ASSESSMENT OF PELLET INJECTION FOR NET
PART IV:
An Estimate of the Effect of Energy Carriers other than Thermal Electrons on the Ablation of Pellets in Plasmas. An Extension of the Electron Temperature Range Previously Considered

L. L. Lengyel

IPP 5/7 December 1985

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Die nachstehende Arbeit wurde im Rahmen des Vertrages zwischen dem Max-Planck-Institut für Plasmaphysik und der Europäischen Atomgemeinschaft über die Zusammenarbeit auf dem Gebiete der Plasmaphysik durchgeführt.

Abstract

The effect of runaway electrons, NB ions and alpha particles is estimated by calculating the reduced ablation rates due to these particles in fusion plasmas and using the ablation rate induced by thermal electrons as reference quantity. Calculations were made for various energy content (i.e. beta) ratios and for a fusion-relevant electron temperature range (T_e up to 25 keV).

In a previous study [1], the effect of non-thermal particles that may be present in fusion plasmas on the ablation rate of pellets was estimated for the electron temperature range from 200 eV to 2 keV. It was found that the relative importance of all non-thermal species considered (NB ions, alpha particles, runaway electrons) rapidly decreases with increasing plasma electron temperature. Since runaways may affect pellet ablation quite substantially also at high temperatures, it became of interest to extend the calculations described in [1] to a fusion-relevant temperature range (for T_e up to 25 keV).

As in Ref. [1], the simplified ablation model of Vaslow [2] was applied. According to this model, the ratio of the ablation rates caused by species k and thermal electrons e can be expressed in terms of the energy fluxes Q carried by these particles to the pellet surface and their stopping lengths λ in the solid pellet:

$$\frac{\dot{N}_k}{\dot{N}_e} = \left(\frac{Q_k}{Q_e}\right)^{1/3} \left(\frac{\lambda_k}{\lambda_e}\right)^{2/3} .$$

The expressions used in calculating Q and λ are given in Ref. [1].

The ablation rate ratios $\dot{N}_k/\dot{N}_e$ are given in Figs. 1 to 9 as functions of the (thermal) electron temperature for the temperature range $2\,\mathrm{keV} \leq T_e \leq 25\,\mathrm{keV}$, for different non-thermal particle energies E_k, and for different beta ratios $\beta^* \equiv \beta_k/\beta_e$. The following particle energies and beta ratios were considered:

NB ions	(Figs. 1-4): 80, 120, 160, 175 keV,	$0.2 \leq \beta^* \leq 1.0$;
Alpha particles	(Figs. 5-7): 1.0, 2.0, 3.5 MeV,	$0.2 \leq \beta^* \leq 0.5$;
Runaway electrons	(Figs. 8-9): 0.5 and 1.0 MeV,	$10^{-4} \leq \beta^* \leq 10^{-2}$.

For the sake of completeness, the results of Ref. [1] covering the electron temperature range $0.2\,\mathrm{keV} \leq T_e \leq 2.0\,\mathrm{keV}$ are reproduced in this report as well (see Figs. 10 to 18: Figs. 10 to 13 for NB ions, Figs. 14 to 16 for alpha particles, and Figs. 17 and 18 for runaway electrons).

As can be seen, the relative importance of the non-thermal particles increases with increasing particle energy and beta ratio, monotonically decreases with increasing bulk electron temperatures, and becomes negligible under thermonuclear plasma conditions. However, it should be noted that at intermediate electron temperatures the synergetic effect of the two particle species (k, e) may become important, an effect that is not taken into account in this estimate. Furthermore, the validity of the present approximation is limited to particle energy ranges in which the condition of surface ablation is fulfilled: the penetration depths of the energetic particles must be small compared with the characteristic pellet dimension.

The results of these ablation rate ratio estimates can be summarized as follows:

(a) **NB ions**: For $E_{bi} \geq 80\,\mathrm{keV}$ one has $\dot{N}_{bi}/\dot{N}_e > 1$ in the temperature region $T_e \lesssim 1.3\,\mathrm{keV}$ for all beta ratios considered. For $E_{bi} = 175\,\mathrm{keV}$ and $\beta_{bi}/\beta_e \approx 0.6$ one obtains $\dot{N}_{bi}/\dot{N}_e \approx 1$ at $T_e \approx 2.5\,\mathrm{keV}$ and ≈ 0.1 at $T_e \approx 12.5\,\mathrm{keV}$.

(b) **Alpha particles**: For $E_\alpha = 3.5\,\mathrm{MeV}, \dot{N}_\alpha/\dot{N}_e$ was found to be unity for $\beta_\alpha/\beta_e = 0.2$ and 0.5 at $T_e = 3.7\,\mathrm{keV}$ and $4.4\,\mathrm{keV}$, respectively. With $E_\alpha = 1.0\,\mathrm{MeV}$, the ablation ratio becomes less than unity for $T_e \gtrsim 1\,\mathrm{keV}$ for all beta ratios considered.

(c) **Runaway electrons**: The results show that for $E_{ee} \geq 0.5\,\mathrm{MeV}$ and $\beta^*_{ee}/\beta_e \geq 10^{-3}$ one has $\dot{N}_{ee}/\dot{N}_e \geq 500$ in the electron temperature range $T_e \lesssim 500\,\mathrm{eV}$ (alternatively, if $\beta_{ee}/\beta_e \geq 10^{-2}$, or $E_{ee} \gtrsim 1\,\mathrm{MeV}$ one has $\dot{N}_{ee}/\dot{N}_e \gtrsim 10^3$). At $T_e = 25\,\mathrm{keV}$ and with $\beta_{ee}/\beta_e = 10^{-3}$ one still has $\dot{N}_{ee}/\dot{N}_e \approx 2.5$.

However, since the stopping range of 1 MeV electrons in condensed hydrogen is $\approx 25\,\mathrm{mm}$ (and $\approx 1.6\,\mathrm{mm}$ at $E_{ee} \approx 200\,\mathrm{keV}$), the validity of the results is limited to low runaway energies and large pellet sizes. At high energies and small pellet sizes one rather has volumetric heat deposition, which could leat to pellet disintegration as well as partial shine-through, neither of which phenomenon was taken into account in the model. Nevertheless, the results indicate that runaway electrons may have a significant effect on pellet ablation.

References

[1] L.L. Lengyel, Assessment of Pellet Injection for NET, Part IV: An estimate of the effect of energy carriers other than thermal electrons on the ablation of pellets in plasmas. IPP Report 1/233, Sept.1984.

[2] D.F. Vaslow, IEEE Trans.Plasma Sci., PS-5 (1977) 12.

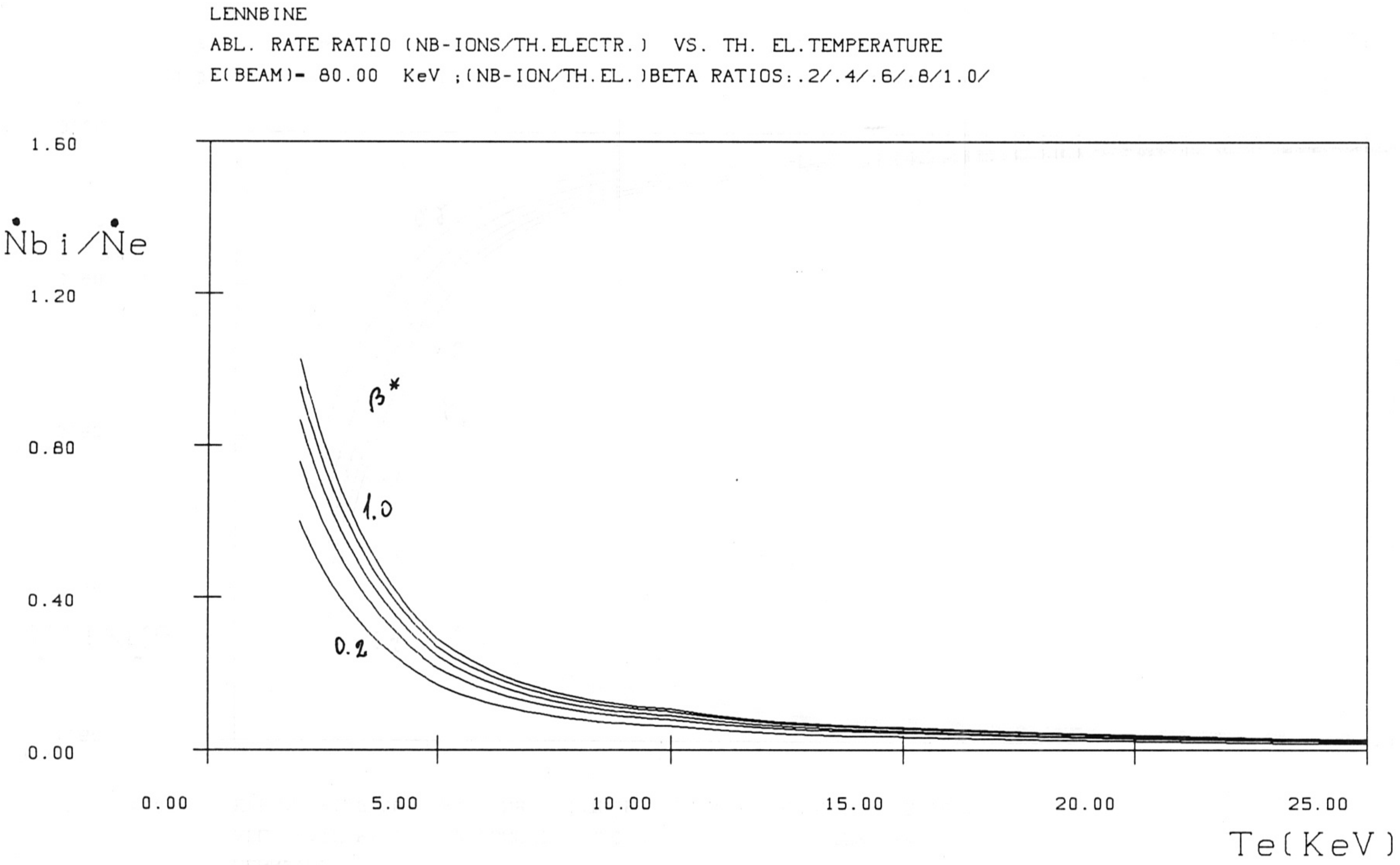
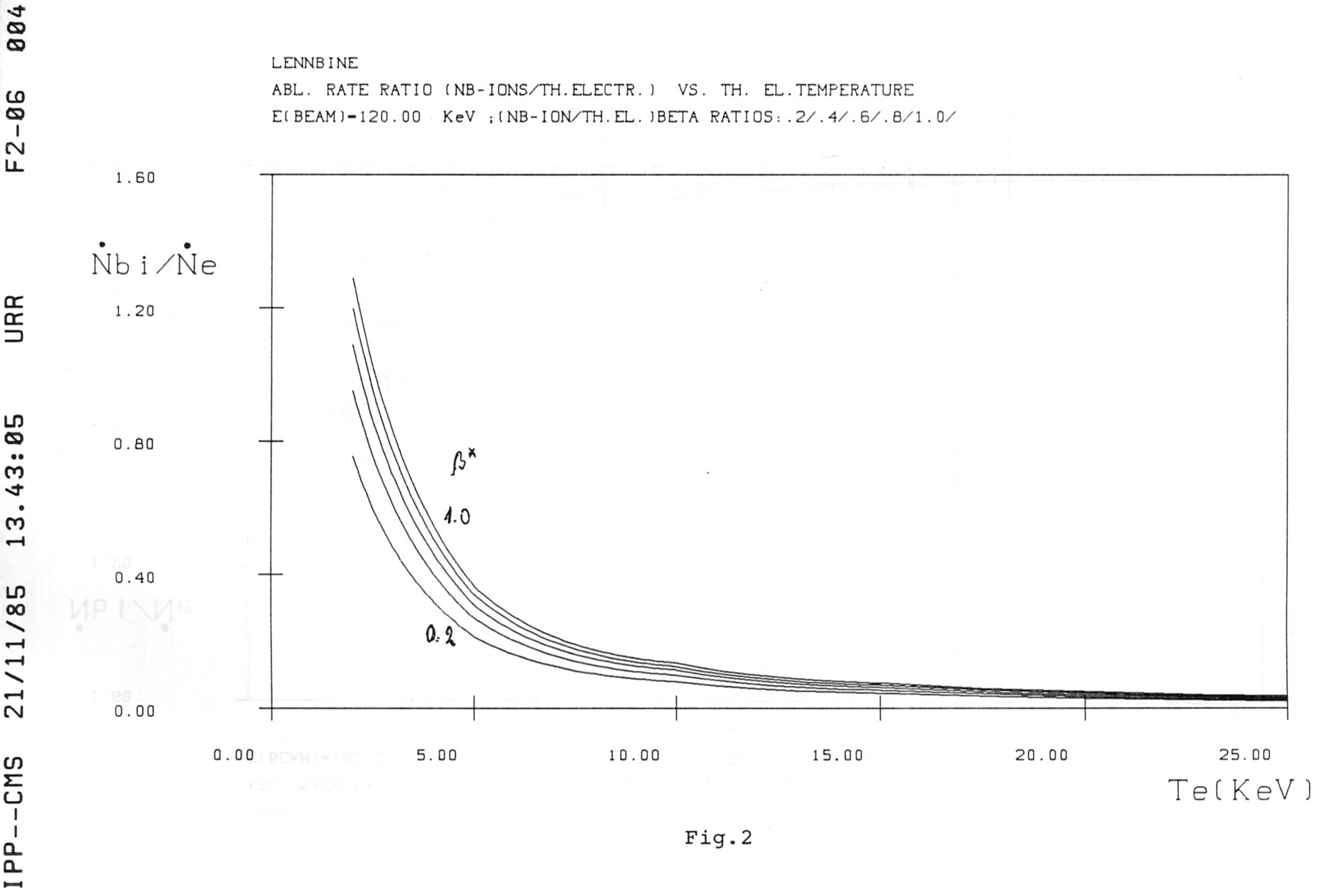


Fig.1

IPP--CMS 21/11/85 13.43:03 URR F2-06 002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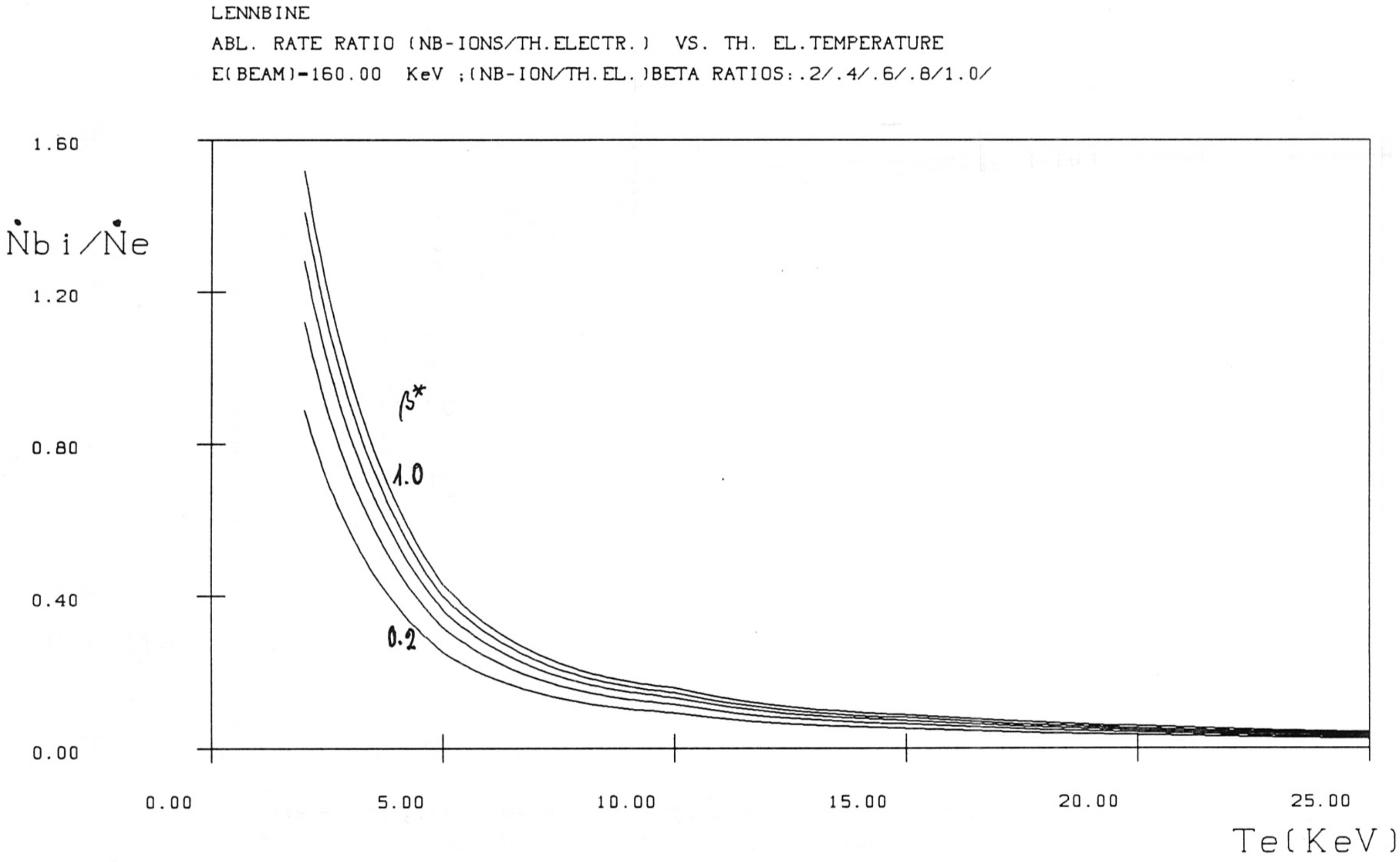
E(BEAM)-120.00 KeV ;(NB-ION/TH.EL.)BETA RATIOS:.2/.4/.6/.8/1.0/
$\dot{N}bi/\dot{N}e$
1.60
1.20
0.80
0.40
0.00
0.00
5.00
10.00
15.00
20.00
25.00
Te(KeV)
β^*
1.0
0.2

Fig.2



LENNBINE
ABL. RATE RATIO (NB-IONS/TH.ELECTR.) VS. TH. EL.TEMPERATURE
E(BEAM)-160.00 KeV ;(NB-ION/TH.EL.)BETA RATIOS:.2/.4/.6/.8/1.0/

Fig.3

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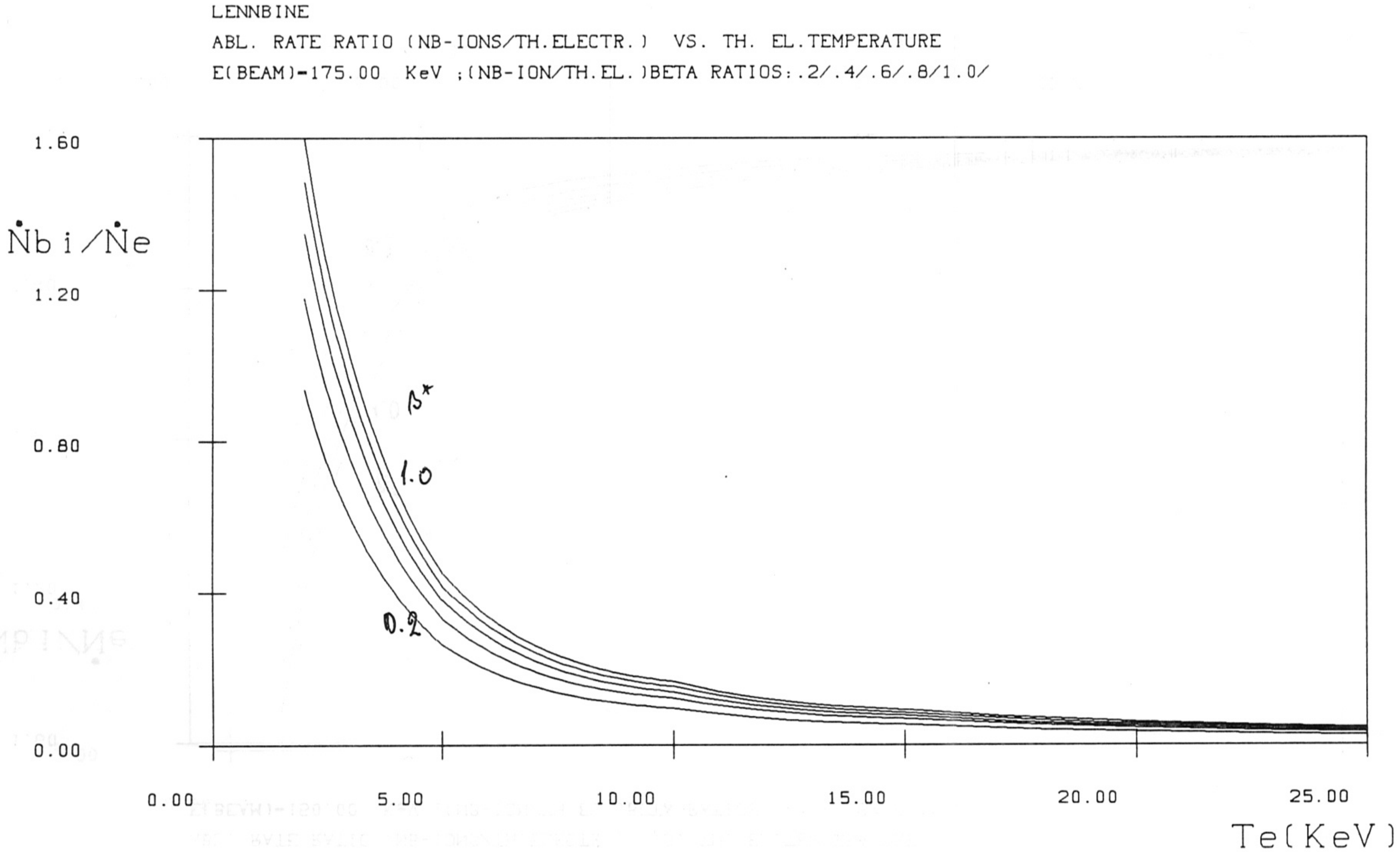

Fig.4

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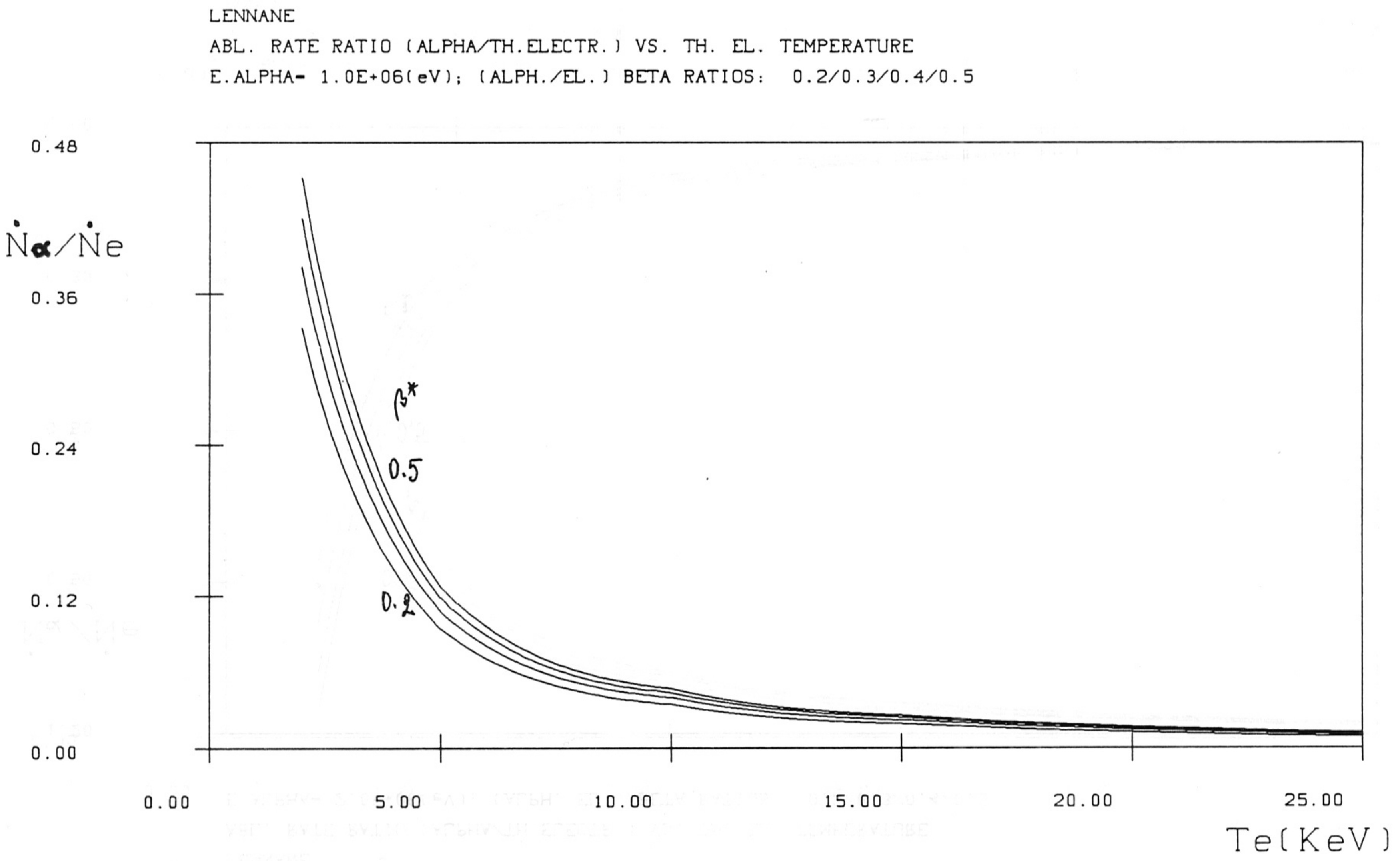

Fig.5

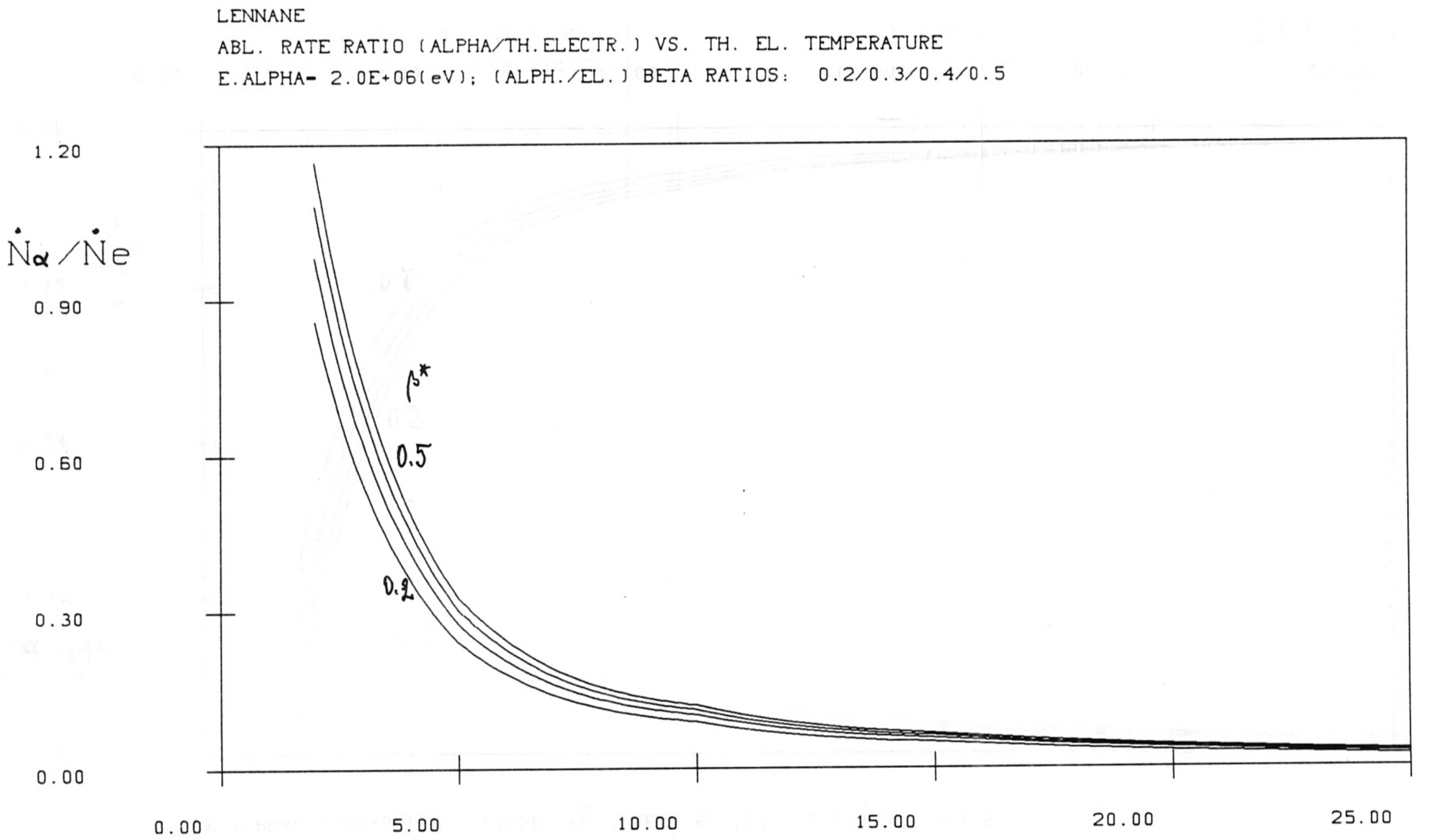
LENNANE
ABL. RATE RATIO (ALPHA/TH.ELECTR.) VS. TH. EL. TEMPERATURE
E.ALPHA- 2.0E+06(eV); (ALPH./EL.) BETA RATIOS: 0.2/0.3/0.4/0.5
$\dot{N}_\alpha / \dot{N}_e$
1.20
0.90
0.60
0.30
0.00
0.00
5.00
10.00
15.00
20.00
25.00
Te(KeV)
β*
0.5
0.2

Fig.6

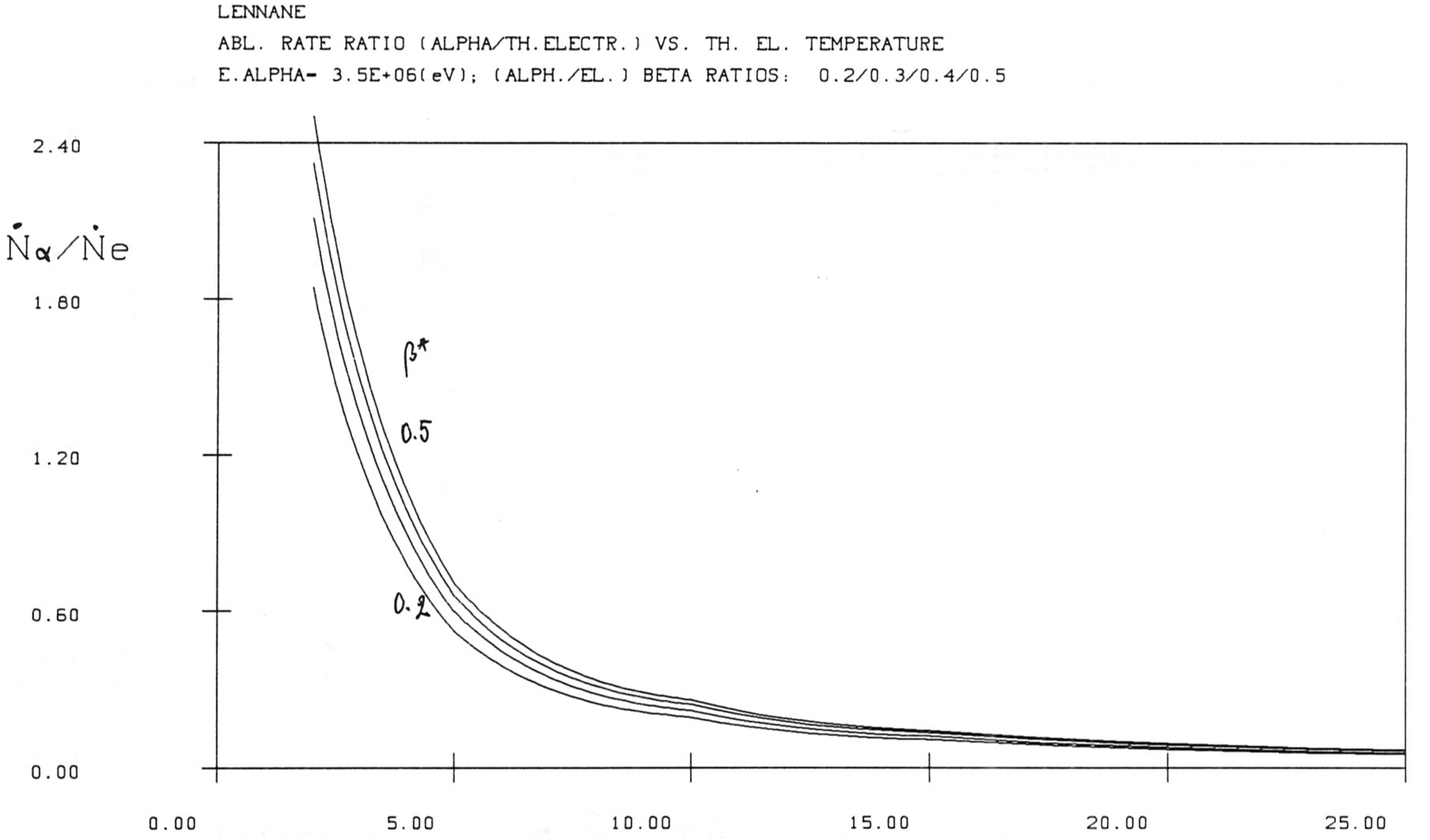
LENNANE
ABL. RATE RATIO (ALPHA/TH.ELECTR.) VS. TH. EL. TEMPERATURE
E.ALPHA- 3.5E+06(eV); (ALPH./EL.) BETA RATIOS: 0.2/0.3/0.4/0.5
$\dot{N}_\alpha/\dot{N}e$
2.40
1.80
1.20
0.60
0.00
β*
0.5
0.2
0.00
5.00
10.00
15.00
20.00
25.00
Te(KeV)

Fig.7

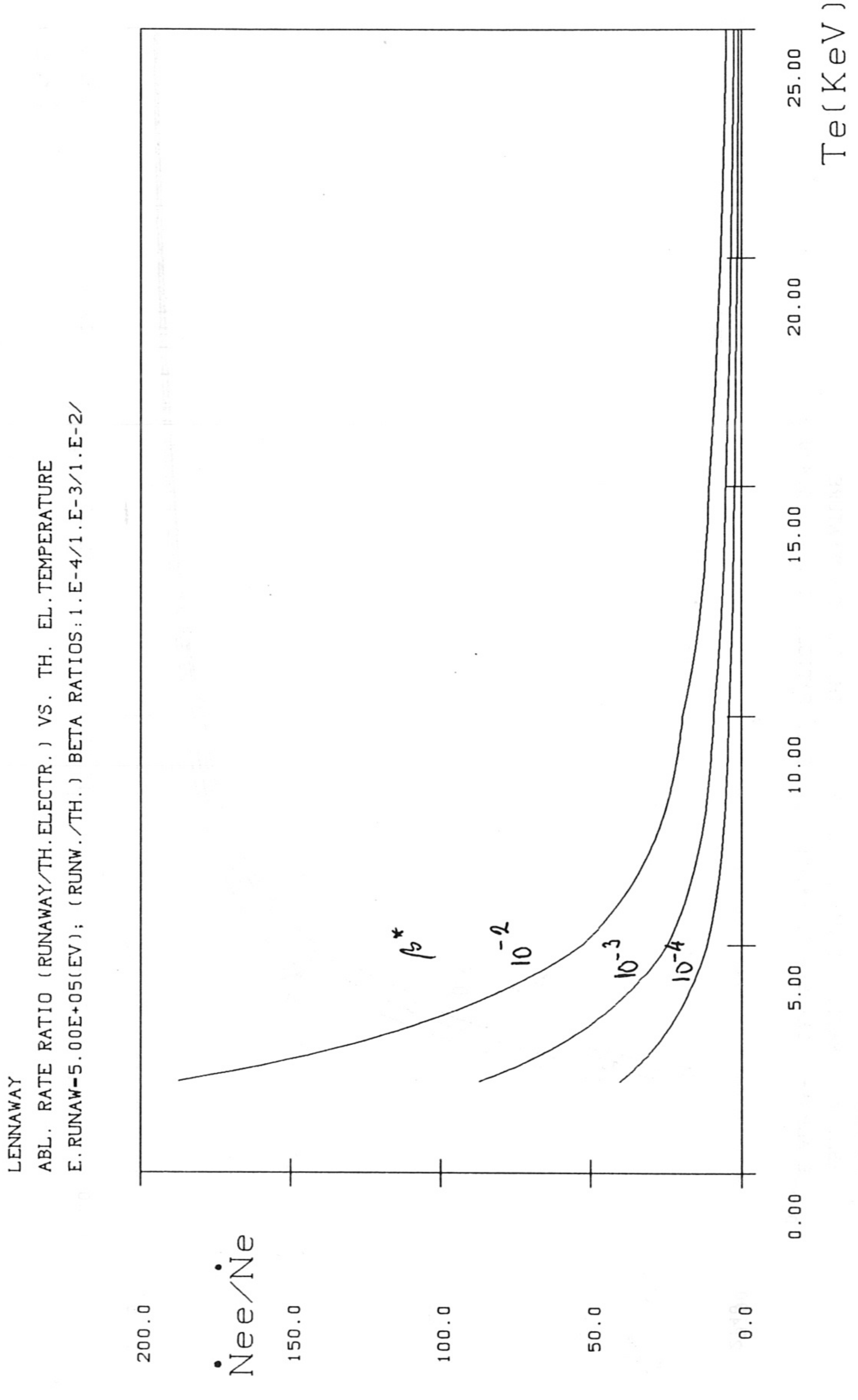
LENNAWAY
ABL. RATE RATIO (RUNAWAY/TH.ELECTR.) VS. TH. EL.TEMPERATURE
E.RUNAW=5.00E+05(EV); (RUNW./TH.) BETA RATIOS:1.E-4/1.E-3/1.E-2/
$\dot{N}ee/\dot{N}e$
200.0
150.0
100.0
50.0
0.0
0.00
5.00
10.00
15.00
20.00
25.00
Te(KeV)
β^*
10^{-2}
10^{-3}
10^{-4}

Fig.8

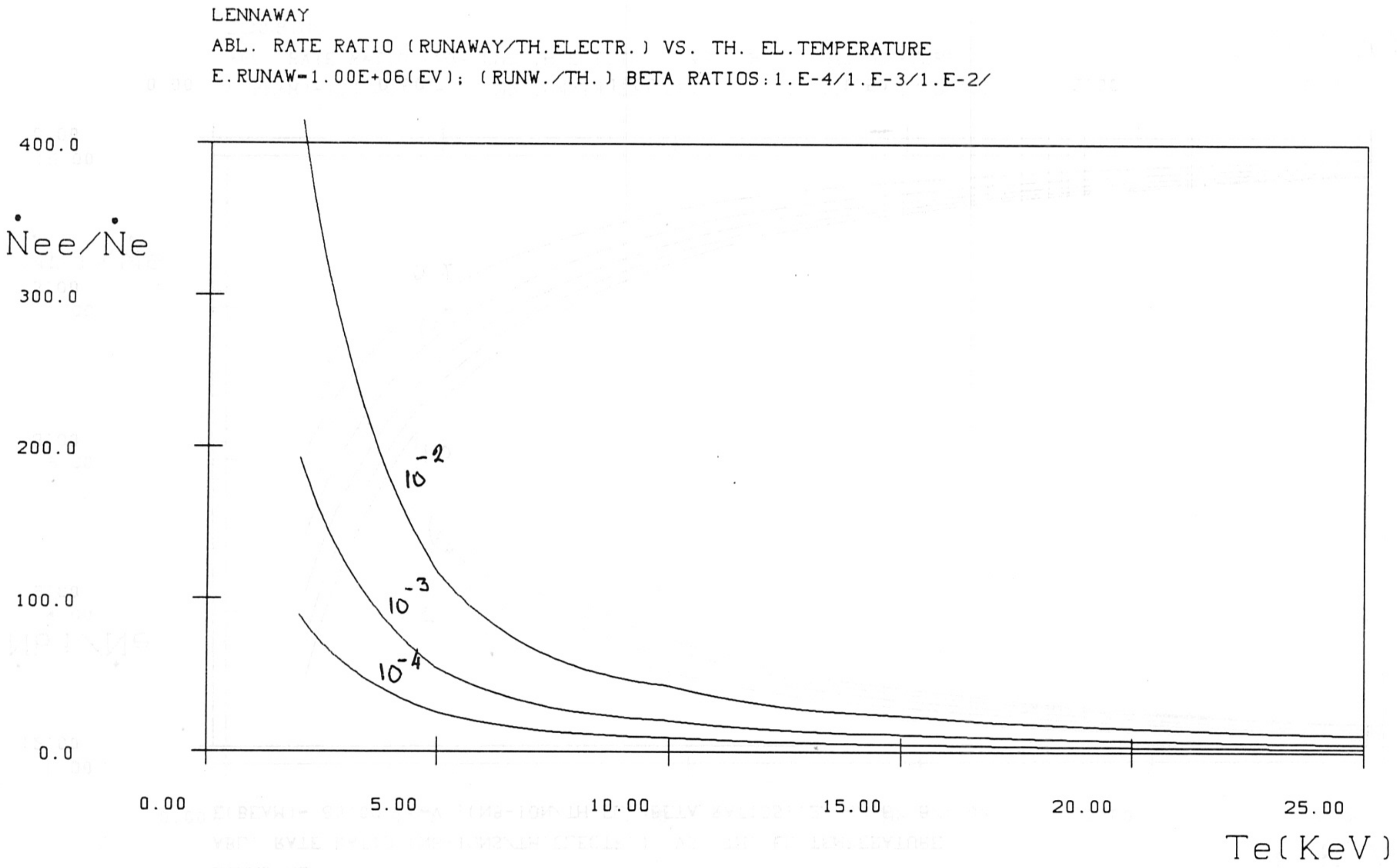
LENNAWAY
ABL. RATE RATIO (RUNAWAY/TH.ELECTR.) VS. TH. EL.TEMPERATURE
E.RUNAW-1.00E+06(EV); (RUNW./TH.) BETA RATIOS:1.E-4/1.E-3/1.E-2/
Ṅee/Ṅe
400.0
300.0
200.0
100.0
0.0
0.00
5.00
10.00
15.00
20.00
25.00
Te(KeV)
10^-2
10^-3
10^-4

Fig.9

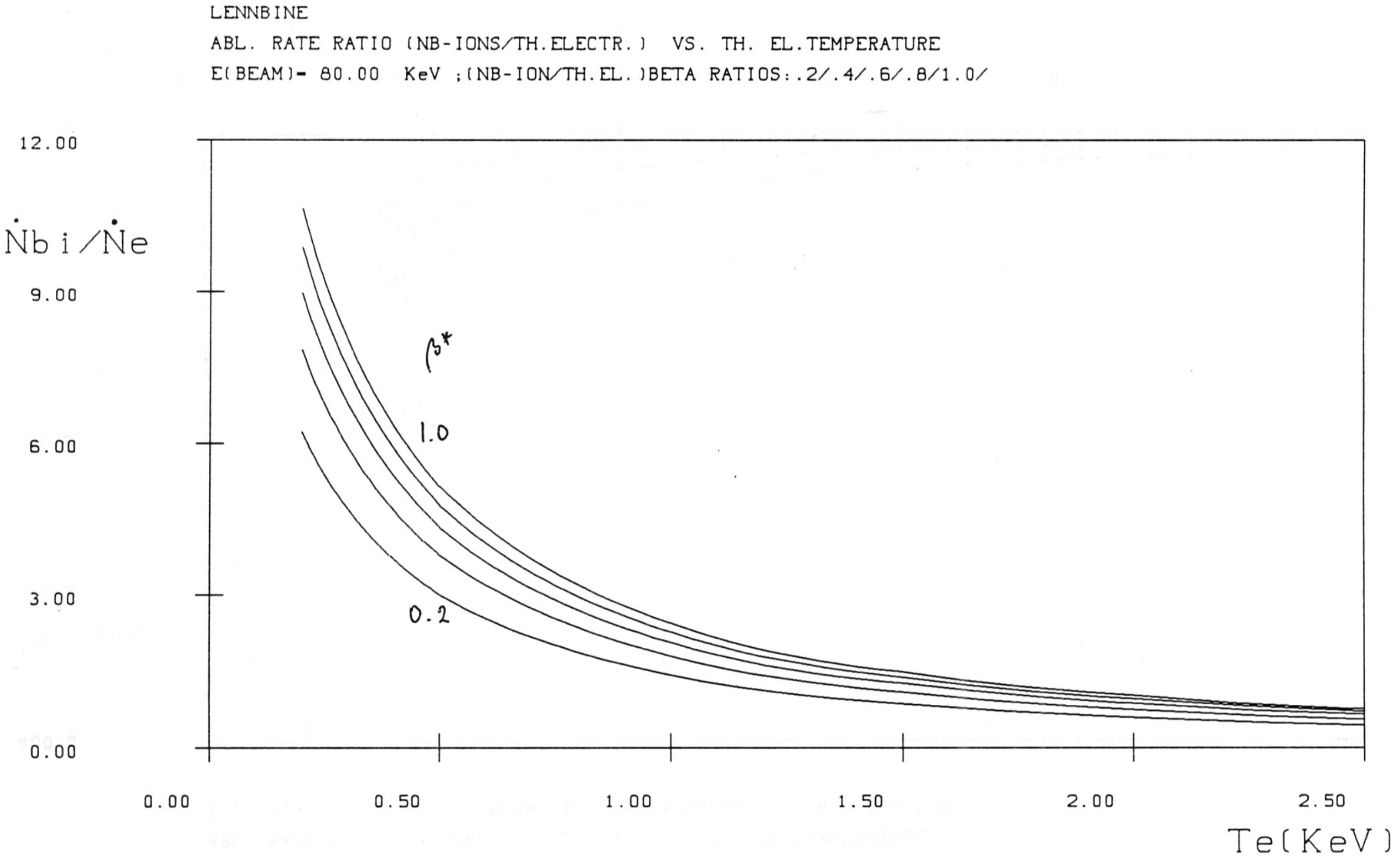
LENNBINE
ABL. RATE RATIO (NB-IONS/TH.ELECTR.) VS. TH. EL.TEMPERATURE
E(BEAM)- 80.00 KeV ;(NB-ION/TH.EL.)BETA RATIOS:.2/.4/.6/.8/1.0/
Ṅbi/Ṅe
12.00
9.00
6.00
3.00
0.00
0.00
0.50
1.00
1.50
2.00
2.50
Te(KeV)
β*
1.0
0.2

Fig.10

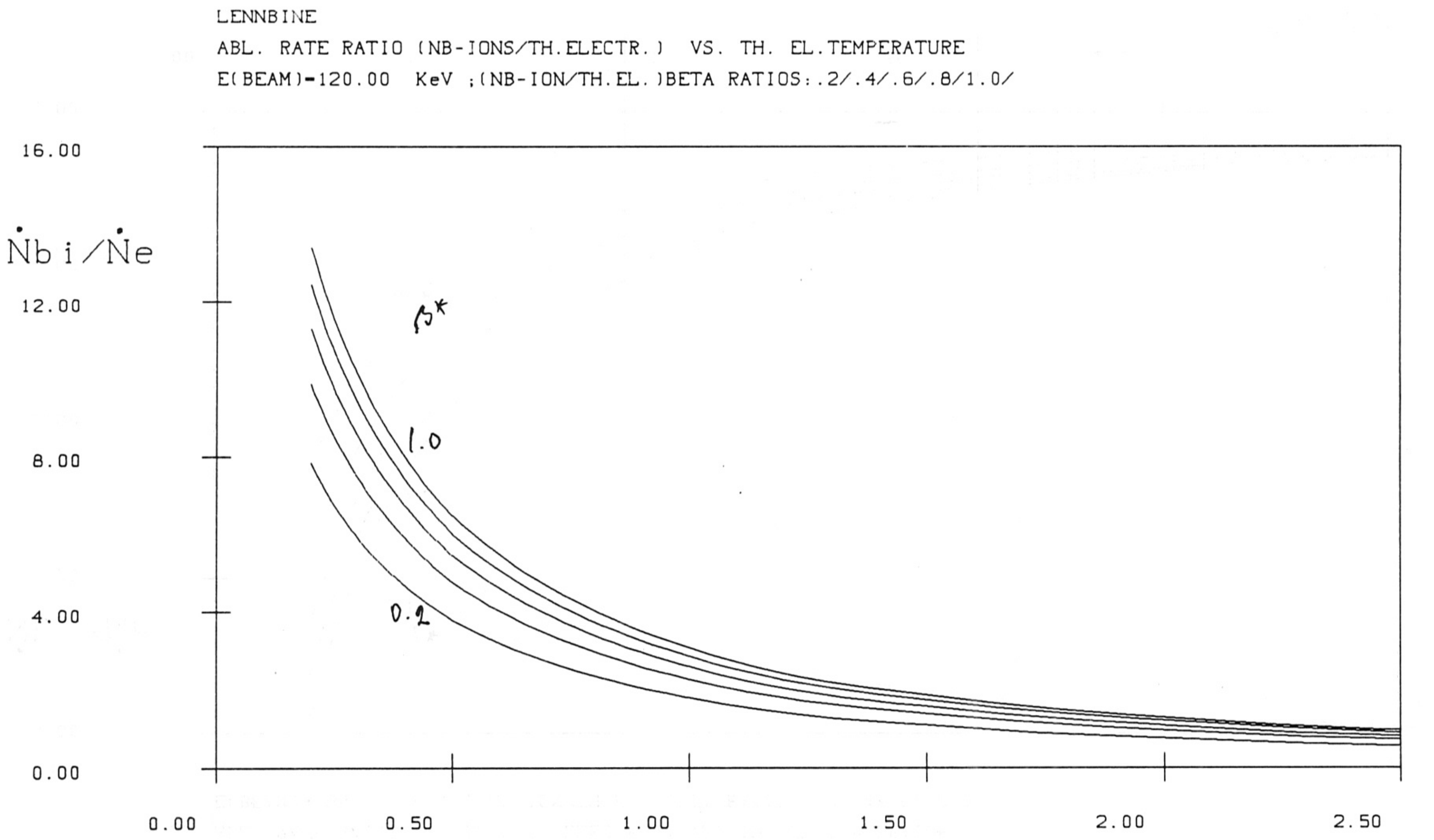
LENNBINE
ABL. RATE RATIO (NB-IONS/TH.ELECTR.) VS. TH. EL.TEMPERATURE
E(BEAM)-120.00 KeV ;(NB-ION/TH.EL.)BETA RATIOS:.2/.4/.6/.8/1.0/
$\dot{N}bi/\dot{N}e$
16.00
12.00
8.00
4.00
0.00
0.00
0.50
1.00
1.50
2.00
2.50
Te(KeV)
β^*
1.0
0.2

Fig.11

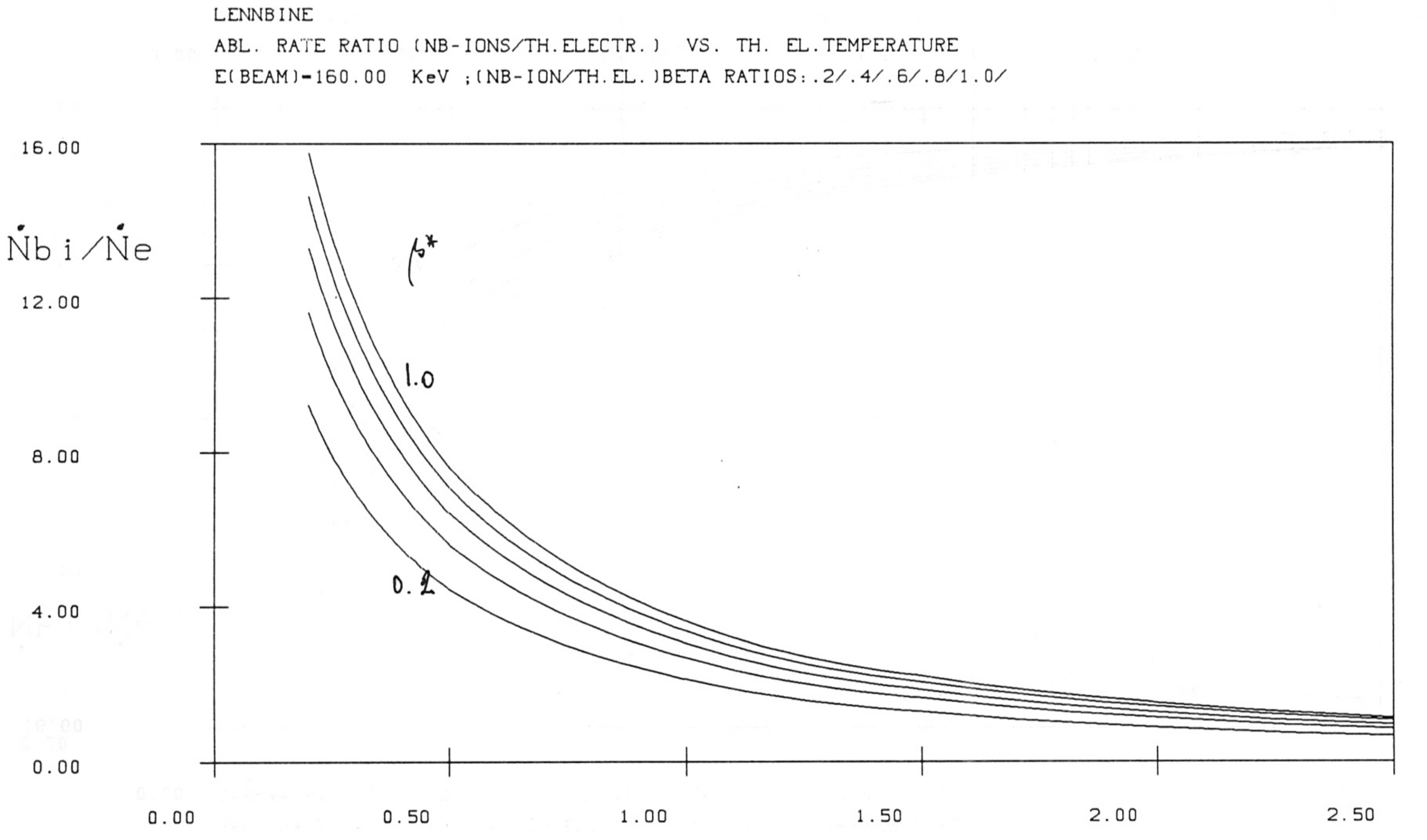

Fig.12

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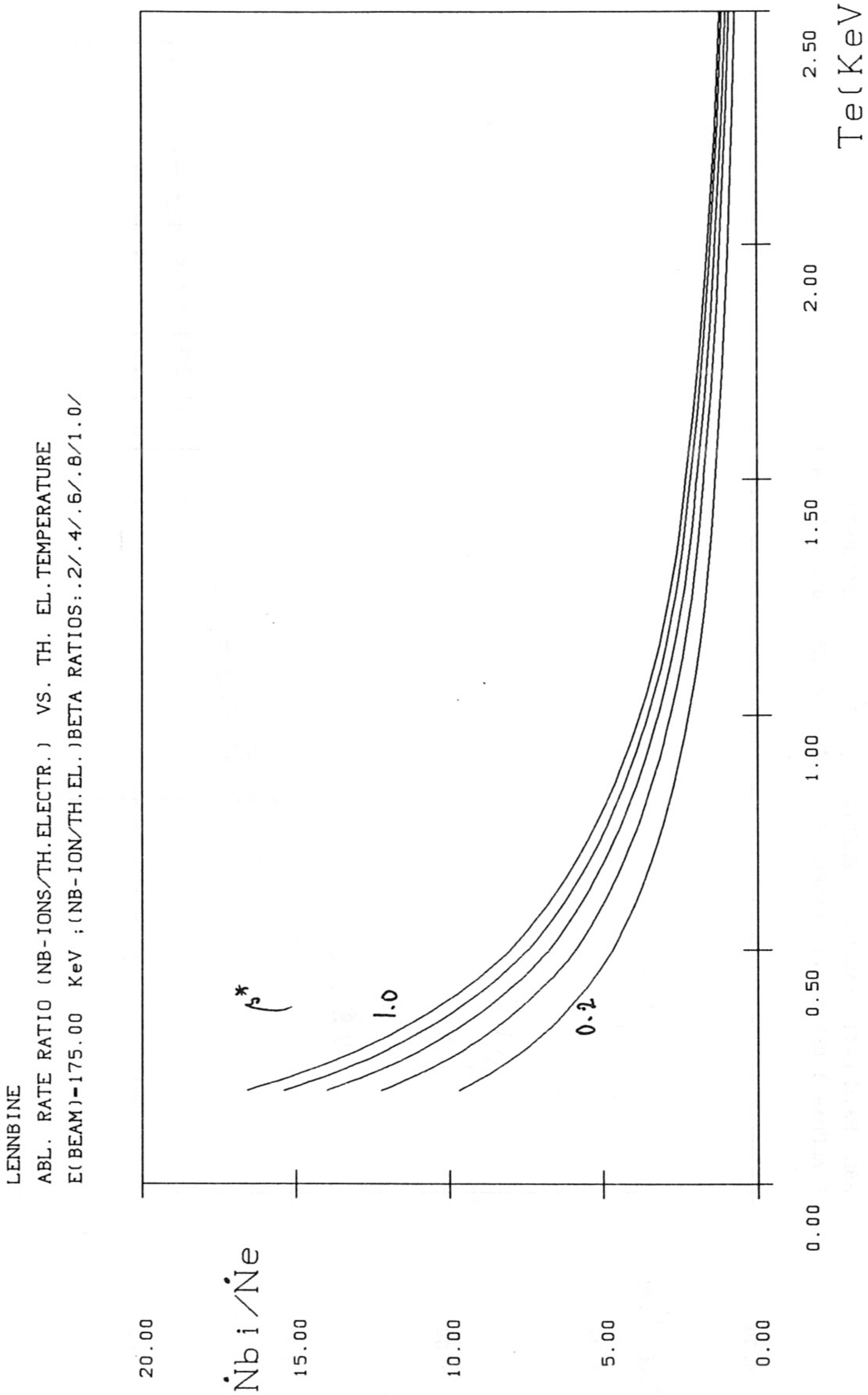

LENNBINE
ABL. RATE RATIO (NB-IONS/TH.ELECTR.) VS. TH. EL.TEMPERATURE
E(BEAM)-175.00 KeV ;(NB-ION/TH.EL.)BETA RATIOS:.2/.4/.6/.8/1.0/
β^*
1.0
0.2
$\dot{N}bi/\dot{N}e$
20.00
15.00
10.00
5.00
0.00
0.00
0.50
1.00
1.50
2.00
2.50
Te(KeV)

Fig.13

LENNANE
ABL. RATE RATIO (ALPHA/TH.ELECTR.) VS. TH. EL. TEMPERATURE
E.ALPHA- 1.0E+06(eV); (ALPH./EL.) BETA RATIOS: 0.2/0.3/0.4/0.5

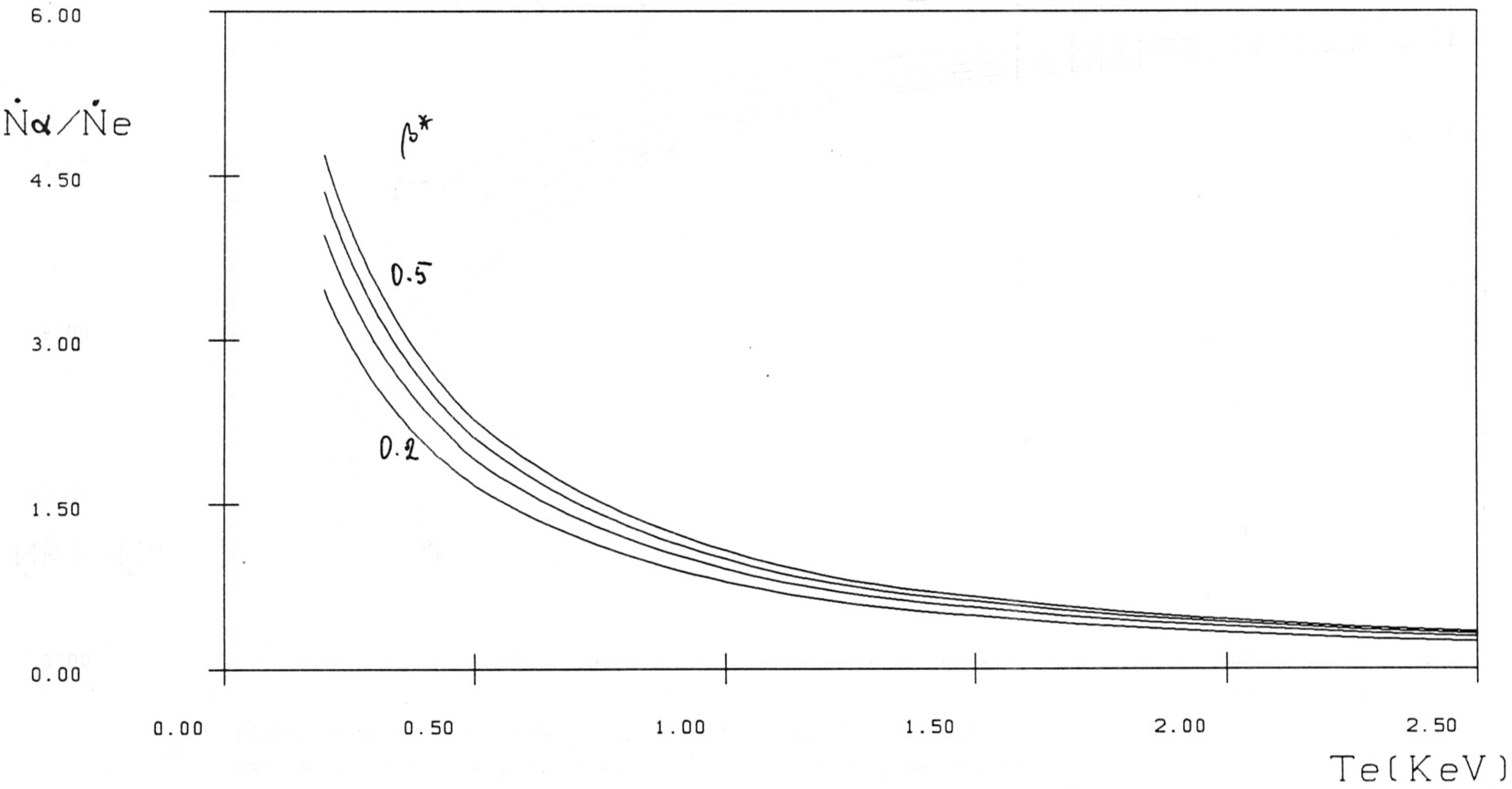
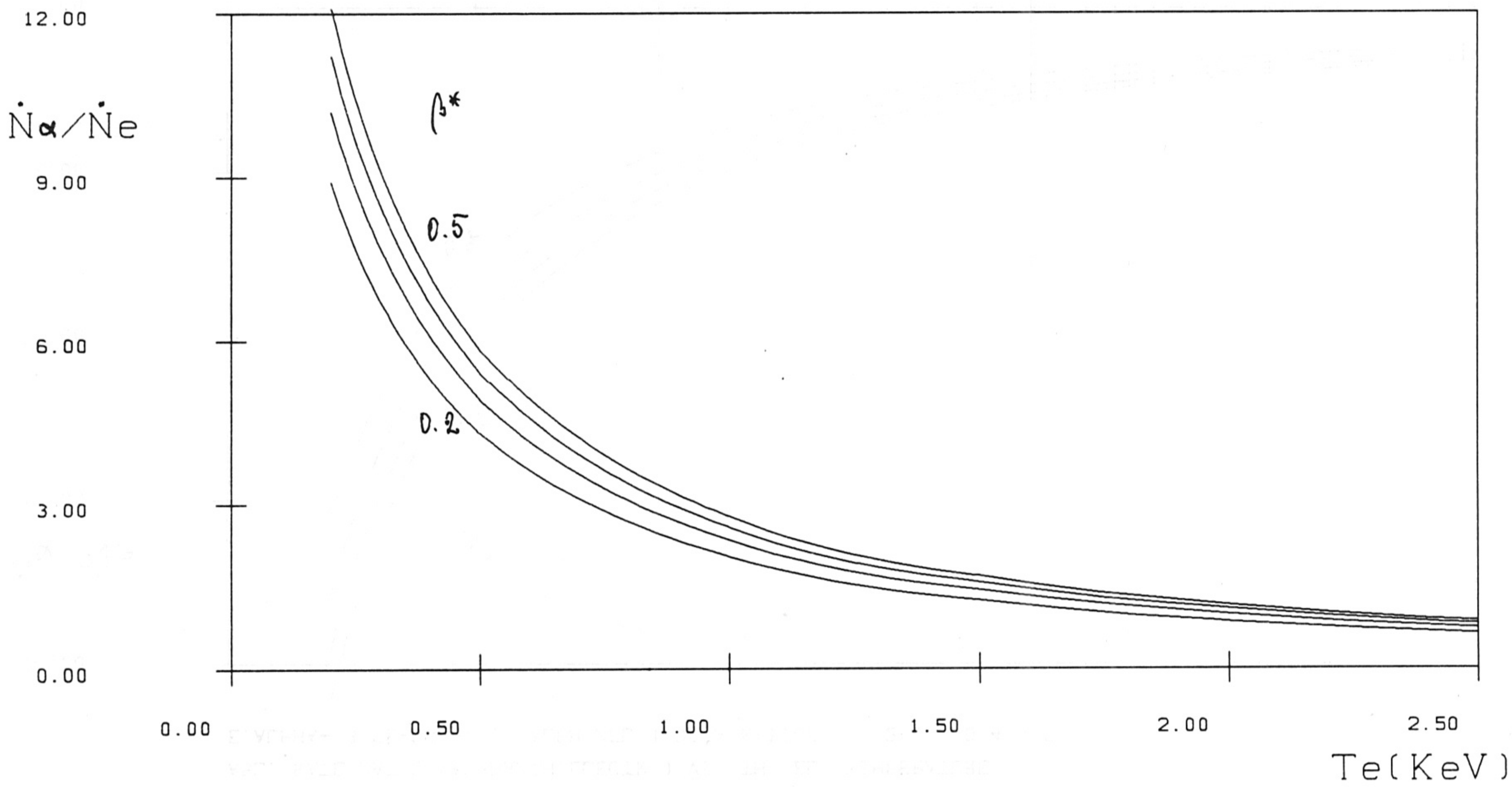


Fig.14

IPP--CMS 22/11/85 13.22:53 URR046 F2-06 006

IPP--CMS 22/11/85 13.22:52 URR046 F2-06 004



LENNANE

ABL. RATE RATIO (ALPHA/TH.ELECTR.) VS. TH. EL. TEMPERATURE

E.ALPHA= 2.0E+06(eV); (ALPH./EL.) BETA RATIOS: 0.2/0.3/0.4/0.5

Fig.15

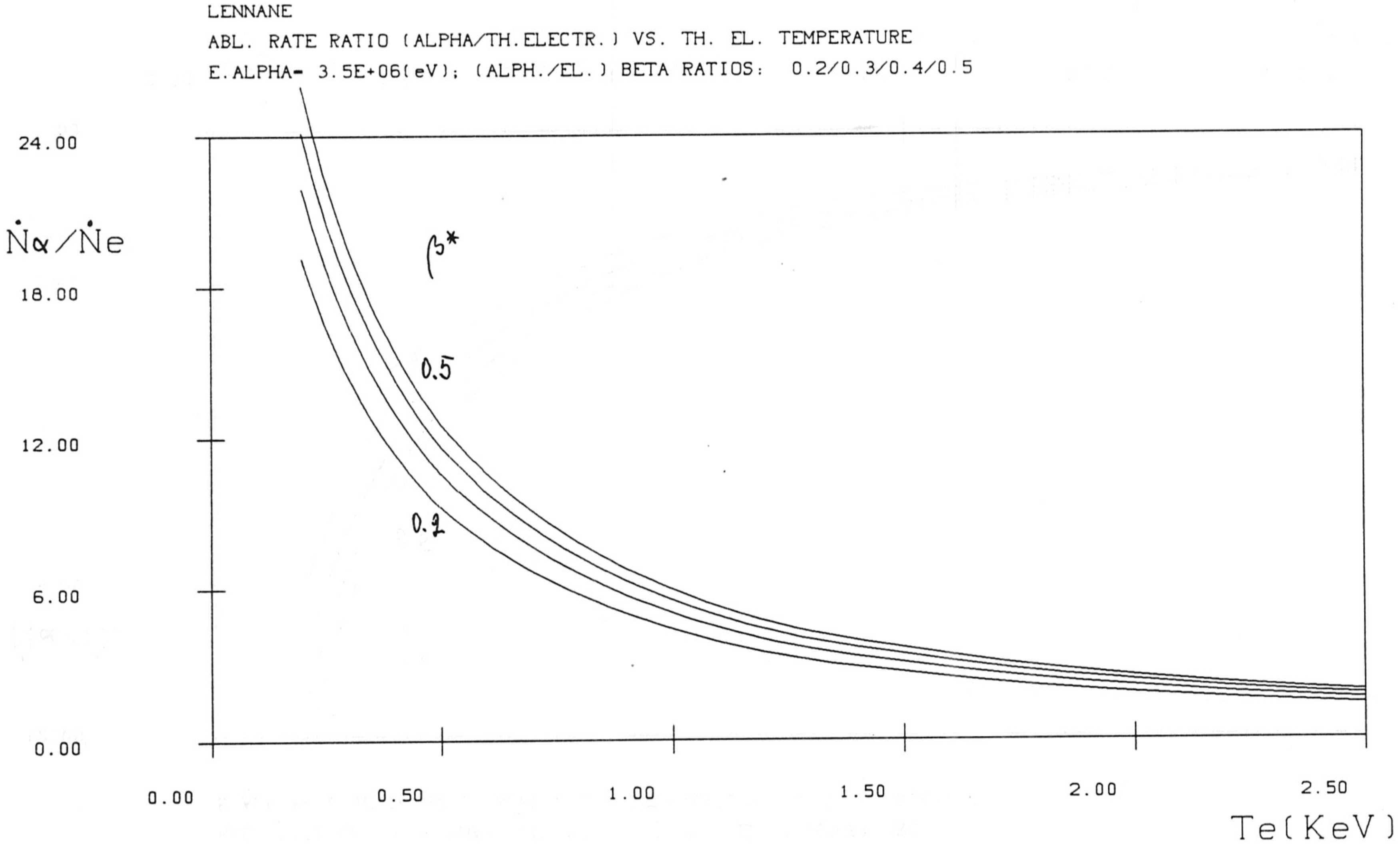


Fig.16

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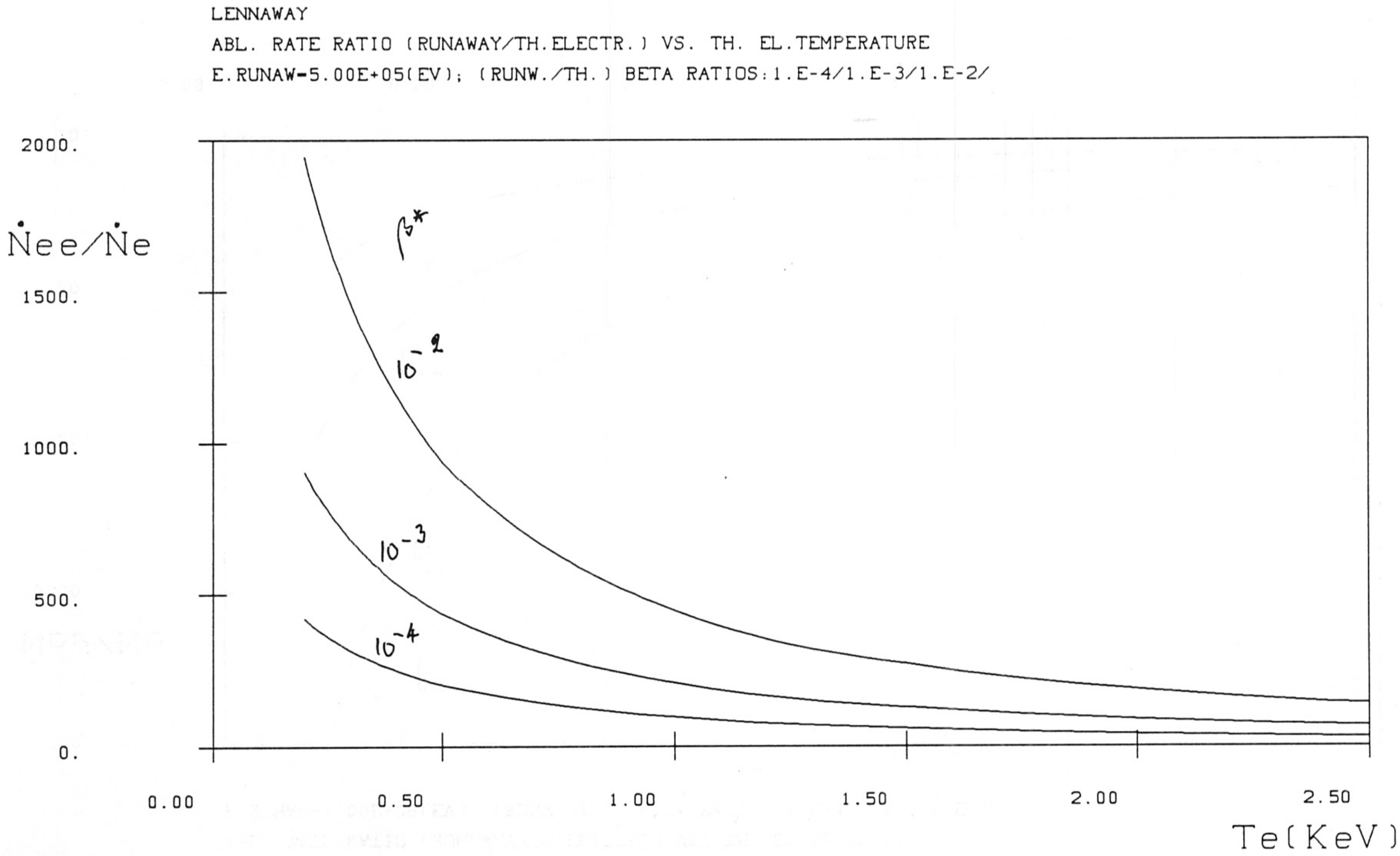
LENNAWAY
ABL. RATE RATIO (RUNAWAY/TH.ELECTR.) VS. TH. EL.TEMPERATURE
E.RUNAW=5.00E+05(EV); (RUNW./TH.) BETA RATIOS:1.E-4/1.E-3/1.E-2/
Ṅee/Ṅe
2000.
1500.
1000.
500.
0.
0.00
0.50
1.00
1.50
2.00
2.50
Te(KeV)
β*
10^-2
10^-3
10^-4

Fig.17

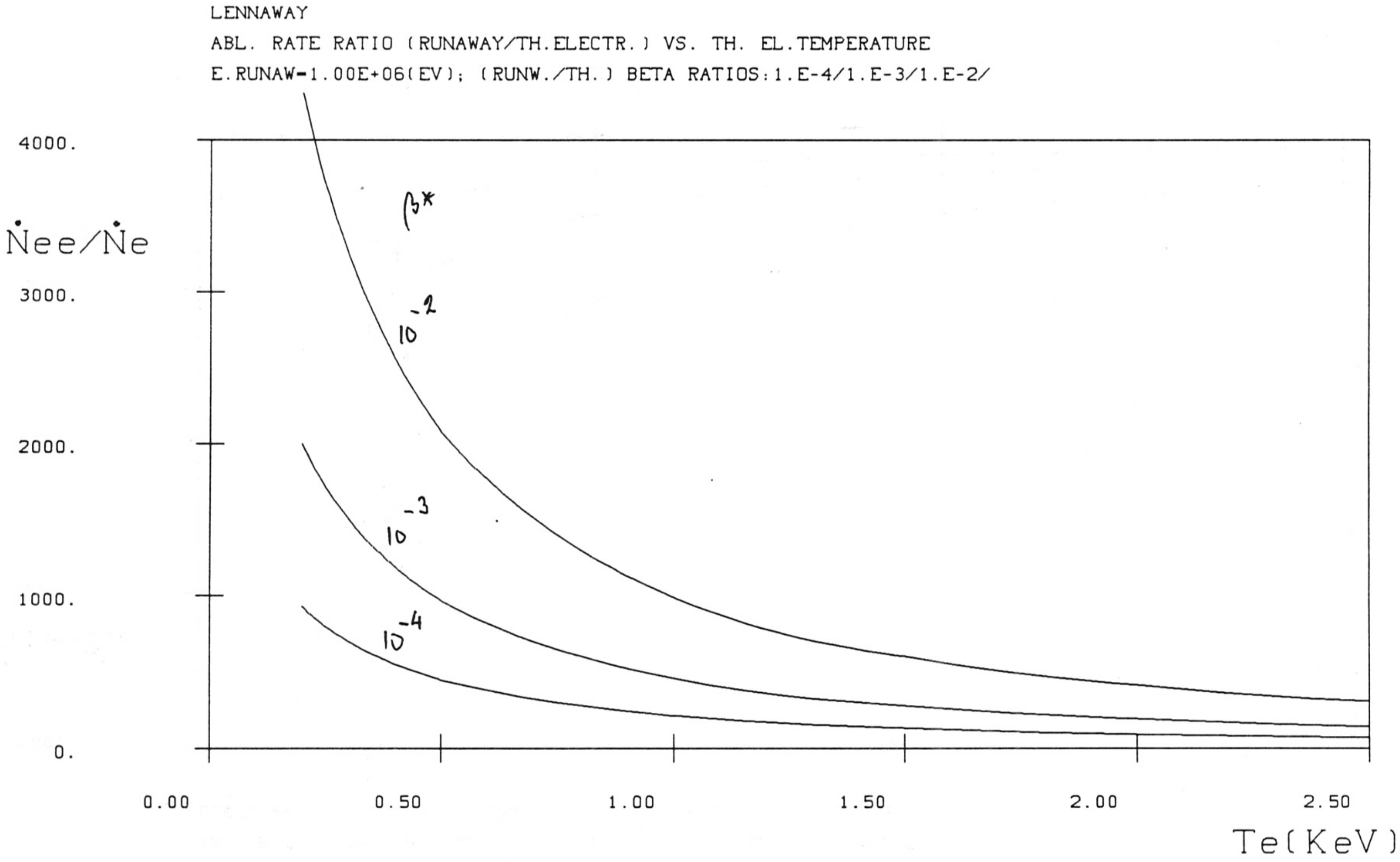
LENNAWAY
ABL. RATE RATIO (RUNAWAY/TH.ELECTR.) VS. TH. EL.TEMPERATURE
E.RUNAW=1.00E+06(EV); (RUNW./TH.) BETA RATIOS:1.E-4/1.E-3/1.E-2/
Ṅee/Ṅe
4000.
3000.
2000.
1000.
0.
β*
10⁻²
10⁻³
10⁻⁴
0.00
0.50
1.00
1.50
2.00
2.50
Te(KeV)

Fig.18