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DEVELOPMENT OF TiC AND TiN COATED MOLYBDENUM LIMITER SYSTEM AND INITIAL RESULTS OF THE THERMAL TESTING IN NEUTRAL BEAM HEATED JFT-2 TOKAMAK

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Japan Atomic Energy Research Institute

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Development of TiC and TiN Coated Molybdenum Limiter System and Initial Results of the Thermal Testing in Neutral Beam Heated JFT-2 Tokamak

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(Received May 25, 1982)

This paper describes the limiter drive system for TiC and TiN coated molybdenum limiters and the thermal testing results of the TiC coated limiter in the JFT-2 tokamak using neutral beam injection (0.7MW). To investigate the influence of TiC coated limiter on plasma behavior and adhesion property under tokamak plasma, a full scale limiter test has been performed in the JFT-2. Reproducible plasma was obtained after the plasma conditioning. Maximum heat flux to the limiter, measured by IR camera, was $1.5 \sim 6.5$ kW/cm^2 in 25 msec. Cracking, exfoliation and melting on TiC coated limiter were not observed, except for a number of arc tracks. Finally, the permissible heat fluxes of TiC coated molybdenum first wall are discussed.

Keywords: Fusion, First Wall, Chemical Vapor Deposition, Titanium Carbide, Titanium Nitride, Adhesion Strength, Infra-red Camera, High Heat Flux, Evaporation, Exfoliation, Melting, Molybdenum Substrate, Limiter Test, JFT-2, Neutral Beam Injection, Impurity Control

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TiCおよびTiNコーティングモリブデンリミタ系の開発と，中性粒子入射加熱JFT－2トカマクでの熱負荷試験初期結果

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（1982年5月25日受理）

TiCおよびTiNコーティングされたモリブデンリミタ用のリミタ駆動機構系と，中性粒子入射加熱されたJFT－2トカマクでの，TiC／Moリミタの熱負荷試験の初期結果について述べた。JT－60では，壁材不純物制御の一つとして，TiC／Mo第一壁の開発が行なわれており，種々の評価試験が行なわれている。JT－60実機への適用に先立ち，TiC／Moリミタのプラズマへの影響を調べる為と，トカマクプラズマ照射下でのTiCコーティングの付着特性を調べる為に，実機規模のリミタ実験がJFT－2トカマクにおいて行なわれた。

プラズマコンディショニングの後，再現性の有るプラズマが得られた。赤外線カメラによりリミタ温度が測定され，最高熱負荷は1.5～6.5 kw／㎠×25 msecであった。この条件下で，リミタ表面には，アークこん跡が見られたが，マイクロクラック，はがれや蒸発は見られなかった。許容熱負荷特性を更に詳しく調べる為に，より高熱負荷のより長パルスの実験が計画されている。

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1. Introduction

To realize fusion reactor plasma, importance of first wall problem was emphasized by many researchers [1], [2]. Recently, as plasma temperature has been improved by high power additional heating such as neutral beam injection and radio frequency, interaction between plasma and first wall, especially limiters, becomes severe problem. Therefore, impurity control of first wall material understood as an actual problem to be solved urgently. In this respect, divertor or magnetic limiter is effective to shield impurity and reduce plasma wall interaction [3]. On the other hand, in the case of material limiter, another impurity control is necessary to reduce detrimental effects of wall material impurity. For this purpose, low-Z material first wall is considered to be most promising because larger impurity concentration and higher boundary plasma temperature are permitted than medium and high-Z one [4], [5]. In addition to impurity control, high heat flux deposited on limiters is severe problem in tokamaks with high power additional heating. In these tokamaks, melting and evaporation of limiters can be obsereved even in normal conditions. Therefore, the development of first wall materials, which satisfy the requirements of both impurity control and high heat flux problems, is now under way in large tokamak projects, that is, TFTR [6], JET [7], and JT-60 [8].

In JT-60, TiC coated molybdenum first wall is under development. As a substrate material, Mo was selected because of its better thermal shock properties and lower surface temperature rise compored with graphite in long pulse operation [9]. As a coating material, TiC was selected because of its low chemical sputtering yield [10], high melting point, and relatively low Z number. To study it surface properties, thermal properties and so on, various evaluation tests are performed using small size samples [11], [12], [13]. But, in the case of full scale first wall adhesion strength of coating is considered to be, especially, different from small samples. This tendency has been observed in TiC coated POCO graphite limiter tests in ISX-B [14], D-III [15], and PDX [16]. Therefore, prior to applying TiC coated Mo first wall to JT-60, full scale limiter test in a tokamak with high power additional heating is necessary to investigate the influence of TiC coated Mo limiter on plasma behavior and adhesion property under tokamak plasma. On the other hand, in JFT-2, MW-grade additional heating experiments are now under way for high-β study [17], [18]. Therefore, TiC coated Mo limiter experiment was performed in the JFT-2 using neutral beam injection.

In this paper, the development of limiter drive system for full scale limiter test and , TiC and TiN coated molybdenum limiter, and initial results of thermal testing on TiC coated molybdenum limiter are described. The details of plasma behavior and heat flux on the limiter will be reported by S. Sengoku et al [19], and M. Maeno et al [20].

2. Experimental

2.1 JFT-2 device and diagnostics

The JFT-2 device is a circular tokamak with a major radius of 90 cm and a wall radius of 31 cm. It has a stainless steel guard limiter with a minor radius of 25 cm and a limiter thickness of 1.5 cm. In JFT-2, study of high power additional heating such as NBI, ICRF, ECRH, and LHH experiments are under way. In this limiter experiment, NBI system (co-injection) was used. Its inejction power to plasma is about 0.7 MW. Deuterium was used as a working gas. The experimental setup is shown in Fig. 2-1. TiC coated Mo limiter was installed in a limiter drive chamber, 180° away from the guard limiter in a toroidal direction. The cross sectional view of the limiter drive chamber section is shown in Fig. 2-2. In this figure, the guard limiter is also shown for reference.

To estimate the heat flux to the coated limiter, the surface temperature was measured with an infra-red camera (AGA 680) through a sapphire window as shown in Fig. 2-2. Details of surface temperature measurement in JFT-2 were reported by M. Maeno et al [21]. Calibration of the infrared camera was carried out during gradual cooling after heated up to 400°C. Baking was performed by sheath heater embeded on copper substrate. The limiter temperature in a baking was measured by thermocouple inserted into the molybdenum limiter. Prior to limiter experiment, the limiter was degassed in JFT-2 during 8 hrs at 400°C and Taylor type discharge cleaning was carried out. To study surface damage of the TiC coated Mo limiter, photographs were taken by a camera before and after the experiment. Typical discharge parameters are shown in Table-1.

2.2 Development of coated limiter system

TiC and TiN coating onto molybdenum limiter were performed by chemical vapor deposition (CVD) method. This is most promising coating method in JT-60 low-Z coating. In the case of these coating, working gas and deposition temperature were $CH_4 + TiCl_4$ and 1100°C for TiC, and $N_2 + TiCl_4$ and 1000°C for TiN, respectively. Both coatings were 20 μm, in thickness. Photographs of these coated limiters as coated are shown in Fig. 2-3, 2-4, and 2-5. Recent result of thermal shock test by neutral beam ion source showed that TiC coating by CVD had the best adhesion strength and TiN coating by CVD discolored from gold to white [11]. Therefore, limiter experiment in JFT-2 was carried out for TiC coated Mo limiter.

Molybdenum limiter is composed of three blocks. The dimensions of center block and side ones are $10^{L} \times 9^{w} \times 4^{t}$ cm^3 and $7^{L} \times 9^{w} \times 4^{t}$ cm^3, respectively. These blocks are fixed by bolts to copper substrate as shown in Fig. 2-6. Copper substrate was cooled by water which flowed through the inside of limiter drive shaft. In the front surface of copper substrate, sheath heater, 1.6 mm in diameter, was embeded for limiter baking in vacuum vessel. Also, four thermo-couples were inserted to the limiter blocks. To protect the thermo-couples and sheath heaters against arc damage, stainless steel arc shield was attached to ion and electron sides as shown in Fig. 2-7. Limiter drive system is composed of limiter chamber, limiter drive/cooling shaft, shaft support, insulated flange and movable bellows. Details is shown in Fig. 2-8. To use the coated limiter head as a limiter probe, the head was insulated from vacuum vessel by aluminum insulators and insulated bellows as shown in Fig. 2-6. Limiter head can be drived between minor radius of 23 cm to 33 cm and fixed at a desired radius before experiment.

3. Results

3.1 Heat flux to limiter

TiC coated limiter was exposed to 100 discharges during 2 days experiment. TiC/Mo limiter was positioned at a minor radius of 25 cm. Duration of discharge was 150 msec and neutral beam heating power (0.7 MW × 50 msec) was applied 100 msec after the beginning of the discharge. Typical discharge characteristic of plasma current, loop voltage, horizontal displacement, and limiter temperature is shown in Fig. 3.1(a)-(c). In this experiment, plasma was initially produced on the linner side of vacuum vessel with contacting guard limiter. Then, with increasing β_p (poloidal β), plasma was gradually shifted toward the outer side and plasma contacted with TiC/Mo limiter completely at $t = 120$ msec. After that, surface temperature increase rapidly and reach 230°C during 25 msec. While during ohmic heating phase, surface temperature of TiC/Mo limiter is relatively low. This characteristic is shown in Fig. 3.1.

Heat flux to the limiter was numerically calculated from the applied surface temperature rise using an integral equation. In this calculation, the model which includs a TiC coating layer is applied. Details of the calculation are shown in Appendix. Temporal behavior of the calculated heat flux is shown in Fig. 3-1(c). This figure shows that the heat flux begin to increase from 120 msec when plasma shift outward 4 cm from the center of the vacuum vessel. The heat flux changes from 1.5 kW/cm^2 to 6.5 kW/cm^2 in this experiment.

3.2 Limiter surface observation

Photographs of TiC coated Mo limiter after exposure of 100 shots are shown in Fig. 3-2. These photographs show that there are no cracking, exfoliation and melting on the limiter surface, except for many arc tracks. Color of the limiter surface on electron side changed slightly as shown in Fig. 3-2(c). This is due to titanium deposition during gettering prior to discharge without withdrawing the limiter because of a careless mistake. Arc tracks on the limiter surface were straight type on both sides. Direction of the arc track is one of retrograde movement. On the other hand, on the arc shield, perpendicular to the magnetic field, zigzag type tracks were found [22]. Moreover, the different directions of the zigzag type arc tracks were found on each side. These are shown in Fig. 3-3(a) and (b).

4. Discussion

To obtain the relation between permissible heat flux and duration time is useful for first wall design and plasma experiment in large tokamaks. However, little is known about adhesion mechanism of coating for exact estimation of the above relation. Recent results of thermal shock tests show that TiC coating layer on Mo survives until substrate melting [11], [23]. Therefore, we define the permissible heat flux in normal discharge using semi-infinite model as the following equation.

$$q_{max} = 0.5\ \Delta T_{max} \sqrt{\lambda c \rho \pi}/\sqrt{t} \qquad (1)$$

where q_{max}; permissible heat flux, ΔT_{max}; permissible temperature rise, λ; thermal conductivity, c; specific heat, ρ; density, and t; duration time.

Further, we define three conditions as an upper limit of TiC coated molybdenum, that is, Mo melting limit, TiC evaporation limit, and Mo recrystallization limit. In these cases, initial temperature is assumed to be room temperature. In the case of higher initial temperature, the permissible heat flux becomes lower. The permissible heat flux for Mo melting limit can be obtained by using 2600°C as ΔT_{max}^{melt}. This heat flux is maximum value among three conditions. On the other hand, from a view point of impurity contamination, the permissible heat flux for TiC evaporation limit can be obtained by using 1800°C as ΔT_{max}^{evap}. This temperature is calculated with the condition that impurity due to evaporation is below the permissible level. Finally, the permissible heat flux for Mo recrystallization limit can be obtained by suing 800°C as $\Delta T_{max}^{recryst}$. Above 800°C, pure molybdenum begins to recrystallize and its mechanical strength decreases as one third of initial value after 100% recrystallization.. Therefore, in the case of first wall which severe electromagnetic forces are induced, such as neutral beam aromor plates in JT-60, the permissible heat flux is limited by Mo recrystallization. As a result, the three permissible heat fluxes are obtained as follows.

$$q_{max}^{melt} = 4257/\sqrt{t(sec)}\ \ W/cm^2 \qquad (2)$$

$$q_{max}^{evap} = 2947/\sqrt{t(sec)}\ \ W/cm^2 \qquad (3)$$

$$q_{max}^{recr} = 1310/\sqrt{t(sec)} \quad W/cm^2 \qquad (4)$$

These results are shown in Fig. 4-1. Also, similar results of thermal shock tests are shown. Datum of SiC coated graphite is shown as a reference of long pulse experiment. According to this figure, the condition of this limiter experiment is below the three limits. In normal discharge of JT-60, the heat flux to toroidal fixed limiter is designed to be 49 $W/cm^2 \times 10$ sec for the deposition to all toroidal fixed limiters. This value is below the Mo recrystallization limit. But, in the case of abnormal discharge such as major disruption or runaway discharge, evaporation and melting become severe problems. Recent analysis of first wall erosion shows that TiC evaportaed a few μm and melted a few tens μm in a major disruption of $100 \sim 200$ J/cm^2 in 0.5 msec [24]. The energy density and energy deposition time are typical value of large tokamaks (TFTR, JET, JT-60). Careful operation without major disruption or first wall exchange is necessary, because the exfoliation of TiC coating can not be avoided in these severe conditions.

5. Conclusion

Limiter drive system for full scale limiter experiment was operated successfully. Reproducibel plasma was obtained after the plasma conditioning. The maximum heat flux was 1.5 ∿ 6.5 kW/cm^2 during 25 msec. Cracking, exfoliation and melting on TiC coated limiter were not obsereved except for many arc tracks. TiC coated Mo limiter can survive under high heat load. To investgate the permissible heat flux in detail, experiments with higher heat flux and longer duration time will be planned. Also, TiC coated Mo Faraday shield for ICRF experiment and carbon guard limiter will be tested to study effectiveness of low-Z materials [25].

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We are grateful to Drs. Y. Obata, M. Tanaka, and Y. Tanaka for encouragement and help. It is a pleasure to thank Drs. S. Kunieda, Y. Matsuzaki, K. Anno and other members of the operating group, and the JFT-2 group for the reliable work in the experiment. We are also grateful to Drs. A. Tomabechi, M. Yoshikawa, T. Iijima, H. Tomioka, Y. Murakami and M. Ohta for their continuing encouragement.

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TABLE-1 TYPICAL DISCHARGE PARAMETERS

TOROIDAL MAGNETIC FIELD	13 kG
PLASMA CURRENT	120 kA
LOOP VOLTAGE	1-2 V
DISCHARGE DURATION	150 msec (50 msec NB)
MAXIMUM ION TEMPERATURE	600 eV
MAXIMUM ELECTRON TEMPERATURE	800 eV
MEAN ELECTRON DENSITY	2.6×10^{13} cm^{-3}
HEATING POWER	OH 0.2 MW NB 0.7 MW

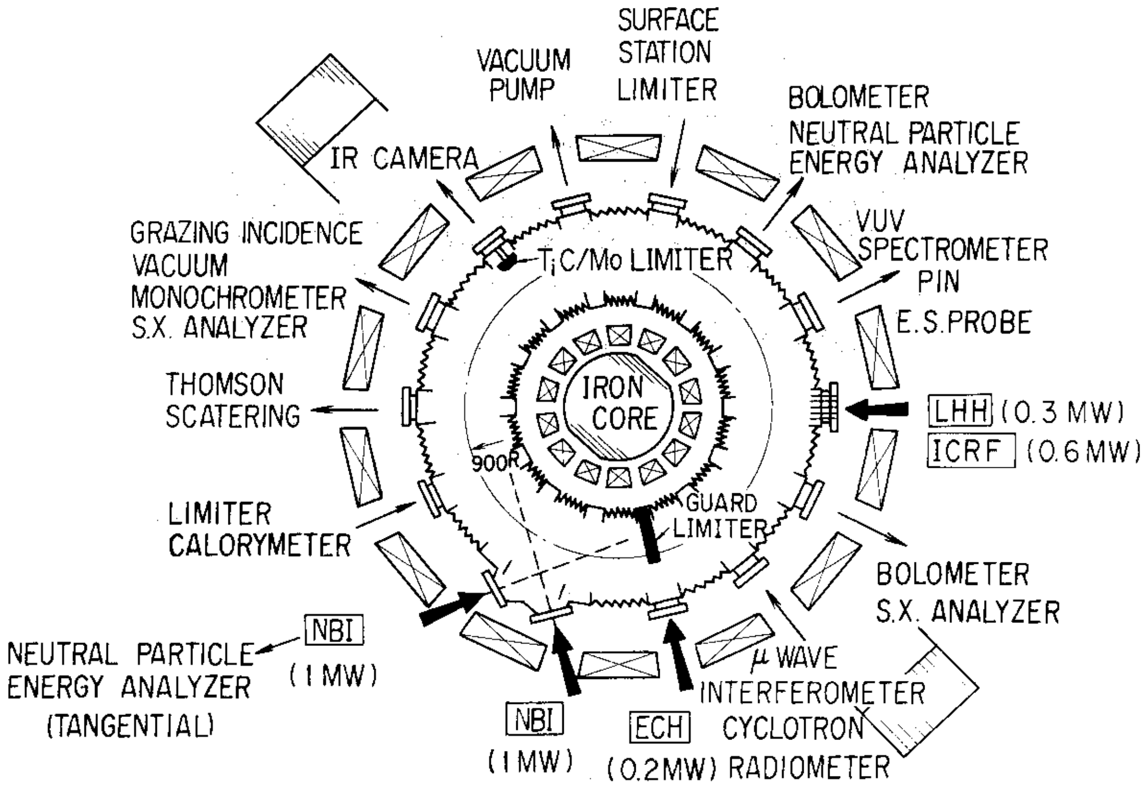


Fig. 2-1 Plane view of JFT-2 device and its diagnostics

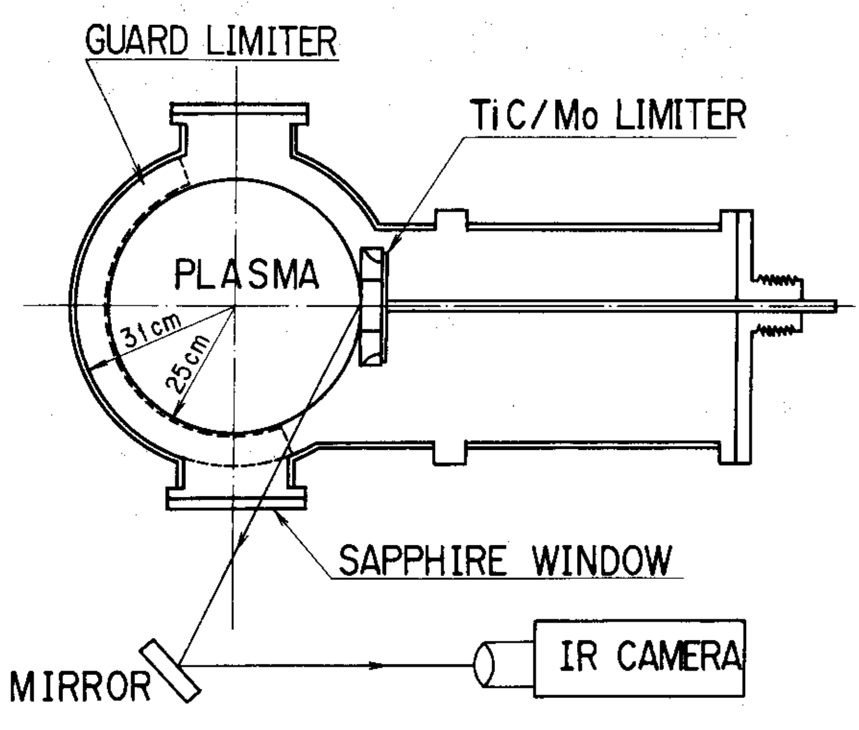
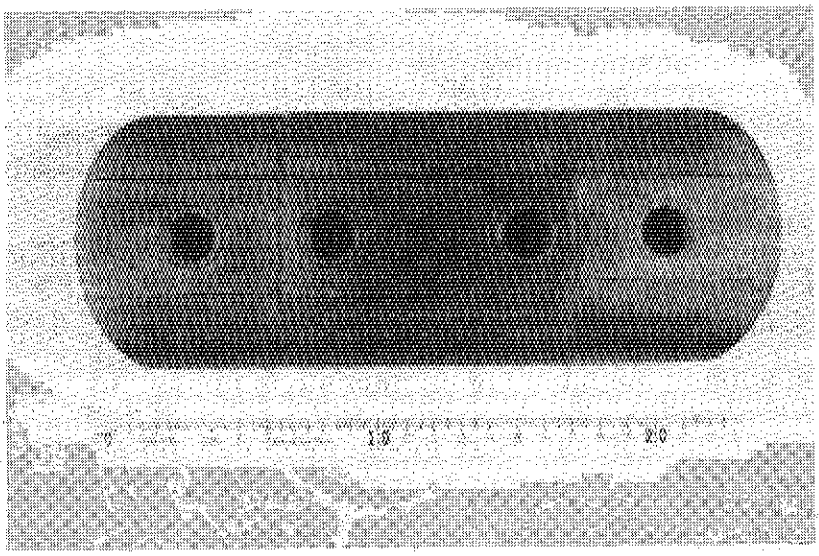
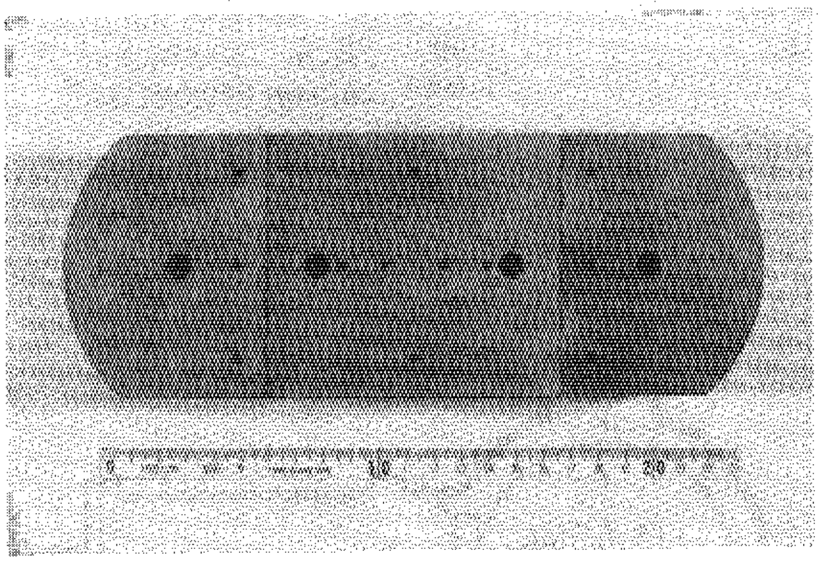


Fig.2-2 Cross sectional view of limiter drive system section and surface temperature measurement system

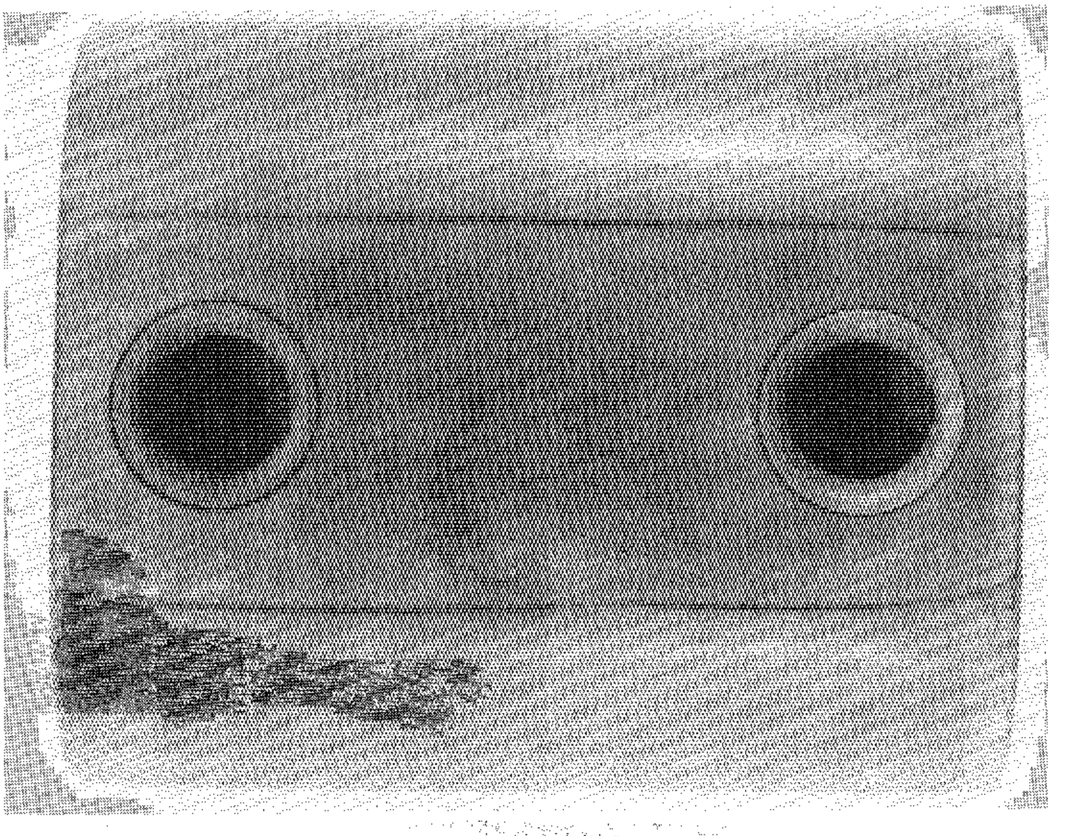


(a)



(b)

Fig. 2-3 TiC coated Mo limiter
(a) Plane view (b) Back surface view



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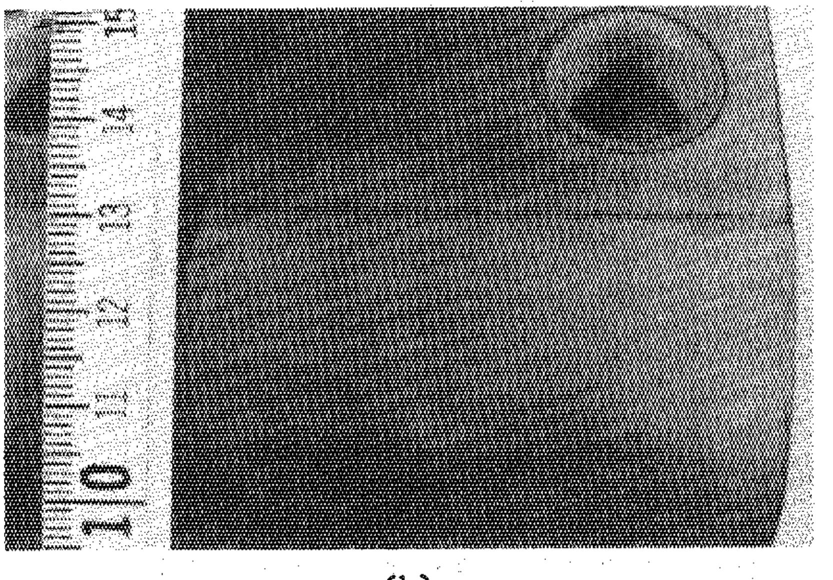
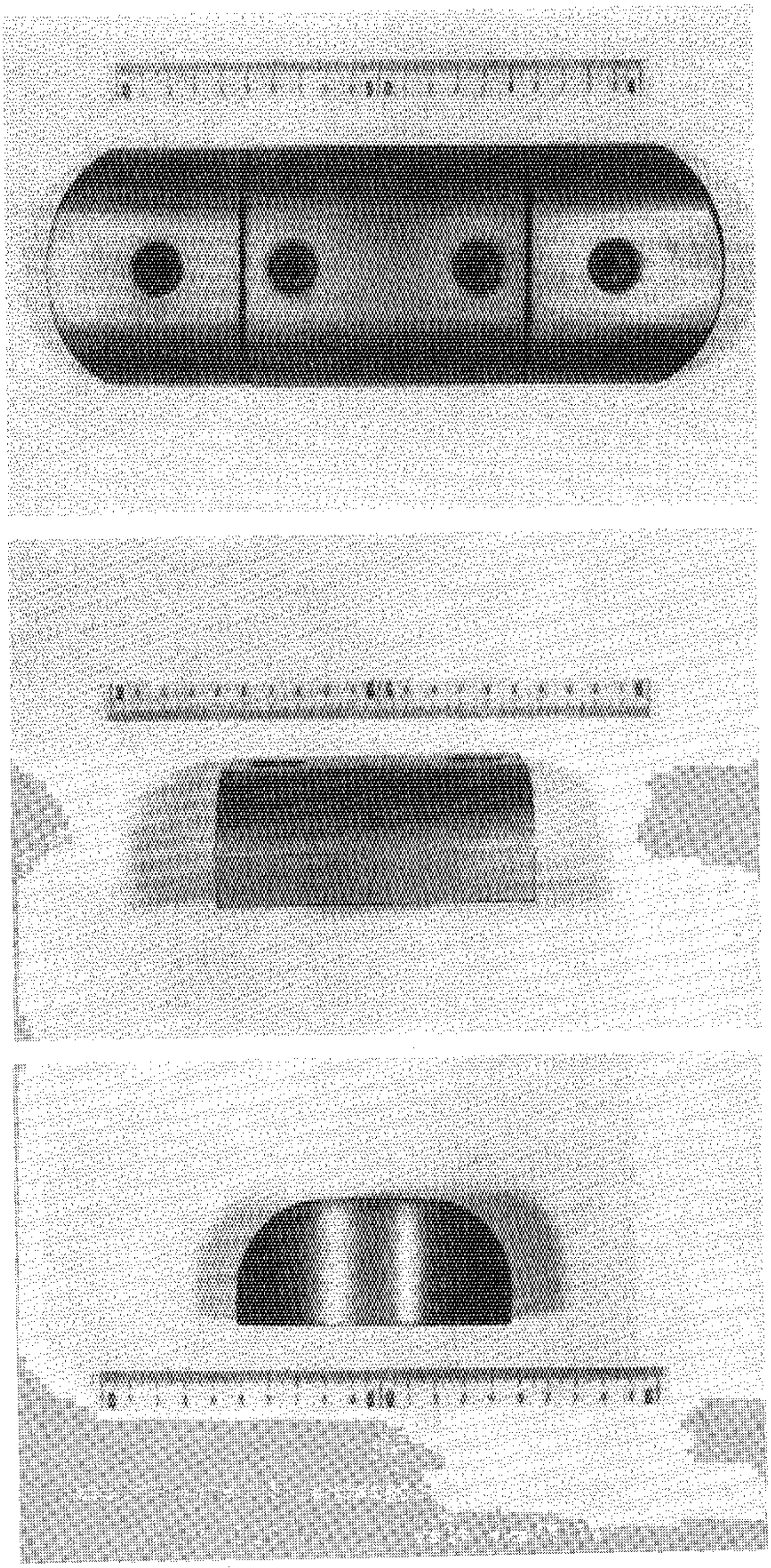


(b)

Fig. 2-4 Magnified photographs of center block
(a) Plane view (b) Side view



(a)

(b)

(c)

Fig. 2-5 TiN coated Mo limiter
(a) Plane view (b) Side view of center block
(c) Edge view of side block

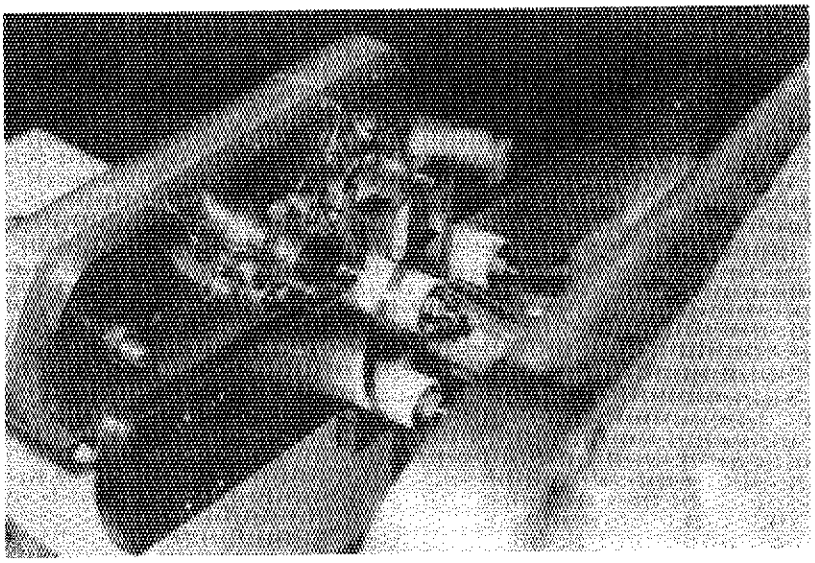


Fig. 2-6 Limiter shaft support, aluminum insulators and copper substrate. Arc shields are not attached in this figure.

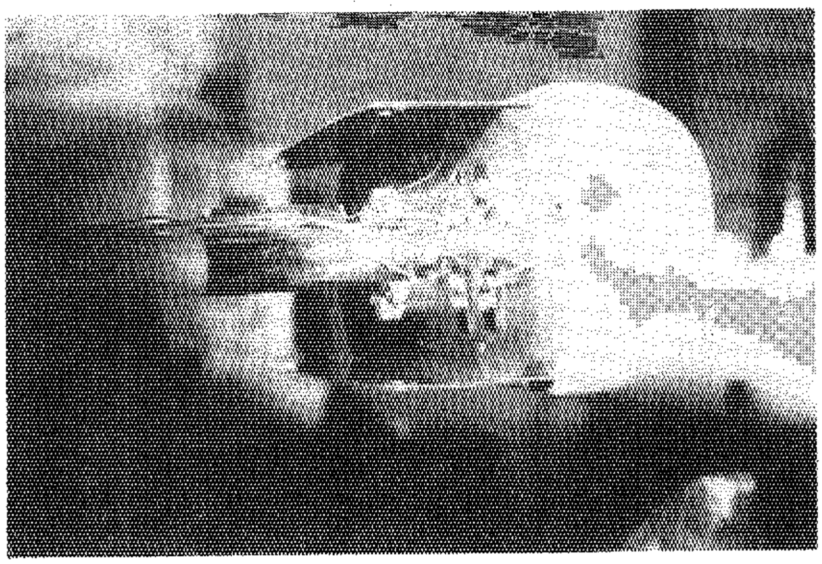


Fig. 2-7 Stainless steel arc shield

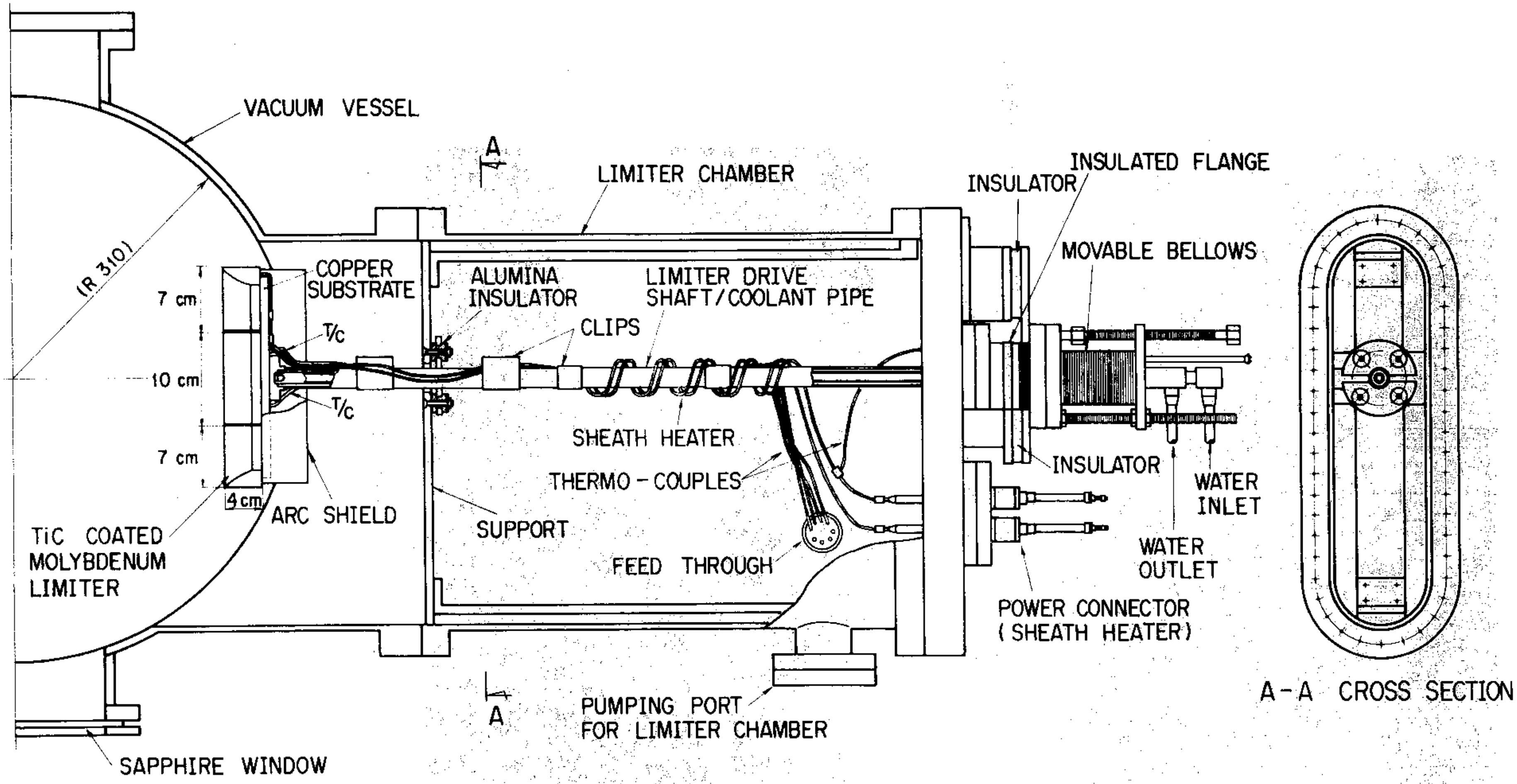


Fig. 2-8 Details of limiter drive system and coated limiter head

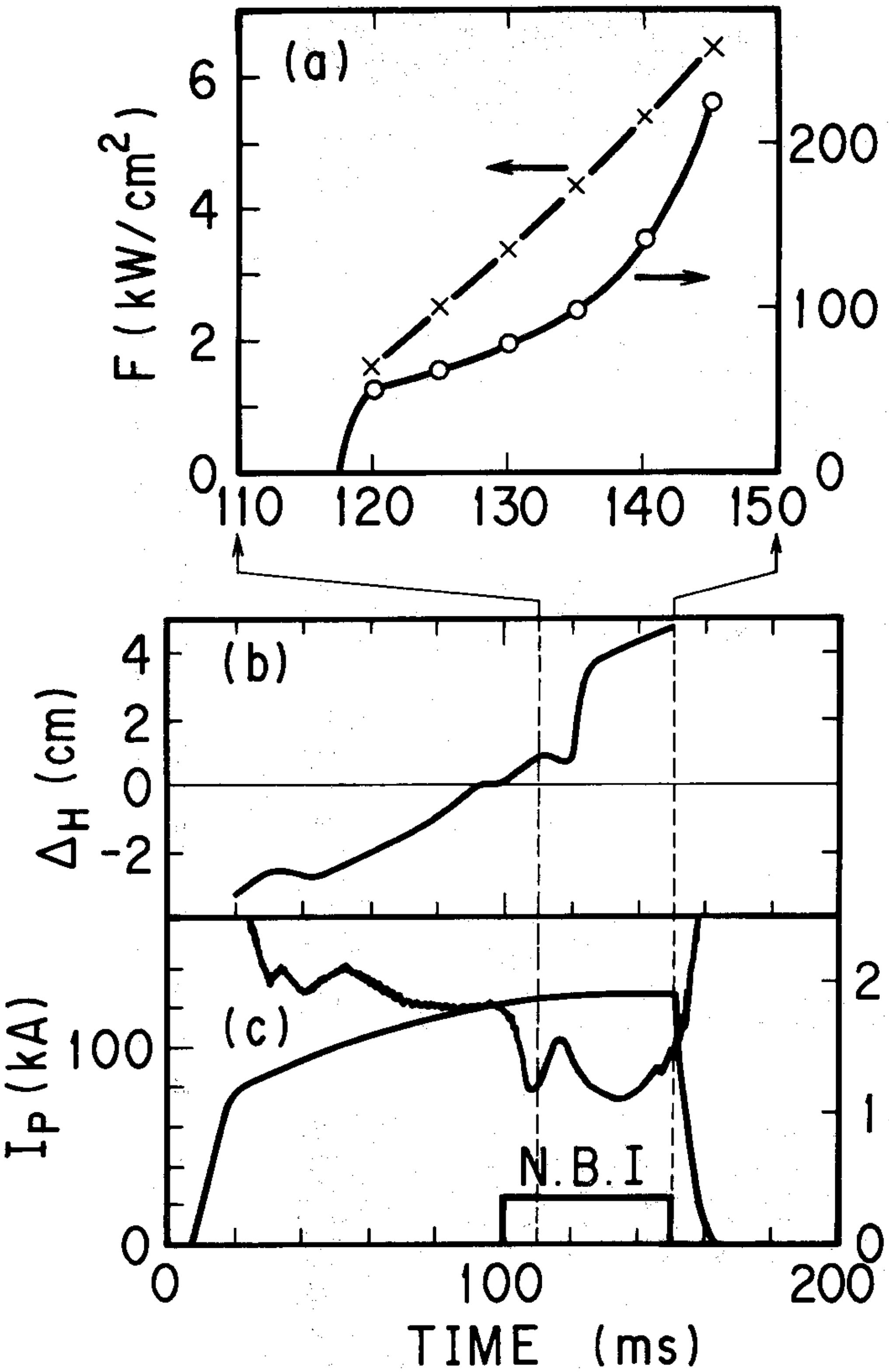
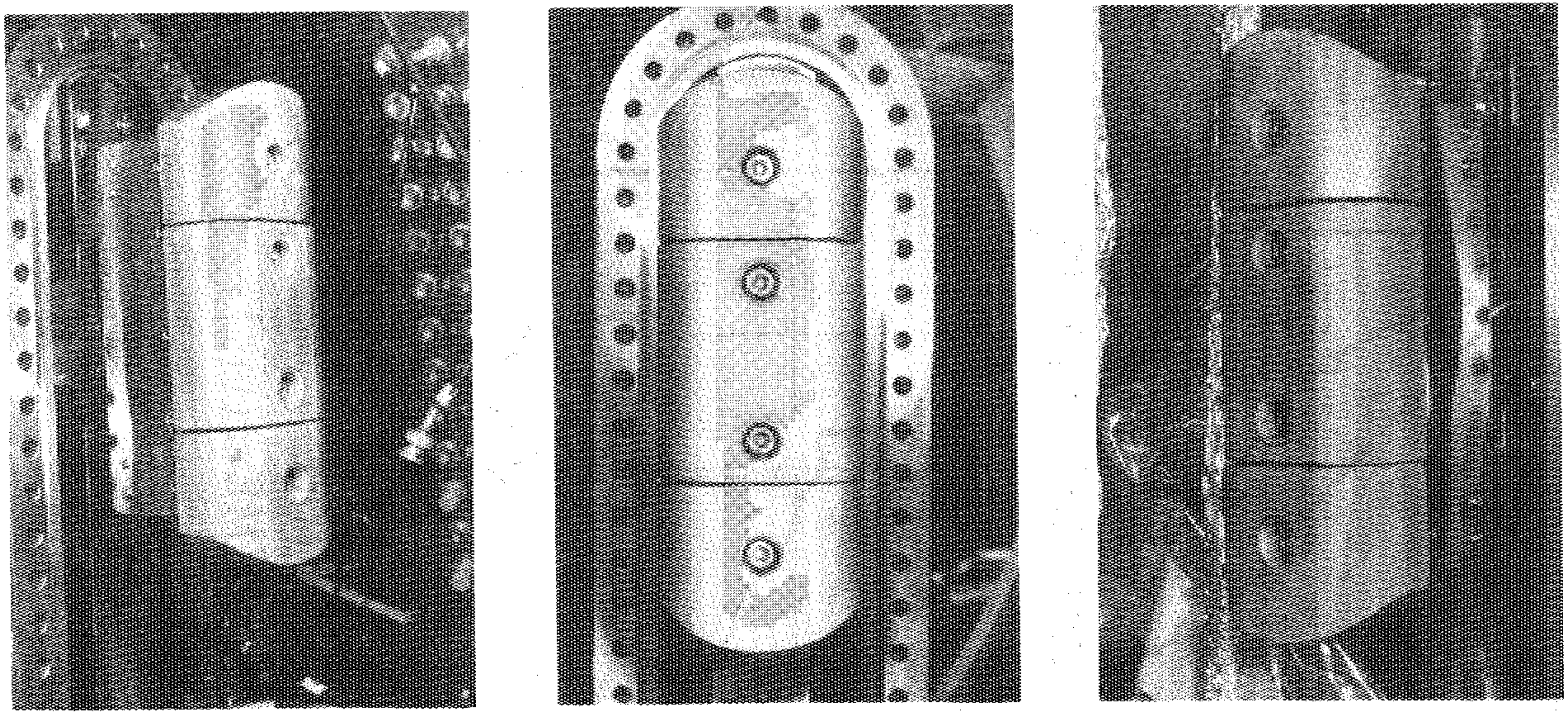
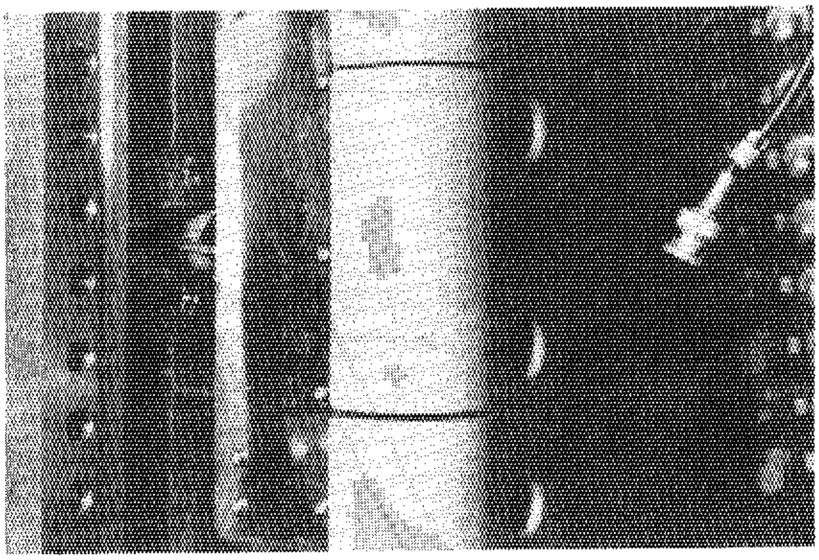


Fig. 3-1 Time variations of plasma current, loop voltage and plasma displacement, and time behavior of surface temperature and heat flux on the limiter.

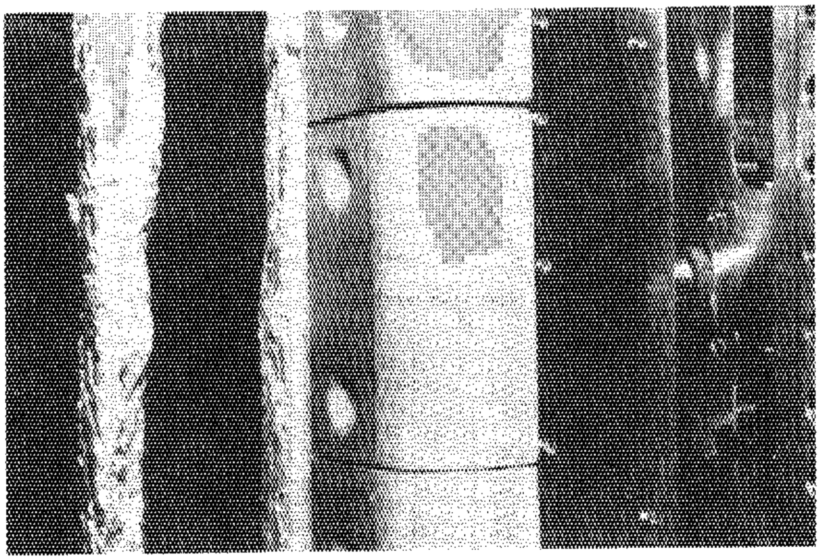


(a) (b) (c)

Fig. 3-2 TiC coated Mo limiter after plasma experiment
(a) ion side (b) front surface (c) electron side

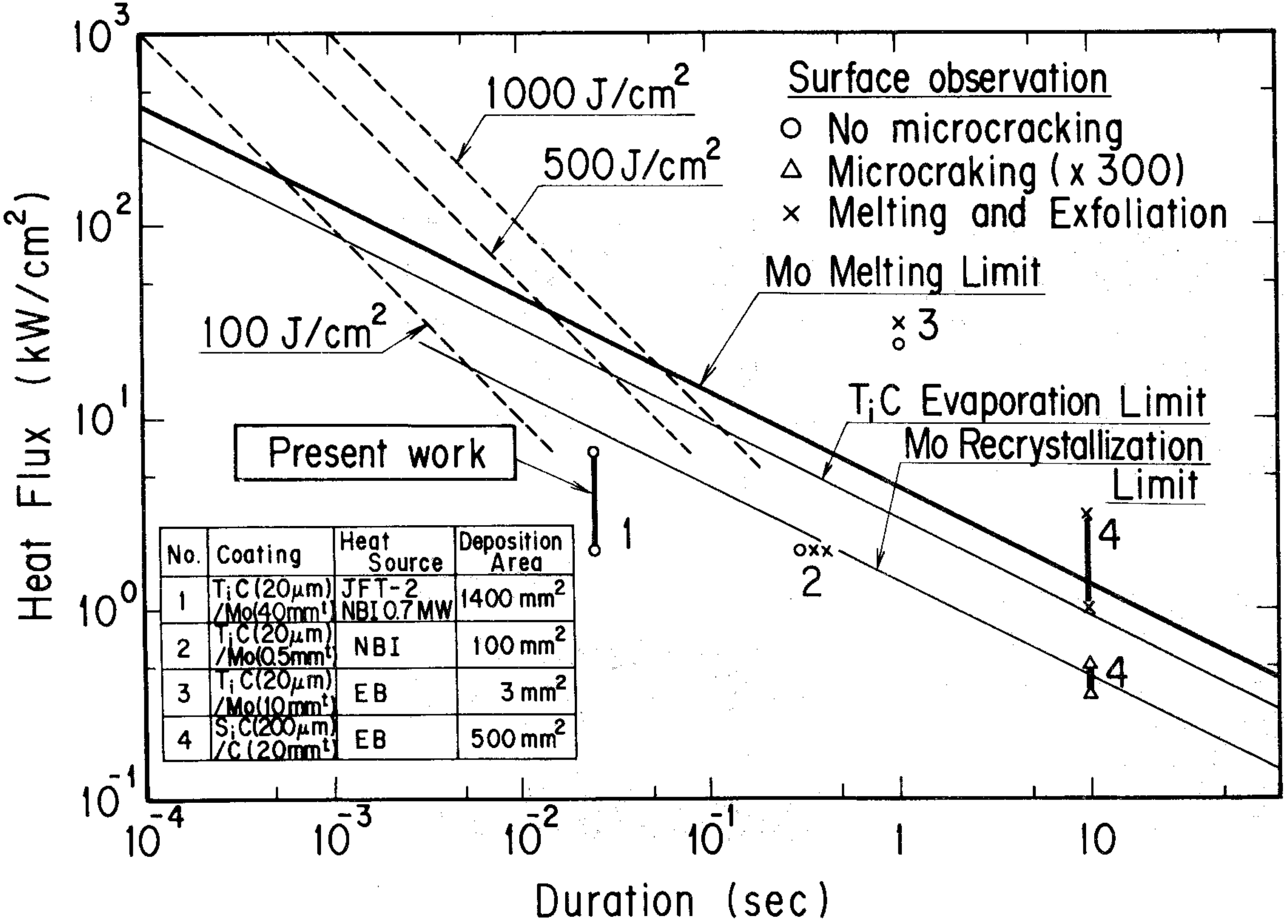


(a)



(b)

Fig. 3-3 Arc tracks on the stainless steel arc shield
(a) ion side (b) electron side

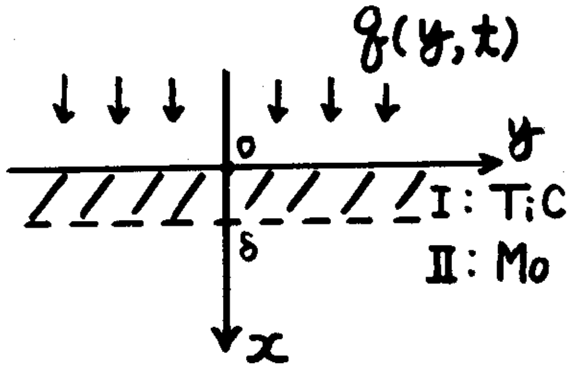


No.	Coating	Heat Source	Deposition Area
1	TiC (20μm) /Mo(40mm^t)	JFT-2 NBI 0.7MW	1400 mm^2
2	TiC (20μm) /Mo(0.5mm^t)	NBI	100 mm^2
3	TiC (20μm) /Mo(10mm^t)	EB	3 mm^2
4	SiC (200μm) /C (20mm^t)	EB	500 mm^2

Fig. 4-1 Results of thermal shock tests and the relation between permissible heat flux and duration time for TiC coated molybdenum by chemical vapor deposition.

Appendix Heat flux calculation using a composit semi-infinite solid model

A model used for the heat flux calculation of a limiter surface is shown in the following figure.



The basic equation of heat conduction is

$$\frac{\partial T}{\partial t} = \alpha \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) \quad . \tag{A-1}$$

where α : thermal diffusivity

In this experiment, temperature distribution of y-direction was not obtained. Therefore, eq(A-1) is modified using an averaged temperature $\overline{T}$, which is a mean value in the direction of y.

$$\frac{\partial \overline{T}}{\partial t} = \alpha \frac{\partial^2 \overline{T}}{\partial x^2} \tag{A-2}$$

$$\overline{T}\ (x=0) = f(t) \tag{A-3}$$

By solving eq(A-2) and (A-3), we can obtain a solution for $q_s(t)$ as obtained.

$$-\lambda_1 \frac{\partial T_1}{\partial x}\Big|_{x=\delta} = -\lambda_2 \frac{\partial T_2}{\partial x}\Big|_{x=\delta} = q_s(t) \tag{A-4}$$

$$T_1 = T_2 \tag{A-5}$$

where λ_1 ; thermal conductivity of TiC

λ_2 ; thermal conductivity of molybdenum

T_1 ; temperature of TiC

T_2 ; temperature of molybdenum

δ ; thickness of TiC coating

q_s ; heat flux on limiter surface

Here, we use the following assumption because surface heat load passes through TiC coating layer in a very short time of 50 μsec.

- Thermal resistance of TiC coating layer is neglected.
- Thermal capacity of TiC coating layer is considered.

Eq.(A-2) and (A-3) can be rewritten as

$$\frac{\partial T}{\partial t} = \alpha_M \frac{\partial^2 T}{\partial x^2} \qquad \text{(A-6)}$$

$$t = 0 \quad ; \ T = 0 \qquad \text{(A-7)}$$

$$t > 0,\ x = 0 \ ; \ T = f(t) \qquad \text{(A-8)}$$

where α_M ; thermal diffusivity of molybdenum

The solution of eq(A-6) is

$$T = \frac{x}{2\sqrt{\pi\alpha}} \int_0^t f(\tau) \frac{e^{-x^2/4\alpha_M(t-\tau)}}{(t-\tau)^{3/2}} d\tau \qquad \text{(A-9)}$$

Here, $\tau = t - (x^2/4\alpha\mu^2)$

$$T = \frac{2}{\sqrt{\pi}} \int_{x/2\sqrt{\alpha t}}^{\infty} f(t - \frac{x^2}{4\alpha\mu^2})\, e^{-\mu^2} d\mu \qquad \text{(A-10)}$$

To integrate eq(A-10), function f( ) is rewritten as follows.

$$\begin{aligned} f(t - \frac{x^2}{4\alpha\mu^2}) &= T_N - G_N t_N + G_N(t - \frac{x^2}{4\alpha\mu^2}) \\ &= T_N - G_N t_N + G_N t - \frac{G_N x^2}{4\alpha\mu^2} \end{aligned} \qquad \text{(A-11)}$$

where $t_N \leq \tau \leq t_{N+1}$

$f(\tau) = T_N + T_N(\tau - t_N)$

$G_N = (T_{N+1} - T_N)/(t_{N+1} - t_N)$

$x/2\sqrt{\alpha\ t_{N+1}} \leq \mu \leq x/2\sqrt{\alpha\ t_N}$

Eq(A-10) becomes

$$T = \frac{2}{\sqrt{\pi}} \sum_{N=1}^{M} \int_{x/2\sqrt{\alpha\ t_{N+1}}}^{x/2\sqrt{\alpha\ t_N}} \{[T_N - G_N t_N + G_N t] - \frac{G_N x^2}{4\alpha\mu^2}\} e^{-\mu^2} d\mu$$

------- (A-12)

$$= \frac{2}{\sqrt{\pi}} \sum_{N=1}^{M} \{ \int_{x/2\sqrt{\alpha\ t_{N+1}}}^{\infty} - \int_{x/2\sqrt{\alpha\ t_N}}^{\infty} \}$$

$$= \sum_{N=1}^{M} \{ (T_N - G_N t_N + G_N t)(\mathrm{erfc}\ \frac{x}{2\sqrt{\alpha\ t_{N+1}}} - \mathrm{erfc}\ \frac{x}{2\sqrt{\alpha\ t_N}})$$

$$- \frac{G_N}{4\alpha} x^2 [\frac{2}{\sqrt{\pi}} (\frac{e^{-\mu_{N+1}^2}}{\mu_{N+1}} - \sqrt{\pi}\mathrm{erfc}\ \mu_{N+1} - \frac{e^{-\mu_N^2}}{\mu_N} + \sqrt{\pi}\ \mathrm{erfc}\ \mu_N)]\} \quad \text{-------- (A-13)}$$

Here, we define $F_N = T_N - G_N t_N + G_N t$

$$T = \sum_{N=1}^{M} \{ F_N (\mathrm{erfc}\ \frac{x}{2\sqrt{\alpha\ t_{N+1}}} - \mathrm{erfc}\ \frac{x}{2\sqrt{\alpha\ t_N}}$$

$$- \frac{G_N}{2\alpha\sqrt{\pi}} x^2\ (\frac{2\sqrt{\alpha\ t_{N+1}}}{x} e^{-x^2/4\alpha t_{N+1}} - \sqrt{\pi}\ \mathrm{erfc}\ \frac{x}{2\sqrt{\alpha\ t_{N+1}}}$$

$$- \frac{2\sqrt{\alpha\ t_N}}{x} e^{-x^2/4\alpha t_N} + \sqrt{\pi}\ \mathrm{erfc}\ \frac{x}{2\sqrt{\alpha\ t_N}} \} \quad \text{-------- (A-14)}$$

If $t_N \neq 0$

$$\frac{\partial T}{\partial x}\Big|_{x=0} = \sum_{N=1}^{M} \{ \frac{F_N}{\sqrt{\pi\alpha}} (\frac{1}{\sqrt{t_N}} - \frac{1}{\sqrt{t_{N+1}}}) - \frac{G_N}{\sqrt{\pi\alpha}} (\sqrt{t_{N+1}} - \sqrt{t_N}) \}$$

$$q_s(t) = -\lambda_{M_0} \frac{\partial T}{\partial x}\Big|_{x=0}$$

$$= \frac{-\lambda_{M_0}}{\sqrt{\pi\alpha}} \sum_{N=1}^{M} \{ F_N (\frac{1}{\sqrt{t_N}} - \frac{1}{\sqrt{t_{N+1}}} - G_N (\sqrt{t_{N+1}} - \sqrt{t_N}) \} \quad \text{(A-15)}$$

If $t_N = 0$

$$T = Gt\{ (1 + \frac{x^2}{2\alpha t})\ \mathrm{erfc}\ \frac{x}{2\sqrt{\alpha t}} - \frac{x}{\sqrt{\pi\alpha t}} e^{-x^2/4\alpha t} \}$$

$$\frac{\partial T}{\partial x} = Gt\{ \frac{x}{\alpha t}\ \mathrm{erfc}\ \frac{x}{2\sqrt{\alpha t}} + (1 + \frac{x^2}{2\alpha t}) \frac{1}{2\sqrt{\alpha t}} \frac{-2}{\sqrt{\pi}} e^{-x^2/4\alpha t}$$

$$- \frac{1}{\sqrt{\pi\alpha t}} e^{-x^2/4\alpha t} - \frac{x}{\sqrt{\pi\alpha t}} \frac{-x}{2\alpha t} e^{-x^2/4\alpha t} \}$$

$$= \frac{-2Gt}{\sqrt{\pi\alpha t}}$$

$$q_s(t) = \frac{2G\lambda_{M0}}{\sqrt{\pi\alpha}} \sqrt{t} \qquad \text{(A-16)}$$

To obtain an effective heat flux considering TiC coating layer, heat load absorbed in TiC layer must be added to eq(A-15), that is,

$$q_s^{eff}(t) = q_s(t) + \rho C_p \delta \frac{dT}{dt} \qquad \text{(A-17)}$$

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JAERI-M 82-065

Development of TiC and TiN Coated Molybdenum Limiter System and Initial Results of the Thermal Testing in Neutral Beam Heated JFT-2 Tokamak

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Please correct the appendix after eq.(A-11) and Fig. 3.1.

Appendix

where $t_N \leq \tau \leq t_{N+1}$

$$f(\tau) = T_N + G_N(\tau - t_N)$$

$$G_N = (T_{N+1} - T_N)/(t_{N+1} - t_N)$$

$$x/2\sqrt{\alpha(t - t_{N+1})} \leq \mu \leq x/2\sqrt{\alpha(t - t_N)}$$

Eq.(A-10) becomes

$$T = -\frac{2}{\sqrt{\pi}} \sum_{N=1}^{M} \int_{x/2\sqrt{\alpha(t - t_{N+1})}}^{x/2\sqrt{\alpha(t - t_N)}} \{[T_N - G_N\ t_N + G_N\ t] - \frac{G_N x^2}{4\alpha\mu^2}\} e^{-\mu^2} d\mu \qquad \text{-------- (A-12)}$$

$$= -\frac{2}{\sqrt{\pi}} \sum_{N=1}^{M} \{ \int_{x/2\sqrt{\alpha(t - t_{N+1})}}^{\infty} - \int_{x/2\sqrt{\alpha(t - t_N)}}^{\infty} \}$$

$$= \sum_{N=1}^{M} \{(T_N - G_N t_N + G_N t)(\mathrm{erfc}\ \frac{x}{2\sqrt{\alpha(t - t_{N+1})}} - \mathrm{erfc}\ \frac{x}{2\sqrt{\alpha(t - t_N)}})$$

$$- \frac{G_N}{4\alpha} x^2 [\frac{2}{\sqrt{\pi}} (\frac{e^{-\mu_{N+1}^2}}{\mu_{N+1}} - \sqrt{\pi}\mathrm{erfc}\ \mu_{N+1} - \frac{e^{-\mu_N^2}}{\mu_N} + \sqrt{\pi}\ \mathrm{erfc}\ \mu_N)]\} \qquad \text{-------- (A-13)}$$

Here, we define $F_N = T_N - G_N\ t_N + G_N\ t$

$$T = -\sum_{N=1}^{M} \{F_N(\mathrm{erfc}\frac{x}{2\sqrt{\alpha(t-t_{N+1})}} - \mathrm{erfc}\frac{x}{2\sqrt{\alpha(t-t_N)}})$$

$$-\frac{G_N}{2\alpha\sqrt{\pi}} x^2 (\frac{2\sqrt{\alpha(t-t_{N+1})}}{x} e^{-x^2/4\alpha(t-t_{N+1})} - \sqrt{\pi}\ \mathrm{erfc}\frac{x}{2\sqrt{\alpha(t-t_{N+1})}}$$

$$-\frac{2\sqrt{\alpha(t-t_N)}}{x} e^{-x^2/4\alpha(t-t_N)} + \sqrt{\pi}\ \mathrm{erfc}\frac{x}{2\sqrt{\alpha(t-t_N)}})\} \quad \text{------- (A-14)}$$

If $1 \leq N \leq M-1$

$$\frac{\partial T}{\partial x}\Big|_{x=0} = -\sum_{N=1}^{M} \{\frac{F_N}{\sqrt{\pi\alpha}}(\frac{1}{\sqrt{t-t_N}} - \frac{1}{\sqrt{t-t_{N+1}}}) - \frac{G_N}{\sqrt{\pi\alpha}}(\sqrt{t-t_{N+1}} - \sqrt{t-t_N})\}$$

$$q_s(t) = -\lambda_{M_0} \frac{\partial T}{\partial x}\Big|_{x=0}$$

$$= \frac{\lambda_{M_0}}{\sqrt{\pi\alpha}} \sum_{N=1}^{M} \{F_N(\frac{1}{\sqrt{t-t_N}} - \frac{1}{\sqrt{t-t_{N+1}}} - G_N(\sqrt{t-t_{N+1}} - \sqrt{t-t_N})\} \quad \text{(A-15)}$$

If $N = M$,

$$q_s(t) = \frac{\lambda_{M_0}}{\sqrt{\alpha\pi}} \{F_M \frac{1}{\sqrt{t-t_M}} + G_M\sqrt{t-t_M}\} \quad \text{(A-16)}$$

To obtain an effective heat flux considering TiC coating layer, heat load absorbed in TiC layer must be added to eq.(A-15), that is,

$$q_s^{eff}(t) = q_s(t) + \rho\ C_p\ \delta \frac{dT}{dt} \quad \text{(A-17)}$$

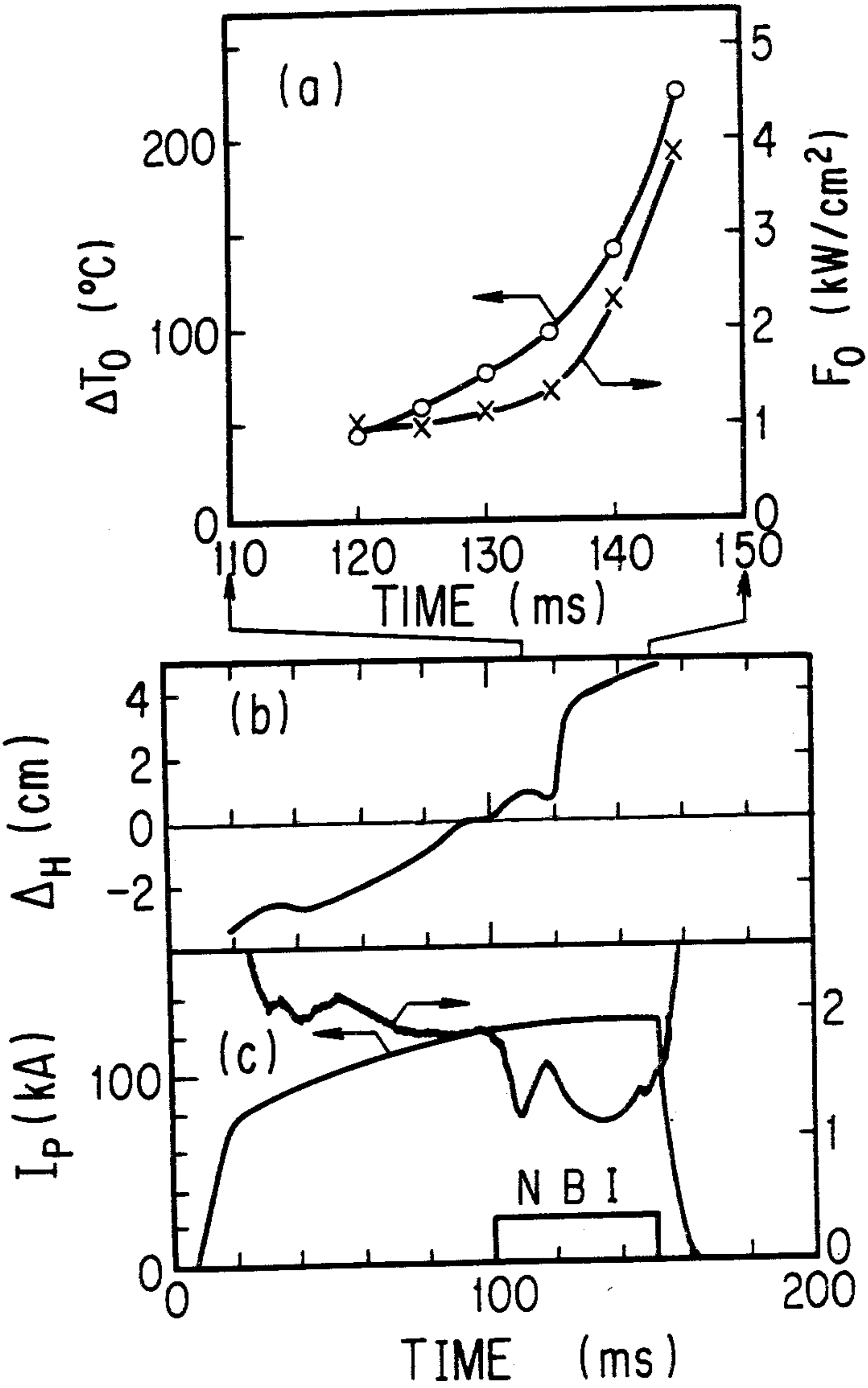

Fig. 3-1 Time variations of plasma current, loop voltage and plasma displacement, and time behavior of surface temperature and heat flux on the limiter.