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SHINE THROUGH MEASUREMENTS WITH HYDROGEN BEAM IN JT-60

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Mamoru MATSUOKA, Makoto MIZUNO
Yoshihiro OHARA, Hiroshi OOHARA
and Kazuhiko MOGAKI

日 本 原 子 力 研 究 所
Japan Atomic Energy Research Institute

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Masaaki KURIYAMA, Shunsuke KUNIEDA, Mamoru MATSUOKA
Makoto MIZUNO, Yoshihiro OHARA+, Hiroshi OOHARA
and Kazuhiko MOGAKI

Department of Fusion Facility
Naka Fusion Research Establishment
Japan Atomic Energy Research Institute
Naka-machi, Naka-gun, Ibaraki-ken

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The shine-through rate with hydrogen beams in the JT-60 neutral beam injection experiments was measured in a beam energy range of 40-75 keV and plasma densities of $(1-7)\times10^{19}$ m^{-3} for the estimation of absorbed beam power in the plasma. The shine-through rate was calculated from the temperature rise measurement with thermocouples installed in an armor plate. The shine-through depends on the plasma density inverse-exponentially and the beam energy linearly. Additionally the rate changes with the plasma species and the plasma facing materials which effect impurity contamination of the plasma. An enhancement of beam stopping cross-section by multi-step collisions was also found even in a beam energy range of 40-75keV.

Keywords: Shine Through, NBI, Beam Injected Heating, Beam Energy, Plasma Density

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+ Department of Fusion Engineering Research

ＪＴ－６０における水素ビームでの突抜け率測定

日本原子力研究所那珂研究所核融合装置試験部
栗山　正明・国枝　俊介・松岡　守・水野　誠
小原　祥裕[+]・大原比呂志・藻垣　和彦

（1993年２月22日受理）

ＪＴ－６０ＮＢＩ実験におけるプラズマへのビームの吸収パワーを評価するために，水素ビームでの突抜け率を，ビームエネルギー：40－75keV，プラズマ密度：$(1\text{-}7)\times10^{19}\,\mathrm{m}^{-3}$の範囲で測定した。突抜け率は，ＮＢＩ対向面にセットされた熱電対の温度上昇から計算によって求めた。突抜け率は，プラズマ密度に逆指数関数的に依存し，またビームエネルギーには直線的に依存する。更に突抜け率は，ターゲットプラズマ種，第１壁材料によっても変化する。多重衝突過程によるビーム衝突断面積の増大についても評価し，ビームエネルギーが40－75keV の範囲でも断面積の増大が認められた。

那珂研究所：〒311-01　茨城県那珂郡那珂町大字向山801-1
[+]　核融合工学部

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1. Introduction

The JT-60 device had been operated both a divertor and a limiter discharges with hydrogen in the operation parameters of Bt< 4.8T, R<3m, a<90cm and Ip<3.2MA. TiC-coated Mo was used as first wall materials in the vacuum vessel at initial experiments, and then that was altered to graphite. The JT-60 neutral beam injection system (JT-60NBI), which could inject a hydrogen neutral beam power of 26MW at a beam energy of 75 keV for 10sec, was a key device in JT-60 plasma heating.[1][2] The JT-60 NBI consisted of 14 beamlines and was arranged at seven places around the JT-60 as shown in Fig.1. One beamline unit could deliver a neutral hydrogen beam power of about 1.8 MW in maximum. The beam injection angles to the plasma column are 35.5 degrees for a plasma mid-plane, and are quasi-perpendicular to the toroidal direction; eight units were slightly directed to the co-injection and the other units to counter-injection as shown in Fig.1. The beam species of the JT-60NBI ion source were $H^{+}:H^{2+}:H^{3+}=90:7:3$ for the ion beams before neutralized, and $H^{0}(E):H^{0}(E/2):H^{0}(E/3) =80:13:7$ for the neutral beams at the beam energy of 75keV.[3] The impurities contained in the neutral beam were less than 0.2% for low-Z impurities such as carbon and oxygen, and less than 0.01% for high-Z impurities such as tungsten, and copper.[3]

In the neutral beam heating experiments on the JT-60, the measurement of a beam shine-through in the plasma was very important by the following reasons: One is for obtaining a beam power absorbed in the plasma to estimate a plasma confinement time. The absorption power is obtained by subtracting a shine-through power from a neutral beam power injected into a tokamak. In particular, since the JT-60 NBI injected the beam perpendicularly against the plasma axis, the shine-through could not to be neglected in the estimation of the beam absorption power in a plasma. Another is for a protection of the beam armor plate against a shine-through beam. If the excess beam deposition on the armor plate would be found, the beam injection must be stopped immidiately to prevent the armor from meltdown.

Since the beam shine-through rate depends on various parameters such as a beam energy, an electron density, the equivalent charge number,Z_{eff}, and the electron temperature of plasmas, those values must be measured shot by shot. The shine-through measurement has been so far reported from TFR team.[4] They measured the shine-through at a beam energy of 34keV and a plasma density up to 3×10^{19} m^{-3}, and they discussed an enhancement factor of beam stopping cross-section by multi-step collisions[5]. Tobita et al[6] also has reported that the enhancement of the beam stopping cross-section was

confirmed with a diagnostic beam injection system at a beam energy of 140keV.

This paper describes the measurement method, and the beam shine-through during 1986~1988 with hydrogen beam injection experiments, and then discusses the effcts of the first wall material, the beam energy, the enhancement of the stopping cross-section.

2. Shine-through measurement

The shine-through is estimated from a temperature rise of thermocouples brazed in Mo chips on the beam armor plate. The Mo chips, as shown in Fig.2, are set a few milimeters lower than a first wall surface to prevent touching edge plasmas. Five thermocouple chips are arranged on straight at the interval of about 8cm along the toroidal direction. The shine-through beams by adjacent two beamlines hit a same group of the thermocouple chips as shown in Fig.1. The thermocouples of eight groups are placed corresponding to every beamline.

To estimate accurately an incident power onto the thermocouple chips, the thermal resistivity for every chip has been evaluated by measuring a response time when the chips are irradiated by a beam. The power densities by a shine-through beam at the thermocouple chip positions are calculated from a temperature rise with heat conduction analysis by taking the thermal resistivity into account. Assuming the beam divergence as a gaussian profile and considering a beam axis displacement measured, the beam deposition profile on the armor plate are estimeted from the power densities at five positions. The total shine-through power is evaluated by integrating the profile. The error of the measured values is estimated as about 10% which is caused by the measurement error of the temperature rise, the calculation error of the heat conduction and the inconsistency of the deposition profile with the gaussian.

3. Shine-through results

The NBI heating experiments in the JT-60 have been performrd at the energies of 40 to 75keV, at the plasma electron densities of 0.5 ~ 7 $\times 10^{19}/m^3$. The shine-through rates measured are shown in Fig.3 ~ Fig.5 for the beam energies of 40 to 75keV. The plasma electron density, n_e, on the horizontal axis shows an average value in the beam duration time, since the shine-through is estimated by the temperature rise of the thermocouple chip which can measure the average value only.

The shine-through rate depends largely on the plasma electron density and decreases exponentially with increasing the electron

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The shine-through rate depends largely on the plasma electron density and decreases exponentially with increasing the electron

density. The rate also depends on the beam energy. In the JT-60 hydrogen plasmas of 80-90 cm in a minor radius, the shine-through rate increases more than 40% below a density of 1×10^{19} m^{-3} and, on the other hand, it decreases less than a few % over 5×10^{19} m^{-3} at a beam energy of 40-75keV. The shine-through rate, η, can be expressed as a following equation with a function of the electron density,n_e, at a constant beam energy,

$$\eta=\exp(-c.n_e)$$

where, c is a constant which depends on a beam energy, plasma species and a first wall material. The value c is in the range from 0.7 to 1.3 in the JT-60 experiments.

The shine-through rate with some combinations of plasma species and plasma facing materials are shown as follows at the same plasma density and the same beam energy.

$$\eta(H^+/_{\mathrm{graphite}}) \leq \eta(He^+/_{\mathrm{TiC}}) \leq \eta(H^+/_{\mathrm{TiC}})$$

where, a dominator in the parentheses shows the first wall material and a numerator the plasma species.

4. Discussion

The following items are discussed; the effects of the plasma parameters and the beam energy, the beam penetration in a plasma and the enhancement of beam stopping cross-section by multi-step collisions defined by C.D.Boly[5]. Since the proton ratio of the neutral beam is about 80% in the JT-60NBI, the beam acceleration voltage is considered as a representative value of the beam energy.

4.1 The effects of the target plasma parameters and the beam energy

The TiC coated Mo was used as the JT-60 plasma facing material in the initial NBI heating experiments, , and the Z_{eff} values were in the range between 1.5 and 2.5 at electron densities of (1-5) $\times10^{19}$ m^{-3}.[7] In these experiments, the shine-through could be shown with the equation of $\eta_{th}=\exp(-0.7n_e)$ at a beam energy of 75keV. In the experiments from June, 1988, meanwhile, the graphite was used as the plasma facing material, and the Z_{eff} values were in the range 2 to 4 [7], which were about 1.5 times larger than the case of TiC coated Mo. The shine-through at that time could be expressed as $\eta_{th}=\exp(-0.9n_e)$ with the same beam energy.

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In the hydrogen beam injection into a helium plasma, the shine-through were smaller than a hydrogen plasma with the same plasma facing material and at the same beam energy.

The relation between the shine-through and the beam energy is shown in Fig.6 in the case of the hydrogen plasma and the plasma facing materials of both TiC and graphite. The shine-through increases monotonously with the beam energy in the range of 38-70keV. As the plasma density decreases, the shine-through is very susceptible to the beam energy.

4.2 The NBI heating experimental range on the JT-60 from the view point of the beam penetration

In the NBI heating experiments, a beam penetration factor,F, is defined as follows, as a factor of determining a suitable target plasma.

$F=a/\lambda$

where, a is a plasma minor radius and λ is a penetration depth of the neutral beam.

The measured shine-through rate, η, can be expressed as $\eta=\exp(-2a/\lambda)=\exp(-2F)$. Hence, the F value can be expressed as $F=-\ln(\eta)/2$. The relation of the F value vs the electron density is shown in Fig.7. The F value is distributed in the range from 0.4 to 2.5 in the JT-60NBI experiments, though the suitable F value to heat the plasma core region is F=1.2~2.0. In the beam injection at F<1.2, the beam interlock to protect the armor plate works within 2-3 sec after its injection starts on account of excessive heat load to the NB armor plate. On the other hand, the injected beam heats only the peripheral region of the plasma at F>2.0.

4.3 Rough estimation of enhancement of the beam stopping cross section by multiple collisions

The shine-through rates were calculated by using the Orbit Following Monte Carlo code (the OFMC code) in order to estimate the fractional enhancement factor, δ, by the multiple collisions, defined by Boly[5]. In the calculation, the impurity in the plasma was identified with O^{+8} for the divertor plasma, and with C^{+6} for the limiter one, since the impuriy ratio of O^{+8} : C^{+6} in the JT-60 plasma was roughly evaluated as 3:1 for the divertor and 1:3 for the limiter plasmas, respectively[7]. And an effective cross-section was assumed to be σ_{eff} $Z^{1.4}$. In the plasma parameters of a electron density; (1-5) $\times 10^{19}/m^3$ and the Z_{eff}; 1.5-4.2, the calculated results for the fractional enhancement factor,δ, are 0.2 ± 0.2 at a beam energy of 40 keV, and 0.3 ± 0.2 at 75 keV. Although these enhancement factors are estimated roughly from the measured values of the shine-through rates and Z_{eff},

the effect of the multi-step collisions on the stopping cross section seems to be found slightly.

5. Conclusion

The beam shine-through was measured in the JT-60NBI experiments and the following were clarified for a beam energy of 40-75 keV, a plasma electron density of $(1\text{-}5)\text{x}10^{19}\ \text{m}^{-3}$, and Z_{eff} of 1.5-4.2.

1) The shine-through rate can be expressed as a function of the electron density,n_e, such as the equation of $\eta=\exp(-c.n_e)$, where c=0.7-1.3 at a beam energy of 40-75keV.

2) The shine-through decreases almost monotonously with decreasing beam energy.

3) The magnitude of the shine-through rates concerning plasma species, and plasma facing materials at the same beam energy are shown as follows.

$$\eta(H^+/\text{graphite}) \leq \eta(He^{++}/\text{TiC}) \leq \eta(H^+/\text{TiC})$$

4) The F value, which shows a beam penetration length in a plasma, was in the range of 0.4-2.5 in the JT-60 NBI experiments.

5) The fractional enhancement factors by the multiple collisions are in the range (0.2-0.3) ±0.2 with a beam energy of 40-75keV.

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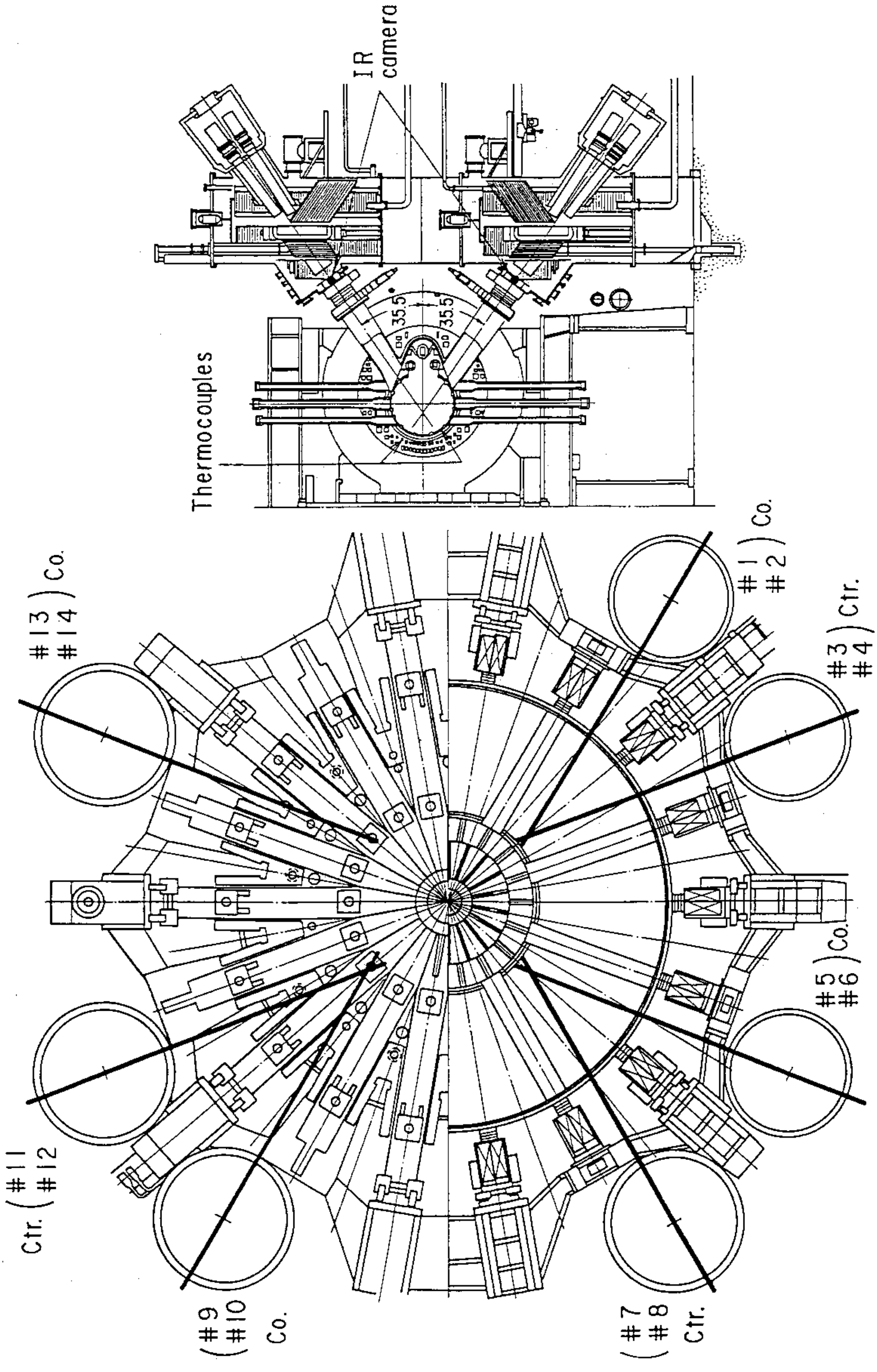

Fig. 1 Beam injection angle in the JT-60 NBI

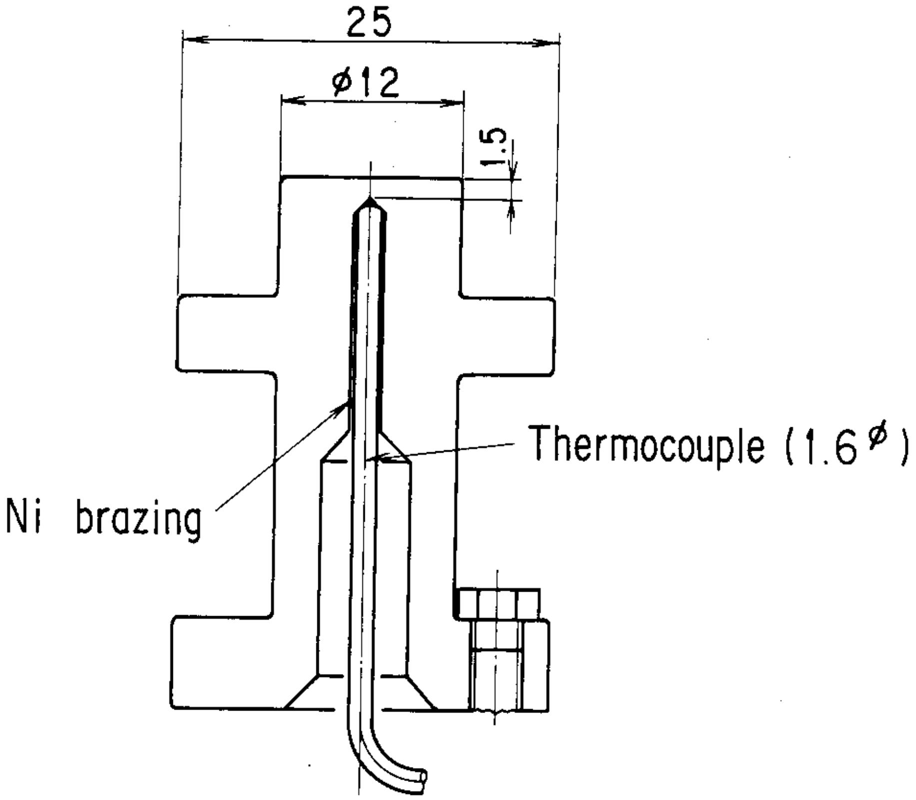

Fig. 2 Mo chip for temperature measurement

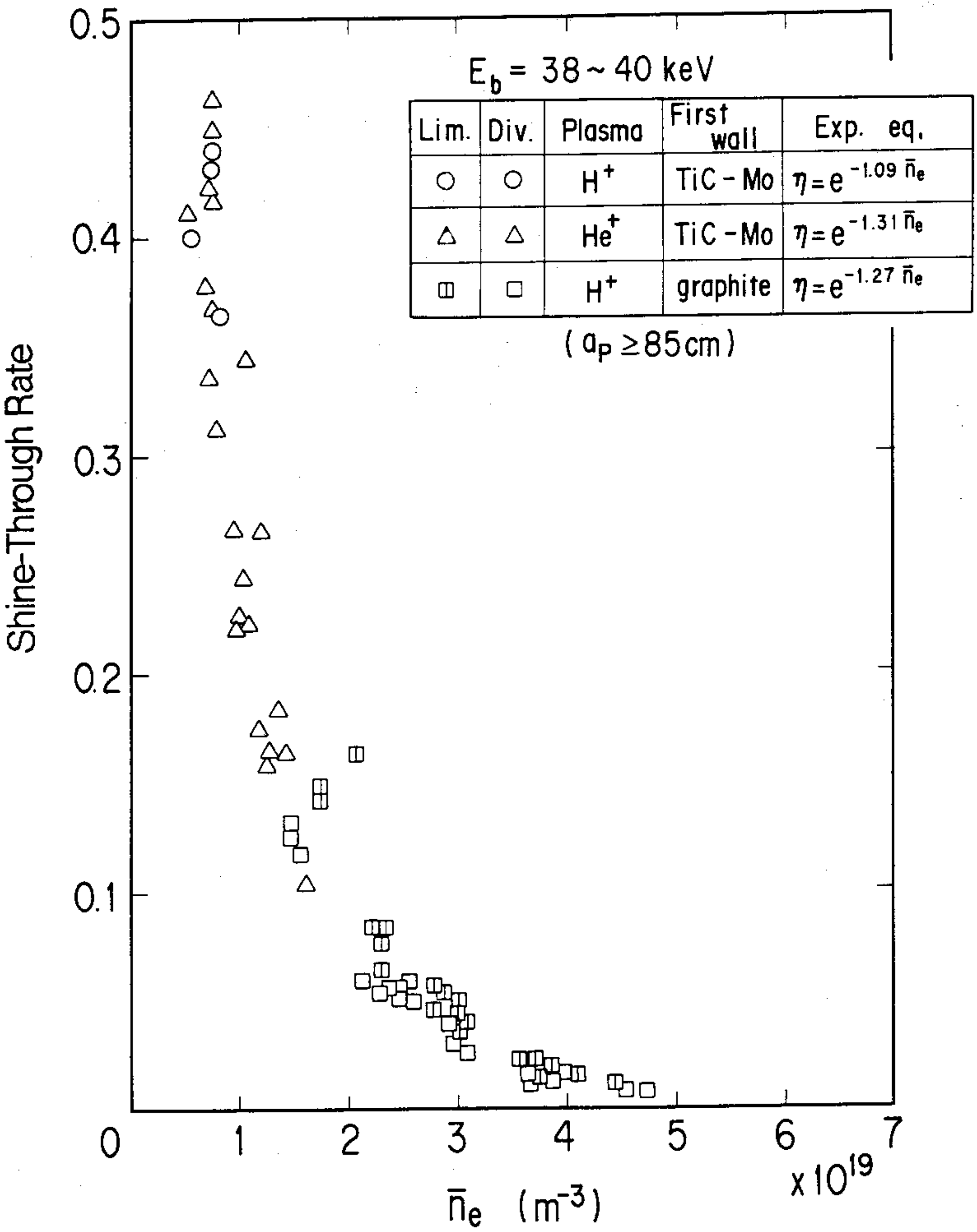

Fig. 3 Shine through in the JT-60 NBI experiment
(Beam energy: 30-40keV)

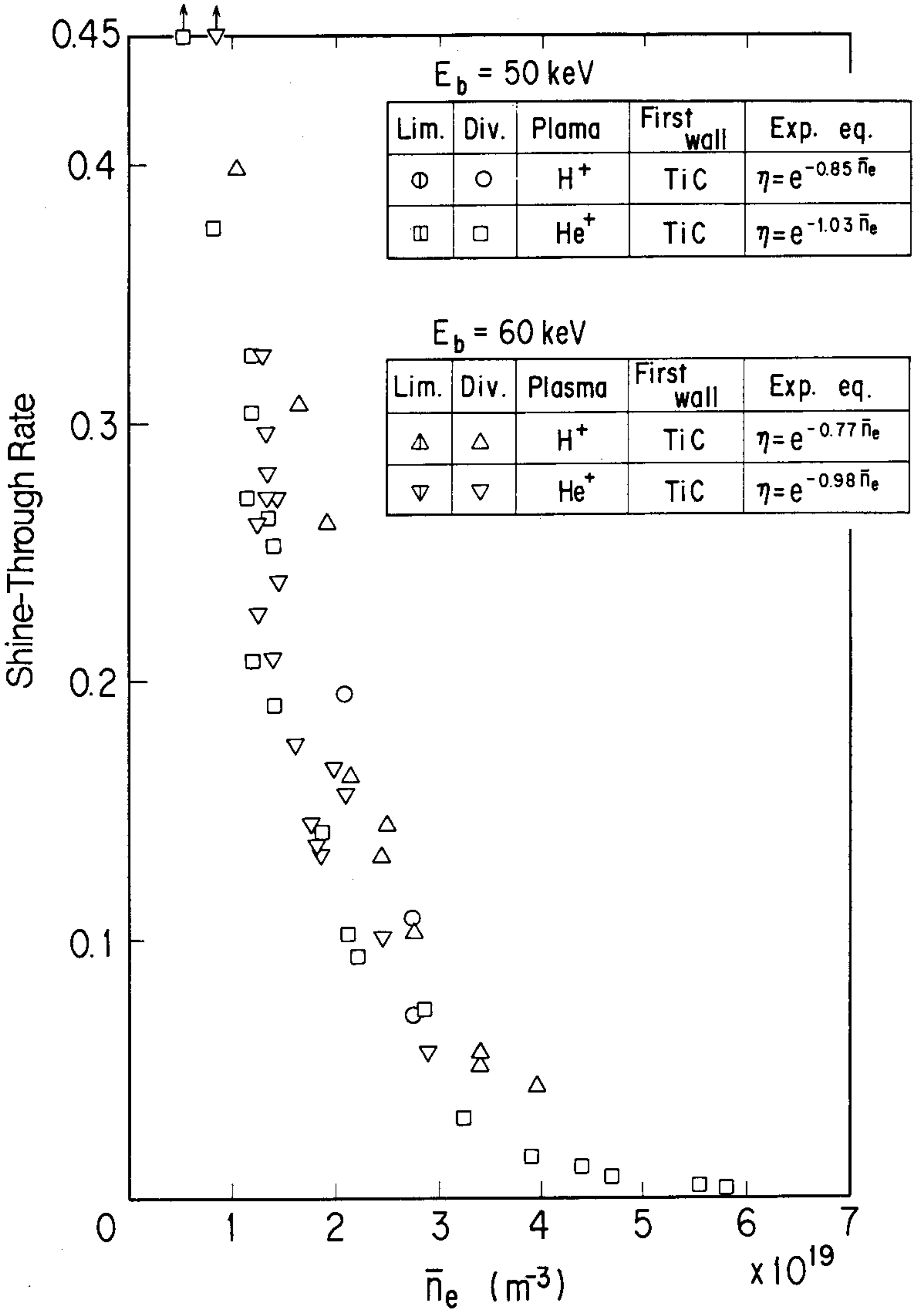

Fig. 4　Shine through in the JT-60 NBI experiment
(Beam energy: 50-60keV)

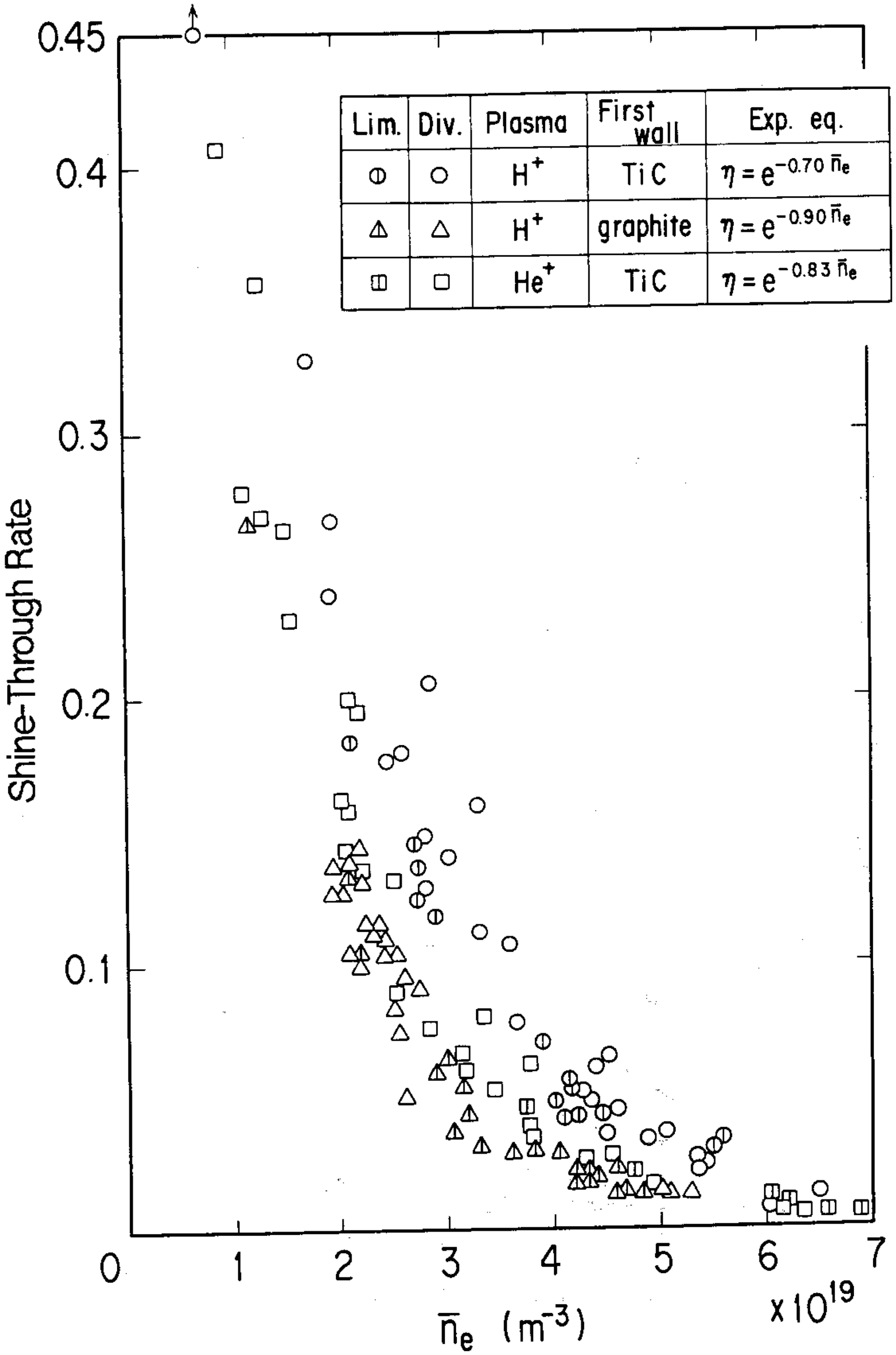

Fig. 5 Shine through in the JT-60 NBI experiment
(Beam energy: 70-75keV)

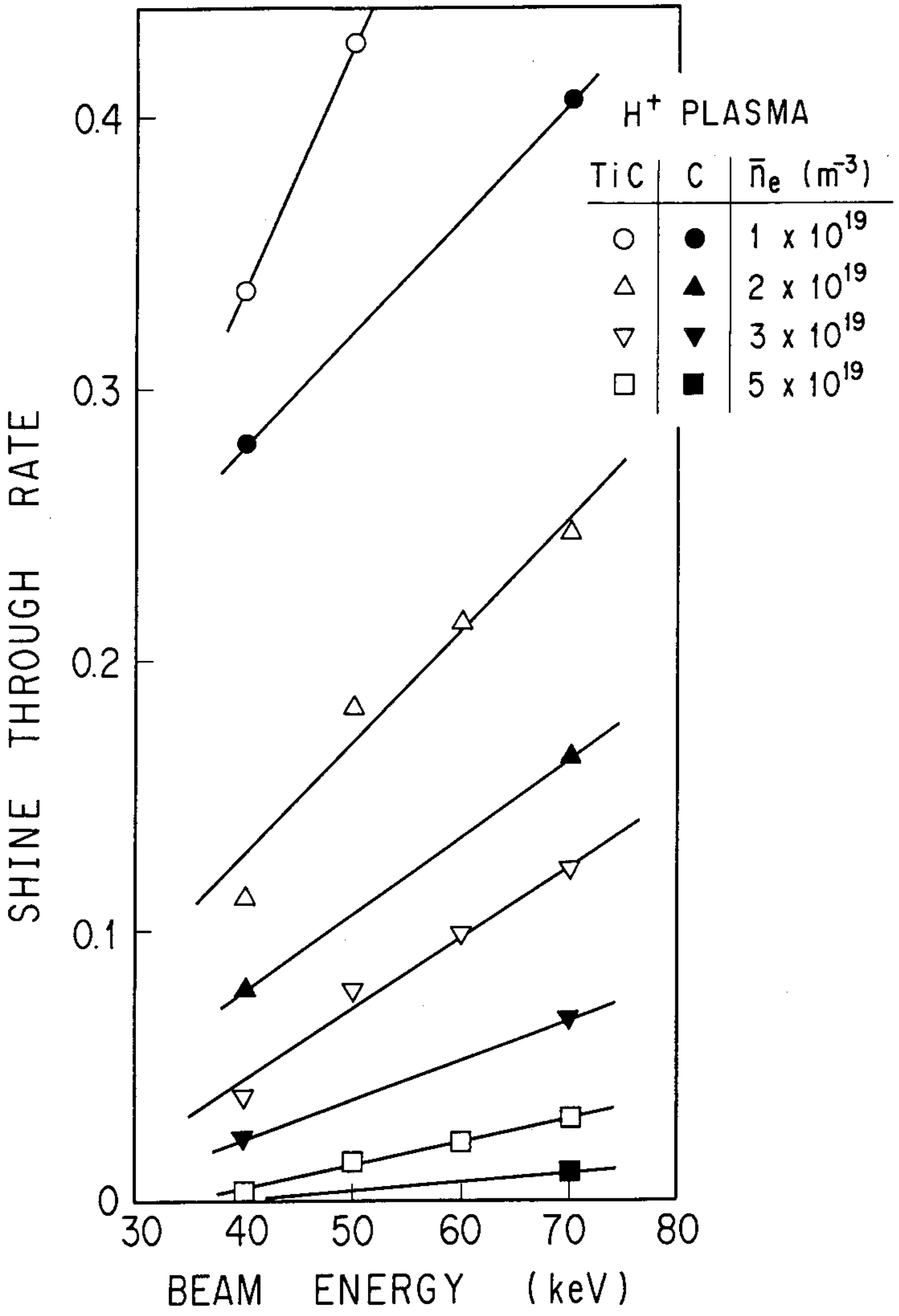

Fig. 6 Effect of the beam energy

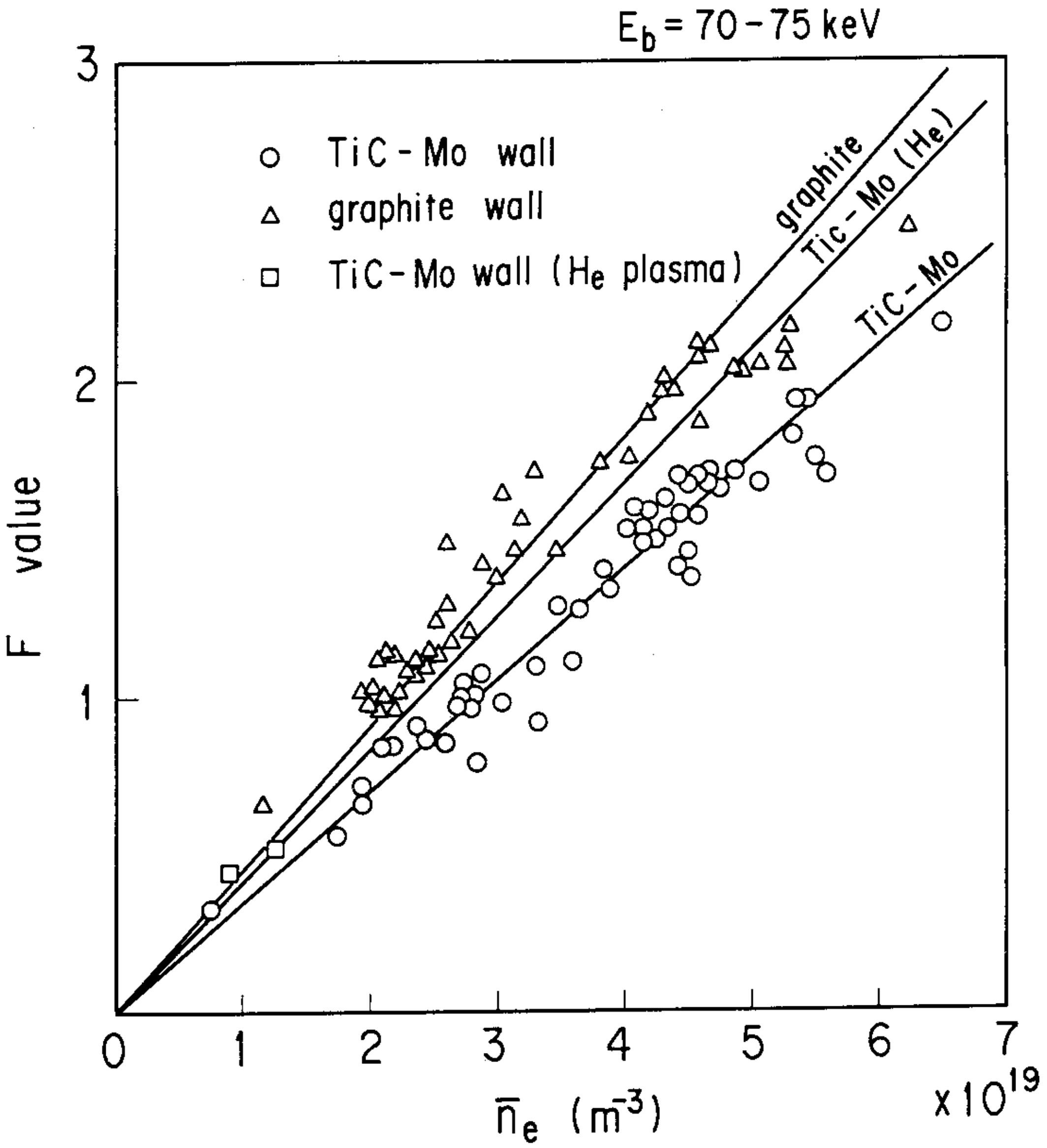

Fig. 7 The NBI experimental range in the JT-60 from the view point of beam penetration