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HEAT REMOVAL FROM THE SIMULATION
ELECTRODE OF A HIGH POWER LONG
PULSE ION SOURCE

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An experiment was made on the cooling of the target that simulated
an electrode of the ion source operating in a megawatt regime. A
copper disk with thin parallel cooling tubes were bombarded by hydrogen
beams of 1 to 4 A at 30 KeV for up to 7.6 s. The average heat loading
to the target surface and to the cooling surface was as high as 220 W/cm^2
and 570 W/cm^2, respectively. The temperature of the target was measured
by thermocouples and found to be suppressed below 200 °C owing to an
increase of heat transfer coefficient by subcool boiling of the cooling
water. On the basis of this result, the extraction electrode of an ion
source for JT-60 can be designed to withstand the operation exceeding
35 A at 75 KeV for 10 s from the heat transfer point of view.

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a) On leave from Nissin Electric Co., Ltd.

b) On leave from Mitsubishi Heavy Industries, Ltd.

ハイパワーロングパルスイオン源の電極冷却模擬実験

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　メガワット級のイオンビームを引き出すイオン源の加速電極を模擬したターゲットの冷却実験を行った。直径 18 cm の銅板をターゲットとして，30 keV で 1 〜 4 A の水素ビームにて最大 7.6 秒間これを照射し加熱した。この時得られた最大熱負荷は，冷却面の平均値で 570 W／cm² であった。また，ターゲットの表面での熱負荷は 220 W／cm² であった。ターゲット表面温度は冷却水の沸騰のため 200 °C 以下に抑えられることが確認された。この実験の結果，JT—60 用イオン源の加速電極を 75 keV で 35 A のビームの 10 秒間の引出しに耐える様に熱的には設計できることがわかった。

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INTRODUCTION

High power neutral beam injection plays an increasingly important role in controlled thermonuclear fusion research as a method for heating a magnetically confined plasma. Intense ion sources are being developed to produce quasi-continuous megawatt neutral beam. For instance the ion source for JT-60 neutral beam injection is specified to deliver an ion beam of 35 A at 75 KeV for up to 10 s.[1] Each extraction electrode is equipped with alternately arranged rows of apertures and water cooling pipes over the 12 cm × 27 cm area, which determines a beam transparency of 40 %.

In these ion sources, heat loading to the extraction electrode is one of the crucial problems which limit the ion beam power density. Measurements of the heat loading to a two stage extraction system showed that up to 2 % of the extracted beam power was dissipated in an electrode under the typical beam divergence and gas pressure.[2] The corresponding heat loading averaged over the cooling surface is 270 W/cm^2. This heat loading may cause thermal deformation or melting of the electrode during a pulse of 10 s. due to its small heat capacity.

While we have performed long-pulse beam extraction of 4 A at 30 KeV with intentionally disarranged grid system, the heat flux obtained have been only a half of the above mentioned value.[3] Several authors[4,5] have also operated ion sources with a long pulse but with small heat loading to the extraction electrodes. Recently, M. Seki et al.[6] conducted a heat removal test from a high energy neutron source target, where a heat flux was up to 0.8 KW/cm^2. Their experiment was, however, performed with a small target (about 1 cm in diam.), it can not be directly applied to the design of our electrode cooling system.

To test the cooling capability of a larger electrode at high heat flux, a disk target that simulated the electrode of the ion source was irradiated by the intense ion beam.

1. EXPERIMENTAL

The target was a copper disk of 18 cm in diam. and 5 mm in thick-ness. It was irradiated by hydrogen beams from a duoPIGatron ion source. This source is equipped with a water-cooled extraction electrode system and is capable of operating for 10 s. The detailes on this ion source performances and its operating characteristics are discribed in a separate paper.[3] Eighteen parallel cooling tubes were attached to the rear side of the target. These copper tubes, 2.5 mm in outer diam. and 0.5 mm in thickness were silver brazed in such a way that they were wholly buried in the target plate as shown in Fig. 1.

The experimental set up is illustrated in Fig. 2, where the target was set 70 cm apart from the extraction electrode of the ion source. The beam profile was chosen to become broad at the target position with the e-folding divergence of 3 deg. The disk temperature was measured with chromel-alumel thermocouples buried at various positions indicated by filled circles in Fig. 1. The temperature rise of cooling water was measured with a differential platinum resister caloriemeter. In the present experiment the flow rate of cooling water was set constant at 10 ℓ/min. Water pressures at the inlet and outlet of the test section were 7.2 kg/cm^2.g and 6.8 kg/cm^2.g, respectively.

2. RESULTS AND DISCUSSION

The incident power to the target was obtained by measuring the temperature rise of the cooling water. Since the time constant of the

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2. RESULTS AND DISCUSSION

The incident power to the target was obtained by measuring the temperature rise of the cooling water. Since the time constant of the

caloriemeter is very long, the temperature rise of the cooling water did not indicate an observable change within a single short pulse. Instead, average temperature rise was measured by repetitious short pulse irradiations with a constant time interval which was shorter than the time constant of the caloriemeter. This average value is divided by the duty cycle of the operation to give the incident power of a single short pulse.

In Fig. 3 is shown the evolution of the temperature rise at the center of the target when it was irradiated by an ion beam of 3.8 A at 30 KeV for 7.6 s. The temperature rise was saturated at about 180 ° at 0.8 s. after the beam initiation. This figure also shows that all the input power after this saturation was transferred to the cooling water except for small radiated power. Figure 4 indicates the evolution of the temperature rise of the cooling water. Since time response of the caloriemeter was very slow due to its large heat capacity, the temperature rise shows a gradual evolution. Integration of this curve gives the total incident evergy of 440 KJ to the target. On the other hand 50 % of the extracted ion beam power turned out to be deposited on the target in the repetitious short pulse operations. The incident power to the target calculated from the former and the latter agree well to give the value of 57 KW. Thus the average heat loading to the cooling surface and to the target surface becomes 570 W/cm^2 and 220 W/cm^2, respectively.

The saturation temperature at the center of the target is shown in Fig. 5 as a function of the heat flux averaged over the target surface area with the corresponding ion beam current. Solid line shows the temperature of the cooling pipe wall that is estimated from the Jens-Lottes equation:[7]

$$T = 0.82 \, q^{1/4} \exp(-P/63) + Tsat$$

where T is the temperature of the cooling pipe wall, q the heat flux of the cooling surface, P the water pressure, Tsat the coresponding saturation temperature. This figure indicates that the incident power after the saturation of the temperature was removed by the forced-convection boiling heat transfer when the ion beam current exceed 2 A, while it was removed by the convective heat transfer in the case of 1 A beam current. The critical heat flux of the present case was calculated and found to be 600 W/cm^2 from the Zenkevich's equation.[8] The target was bombarded more than 100 times by the ion beam ranging from 1 to 4 A at 30 KeV for 1 to 7.6 s. But no sign of burn-out was observed.

3. DISCUSSION

A disk target was irradiated by hydrogen beams of up to 4 A at 30 KeV for 7.6 s. The average heat loading was as high as 570 W/cm^2 on the cooling surface and 220 W/cm^2 on the target surface.

From the temperature measurement by thermocouples, the target was observed to reach the thermal equilibrium state due to flow boiling at 0.8 s. after the beam initiation. The heat loading to the cooling surface exceeds the requirements of the ion source for JT-60. The extraction grid can be designed to withstand the operation of 35 A at 75 KeV for 10 s. from the heat transfer point of view.

On the other hand the average heat flux to the electrode surface, 220 W/cm^2 can not be justified for the design bases. It should be evaluated from the point of view of thermal deformation and fatigue, taking into account of the actual electrode geometry. This problem is under way in our lavoratory both numerically and experimentally and will be reported else where.

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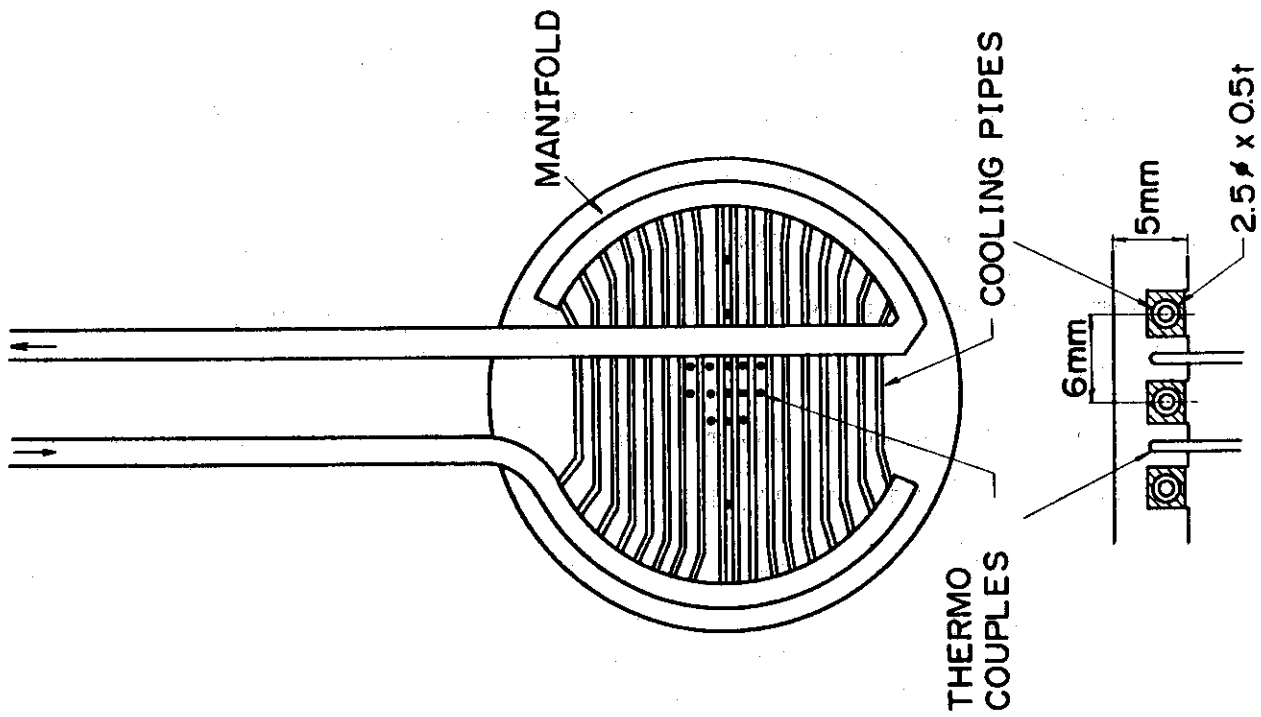
Fig. 2 Experimental set up

Fig. 1 Plain view and cross sectional view of the target.

Fig. 5　Temperature at the center of the target as a
function of the incident heat flux.
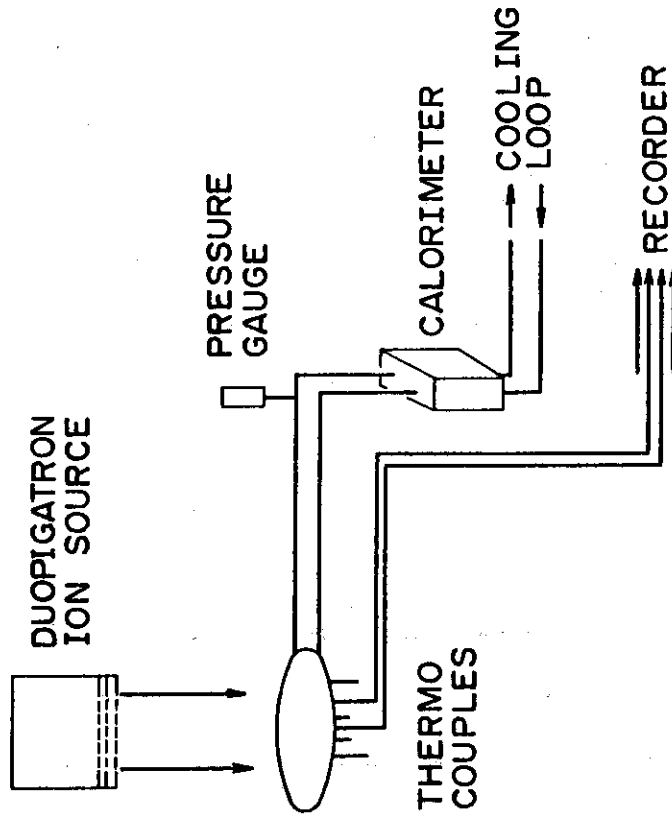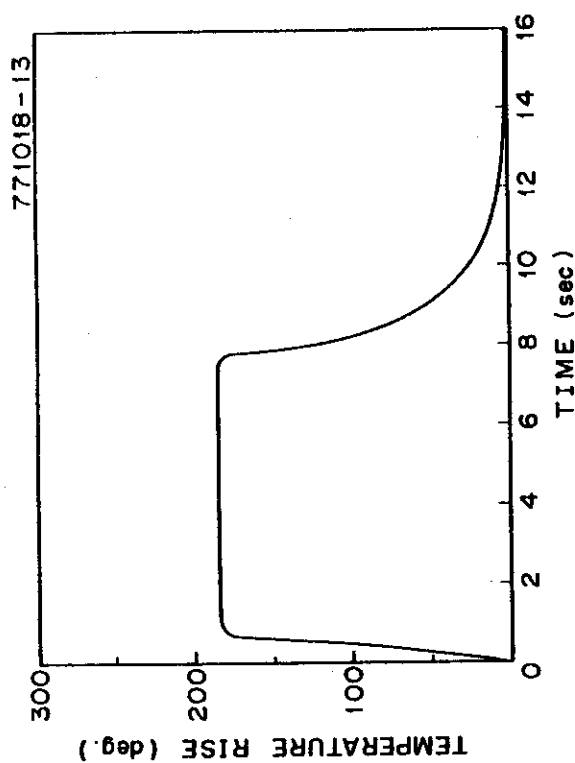

Fig. 3　Time evolution of the temperature at the center of
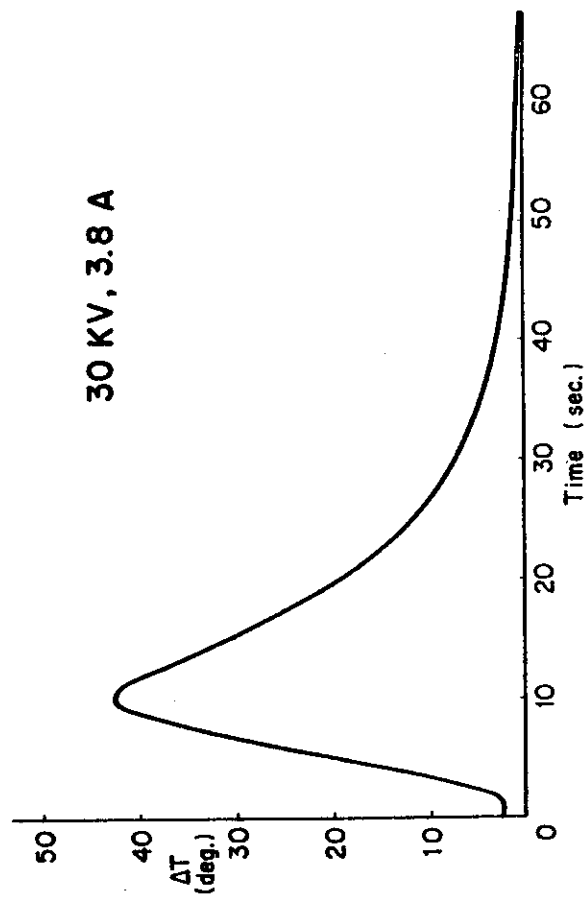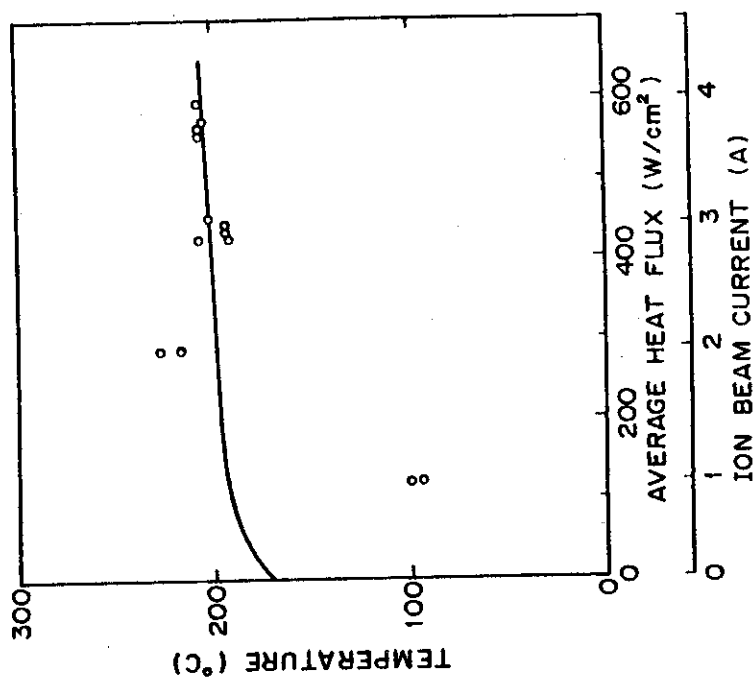the target in the case of 3.8 A at 30 KeV for 7.6 s.

Fig. 4　Time evolution of cooling water temperature measured by the
differential caloriemeter in the case of Fig. 3.