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A MULTI-CHANNEL BOLOMETER FOR RADIATION MEASUREMENT ON THE TCA TOKAMAK

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A multi-channel bolometer for radiation measurements on the TCA tokamak

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Abstract

A multi-channel radiation bolometer has been developed for the TCA tokamak. It has 16 equally spaced chords viewing the plasma through a narrow horizontal slit. Almost an entire vertical plasma cross-section can be observed. The bolometer operates on the basis of a semiconducting element which serves as a temperature dependent resistance. A new electronic circuit has been developed which takes advantage of the semiconductor characteristics of the detector by using feedback techniques. Measurements made with this instrument are discussed.

Introduction

Bolometers constitute an important diagnostic for measurements of the total radiated power loss of a high-temperature plasma as obtained commonly in tokamaks, stellarators and related devices. The knowledge of the radiated power is most relevant to the energy balance and the impurity content of a specific device[1,2]. Large machines such as JET[3,4] and TFTR[5,6] have bolometer-arrays at several toroidal and poloidal locations whereas other machines often use a single plasma-chord detector scannable on a shot-to-shot basis. Several types of detectors have been succesfully used, e.g. pyroelectric detectors[7], thermistors[8], thermocouples[9] and metal resistance bolometers[10].

A multi-channel bolometer has recently been commissioned on the TCA tokamak. The main objective of this tokamak experiment is the study of plasma heating by resonant absorption of Alfvén waves which has been described elsewhere[11]. Initial heating experiments were accompanied by a large radiated power loss[12]. Subsequent changes in the design and the material of the limiters and the rf antennae led to a substantial reduction of the radiation from high-Z impurities[13]. At this time the radiated power was measured with a single-chord detector which was scannable vertically over one half of a poloidal cross-section from shot to shot, each spatial profile taking about 10 to 15 reproducible discharges. The advantage of having a measurement of the radiated power profile for each discharge thus became evident.

The plan of the paper is as follows. In section I we discuss the choice of the detector appropriate for the TCA tokamak and in section II its installation. In section III, we present some of the basic underlying bolometer theory. In section IV, we discuss our new kind of electronic circuit which takes advantage of the semiconductor characteristics of the bolometer. Finally the capabilities of the system and some results are presented in section V.

I. Detector Choice

The TCA tokamak (R,a = 0.61,0.18 m) has basic plasma parameter capabilities of $B_T \leq 1.51$ T, $I_p \leq 170$ kA, $n_{eo} \leq 1.0\ 10^{20}\ m^{-3}$ and a flat-top current phase of 100 ms. The minimum requirements for a bolometer are given by the viewable plasma volume and the desired spatial and temporal resolution. For a poloidal resolution of 2.2 cm the radiation flux has typical values of 1-20 mW/cm^2 at the detector surface, depending on the viewing geometry. The time resolution design value was 1 ms. In order to cover the spectral range where most of the power is lost the bolometer has to absorb electromagnetic radiation with wavelengths from a few up to about 2000 Å originating mainly from line radiation of impurities[14].

In the earlier phase of the TCA tokamak a pyroelectric detector had been used[15]. The relative response of this type of detector was very good but difficulties were encountered with the absolute magnitude of the measured power level. The complicated physical process of pyrodetectors could very well be sensitive to the operating environment of the tokamak, i.e. electric and magnetic fields, hard X-rays or electrons produced by secondary emission.

The next type of bolometer used on TCA was a Germanium semiconductor resistance bolometer developped for the stellarator W VII A[16]. A resistance bolometer has the advantage of a very simple physical process which consists of a change in electrical resistance due to the temperature change provoked by the amount of radiation absorbed. Using a semiconducting material as the resistive element results in a larger temperature coefficient with respect to metal resistors. Good experience was obtained with this type of detector for several years of operation on TCA. Semiconducting bolometers are likely to be subject to nuclear irradiation but this restriction is not relevant for the case of the TCA tokamak.

When designing the multi-channel bolometer two types of detectors were finally discussed: the semiconducting bolometer mentioned and a metal resistor bolometer similar to those used on JET and ASDEX tokamaks[3,4]. In comparing the two possibilities the metal resistor bolometer revealed itself to be not sensitive enough for the desired time resolution due to the smaller value of the temperature coefficient. The good experience obtained with the existing semiconducting bolometer on TCA encouraged us to reuse this type of detector.

II. Installation

The semiconducting bolometer has an active area of 1.5 cm^2. A schematic diagram of the bolometer element is shown in Fig.1. The incident electromagnetic radiation is absorbed efficiently by a stainless steel foil (4 μm) for the spectral range discussed above[17,18]. This foil is mounted into a ring and serves as substrate for the subsequent thin films obtained by vacuum deposition[19]. A thin layer of MgO_2 (1.5 μm) serves as an insulator to the Germanium layer (1 μm). An electrode structure made of gold (0.5 μm) reduces the resistance of the Germanium layer to a practical value ranging between 20 and 60 kΩ. The electrical contacts are realised by gold-covered tungsten wire touching the contact areas of the gold film of the bolometer. The temperature coefficient of the electrical resistance α ($\alpha = 1/R\ dR/dT$) has values of -2.5 to -3.0 10^{-2} $°K^{-1}$. The linearity of this coefficient has prooved to be very good over a wide temperature range from 20 °C up to 60 °C depending on the bolometer resistance[19]. This temperature range exceeds the practical operation range by far since the temperature variations resulting from typical radiation fluxes are of the order of a few percent of 1 °C. The maximum power level is thus mainly determined by the operational range of the amplifiers used in the electronic circuit. The thermal time resolution is about 5 μs.

A 150 mm diameter port was available for the new bolometer on the vacuum vessel of TCA. Fig.2 shows a schematical diagram of the experimental layout. The distribution of the detectors follows a pinhole-camera design. Given the constraint of adjacent toroidal field and vertical positioning coils a maximum of 16 detectors could be placed in the available space. This enables a simultaneous view of almost an entire vertical cross-section, ranging from full plasma radius (18 cm) at the bottom to 15 cm at the top of the plasma. A variable vertical collimator results in a spatial resolution of 1.7 to 3.3 cm at the plasma centre. In the toroidal direction the maximum aperture given by the vacuum port was chosen in order to increase the incident flux and therefore the measured signal.

The elements are individually mounted on vacuum flanges electrically insulated from the bolometer main vessel. The electronic circuit proper to each detector is situated right next to the electrical feed-throughs. The bolometer vessel is mounted onto the tokamak vessel through a bellows which ensures the vacuum tightness in the presence of vibrations and slow movement of the tokamak. The two vacuum vessels are separated by a 200 mm diameter pneumatic valve. The modular design of the detectors and a separate turbo-molecular vacuum system guarantee a large flexibility of the multi-channel bolometer, particularly in the commissioning phase and in the case of any eventual trouble with one of the detectors.

Having the electronic circuit close to the detectors minimizes the amplification of parasitic noise of electromagnetic origin. Open loops in the cabling were avoided wherever possible. The amplifiers are connected to a common power and control unit inside the experimental area. The analog signals are digitized and multiplexed by an ADC designed for the TCA acquisition system[20] before being transmitted by fiber-optic links to the computer in the control room. In this way a test of the whole bolometer system can be carried out from the computer.

In order to minimize the effects of the ohmic heating transformer system ($E_{oh} \simeq 370$ kJ) and the rf pulse ($P_{rf} \leqq 400$ kW, f = 2.5 MHz, 30 ms) care had to be taken in the shielding of the detectors as well as in the separation of the different electrical earths.

III. Bolometer Theory

The physical properties relevant to bolometers , in particular to semiconducting resistance bolometers, will be outlined. The electrical resistance of a semiconducting material follows an exponential law with respect to its temperature of the form:

$$R(T) = R(T_o) \exp(\alpha T) \qquad (1)$$

where α : temperature coefficient

T_o: reference temperature

The salient feature of the semiconducting material is the inverse dependence on temperature expressed by a negative temperature coefficient α. Thus if the electrical resistance is measured as a function of time the corresponding temperature evolution of the bolometer can be obtained:

$$T(t) = 1/\alpha \ \ell n \ (R(t)/R_o) \quad ; \quad R_o = R(T_o) \qquad (2)$$

If the specific heat c of the bolometer is known, the power flux incident on the detector can be derived from its temperature. The specific heat c can in general be obtained from a calibration procedure. In our case the bolometer would have had to be calibrated in the VUV spectral range by a source of known emissivity. As this was not possible the quantity c was determined from the different materials of which the bolometer was made. The value thus obtained is c = 1.7 mJ

$cm^{-2}\ {}^{\circ}K^{-1}$. The bolometer acts as an integrator and the power flux can be written as:

$$\varepsilon\Phi = c\ d(T(t))/dt \qquad (3)$$

where ε : emissivity of the detector surface material

As the incident radiation is well absorbed by the surface material the emissivity ε of the detector will subsequently be considered to be unity. This calculation assumes no losses on the bolometer. However heat can diffuse through the bolometer support. This results in a lower effective temperature. An adiabatic correction has to be carried out which can become very important if the tokamak discharge is long enough. If we consider a temperature increase ΔT we can write:

$$\Phi = c\ d(\Delta T)/dt + G\ \Delta T \qquad (4)$$

where G is the thermal conductance

From this correction the cooling constant of the bolometer can be defined as $\tau_c = c/G$ and (4) becomes:

$$\Phi = c\ (d(\Delta T)/dt + 1/\tau_c\ \Delta T) \qquad (4')$$

This correction is performed numerically by calculating an adiabatically corrected temperature T_c assuming an exponential decay of the measured temperature when the source of radiation is turned off:

$$T_c = T + 1/\tau_c \sum T_m \Delta t \qquad (5)$$

where T_m : average temperature increase during Δt

The cooling constant τ_c was verified experimentally to be of the order of 2 s. The flux can now be obtained directly:

$$\Phi = c\ dT_c/dt \qquad (6)$$

The value thus determined represents the integral of the radiated power along a line of sight :

$$I(h) = \int P(r)\ dl \qquad (7)$$

where h : distance from the plasma axis to the line of sight

In order to obtain the local value of the radiated power one has to perform an Abel inversion or similar unfolding technique.

IV. Electronic Circuit

There exists a variety of electronic techniques to treat the signals provided by bolometers. On some devices a Wheatstone-bridge is used with two bolometers as branches, one of them being shielded against radiation[21]. Both detectors operate under identical conditions such as temperature and noise. By unbalancing the bridge during the plasma-discharge the effect of radiation is revealed. This technique evidently has large advantages but it requires detectors with fairly similar characteristics, particularly as far as the temperature coefficient α is concerned. This is unfortunately not the case for the semiconducting bolometers used here. Resistance and temperature coefficients are extremely sensitive to variations in the thickness of the thin layers obtained by vacuum-deposition.

Another possibility consists of applying constant voltage or current to the bolometer. This works out fine but there is a disadvantage that the initial value of resistance has to be known in order to calculate the change in resistance. If this first value is perturbed the whole subsequent calculation can be wrong. This problem may be avoided when taking advantage of the semiconductor characteristics of the detector.

The temperature variation provoked by the amount of radiation absorbed by the detecting element is very small. The associated change in electrical resistance of the thin germanium film is therefore also very weak. The electronic circuit has to detect this variation in the presence of strong, perturbing magnetic and electric fields. In fact, currents of some 100 nA have to be measured in the neighbourhood of perturbing fields induced by currents of the order of 100 kA.

IV.1.Description of the main circuit

The duration of a plasma discharge in TCA is about 200 ms. During this time the multi-channel bolometer is switched into the measuring mode. Following the discharge the instrument returns to a condition of rest which is maintained until the next plasma discharge is triggered.

While the device is in the resting mode the voltage applied to the bolometer is continually ajusted in order to keep the current equal to a specified reference current. In this way variations of the temperature of the operating environment are automatically taken into account. The current flowing through the sensing element must be small enough not to heat up excessively the bolometer by Joule dissipation. Typically about 0.5 mW of electrical power are dissipated in the bolometer resulting in a temperature increase up to about 0.5°C above ambient temperature.

In the operating mode the applied voltage is kept constant and a variation of the current due to a change in temperature is detected. This new concept has the advantage of being independent of the operating temperature. In other words, the procedure of measurement is identical for every initial temperature and only the variation has to be considered.

Fig.3a shows the principal arrangement of the main circuit elements. During the resting mode, the switch k is closed. The output of the amplifier chain is fed back to the input of the integrator. When the system reaches a steady state, the voltage output of the integrator is constant. This is only possible when the voltage at the integrator input vanishes. Consequently the output is zero for any value of the ambient temperature and we have:

$$I_B + I_R = 0 \tag{8}$$

$$U_B(T) = R_o \exp(\alpha T)\ I_B \tag{9}$$

where subscript B stands for bolometer and R for reference

The dynamics of this feedback loop as shown in Fig.3b is given by:

$$I_B/I_R = 1/(1 + \Delta\tau) \tag{10}$$

$$\tau = (R_2\ R_4\ R_B\ C)/(R_1\ R_3) \tag{11}$$

The resistance R_4 is chosen to be very large in order to have a long time constant.

In the operating mode, the switch k is open. The voltage at the integrator output is fixed at the value preceding the opening of k. The current can be written as:

$$I_B = U_B/(R_o \exp(\alpha T)) \tag{12}$$

For a small variation in temperature we can write:

$$dI_B/dT = -\ \alpha\ U_B/(R_o \exp(\alpha T)) \tag{13}$$

or

$$dI_B/dT = - \alpha\ I_B = \alpha\ I_R \tag{14}$$

After amplification this change in current varies the output voltage:

$$dU_S/dT = dI_B/dT\ (R_1\ R_3)/R_2 = \alpha\ I_R\ (R_1\ R_3)/R_2 \tag{15}$$

We can define a transfer resistance given by $R_G = (R_1\ R_3)/R_2$ and we then have:

$$dU_S/dT = \alpha\ I_R\ R_G \tag{16}$$

The temperature increase dT can now easily be calculated from the output voltage dU_S and the values of the constants α, I_R and R_G. Given a sampling rate Δt, the evolution of the bolometer temperature increase during the plasma discharge is readily obtained. This value is then substituted into (5) to give the adiabatically corrected temperature increase.

The advantage of this new circuit can be summarized as follows. Feeding back the output signal to the bolometer in the resting mode results in a zero output signal. Temperature drifts are thus automatically taken into account. Using the fact that a semiconductor resistance is described by (1), the temperature evolution of the bolometer may be determined across the temperature coefficient α.

The value of R_3/R_2 can be varied in the ratios 1:2:4:8 to change the overall gain of the amplifier chain. The bandwidth of the bolometer is limited by a Butterworth[22] filter of third order at 820 Hz.

As the sensing element is fed by a constant voltage the electric power dissipated in the detector varies as the resistance varies. The error introduced by this effect has been estimated up to 0.4 %.

The parasitic effects of the magnetic field strength at the detector are counteracted by cylindrical shielding of the bolometer and the electronic circuit by soft iron.

The perturbations which occurred in the presence of the rf heating (2.5 MHz) were overcome by decoupling certain sensitive points in the circuit and by carefully treating the system of the electrical earths.

IV.2.Auxiliary circuits

In addition to the principal circuit, the multi-channel bolometer is equipped with two auxiliary circuits. As we have outlined above the bolometers are installed in a vacuum vessel separate from the torus main vessel. When the instrument is put into operation after letting in air, a heating circuit allows a current to flow through the detector. The temperature of the bolometer is gradually raised to typically 120 °C, at which the current is kept constant. After 10 to 15 minutes of out-gasing, the resistance reaches a stable value which corresponds to its nominal value. Combined with a powerful turbomolecular pump (100 l/sec) this system ensures that the multi-channel bolometer is operational in a very short time.

The second auxiliary circuit is destined for a test procedure of the bolometer, to be carried out at any time. With 16 channels, a complete measurement of the operational status of the instrument would otherwise be very troublesome to obtain. An analogue multiplexer switch enables us to carry out, for each channel, a series of 8 measuments of internal operating parameters. These test measurements, which are evaluated by the computer, provide instantaneous values for parameters such as the reference current, the applied voltage, the bolometer resistance, current and voltage during the heating procedure and the gain of the amplifier chain for all 16 channels. In this way access to the experimental area is not essential to check out the instrument.

V.Results

The time evolution of one bolometer trace for a tokamak discharge with Alfvén wave heating is shown in Fig.4. After calculation of the adiabatically corrected temperature increase as outlined in (5) this value is smoothed in time before being time-differentiated in order to obtain the time evolution of the emitted flux (Fig.5). The increase in line-integrated radiated power partly due to a large increase in plasma electron density during the rf pulse is evident.

When the multi-channel bolometer is in operation the TCA acquisition system stores the 16 voltage traces corresponding to each detector on disk under a file which contains all parameters of one particular discharge. A first, rough and standard data analysis may be performed automatically after each discharge. The same evaluation program can be run on any discharge at any time after. At this stage, the soft ware allows an interactive choice of the options in the data analysis to be carried out. Parameters such as for example the first time value, the sampling rate, the number of time intervals, the smoothing degree in time, the manner of display, e.g. the voltage traces or the line integrated profile, a symmetric or asymmetric regression of the data may be chosen by the operator. The plasma edge, which has a nominal value of 18 cm given by the plasma limiter position, is estimated from the bolometer data where the plasma radiation vanishes. On request, the analysed data of the multi-channel bolometer can be stored in a new file for further analysis such as an Abel inversion. Following the the nature of the data analysis a symmetric or asymmetric inversion can be carried out. When strongly hollow radiation profiles occur, care has to be taken in the interpretation of the central radiated power which may have quite large error bars due to the small absolute value ($P_{rad}(0) \geq 0$). Fig.6 shows a line-integrated radiation profile after fitting by regression techniques. The corresponding spatial profile after a symmetric Abel inversion is plotted in Fig.7.

Due to the increased data-taking efficiency the multi-channel bolometer has allowed us to carry out a variety of experiments which were not possible before. Radiation profile analysis can now be performed for different tokamak discharge conditions such as plasma current, density or rf power for example. The results of such a profile analysis has recently been presented for ohmically heated discharges[23]. The effect of the rf pulse on the behaviour of the radiated power has revealed interesting facts about the content and production of impurities[24].

Acknoledgements

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Figure captions

Fig.1 Schematic diagram of the Germanium bolometer

Fig.2 The experimental layout of the multi-channel bolometer system

Fig.3a The arrangement of the main elements in the electronic circuit

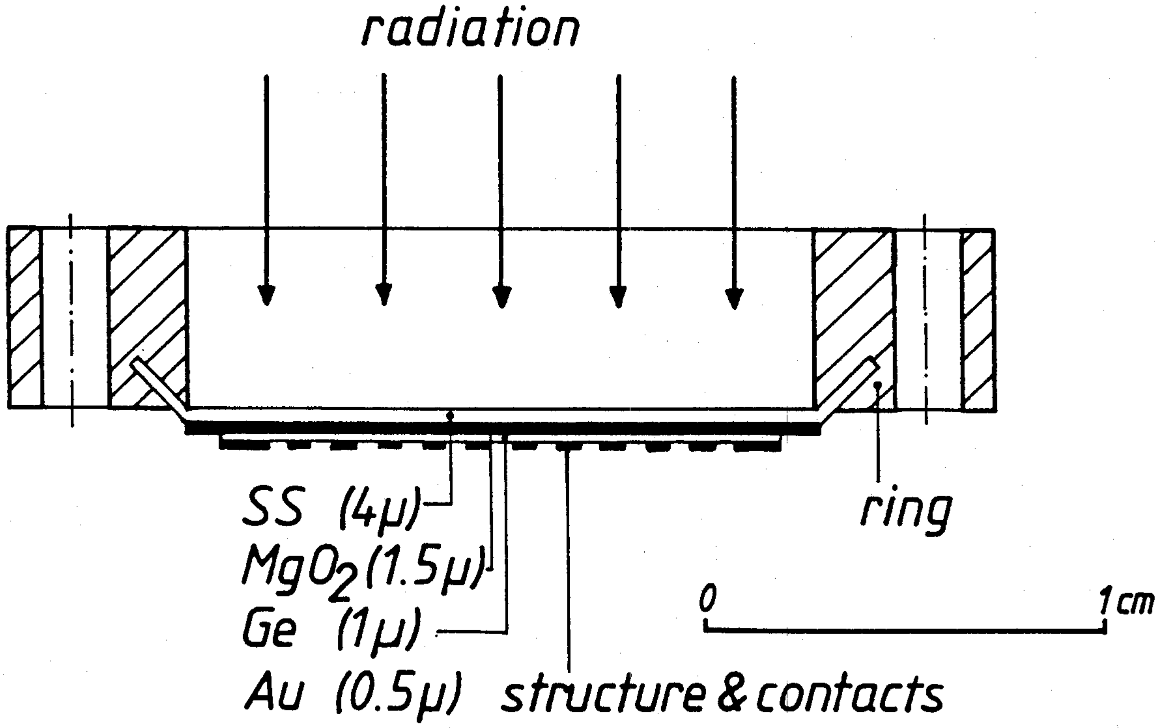
Fig.3b The dynamics of the electronic circuit

Fig.4 The voltage trace of one bolometer element for a plasma discharge with rf heating

Fig.5 The radiation flux corresponding to Fig.4

Fig.6 The time-evolution of the line integrated radiated power profile for a plasma discharge with rf heating

Fig.7 The time-evolution of the local radiated power profile obtained by a symmetric Abel inversion of the profile represented in Fig.6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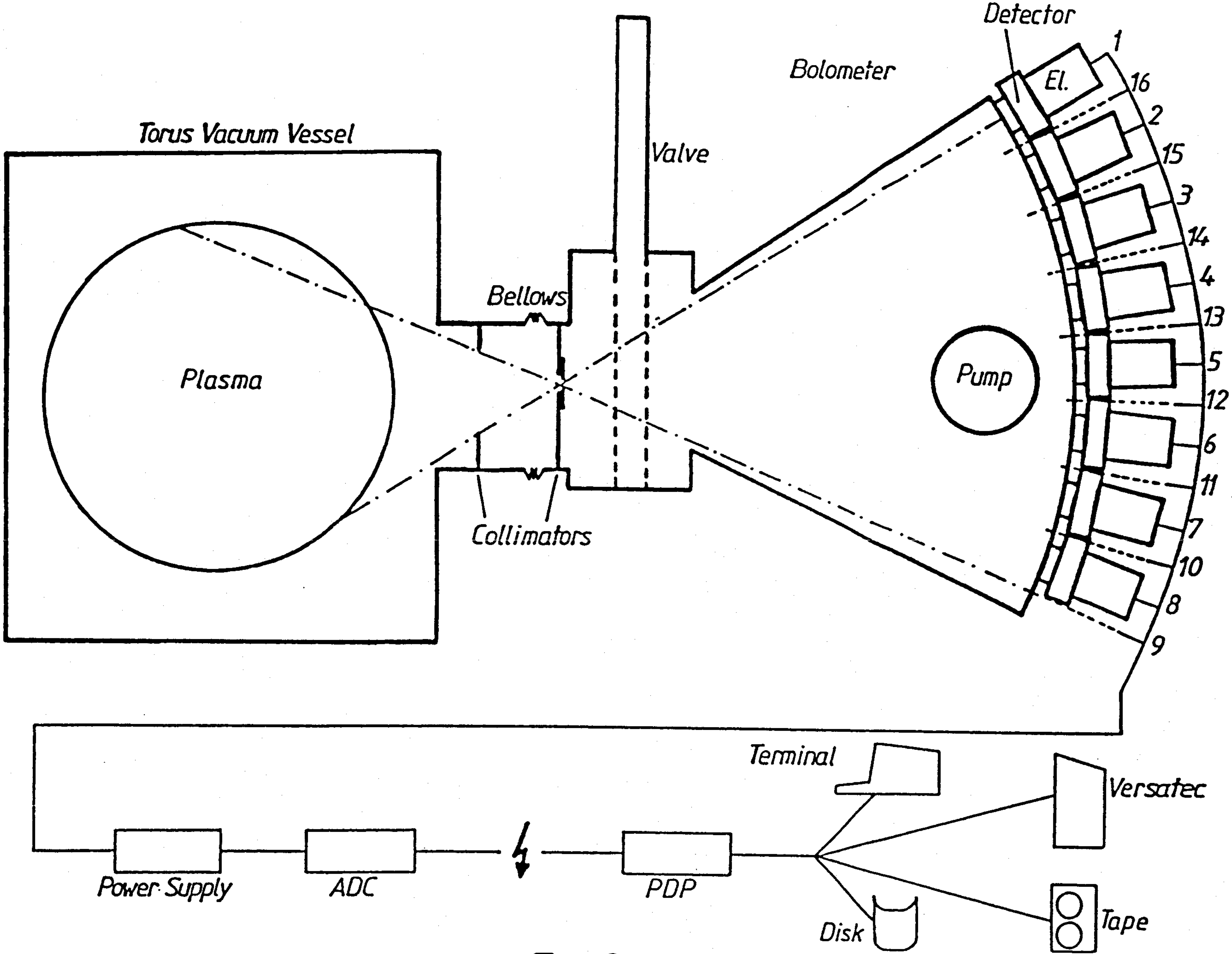
MgO2 (1.5μ)
Ge (1μ)
Au (0.5μ)
structure & contacts
ring
0
1cm

Fig. 1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Plasma
Bellows
Collimators
Valve
Bolometer
Detector
El.
Pump
1
16
2
15
3
14
4
13
5
12
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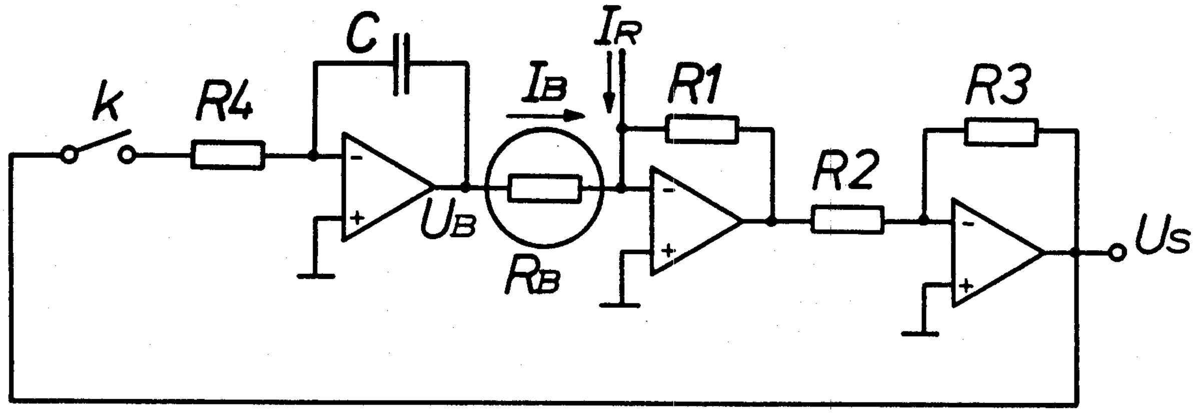
11
7
10
8
9
Terminal
Versatec
Power Supply
ADC
PDP
Disk
Tape

Fig. 2

a)



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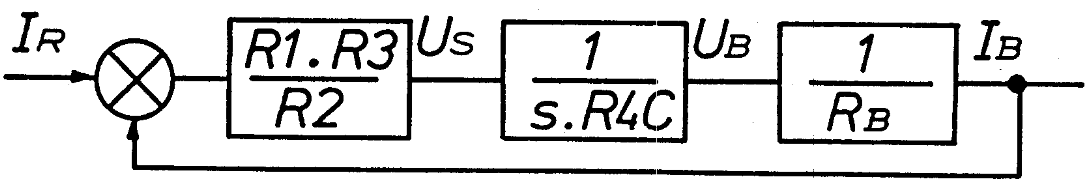

Fig. 3

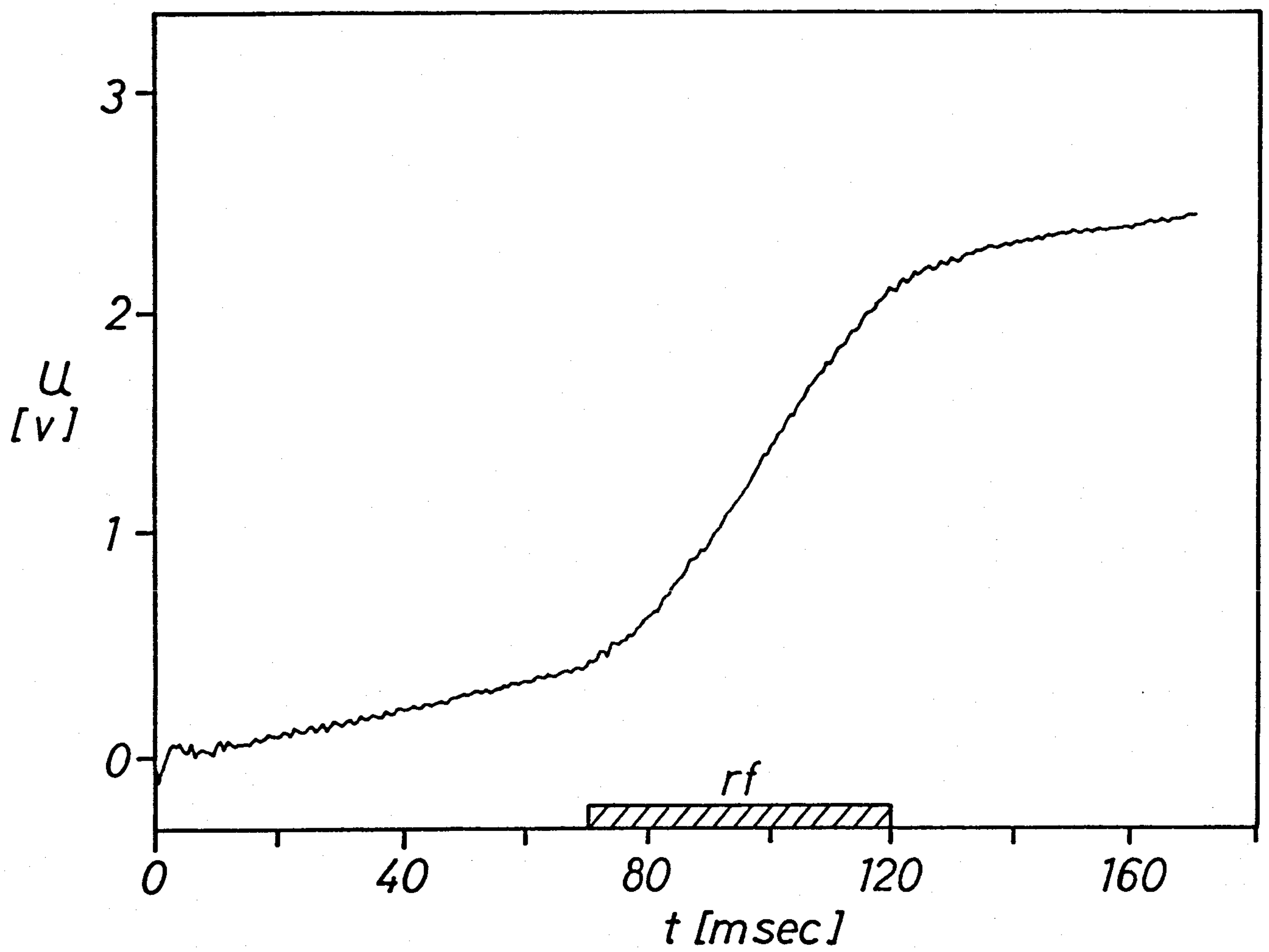

Fig. 4

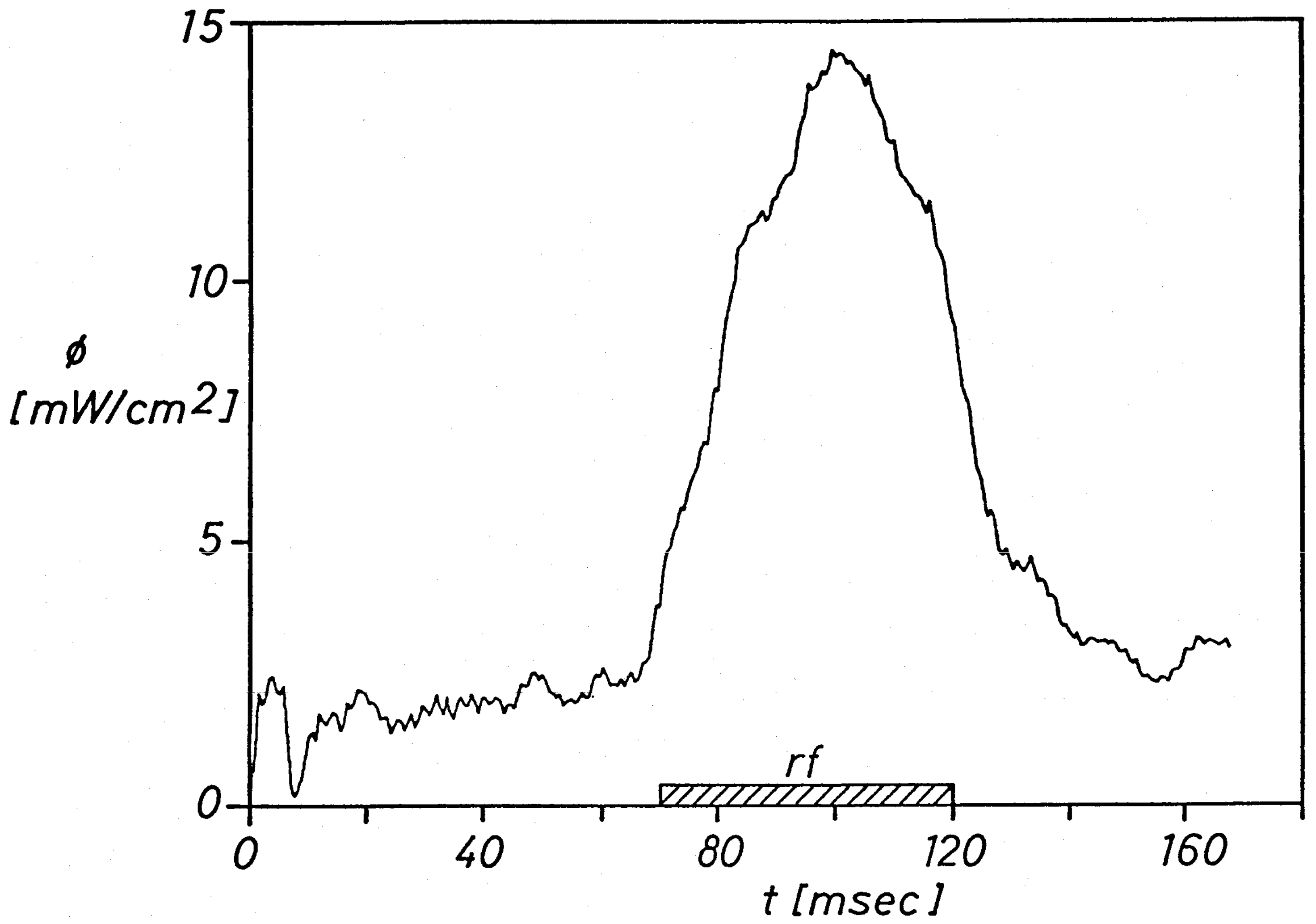

Fig. 5

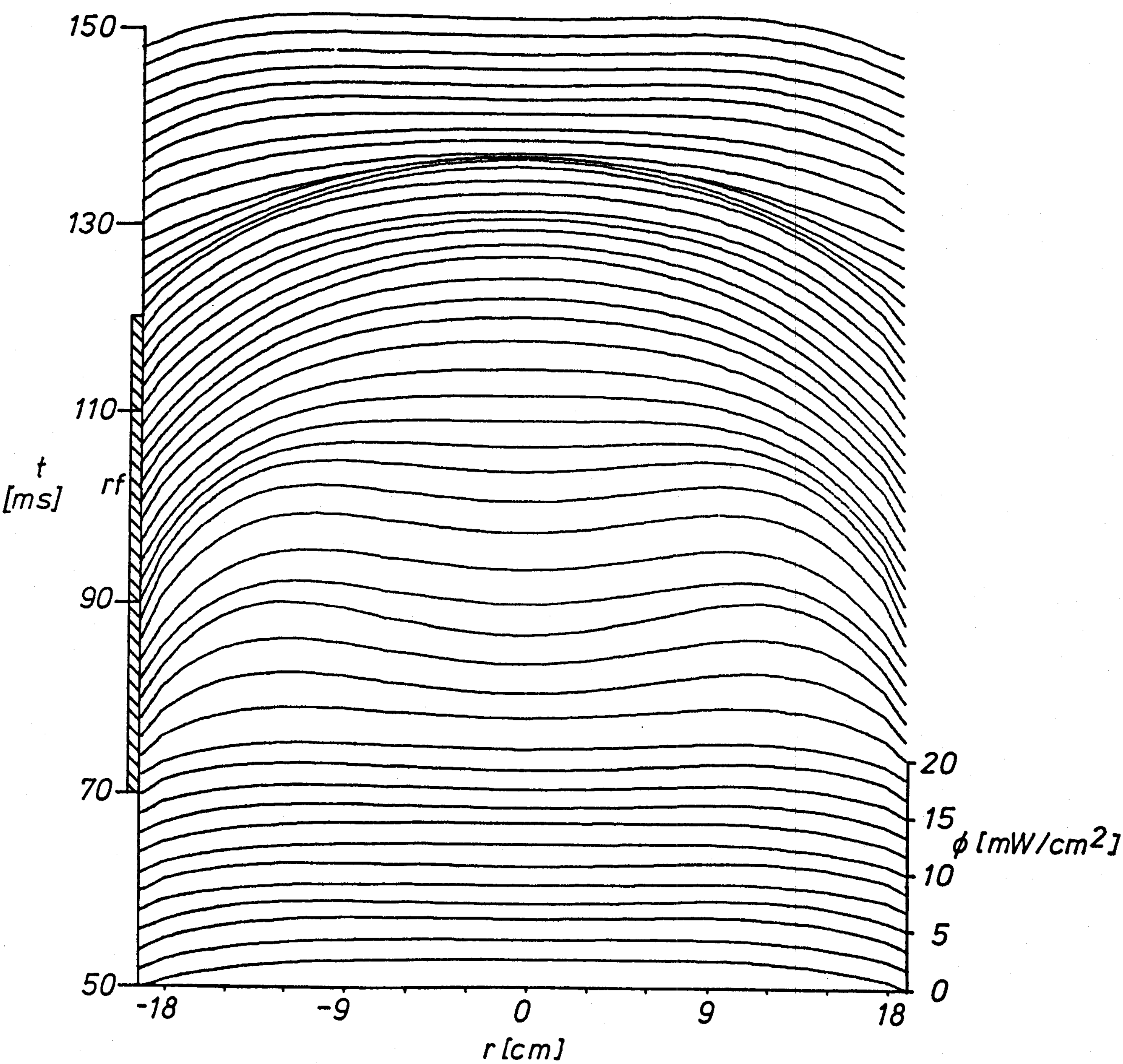

Fig. 6

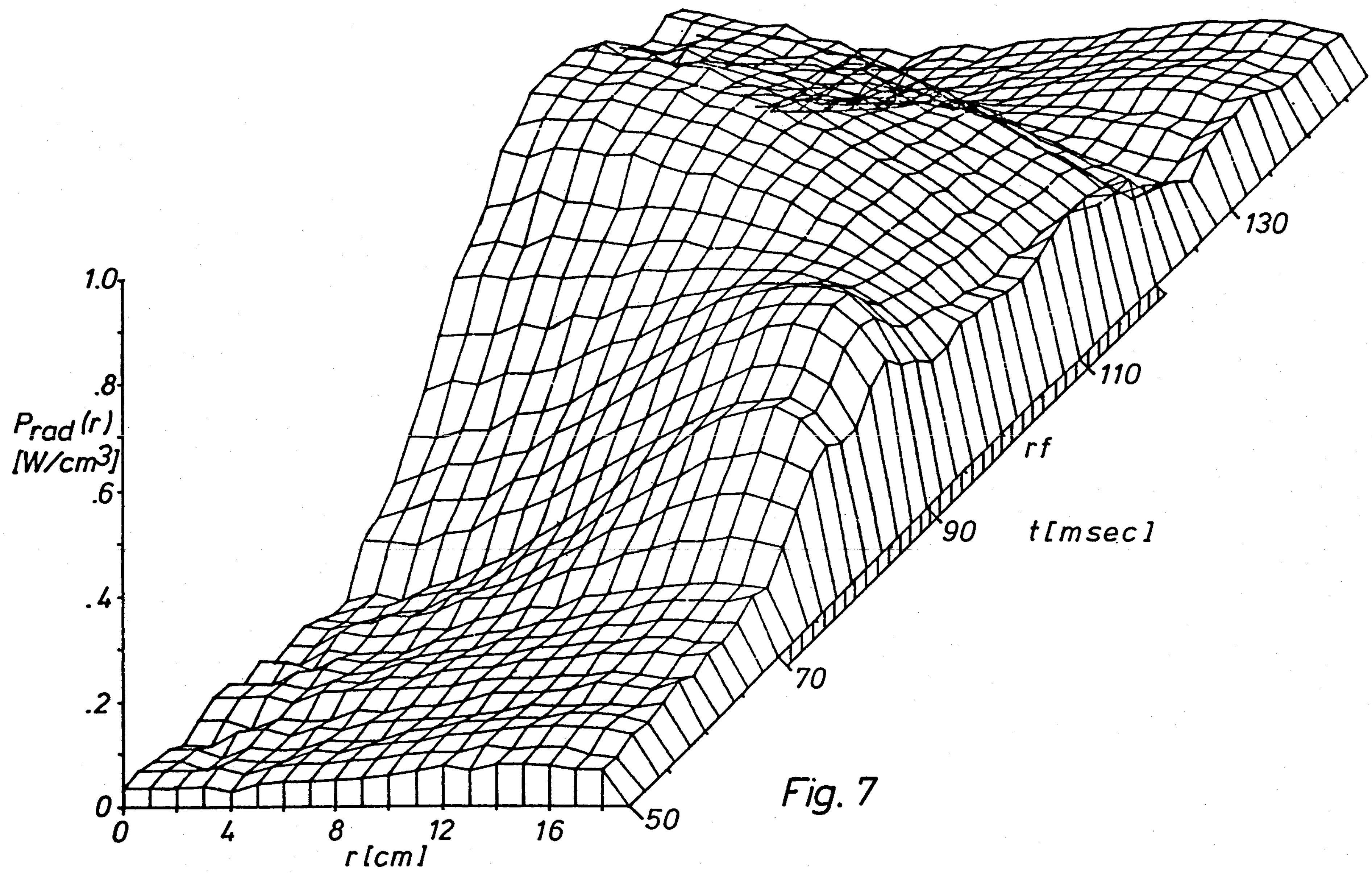

Fig. 7