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MECHANICAL AND OPTICAL COUPLING OF A THOMSON SCATTERING LASER T_e MEASUREMENT TO THE ORMAK MACHINE*

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Summary

A combination laser, spectrometer device has been constructed to observe the electron density and temperature of the ORMAK plasma by Thomson scattering in the range of 50 eV–2 keV. The apparatus can observe the plasma at six radial positions and fire four 30 nanosecond pulses of Q switched ruby laser light during an ORMAK shot. The apparatus and some of its optical components are described.

Introduction

Diagnostic devices on a plasma physics experiment should give as much information as possible without disturbing the plasma in any way. Observations of 90° Thomson scattered laser light meet these requirements by giving both the temperature and density of the electrons in a plasma directly.

The device recently completed for the ORMAK machine can observe the plasma at six radial positions and produce four laser light pulses during a single shot, providing a radial profile of electron temperature and density.

Features Unique to the ORMAK Machine

The ORMAK machine (see Fig. 1) has, in addition to the usual problems on Tokamaks, several features that complicated the design of the Thomson scattering apparatus, as follows:

1. The vacuum system is composed of two differentially pumped vessels requiring double windows at each penetration.
2. The inner liner surrounding the plasma is cooled to 80°K and baked to 500°K, putting severe thermal expansion and sealing restrictions on the components.
3. Because of the size of the outer vacuum tank (4 m in diameter) long reentrant tubes are required to allow the optical system to "reach" the plasma region.
4. In past operation large bursts of energetic X-rays were often emitted throughout each shot. Prior to the addition of massive lead shielding (a 6-in. shadow shield and 1/2 in. skyshine shield), the photomultiplier tubes were completely overwhelmed by X-ray induced noise making light measurement impossible. (Fortunately current operating procedures have drastically reduced the X-ray emissions.)

In addition to the above, the usual problems of access to a Tokamak machine are present such as finding a place to put 13 input and viewing ports without disturbing the conductors producing the vertical, ohmic heating, and toroidal fields. It was also necessary to design shutters to protect the windows during baking. Due to the massive X-ray shield problem, the designer was faced with the problem of providing a reliable, precise method of supporting a movable 1500# optical system operating 10 feet above the floor.

Previous Laser System on ORMAK

The previous Thomson scattering system on ORMAK posed severe alignment problems since a major portion of the optics were inside the vacuum tank which often stayed closed for months, precluding adjustment or modification. Cooling the system to liquid nitrogen temperatures produced large movements of the optical components which could only be corrected within the limits of the external optics.

In addition to the adjustment problem, the system had a limited light gathering capability which was further reduced by the large number of optical components and the low transmission efficiency of the fiber optics light guides used to transmit the light from the polychromator to the photomultiplier tubes. Also, this system could only look at three radial positions in the plasma.

Requirements of the New Machine

In designing the new system the following general criteria were established:

1. The entire optical system should be self-contained and operate at room temperature.
2. A high level of mechanical stability and overall reliability was mandatory.
3. All alignment and calibration to be done external to the vacuum system.
4. Observations were to be made at as many radial positions as possible to provide a representative profile of the plasma.
5. Collecting optics should have maximum possible light gathering capability.
6. All windows, shutters, etc., attached to the liner should withstand baking at 200°C.

The New Thomson Scattering System

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Modifications to the Tank and Liner

Reentrant Tubes in the Vacuum Tank. Referring again to Fig. 1, one can see the new laser diagnostic system. The long reentrant tubes attached to the vacuum tank are a part of the primary vacuum system and were necessary to allow the optical system to operate in air. Because of the low ambient temperature inside the tank (80°K), it is necessary to insulate these tubes with aluminized Mylar and keep them at or near room temperature to retain vacuum integrity of the window O-ring seals. Dry nitrogen at room temperature is circulated through passages in the tubes to keep them warm. A constant dry nitrogen purge to the interior of the tubes is maintained to prevent fogging of the windows by atmospheric moisture. Antireflection coated quartz windows are used throughout as are prebaked Viton O-rings.

The choice of six separate windows was a hedge against the possibility that, due to loss of warm gas flow, the temperature of the tubes might drop to where the seals would leak or a window might crack due to thermal stress. Because of the low internal temperature in the machine, a large air leak is catastrophic. Weeks of operating time are lost when it becomes necessary to warm up the machine and let it up to air for repairs or modification.

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Window Shutters. During periods of discharge cleaning and experimental operation, material is sputtered from the interior wall of the ORMAK liner and limiter. If not protected by shutters, all of the exposed glass surfaces would become coated, decreasing their light transmitting efficiency. In the case of the laser input windows and laser light dumps the laser beam will shatter a dirty glass surface. To guard against this, all openings are protected by mechanically coupled shutters providing all windows with protection when the laser system is not in use. In operation the six windows may be opened in either of two groups of three alternate ports. The corresponding laser beam dumps open simultaneously.

Light Dumps. The laser beam dumps are made up of two pieces of Corning CS4-72, blue-green filter glass. This glass transmits only $10^{-3}\%$ of the 6943 Å laser light. The primary target surface is set at the Brewster angle and the second piece is placed alongside, parallel to the incident beam to absorb any light reflected from the target surface.

The position of the "viewing dump" is indicated in Fig. 1. This device is necessary to provide the black background for the collecting optics which would otherwise look directly at the plasma light reflected from the liner wall. Due to space limitations it was necessary to put the assembly inside of the liner where it is exposed to the plasma and the material sputtered off the liner wall. It is so designed that it is outside the limiter radius.

After trying several surfaces, it was decided to use razor blades stacked edge on to the collector lens. Because of the high, pulsed magnetic field, these blades had to be made of a non-magnetic material. A commercial blade manufacturer supplied blades of 302 stainless steel with edges ground and honed in the usual manner and then polished to a mirror surface on the "cutting" edge to reduce diffusive reflection. Vacuum considerations required that the blades be spaced apart leaving a void through which parallel light could penetrate and be reflected. To dispose of this light the stainless steel blade holder had a sawtooth thread machined into its surface and the holder was then blackened by a chemical oxidizing process. The assembly is shown in Fig. 2. Comparative tests of this combination showed it to be better than any other combination of blades or surfaces tested.

Laser System and Receiving Optics

Input System. The self-contained laser system and collecting optics are shown in Fig. 3. The source of laser light is a 10 joule, Q switched, ruby laser capable of four consecutive light pulses of 30 nanoseconds duration during each shot of the ORMAK machine. A Pockels cell performs the Q switch function.

The slightly divergent (~1 m rad.) light beam of about 10 mm diameter is directed downward by an adjustable prism and then focused to 1 mm at the optical axis of the viewing system by a single lens of 75 cm focal length. Output energy is monitored by diverting a small portion of the beam into a calorimeter with a beamsplitter. A second beamsplitter diverts half of this light to a diffuse reflector made of magnesium oxide which illuminates a photomultiplier tube monitoring input power.

In addition to the ruby laser, the machine also contains a He-Ne laser which is used for alignment of the system. By inserting a mirror and combination beamsplitter and telescope, mounted on kinematic supports, it is possible to direct the He-Ne laser beam into the ORMAK machine and observe the alignment of all input apertures. To assure co-linearity of the input and collecting optical systems the ruby laser is fired at a piece of brass shim stock placed at the focal point. By illuminating the resulting small hole (0.5 mm) the collecting system can be aligned.

Collecting System. The details of the collecting system are shown schematically in Fig. 4. The objectives lens is 185 mm in diameter and has an effective focal length of about 480 mm (thus f 2.5). A segment of the scattered laser light 20 mm high and 1 mm wide is observed by this lens. Since the laser light source and the collecting system are mounted on the same movable carriage the light source is always in focus as the device is rolled from one input port to another. To reduce stray light the lens is masked down to a rectangular aperture just sufficiently large to receive all scattered light emanating from the liner output window. Additional rectangular apertures in the lens support tube further reduce the transmission of unfocused stray plasma light.

Two notch filters (made of a high transmission 6943 Å interference filter with a blue filter glass backing) absorb the 6943 Å stray light and reflect the rest of the spectrum. The effective rejection ratio is about 15 for each filter. The field stop and field lens are placed at the intermediate image position between the two filters. A four-element relay lens then focuses the light on the polychromator slit (30 mm x 1.5 mm). The field lens before the slit projects the aperture of the relay lens onto the grating of the polychromator.

The polychromator is a commercial 50 cm Czerny-Turner instrument having a 64 x 64 mm grating with 600 lines/mm blazed at 5000 Å. Dispersion is 32 Å/mm. The observed range in the SCAT-PAK is from 6943 Å–5500 Å allowing measurement of electron temperatures up to about 2 keV. Blue glass baffles have been added to the polychromator to eliminate the zeroth and higher order diffracted light. In order to prevent line radiation of working gas (H_2, He), three light dumps are placed at the exit of the polychromator between light guides. In addition, there is a thick, concave stack of razor blades to absorb the 6943 Å stray light.

Light Guides and Photomultiplier Tubes. Perhaps the region of greatest novelty in the entire optical system is the light guide and photomultiplier system shown in Fig. 5. Tests of many configurations were made in an attempt to get maximum light transmission efficiency and, if possible, some gain in the photomultiplier signal by multiple internal reflections.

The RCA 8852 ("extended red cathode") photomultiplier tubes used have a plano-concave window with the photocathode on the concave surface. The only known method for improving the output signal of this type of tube by multiple internal reflection is to direct a narrow band of highly collimated light into the edge of the window. By careful alignment two or three internal reflections can be obtained. Because of the thickness of the 3/16-in. plastic light guides we were unable to profit by this approach.

The system finally adopted involved silver plating the photocathode end of the tube as shown in Fig. 6, leaving a window slightly larger than the acrylic light guide on the cylindrical surface of the tube. The silver surface must be tied electrically to cathode potential requiring that the tube support be insulated from ground.

The end of the acrylic light guide was machined and polished to match the cylindrical radius of the p.m. tube. A drop of silicone oil optically couples the light guide to the glass surface. Comparison tests showed that this arrangement gave a signal about 50% greater than that obtained with the conventional head-on configuration.

In addition to the [illegible]ase in output signal the geometry of the modified [illegible]be permitted a simple and compact design of the acrylic light guide. Since the entire assembly had to be enclosed in a 1/2-in.-thick lead X-ray shield, a compact design was most desirable.

Laboratory tests showed that twists and bends in the light guides did not materially reduce the transmission efficiency; however, when some sort of clamp for the p.m. tube was cemented to the end of the light guide, the light transmission was often cut in half. Many geometries were tested and all showed large amounts of light radiating from the clamp itself. Finally, a clamp was constructed which was mechanically clamped to the guide and only made line contact on the four corners minimizing the contact area between clamp and guide. Losses in this design were negligible.

Casual observation of light transmission through one of the light guides were not coupled to a p.m. tube is deceptive. The cylindrical surface at the end of the plastic guide presents some surface at an angle greater than the critical angle for internal reflection. Where this occurs, the light is reflected back to the source. When coupled to a p.m. tube with matching fluid, this does not occur.

Earlier experience in ORMAK showed that the most intense plasma light saturated the photomultiplier tubes making observation of the Thomson scattered laser light impossible. A mechanical shutter was used to blank out this portion of the observed light but was not found fast enough to be satisfactory. In the new machine, G. R. Dyer[1] has developed photomultiplier bases which enables us to turn on the tubes in a short time (~2 msec) only when desired. The output of the p.m. tube is now interfaced to a PDP8E computer through 10 dual double gated integrators.

Conclusion

The SCAT-PAK has operated successfully now for several weeks on the ORMAK machine giving profiles of electron temperature and density over a range of operating parameters. A typical profile is shown in Fig. 7. Electron temperatures can be measured up to 2 keV and have been observed in the range of 50–1100 eV.

Plasma background and stray light have been reduced to below the threshold of detection sensitivity. Mechanical stability of the optical system has been satisfactory and, as experience is gained, more sophisticated alignment aids will be constructed to speed up these procedures.

Reference

1. G. R. Dyer, Fifth Symposium on Engineering Problems of Fusion Research, November 6–9, 1973, Princeton.

Figure Captions

Fig. 1 ORMAK Machine and Thomson Scattering Apparatus.

Fig. 2 Viewing Light Dump

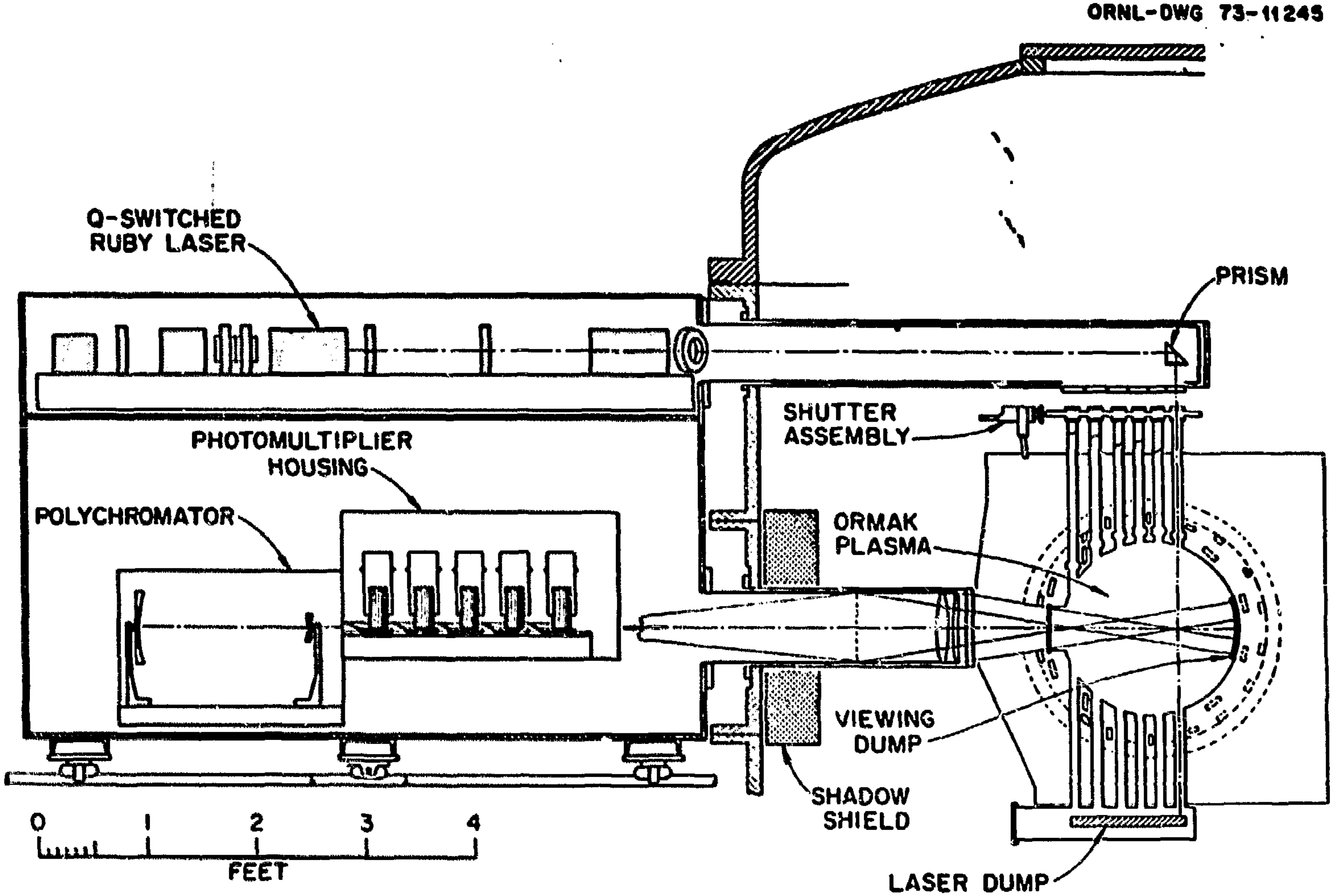
Fig. 3 Thomson Scattering Apparatus - SCAT-PAK

Fig. 4 Collecting Optics

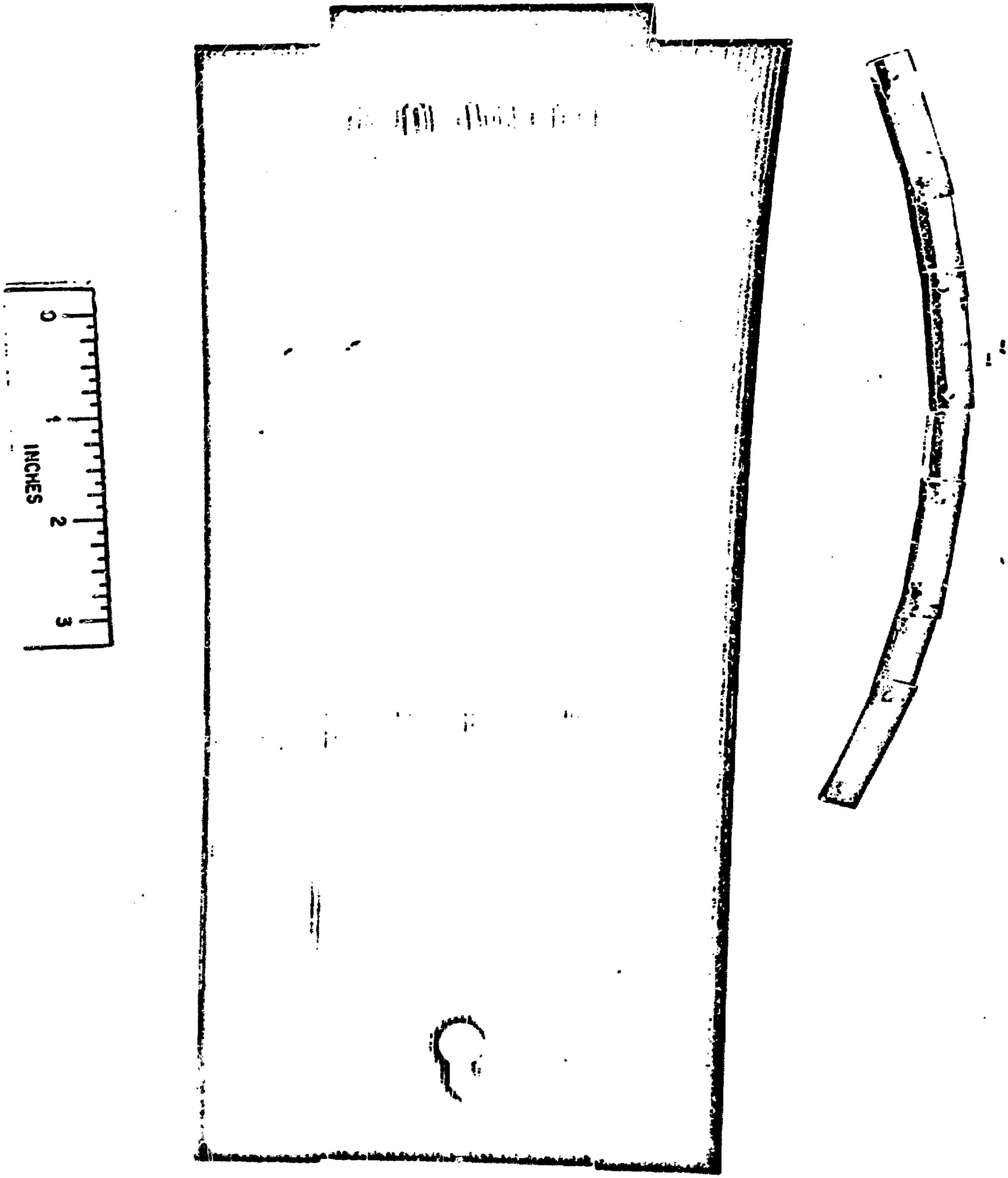
Fig. 5 Light Guides and Photomultiplier Tubes

Fig. 6 Silverplated Photomultiplier Tube

Fig. 7 Typical Profiles Of Electron Density And Temperature Obtained With The Thomson Scattering Apparatus



Thomson Scattering Package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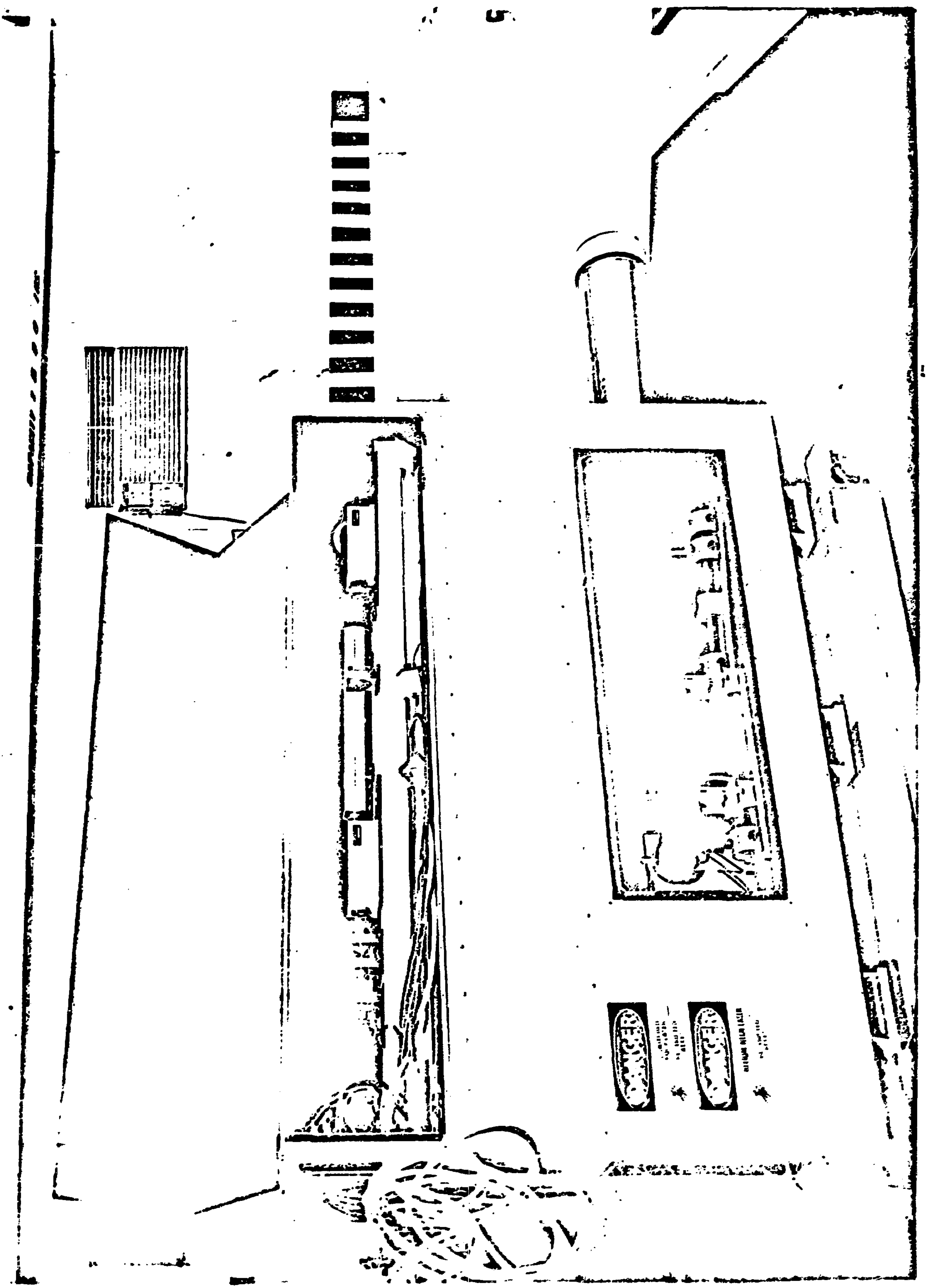

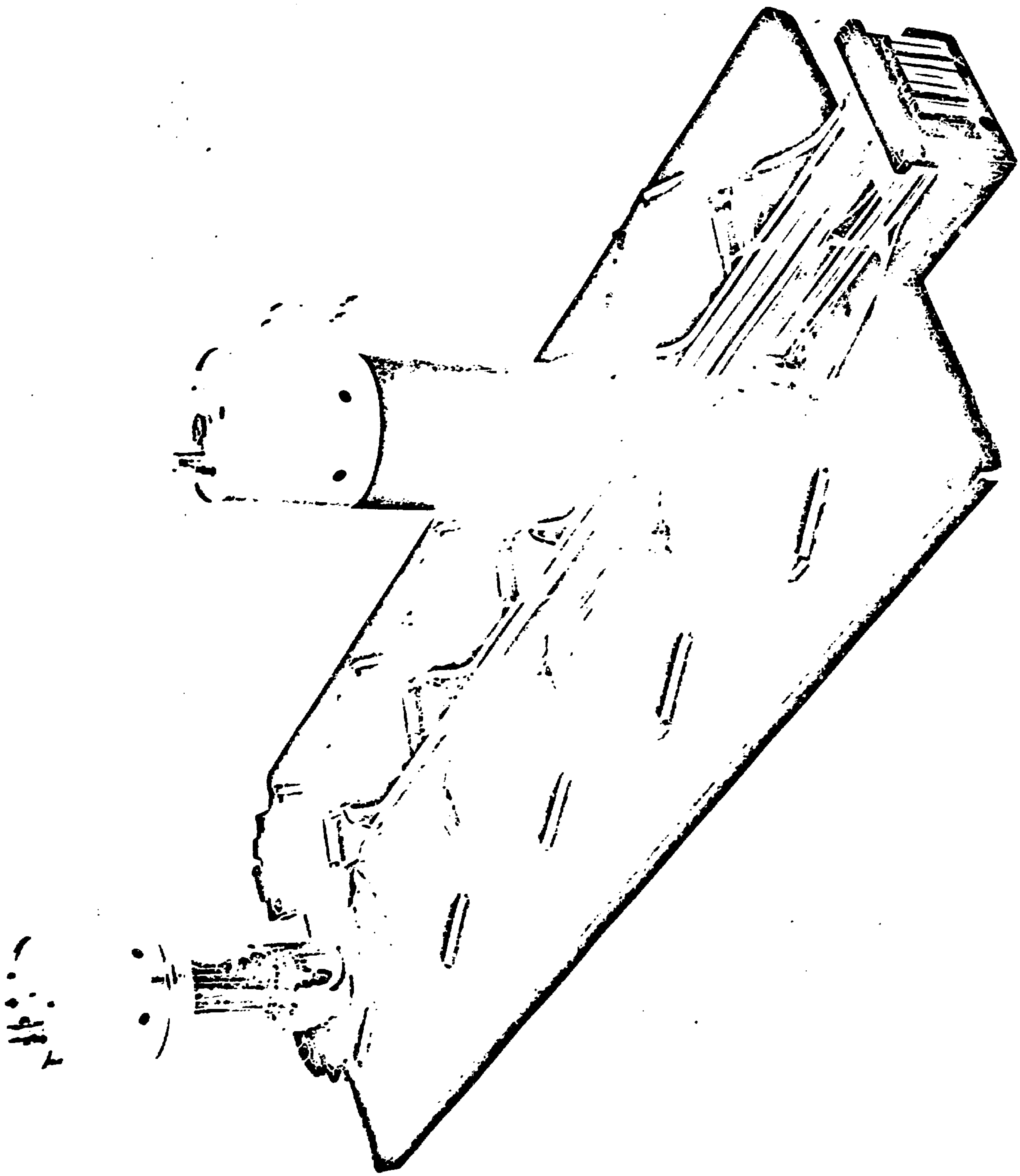

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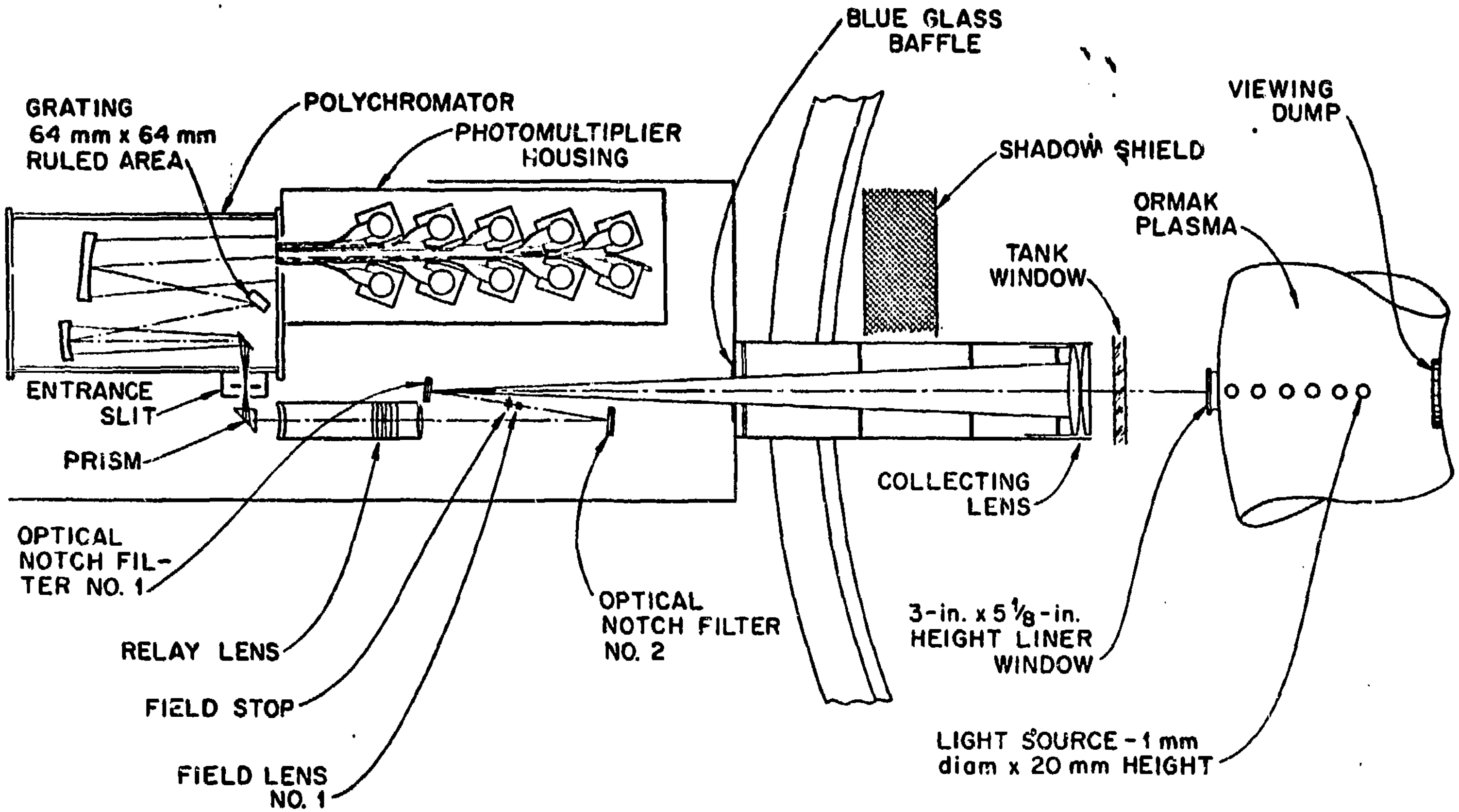
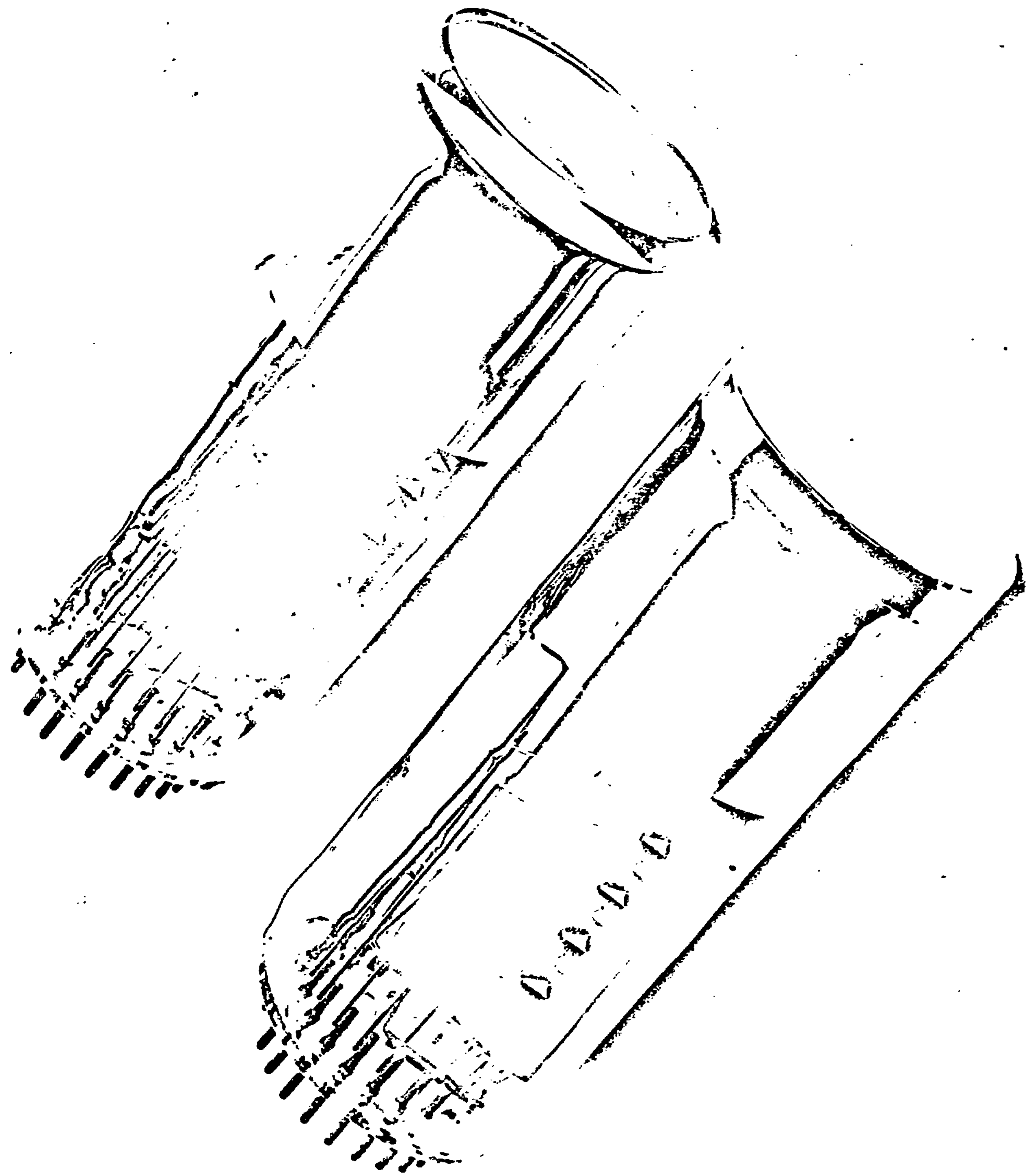


Collecting Optics Layout for Scat-Pak.



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NEW THOMSON SCATTERING
NO. 1433–1447
I_p = 98 kA, V = 2.3 V
B_T = 18 kG
$\bar{n}_e = 3 \times 10^{13} cm^{-3}$
m = 2 MHD INSTA