Diagnostic Methods in the Field of Plasmaphysics

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Abstract

The basis of some essential diagnostic methods is treated in plasmaphysics. At first it is reported on methods which are technically simple such as electrical and probe measurements. The high-speed photography with its special requirements in plasmaphysics is described. Some diagnostic instruments for density measuring, especially designed for plasmaphysics, such as interferometric measurements with light and microwaves, light scattering and Faraday rotation are explained.

Contents

Preface

When Mr. Schmitter asked me to talk about plasma diagnostic instruments, I thought at first only to have to describe the progress made in the last two years. There are two reasons for not doing so. It is the first time that diagnostic instruments are the subject of this conference and the latest contributions are the subject of the individual papers. For these reasons I would like to bring several underlying principles of diagnostic methods and also to describe a few typical technical arrangements. In considering diagnostic methods the first question that arises is: "What is to be measured"? The answer is in the first approximation: "Density and temperature of electrons and ions as a function of time for given experimental conditions".

I shall now discuss the measurement methods **technically simple.**

Electrical Data

In many measurements it is possible to determine the electron temperature by measuring the electric data. Equation 1 on the first slide shows the dependence of the plasma resistivity η on the electron temperature T_e. T_e is here measured in keV. Λ is nondimensional and depends on temperature and density. Λ is set equal to 20 as a first approximation. We thus see that the resistance of a plasma falls with increasing electron temperature.

The slide shows how to obtain the plasma resistance from a simple linear discharge with electrodes. Equation 2 is a formular for the voltage V at the terminals of the apparatus. In stationary or slow experiments the term $\frac{d\emptyset}{dt}$ can be neglected. In this case we need only to measure the voltage V and the current I.

In faster experiments $\frac{d\,\emptyset}{d\,t}$ must be determined. Variations of I and L are included. It is possible to determine $\frac{d\,\emptyset}{d\,t}$ through magnetic probe measurement.

Magnetic Probes

The next slide shows a diagram of a typical magnetic probe. It consists of a small coil of 10 to 50 turns. These are wound on a form of about 1 mm in diameter. The coils are of very thin copper wire. Since the measurements are made in the plasma the leads are between 10 to 20 cm long. These wires are twisted in order to cancel the stray inductance. This of course introduces inevitable capacity. This capacity together with the coil inductance produces a limiting frequency of around several tens of megacycles with suitable cathode followers. The probe is enclosed in a quartz tube in order to protect it from electric discharges, uncontrollable electric fields and from thermal destruction. Moreover to avoid displacement current the probe is electrostatically shielded. Probes are often made of two symmetrical parts in order to avoid such difficulties.

Equation 1 shows that for a high input resistance the voltage V_i is proportional to the time-differential of the magnetic field $\frac{\partial B}{\partial t}$. N is the number of turns and A is the area of the coil. If we wish to measure the magnetic field, we can follow up with an electrical R C - integrator. Equation 2 shows the appropriate relation.

With the help of Maxwell's equations 3 and 4 it is possible to obtain the current J from the magnetic field B and the electric field E from $\frac{\partial B}{\partial t}$.

Another usefull measurement is by Hall-probes. With the previously described probes one can only measure $\frac{\partial B}{\partial t}$. With Hall-probes one can also measure constant magnetic fields. It is also possible to eliminate stray-signals by measuring the stray-voltage without the Hall-current. The Hall-probe is of course relatively more sensitive and larger. As a result its use is limited.

Electrical Probes

An electrical probe consists essentially of a small auxiliary electrode. This sticks into the plasma and may be connected for example to one of the plasma electrodes.

If we plot the current through the probe against the applied variable voltage, we obtain the probe characteristic shown on the next slide. The left branch of the curve corresponds to the random ion current i_i and the above right branch to the electron saturation current i_e. For i equal 0 as many electrons as ions reach the probe. We refer to this point as the floating potential. The upper exterpolated edge A corresponds to the thermal electron current. That is the probe potential is the same as the plasma potential.

In the case of a Maxwell-distribution the increase would be exponential, that is with half logarithmic proportion the curve has a slope of $e \times v/k \times T_e$. All values are known except for the electron temperature. So it is possible to determine the electron temperature from the curve. One may also ascertain for example the distribution of electron velocity as well as the electron and ion current density, the plasma potential and the electron temperature.

If the curve is not linear then we do not have a Maxwell-distribution. But according to Drugvestein one can obtain the velocity distribution from the second differential of the probe curve. It will be carried out through electronic differentiation. One superposes the probe direct-voltage and a sinus voltage. The change in direct-current that will be measured is proportional to the second differential. In a second method the first harmonic is filtered.

In the case of the single electrical probe, the socalled Langmuir probe, a strong current must be extracted from the plasma. Usually one carries out the voltage-sweep with a generator since the probe sometimes gives up energy.

In the case of fast experiments it is hardly possible to find an appropriate potential because of the rapidly changing fields both in time and in space. Due to this the Langmuir probe is practical only for use in stationary experiments. In the case of fast experiments it is normal to use a double-probe since it is not bound to a fixed potential and moreover only absorbs a small probe current. With such probes it was at all possible to carry out mearsurements for fast experiments with high current densities.

In the case of reproducible experiments the double-probe characteristic can be determined point by point. If the measurement is not reproducible an electronic apparatus makes it possible to examine in a relatively short time during the course of the experiment at least parts of the characteristics.

A lot more could be said about the various sorts and uses of probes, but this should be enough about the at least technically simple diagnostic possibilities.

High Speed Photography

High speed photography gives a good general view in many experiments. Technically we may distinguish between 3 different types. Mechanical cameras, kerrcells and image converters.

There are several principles for mechanical cameras Firstly the film can be moved rapidly, secondly it can be placed in a rotating drum and thirdly the film can be static and the time dependency will be produced by a rotating mirror. Moreover a film can be made of several single pictures or a streak picture can be produced. In fast experiments the events are so rapid, that usually only the fastest cameras, namely the rotating mirror cameras, can be used.

The next slide shows the diagram of a rotating mirror camera with streak operation. The slit is reproduced on the film over the rotating mirror. The highest speed obtainable is limited by the breakage possibility of the mirror material. A typical value for a small aperture is 1 ns resolution for a slit width of 10 microns. For small light intensities, the aperture must be larger and the time resolution is of course not so good. A framing camera has no slit but instead of it a chain of lenses between the mirror and the film. With each lens 1 picture can be produced on the film. The fastest framing cameras can produce up to several million pictures per second, although each picture is 8 mm wide.

Kerrcells are optical shutters without any mechanical movable parts. They use the wellknown effect of rotation of the polarization plane by the electric field. The emitted light is plane polarized. Only about 5 to 10% of the incident light actually traverses the kerrcell. They can therefore only be used when the process itself produces enough light.

The next slide is a diagram of an image converter. An evacuated glass-tube contains a semi-transparent photocathode. Opposite the cathode is the anode which is a fluorescence layer. An accelerating voltage is applied to both electrodes. If light falls on the photocathode, electrons are emitted and accelerated by the applied voltage. On the flourescence layer the energy is converted back into light. If the electrons are focused either magnetically or electrostatically a sensitive picture appears on the screen.

One can discuss the particularities and possibilities of image converters even from this simple principle. Thus the wavelength of the light emitted by the screen is different from that of the incident light. It is independent of that of the incident light as well as of the type of the cathode-layer. By pulsing the acceleration voltage the image converter tube can be used as a high speed shutter.

The next slide shows the typical absolute spectral response characteristics of such photoemissive devices. These curves are naturally also valued for multiplier cathodes. With the S5 cathode one descends to 2,000 Å and with the S1 cathode up to 11,000 Å. S 1, S 11 and S 20 are frequently used cathodes. The diagram also shows curves for the quantum efficiency. For the S 20 cathode the quantum efficiency is over 10% in the wavelength region 3,200 up to 5,400 Å, that is 10 quanta can deliver 1 electron.

The next slide shows diagrams of several typical image converter tubes.The first tube on the left is electrically focused. It is a universal tube for high speed photography. With a wire gitter G_1 in the vacuum in front of the cathode the tube can be opened and closed with only

300 V down to esposures of 5 ns.

As for an oscilloscope tube it is possible to deflect the electrons with built-in deflection plates. We can e.g. use this tube to take 3 pictures with time distances between each picture of less than 50 ns or a streak picture. In the latter case a slit image is projected on the cathode. The light gain for this tube is about 60 with an acceleration voltage of 15 kV.

The next converter is also electrically focused . Originally it was designed as an X-ray image intensifier. The electron optical magnification of 1/7 together with a light gain of about 100 and an accelerating voltage of 24 kV gives a brightness-gain of about 5,000.This relatively high amplification for a single step tube can e.g. be applied to increase the field depth. In this case we need only to place a simple aperture lens in front of the cathode.

If a higher light gain is necessary it is generally useless to place several one-stage image converters in series with optical focusing in between, because the amplification usually is completely lost by the intermediate focusing lenses. The third image converter has several stages. The 5 dynodes work on the electronic multiplication principle. This multistage tube is focused with a longitudinal solenoid. The magnification between cathode and screen is therefore 1. If only one electron is emitted from the cathode, a point appears on the anode screen which can be photographed. This tube therefore has given us the greatest possible and reasonable photon gain. For a total accelerating voltage of 36 kV this is about 2 x 10^5. More could only be obtained with more sensitive cathodes. By electronically pulsing the first stage with 2 kV we obtain exposure times of less than 20 ns.

The last diagram shows a superorthicon. Actually it is not an image converter. The first stage consists of a 1-stage image converter. The image produced is contained for a small time and probed by an electron beam, then intensified with a multiplier and finally written on a television screen in the conventional way. Naturally one cannot obtain the highest sensitivity with this sort of an intensifier since for the primary storage of the image sufficient electrons must be produced.

The superorthicon is the transition from the image converter tube to the multipliers. If several multipliers are used at the same time, the voltages can of course be applied to the Wehnelt cylinder of an oscilloscope tube. It is possible in this manner to produce a streak picture, the resolution of which is equal to the number of multipliers.

On the instruments of high speed photography we may conclude with the following. The resolution and the freedom from distortion are generally better for rotating mirror cameras and kerrcells than for electronic cameras. If the light provides by the experiments is not sufficient to illuminate the film then electronic cameras must be used. This type of apparatus is of course sensitive to exterior fields. Only mechanical cameras can be completely shut.The transmission ratio is defined as the ratio of the output from the tube when it is electrically cut off to the output in operation. The transmission ratio for kerrcells and for electronic cameras is around $1 : 10^3$ to $1 : 10^6$. On the account of the brightness this can be increased by placing several kerrcells in series. In the case of image converters the total acceleration voltage can be additionally pulsed. With image converters the shortest exposure times are obtainable and by streak operation the greatest time resolution is possible.

Interferometric Measurements

High speed photography is not only used in order to picture the discharge directly but for instance also in optical interferometers for density measurements. The relationship between electron density and refractive index is given by the dispersion equation for electromagnetic waves in the plasma. In plasmaphysics this method was introduced in particular by Alpha, White, Ascoli-Bartoli, Rasetti as well als Fünfer.

The next slide shows the schematic arrangement of a Mach-Zehnder interferometer. It was used by Medford et al. In this arrangement the ratio of density distribution can be examined for example in a theta-pinch. The light from a spark flash traverses the measurement comparison path. The interference lines appear perpendicular to the slit. They are registrated as a function of time. The magnetic field must be perpendicular to the light, Instead of a rotating mirror camera one may of course use a streak image converter. If instead of a rotating mirror camera one uses e.g. a 3 picture image converter, one obtains, as Küpper did, for 3 different times interference pictures of the total cross-section of the discharge.

One of the error sources comes from the fast that the light rays traverse different regions of the plasma. This is because the rays are not parallel. Since the production of sufficiently strong light intensities produces difficulties, measurements with a laser will certainly be of interest. If in particular a ruby laser is connected in series with a kerrcell as a so-called Q-switch, it is possible to obtain powers of more than

10 meagwatts. Although other applications of the laser in the plasma diagnostic will be described, I do not wish to go into details about their operation since in the last two years hardly a conference has been held without a description of such lasers.

Microwave Diagnostic

Interferometer measurements are also made with microwaves. The next slide shows a simplified schematic of a microwave interferometer system as used by Wharton and others. The microwaves which are generated in the oscillator are split into two paths, the transmitting path with the horns and the nulling or reference path with an attentuator and a phase shifter. The latter is adjusted so that in the absence of a plasma the output is zero. If a plasma of sufficient density is in the transmission path a phase shift occurs. The resulting signal is recorded on an oscilloscope. This signal appears as a series of waves or interference fringes.

The next slide shows an interpretation of a microwave interferometer response. The lower curve indicates the interferometer response and the upper one represents the variation with time of the electron density of the plasma.

In the interferometer response there are five fringes while the plasma density increases. The density then exceeds a value, the so-called cut-off point. A total reflection appears from that point. This value can be derived from the dielectric constant of the plasma as shown in equation 1. That means one needs lower wave lengths to measure higher density. At the time t_o the density is just decayed to the cut-off value.

The crowding of the fringes before cut-off, as compared to those after cut-off, show that the plasma was building up faster than it decayed. Equation 2 shows in a first approximation a relation between the phase angle $\Delta \phi$ and the electron density n_e . Thereby D is an equivalent plasma diameter for a uniform distribution of a plasma density. The electron density is proportional to the phase shift. In our case that means that the total phase shift is $5 \, . \, 2\pi$ and therefore each fringe represents a change of o,2 in density. So it is possible to plot the upper curve.

When making measurements with the microwave interferometer as described the microwaves should be polarized so that the electric vector is exactly parallel to the field. If this is not the case the measurement becomes more complicated.

The microwave circuits have been modified in various ways. Equation 2 e.g. has two unknowns, the density and the diameter of the plasma. Both change in time. A dual interferometer has been designed by Lisitano.
Two microwaves with wave lengths of 8 and 4 mm are sent across one pair of horns. Thus one gets two equations with two unknowns.

There is a second microwave technique of an entirely different type for the determination of electron temperature. One takes advantage from the fact that a heated plasma is behaving as a block-body radiator in the frequency range of the microwave receiver. The microwave "noise" in a suitable arrangement is directly proportional to the electron temperature. Thereby one assumes that there is a Maxwell distribution of electron energies.

Faraday-Rotation

The rotation of the polarization plane of plane polarized electromagnetic waves in traversing the material in the direction of the magnetic field is the wellknown Faraday effect. Density measurements with the Faraday Effect with microwaves are limited to higher densities by the cut-off point. With e.g. 8 mm one can measure up to $1{,}5 \cdot 10^{13}$ cm^{3}.

Among others Grassmann and Wulff examined the Faraday rotation for dense plasmas with the light of a pulsed ruby-laser. The experimental plan is shown in the next figure. On the left-hand side a plane polarized ruby-laser is depicted. A Glan-Thompson-prisma improves the polarization. After traversing the discharge tube, the light strikes the analyzer, whose polarization plane is perpendicular to that of the polarizer. The multiplier 1 yields a signal I. In front of the analyzer a half transparent mirror diverts a second signal which is measured with multiplier 2. The second signal gives a measurement of the primary intensity I_o.

The equation 1 applies to the light that traverses to polarizers inclined to one another with an angle $\frac{\pi}{2} + \delta$. This is only valid for a small angle. I_R is the inevitable remaining intensity. If this is compensated for, so that without any discharge $I' = I = I_R$, then the right-hand side of the equation is valid. The measurement on the oscilloscope is indicated in the picture. $I - I'$ is obtained electronically. An absolute measurement uses the ratio $\frac{I}{I_o}$ by rotating the prisma through a definite angle. The electron density can be obtained directly from the angle measurement.

Light Scattering

The development of the laser has also made possible the measurement of local plasma parameters by the scattering of light in spite of the smallness of the electron scattering cross section. At first this method was tried by Fünfer, Kegel, Kronast and Kunze as well as by Thompson and Fiocco.

The next slide shows an experimental arrangement from Fünfer et al. A highly transient plasma is produced in a theta-pinch. The light of a high-power ruby laser delivering polarized light of about 100 kW during 100 µsec is focused into the center of the coil. The scattered light is observed through the slit in the coil at right angles to the incident beam.

The scattered laser-light and the plasma-light go through a monochromator to separate all other light which does not have the wavelength of the ruby-laser of 6943 Å. In this experiment the radiation of the plasma at the laser frequency, mainly bremsstrahlung, is about 20 times larger than the scattered light. Since the polarization of the internal plasma radiation is small it is possible to distinguish this internal radiation from the totally polarized scattered light by means of a differential method. With the double refracting plate the emitted light is split into two beams, one polarized parallel to the polarization of the scattered light and the other perpendicular. The desired signal is therefore in only one of these beams. After passing the monochromator the two components are measured with multipliers. With a differential amplifier the plasma light is compensated and the scattered light can be measured with an oscilloscope.

In this experiment it is difficult to avoid completely the laser stray light. Here one uses the fact that the scattered light from the plasma but not from the stray light is broadened. Therefore the exit slit of the monochromator is located at one wing of the broadened line. At plasma densities of 10^{17} cm^{-3} and with the available solid angle of 2.10^{-2} steradians the ratio of scattered light to the incident light is of the order of 1 : 10^{11}.

One can deduce the electron density and temperature from the position of the peak and the ratio of the total energy contained in it to that of the central peak.

To complete the general view of diagnostic methods in plasmaphysics I actually would have to go into details at least in the field of spectroscopy and the radiation measurements. However, I did not press them into this half hour in order to avoid that from the many diagnostic methods I report so little that in the end I report nothing of all diagnostic methods.

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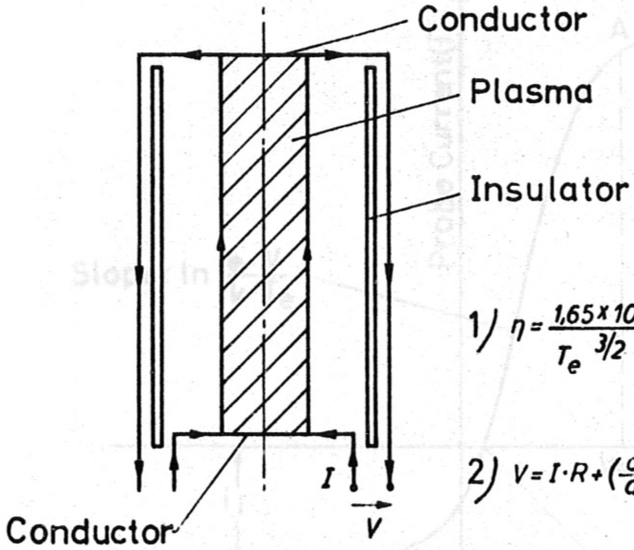
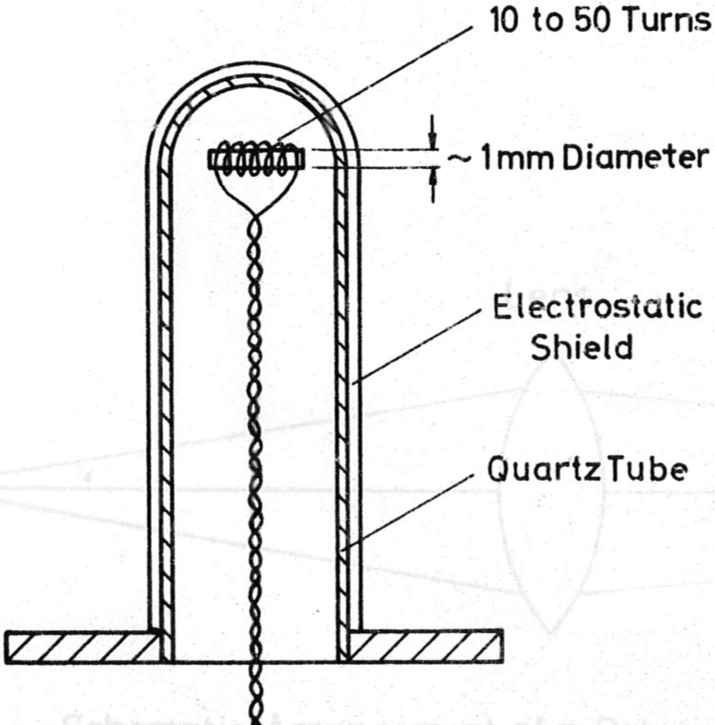


$$1)\ \eta = \frac{1{,}65\times10^{-7}}{T_e^{3/2}}\ln\lambda \approx \frac{3{,}3\times10^{-6}}{T_e^{3/2}}\ [\Omega\mathrm{cm}]$$

with $\lambda = 20$

$$2)\ V = I\cdot R + \left(\frac{d\phi}{dt}\right)$$

Simple Linear Discharge System



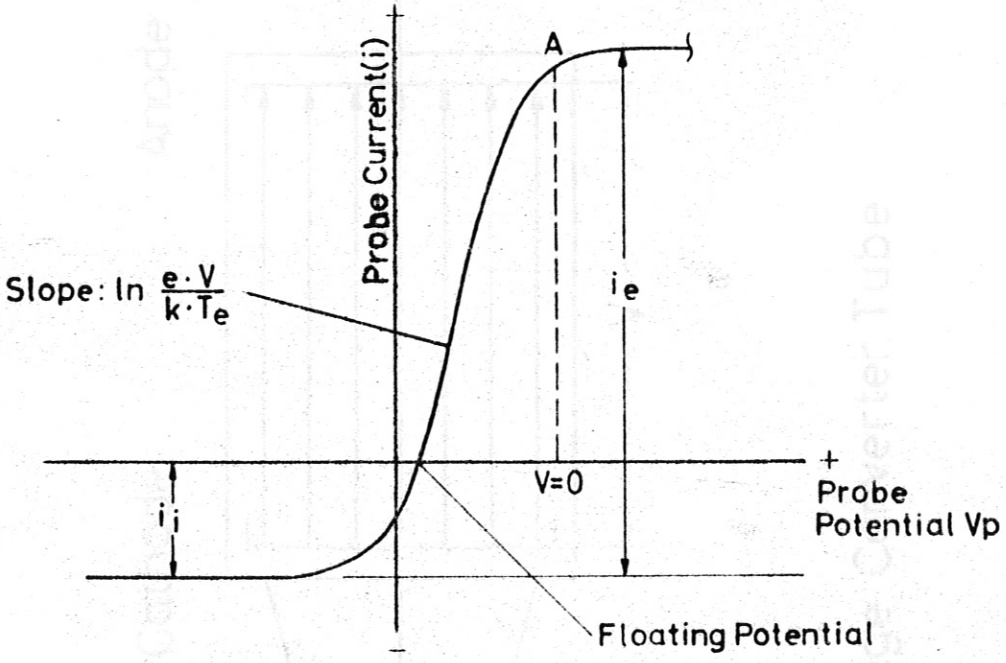
$$1)\ V_i = nA\frac{dB}{dt}$$

$$2)\ B = 10^{8}\times\frac{V_0RC}{nA}$$

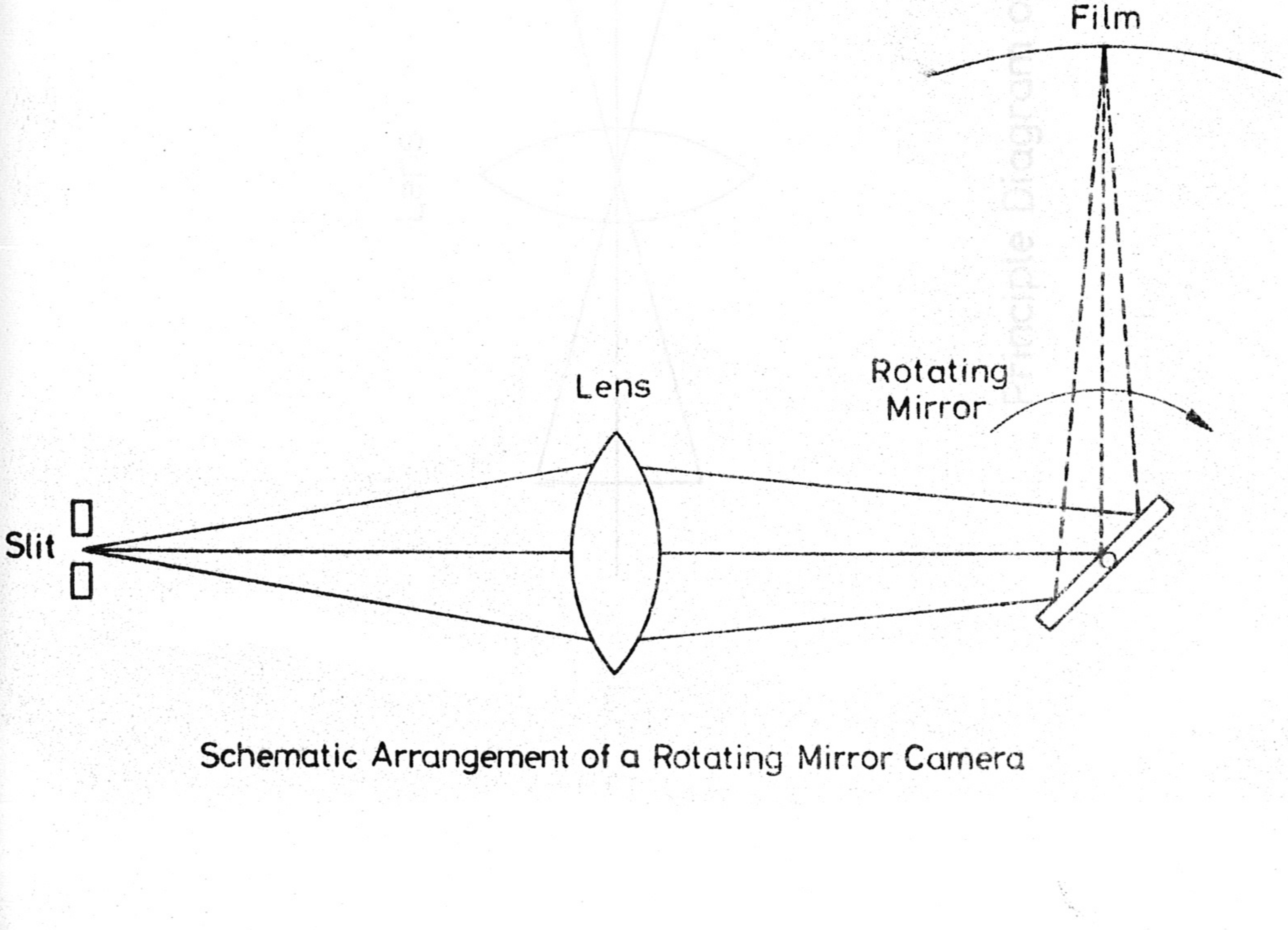
$$3)\ \nabla\times B = \mu j$$

$$4)\ \nabla\times E = \frac{\partial B}{\partial t}$$

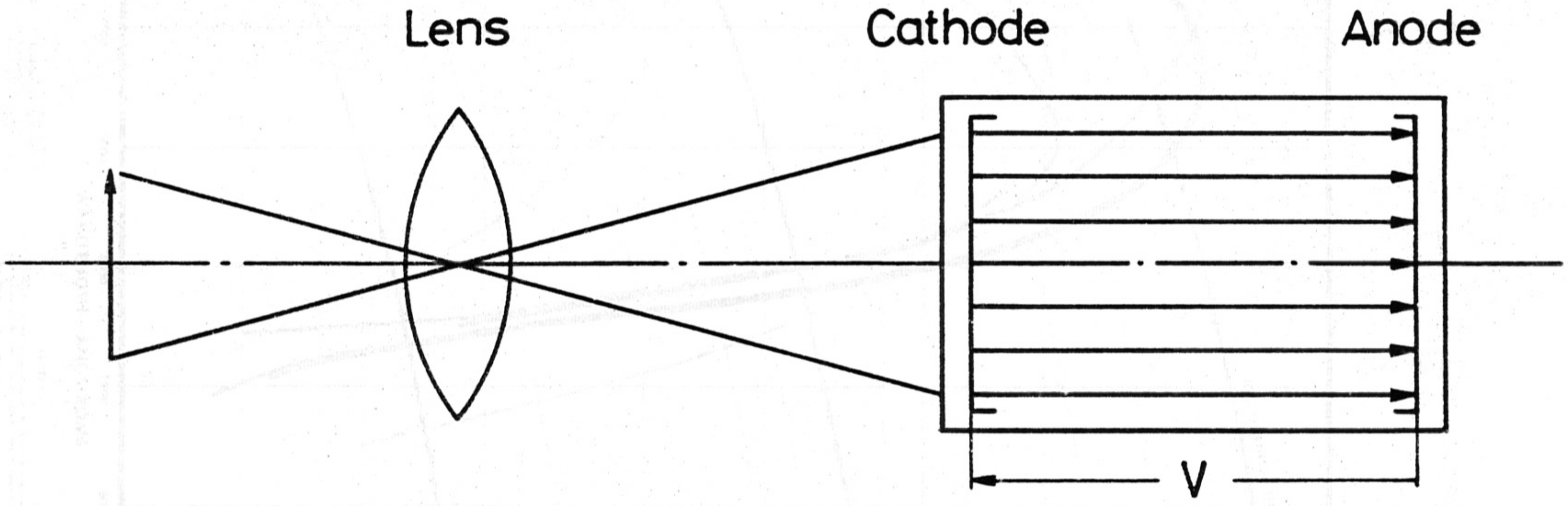
Magnetic Probe Techniques



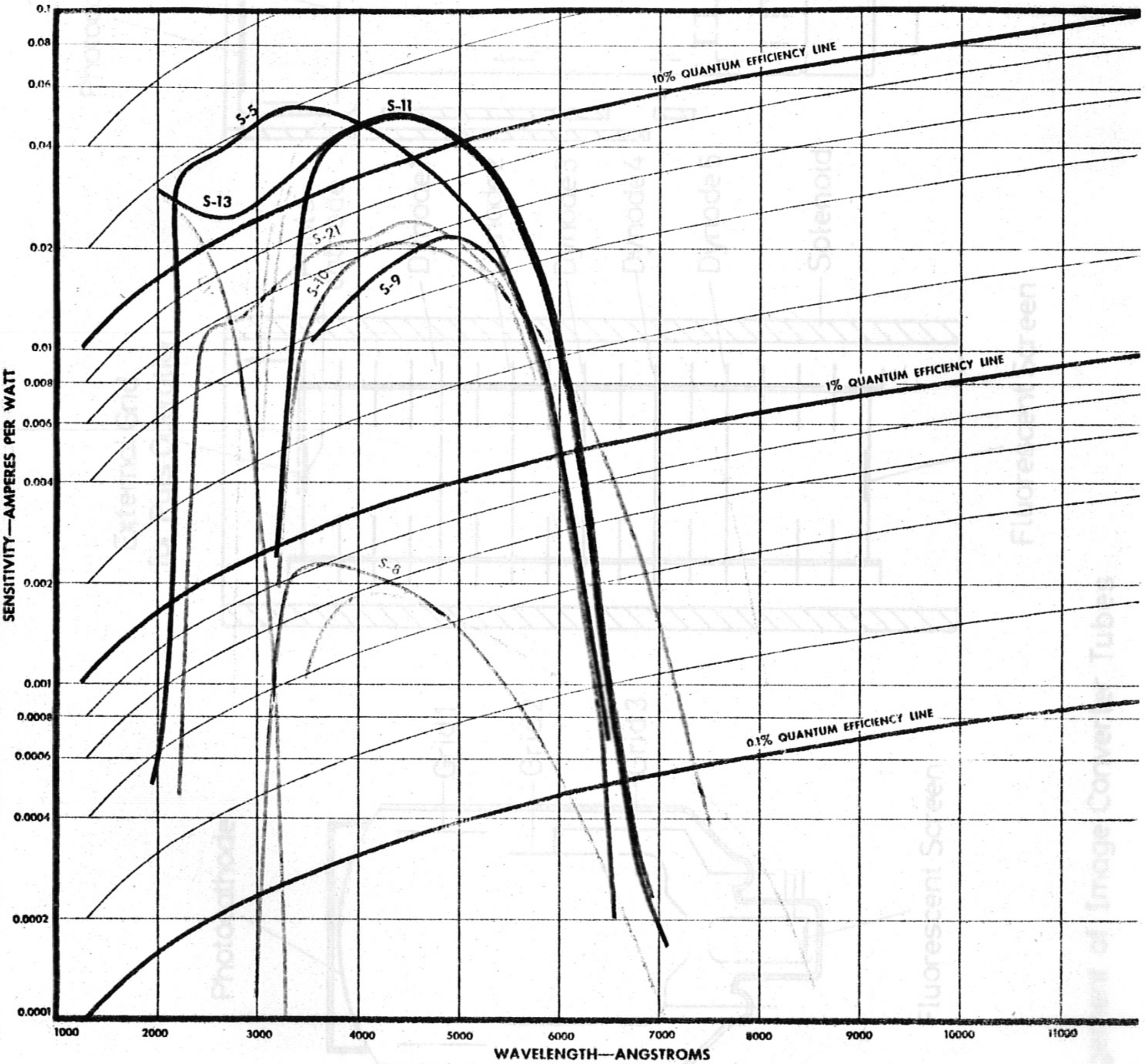
Idealised Probe Characteristic



Schematic Arrangement of a Rotating Mirror Camera



Principle Diagram of an Image Converter Tube



Device S - Number[1]	Principal Photocathode Components[2]	Entrance Window Material	Photocathode Supporting Substrate[3]	Luminous Sensitivity[4] (μa/lumen)	Typical Photo cathode Dark Current[5] @25°C (amps/cm²)
	Ag-O-Cs	Visible light transmitting glass[6]	Entrance window or opaque material[7]	75	10^{11} - 10^{12}
	Ag-O-Rb	Visible light transmitting glass[6]	Opaque material[7]	6.5	10^{12}
S-4	Cs-Sb	Visible light transmitting glass[6]	Opaque material[7]	40	10^{14}
S-5	Cs-Sb	U.V. transmitting glass[6]	Opaque material[7]	40	10^{14}
S-8	Cs-B	Visible light transmitting glass[6]	Opaque material[7]	3	10^{14} - 10^{15}
S-9	Cs-Sb	Visible light transmitting glass[6]	Entrance window	30	10^{14}
S-10	Ag-Bi-O-Cs	Visible light transmitting glass[6]	Entrance window	40	10^{13} - 10^{14}
S-11	Cs-Sb	Visible light transmitting glass[6]	Entrance window	60	10^{14} - 10^{15}
S-13	Cs-Sb	Fused silica	Entrance window	60	10^{14} - 10^{15}
	Cs-Sb	Visible light transmitting glass[6]	Opaque reflecting material[7]	125	10^{14} - 10^{15}
S-19	Cs-Sb	Fused silica	Opaque material[7]	40	10^{14}
	Sb-K-Na-Cs	Visible light transmitting glass[6]	Entrance window	150	10^{15} - 10^{16}
S-21	Cs-Sb	U.V. transmitting glass	Entrance window	30	10^{14}
UV	Cs-Te	Sapphire	Opaque material[7]	9	

NOTES

1. The S number is the designation of the spectral response characteristic of the device and includes the transmission of the device window material.
2. Principal components of the photocathode are listed without regard to order of processing or relative proportions.
3. When the supporting substrate is the entrance window, an intermediate semitransparent electrically conductive layer may be used.
4. Corresponding to the specific absolute response curves shown in the figure using a 2870 K color temperature tungsten lamp test source.
5. Specific dark current excludes DC leakage.
6. Lime glass and Kovar sealing borosilicate glass are commonly used for visible light transmitting glass.
7. The opaque material used as the supporting substrate for photocathodes in which the input radiation is incident on the same side as the emitted photoelectrons is usually metallic in nature.
8. An S-number designation has not yet been assigned to this experimental "solar blind" photoemissive surface.

Ultraviolet photodiodes and multipliers

Infrared and visible photomultipliers

Direct view storage tubes

Electrical read-out storage tubes

Pulsed image tubes and shutter tubes

Multialkali cathodes

Transparent phosphors

Phototubes for nuclear detection

High current phototubes and multipliers

Infrared detectors and cryogenics

Infrared-to-visible image converter tubes

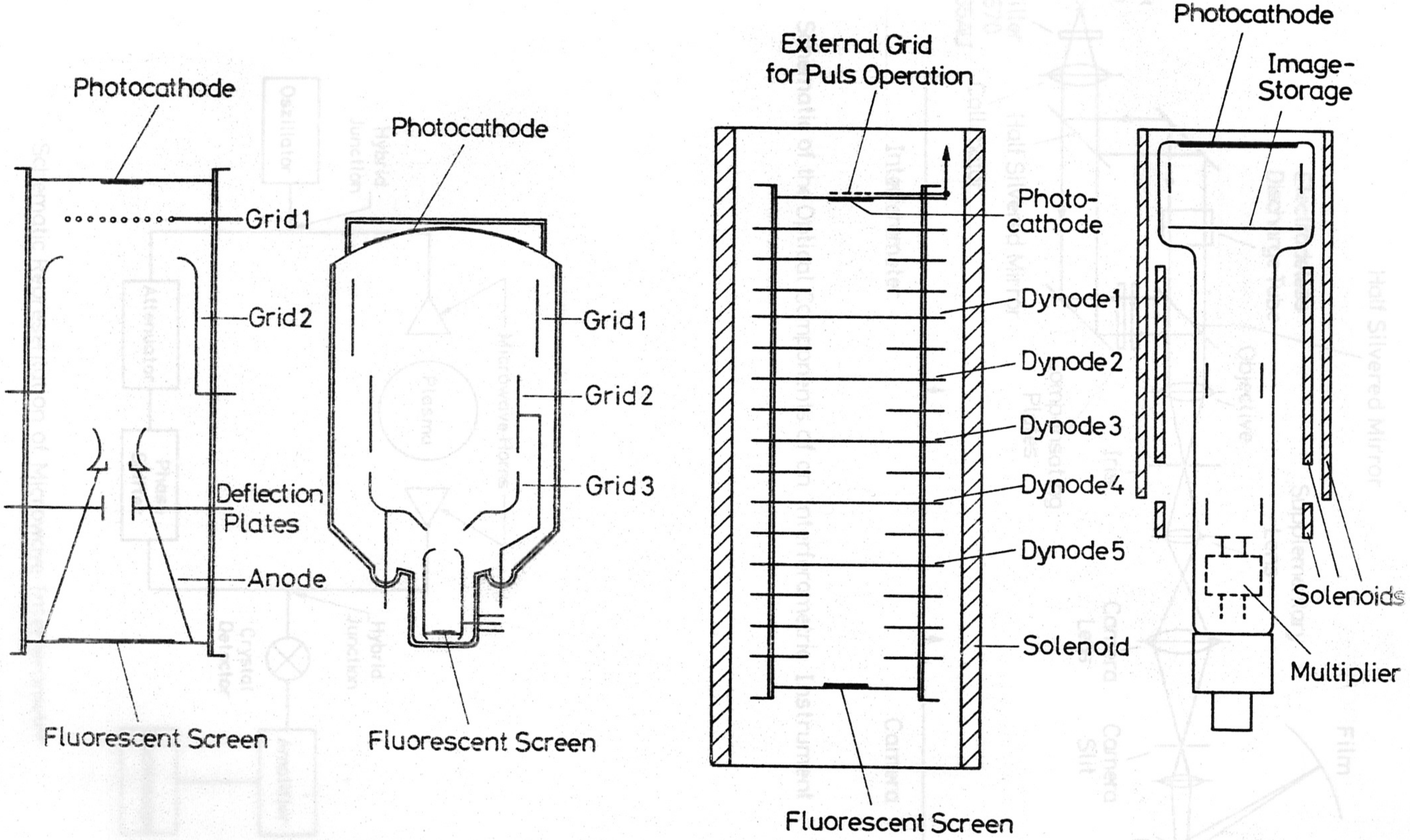
Star tracking photomultipliers

Image dissector tubes for spectrometry

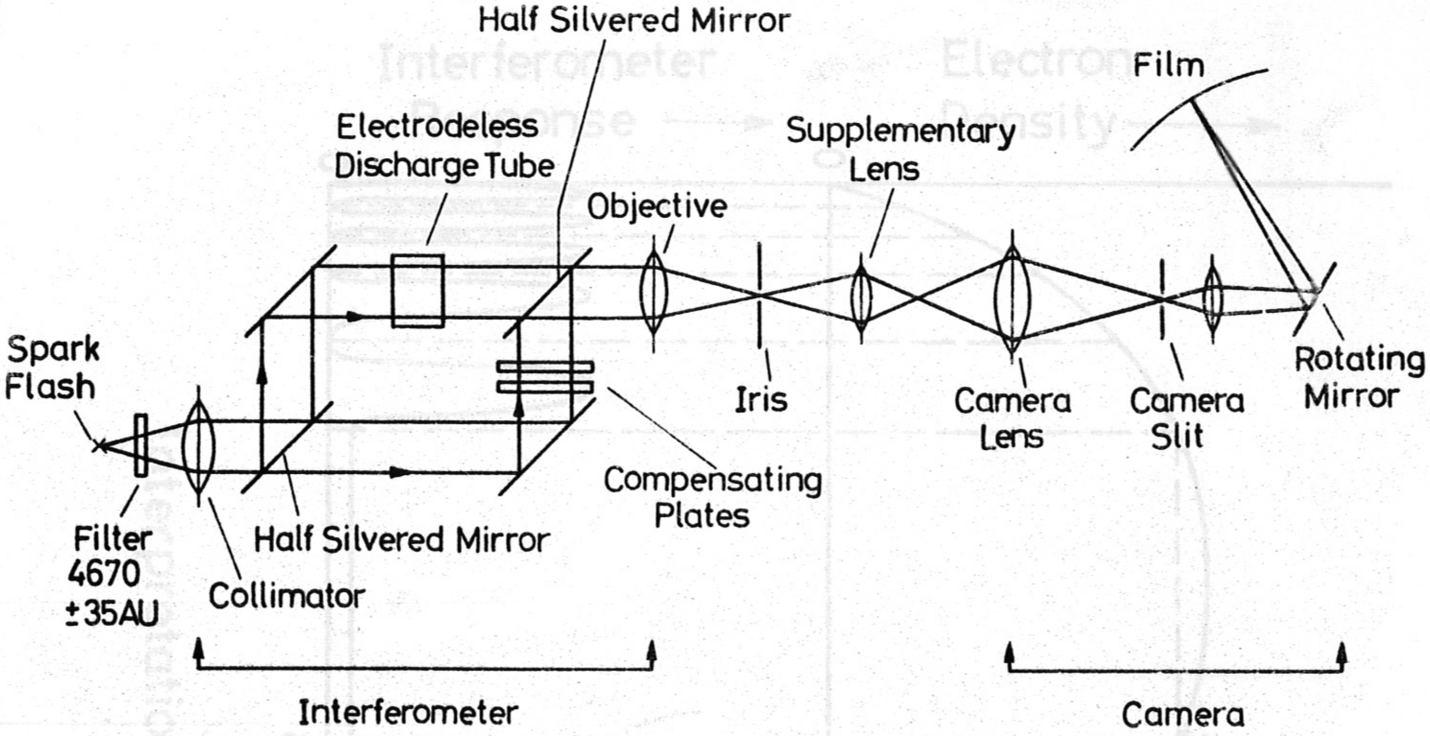
Image intensifiers and light amplifier tubes

Mica window image tubes

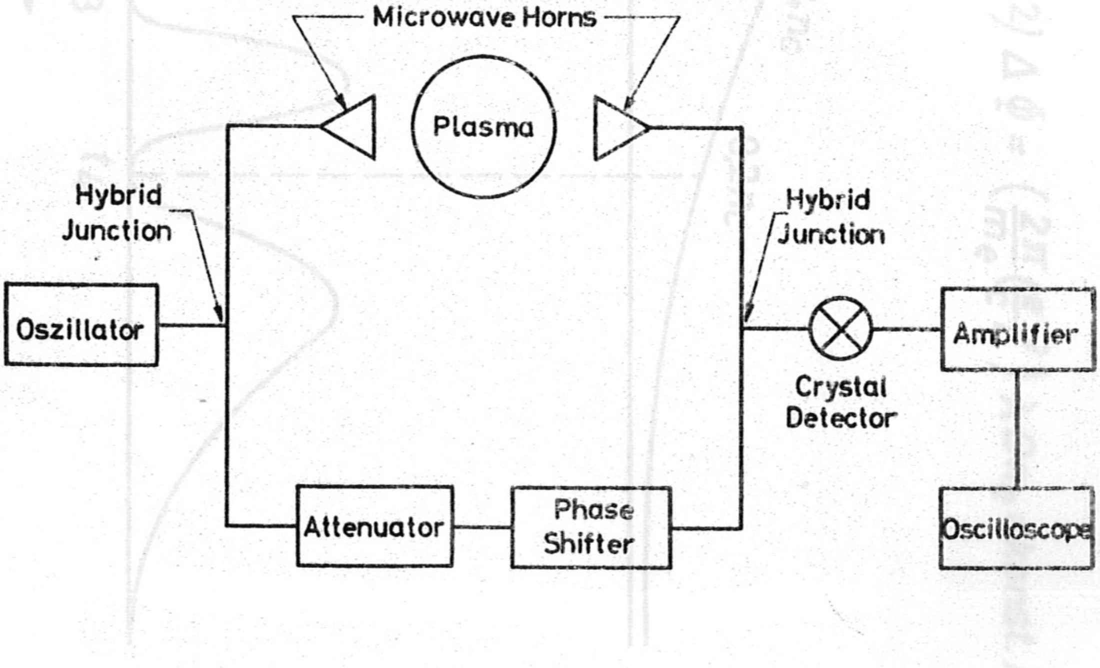
Storage image tubes



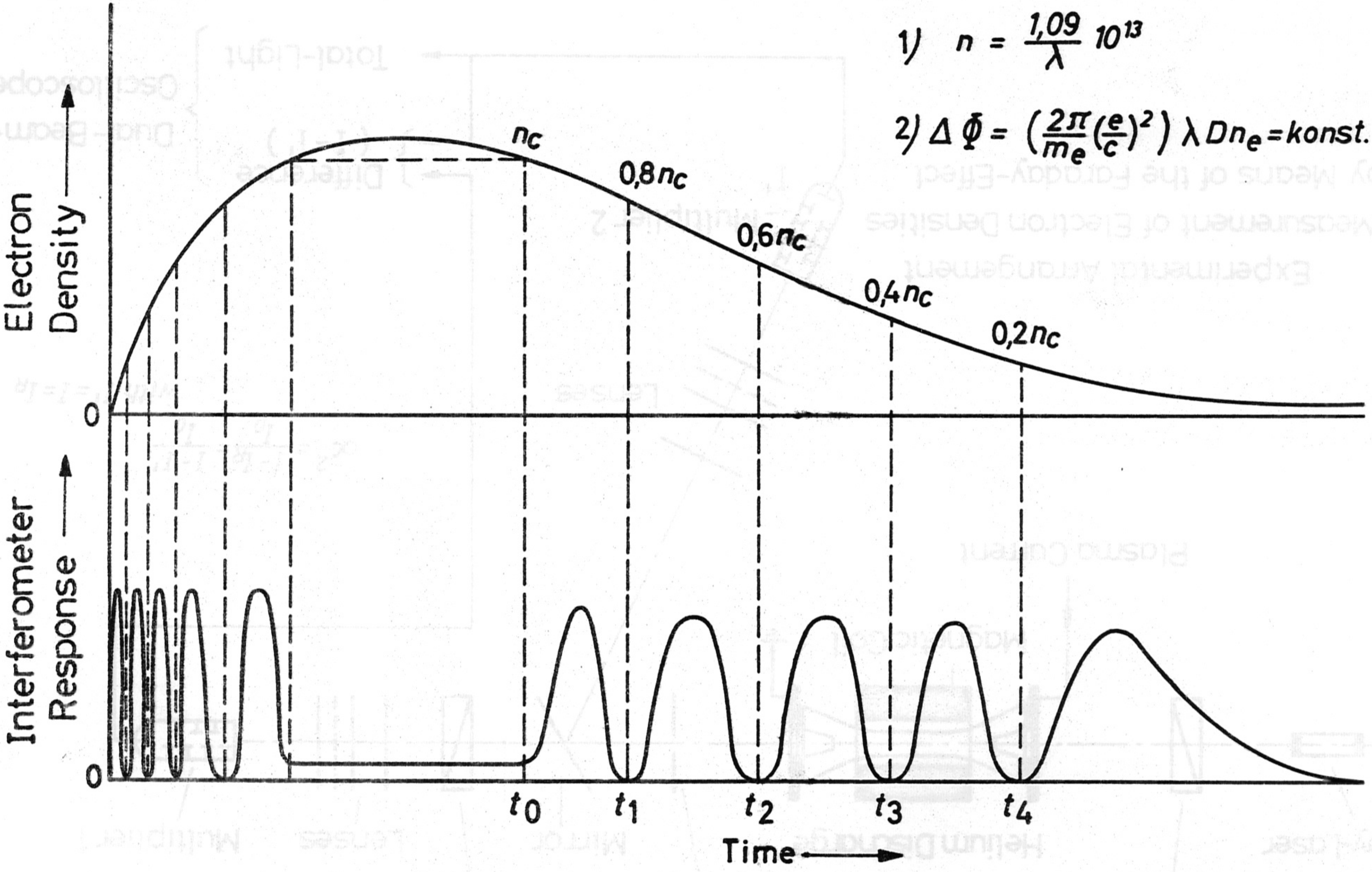
Schematic Arrangement of Image Converter Tubes



Schematic of the Optical Components of an Interferometric Instrument



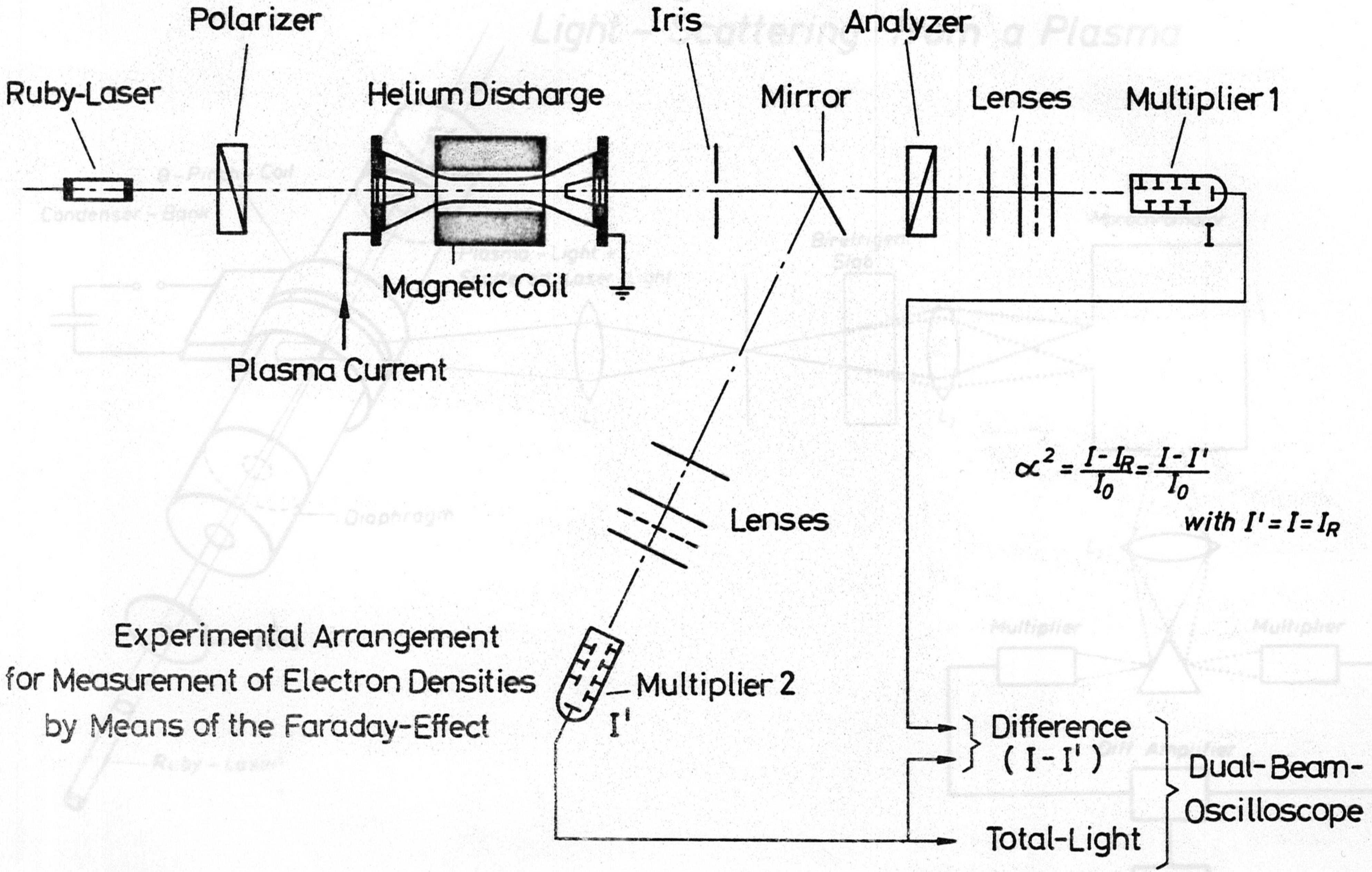
Schematic Representation of Microwave Interferometer



1) $n = \frac{1{,}09}{\lambda} 10^{13}$

2) $\Delta \Phi = \left(\frac{2\pi}{m_e}\left(\frac{e}{c}\right)^2\right) \lambda D n_e = \text{konst.}\, \lambda D n_e$

Interpretation of Microwave Interferometer Response



Experimental Arrangement
for Measurement of Electron Densities
by Means of the Faraday-Effect

Arrangement for Studies of Light – Scattering from a Plasma