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Thermal-Hydraulic Design Concept of the N-Arena Solid-Target System

Kaichiro Mishima, Yasushi Saito and Takashi Hibiki
Research Reactor Institute, Kyoto University

ABSTRACT

In relation to thermal-hydraulic design of the proposed spallation neutron source of the N-Arena of the Japan Hadron Facility (JHF), the basic concpet of solid target, criteria for thermal-hydraulic design, and subjects to be clarified are discussed. Next, the outline of R & D on the target design is described, and finally some results of feasibility study on the maximum beam power which can be attained with a solid target are presented.

1. INTRODUCTION

In relation to thermal hydraulic design of the proposed spallation neutron source of the N-Arena of the Japan Hadron Facility (JHF), a joint study between the High Energy Accelerator Research Organization (KEK) and research groups including Hokkaido University, Tsukuba University, Kyoto University and Kobe University started in 1997. Several research meetings were held to discuss the basic concept of the target and cooling system design, to define the subjects to be solved, to plan, to perform and to assess the results of the R & D on the thermal-hydraulic design as well as material problems.

In this paper, the basic concpet of solid target, criteria for thermal-hydraulic design, and subjects to be clarified are discussed. Next, the outline of R & D on the target design is described, and finally some results of feasibility study on the maximum beam power which can be attained with a solid target are presented.

2. THERMAL-HYDRAULIC DESIGN CONCEPT AND DESIGN CRITERIA

2.1 Target Design Concept

The geometrical arrangement of the solid target could be as shown in Fig.1. In the present design, parallel plate geometry was chosen because of its simplicity and experience.

2.2 Target Design Criteria

The following criteria are imposed on the thermal-hydraulic design of the solid target and the cooling system.

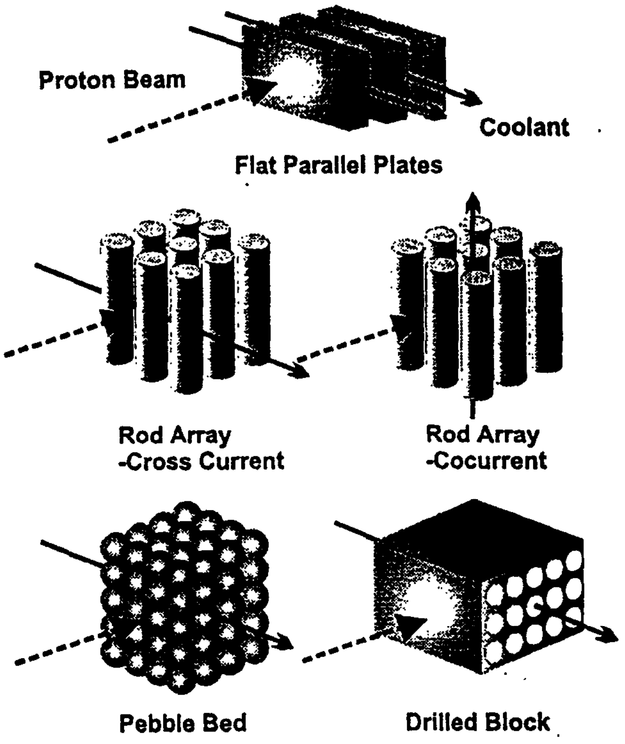

Fig.1 Basic concept of the solid target.

(1) Generally coolant boiling has undesirable effects on the solid (the target and the beam window) surface and maybe on the neutronics. For this, no boiling should be allowed in the target coolant channels under normal operating conditions, therefore:

$$T_w < T_{ONB} - \text{(safety margin)}$$

(2) To maintain the integrity of the solid target and the beam window, the temperatures in the solid, i.e.the target and the beam window, should be below the maximum permissible temperature of the material at any time and anywhere, so that

$$T_{solid} < T_{max}$$

The valued of T_{max} should be determined taking account of the melting temperature, the effects of temperarure on mechanical strength, etc. Temporarily,

T_{max} is set at 573K.

(3) If the boiling crisis occurs on the solid surface, the solid temperature may rise beyond the maximum permissible temperature of the material. Therefore, the critical heat flux for the occurrence of boiling crisis should not be reached under normal and abnormal operating conditions:

$$q_w < q_{CHF}/(\text{safety margin})$$

Note that under some special conditions, no sharp increase of solid temperature is observed even if CHF is reached. If this happens in the solid target cooling, this criterion can be ignored.

(4) The coolant flow should not cause any significant vibration, deformation, erosion of the solids, therefore:

$$v < v_{cnt}$$

where V_{cnt} denotes the critical velocity to initiate significant vibration which may cause deformation or damage of the solid target. The critical velocity can be estimated to be, for example, one half of Miller's velocity [1].

(5) Temperature gradient and transients in the solid should not cause excessive thermal stress, thermal shock and fatigue during the lifetime of the solid material, therefore:

$$\sigma_{solid} < \sigma_{max}$$

where σ_{solid} and σ_{max} denote the stress in the solid and the maximum permissible stress for the solid material, respectively.

(6) In addition, all the above criteria should be met even under the influence of radiation damage, radio-isotope production and chemical reaction throughout the life time of the solid material. Therefore, care should be taken for the effects of swelling of the slid target and beam window, accumulation of ^{7}Be and ^{3}H in the solid and the cooling system, as well as hydrogenation and embrittlement of the solid material.

2.3 Cooling System Design Criteria

(1) Primary cooling system (PCS) should have enough cooling capacity not to cause any damage of the target and the beam window under normal and abnormal operating conditions as well as in the decay heat removal after shut down of the beam.

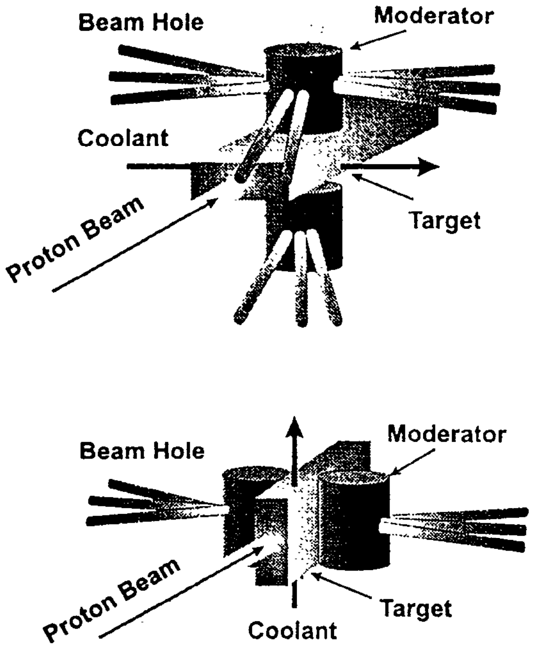

Fig. 2 Arrangement of the solid target and moderator assembly.

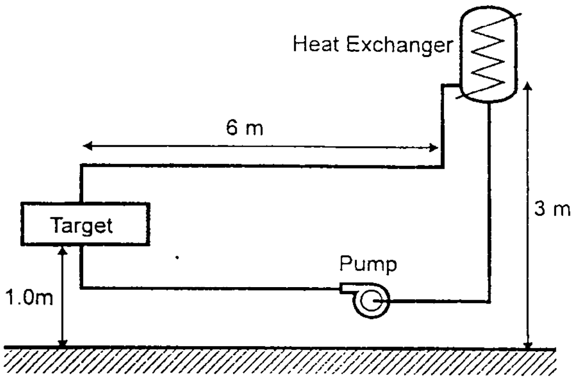

Fig.3 Skeleton of the primary cooling system.

(2) PCS should fit in the available space but should not interfere with the accessories, so that the arrangement of the target, moderator and PCS is chosen as the one on the top in Fig.2 because of the convenience for the arrangement of beam tubes, and the coolant flow direction should be horizontal. The skeleton of the PCS should be as shown in Fig.3.

(3) Adequate seismic design should be applied to PCS, namely, the system should stand for earth quakes of 0.3G, for example.

(4) PCS should be accessible or can be remote handled for maintenance and repairment throughout in-service.

(5) Care should be taken for radiation from radioisotopes and corrosion products accumulated in PCS. For example, to cope with ^{3}H and ^{7}Be production, ^{3}H handling system, filtration and purification system, cold trap should beprepared and the biological shielding should be applied to PCS.

3. THERMAL-HYDRAULIC DESIGN CONDITIONS AT PRESENT

(1) Heat generation

The power density in the solid (target and beam window) was calculated by the Monte Carlo method. The resultant power density profile along the center axis of the solid target is as shown in Fig.4. The vertical axis denotes the power density per unit beam power. From this, the maximum heat generation density at the beam power of 0.6MW is estimated to be 840 MW/m^3.

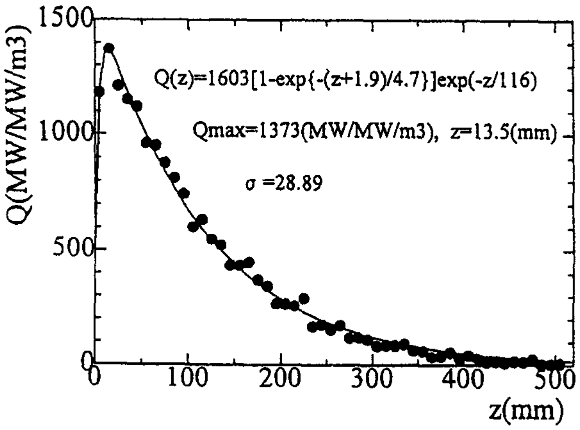

Fig. 4 Heat generation density per beam power along the center axis of the target

(2) Target material and dimensions are tabulated as follows:

material : Ta-coated W, W, (U)
target shape : flat plates
dimensions : 167mm×60mm, 5 mm thick
supporting : welded, swaged, inserted, spring-supported

(3) Heavy water was selected as primary coolant because of its neutronics characteristics. Some additives in the coolant maybe necessary to suppress certain kind of corrosion or chemical rea

(4) The conditions in the coolant channel which faces to the hottest target is as follows:

gap ×width : 1.5 mm×60 mm
flow direction : horizontal
inlet temp. : 30℃ or 20℃ if necessary
inlet pressure : atmospheric pressure or elevated pressure to suppress onset of nucleate boiling

4. SUBJECTS AND R & D RELATED TO THERMAL-HYDRAULIC DESIGN

4.1 Loop Tests

The loop test is being performed by Kobe University for the following purposes:

(1) To obtain data on flow distribution and pressure drop in the target coolant channels, which results are reflected to the distributor design,

(2) To test the proposed target design against flow induced vibrations and deformations,

(3) To study parallel channel flow instability under boiling conditions,

(4) The loop characteristics under natural circulation during decay heat removal.

The explanation of this test will be presented in the separate paper. It should be noted also that the flow visualization study is being performed by University of Tsukuba in relation to the thermal-hydraulic design of liquid metal target.

4.2 Heat Transfer Experiments

The heat transfer experiments are being conducted or planned by Kyoto University as follows:

(1) To obtain the data and to propose correlations to be used in the design calculations for heat transfer coefficient, conditions for onset of nucleate boiling (ONB) and critical heat flux (CHF),

(2) To find a way to heat transfer enhancement if necessary for heat removal from the solid target with very high heat flux.

The results from this experiment will be presented in the separate paper.

4.3 Material Problems

The following subjects are anticipated concerning the materials of the target and the beam window.

(1) Water chemistry, such as ^{7}Be-production and

deposition rate, ^{3}H-production and its handling, release of ^{3}H into environment and its influence is being studied by KEK.

(2) Effects of radiation damage, such as swelling, change in target material properties, i.e. thermal condutivity, mechanical strength, thermal expansion coefficient, etc. are being studied by Kyoto University.

(3) The impact of chemical reactions, such as the compatibility of the target material with D_2O, the formation of oxidation layer on the solid target and its effect, for example, small thermal conductivity, etc., and hydrogenation and embrittlement of the solid materials should be investigated.

4.4 Target Design and Calculations

The following target design and calculations are being performed by the participating research groups.

(1) Target design, such as material selection, i.e. Ta-coating of W, target dimensions, flow distributor and target holder desing is being performed by Kobe University.

(2) Heat generation rate was derived from neutronics calculations performed by Hokkaido University.

(3) Design calculations are being performed by the participating research groups, i.e. HokkaidoUniversity, Kobe University, Kyoto University, and KEK, such as: finite element calculation of temperature profile and thermal stress in the solid, estimation of margins to ONB and CHF, optimization of target design, maximum beam power which can be attained with a solid target.

4.5 Cooling System Design

Concerning the design of PCS, the following subjects are being or to be investigated: pressure and heat balance in PCS and the secondary system, design of natural circulation loop for decay heat removal, consideration of emergency cooling or heat sink under LOCA conditions, filtration and purification system to remove raio-isotopes and corrosion products in PCS, biological shielding for PCS, safety system, i.e. interlocks, pump trips, emergency power supply, etc, if necessary.

5. FEASIBILITY STUDY ON MAXIMUM POWER WITH SOLID TARGET

5.1 Limiting Factors (except material properties)

In view of thermal-hydraulic design, the following factors may limit the maximum beam power which can be imposed on the solid target.

(1) If no boiling is allowed in the coolant channel, the condition for the onset of nucleate boiling may be a major limiting factor for beam power. The temperature for onset of nucleate boiling T_{ONB} increases as the coolant velocity and the pressure increases. The onset of nucleate boiling can be delayed by decreasing the inlet coolant temperature T_{in}.

(2) Critical heat flux limits the maximum power because it indicates the limit of heat removal from the solid surface. CHF increaseas the heated length decreases, the coolant velocity increases, the pressure increases, and the inlet coolant temperature T_{in} decreases.

(3) Maximum temperature in the solid can be a limiting factor to repvent the melting or damage of the solid target. The maximu temperature increases as the cololant velocity decreases and the target thickness increases. The maximum teperature also increases if the thermal conductivity decreases due to radiation damage and if an oxide layer is formed on the surface

(4) The thermal stress and the fatigue can be a limiting factor if the temperature difference and the thickness of the solid target is large.

(5) Flow induced vibrations can be also a limiting factor if a very high coolant velocity is required for target cooling. The critical velocity for significant vibrations v_{crit} depends on holder design, and increases as the target thickness increases and the target widthdecreases. The critical velocity is higher for curved plates, and if support comb is applied to the leading edge of the target plates.

(6) Embrittlement of the solid material can be a limiting factor if the effect of radiation damage and hydrogenation is significant.

5.2 Tentative Results of the Feasibility Study

The calculations were peformed with the following conditions:

(1) The heat transfer coefficient for single-phase flow was calculated by the Dittus-Boelter correlation [2].

(2) The heat transfer coefficient for boiling region was calculated by the Thom's correlation [3].

(3) Condition for the onset of nucleate boiling was calculated by the intersect between Thom's correlation and the Dittus-Boelter correlation.

(4) CHF was calculated by the Bernath correlation [4].

(5) The bulk coolant temperature was calculated by the half of the total heat generation per one target plate at the peak power density, but the coolant channel recceived the heat from both of the target plates adjacent to the channel, and the target temperature was calculated with this bulk coolant temperature and the peak power density obtained from Fig.4.

The results of the calculations are shown in Figs. 5, 6 and 7 where the maximum heat flux in the target, CHF, and the onset of nucleate boiling point, surface and peak temperatures of the target are shown as functions of the beam power for the target thicknesses 3, 5 and 7 mm, respectively. The other conditions are: the coolant gap was 1.5 mm, coolant velocity 10 m/s, system pressure 0.1 MPa and the inlet temperature 30 ℃. From these figures, it can be seen that the most severe condition to limit the beam power is the onset of nucleate boiling, although sufficient margin to CHF exists, and when the target thickness is 7 mm, the maximum temperature also bcomes a limiting factor.

Fig. 8 shows the effect of changing the coolant velocity from 10 m/s to 15 m/s. From this, it can be seen that CHF is increased, the onset of nucleate boiling is supressed by increasing coolant velocity.

Fig. 9 shows the effect of system pressure. From this figure, it can be seen that CHF is increased and the onset of nucleate boiling is supressed by increasing system pressure.

Fig.10 shows the effect of swelling. If the channel gap is decreased to 1.0 mm due to swelling, then CHF decreases and ONB occurs at lower beam power, because of reduced coolant flow rate and as a consequence increased coolant bulk temperature.

Fig.11 shows the effect of oxide layer on the target temperarure. Here the thermal conductivity of the oxide layer is assumed to be reduced to one tenth.

Fig. 12 shows the effect of assumption that the peak heat flux location. Here it is assumed that the peak heat flux occurred at the outlet of the heated channel, i.e. location of highest bulk coolant temperature. In reality, if one uses realistic power profile along the coolant channel, the result may be in between Figs. 5 and 12.

6. SUMMARY

In relation to thermal-hydraulic design of the proposed spallation neutron source of the N-Arena of the Japan Hadron Facility (JHF), the basic concpet of solid target, criteria for thermal-hydraulic design, and subjects to be clarified were discussed. Next, the outline of R & D on the target design was described, and finally some tentative results of feasibility study on the maximum beam power which could be attained with a solid target were presented. The result indicated that the condition for the onset of nucleate is the most significant limiting factor to the maximum beam power. The results also indicated that the maximum beam power can be as high as 1 MW. The final conclusion should be drawn by more detailed and reliable calculations.

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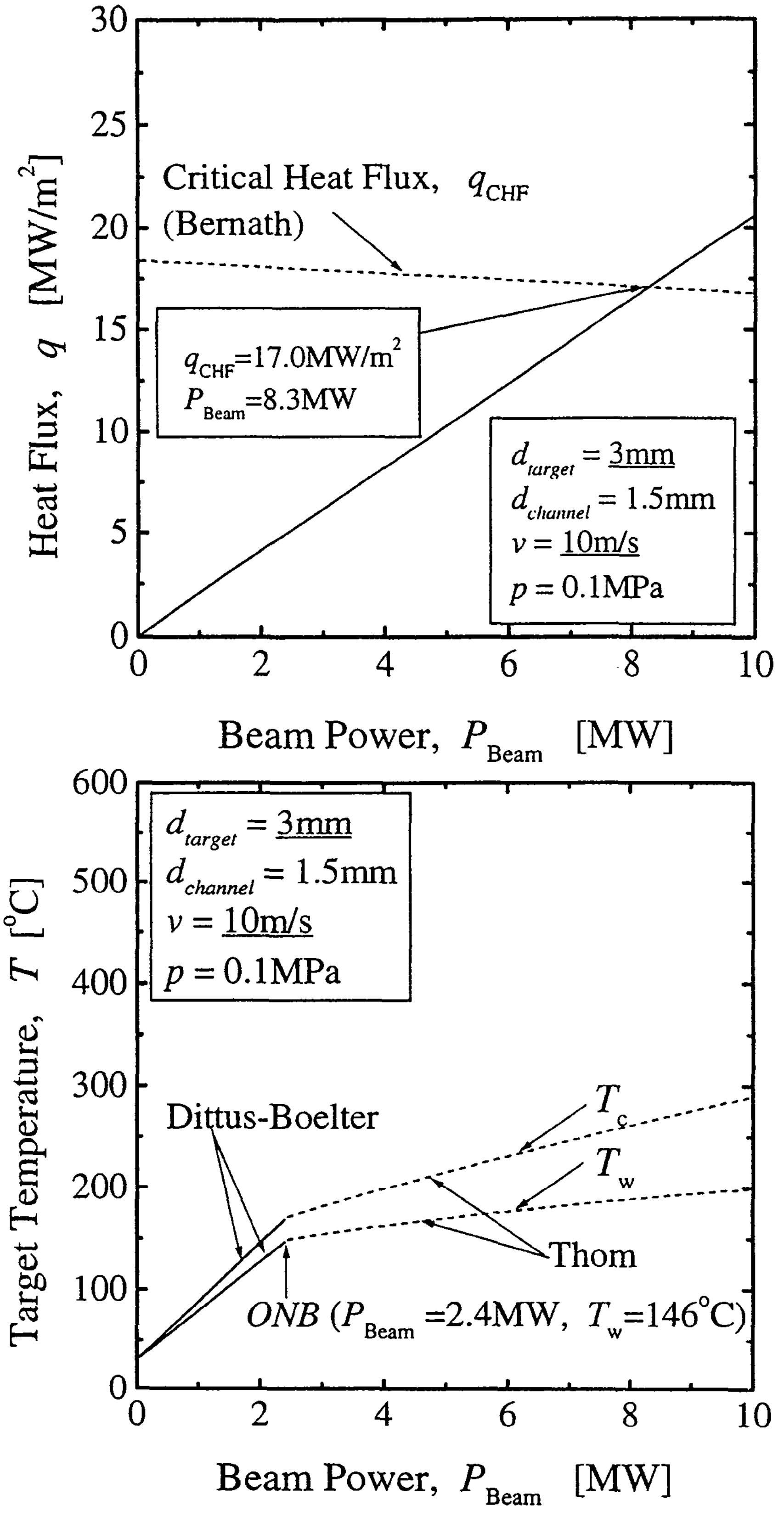

Fig.5 Maximum heat flux, CHF and target temperature vs. beam power for **target thickness 3mm**, gap 1.5mm, coolant velocity 10m/s at 0.1MPa and inlet temperature 30 °C.

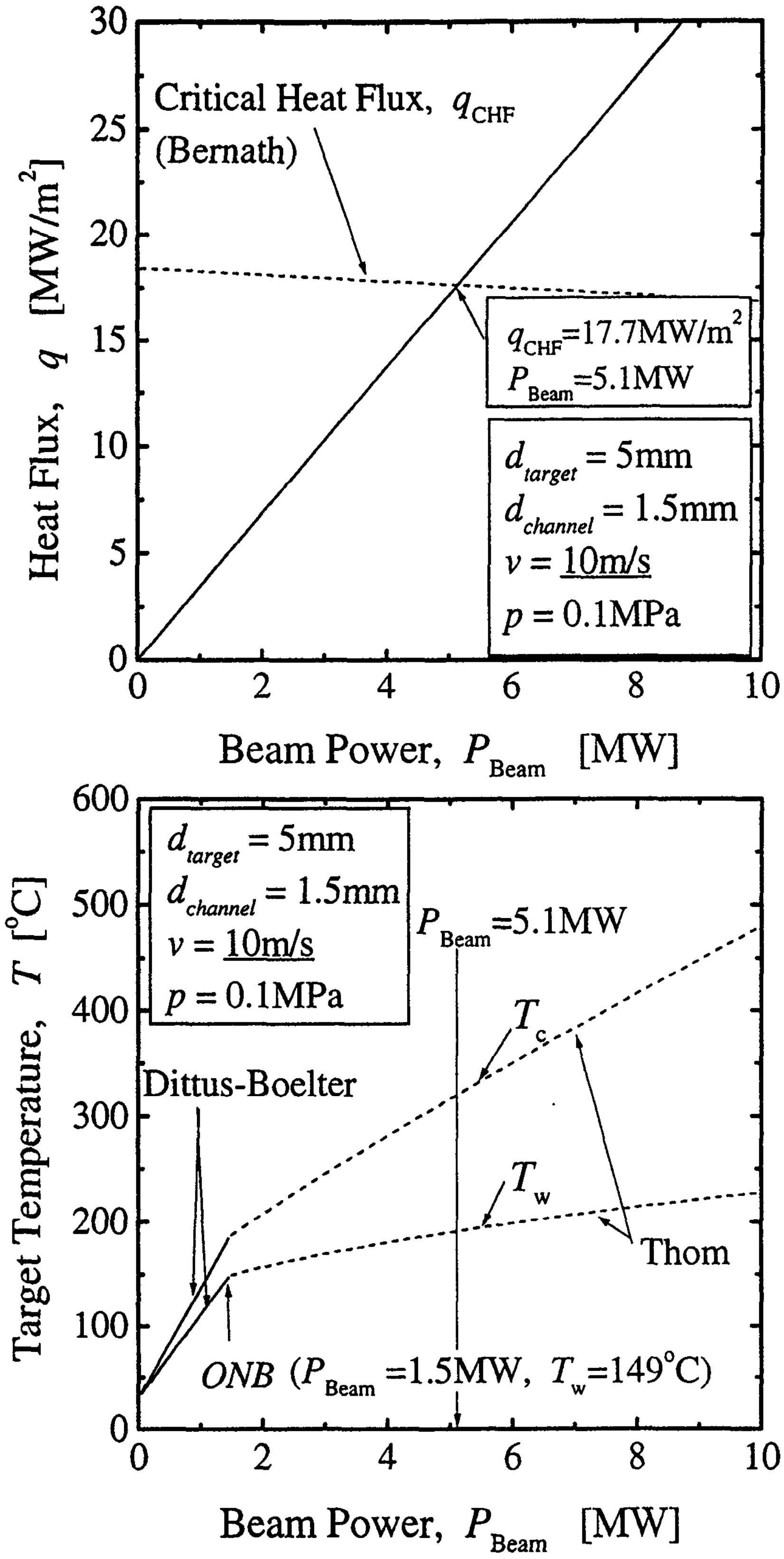

Fig.6 Maximum heat flux, CHF and target temperature vs. beam power for target thickness 5mm, gap 1.5mm, coolant velocity 10m/s at 0.1MPa and inlet temperature 30 °C.

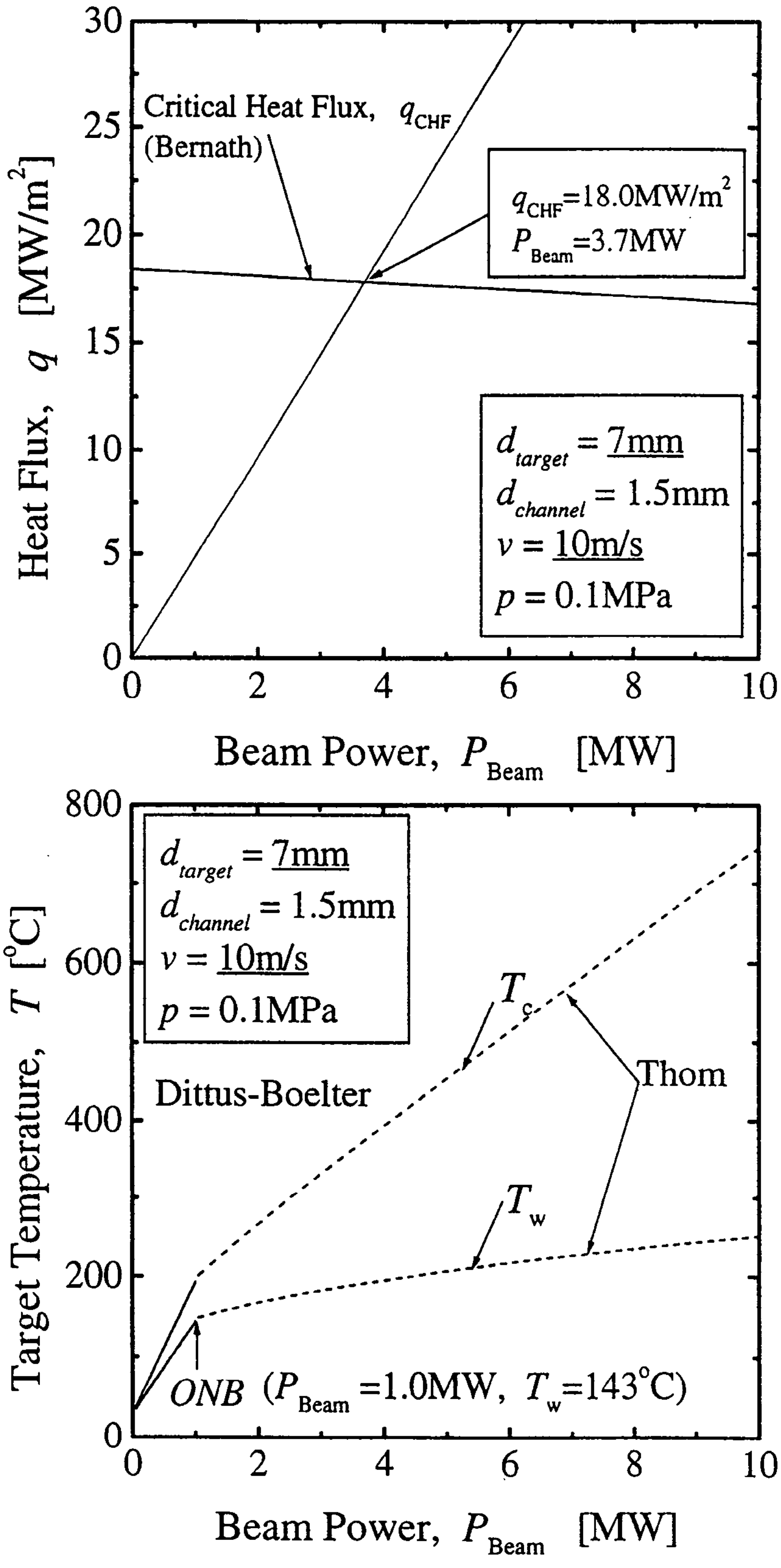

Fig.7 Maximum heat flux, CHF and target temperature vs. beam power for **target thickness 7mm**, gap 1.5mm, coolant velocity 10m/s at 0.1MPa and inlet temperature 30 °C.

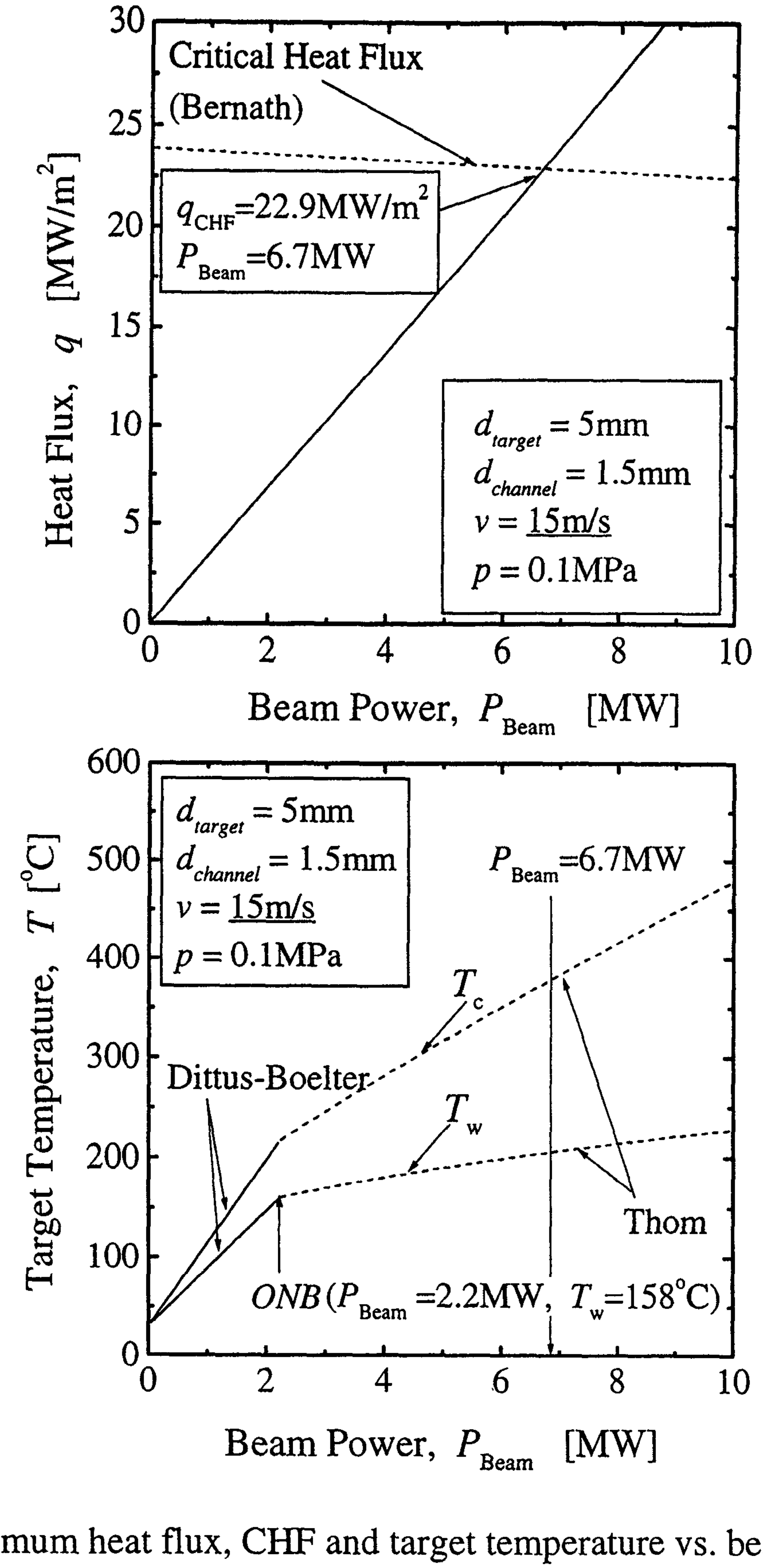

Fig.8 Maximum heat flux, CHF and target temperature vs. beam power for target thickness 5mm, gap 1.5mm, **coolant velocity 15m/s** at 0.1MPa and inlet temperature 30 °C.

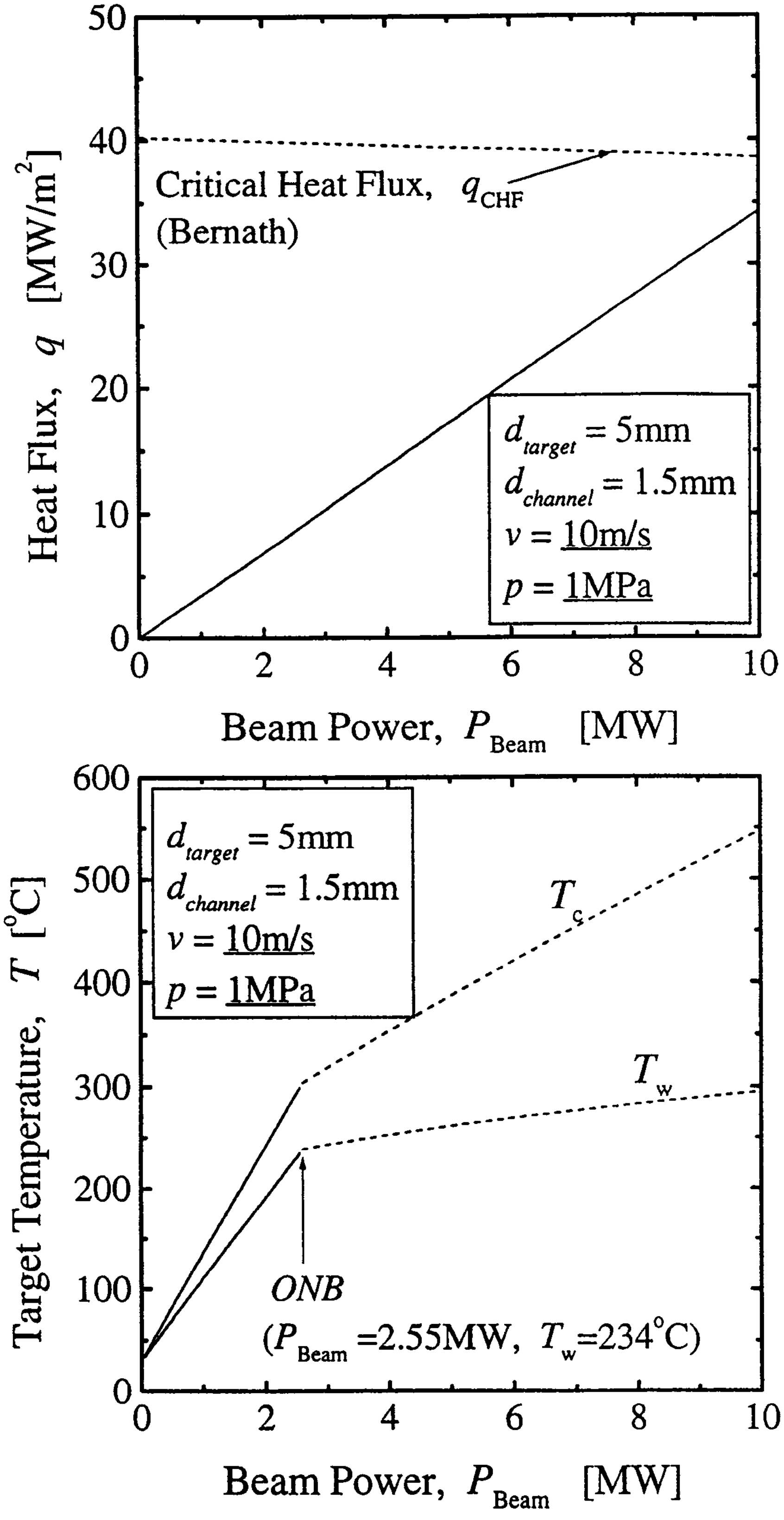

Fig.9 Maximum heat flux, CHF and target temperature vs. beam power for target thickness 5mm, gap 1.5mm, coolant velocity 10m/s at **1 MPa** and inlet temperature 30 °C.

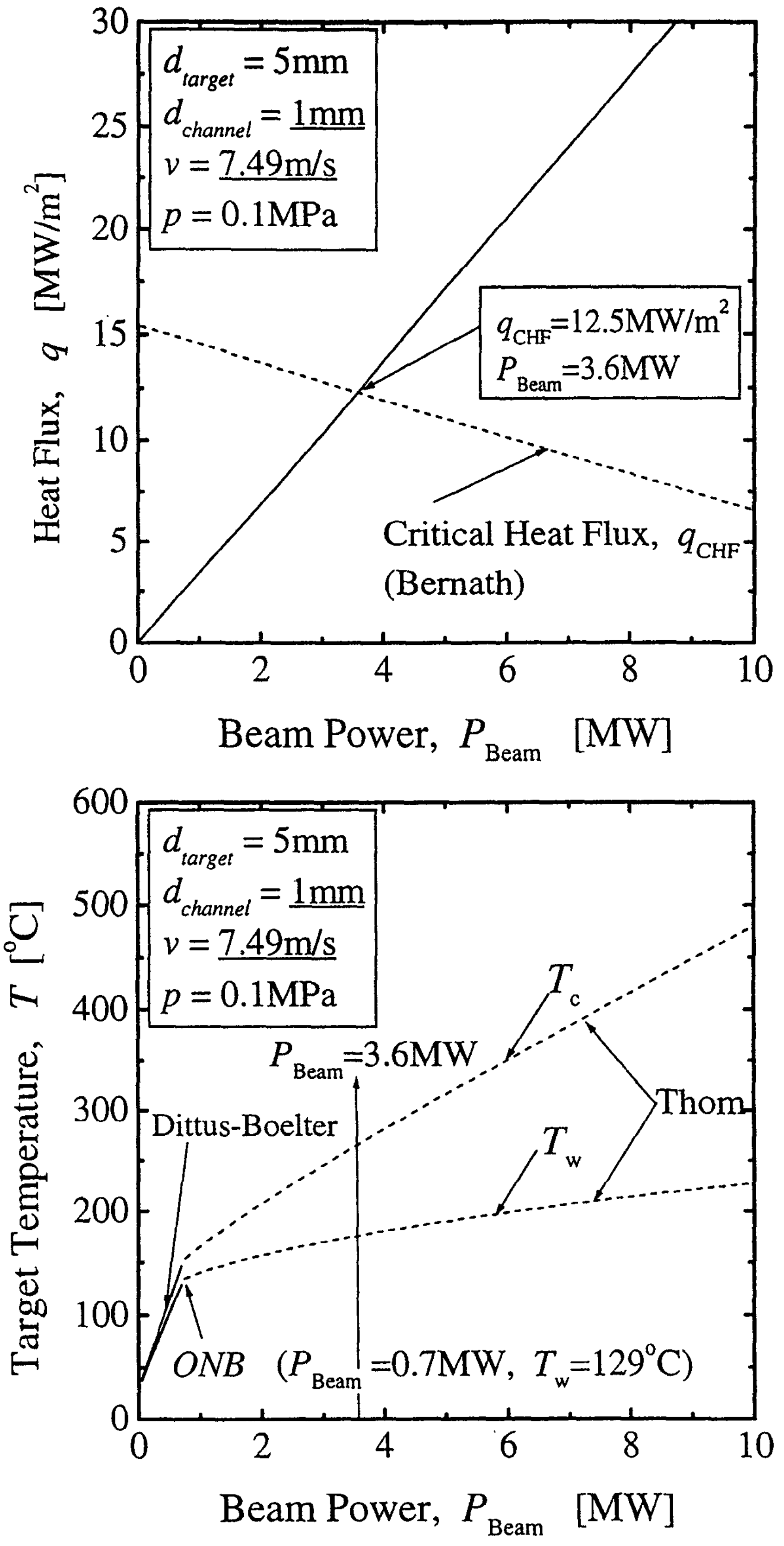

Fig.10 Maximum heat flux, CHF and target temperature vs. beam power for target thickness 5mm, **gap 1mm**, **coolant velocity 7.49m/s** at 0.1Mpa and inlet temperature 30 °C.

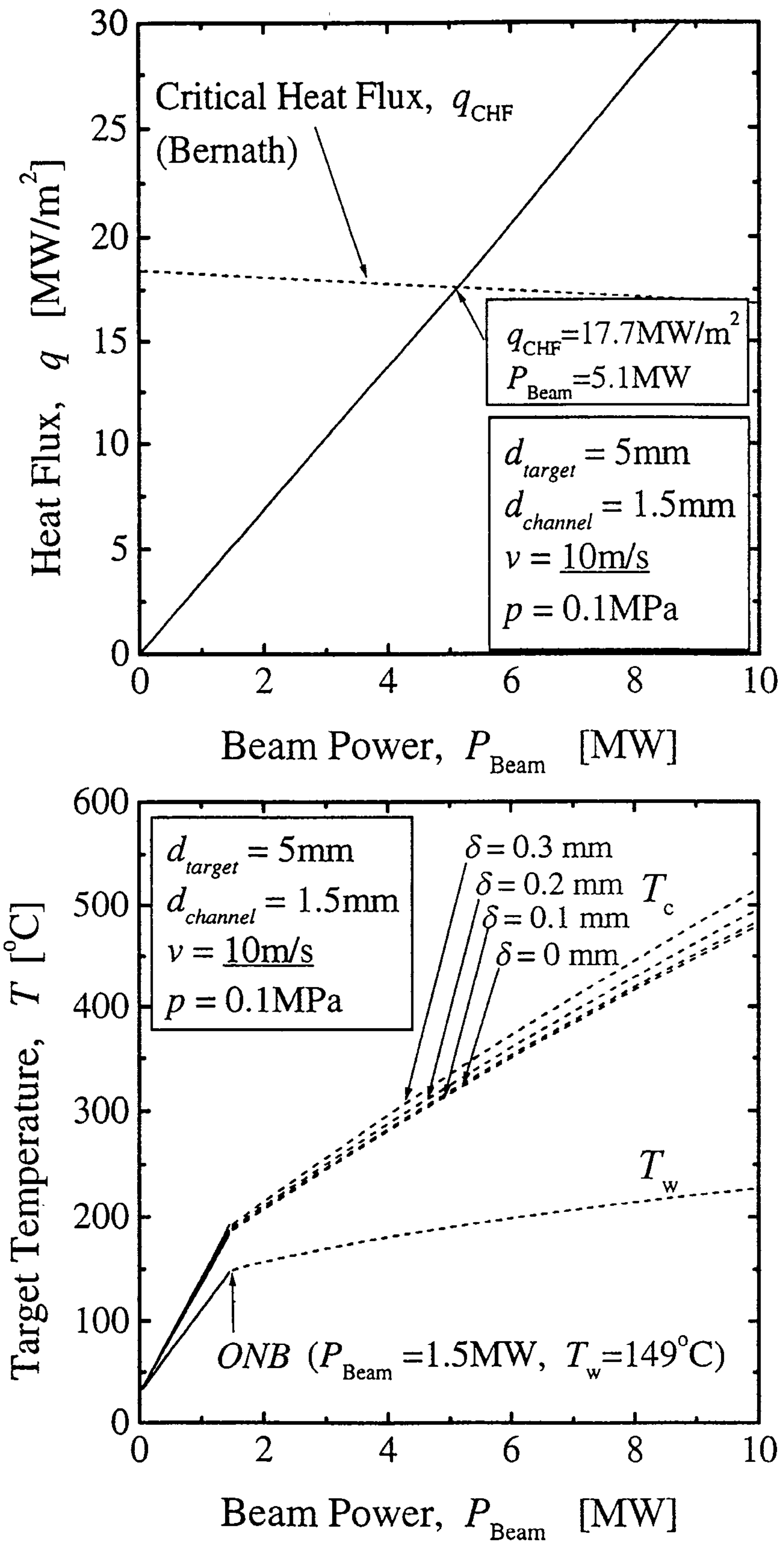

Fig.11 The effect of oxide layer on the target temperature for target thickness 5mm, gap 1.5mm, coolant velocity 10m/s at 0.1MPa and inlet temperature 30 °C.

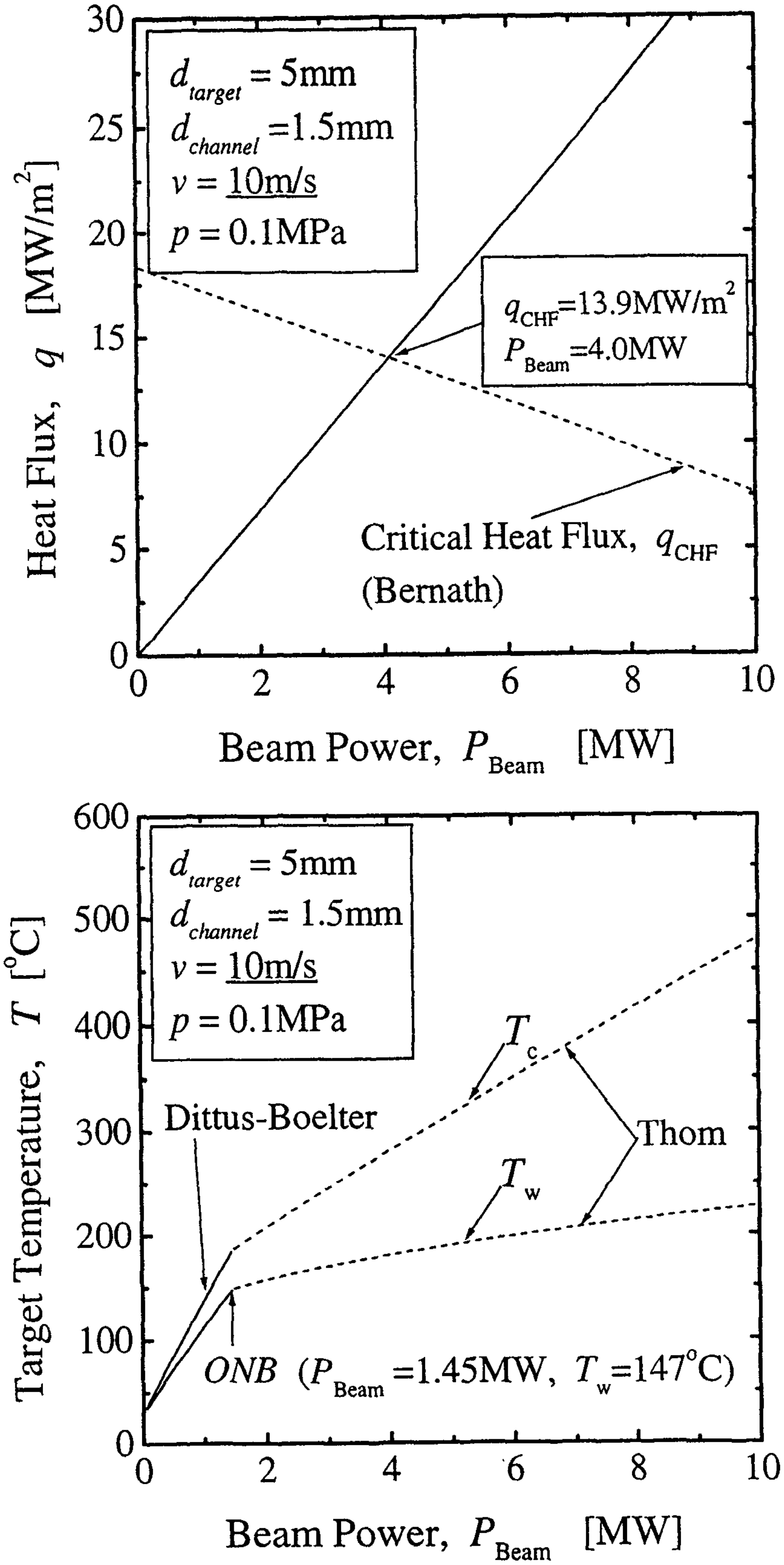

Fig.12 The results obtained assuming peak heat flux occurred at the outlet otherwise the same conditions as Fig.6 for target thickness 5mm, gap 1.5mm, coolant velocity 10m/s at 0.1MPa and inlet temperature 30 °C.