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MULTI-CHANNEL BOLOMETER SYSTEM ON JFT-2M TOKAMAK

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Multi-Channel Bolometer System on JFT-2M Tokamak

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(Received June 6, 1988)

Multi-channel bolometer system is designed and installed to observe the radiation profile on JFT-2M tokamak. Sensor head is made of Thinistor, which is a kind of semiconductor, because it has the advantage of higher sensitivity of about one order of magnitude than the conventional metal foil bolometer and is suitable for the profile measurement in which the signal from the plasma is relatively small.

The response and cooling characteristics of the bolometer sensor are suitable for the condition of JFT-2M tokamak plasma. Low noise circuit of bridge and differentiator is developed to optimize the signal to noise ratio in the JFT-2M operating condition.

With use of the bolometer system, the radiation profile in joule heating plasma as well as additional heating plasma especially in H-mode plasma is successfully observed.

Keywords: Multi-channel Bolometer System, JFT-2M Tokamak, Radiation Profile, Thinistor, Low Noise Bridge & Differentiator, H-mode Plasma

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+ Department of JT-60 Facility
++ Department of Large Tokamak Research

ＪＦＴ－２Ｍトカマク用多チャンネルボロメータ測定系

日本原子力研究所那珂研究所核融合研究部
玉井　広史・前野　勝樹＋・松田　俊明・的場　徹＋＋

（１９８８年６月６日受理）

ＪＦＴ－２Ｍトカマクにおいて輻射損失分布を観測する為の多チャンネルボロメータ測定計を設計・製作した。受熱素子には半導体タイプのシニスターを用いた。シニスターは従来用いられて来た金属フォイルボロメータに比べ一桁以上高い感度を持っているので，プラズマからの信号が比較的小さい分布測定に適している。

シニスターの応答時間・冷却時間を測定したところ，これらの特性はＪＦＴ－２Ｍトカマクプラズマの実験条件に適していることが確認された。また，シニスターの高感度特性を損わず精度の良い分布測定が行えるように，シニスターからの信号を処理する為の低雑音型ブリッジ・微分回路も開発した。

このボロメータ測定系を用いて，特に追加熱時に現れる閉じ込めの良いモード（Ｈモード）における輻射損失分布を精度良く観測することができた。

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＋　　ＪＴ－６０試験部
＋＋　臨界プラズマ研究部

Contents

目　　　　次

1. Introduction

Recent study in tokamak plasma is available for the high power auxiliary heating such as neutral beam injection (NBI), ion cyclotron range of frequency (ICRF), electron cyclotron resonance (ECR) etc. In such heating experiments, especially in new experimental stage like as H-mode discharges[1][2] energy balance in the plasma is to be investigated to establish the good confinement regime. This requires more precise observation to estimate the power loss from the plasma. Radiation power loss due to the summation of impurity line emission is one of the dominant power loss channel, and it is important to observe the radiation profile for comprehension of more precise property. In addition, radiation profile is considered to be the unhomogeneous in the asymmetrical plasma shape like the divertor configuration.[3] Therefore, the profile measurement is greatly required.

For these reasons multi-channel bolometer system is designed to be suitable for the various configuration of JFT-2M tokamak plasma.

In this report, design of bolometer array (Chapter 2), signal monitor system including the development of low noise bridge and differentiator (Chapter 3), calibration of bolometer sensor (Chapter 4), application to the JFT-2M tokamak plasma (Chapter 5), and some discussions in the measurement (Chapter 6) are presented.

2. Design of Bolometer Array

2.1 Sensor Head

As the sensor head of bolometer, the following characteristics are required;

- (i) high sensitivity to gain the signal to noise (S/N) ratio because of relatively small signal in the profile measurement,
- (ii) large cooling time to remove the effect of heat conduction during plasma pulse,
- (iii) quick response to pick up the rapid change at the onset of heating pulse.

Based on the above requirement, Thinistor 51K1C237 (Victory Engineering Co. Ltd.) is adopted for the sensor head.[4] Thinistor is a kind of semiconductor and changes the resistance with negative temperature coefficient for the wide spectrum range of irradiation from soft X-ray to

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The uncertainty of Thinistor response by the influence of secondary electron emission around Thinistor is often pointed out.[6] Such a influence is removed by the additional front limiter for particles not to hit the lead wire or electrodes, and by the bias between the sensor head and the front limiter to repel the secondary electrons. The appropriate bias is chosen by the irradiation of plasma to minimize the emission.

2.2 Assembly

Structure diagram of bolometer array is illustrated in Fig. 2. Bolometer array is constructed by 29 sensor heads of Thinistor. Each channel of sensor looks upon the plasma through the entrance slit of 2 cm × 2 cm square, located in front of the sensor apart from 20 cm. In order to keep from the direct incidence of ECR wave, shield mesh of gold-plated tungsten grid (0.05 mm in diameter, grid interval of 1 mm) is attached at the entrance slit.

Secondary emission shield of 5 mm × 5 mm square window is located in front of the sensor apart from 1 cm. It is electrically connected to the shield box, and repelling bias is applied between each sensor head.

By using the triple-shielded vacuum feedthru, sensors and the shield box are electrically insulated from the torus chamber wall, also sensors and shield box insulated each other. The shield box is grounded to the common earth of JFT-2M diagnostics system.

3. Signal Monitor System

3.1 Flow Chart

The block diagram of the signal monitor system is illustrated in Fig. 3. The resistance change of Thinistor is converted to the corresponding voltage change through bridge and differentiator. Through isolation amplifier, differentiator output is fed to CAMAC transient recorder (LeCroy 8212A, 8800A) and stored in JFT-2M data acquisition system.[7] CAMAC output is also led to the personal computer (NEC PC-9801) in order to deal the real time data on experimental phase. Temporal behavior of each bolometer channel (like Fig. 9(a)) is printed out within 2 minutes after the plasma shot. Another analysis like more precise presentation (e.g. Fig. 9(b)) or Abel inversion are done afterward by the access to the recorded data.

3.2 Development of Low Noise Bridge and Differentiator

As previously described, it is important especially for the profile measurement to gain the high signal to noise (S/N) ratio. Then, low noise circuit of bridge and differentiator had been developed for our bolometer array. (model P-34 manufactured by NF Circuit Design Block Co. Ltd.)[8] The circuit is arranged to minimize the circuit noise and the plasma pulse noise in the real experimental condition, and has the following characteristics;

1) wide balance range of sensor resistance in 2-200 kΩ,
2) very low output equivalent noise less than 1 mV,
3) high gain amplifier of differentiator more than 70 dB.

Through these improvement, the circuit achieves the S/N ratio of about 30 dB, and the sensor is used in single application rather than in differential application which is generally used in another machine.[5] The DC offset of bridge output is automatically compensated by differential comparator and CdS feedback circuit. The differentiator output at the plasma discharge is indicated in Fig. 4.

4. Calibration of Bolometer Sensor

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The response time τ_r is defined as the interval from the initiation of heating pulse to the 90% of maximum output. From this definition response time of sensor head is about 10 μs. In the real application, pulse response is aggravated through the active differentiator which sacrifices the fast response for attaining the high S/N ratio, and by the smoothing in data processing. Therefore, resultant response time over the system is about 10 ms.

4.2 Cooling Time

Cooling time of the bolometer is estimated in situ. by the time evolution of the bridge output signal just after the termination of heating bias pulse. In Fig. 6, test circuit (a), typical temporal behavior of bridge output of linear plot (b) and semi-logarithmic plot (c) are shown. Cooling behavior obeys the exponential decay which is mainly due to the conduction heat loss to the suspending Pt-Ir wire. Cooling time τ_c, defined as the e-folding duration of each sensor head, is larger than 10 s and is summarized in Table 2. In the same way, cooling time after the plasma pulse is observed as shown in Fig. 6(d). This is about 10 s which is a little shorter than the case of heating bias mainly due to aggravating convection heat loss by surrounding particles.

The cooling time of about 10 s is enough long as compared to the plasma pulse length of about 1 s, so that the additional thermal correction including the effect of heat conduction from the sensor head is not required in applying to JFT-2M tokamak plasma.

4.3 Relative Sensitivity

The relative sensitivity of each sensor head is calibrated by the irradiation of standard illuminant (tungsten filament λ_p = 632.8 nm) located at the entrance slit in atmosphere. The steady state intensity of bridge output I is observed. In the steady state, deposited energy on sensor head W, which is the function of heat capacity and temperature, is constant as $W/\tau_c = P$, where the P is incident power, τ_c is cooling time. The sensitivity of sensor head is defined as the ratio of the bridge output intensity to the deposited energy, then $\eta = I/W = I/P\tau_c$. Because of P = const. we obtain $\eta = I/\tau_c$. Therefore relative sensitivity of each sensor head is represented by η. As shown in Fig. 7, each relative sensitivity agrees well with the cosθ-dependence, where θ is the angle between the viewing line of each sensor and the normal line of entrance slit. There exists a scattering of 20% at most.

The characteristics observed in above calibration are listed in Table 2.

5. Application to JFT-2M Tokamak Plasma

5.1 Installation of Bolometer Array

The installation of the bolometer array on JFT-2M tokamak is shown in Fig. 8. Array is connected to the torus horizontal port.

Whole viewing area of array is corresponding to cover the largest D-shaped plasma cross section indicated by the solid line. The viewing area of each channel at the plasma center (R=1.31 m) is about 8.1 cm × 8.1 cm, therefore cross-over region with the neighbor channel is about 3.3 cm in vertical direction, which is 58% in cross-over region.

Among the 29 channels of bolometer viewing chords, 8 channels from No. 6 to No. 13 observe the lower divertor plate throughout the bulk plasma region, likewise 4 channels from No. 23 to No. 26 observe the upper one.

5.2 Observation of Radiation Profile

With using the bolometer array, vertical radiation profile of the several type of discharges, such as limiter discharges with circular, D-shaped and divertor discharges with upper single null, lower single null, and double null are obtained.[10][11] Radiation observed by the bolometer includes the charge exchange neutral flux as well as the impurity line emission.

Figure 9 shows the radiation profile with the H-mode transition during NBI heating in upper single null divertor plasma. The profile is the chord integrated one. Figure 9(a) shows the time behavior, and Fig. 9(b) is the slice cut of Fig. 9(a) at the fixed time, respectively. In the ohmic phase there appears the intense radiation locality in the chord viewing the upper divertor plate, which conserves the remote radiative cooling. After transition to the H-mode phase at 710 ms radiation profile at first stage is similar to that at ohmic phase, but gradually becomes peeking to the plasma center, which agrees well with the metal impurity accumulation resulted from the spectroscopic observation.[2][12]

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6. Discussion

In spite of the front shield mesh, Thinistor is affected by the ECR wave like as shown in Fig. 10. The radiation for only about 110 kW of launched ECR power exceeds that for OH power of 200 kW. This may be caused by the rectification of leakage ECR incidence. More complete shield is required on the entrance slit.

Since the bolometer also receives the incident of charge exchange(CX) neutrals as well as impurity line emission, the signal of the bolometer at the plasma discharge might be the summation of these contribution. In order to distinguish the impurity line emission, which is usually discussed as radiation power, appropriate estimation for the bolometer sensitivity for CX neutrals is required.

The inversion from the chord integrated value to the real profile has not yet been completed, because of difficulty in non-circular and asymmetrical plasma shape. In order to establish the 2-dimensional profile measurement, another array is being designed to observe into the vertical line of sight. The vertical array is expected to identify the strong locality of radiation profile in the inside/outside of the torus like as the "MARFE" phenomena.[13]

7. Summary

Multi-channel bolometer system is installed to observe the radiation profile in the various plasmas of JFT-2M tokamak.

Thinistor is adopted as the sensor head because of higher sensitivity and larger cooling time than the conventional metal foil bolometers.

Low noise circuit of bridge and differentiator is newly developed and resultant S/N ratio more than 30dB is achieved in profile measurement.

Through the CAMAC transient recorder, the chord integrated radiation profile is stored in data acquisition system and displayed in real time by personal computer.

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Acknowledgement

The authors are grateful to the members of the JFT-2M experiment group for their constructive advice and fruitful discussion. They also thank the members of JFT-2M operation group for their excellent co-operation and helpful support. They are indebted to Drs. H. Maeda, A. Funahashi, Y. Tanaka, M. Tanaka, M. Yoshikawa, K. Tomabechi and S. Mori for their continuous encouragement.

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Table 1 Comparison of bolometer characteristics

	Thinistor(1)	Metal	
		JFT-2M(2)	JET/ASDEX(3)
Foil Size [mm^2]	2 x 2	π x 10^2	11 x 11
Electrical Resistance [kΩ]	200	2.2	4.8
Cooling Time [s]	> 10	3.4	0.2
Response Time [ms]	< 0.2	0.1	0.1
Temperature Coefficient [K^{-1}]	7.7 x 10^{-2}	3.8 x 10^{-3}	2.7 x 10^{-3}
Heat Capacity [mJ/K]	0.35	12.3	2.2

(1) from Product Bulletin VM2056, Victory Engineering Co. Ltd.

(2) for measurement of total radiation, T-2033, Hamamatsu Photonics Co. Ltd.

(3) from reference [5]

Table 2 Results of calibration

Channel Number	Cooling Time (τ_c)		Sensitivity		
	Bias	Plasma	η	$\cos\theta$	scatter
2	12.9 s	----	.694	.707	1.8 %
3	11.7	----	.755	.734	2.9
4	13.5	----	.703	.760	7.5
5	11.2	----	.788	.785	.4
6	11.1	8.24 s	.765	.809	5.4
7	11.9	9.15	.855	.831	2.9
9	13.0	12.3	.703	.872	19.4
10	12.7	10.3	.906	.891	1.7
11	12.8	11.0	.826	.908	9.0
12	12.4	10.7	.817	.924	11.6
13	12.8	11.2		.938	
14	28.5	15.0		.951	
15	12.0	10.1	1.00	.972	2.9
16	12.5	10.6	.944	.988	4.5
17	10.3	9.10	1.09	.997	8.9
18	15.4	12.7	.883	1	11.7
19	11.9	11.3	1.00	.997	.3
20	12.9	11.4	.973	.988	1.5
21	12.6	11.4	.944	.972	2.9
22	13.8	11.1	.755	.951	20.6
23	11.5	9.06		.924	
24	12.3	10.2	.822	.891	7.7
25	11.2	8.76		.853	
26	12.1	7.88		.809	
27	12.3	----	.633	.760	16.7
28	12.1	----		.707	

* Channel number 1, 8, 29 are now not measurable.

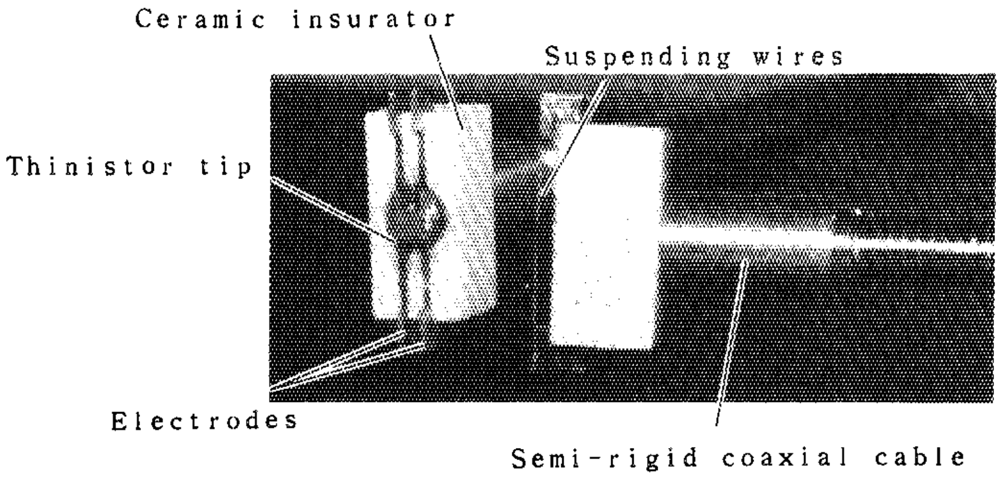


Fig. 1 Thinistor sensor head

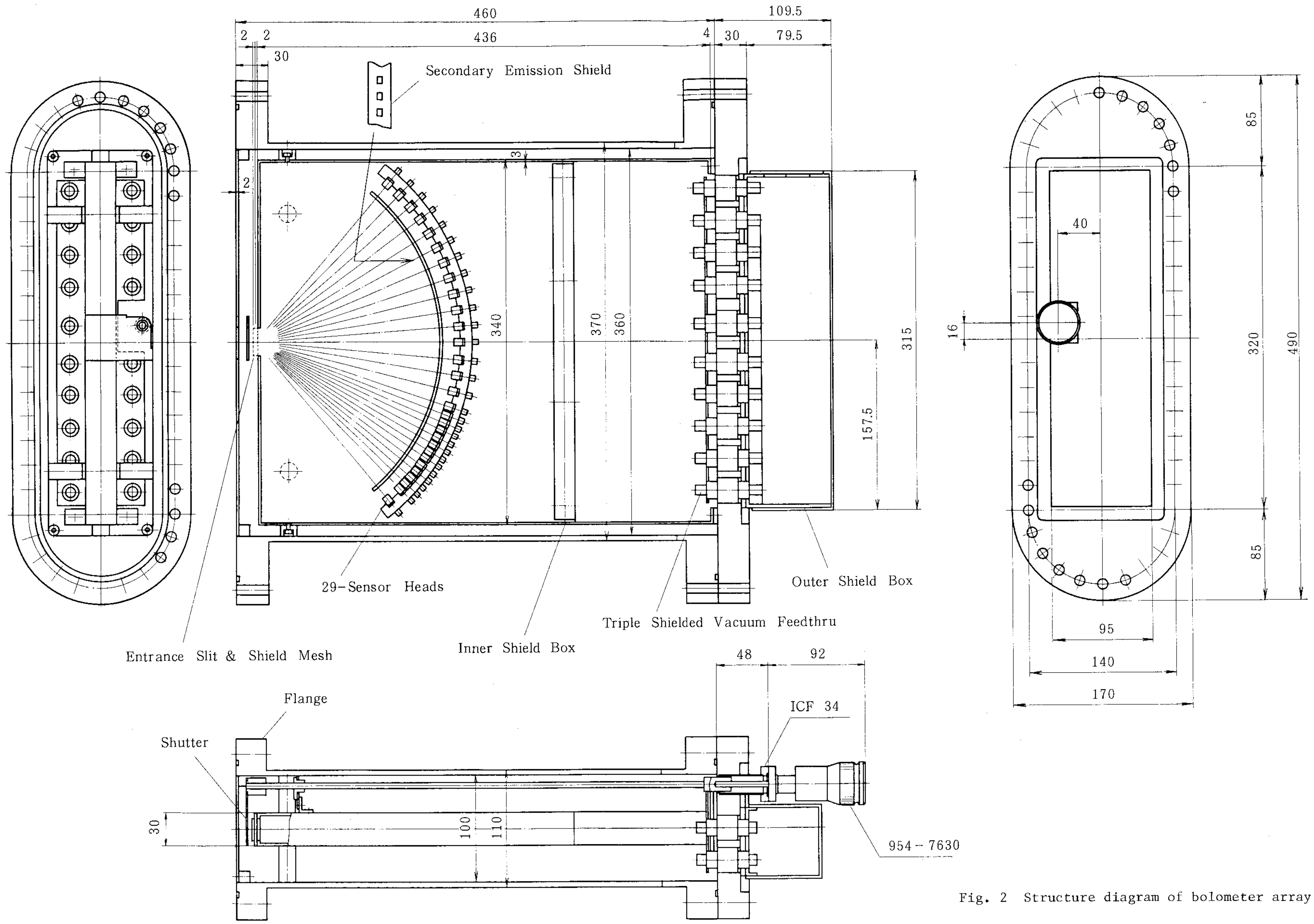


Fig. 2 Structure diagram of bolometer array

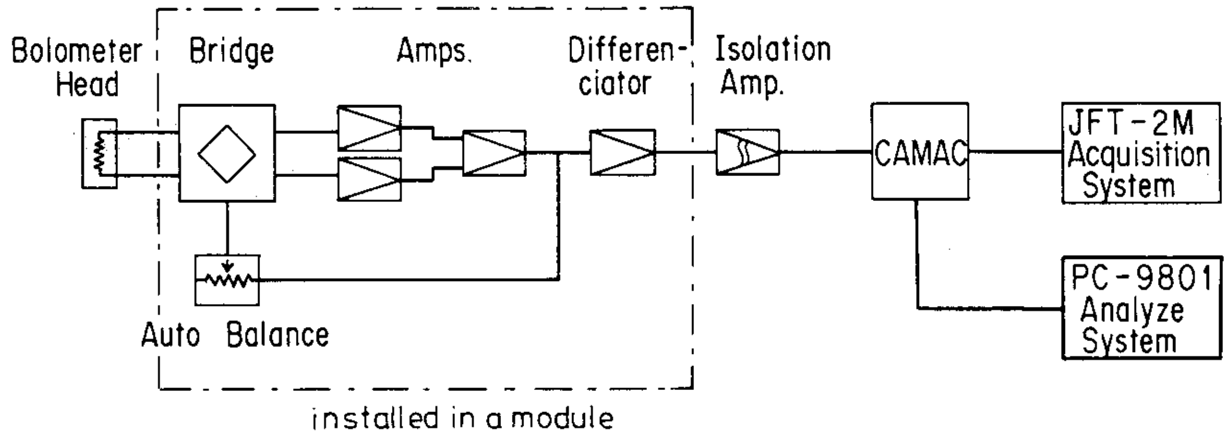
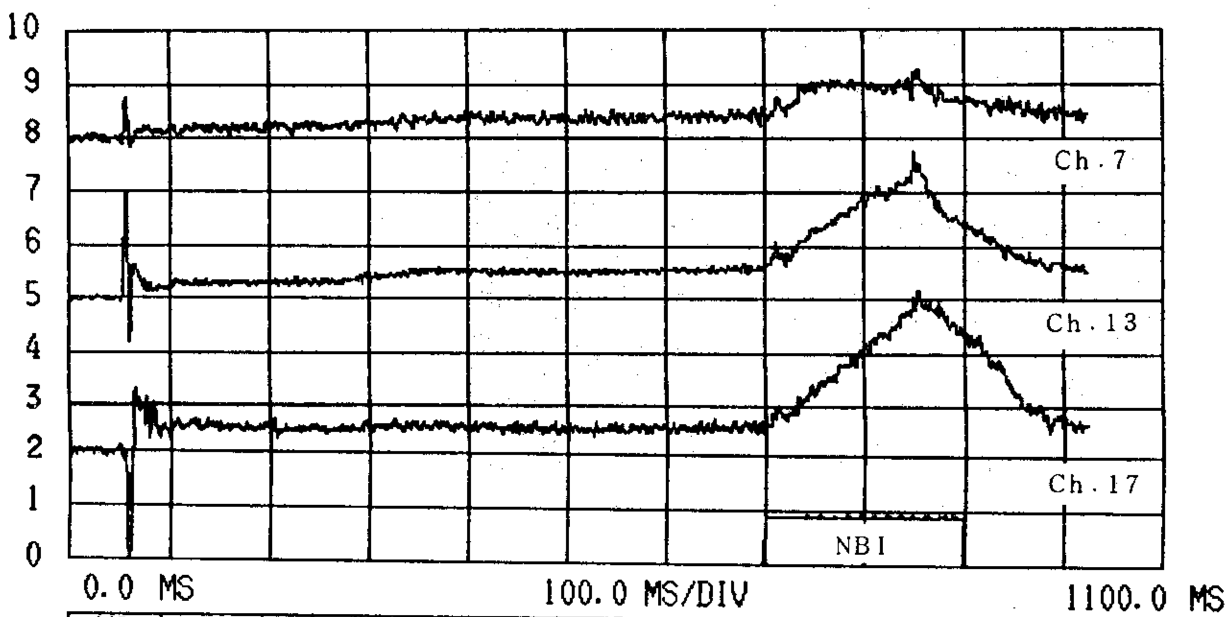


Fig. 3 Block diagram of signal monitor system



NO	SHOT	SIGNAL	CH	YSCALE	BASE	MODE	NAVER
1	39868	BOLO	7	0.50 E 0	8	30	1
2	39868	BOLO	13	0.50 E 0	5	30	1
3	39868	BOLO	17	0.50 E 0	2	30	1
4	39868	PNBI	2	2.00 E 0	0	30	1

Fig. 4 Differentiator output at the plasma discharge

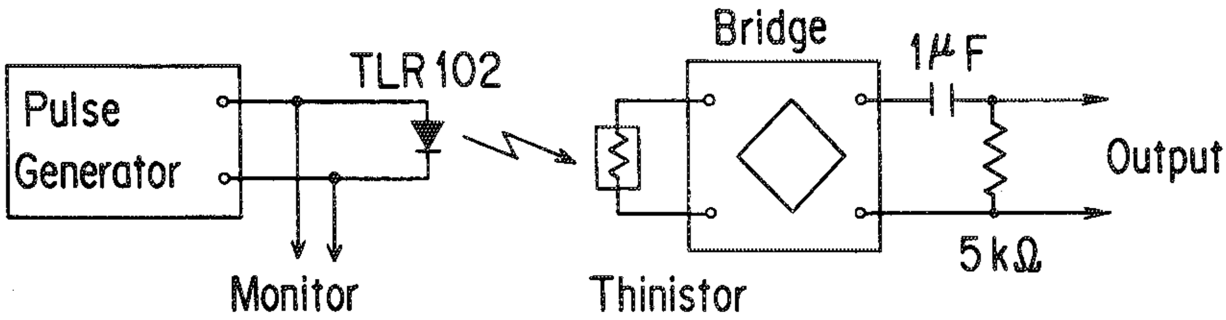
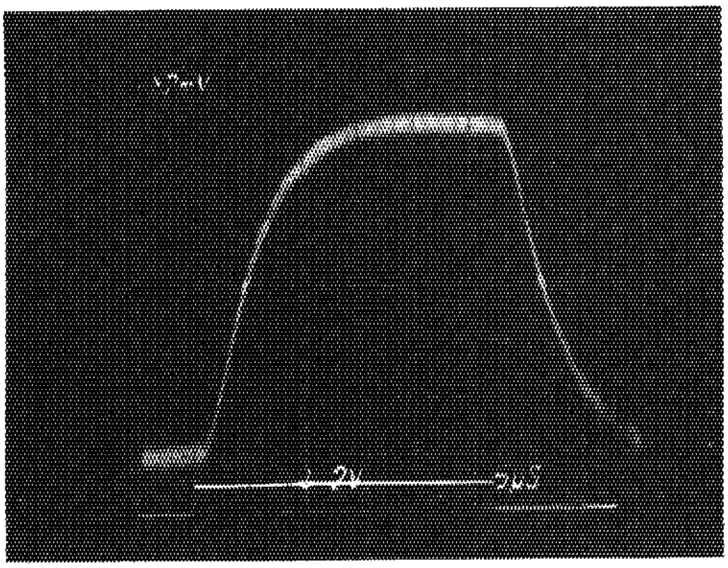


Fig. 5(a) Test circuit for response time measurement



Differenciated output

LED monitor

5 μs/div

Fig. 5(b) Response to the LED flash

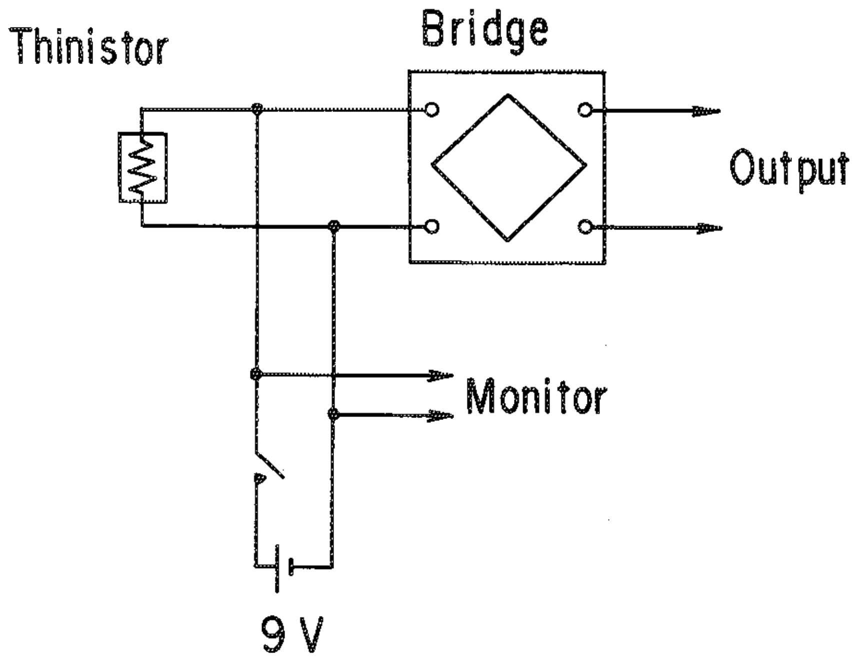


Fig. 6(a) Test circuit for cooling time measurement

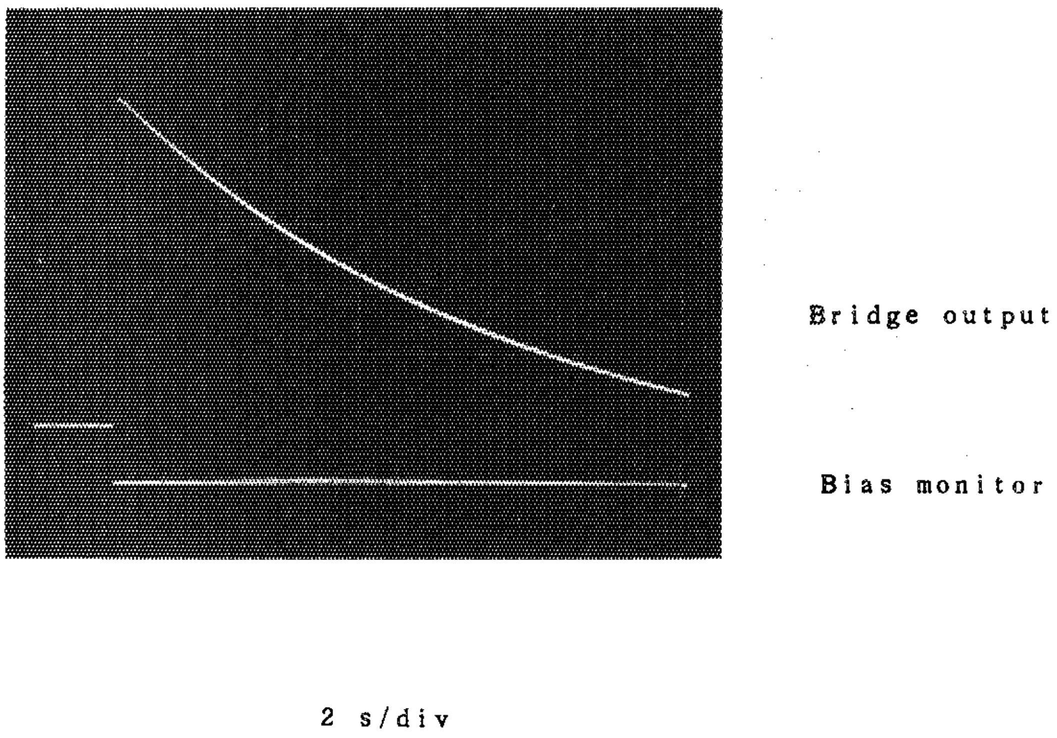


Fig. 6(b) Typical temporal behavior of bridge output

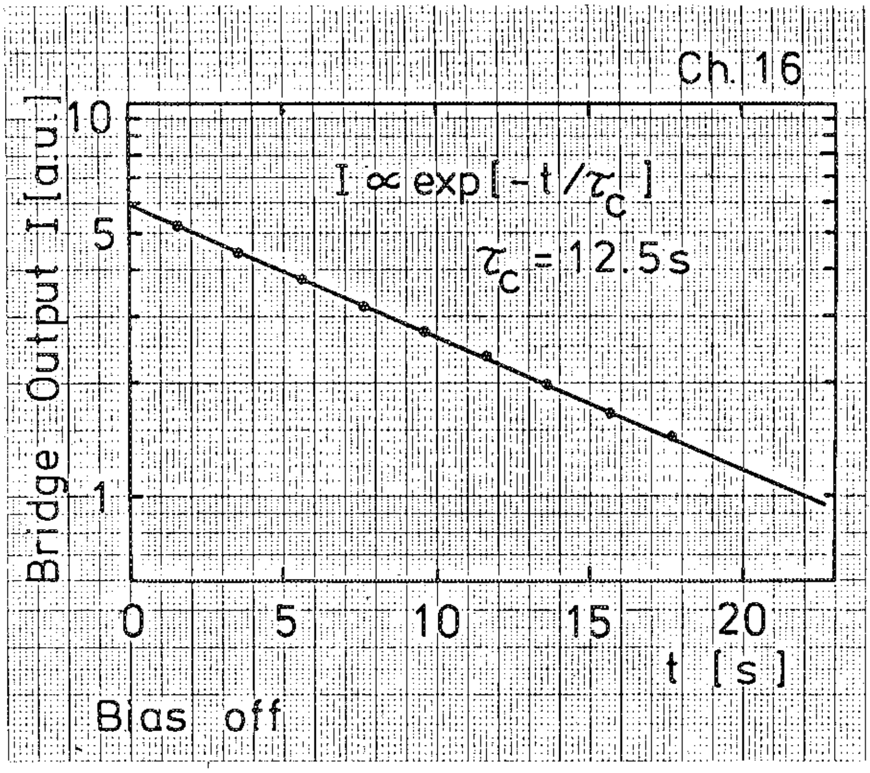


Fig. 6(c) Definition of cooling time

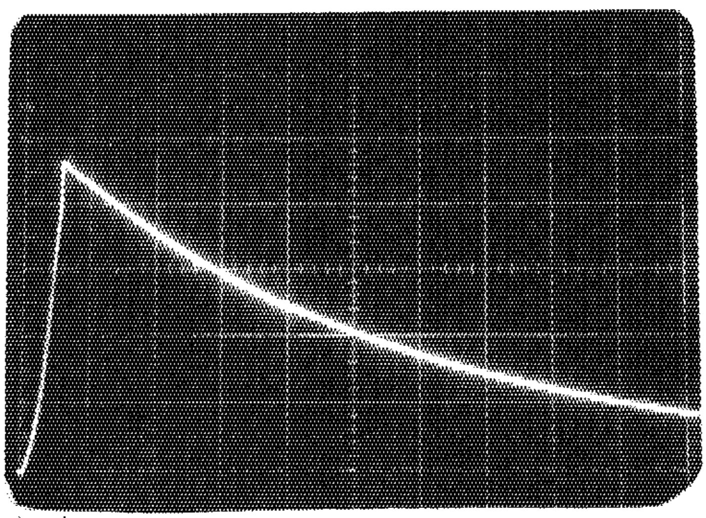


Fig. 6(d) Decay of bridge output after the plasma termination

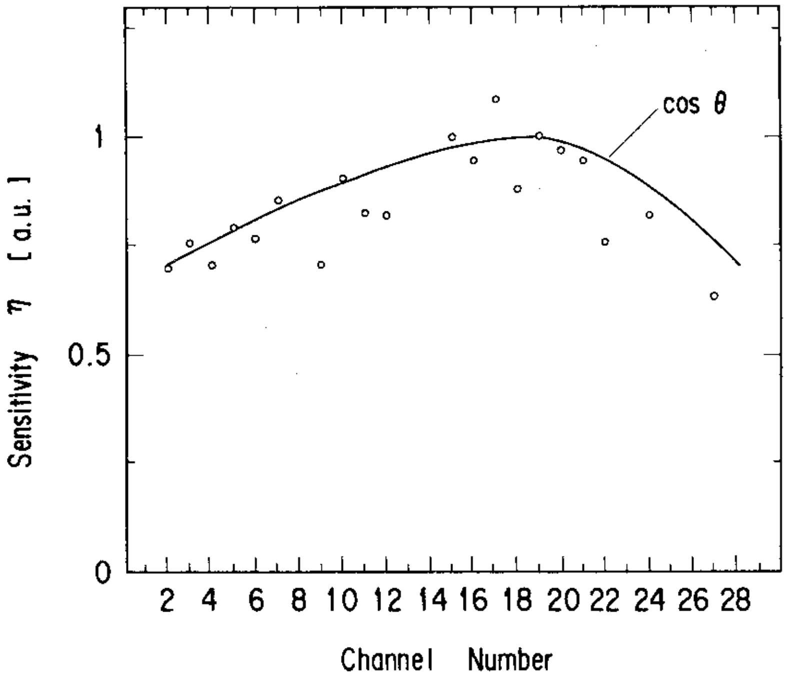


Fig. 7 Relative sensitivity of each sensor head

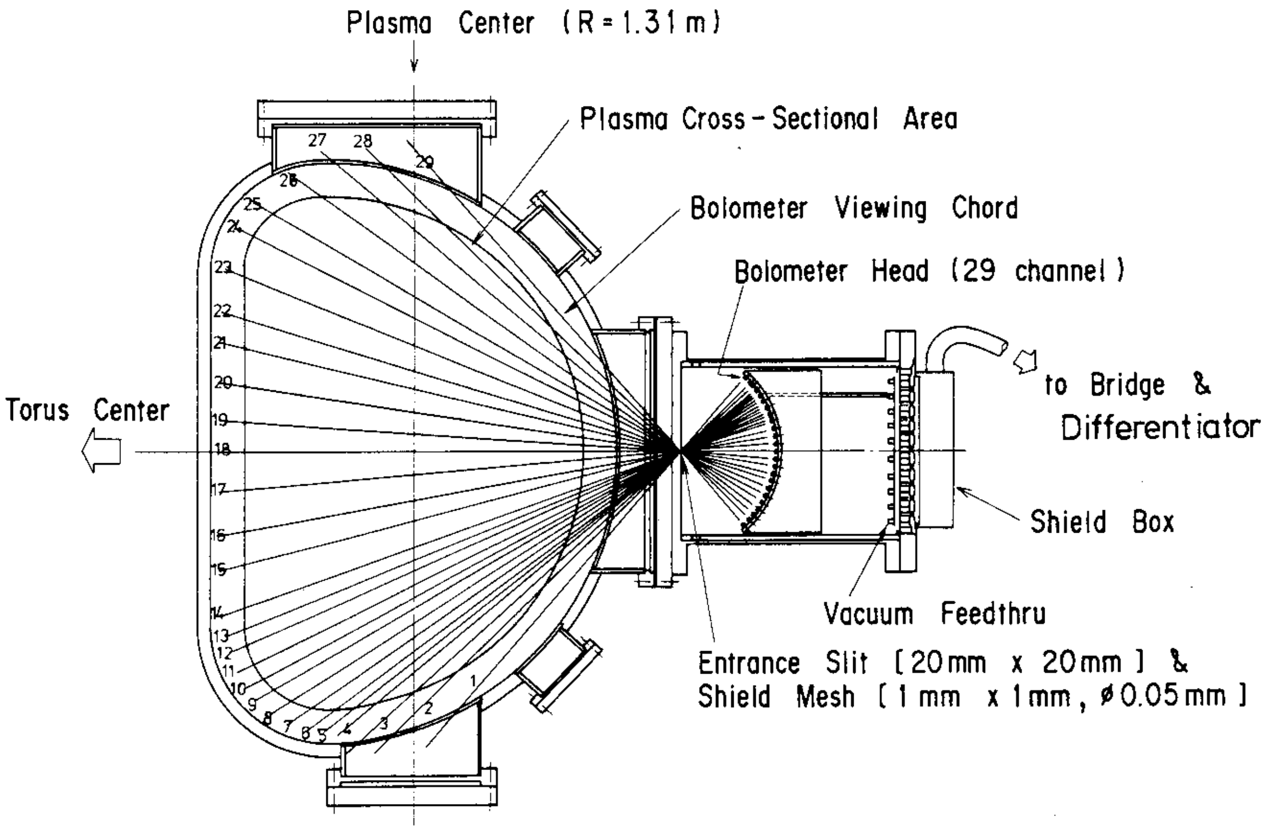


Fig. 8 Installation of the bolometer array on
JFT-2M tokamak

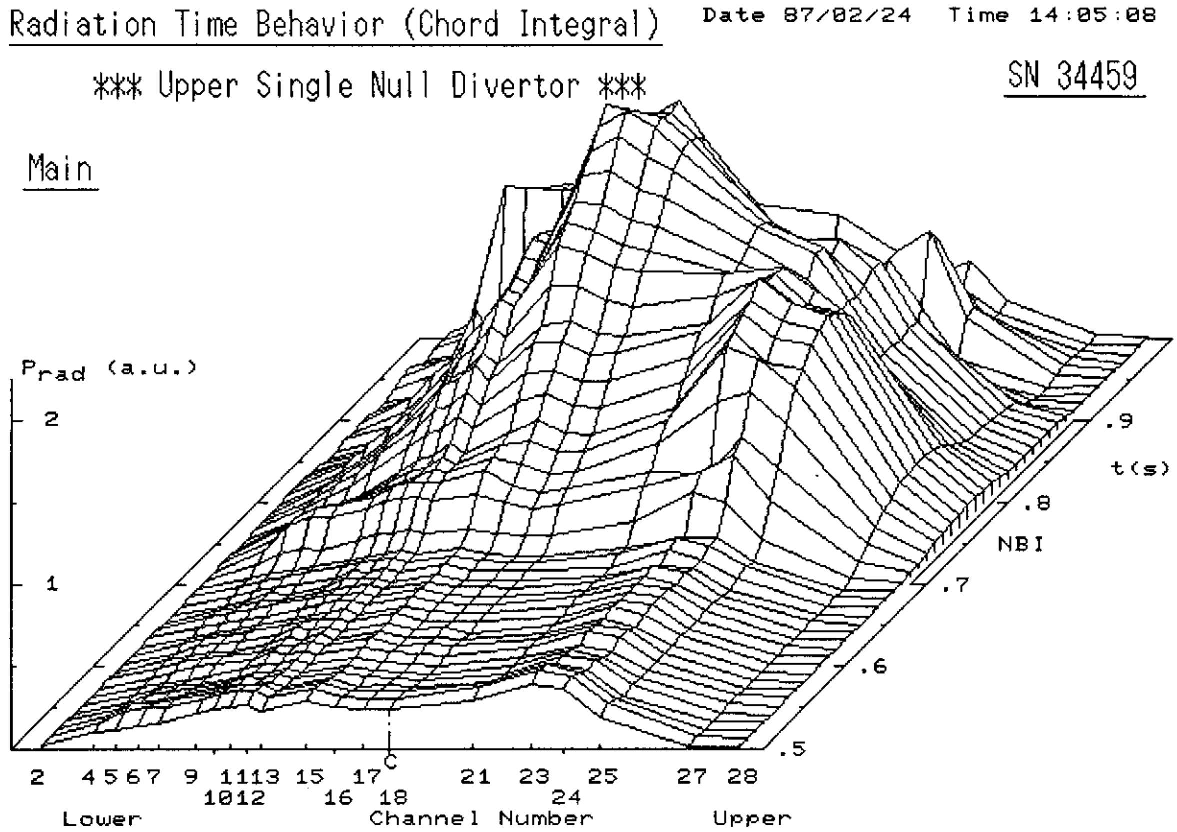


Fig. 9(a) Time behavior of the multi-channel bolometer signal

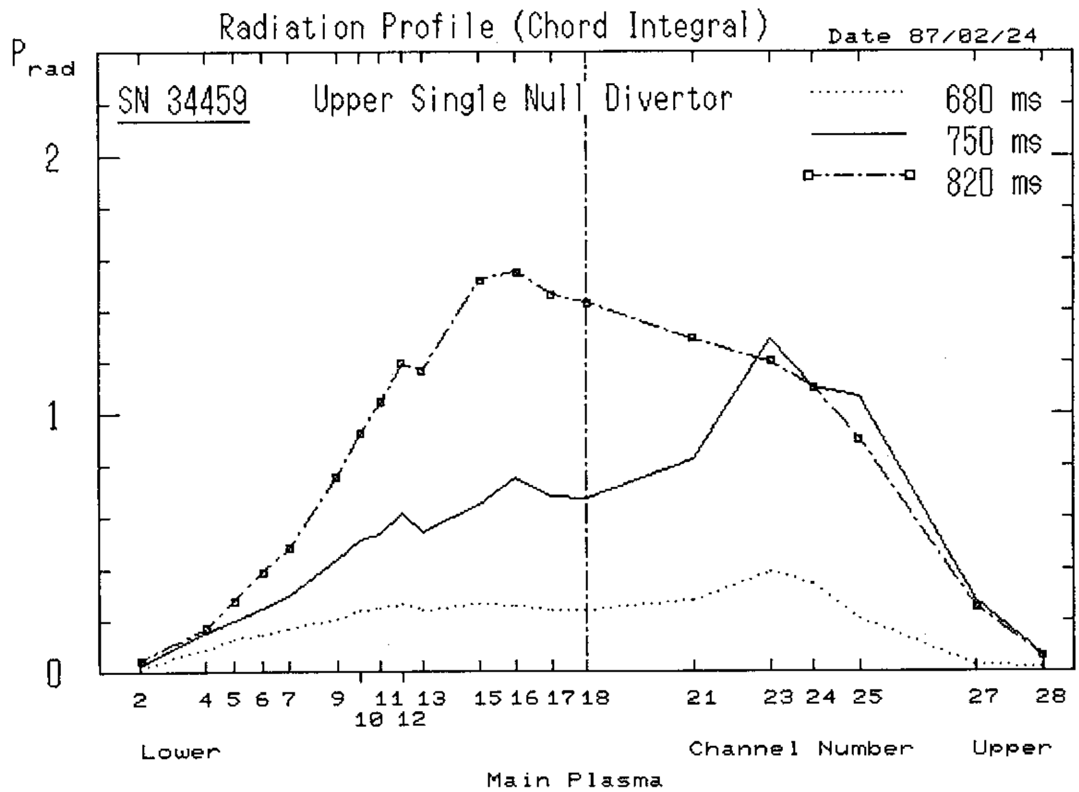
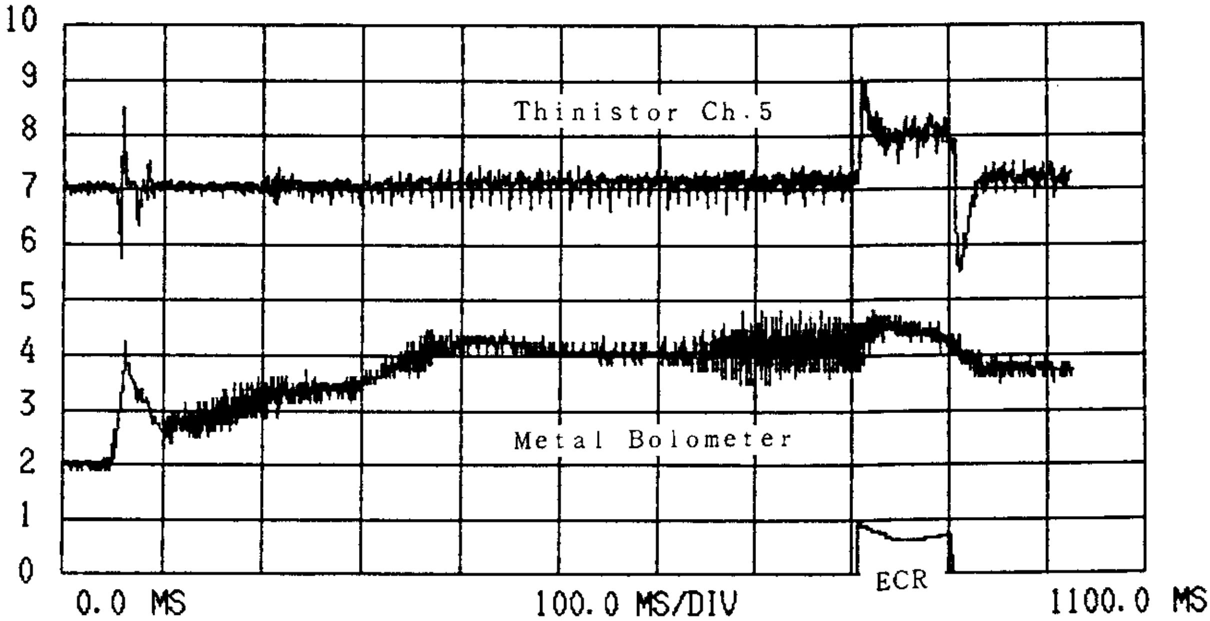


Fig. 9(b) Chord integrated radiation profile at the fixed time



NO	SHOT	SIGNAL	CH	YSCALE	BASE	MODE	NAVER
1	34858	BOLO	5	0.50 E 0	7	30	1
2	34858	DIV	16	0.20 E -1	2	30	1
3	34858	PNBI	25	2.00 E 0	0	30	1

Fig. 10 Affect of ECR wave