta \left(1 + \frac{a^2}{b^2} \right) \right] \delta_0^2, \quad (8)$$

where b is the (metal) wall radius, and δ_0 is the plasma "bump" amplitude, normalized to the plasma radius a :

$$\delta_0 = \frac{1}{2(1-\beta)} \left(\frac{B_{\lambda=0}}{B_0} \right). \quad (9)$$

In Eq. (8) we have retained only the most important wall stabilization term, namely the one which can change the sign of γ_0^2 and hence cause a transition from stability to instability. In the proposed variable-epsilon experiments, $(a/b)^2$ will be very small, of order 10^{-2} , and may be neglected. In analogy with the procedures developed in Sec. II-A, we can express the sharp-boundary growth rate γ_0 (for either the old or the new ordering) in terms of directly measurable quantities:

$$\gamma_0 = \frac{5.79 \times 10^7}{\sqrt{\beta}} \frac{B_0 a}{\lambda R_t} \left[\frac{3(3-2\beta)}{(2-\beta)(1-\beta)} \right]^{1/2} \left(\frac{B_{\lambda=0}}{B_0} \right) \text{sec}^{-1} \quad (10)$$

[same units as Eq. (5)]. Assuming $(B_{\ell=0}/B_0) = 0.06$ and taking the same Scyllac parameters as before yields $\gamma_0 = 0.52 \times 10^6 \text{ sec}^{-1}$ and $\delta_0 = 0.15$. In terms of the $\ell = 0$ field strength and wavelength, the growth rate scales as $\frac{1}{\lambda} (B_{\ell=0}/B_0)$, i.e., analogous to the $\ell = 1$ growth rate, based on the old ordering.

Typical parameters for the $\ell = 0$ experiments are given in Table II.

C. Experimental Techniques for Measuring Growth Rates

The approximate range of $\ell = 1$ and $\ell = 0$ growth rates which may be encountered in the Scylla IV-P scaling experiment is $\sim 0.07 \times 10^6 \text{ sec}^{-1} \leq \gamma \leq 2 \times 10^6 \text{ sec}^{-1}$, i.e., a range of about 30. In order to have a viable measurement, the plasma column must undergo a displacement of 1-2 plasma diameters during the available observation time, which time is limited by the onset of the "wobble" effect¹⁴ to about one Alfvén transit time from the ends to the center of the machine. The Alfvén velocity can be written in terms of experimental quantities as

$$V_A = 1.84 \times 10^7 \frac{B_0 \text{ (kG)}}{\sqrt{P \text{ (mtorr)}}} \left(\frac{a}{R_t} \right) \text{ cm/sec. (11)}$$

For our values of $B_0 = 50 \text{ kG}$, $a = 1 \text{ cm}$, $P = 15 \text{ mtorr}$, and $R_t = 4.4 \text{ cm}$, we find $V_A = 5.41 \times 10^7 \text{ cm/sec}$. In a 5-m-long machine, therefore, the theoretical Alfvén time is $\sim 4.6 \text{ } \mu\text{sec}$. Based on past experience^{15,16} we can expect slightly more time than this before the wobble sets in, e.g., 6-7 μsec .

If we assume that the unstable plasma motion obeys the simple equation

$$\xi(t) = \xi_0 e^{\gamma t} \quad (12)$$

where ξ_0 is the initial displacement away from equilibrium, and γ is the growth rate, then for $\xi(t) \approx 4a = 4$ and $t = 6 \text{ } \mu\text{sec}$, we require a minimum initial displacement of

$$\xi_0 = 4e^{-(6 \times 10^{-6}) \gamma} \text{ cm} \quad (13)$$

for a viable measurement. For example, if $\gamma = 0.5 \times 10^6 \text{ sec}^{-1}$, then an initial displacement of 2 mm is necessary to produce a meaningful experiment in the $\sim 6 \text{ } \mu\text{sec}$ available.

The initial displacement ξ_0 in Eqs. (12) and (13) can be controlled by controlling the position of the discharge tube relative to the $\ell = 1$ or $\ell = 0$ magnetic axis, since the plasma always seems to implode to the geometric center of the discharge tube to form the initial plasma column. The magnetic axis can be located empirically, by positioning the discharge tube until no instability motion is detected.⁷

This method of positioning the discharge tube to tailor the instability motion to the experimental conditions is a very powerful tool, which we expect to use to advantage in Scylla IV-P to investigate a wide range of growth rates. Figure 2 shows the effect of discharge tube position on $\xi(t)$ as seen in previous $\ell = 1$ Scylla IV-3 experiments⁷ ($B_{\ell=1}/B_0 = 0.06$, $\lambda = 30 \text{ cm}$). Note in particular the reproducibility of the instability motion for the two shots (1008 and 1009) where ξ_0 was held constant at 3 mm. Figure 3 shows that, in spite of their very different visual appearances, all the shots in Fig. 2 have the same value for the growth rate: in this case about $1.0 \times 10^6 \text{ sec}^{-1}$ as shown by the solid line. These numerical data were obtained by digitizing luminosity traces and plotting the results on semi-log graph

TABLE II
TYPICAL PARAMETERS FOR SCYLLA IV-P $\ell = 0$ SCALING EXPERIMENTS

$B_{\ell=0}$ B_0	λ (cm)	B_0 (kG)	P (mtorr)	R_t (cm)	b (cm)	a (cm)	n (cm ⁻³)	T_e (keV)	T_i (keV)	β	δ_0	γ_0 (sec ⁻¹)
0.06	42	50	15	4.4	6.0	1.0	2×10^{16}	0.6	2.5	0.8	0.15	0.52×10^6
0.06	21	50	15	4.4	6.0	1.0	2×10^{16}	0.6	2.5	0.8	0.15	1.04×10^6
0.03	42	50	15	4.4	6.0	1.0	2×10^{16}	0.6	2.5	0.8	0.075	0.26×10^6
0.03	21	50	15	4.4	6.0	1.0	2×10^{16}	0.6	2.5	0.8	0.075	0.52×10^6

Fig. 2. Streak photographs taken on Scylla IV-3 showing the $m = 1$ plasma motion vs initial discharge tube position.

paper. Similar results have also been obtained using end-on laser holograms and by digitizing streak photographs of the plasma. This redundancy allows valuable crosschecks on the growth rate measurements.

Other plasma diagnostic techniques are planned to measure other plasma parameters of interest. The luminosity profiles, when combined with excluded flux data from balanced probes, will yield the plasma beta as a function of time. The plasma density will be monitored using both a side-on coupled-cavity He-Ne laser interferometer and the end-on ruby laser holograms. The plasma distortion parameters δ_1 and δ_0 will be measured using two independent luminosity arrays positioned one-half wavelength apart along the axis. Several high-speed streak cameras will be used to monitor the overall plasma behavior and to assure that $m = 1$, $k = 0$ motion has been obtained for the measurements.

All diagnostics firmly projected in this proposal to complete the various objectives have been previously applied on either the Scyllac sector^{1,2} or linear theta-pinch devices under equivalent conditions,^{3-7,15,16} as regards sensitivity limits.

Fig. 3. Plasma position vs time for the shots in Fig. 2. The solid line indicates the "best-fit" to the data. The growth rate is determined from the slope.

Furthermore, since the original proposal was written, we have successfully developed: a) Thomson scattering measurements¹⁷ (50-eV lower limit on T_e , without any special laser beam entrance or exit ports), and b) side-on coupled-cavity interferometry measurement of preionization density to 10% accuracy¹⁸ (for 10-mtorr filling pressure in a 10-cm-diameter tube). Work is proceeding on a) extending the laser scattering to several radial points on a single discharge, and b) increasing the sensitivity of side-on holographic interferometry to make it useful at conventional ($2 \times 10^{16} \text{ cm}^{-3}$) theta-pinch densities. The well-established ruby laser holography techniques^{15,19} will certainly be applicable as a side-on measurement for the high-density experiments.

III. FINITE-LARMOR-RADIUS STABILIZATION OF $m \geq 2$ MODES

Historically, the theoretical analysis of high-beta configurations has been predominantly based upon the plasma model furnished by ideal magnetohydrodynamics (MHD). In actual practice, however, the high-beta theta-pinch experiments of interest to the CTR program 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. This turns out to be the case, since MHD theory gives predictions in approximate agreement with experiment for the $m = 1$ mode, but in poor agreement for $m \geq 2$ modes. In the case of $m \geq 2$ modes, which describe higher harmonics of the azimuthal distortion of the plasma column, ideal MHD theory predicts larger growth rates than for the $m = 1$ mode, when in fact such modes are not observed to be unstable experimentally, and usually are not seen at all.

Recent work by Freidberg^{20,21} has addressed this question by incorporating a physically more realistic description of the ions in the theoretical model. The improved model treats the ions through the Vlasov equations and the electrons through a fluid equation, and thus retains finite-Larmor-radius (FLR) effects in the description. We apply this theory to the Scylla IV-P experiments below, expressing our equations, as in the previous discussion of variable-epsilon scaling experiments, in terms of quantities which can be experimentally controlled.

The existence of FLR stabilization and the magnitude of the effect are important subjects for the future direction of Scyllac and, more generally, the toroidal theta-pinch program itself. Scyllac and its linear predecessors have been stable to $m = 2$ modes precisely because the plasma column has been highly compressed, leading to large values of the parameter (r_L/a) , and hence to strong gyroradius effects. Staged heating,^{22,23} by contrast, leads to "fat" plasmas with large a/b ratios required for wall-stabilization, and hence the parameter (r_L/a) may be much reduced. The question of FLR stabilization is central to future staged theta-pinch experiments.

A. Summary of the Theory

Let γ_m^{MHD} be the MHD growth rate for modes with $m \geq 2$, and let $v_T = (2 kT_i/m_i)^{1/2}$ be the ion thermal speed. FLR stabilization is operative if the plasma parameters satisfy the inequality²¹

$$1 \gg \frac{1}{(1-\beta)^{1/2}} \left(\frac{r_L}{a} \right) \gg \frac{4\gamma_m^{\text{MHD}}}{(v_T/a)} \quad (14)$$

Here r_L is the ion gyroradius and a is the plasma radius. The quantity v_T/a is the ion thermal transit time across the plasma radius. For devices which

are basically theta pinches, $\gamma_m^{\text{MHD}} \ll v_T/a$.

If inequality (14) is satisfied (FLR effects operative), the growth rate γ_m is much lower than predicted by ideal MHD theory, and given by²¹

$$\gamma_m \approx \left(\gamma_m^{\text{MHD}} \right)^2 \left[2\pi^{1/2} \frac{\zeta^2}{(v_T/a)} \exp(-\zeta^2) \right] \quad (15)$$

where ζ is the dimensionless parameter

$$\zeta = \frac{1}{(1-\beta)^{1/2}} \left(\frac{r_L}{a} \right) \quad (16)$$

B. Stabilization of $m = 2$ Modes in Scyllac

We now apply this theory to the Scyllac experiment and, by extension, to Scylla IV-P. In the proposed Scylla IV-P configuration, small $\ell = 1$ and $\ell = 0$ fields can be superimposed separately on a high-beta linear theta-pinch plasma.

1. $\ell = 1$. Ideal MHD theory predicts an $m = 2$ growth rate for the $\ell = 1$ configuration given by^{9,10,21}

$$\gamma_2^{\text{MHD}} = \left(\frac{v_A}{a} \right) \left[\frac{\beta^3}{2(2-\beta)} \right]^{1/2} \epsilon \delta_1 \quad (17)$$

where $\epsilon = ha$, v_A is the Alfvén velocity [Eq. (11)], and δ_1 is the helical distortion given by Eq. (2).

For the Scyllac parameters given in Table I ($B_{\ell=1}/B_0 = 0.06$, $\lambda = 42$ cm, $B_0 = 50$ kG, $P = 15$ mtorr, $R_t = 4.4$ cm, $a = 1.0$ cm, $T_i = 2.5$ keV, $\beta = 0.8$, $\delta_1 = 0.67$), we find $\gamma_2^{\text{MHD}} = 2.50 \times 10^6 \text{ sec}^{-1}$ compared with $\gamma_1^{\text{MHD}} = 0.79 \times 10^6 \text{ sec}^{-1}$ for the $m = 1$ growth rate on the old ordering.

In the case of a deuterium plasma the thermal velocity is given by

$$v_T = 3.10 \times 10^7 T_i^{1/2} (\text{keV}) \frac{\text{cm}}{\text{sec}} \quad (18)$$

and the ion gyroradius is given by

$$r_L = 6.46 \frac{T_i^{1/2} (\text{keV})}{B (\text{kG})} \text{ cm} \quad (19)$$

For our test parameters we find $v_T = 4.9 \times 10^7 \text{ cm/sec}$ and $r_L = 0.20$ cm, in which case inequality (14) is satisfied: $1 > 0.45 > 0.20$. We can therefore use Eq. (15) to predict the $m = 2$ growth rate including FLR effects. The result is $\gamma_2 = 1.61 \times 10^4 \text{ sec}^{-1}$. Thus the theoretical growth rate is reduced by a factor of 155 when FLR effects are taken into

account; the corresponding growth time, $\tau = \gamma^{-1}$, is increased from 0.4 μsec to 62 μsec .

These results can be interpreted in the following simple way: when the Larmor radius becomes sufficiently large, FLR effects essentially stabilize unstable MHD modes. There remains, however, a very low growth rate mode driven by resonant ions,²¹ which persists until the ideal MHD threshold is reached.

Since the right-hand inequality in Eq. (14) is easily satisfied under most experimental situations, the condition that the $\ell = 1$, $m = 2$ mode in the Scyllac configuration be effectively stabilized is obtained by substituting Eq. (17) for γ_2^{MHD} into the right-hand side of inequality (14):²¹

$$\frac{r_L}{a} \geq \left[\frac{8\beta^2(1-\beta)}{(2-\beta)} \right]^{1/2} \epsilon \delta_1 \quad (20)$$

[where we have used the fact that $(v_A/v_T)^2 = 1/\beta$].

This instability criterion can be written in terms of more convenient experimental parameters with the help of Eqs. (2) and (19):

$$\left(\frac{B_{\ell=1}}{B_0} \right) \leq 2.28 \frac{T_1^{1/2}}{a B_0} \left[\frac{(1-\beta/2)^2(2-\beta)}{\beta^2(1-\beta)} \right]^{1/2} \quad (21)$$

(T_1 in keV, a in cm, B_0 in kG). Note that the dependence on λ drops out.

Equation (21) expresses the critical field ratio for which the transition between stability and instability occurs. For Scyllac parameters ($B_0 = 50$ kG, $T_1 = 2.5$ keV, $\beta = 0.8$ and $a = 1.0$ cm), we find $(B_{\ell=1}/B_0)_{\text{crit}} = 0.13$. Since Scyllac has field ratios smaller than 0.13 (e.g., 0.06), Eq. (21) predicts stability to the $\ell = 1$, $m = 2$ mode, in agreement with experiment.

We propose to test Eq. (21) experimentally on Scylla IV-P by using a computer designed $\ell \approx 1$ coil having $B_{\ell=1}/B_0 \approx 0.13$. A variation of parameters (a , B_0 , T_1 , or β), which are under the experimenter's control, should therefore allow the right-hand side of Eq. (21) to take on values both above and below the critical value, providing a test of the theory.

2. $\ell = 0$. The question of FLR stabilization of $\ell = 0$, $m = 2$ modes does not appear to have been addressed before, theoretically or experimentally. Previous theoretical treatments of the $m = 2$

instability relevant to Scyllac have focused attention on the $\ell = 1$ driven modes.^{20,21,24,25} However, it is clear that $\ell = 0$ fields can be associated with $m = 2$ modes also, as shown in Fig. 4. A strong $m = 2$ plasma motion is plainly discernible in these stereoscopic streak photographs, taken during preliminary $\ell = 0$ scaling studies⁷ on Scylla IV-3 in 1973. The $m = 2$ motion is visible in both land and groove regions.

Ideal MHD theory predicts an $m = 2$ growth rate for the $\ell = 0$ configuration given by¹⁰

$$\gamma_2^{\text{MHD}} = \left(\frac{v_A}{a} \right) \left[\frac{\beta(3-2\beta)(1-\beta) + \beta^2}{(2-\beta)} \right]^{1/2} \epsilon \delta_0 \quad (22)$$

where δ_0 is the bump distortion given by Eq. (9).

For the Scyllac parameters given in Table II ($B_{\ell=0}/B_0 = 0.06$, $\lambda = 42$ cm, $B_0 = 50$ kG, $P = 15$ mtorr, $R_c = 4.4$ cm, $a = 1.0$ cm, $T_1 = 2.5$ keV, $\beta = 0.8$, $\delta_0 = 0.15$), we find $\gamma_2^{\text{MHD}} = 1.03 \times 10^6 \text{ sec}^{-1}$. This value can be compared with the value $0.52 \times 10^6 \text{ sec}^{-1}$ for the $m = 1$ growth rate.

Proceeding on the same basis as used in the $\ell = 1$ discussion above, we evaluate inequality (14) and find that it is satisfied for Scyllac $\ell = 0$ parameters: $1 > 0.45 > 0.084$. Therefore Eq. (15) can be used to derive the $\ell = 0$, $m = 2$ growth rate corrected for FLR effects. The result is $\gamma_2 = 2.74 \times 10^3 \text{ sec}^{-1}$, i.e., a reduction by a factor of 376 over the ideal MHD calculation of $1.03 \times 10^6 \text{ sec}^{-1}$. The corresponding growth time, $\tau = \gamma^{-1}$, is increased from 0.97 μsec to 365 μsec .

As before, we can derive an instability criterion in terms of the Larmor radius r_L , using inequality (14):

$$\frac{r_L}{a} \geq 4 \left[\frac{(3-2\beta)(1-\beta)^2 + \beta(1-\beta)}{(2-\beta)} \right]^{1/2} \epsilon \delta_0 \quad (23)$$

Eliminating δ_0 , ϵ , and r_L allows this criterion to be rewritten as

$$\frac{B_{\ell=0}}{B_0} \leq 0.514 \frac{\lambda T_1^{1/2}}{a B_0} \left[\frac{(1-\beta)(2-\beta)}{(3-2\beta)(1-\beta) + \beta} \right]^{1/2} \quad (24)$$

Fig. 4. Stereoscopic streak photographs taken on Scylla IV-3 showing damped $\ell = 0$, $m = 2$ modes.

(λ and a in cm, T_1 in keV, B_0 in kG). For Scyllac parameters ($a = 1.0$ cm, $T_1 = 2.5$ keV, $B_0 = 50$ kG, $\beta = 0.8$), we find, for stability,

$$\frac{B_{\ell=0}}{B_0} \leq 7.66 \times 10^{-3} \lambda \text{ (cm)} \quad (25)$$

which for $\lambda = 42$ cm becomes $(B_{\ell=0}/B_0) \leq 0.32$. This shows that Scyllac is stable to $\ell = 0$, $m = 2$ modes, as observed, but 0.32 is a poor choice for the field ratio in Scylla IV-P experiments due to the large bump size ($\delta_0 = 0.8$), which would probably require many μ sec for axial pressure equilibrium to be reached. A better choice is $\lambda = 12$ cm, in which case the theory is still valid ($\epsilon = 0.5 < 1$), but $B_{\ell=0}/B_0$ is reduced to a more attractive value of 0.09. A parameter variation around the values quoted here should enable the stability-instability transition to be studied in detail in Scylla IV-P $\ell = 0$ experiments in a manner analogous to that discussed above for the $\ell = 1$ experiments.

Since the FLR and variable-epsilon experiments have much in common, being concerned with $m = 2$ and $m = 1$ modes respectively in $\ell = 1$ and $\ell = 0$ systems, these two experiments will probably be done concurrently.

IV. COMPUTER CONTROL SYSTEM

The computer control system mentioned in Sec. V on Design and Construction Schedule must also be regarded as a legitimate experiment to be performed on Scylla IV-P. Obviously this machine could be manually controlled, as its predecessors have been. However, it is essential to gain some experience with computer control, which is deemed absolutely necessary on the larger, follow-on, next generation devices. Furthermore, we expect that any delays incurred in start up of Scylla IV-P, which might be due to a new control philosophy, will be more than compensated during the Scylla IV-P lifetime as it progresses through the very tightly projected experimental timetable.

V. DESIGN AND CONSTRUCTION SCHEDULE

A. Timetable

The timetable for Scylla IV-P construction is given in Table III. The success of this schedule depends upon material deliveries being made on time. Critical hardware has already been ordered to spend the $\sim$ \$200 K available in fiscal 1974. Delivery of steel for the platform is expected in June 1974. The computer is a critical long-lead-time item, and its procurement should be expedited.

TABLE III
SCYLLA IV-P CONSTRUCTION SCHEDULE

	Start	Complete
Preliminary layout and platform design	10-15-73	11-15-73
Detailed layout and design	11-15-73	3-1-74
Control system design and computer interfacing	3-15-74	1-15-75
Collector plate design	4-15-74	6-1-74
Cleanup of Scylla IV-P area	5-28-74	6-10-74
Rack and platform installation	6-10-74	7-8-74
Auxiliary system installation (cable trays, air, SF_6)	7-15-74	11-4-74
Capacitor installation	10-7-74	12-9-74
Charge system installation	10-28-74	1-20-75
Collector plate assembly	9-2-74	11-25-74
Collector plate installation	11-11-74	12-9-74
Lead cable installation	10-21-74	1-6-75
Trigger cable installation	12-9-74	1-13-75
Control system installation and checkout	11-11-74	1-6-75
Charge system checkout	1-20-75	2-3-75
Trigger system checkout	2-3-75	3-3-75
Main bank checkout	3-3-75	4-7-75
Slow bank checkout	3-3-75	4-7-75

B. Costs by Fiscal Year

In the following tabulation (Table IV) of costs for Scylla IV-P, we assume that the construction is initiated in FY-74 and completed in FY-75. Total construction cost is estimated at \$2.4 M. In FY-76 and beyond, the experiment will be operational and only costs estimated for normal operation are included.

TABLE IV
SCYLLA IV-P COSTS BY FISCAL YEAR

FY-74	Initiate construction	\$200 K
FY-75	Complete construction	2200 K
FY-76	Operation	338 K
FY-77	Operation	338 K

VI. EXPERIMENTAL PRIORITIES AND SCHEDULING

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 emphasis will be determined by the needs of the Scyllac toroidal experiment as that program evolves. At the present time the projected research priorities are: (1) a test of wall-stabilization using plasma injected into a 1-meter-long $\ell = 1$ coil from a 2-meter-long linear theta-pinch plasma source at each end, (2) FLR stabilization effects for $m \geq 2$ modes, (3) variable-epsilon scaling experiments to explore the $\ell = 1$ and $\ell = 0$, $m = 1$ growth rates and plasma surface excursions relevant to the Scyllac and SPX/FTR configurations, (4) investigation of the high-density linear theta-pinch concept using a new high-field (250-400 kG) multi-turn compression coil of 3- to 5-meters length to produce thermonuclear plasmas with densities in the few $\times 10^{17} \text{ cm}^{-3}$ range, and (5) laser-heating experiments on the high-density theta pinch. A tentative schedule for these experiments is given in Table V.

This projected timetable should be regarded as a tentative guide rather than a commitment to a rigid schedule. Developments in the Scyllac program or on Scylla IV-P itself may make changes necessary. Unanticipated problems in the experiment can also lead to delays and other revisions in the schedule.

VII. OPERATING COSTS AND PERSONNEL REQUIREMENTS

The cost of operating the Scylla IV-P experiment after construction has been completed is given in

TABLE V

PROJECTED TIMETABLE FOR SCYLLA IV-P EXPERIMENTS

	<u>Start</u>	<u>Completion</u>
Initial injection experiments	4-15-75	6-1-75
Injection experiments with wall stabilization	6-1-75	9-15-75
FLR stabilization experiments	9-15-75	3-15-76
Variable-epsilon scaling experiments	9-15-75	3-15-76
High-field coil test	3-15-76	5-1-76
High-density theta-pinch experiments	5-1-76	4-1-77
Laser-heating experiments	4-77	-

Table VI. We propose to staff the experiment with a regular operating crew consisting of one engineer, two physicists (a Ph.D. plus a BS/MS new hire), and four technicians. In addition to the permanent operating crew, various experimental physicists and their supporting technicians will perform measurements on the facility as required. We estimate one experimental physicist and one technician will be needed on the average. Due to the substantial interest of various members of the theory group (CTR-6) in this experiment, we also can rely on strong theoretical support when needed.

The engineer for the Scylla IV-P experiment has been transferred to the new project from the previous experiment which operated in the pit area - the Scyllac prototype. (This experiment has now been removed from the CTR division.) The two physicists on the operating crew are new hires in FY-74. The supporting diagnostics physicist has been accounted for by a new hire in CTR-8 in FY-75. The five technicians will be new hires added in FY-75. Therefore, the Scylla IV-P experiment will be staffed entirely by new hires or their equivalents in CTR-3, CTR-4, and CTR-8, and should accordingly have no adverse impact on other parts of the LASL-CTR program. On the contrary, we expect the overall program to be strengthened by the addition of the new personnel.

TABLE VI

OPERATING COSTS AND PERSONNEL REQUIREMENTS

Operating Crew

1 Engineer	CTR-4	\$52 K
1 Ph.D. Physicist	CTR-3	52
1 BS/MS Physicist	CTR-3	52
2 Electrical Techs.	CTR-4	52
2 Mechanical Techs.	CTR-3	52

Diagnostics Support

1 Ph.D. Physicist	CTR-8	52
1 Technician	CTR-8	<u>26</u>

TOTAL OPERATING COSTS PER YEAR \$338 K

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