200
10-22-75

Qr-170Z

LA-5966-P

Proposal

UC-20

Reporting Date: July 1975

Issued: September 1975

Proposal for the Construction of the Staged Scyllac Prototype

by

W. C. Nunnally
T. E. McDonald

MASTER

los alamos
scientific laboratory

of the University of California

LOS ALAMOS, NEW MEXICO 87545

An Affirmative Action/Equal Opportunity Employer

UNITED STATES
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
CONTRACT W-7408-ENG. 36

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

In the interest of prompt distribution, this report was not edited by the Technical Information staff.

Printed in the United States of America. Available from
National Technical Information Service
U S Department of Commerce
5285 Port Royal Road
Springfield, VA 22151
Price: Printed Copy \$4.00 Microfiche \$2.25

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

CONTENTS

ABSTRACT	1
I. INTRODUCTION.	1
II. STAGING AND STABILIZATION	2
III. STAGED SCYLLAC.	5
IV. LARGE STAGED SCYLLAC (LSS).	5
V. STAGED SCYLLAC PROTOTYPE JUSTIFICATION AND OBJECTIVES	6
VI. ENGINEERING DESIGN OF PROTOTYPE	
A. General Considerations	10
B. Basic Prototype Configuration.	11
C. System Operation	14
D. Prototype Systems Design	
1. Implosion System	17
2. Staging System.	20
3. Trigger System.	27
4. Gap-Monitoring System	32
5. Overall System Reliability.	34
E. Mechanical Layout	37
VII. ADDITIONAL DEVELOPMENT.	39
VIII. COST ESTIMATE AND SCHEDULING	
A. Budget	39
B. Scheduling	41

NOTICE

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

PROPOSAL FOR THE CONSTRUCTION OF THE STAGED SCYLLAC PROTOTYPE

by

W. C. Nunnally and T. E. McDonald

ABSTRACT

After the completion of the present feedback experiment on Scyllac, the machine will be reconfigured into a toroidal staged theta pinch. A 0.9-m prototype of the Staged Scyllac experiment is proposed which will be used to test the components required for the implosion-heating and staging circuits in a system environment. In addition, various systems of the Staged Scyllac, such as the trigger system and the gap-monitoring system, can be developed on the prototype before installation on the full experiment.

I. INTRODUCTION

The next configuration of the Scyllac experiment is expected to be a toroidal staged theta pinch. The implosion-heating* circuit will be essentially identical to that used in the present Staged Theta-Pinch experiment and the Scyllac capacitor bank will be used as the staging bank. The components which have been designed for the Staged Theta-Pinch experiment such as the start gaps for the implosion-heating circuit and the staging gaps will be employed in the Staged Scyllac experiment; however, refinements on these components are expected to be required for reduced cost and increased reliability. In addition, various systems within the machine such as the trigger system must be developed. Component development will be carried out in the usual manner in the "loft" operation; however, overall system development can only be carried out in the larger configuration of the machine itself.

---

*The terms shock heating and implosion heating are used interchangeably in this proposal.

It is proposed that a 0.9-m prototype of the Staged Scyllac be constructed in order to evaluate and develop the components in the environment of the overall system. The prototype, which will be used in much the same manner as the Scyllac prototype prior to the construction of Scyllac, will also be used to test and develop systems such as the shock-heating trigger system and the pulse-charging system. In addition, the Staged Scyllac Prototype will be used to determine the optimum implosion magnetic-field waveform for Staged Scyllac. Unexpected system problems can also be identified and corrected before installation on the large machine.

The cost estimate of the prototype is \$428K and the estimated time for completion is 18 months.

II. STAGING AND STABILIZATION

The idea of using separate shock-heating and compression circuits was first proposed in 1969.¹ Two benefits arise from such a configuration. If one circuit were used, the shock-heating and compression fields would be supplied from one large capacitor bank which would necessarily be high voltage and low inductance, and thus have a high cost per joule. With separate circuits the shock-heating field would be supplied from a high-voltage, low-inductance capacitor bank which, although having a high cost per joule, would be relatively small; the slower-rising compression field would require a large capacitor bank, but because of the slower risetime a relatively low-voltage, high-inductance bank could be employed, thus resulting in a low cost per joule. One advantage to the staging concept is, therefore, a reduction in the system cost. The second benefit from staging is the fact that shock-heating

and compression fields can be programmed in such a manner that the plasma will have a relatively large a/b (plasma-to-wall radius) ratio. This results in wall stabilization of the $\lambda = 1$ instability and eliminates the need for a feedback system, at least on the time scale of field penetration into the first wall.

In order to examine this concept more thoroughly, LASL proposed in September 1972, the Staged Theta-Pinch (STP) experiment to study heating, staging, and wall stabilization of the staged theta-pinch concept.² The Staged Theta-Pinch machine has a 4.5-m-long, 22.4-cm-diameter load coil and a discharge-tube inside diameter of 20 cm. The load coil has two feed slots which are connected to the implosion-heating capacitors via parallel-plate transmission lines. The low-inductance, 125-kV implosion-heating capacitor bank has a total energy storage capacity of 140 kJ and produces an implosion-heating magnetic field which rises to 7 kG in approximately 150 ns. The existing 850-kJ, 50-kV Scylla-IV capacitor bank provides the compression field which is approximately 20 kG.

An electrical schematic of the basic staged theta-pinch circuit is shown in Fig. 1. The capacitors C_1 and C_2 are 0.2 μF , 125 kV and 0.4 μF , 125 kV respectively. Inductances L_1 and L_2 represent the capacitor and start-gap inductances while L_p is the inductance of the parallel-plate transmission line. In order to raise the voltage across the load as rapidly as possible to its peak value, the inductances L_1 , L_2 , and L_p should be as small as possible. The switches S_1 and S_2 are 125-kV spark gaps which are referred to as PFN gaps. The staging capacitor bank C_s is connected to the shock-heating circuit through the staging gap S_3 .

The inductances L_s and L_{sp} are the cable inductances and capacitor-bank inductances respectively. The switch S_4 is the crowbar gap, and L_c is the crowbar inductance. It is not critical that inductances L_s and L_{sp} be as small as possible, as it is for L_1 , L_2 , and L_p because the compression field rises more slowly than the shock-heating field.

Fig. 1. Electrical schematic of the basic staging circuit.

By varying the timing and switching sequence of S_1 , S_2 , S_3 , and S_4 , the magnetic field can be programmed to yield various ratios of a/b ; the objective is to obtain as large a value of a/b as possible. The exact switching sequence which will yield the largest value of a/b can only be determined experimentally; however, a typical switching sequence which is thought to yield close to optimum results is as follows. With all switches open the capacitor banks are charged to rated value. Switch S_1 is closed initially, and the current in the load increases to a peak, then begins to ring down. Switch S_3 is next closed, quickly followed by the closing of S_2 . This keeps the current in the load coil from reaching zero and prevents the plasma from hitting the wall. The current then increases to the peak compression value at which time the crowbar S_4 is closed and the current decays exponentially.

III. STAGED SCYLLAC

Upon completion of the feedback experiment on Scyllac, the machine will be reconfigured into a toroidal staged theta pinch, and the staging concept will then be studied in a large toroidal configuration. The exact configuration has yet to be decided, but will be either a complete 12.5-m radius toroid or a 25-m sector of a 40-m-radius toroid. In either configuration the basic electrical requirements will be much the same.

A 125-kV shock-heating capacitor bank with load coils, which is essentially identical to the staged theta-pinch experiment, will be installed and the 60-kV, 10-MJ Scyllac capacitor bank will be used as the staging bank. The size of the shock-heating capacitor bank will be in the range of 0.3 to 0.4 MJ and will require up to 900 PFN gaps and 340 staging gaps. This compares with 3150 1.85- μ F, 60-kV capacitors and gaps in the present Scyllac bank. A 0.9-m Staged Scyllac Prototype (SSP) will be constructed to ensure an adequate design and reliable components for the larger machine.

IV. LARGE STAGED SCYLLAC (LSS)

The completion of the Staged Scyllac experiment will demonstrate the basic staging concepts in a more favorable configuration than heretofore possible. Nonetheless, some unfavorable crucial parameters, such as end effects in the 40-m-radius sector or inadequate plasma heating in the 12.5-m-radius torus, may present confinement difficulties. The Large Staged Scyllac is the next generation experiment which has none of the disadvantages of the Staged Scyllac and an order-of-magnitude greater confinement time.

The Large Staged Scyllac will have a 40-m major radius and an implosion-heating and compression circuit much like the Staged Scyllac experiment. It is expected that the components and systems similar to those which are being developed for the Staged Scyllac are directly applicable to the Large Staged Scyllac with possibly minor modifications. The Staged Scyllac Prototype will also be used with relatively minor modifications in the Large Staged Scyllac Prototype (with additional low-voltage staging) to ensure proper system design and operation of the larger device. Thus, the prototype will be effectively utilized in both the Staged Scyllac and Large Staged Scyllac experiments.

V. STAGED SCYLLAC PROTOTYPE JUSTIFICATION AND OBJECTIVES

The application of the staging concept to the present Scyllac theta pinch requires further development of the present implosion and staging hardware, as well determining the exact magnetic-field waveform necessary to produce the desired plasma parameters. Much of the hardware development will be carried out on individual components in the component development program; however, development must continue to the system when all components are interconnected. A prototype program allows many of these unforeseen system problems to be identified and solved on a small scale rather than trouble shooting and modifying the large Scyllac system itself. In addition, after reliable system operation has been achieved on the prototype, it is then possible to study the interaction between the magnetic field and plasma parameters to ensure that the proper magnetic-field signature can be achieved.

The initial implosion magnetic-field waveform is so intimately connected to the presence of a plasma in the discharge tube that a true prototype must include a plasma. However, there are several possible modes of implosion system operation including the field-programming mode and the resonant-heating mode. To this point, theoretical and experimental studies of shock heating have not progressed sufficiently to indicate the exact magnetic-field signature necessary. Initial studies do, however, give an indication of the components that will be necessary in terms of the operating voltages, inductances, current and charge levels, and physical dimensions. Components and auxiliary-system configurations can therefore be developed which will meet the requirements for a staged Scyllac even though the exact mode of operation has not been determined. A prototype program is necessary to fully develop reliable, high-voltage, low-inductance components, as well as trigger, charge, and control systems through individual and system operation. The specifications for the spark gaps necessary for the Staged Scyllac are listed in Table I and are discussed further in following sections.

The overall magnitude and risetime of the implosion and staging magnetic fields have also been approximated. Table II lists the basic goals of the implosion and staging systems. The column noted SSP* denotes the final system which will incorporate higher voltage, lower inductance capacitors than are now commercially available. The development program for the capacitors is presently in progress with successful results expected on a six-month time scale.

TABLE I
SPARK GAP PARAMETERS FOR STAGED SCYLLAC

	<u>Implosion Start</u>	<u>Staging Start</u>	<u>Implosion Crowbar</u>
Inductance	10 nH	60 nH	10 nH
Voltage Maximum	200 kV	200 kV	200 kV
Current Maximum	200 kA	650 kA	1 MA
Charge Level	1 C	30 C	25 C
Unit Cost	\$1000	\$2000	\$1000
Number of Shots w/o Maintenance	5000	2000	2000
Trigger Delay	≤ 20 ns	≤ 20 ns	≤ 20 ns
Trigger Jitter	≤ 20 ns	≤ 20 ns	≤ 20 ns
Trigger Amplitude	200 kV	200 kV	200 kV
Trigger Risetime	≤ 20 ns	≤ 20 ns	≤ 20 ns
Number Arc Channels	> 10	> 10	> 10
Assembly Time	1 man-h	3 man-h	1 man-h
Replacement Time	1 man-h	1 man-h	1 man-h
Energy Switched	3 kJ	30 kJ	-

The SSP will be initially used as an engineering test bed to identify and resolve problems with components within the overall system while determining and improving, if necessary, the system reliability.

Theoretical and complementing experimental data from the Staged Theta-Pinch experiment and the 1-m implosion-heating experiment will provide a foundation for determining the magnetic-field signature necessary for Staged Scyllac. At this point, the engineering phase of the Staged Scyllac Prototype will be complete. The Staged Scyllac Prototype will then be retrofitted to investigate the magnetic-field waveform with a plasma in the discharge tube. In this mode of operation, the Staged Scyllac Prototype will be used to determine the optimum magnetic-field signature, and thus, the optimum implosion circuit for the Staged Scyllac.

TABLE II
STAGED SCYLLAC SYSTEM PARAMETERS

<u>IMPLOSION SYSTEM</u>			
	<u>STP</u>	<u>SSP</u>	<u>SSP*</u>
Load-Coil Diameter	22 cm	22 cm	22 cm
Maximum Implosion			
Magnetic Field			
without Plasma	5.7 kG	5.9 kG	7.3 kG
with Plasma	8.2 kG	8.5 kG	11.2 kG
Implosion Field			
Risetime			
without Plasma	270 ns	260 ns	250 ns
with Plasma	190 ns	180 ns	170 ns
Capacitor Inductance	30 nH	30 nH	20 nH
Implosion-Staging Gap Inductance	15 nH	10 nH	10 nH
Implosion-Capacitor Voltage	125 kV	125 kV	150 kV
Transfer Efficiency Maximum			
without Plasma	46 %	67 %	73 %
with Plasma	20 %	28 %	35 %

<u>STAGING SYSTEM</u>			
Staging-Capacitor Voltage	50 kV	60 kV	60 kV
Maximum Staging Field	25 kG	35 kG	35 kG
Energy/0.45 m	24 kJ	30 kJ	30 kJ
Transfer Efficiency	-	55 %	55 %
Staging Field Risetime			
Field Programming	3-5 μ s	3-5 μ s	3-5 μ s
L/R Field Decay Time	-	> 200 μ s	> 200 μ s

The objective of the Staged Scyllac program is divided into four major phases.

1. Hardware development of the components listed in Table I, as well as a 150-kV, 20-nH implosion capacitor.
2. Operation of the individual prototype subsystems without plasma to develop subsystem reliability and operational characteristics.
3. Operation of the complete Staged Scyllac Prototype without plasma to identify and resolve system problems, as well as determine system reliability.
4. Operation of the Staged Scyllac Prototype with plasma to determine the optimum implosion circuit and the optimum magnetic-field waveform necessary for Staged Scyllac. This phase will require the necessary plasma diagnostic systems.

VI. ENGINEERING DESIGN OF PROTOTYPE

A. General Considerations

Since the Staged Scyllac Prototype is designed to evaluate and develop the components with which the present Scyllac system is to be retrofitted, the design of the prototype must be intimately connected to the proposed Staged Scyllac design. The Staged Scyllac is to produce a 1-keV plasma with an implosion capacitor bank and sustain or increase the confining implosion field with the present Scyllac capacitor bank. The value of the L/R decay times for the implosion and the compression fields are to be as large as possible considering the other design constraints and the present Scyllac machine components.

At the present time, two possible configurations are being considered for the Staged Scyllac. One is a 25-m-long sector of a 40-m-radius torus, and the other is a complete 12.5-m-radius torus having an 80-m circumference. The shock-heating system for the two configurations is identical, with the staging system differing only in the amount of staging energy and the number of staging spark gaps per meter of coil length. The sector configuration has the largest number of capacitors per meter and, from an engineering design and evaluation point of view, represents the more difficult case. Thus, the prototype will be designed for the sector configuration, but it should be noted that the component and system development work is directly applicable to either of the configurations.

B. Basic Prototype Configuration

Since the operation of the prototype simulates the Staged Scyllac, it is imperative that the major design elements in the Staged Scyllac be duplicated in the prototype. The present Scyllac experiment is composed of 15 capacitor racks with 210 each, 1.85- μ F, 60-kV capacitors per rack. The 22.4-cm-diameter load coil will be fed from two sides as in the present Staged Theta-Pinch machine. The sector configuration requires the addition of one more capacitor rack so that the number of capacitors in the staging bank will be equal on each side of the machine. A portion of the Staged Scyllac layout is shown in Fig. 2. One Scyllac capacitor rack (210 each, 1.85- μ F, 60-kV capacitors) will supply the staging energy to one side of a 3.14-m section of the load coil. The Scyllac system will be modified by replacing the present start spark gaps with a shorting insert, as shown in Fig. 3. The equipartition of the Scyllac bank on two sides

Fig. 2. Staged Scyllac layout.

Fig. 3. Scyllac spark-gap modification.

of the sector arrangement indicates that 30 Scyllac 1.85- μ F, 60-kV capacitors are allocated to each side of a 0.45-m length of load coil. Also, the nominal coil width needed for the implosion-capacitor system is approximately 0.45 m. Thus, the basic module of the Staged Scyllac system is a 0.45-m length of load coil and collector plates.

Two 0.45-m modular units will be used in the Staged Scyllac Prototype in order to study the intermodule currents and voltages caused by various fault modes. Two modules permit a prototype more representative of the Staged Scyllac system.

Thus, the basic configuration of the Staged Scyllac Prototype will be a 0.9-m-long load coil, 22.4-cm in diameter, driven by four 0.45-m implosion systems, two on each side. A total of 120 Scyllac 1.85- μ F, 60-kV staging capacitors will be connected to the collector-plate load-coil assembly through four 0.45-m staging systems, two on each side. Provisions will also be made to assemble crowbar gaps to the implosion-heating circuit as a minor retrofit. This will allow more flexible operations and a wider range of shock-heating modes to be investigated, in particular the resonant-heating mode. The pre-ionization system used on the Staged Theta Pinch is straightforward and is expected to be used in the Staged Scyllac Prototype.

C. System Operation

A block diagram of the Staged Scyllac Prototype is shown in Fig. 4. The 22.4-cm-diameter load coil is fed symmetrically from two

Fig. 4. Block diagram of Staged Scyllac Prototype.

sides. The implosion-capacitor banks are pulse-charged to 125 kV from two-stage, 60-kV charge Marx banks in 3 to 10 μ s. The implosion-capacitor bank on one side is charged positive while the other side is charged negative. The staging-capacitor banks are constant-current charged to a maximum of 60-kV in 30 s. Again, one side is charged positive, the other negative.

Similarly the staging-crowbar trigger capacitors are charged positive or negative, depending on their location, in 30 s. Figure 4 also illustrates the power supply system for the trigger systems. The trigger transfer cables and the buffer cables of the implosion-start, the implosion-crowbar, and the staging-start trigger systems are pulse-charged to 200 kV in 2 to 3 μ s with separate trigger-charge Marxes. The trigger-charge Marxes are erected by an 8-kV pulser unit upon receiving a light pulse from a screen-room timing unit as discussed in Section VI. D. 3. The implosion-charge Marxes are erected in a similar manner, but use an additional buffer gap and cable system that are discussed in Section VI. D. 3. The various master trigger gaps are also triggered with a buffer cable gap combination upon receiving a light pulse from the screen room via a fiber optic. The staging-crowbar master trigger gap is triggered in a manner similar to the implosion-charge Marxes. Figure 4 also indicates the presence of fiber optics to the screen room. These fiber optics form a staging-crowbar gap-monitoring system which is discussed in Section VI. D. 4.

D. Prototype Systems Design

1. Implosion System. The implosion system of the Staged Scyllac will be similar to that of the present Staged Theta Pinch. The Staged Theta Pinch utilizes two separate implosion capacitor banks and the staging bank to program the coil magnetic field in such a way that it does not reverse. The Staged Scyllac will also be able to operate in the resonant heating mode, which uses an implosion crowbar system to prevent the implosion field from reversing. The hardware for the Staged Theta-Pinch field programming mode and the resonant-heating mode is identical, with the exception of an additional implosion-crowbar spark gap for resonant heating.

In order to produce a 1-keV implosion plasma temperature, the implosion-capacitor bank is required to produce a 10-kG field having a rise-time of less than 400 ns in the load coil with a plasma present. Because of the symmetry of the circuit, only one side of the coil will be discussed.

One side of the implosion circuit for a 0.45-m length of load coil is shown in Fig. 5. The circuit will use 0.2- μ F and 0.4- μ F, 125-kV capacitors which are commercially available. A drawing of the implosion start gap is shown in Fig. 6. The design of these gaps is similar to the start gap developed for the Staged Theta Pinch; however, improvements have been made which result in a simpler, cheaper, and lower inductance gap. Table III compares the parameters of new gap with those of the present gap. Two or three implosion-capacitor start-gap combinations are paralleled per 0.45 m of coil length per side to achieve the desired field magnitude and risetime.

A possible mode of operation, which is referred to as resonant heating, calls for a crowbar gap in the implosion-heating circuit. The

Fig. 5. 0.45 m of Staged Scyllac Prototype circuit.

Fig. 6. Implosion start gap.

TABLE III
COMPARISON OF IMPLOSION START GAPS

	<u>STP</u>	<u>SSP</u>
Inductance	15 nH	10 nH
Maximum Current	250 kA	300 kA
Holdoff Voltage	200 kV	200 kV
Switching Voltage	125 kV	150 kV
Charge Level	≤ 1 C	≤ 1 C
Number Arc Channels	≥ 5	≥ 10
Trigger Delay	≤ 20 ns	≤ 20 ns
Trigger Jitter rms	≤ 20 ns	≤ 20 ns
Trigger Amplitude	150 kV	200 kV
Trigger Risettime	≤ 20 ns	≤ 15 ns
Assembly Time	4 man-h	2 man-h
Replacement Time	1 man-h	1 man-h
Number Shots without Maintenance	5000	5000
Unit Cost	\$2000	\$1000
Configuration	cylindrical rail	concentric rail

design is sufficiently flexible to allow operation of the machine either with or without the crowbar with no major modifications required. In the resonant-heating mode the front implosion capacitors will be replaced with crowbar gaps. The latest design of the implosion-crowbar gap is shown in Fig. 7. The specifications for the implosion-crowbar gap are listed in Table IV. This gap must withstand the 125-kV voltage transient imposed on the collector plates by the implosion start-gap capacitor system. The crowbar gap must then switch when the implosion-capacitor voltage, and thus the collector plate voltage, is zero. The implosion-crowbar trigger system must break down both sides of the gap for current conduction to take place.

2. Staging System. After the implosion bank is fired, the slower-rising staging capacitor bank is applied via the staging gap to sustain and increase the field in the load coil. The staging gap must withstand the 125-kV voltage transient on the collector plate when the

Fig. 7. Implosion crowbar gap.

TABLE IV
SPECIFICATIONS OF IMPLOSION CROWBAR GAP

	<u>SSP</u>
Inductance	10 nH
Maximum Current	1 MA
Holdoff Voltage	200 kV
Switching Voltage	≈ 0 V
Charge Level	≤ 25 C
Number Arc Channels	≥ 10
Trigger Delay	≤ 20 ns
Trigger Jitter - rms	≤ 20 ns
Trigger Amplitude	200 kV
Trigger Risettime	≤ 20 ns
Assembly Time	1 man-h
Replacement Time	1 man-h
Number shots without Maintenance	2000
Unit Cost	\$1000
Arc Resistance	< 2 m Ω
Configuration	concentric rail

implosion-bank start gaps are fired, as well as trigger at the 60-kV level of the staging bank. Each staging start gap, which is shown in Fig. 8, switches ten 1.85- μ F, 60-kV Scyllac capacitors. The staging energy is carried to a 60-cable cartridge on the bottom of the collector plates with the present cable system. The capacitor potential is carried through the collector plates to the staging-gap electrodes where it is connected to the upper collector plates upon switch initiation. There are three staging start gaps per 0.45-m length of theta load coil per side. Three staging gaps are needed so that only 30 kJ of capacitor energy are connected in hard parallel at the staging-gap cable cartridge. NET-2 studies indicate that each staging gap must conduct a maximum current of 650 kA at a charge level of 30 C. Table V compares the parameters of the Staged Scyllac staging gap with those of the Staged Theta-Pinch staging gap. Typical current and charge waveforms from computer simulations are shown in Fig. 9-a and Fig. 9-b.

Fig. 3. Staging start gap.

TABLE V
COMPARISON OF STAGING START GAPS

	<u>STP</u>	<u>SSP</u>
Inductance	100 nH	60 nH
Holdoff Voltage	180 kV	200 kV
Switching Voltage	20-50 kV	20-60 kV
Maximum Current	400 kA	650 kA
Charge Level	≤ 8 C	≤ 30 C
Number Arc Channels	≥ 5	≥ 10
Energy Switched	24 kJ	30 kJ
Trigger Delay	≤ 20 ns	≤ 20 ns
Trigger Jitter - rms	≤ 20 ns	≤ 20 ns
Trigger Amplitude	200 kV	200 kV
Trigger Risetime	≤ 20 ns	≤ 20 ns
Assembly Time		
Gap	1 man-h	1 man-h
Cable Cartridge	1 man-h	2 man-h
Replacement Time		
Gap	1 man-h	1 man-h
Cable Cartridge	1 man-h	2 man-h
Number Shots without Maintenance	2000	2000
Unit Cost		
Gap	\$1500	\$1000
Cable Cartridge	\$ 250	\$1000
Configuration	linear rail	concentric rail

Fig. 9-a. Computer simulation of staging start-gap current waveform.

Fig. 9-b. Computer simulation of staging start-gap charge level.

The staging bank will be crowbarred with the present ferrite-loaded piggyback crowbar gaps in the Scyllac bank (Fig. 3).

3. Trigger System. The implosion-start gap, the implosion-crowbar gap, and the staging start gap are multichannel devices which require a substantial trigger pulse to ensure proper multichannel operation. Thus, the trigger system must have a higher performance than is presently available in the Scyllac trigger system.

The Staged Theta-Pinch machine uses essentially the same gaps as the Staged Scyllac, and thus has a trigger system which should be satisfactory for the Staged Scyllac; however, it is believed that the Staged Theta-Pinch trigger system is marginal in risetime which is 20 ns, voltage amplitude which is 180 kV, and system voltage operating limits. An alternate trigger system has, therefore, been designed for the Staged Scyllac Prototype which has potentially improved performance. The trigger system is illustrated in Fig. 10. The transfer cable is pulse-charged in 2 to 3 μ s to 180 kV; simultaneously the 500-pF capacitor is charged through the 15- μ F inductor. Upon triggering, the spark gap shorts out one end of the cable producing a 230-kV pulse with a risetime of less than 20 ns at the other cable end. A pulse-sharpening gap is used to decrease the trigger-pulse risetime as seen by the gap trigger electrode. NET-2 network simulations indicate the new trigger system delivers 1.4 times the energy delivered by the Staged Theta-Pinch trigger system in the same period of time with similar cable lengths and charge voltages. The new Staged Scyllac trigger system also has the added advantage of less hardware and lower system voltages as compared to the earlier Staged Theta-Pinch design. In addition, the new trigger system has improved trigger

Fig. 10. Representative Staged Scyllac Prototype multichannel trigger system.

cable isolation when multiple cables are switched by a single spark gap. A comparison of trigger systems is presented in Table VI. The buffer systems section includes the pulse-charged cable and the dc-charged cable trigger systems.

Two improvements in the present Scyllac trigger system will also be incorporated in the Staged Scyllac prototype. First, the buffer transformer assembly, which is currently used in Scyllac to initiate the trigger system and other major systems, produces an 80-kV pulse with a risetime of 80 to 100 ns. This risetime is too long to trigger the various implosion and staging spark gaps with a jitter of less than 20 ns. Therefore, a new pulse-charged cable buffer system, shown in Fig. 11, has been designed and tested. This system will be used in the Staged Scyllac prototype and is expected to be installed in the Staged Scyllac. This system uses the same trigger-pulse power supply that charges the transfer cable to charge the buffer trigger cable to one-third the transfer cable voltage. At peak charge voltage, the buffer gap is triggered with an 8-kV pulse transformer producing a 30-kV pulse with 40-ns risetime. The buffer spark gap shorts the buffer cable which produces a trigger pulse for the master gap. The buffer gap can be triggered with a jitter of ± 10 ns. This performance is due to the center electrode of the buffer gap which is split mechanically and electrically. The 8-kV pulse-transformer voltage initially produces a small arc between the two halves of the center electrode which produces photoelectric emission at the center electrode and serves as a pulse-sharpening gap for the voltage pulse seen by the floating half of the center electrode. The photoelectric irradiation reduces the

TABLE VI
COMPARISON OF TRIGGER SYSTEMS

	<u>STP</u>	<u>SSP</u>
A. Multichannel Trigger Systems		
1. Trigger Amplitude	180 kV	200 kV
2. Risettime into 1 k Ω	≤ 20 ns	≤ 20 ns
3. Pulse Length	100 ns	100 ns
4. Maximum System Voltage	300 kV	200 kV
5. Number of Shots without Maintenance	5,000	10,000
B. Buffer Trigger Systems		
1. Trigger Amplitude	80 kV	100 kV
2. Risettime into 1 k Ω	≤ 10 ns	≤ 10 ns
3. Pulse Length	100 ns	100 ns
4. Maximum System Voltage	80 kV	100 kV
5. Number of Shots without Maintenance	10,000	10,000

Fig. 11. Pulse-charge cable buffer system.

jitter and reduces the trigger-input power necessary to switch the gap.

A dc-charged cable buffer system will also be used to trigger the staging-crowbar trigger capacitors and the implosion-capacitor charge Marxes which are shown in Fig. 4. This trigger system is shown in Fig. 12. The power supply that charges the capacitor to be triggered also charges the buffer cable. The buffer gap, which is triggered with a 30-kV, 40-ns risetime pulse from an 8-kV pulse transformer, shorts the buffer cable and triggers the capacitor spark gap.

The second modification of the present Scyllac trigger system will be the use of fiber-optic trigger channel isolation between the screen/control room and the various systems. This system is illustrated in Fig. 13. A timing unit with multiple outputs feeds multiple fiber-optic drivers inside the screen room. At the end of each fiber optic, a receiver detects the light pulse and triggers an 8-kV krytron pulse-transformer combination. Compressed air is supplied to each 8-kV pulser to drive an alternator that supplies power for the krytron high voltage and the optical receiver. The compressed-air alternator system is presently employed on systems manufactured by Boeing Aerospace Corp. and is expected to be available commercially. The system provides for isolation of the individual trigger channels outside the screen room where electromagnetic interference and crosstalk problems are severe.

4, Gap-Monitoring System. Another problem evident in the Scyllac component diagnostic system is the spark-gap monitor. The present system uses electronic components in the harsh electromagnetic

Fig. 12. DC-charged cable buffer system.

Fig. 13. Optical trigger isolation system.

environment of the Scyllac machine and is subject to frequent malfunctions. Many problems have been solved with the present system but further work is indicated.

A new gap-monitor system, which is expected to be immune to the harsh environment of Scyllac, is being developed for the prototype. The system will monitor the staging-crowbar gaps (120 each) and the staging-crowbar trigger gaps (12 each) with a fiber-optic system that utilizes only spark-gap light. The light will be transmitted via a fiber-optic channel into the screen room where data processing can take place in a quiet environment. The system is shown in Fig. 14. The spark gaps that fire within the 500 ± 10 ns interval after staging-crowbar initiation will be displayed on a panel in the screen room with the timing interval being determined from a gate controlled by the digital timing unit. The monitor-system reliability goal is 0.95.

5. Overall System Reliability. The reliability of the Staged Scyllac system depends on the reliability of the individual components. The high reliability of 3150 start and 3150 piggyback crowbar gaps, as well as 3150 capacitors and 20,160 load cables has already been demonstrated in the present Scyllac system. A major problem in overall system reliability of the Scyllac system has been the crowbar-trigger cables. A new, larger crowbar-trigger cable with a higher voltage rating will be initially installed in the Staged Scyllac Prototype. The cables will be evaluated in the prototype, and if the results are positive, the cables will be used immediately in the present Scyllac. This will increase the reliability of the Scyllac, as well as the Staged Scyllac.

Fig. 14. Staging crowbar-gap monitoring system.

The reliability of the various spark gaps and trigger systems that will be added to the present Scyllac will to a large extent determine the overall system reliability since the reliability of the rest of the system (present Scyllac) has been found to be high.

The present Scyllac system produces a good plasma shot 80 out of 100 bank shots. The number of various components now present or to be added or removed for the Staged Scyllac is shown in Table VII. The relatively small number of additional gaps and capacitors necessary to turn the present Scyllac into Staged Scyllac, and the removal of 3150 start gaps now presently used, implies that at least comparable reliability can be achieved.

TABLE VII
COMPONENTS IN STAGED SCYLLAC

<u>Component</u>	<u>Number</u>
Present Scyllac	
Main Bank Capacitors	3,360
Crowbar Gaps	3,360
Individual Load Cable	20,160
Crowbar-Trigger Capacitors	336
Crowbar-Trigger Gaps	336
Individual Crowbar-Trigger Cables	3,360
Additional: Staged Scyllac	
Implosion Start Gaps	336
Implosion Crowbar Gaps	112
Staging Start Gaps	336
Implosion Capacitors	336
Multichannel Master/Submaster Gaps	80
Buffer Cable Gaps	25
Remove: Staged Scyllac	
Start Gaps	3,150

The electrical reliability of the individual multichannel spark gaps and the trigger systems must be developed to the point that required mechanical maintenance is the limiting operational failure. The multichannel gaps will be developed to the point that only a trigger-system failure or necessary mechanical maintenance will produce a prefire, post-fire or nonfire. The trigger systems must be much more reliable than the gap systems. Therefore, the trigger systems will be developed to have a much larger mechanical reliability as indicated in Tables III, IV, V, and VI. In this manner, a high system reliability can be obtained.

An overall system failure is determined by the criterion that a total of 5% of any one component excluding trigger systems fail or malfunction during one shot. Using this criterion and the above indications, the prototype goal is to develop the overall system reliability to the point that less than 100 system failures occur in 1000 shots.

E. Mechanical Layout

The Staged Scyllac Prototype will be located in Room 186, SM 105, TA-3, Los Alamos Scientific Laboratory. This room originally housed the Zeus bank which has recently been removed. A photograph of Room 186 is shown in Fig. 15. The power supplies, screen room, and control racks will be located in adjacent Room 184 which is pictured in Fig. 16.

The collector-plate arrangement is shown in detail in Fig. 17. The overall engineering layout is illustrated in Fig. 18. The prototype system will be located on three levels of structure. The collector-plate assembly of Fig. 17 and half of the 120 Scyllac-type staging capacitors are located on the second level. The remaining staging capacitors are located on the first level. The trigger systems are located on the third level.

Fig. 15. Room location for prototype. (Room 186, Bldg. SM-105).

Fig. 16. Adjacent room for prototype power supplies and screen room. (Room 184, SM-105).

Fig. 17. Layout of Staged Scyllac Prototype collector-plate assembly.

Fig. 18. Overall layout of Staged Scyllac Prototype.

VII. ADDITIONAL DEVELOPMENT

The primary objective of the implosion-heating circuit is to bring the initial shock field to approximately 10 kG in 400 ns or less. The peak field and risetime depends upon the plasma reaction as well as the circuit parameters and therefore cannot be predicted by a simple circuit model. The 125-kV implosion-heating circuit design presently used in the Staged Theta Pinch was based on the plasma physics results and the technological state-of-the-art which was available at the time of design. As research on the Staged Theta-Pinch experiment and analytical work continue, however, it is possible that results will indicate that a higher voltage, lower inductance circuit and components should be employed.

To meet this contingency, a parallel component development program is being initiated to develop a 150- to 160-kV capacitor in a low-inductance configuration. Care is being taken to ensure that the capacitor will fit into the Staged Scyllac layout with as little mechanical modification as possible to the gaps and collector plate. Also, increasing the voltage from 125 kV to 150-160 kV is expected to require relatively minor electrical modifications to the gaps and trigger system.

VIII. COST ESTIMATE AND SCHEDULING

A. Budget

The total cost estimate for the Staged Scyllac prototype is \$428K for machine construction and \$128K for capital equipment. Table VIII is a listing of the major procurement items required for the prototype.

TABLE VIII
COMPONENT LIST FOR STAGED SCYLLAC PROTOTYPE

<u>Item</u>		<u>Quantity</u>	<u>Cost Estimate</u>
1.	0.2- μ F, 125-kV Capacitors	6	\$ 4K
2.	0.4- μ F, 125-kV Capacitors	6	5
3.	1.85- μ F, 60-kV Capacitors	120	70
4.	2.85- μ F, 60-kV Capacitors	16	12
5.	0.25- μ F, 25-kV Capacitors	10	3
6.	0.7- μ F, 75-kV Crowbar Capacitors	12	7
7.	Implosion Start Gaps	12	12
8.	Staging Gaps	12	24
9.	Rail Crowbar Gaps	6	6
10.	Scyllac-Type Crowbar Gaps	120	54
11.	Maxi-Marx Gaps	4	5
12.	Maxi-Marx Hardware		3
13.	Mini-Marx System		24
14.	Master/Submaster Gaps		15
15.	Buffer Transformers		5
16.	Triggering System		12
17.	Charging System		12
18.	Control System		10
19.	Collector Plate/Coil/Header		10
20.	Structural		4
21.	Cable		3
22.	Miscellaneous Hardware		25
		TOTAL	\$325K

The estimate for craft labor is \$15K and for technician support is \$50K. Ten percent is allowed for contingency. The total construction budget is summarized in Table IX.

TABLE IX
CONSTRUCTION BUDGET FOR STAGED SCYLLAC PROTOTYPE

Major Procurement	\$325K
Craft Labor	15
Technician	50
	<u>\$390</u>
Contingency 10%	38
	<u>38</u>
TOTAL	\$428K

The capital equipment required for the prototype is given in Table X.

TABLE X
CAPITAL EQUIPMENT LIST FOR STAGED SCYLLAC PROTOTYPE

1.	Screen Room	\$ 14K
2.	60-kV, 200-mA Power Supply	6
3.	60-kV, 100-mA Power Supply	4
4.	75-kV, 25-mA Power Supply	3
5.	Digital Pulser System	40
6.	Transient Recorders	34
7.	Oscilloscopes	25
8.	Miscellaneous	<u>2</u>
TOTAL		\$128K

B. Scheduling

Figure 19 shows a PERT chart for the prototype program. The development of the implosion-circuit start gap is well along; however, several additional weeks of development will be required for the staging gap. It will also take between three and four months to procure all the required components for the machine, which can be done simultaneously with the gap development. Table XI lists the important PERT chart target dates determined from a starting month-day of 0-1.

Fig. 19. PERT chart for the Staged Scyllac Prototype.

TABLE XI
PERT CHART TARGET DATES

Function	Month-Day	
	Start	Complete
1. Develop Implosion Start Gap	0-1	2-1
2. Develop Staging Start Gap and Cable Cartridge	2-1	4-1
3. Develop Implosion Crowbar Gap	4-1	5-1
4. Test Implosion System and Develop Reliability	5-1	6-1
5. Test Staging System and Develop Reliability	7-1	8-1
6. Test Implosion System with Crowbar	8-1	9-1
7. Develop Total System Reliability without Plasma	9-1	12-1
8. Develop Field Profile with Plasma	12-1	18-1

REFERENCES

1. K. Boyer, W. C. Elmore, E. M. Little, and W. E. Quinn, "Neutrons from Plasma Compressed by an Axial Magnetic Field (Scylla)," Proc. Intern. Conf. Peaceful Uses At. Energy, 2nd, (United Nations, Geneva, 1958), Vol. 32, p. 337.
2. E. M. Little, W. E. Quinn, F. L. Ribe, and G. A. Sawyer, "Studies of Stability and Heating in the Scylla Magnetic Compression Experiment," Nucl. Fusion - 1962 Supplement, Part II, p. 497.