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Lawrence Livermore Laboratory

DIAGNOSTIC MEASUREMENTS RELATED TO LASER DRIVEN INERTIAL CONFINEMENT FUSION

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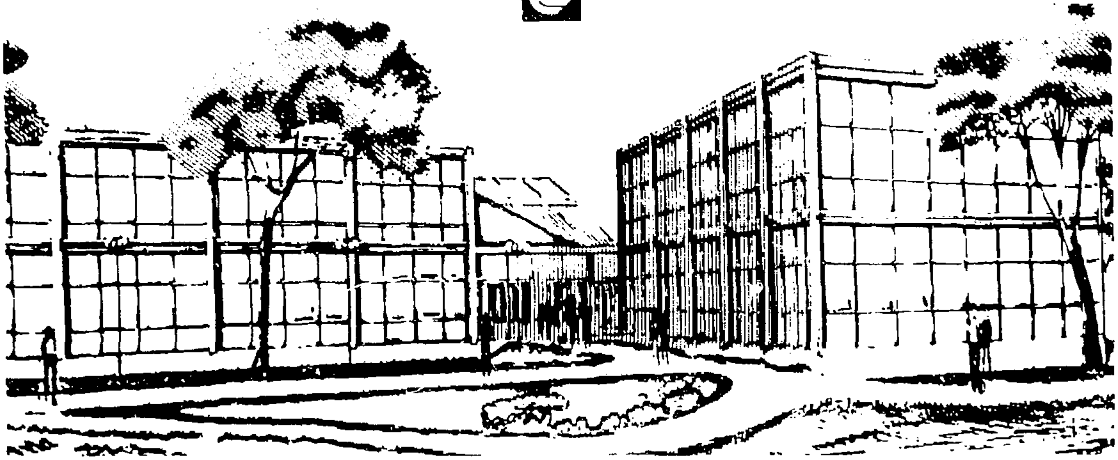

DIAGNOSTIC MEASUREMENTS RELATED TO LASER DRIVEN INERTIAL CONFINEMENT FUSION *

INTRODUCTION

Scientists at the Lawrence Livermore Laboratory have been conducting laser driven inertial confinement fusion experiments for over five years. The first proof of thermonuclear burn (successful fusion) came at the Janus target irradiation facility in the spring of 1975. Since that time three succeedingly higher energy facilities have been constructed at Livermore, Cyclops, Argus and Shiva, where increased fusion efficiency has been demonstrated. A new facility, called Nova, is now in the construction phase and we are hopeful that scientific break even (energy released compared to incident laser energy on target) will be demonstrated here in the early 1980's. Projected progress of the Livermore program is shown in Figure 1.

PAPER OUTLINE

I will discuss the following items related to laser fusion diagnostics.

- Inertial Confinement Fusion
- Diagnosing the Fusion Process
- Electronic Instrumentation
- Picosecond Diagnostics
- Instrumentation Timing and Triggering

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INERTIAL CONFINEMENT FUSION

Fusion is the process of combining or "fusing" atoms of an element together to form a heavier element. In this fusion process, other elemental atomic particles are released that can be captured and their energy converted to heat for use in generating electricity. A conceptual drawing of a laser driven inertial confinement fusion power plant is shown in Figure 2. In our work at Livermore we use hydrogen isotopes, deuterium or tritium, or a mixture of the two, as the atoms to be fused. The fusion reaction formulas for these isotopes are:

$$D + T \longrightarrow \underset{(3.5\text{MeV})}{{}^{4}\text{He}} + \underset{(14.1\text{MeV})}{n}$$

$$D + D \longrightarrow \underset{(0.82\text{MeV})}{{}^{3}\text{He}} + \underset{(2.45\text{MeV})}{n}$$

Approximately the
same probability
of occurrence.

$$D + D \longrightarrow \underset{(1.01\text{MeV})}{T} + \underset{(3.02\text{MeV})}{H}$$

A pictorial representation of the D-T reaction is shown in Figure 3. Notice that the sum of the mass of the particles released is less than the sum of that of the reacting atoms. The difference represents the energy released in the reaction. The efficiency of the reaction, or percent of burn, depends upon the $(n\tau)$(density, containment time, product). This product is referred to as Lawson's criterion and must reach 10^{14} for fusion to occur. In magnetic fusion, containment times are long ($\sim$seconds) and densities are low. In inertial confinement fusion containment times are very short ($\sim$1ns) and densities are correspondingly high. Because the fuel is burned in such a very short time there is no concern about containment of the plasma as inertia prevents the fuel from escaping. Hence the definition "inertial confinement fusion" to our laser driven work. The temperature of this burning fuel or plasma reaches 10^8 degrees Kelvin. In laser driven inertial confinement fusion, we use a glass microballoon to contain the fuel mixture (~ 2 mg/cm^3). This microballoon is 100 to 300 meters in diameter with an approximately 10 μmeter wall thickness. A picture of a typical microballoon is shown in Figure 4. The laser beams, usually two or more, are focused on this "target" with conventional focusing lenses. The focused laser beam spot is of the same order as the target diameter. When the incident laser beam hits the target (100 ps to 1 ns temporal width) energy is absorbed by the glass shell which ablates away the surface. This causes a rocket effect, driving the remaining glass inward, compressing the fuel. The fusion process releases energy in the form of alpha particles, neutrons, electrons and ions as well as a wide spectrum of electromagnetic radiation. (IR to Gamma Rays)

DIAGNOSING THE FUSION PROCESS

It is the task of target diagnosticians to determine as much as possible about the fusion process of each laser/target interaction experiment. The diagnostic measurements lead to a more complete understanding of the fusion process. The theoreticians are very interested in improving their models to reflect experimental insight obtained from our measurements. The target designers use the diagnostics data to optimize future target designs. A not so apparent but exciting benefit of these measurements is the discovery and further understanding of new basic physical processes.

Understanding the complex results of even the slightest experimental parameter change (target, laser, focus, etc.) requires a complete diagnostics data package on each interaction experiment. This includes the precise measurement of:

a. Absorbed laser energy.
b. Scattered and reflected laser energy and its polarization.
c. Alpha particle flux and spectrum

d. X-ray flux and spectrum
e. Neutron yield and spectrum
f. Ion flux and spectrum
g. Electron flux and spectrum
h. Compression

We attempt to measure all of these parameters in as near to real-time as possible so that their origins may be more clearly understood. This proves to be very complex and, therefore, costly at the time scales of inertial confinement fusion where the fuel burning occurs in one nanosecond or less. Therefore, many of the electronic measurements are time integrated, permitting a larger number of channels to be implemented at a greatly reduced cost. A summary of the general parameters of interest for inertial confinement fusion and their range are shown in Figure 5. In the discussion that follows, I will concentrate on the electronic instrumentation required to support diagnostic measurements of these parameters. However, many excellent diagnostic measurements are conducted using passive sensors such as photographic film. A microdensitometer scanned and computer color generated x-ray emission from a target is shown in Figure 6. This is an x-ray microscope photograph obtained using grazing incidence reflection from cylindrical mirrors.

ELECTRONIC INSTRUMENTATION

It should be obvious that the electronic instrumentation used to make these diagnostic measurements is very unique. As a result, much of the instrumentation and its associated electronic circuitry must be developed in-house. In addition, particular attention must be given to sensor placement. Particularly its cable routing and grounding. The Argus and Shiva target chambers with their associated diagnostic cabling are shown in Figures 7 and 8 respectively. Figure 9 shows, in model form, the Shiva target chamber relative to the entire system. Our instrumentation philosophy for diagnosing laser/target interactions has evolved over a five year span based on techniques evaluated at our fusion irradiation facilities at Livermore.(1,2) (Janus, Cyclops, Argus and Shiva) A single point grounding scheme is mandatory for each instrumentation installation due to the potential interference pickup problem of electrical noise generated while pumping the laser amplifiers and driving the optical switches. Single point grounding also minimizes the electrical cross coupling between experiments. The analog signals are digitized as near as practical to the diagnostic sensor thereby minimizing noise pickup in the analog signal cabling. The digitized data is then transmitted to a central recording area using a fiber optic serial data link.(3) Control functions are also implemented via this same link. These control signals are also interconnected using fiber optics preventing noise pickup in the instrumentation electronics.

A TYPICAL INSTRUMENTATION SYSTEM

A block diagram of a typical diagnostics instrumentation system is shown in Figure 10. This particular example consists of NIMS(4) bins and CAMAC(5) crates, their respective modules, a central data acquisition computer and several conventional oscilloscope recording channels. Photographs of the instrumentation and data reduction computer used at the Argus facility are shown in Figures 11 and 12. The NIMS and CAMAC instrumentation concepts are particularly useful in laser fusion target diagnostic systems. This equipment provides a hardware framework that permits quick and efficient system reconfiguration. Similarly, a modular software package provides efficient data acquisition system reconfiguration.

MEASURING SCATTERED LASER ENERGY FROM THE TARGET

In the Shiva target chamber, an array of some 40 photodiodes monitor the scattered and reflected 1.06 μm laser energy from the target pellet.

The total charge output from each photodiode is measured by a CAMAC module developed at LLL for this purpose. (Figure 13) Each module provides 4 channels of bipolar current integration. The full scale sensitivity of each channel within each module is computer programmable. Each silicon photodiode has a leaded glass filter in front of it to prevent x-rays from reaching the PN junction. The output of each photodiode is integrated, held by a sample and hold circuit and then digitized by an A/D converter. The data is stored locally within the CAMAC module to be interrogated at the convenience of the data acquisition system.

A second method in use at the Shiva and Argus facilities for measuring scattered laser energy is that of calorimetry. Here a sensitive thermoelectric module is used to detect the incident energy and the output voltage is recorded as a function of time. A unique calorimeter recording system has been developed for these measurements. A cigar shaped amplifier shown in Figure 14 amplifies each calorimenter output signal by a factor of one thousand at the target chamber feedthru flange. This larger signal is cabled to a CAMAC module with a programmable gain of 1, 10, 100 or 1000 to provide a maximum gain capability of 10^6 for each channel. The CAMAC module can service 16 channels simultaneously and the gain of each channel is computer programmable. This CAMAC module is shown in Figure 15. The 16 amplified output signals are then digitized by a slow transient digitizer module. The entire waveshape (64 data points) of each calorimeter is maintained in the transient digitizer module.

The data acquisition system acquires the data from each CAMAC module based on the acquisition priority established by the system operators. The digitized data is stored on a floppy disc which is then transferred by hand to a larger data processing computer for hard copy readout in the format requested by the experimentalist. The diagnosticians evaluate this scattered 1.06 μm data to better understand the absorption of laser energy by the target. Target design and focusing schemes are then revised on future experiments to optimize energy coupling.

COMPUTERS

Computers are indispensable in our inertial confinement laser fusion research. A drawing of the Shiva system computers architecture is shown in Figure 16.

HIGH SPEED DIAGNOSTICS

We would like to diagnose the x-ray generation from the burning pellet in real time. The fastest real time oscilloscopes manufactured in the U.S.A. are the Tektronix 7900 series and their newest instrument, the 7104, both having a 1 GHz bandwidth. EG&G, in support of DOE nuclear testing, manufacturers a high speed travelling wave oscilloscope with an approximately 2 GHz bandwidth. The highest bandwidth oscilloscope available in the world today, to my knowledge, is manufactured in France. It has a 4 GHz bandwidth and sells for $90 K per unit. We have five of these instruments for high speed fusion diagnostic measurements at LLL. A photograph of the French oscilloscope is shown in Figure 17. We have also developed a 50 psec response x-ray detector. This detector is used in conjunction with the French oscilloscope to provide a 110 psec response x-ray diagnostic system. A cut-away drawing of this detector is shown in Figure 18. Another very useful instrument for high speed data recording is the streak camera. We have developed at LLL streak cameras sensitive to x-ray wavelengths. The streak camera has a temporal resolution of 2 - 5 picoseconds. The conceptual drawing of an ultrafast framing camera is shown in Figure 19. This framing camera permits several 10 to 50 psec "snapshots" of the incident image on the photocathode.

INSTRUMENTATION TIMING AND TRIGGERING

Many of the instruments used for fusion diagnostics require a pretrigger for proper operation. We obtain this trigger by one of several methods. The first and most straight forward method is to use a portion of the switched out laser pulse propagated through the room and steered with mirrors, finally focusing onto a photodiode whose output signal is used for triggering the instruments. Another method is to use a central photodiode with a larger fraction of the beam incident on it. From this central location, the trigger pulses are regenerated to be transmitted to instruments via fiber optics or coaxial cable. Another method used for slower data recording is to use the computer data acquisition system to supply the trigger over the serial data highway. The target room timing sources for the Shiva facility are shown in Figure 20.

SUMMARY

I have discussed just a few of the many diagnostic measurement techniques and instruments used in our laser driven inertial confinement fusion studies at Livermore. We are continually seeking and researching new methods for improving our measurement techniques. The world of fusion diagnostics promises to be a continually challanging endeavor.

References

1. See LLL Laser Fusion Program Annual Report for 1974, 1975, 1976, 1977.
2. D. Campbell, J. Severyn, The Electronics of the Target Diagnostics System for the Shiva Laser Fusion Facility, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-52521 (1978).
3. J. R. Severyn, Serial Fiber Optic Link, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-79279 (1976).
4. U. S. AEC-Report TID-20893 (Rev. 3) December 1969, Standard Nuclear Instrumentation Modules (Specifications of the NIM System).
5. IEEE Stds. 583-1975 and 595-1976 (IEEE, New York, N. Y.).

Figures

LASER FUSION – PROGRESS/PROJECTIONS

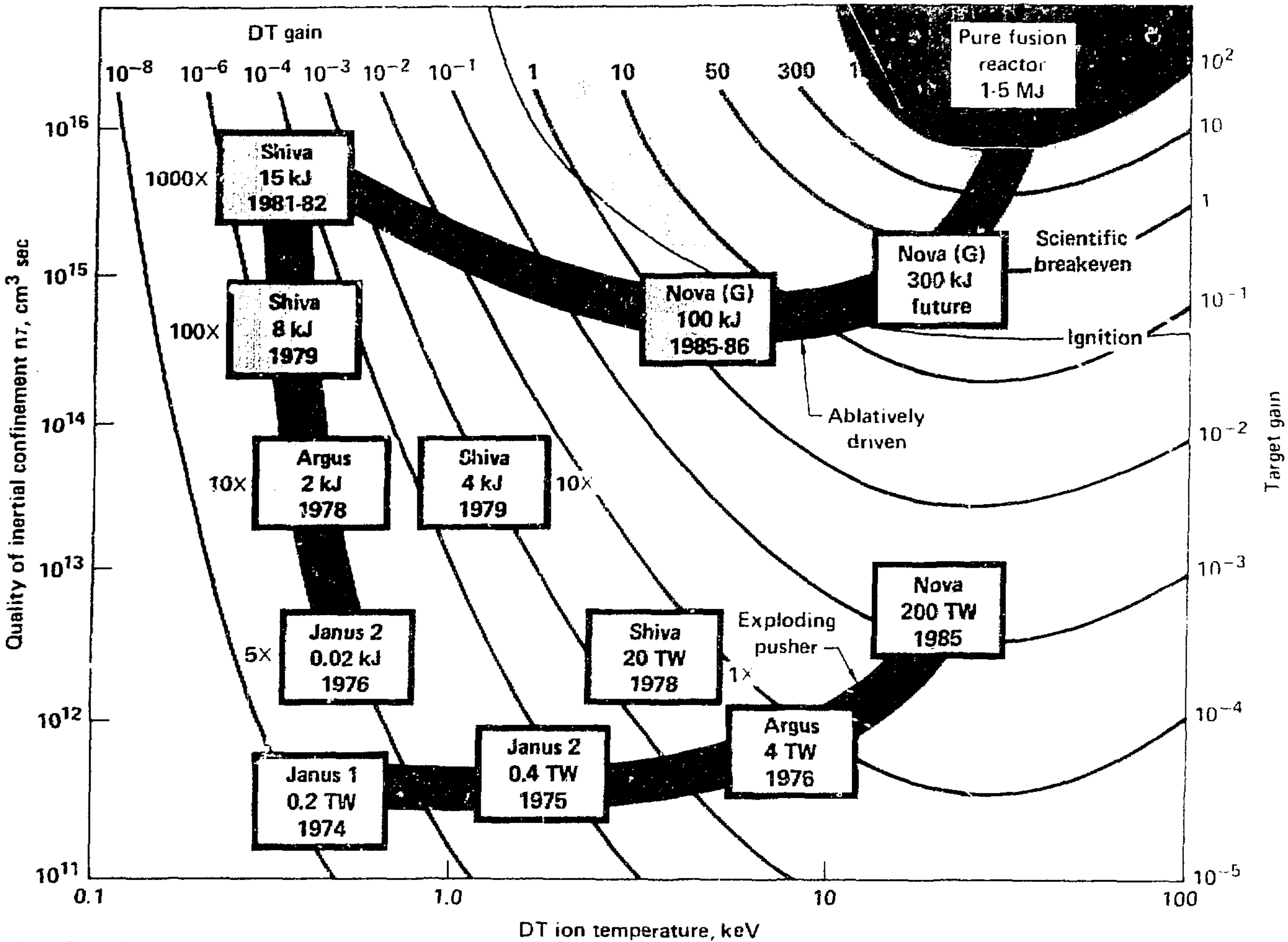

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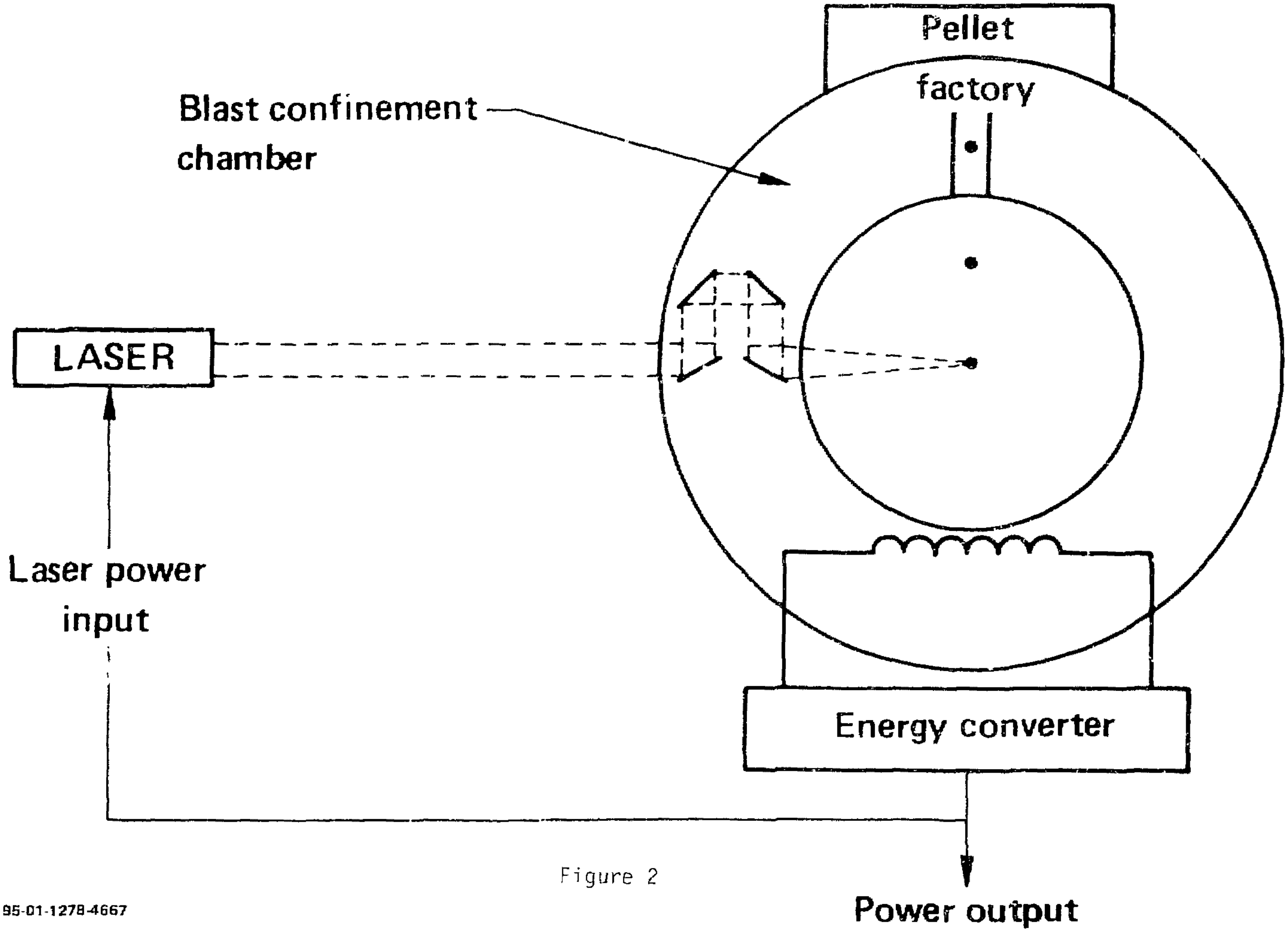
Figure 1

CONCEPTUAL LASER FUSION REACTOR



Pellet factory

Blast confinement chamber

LASER

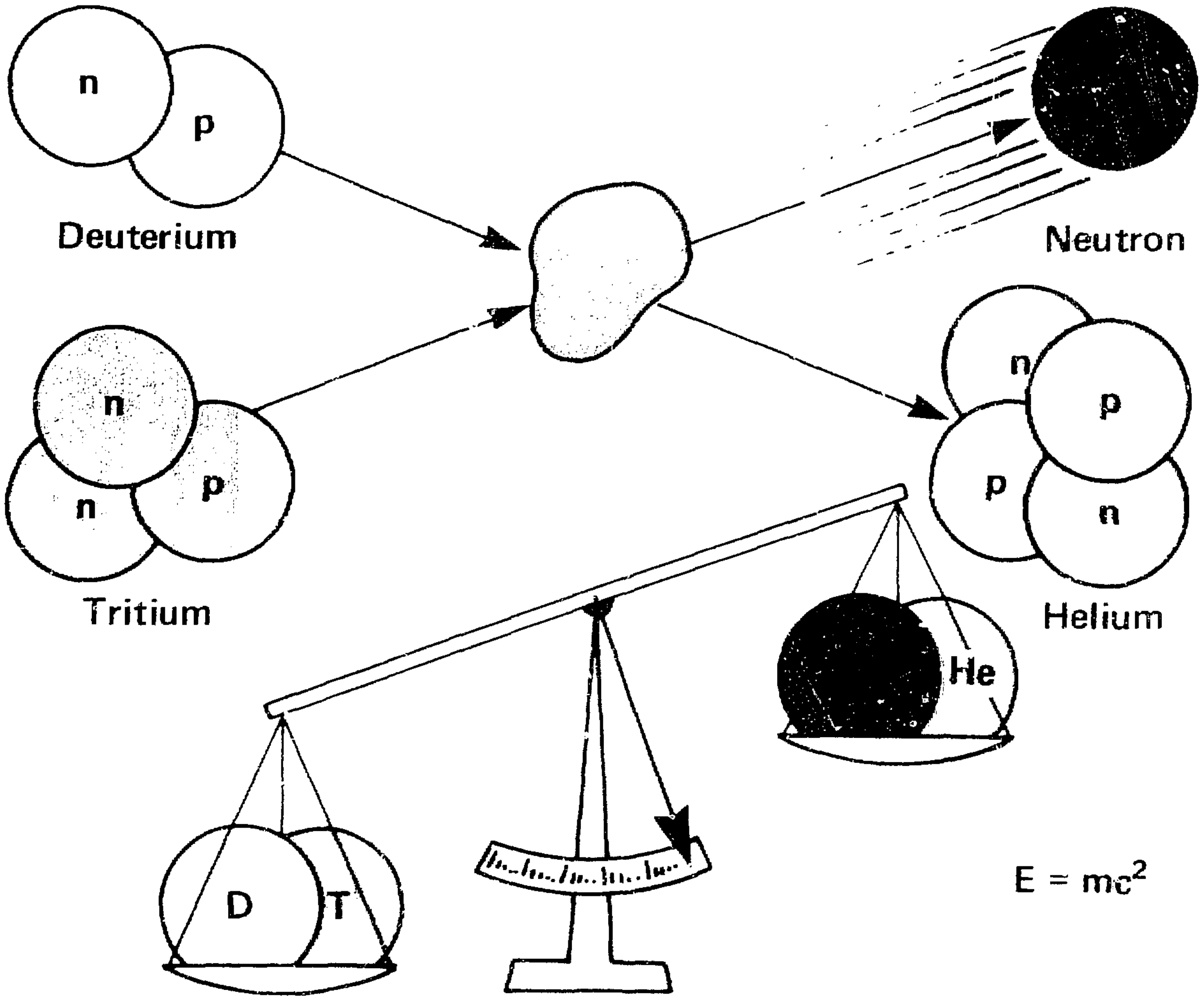
Laser power input

Energy converter

Power output

Figure 2

D-T FUSION REACTION



$E = mc^2$

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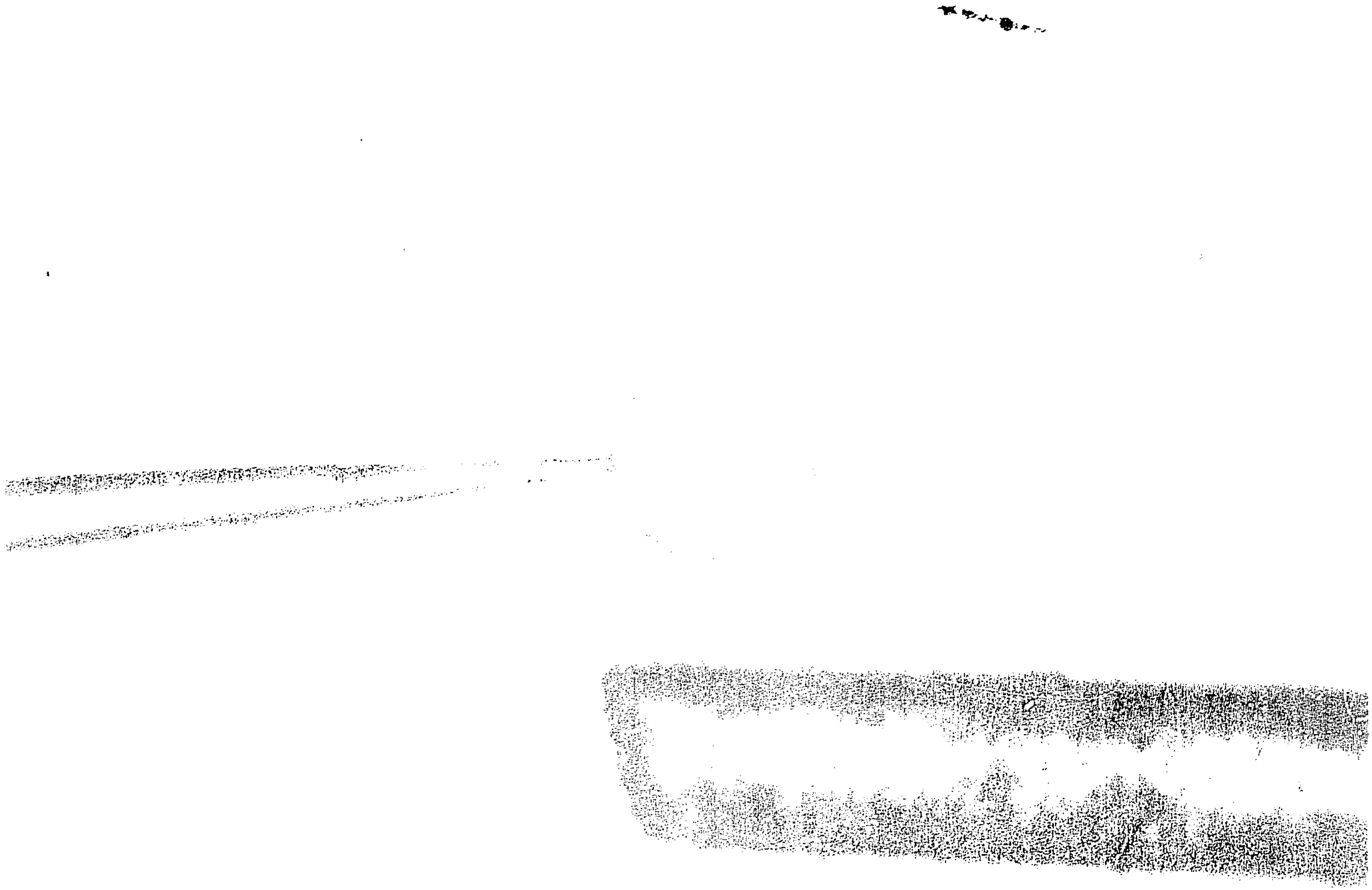
Figure 3



TYPICAL TARGET MOUNTED ON STALK

Figure 4

LASER FUSION DIAGNOSTICS REQUIREMENTS

$10^{16} < N_E < 10^{26}\ \mathrm{cm}^{-3}$

$1\ \mathrm{eV} < H_\nu < 50\ \mathrm{keV}$

$1\ \mathrm{eV} < E < 15\ \mathrm{meV}$

$1000\text{Å} < \Delta x < 1\ \mathrm{cm}$

$1\ \mathrm{ps} < \Delta t < 20\ \mathrm{ns}$

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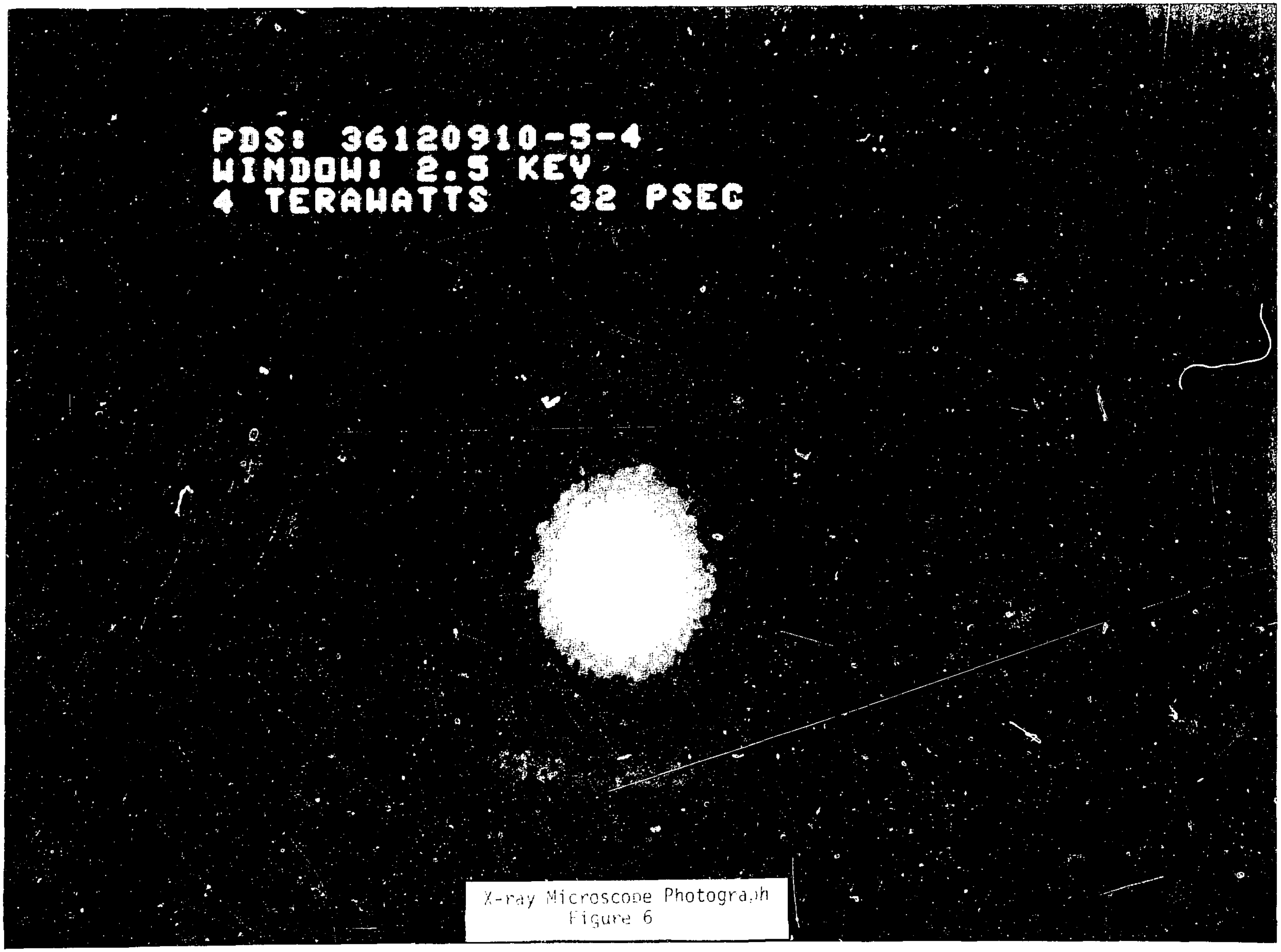
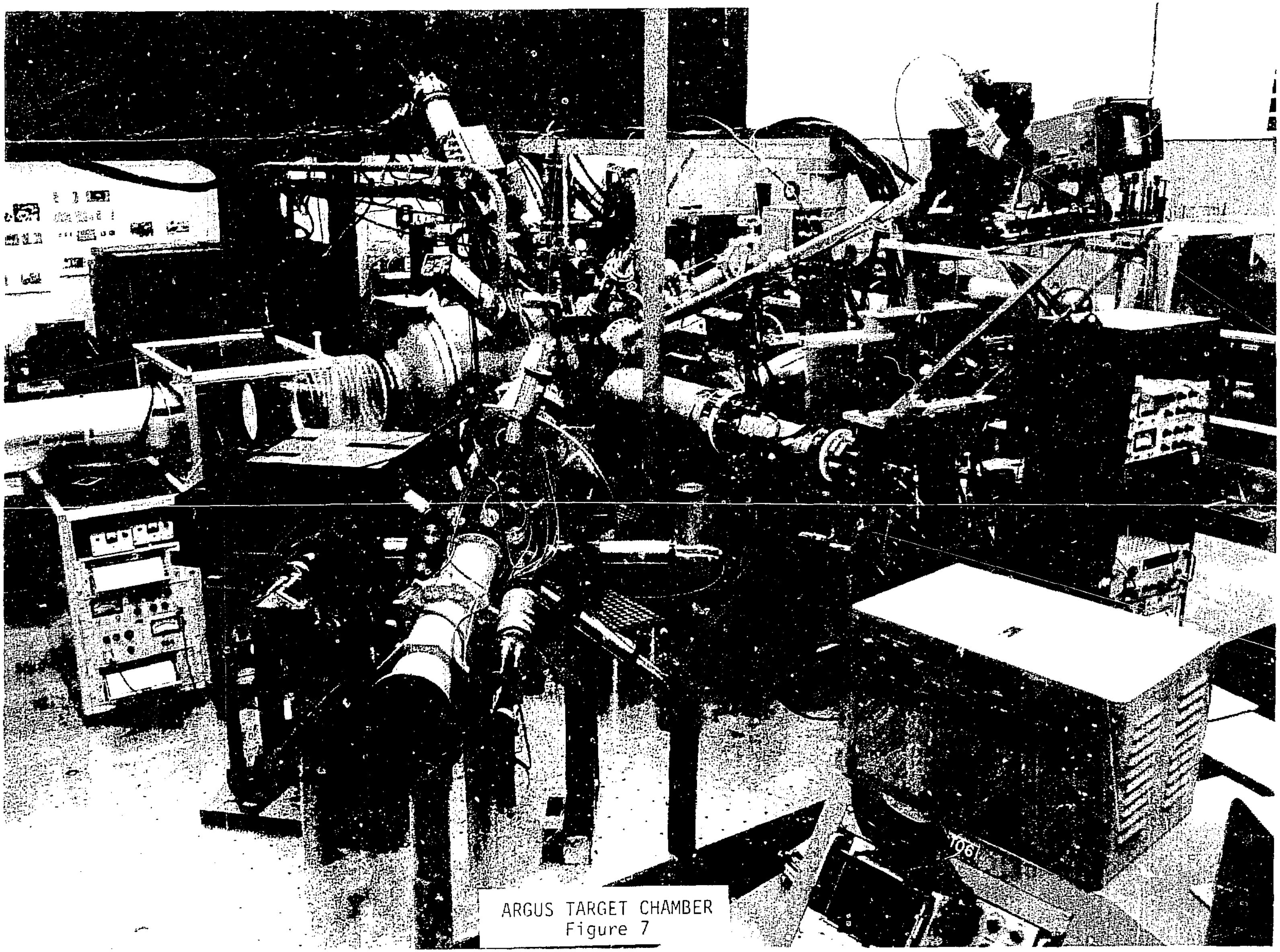
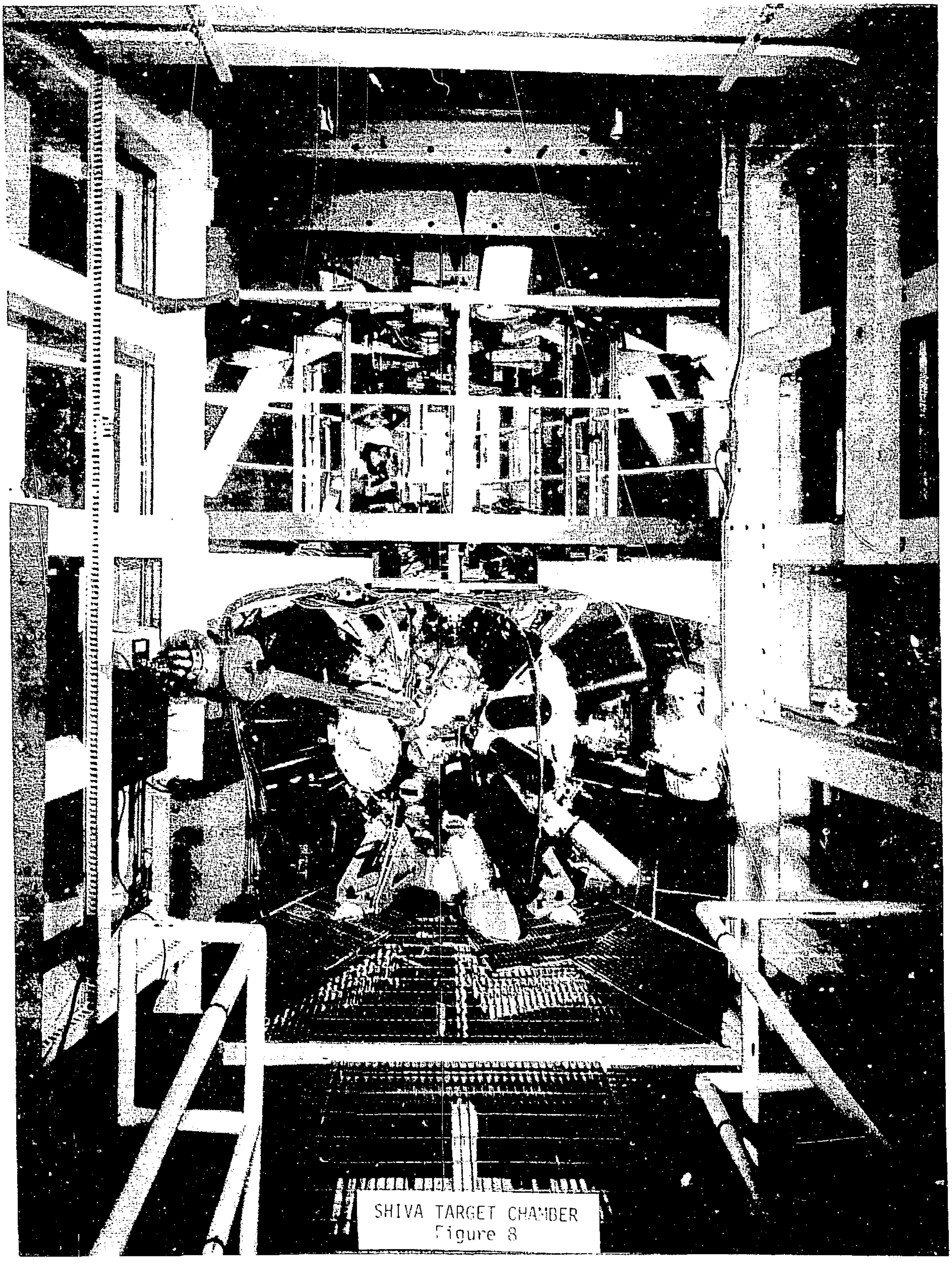
Figure 5



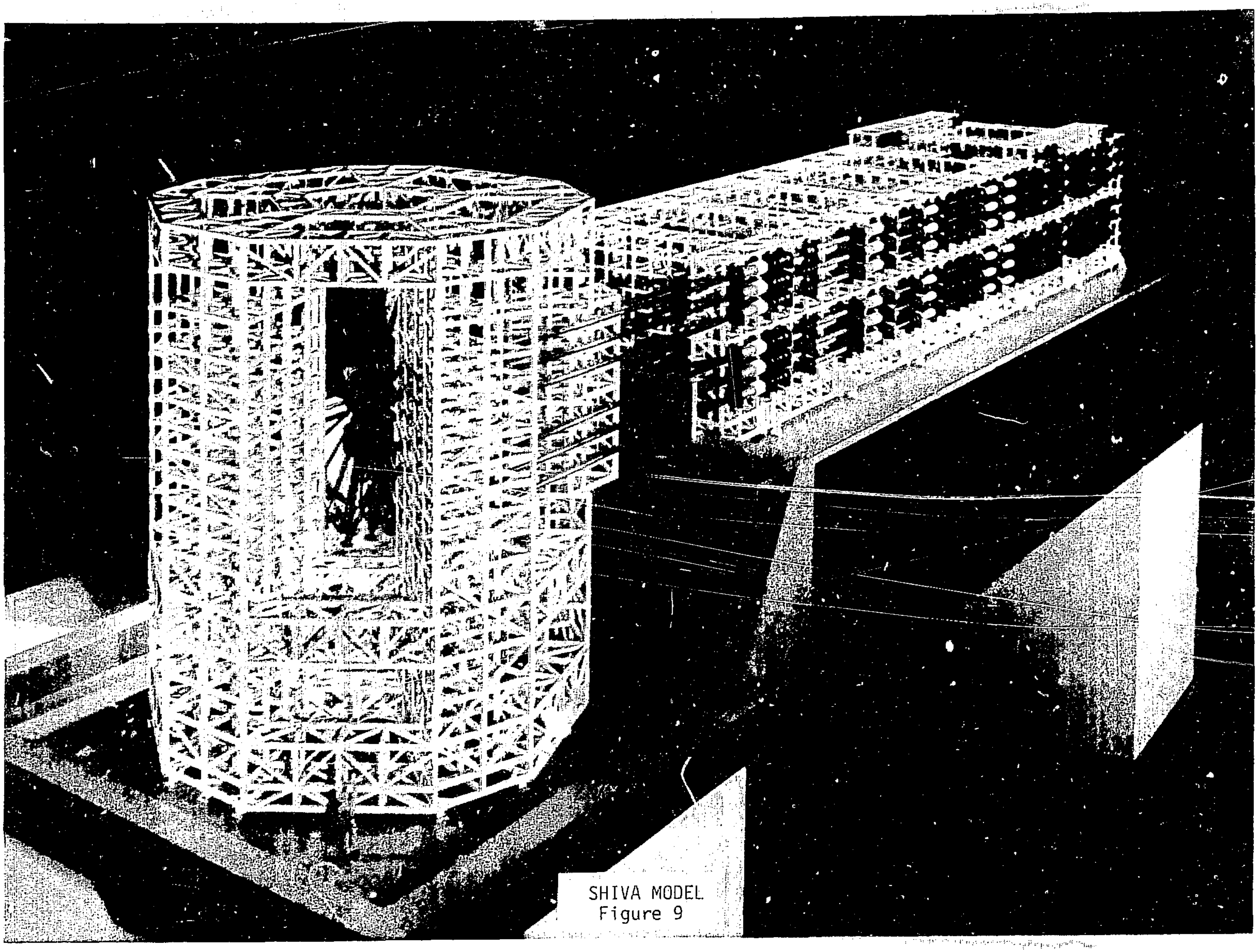
X-ray Microscope Photograph
Figure 6



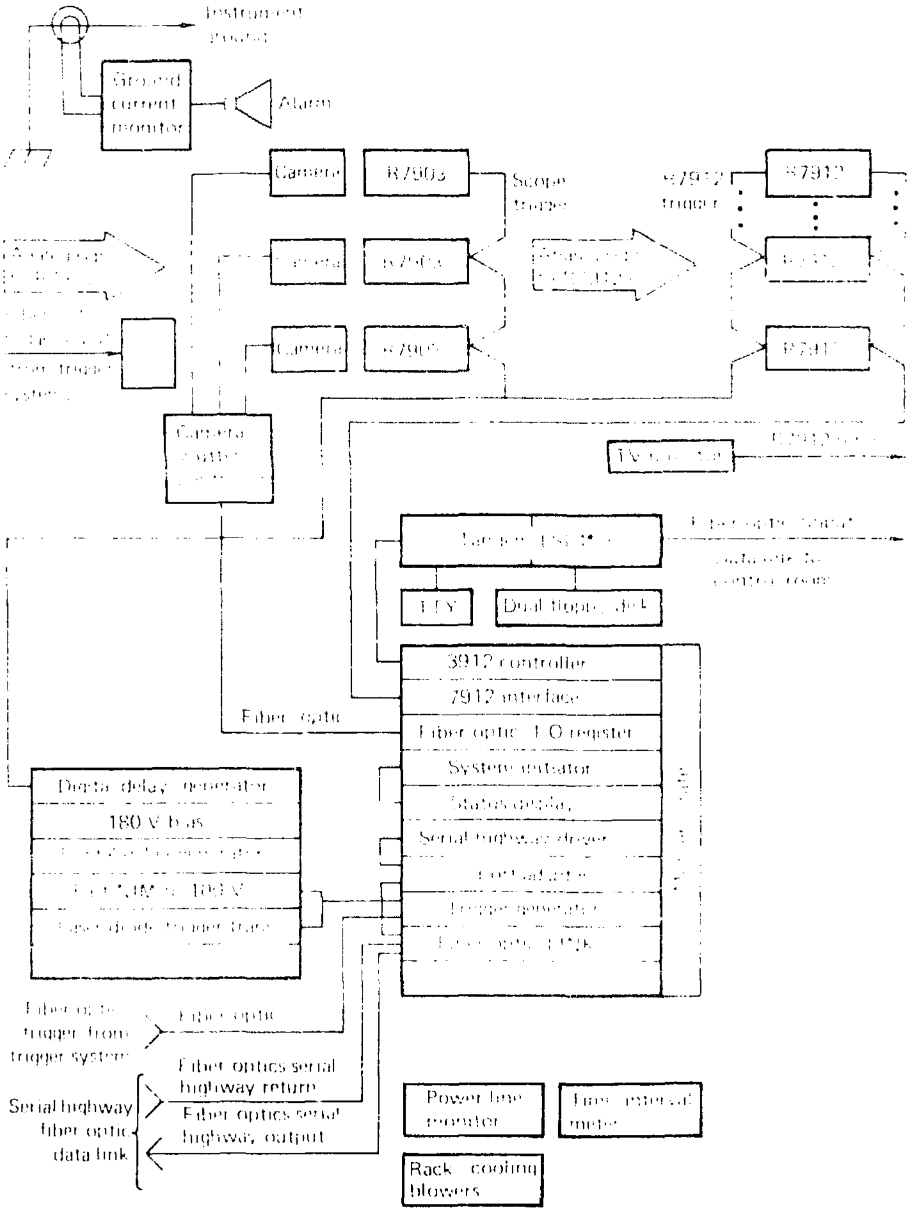
ARGUS TARGET CHAMBER
Figure 7



SHIVA TARGET CHAMBER
Figure 8

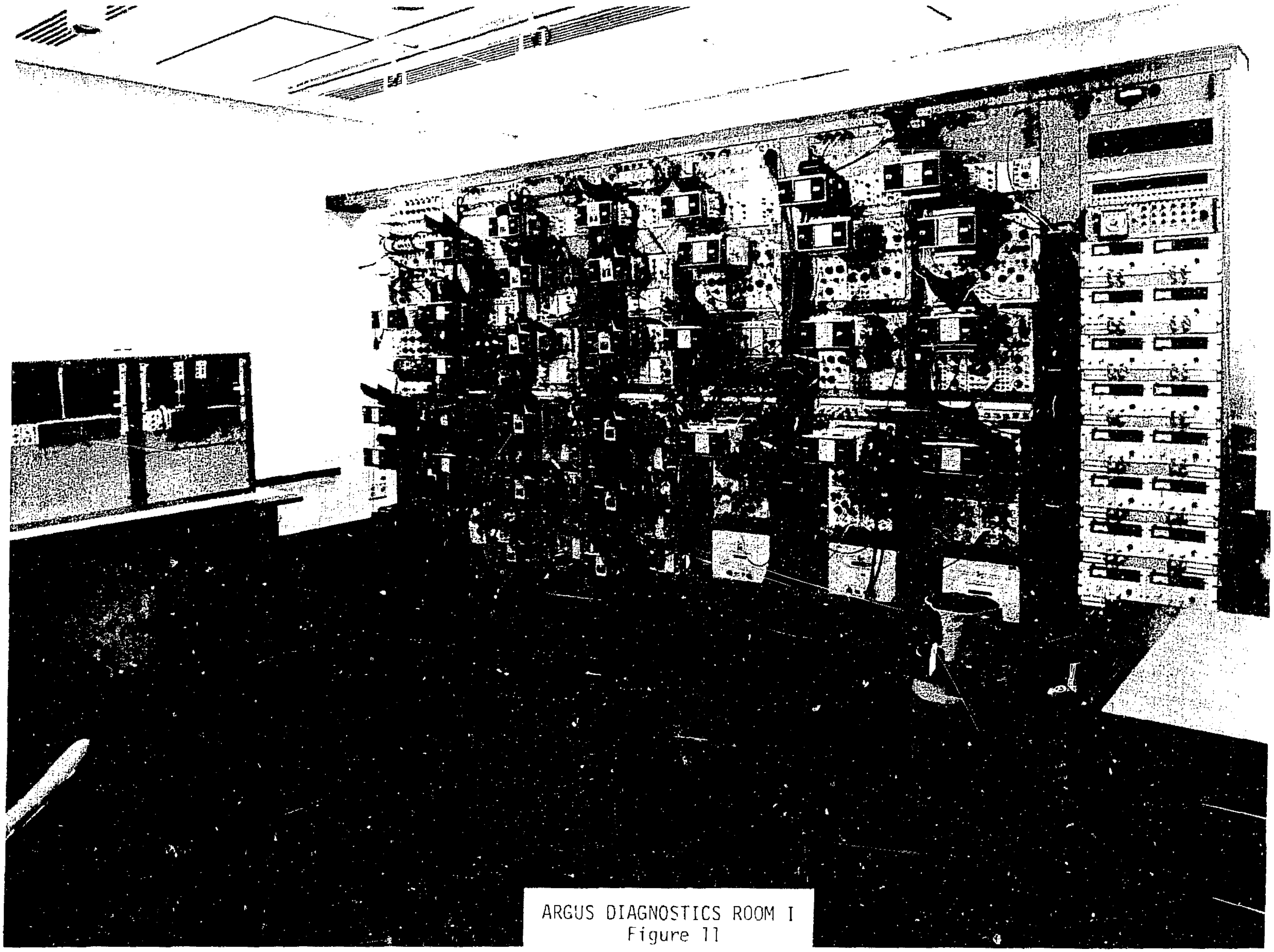


SHIVA MODEL
Figure 9

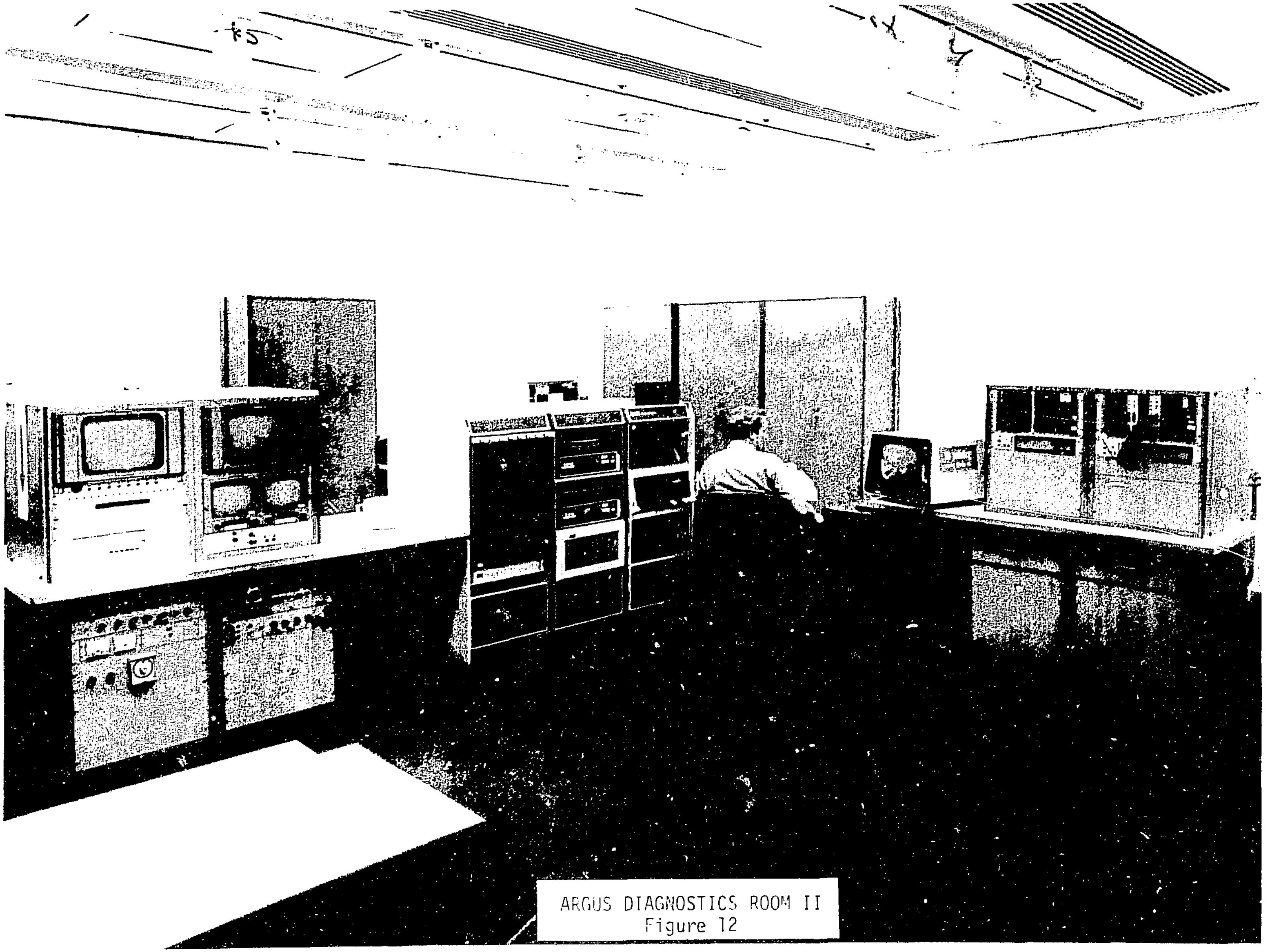


TARGET DIAGNOSTICS DATA
AQUISITION SYSTEM

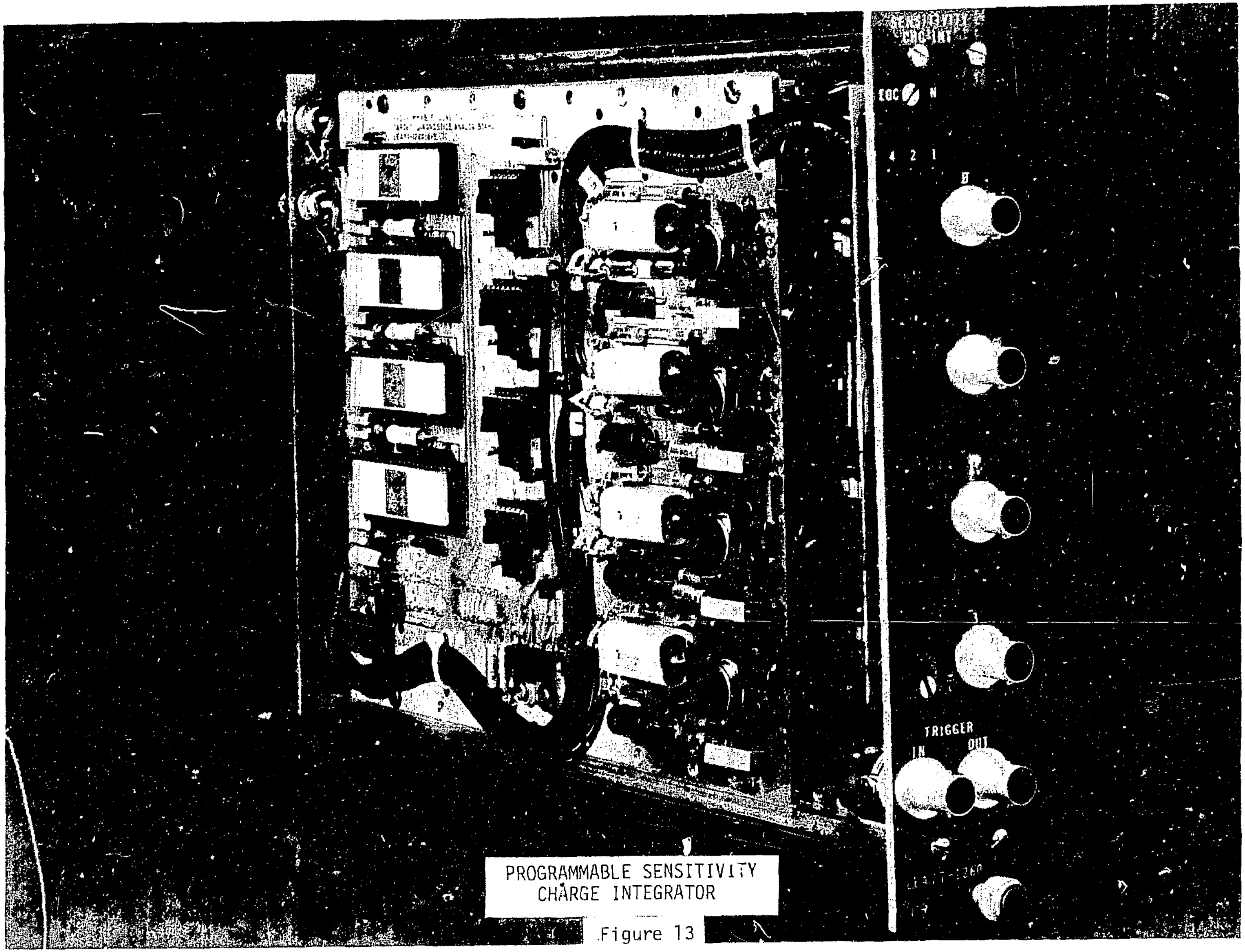
Figure 10



ARGUS DIAGNOSTICS ROOM I
Figure 11

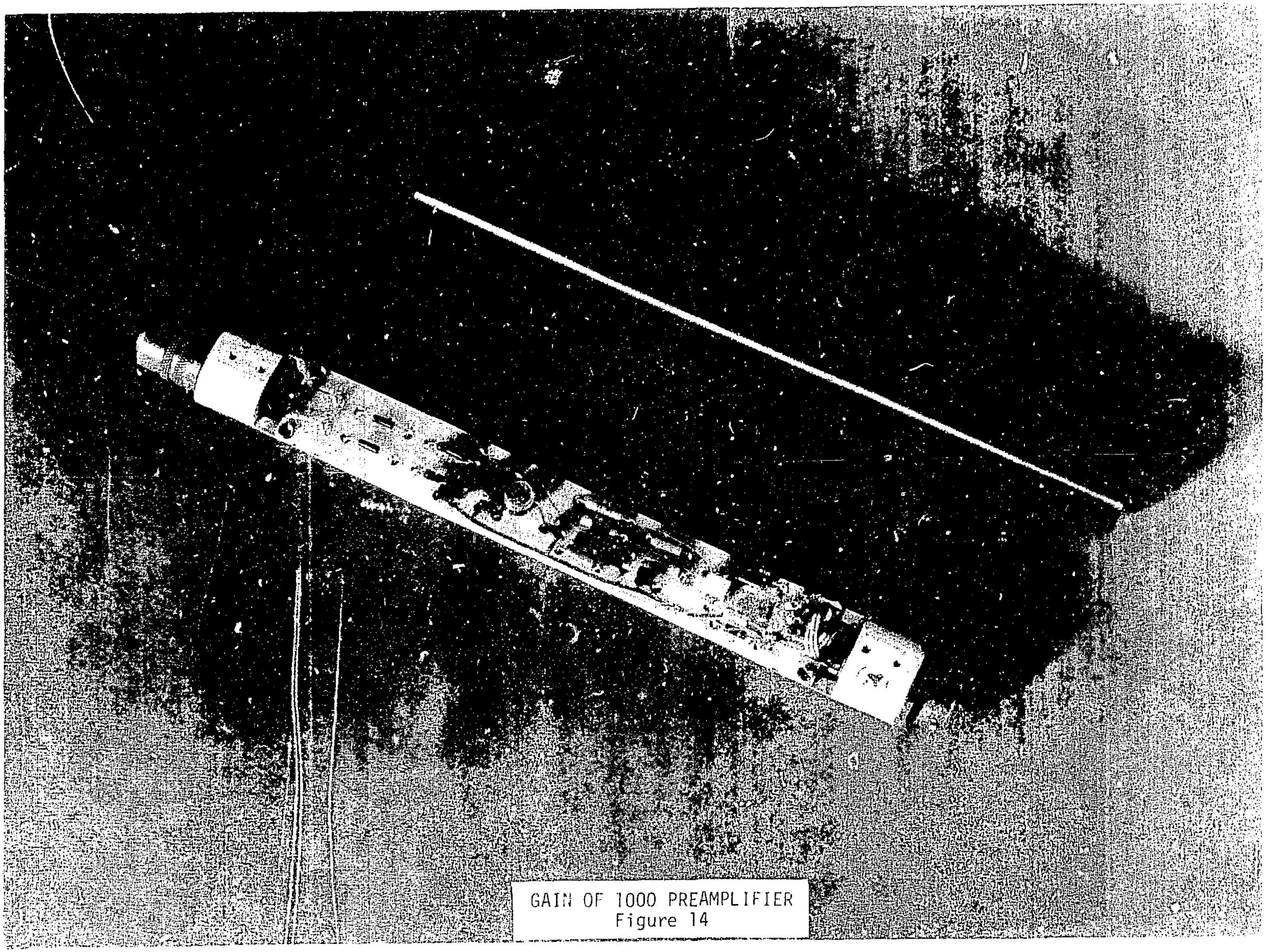


ARGUS DIAGNOSTICS ROOM II
Figure 12

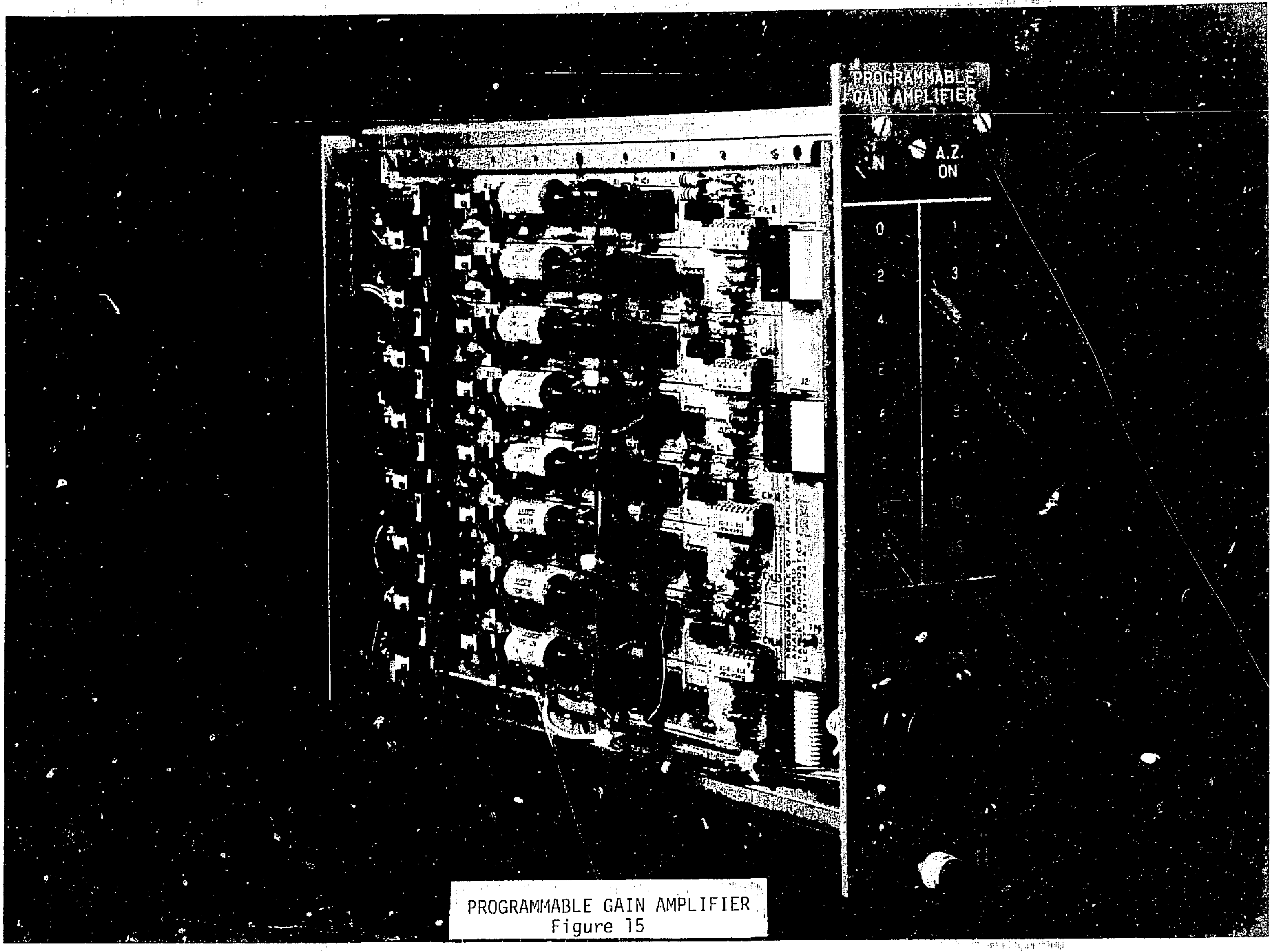


PROGRAMMABLE SENSITIVITY
CHARGE INTEGRATOR

Figure 13



GAIN OF 1000 PREAMPLIFIER
Figure 14



PROGRAMMABLE GAIN AMPLIFIER
Figure 15

SHIVA CONTROL SYSTEM

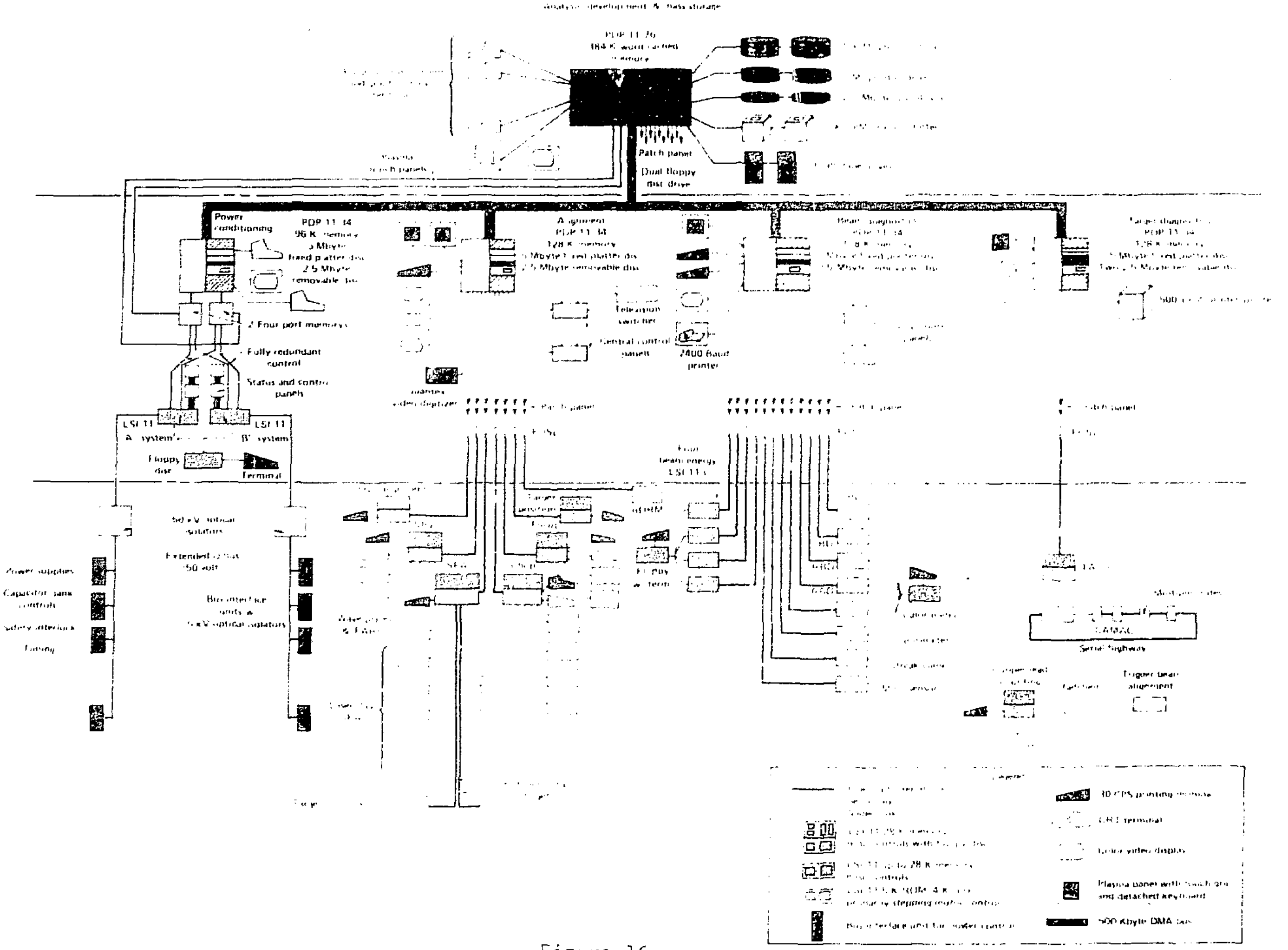


Figure 16

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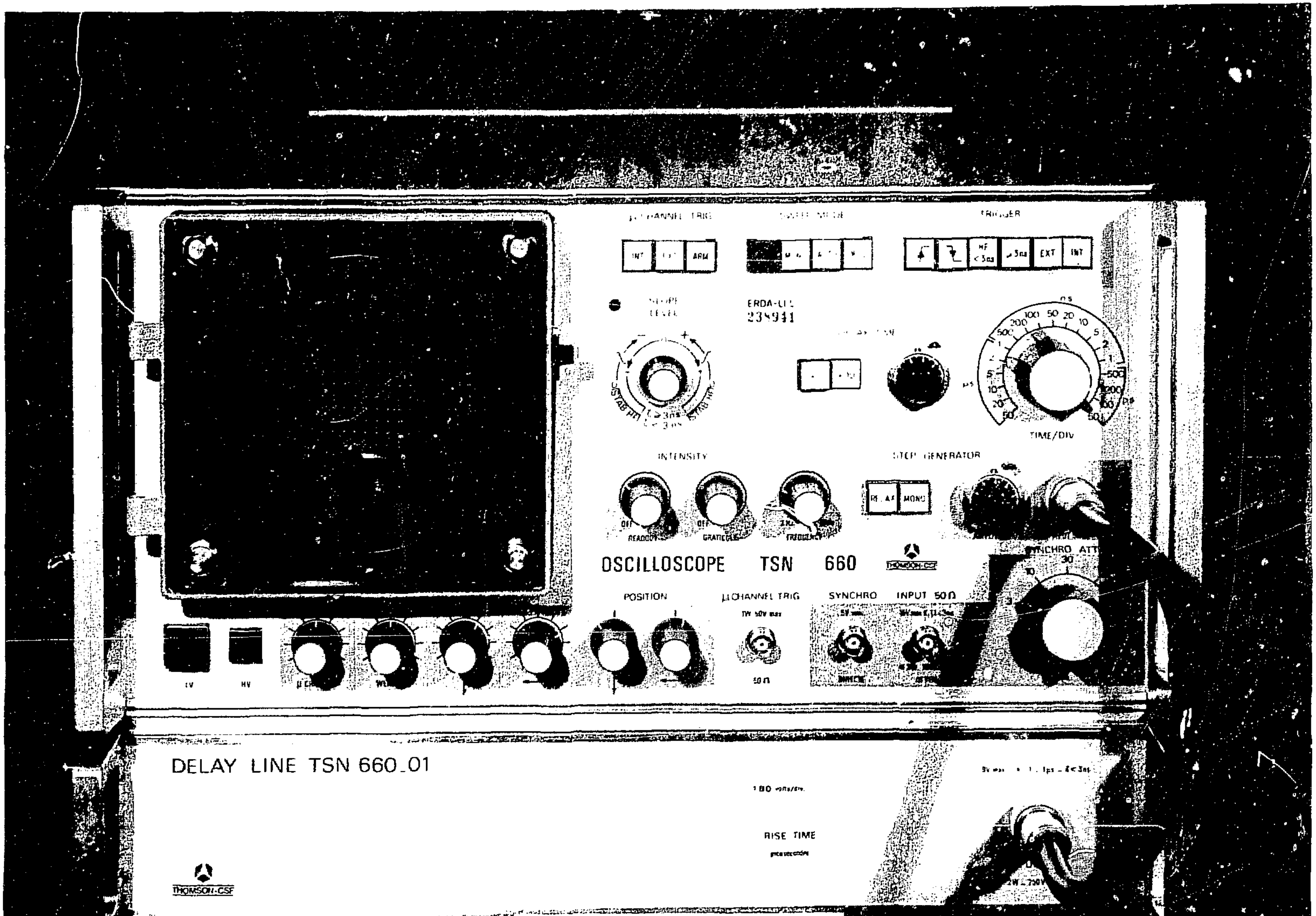
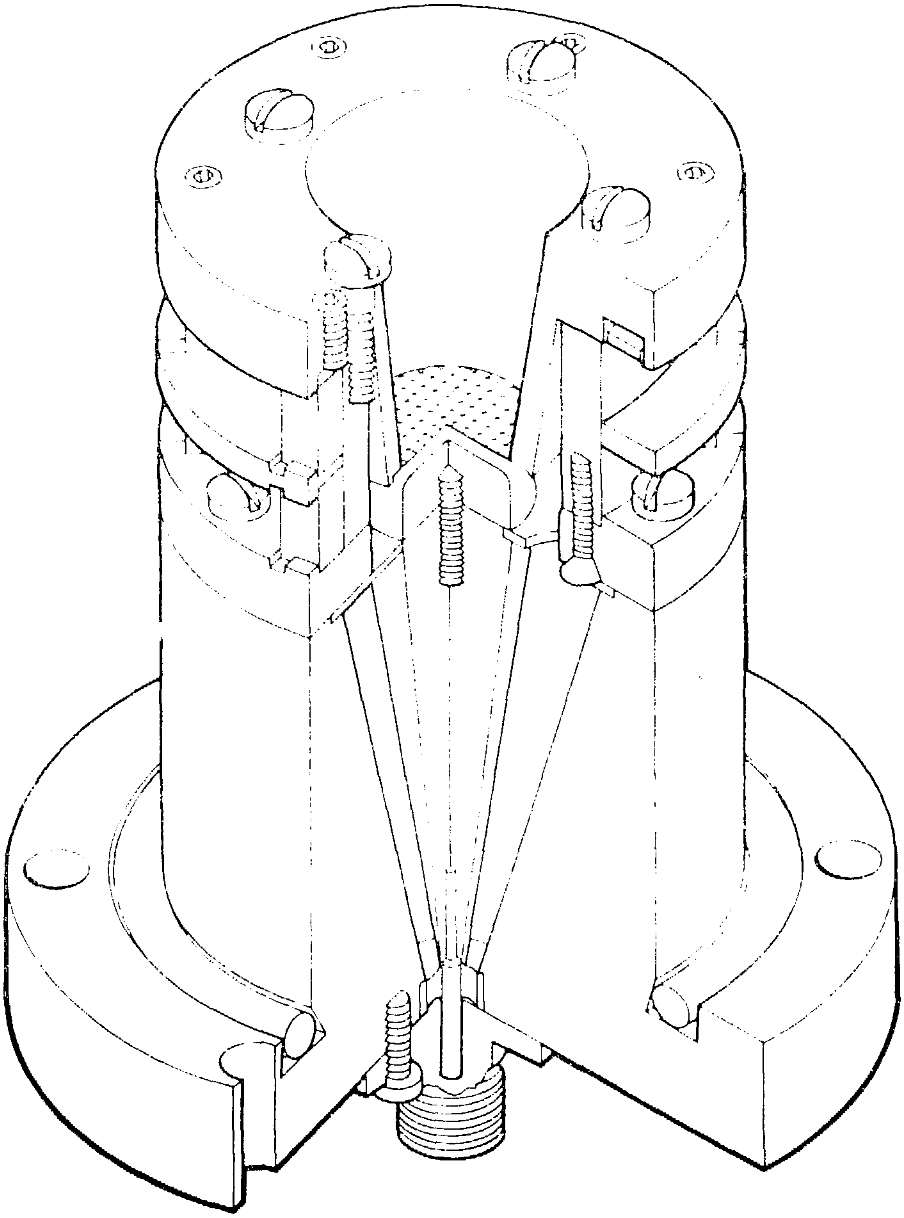


FRENCH OSCILLOSCOPE TSN-660
Figure 17

50 psec X-RAY DETECTOR



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50 PSEC X-RAY DETECTOR
Figure 18

ULTRAFAST FRAMING CAMERA

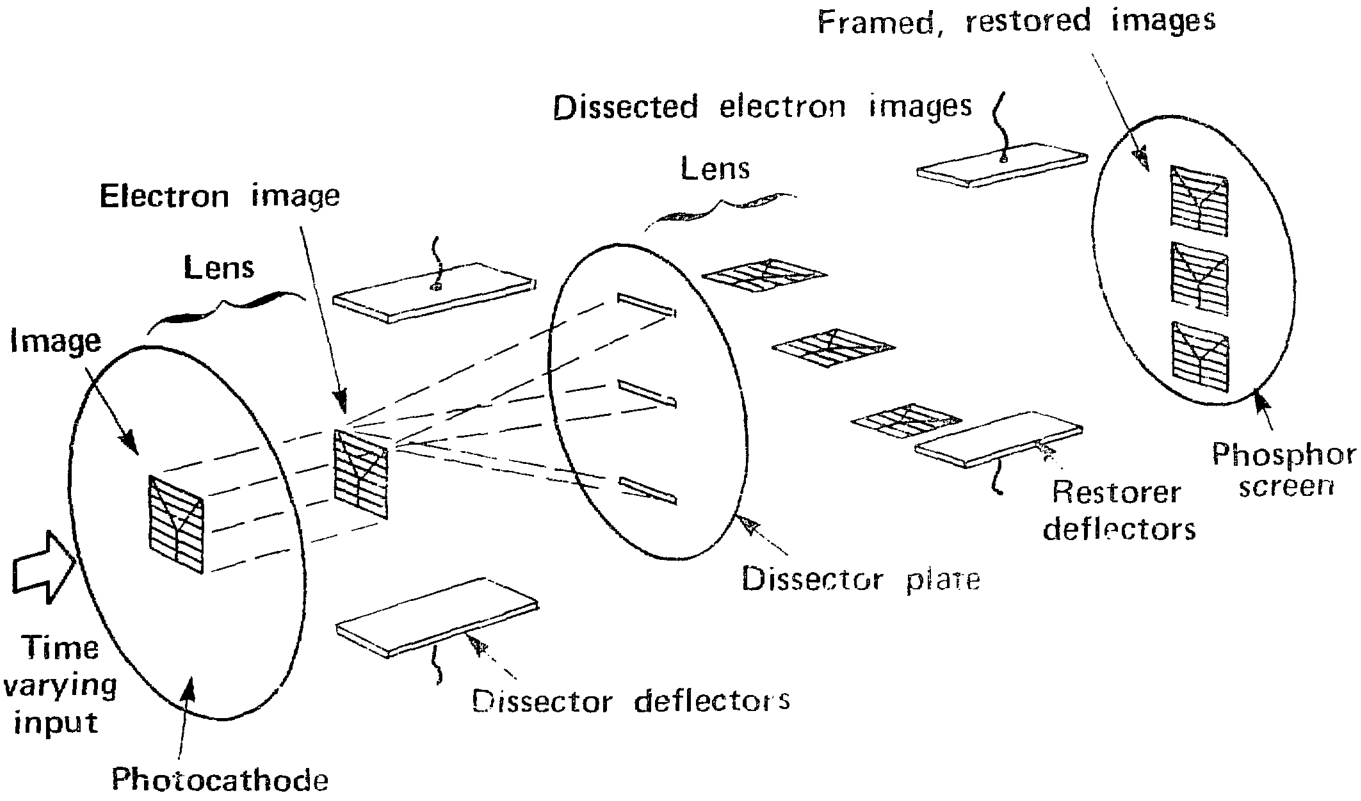

Figure 1[illegible]

TARGET ROOM TIMING SOURCES

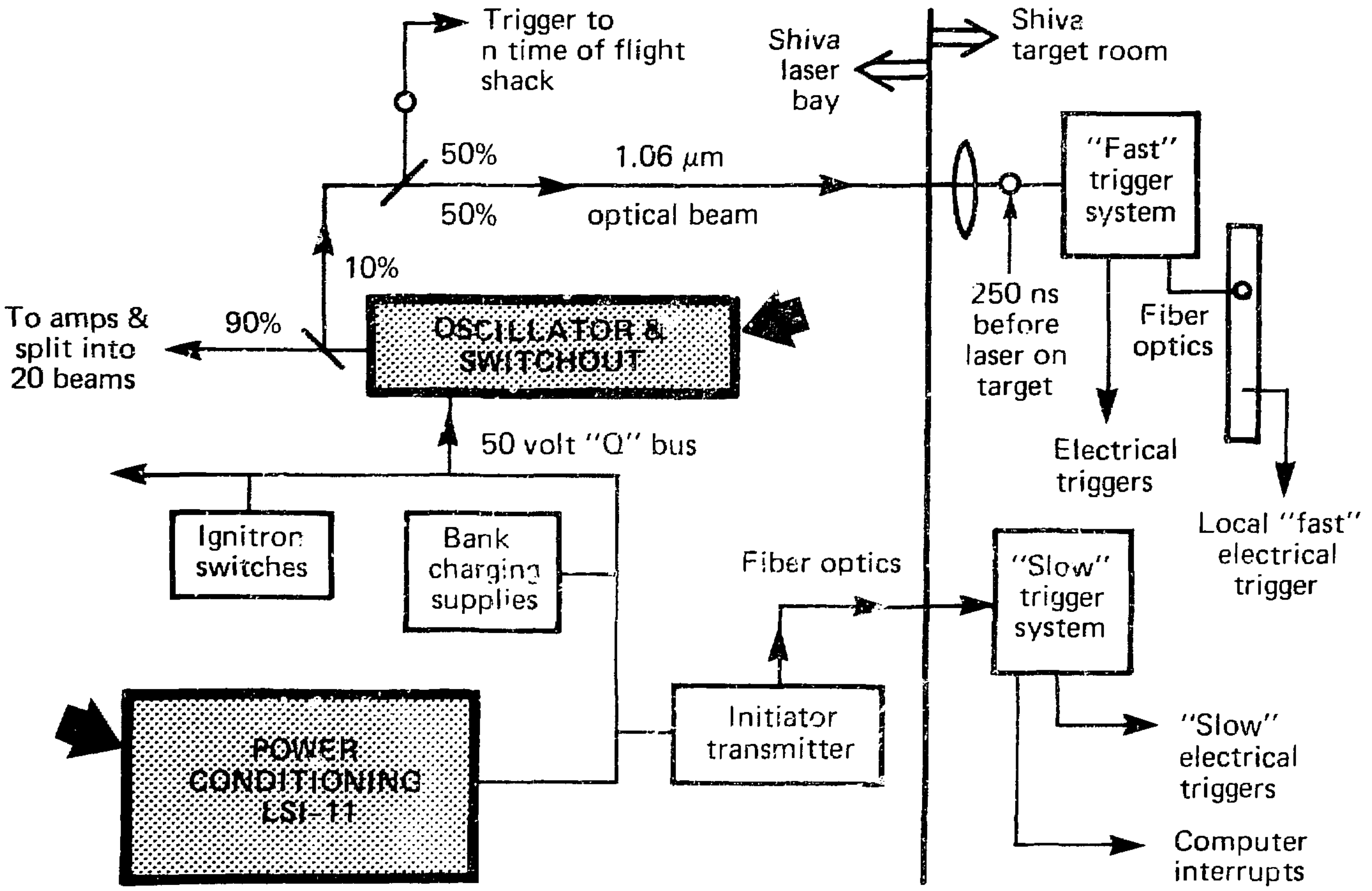

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Figure 20