

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

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ASSESSMENT OF PELLET INJECTION
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Abstract

The effect of runaway electrons, NB ions and alpha particles is estimated by calculating the reduced ablation rates caused by these particles in fusion plasmas and using the ablation rate induced by thermal electrons as reference quantity. Calculations have been performed for various energy content (i.e. beta) ratios. The results show that in certain parameter intervals the effect of non-thermal particles may be significant.

We also... of various... on the basis... ing the details... same kind of... treatment of this... by means of a hydrodynamic... taneous action of different... account. The ablation... as particularly convenient for... according to Vaslow's derivation... pellet \dot{V}_A can be written, in a... following form:

The neutral shielding ablation model /1/ commonly used in pellet ablation calculations only takes into account the energy flux carried by thermal electrons. The results calculated by means of this model are in good agreement with experimental data obtained in thermal discharges at low and intermediate temperatures, but noticeable differences between theory and experiment have been observed at higher temperatures /2/ or in the presence of non-thermal particles in the plasma /3/.

The discrepancies observed at higher temperatures are probably due to magnetic shielding effects and shall be discussed in detail in another report. The existence and presence of non-thermal high-energy particles such as runaway electrons, neutral beam ions or, in fusion plasmas, alpha particles modify the energy input to the pellet and affect the ablation dynamics. Pellets have been observed to have shallow penetration depths in neutral-beam-heated discharges and particularly in discharges in which runaway electrons are present. Similar results are expected from thermonuclear plasmas with alpha particle production.

We shall estimate here the order of magnitude of the effect of various non-thermal energy carriers on the ablation rate on the basis of the existing ablation models without considering the details of the ablation and shielding dynamics. The same kind of estimate has been given in /4/. A more accurate treatment of this problem requires numerical calculations, by means of a hydrodynamic ablation code, in which the simultaneous action of different energy carriers is taken into account. The ablation model proposed by Vaslow /5/ appears to be particularly convenient for order-of-magnitude estimates. According to Vaslow's derivations, the ablation time of a pellet τ_A can be written, in a first approximation, in the following form:

$$\hat{\Gamma}_A \propto \frac{a^{5/3}}{\lambda_0^{2/3}} \left(\frac{m_s m_s}{h Q_0} \right)^{1/3}, \quad (1)$$

where a is the pellet radius, n_s and m_s are the pellet density and atomic mass, λ_0 is the penetration depth of the energy carrier in the pellet, Q_0 is the power flux incident on the pellet surface, and h is the fraction of this flux which is converted to heat. The ratio of the ablation rates corresponding to two different energy carriers, non-thermal species and thermal electrons in particular, can thus be written in the following form:

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

The energy flux Q_k is expressed as the product of the particle flux and the particle energy, whereas the penetration depth λ_k is determined from stopping length calculations.

Energy fluxes

(a) Thermal electrons with maxwellian energy distribution:

$$Q_e = \frac{1}{4} n_e v_{eth} (2kT_e). \quad (3)$$

(b) NB-produced ions:

We shall assume here tangential injection, full conversion of the neutral particle velocity into parallel ion velocity, and negligible gyro-radius effects. This yields

$$v_{bi} = \left(\frac{2E_{bi}}{m_a} \right)^{1/2}, \quad \Gamma_{bi} = n_{bi} v_{bi},$$

and hence

$$Q_{bi} = \Gamma_{bi} E_{bi} = \left(\frac{2}{m_a} \right)^{1/2} n_{bi} E_{bi}^{3/2}. \quad (4)$$

(c) Alpha particles:

The gyro-radii in this case are sufficiently large and the

alpha particle bombardment of the pellets can be assumed to be isotropic. The effect of magnetic fields is thus neglected and the fluxes are defined as in the case of thermal particles (electrons):

$$Q_d = \left(\frac{16}{27 \pi M_d} \right)^{1/2} n_d E_d^{3/2} \quad (5)$$

(d) Runaway electrons:

Only vague estimates can be made regarding the magnitude of the energy flux carried by this species. The electron velocity corresponding to runaway electron energies of 500 keV to 10 MeV is limited by the velocity of light:

$v_{ee} = c = 3 \times 10^8$ m/s. The power flux carried by runaways may thus be written as

$$Q_{ee} = \Gamma_{ee} E_{ee} = 3 \times 10^8 \times n_{ee} E_{ee} \quad (6)$$

The number density n_{ee} may be estimated from the magnitude of the runaway currents in tokamaks: a few hundred A in a 300 kA ASDEX-discharge. Assuming $I_{ee} = 100$ A, we obtain

$$n_{ee} [m^{-3}] = I_{ee} / (e v_{ee} a_{ee}) = \frac{2.1 \times 10^{12}}{a_{ee} [m^2]}, \quad (7)$$

where a_{ee} is the effective cross-section of the runaway current filament and e denotes the electronic charge.

Penetration depths

(a) Thermal electrons

For the sake of consistency, the electron energy loss function used here is the same that used by the authors of the neutral shielding ablation model. It thus follows with (E_e given in eV) that

$$\lambda_e [m] = \frac{1}{n_s} \int_{E_{e0}}^{E_{e\infty}} \frac{dE_e}{L(E_e)} = \frac{1}{n_s} \left[2 \times 10^{15} E_e^2 + 2.35 \times 10^{18} E_e - \frac{2 \times 10^{21}}{E_e} \right]_{E_{e0}}^{E_{e\infty}} .$$

Assuming $n_s = 3.05 \times 10^{28} \text{ (m}^{-3}\text{)}$ for D_2 pellets and taking $E_{e0} \approx 2 \text{ eV}$ as the lower limit of the integral, we have

$$\lambda_e [m] = 3 \times 10^{-8} \left(1 + 2.35 \times 10^{-3} E_{e0} + 2 \times 10^{-6} E_{e0}^2 - \frac{2}{E_{e0}} \right). \quad (8)$$

Note that the penetration depths calculated by means of equ. (8) are lower than the experimental values of Schou and Sørensen /6/.

(b) NB ions

The experimental data on proton energy losses in hydrogen gas /7/ can be reduced to yield $L(E_i) = 1.37 \times 10^{-20} E_i^{0.44}$ for $5 \text{ keV} < E_i < 20 \text{ keV}$, and $L(E_i) = 6.59 \times 10^{-20} E_i^{0.26}$ for $20 \text{ keV} < E_i < 40 \text{ keV}$. Approximating both energy ranges by a single loss function $L(E_i) = 1.95 \times 10^{-20} E_i^{0.4}$ (E_i in eV and L in $m^2 \cdot eV$), we have

$$\lambda_{bi} [m] = 2.87 \times 10^{-9} \cdot E_{bi}^{0.6} [eV]. \quad (9)$$

(c) Alpha particles

Since it holds that $\lambda(\frac{E}{M}) \propto \frac{M}{Z^2} L(\frac{E}{M})$, the range of helium ions can be deduced from that of protons /8/. A semi-empirical power law is given in /8/ for protons in the energy range $E_p < 200 \text{ MeV}$ in air (S.P.T.): $\lambda_{(m)} = 2.86 \times 10^{-13} (E_p \text{ (eV)})^{1.8}$. For the same energy interval, the penetration depth of alpha particles in D_2 ice is thus given by

$$\lambda_\alpha [m] = 2.05 \times 10^{-17} \cdot E_\alpha^{1.8} [eV]. \quad (10)$$

The corresponding expression that could be deduced from equ. (9), $\lambda_\alpha = 1.25 \times 10^{-9} E_\alpha \text{ (eV)}^{0.6}$, yields somewhat higher penetration depths for the energy range $E_\alpha < 3 \text{ MeV}$.

(d) Runaway electrons

In ref. /4/ the experiments of Schou and Sørensen /6/ are cited, according to which the stopping length of monoenergetic electrons with energies of 0.5 keV to 100 keV is given by

$$\lambda_e \text{ (cm)} = 1.75 \times 10^{-5} E_e \text{ (keV)}^{1.72}. \text{ Assuming that this relation}$$

can be extrapolated to the MeV energy range, we have for the runaways

$$\lambda_{ee} [m] = 1.21 \times 10^{-12} E_{ee} (eV)^{1.72} \quad (11)$$

Calculations, results, summary

For computational convenience, the ratio Q_k/Q_e in equ. (2) was expressed as

$$\frac{Q_k}{Q_e} = \text{Const.} \left(\frac{\beta_k}{\beta_e} \right) \left(\frac{E_k}{E_e} \right)^{1/2} \left(\frac{m_k}{M_e} \right)^{1/2} \quad (12)$$

and evaluated for prescribed values of the beta ratio β_k/β_e . The ratio of the ablation rates \dot{N}_k/\dot{N}_e was computed as a function of the thermal electron energy E_e (or electron temperature) for various incident non-thermal particle energies E_k and for various β_k/β_e ratios for all three "k" species considered: NB ions, alpha particles, and runaway electrons. The result of the calculations are given in the form of plots in Figs. 1 to 6. All plots display the same basic characteristics: the relative importance of non-thermal particles decreases as the plasma temperature increases, and it increases as the energy content (measured by the beta ratio) of these particles. The probability of and the conditions for finding non-thermal high-energy particles in low-temperature plasma regions is not discussed here.

In the case of neutral-beam-heated plasmas, low-energy NB ions (1 to 5 keV) may significantly contribute to pellet ablation only in the low-temperature plasma regions: $\dot{N}_{bi}/\dot{N}_e < 1$ for $E_e > 2$ keV (see Figs. 1 and 2). High-energy beam particles (80 to 160 keV, see Figs. 2 and 3) notably affect the ablation rate in the entire plasma temperature range considered.

Notable is the effect of alpha particles at particle energies ≥ 2 MeV in the entire range of plasma temperatures considered (see Fig. 4). For example, if 2 MeV alpha particles are present in a 4 to 5 keV plasma, the ablation rate caused by these

particles may be a factor of 2 higher than that caused of thermal electrons (with $\beta_\alpha/\beta_e \approx 0.2$).

Dramatic is the effect of runaway electrons computed in this approximation. As can be seen from Fig. 6, the ablation rates caused by runaways exceed those caused by thermal electrons ($T_e = 1$ keV) by three orders of magnitude even at moderate runaway energies (0.5 MeV to 1.0 MeV) and low beta ratios ($\beta_{ee}/\beta_e = 10^{-4}$ to 10^{-2}). However, the reliability of these results is limited by the approximation used in the calculations: it was assumed that the electrons are stopped in the pellet. The stopping range of 1 MeV electrons in condensed hydrogen calculated by equ. (11) is approx. 2.5 cm. Typical pellet sizes at present are in the mm range. Runaways would thus not transfer their total energy to small pellets (they would fly through them) and the energy transfer estimates, i.e. the applicability of Vlasov's formula would require more care in this case. Nevertheless, the results indicate the significant effect that runaways may have on pellet ablation.

In summary, the rather simple estimates presented here show that (a) non-thermal particles may have significant effects on the ablation rate of pellets in thermal fusion plasmas; (b) accurate calculations of the respective ablation rates require realistic hydrodynamic models with full allowance for the different stopping ranges of the various species; (c) particular care should be exercised in selecting the analytic approximation for the energy loss functions of the various energy carriers considered.

No attempt has been made in this work to compare and analyze the data available on energy loss functions and stopping ranges.

Acknowledgement

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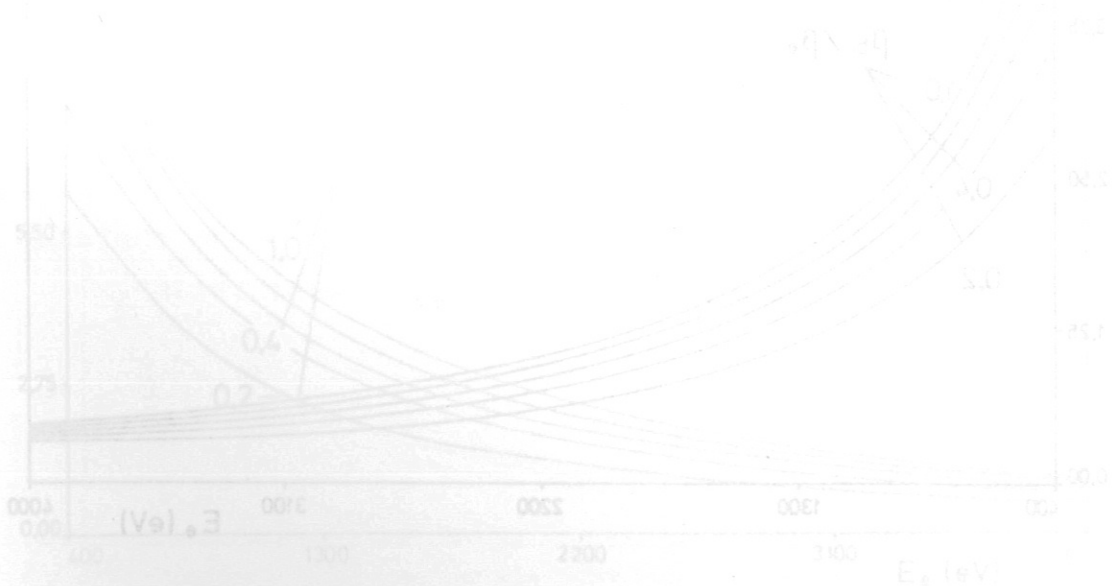


Fig. 1: Ratio of the ablation rates caused by NB ions and the thermal ablation rates as a function of the thermal ablation rates for different beta ratios.

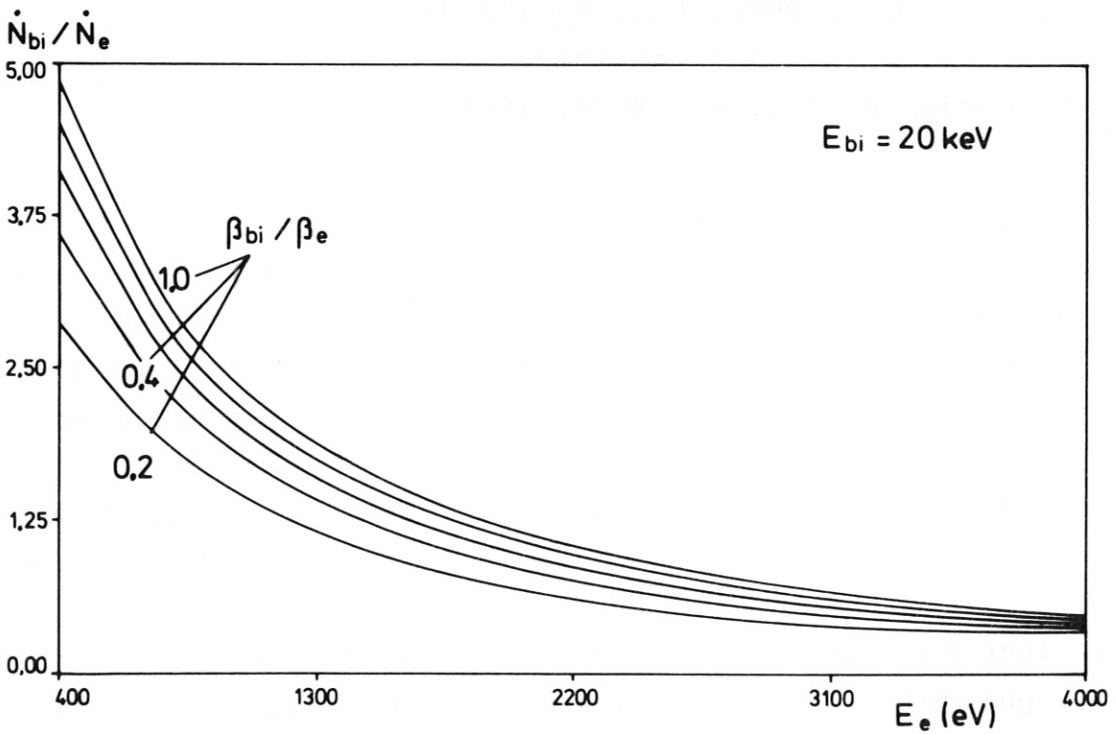
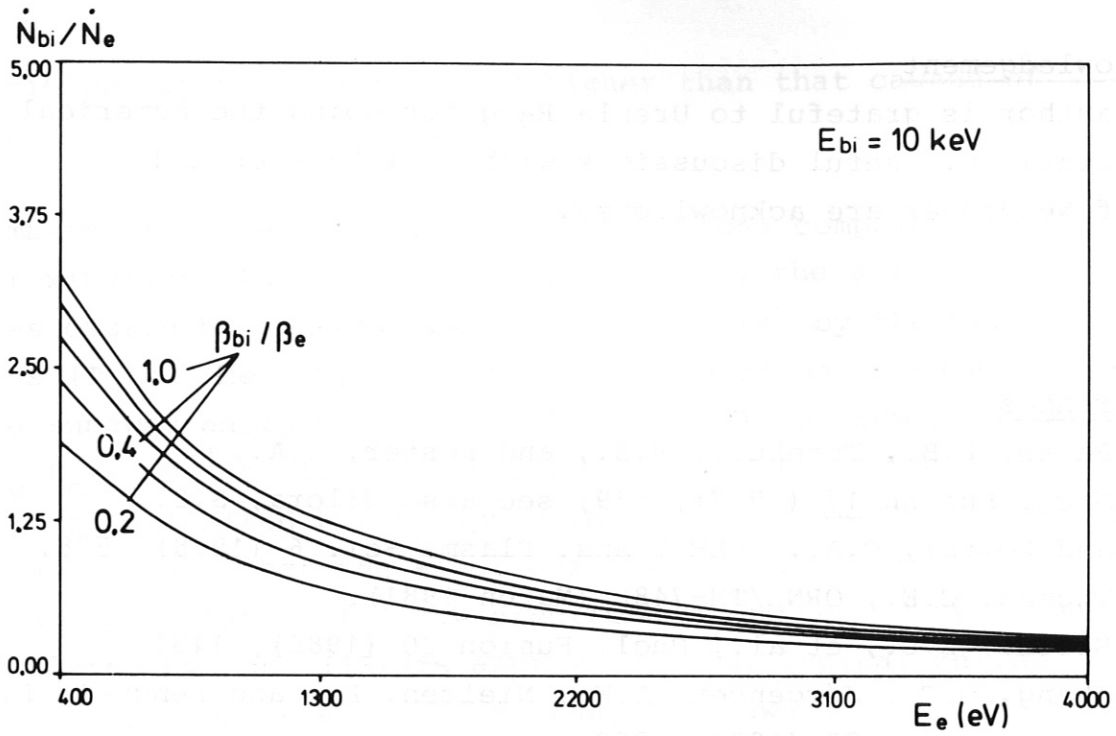


Fig. 1: Ratio of the ablation rates caused by NB ions and thermal electrons as a function of the thermal electron energy for different beta ratios.

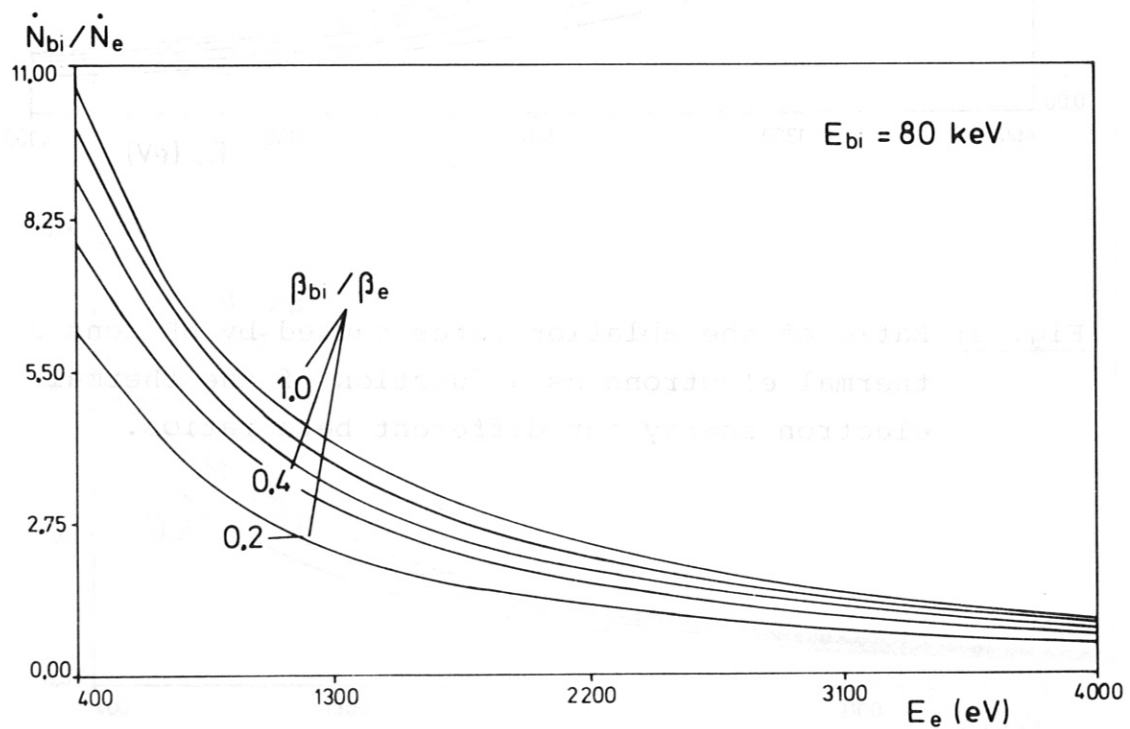
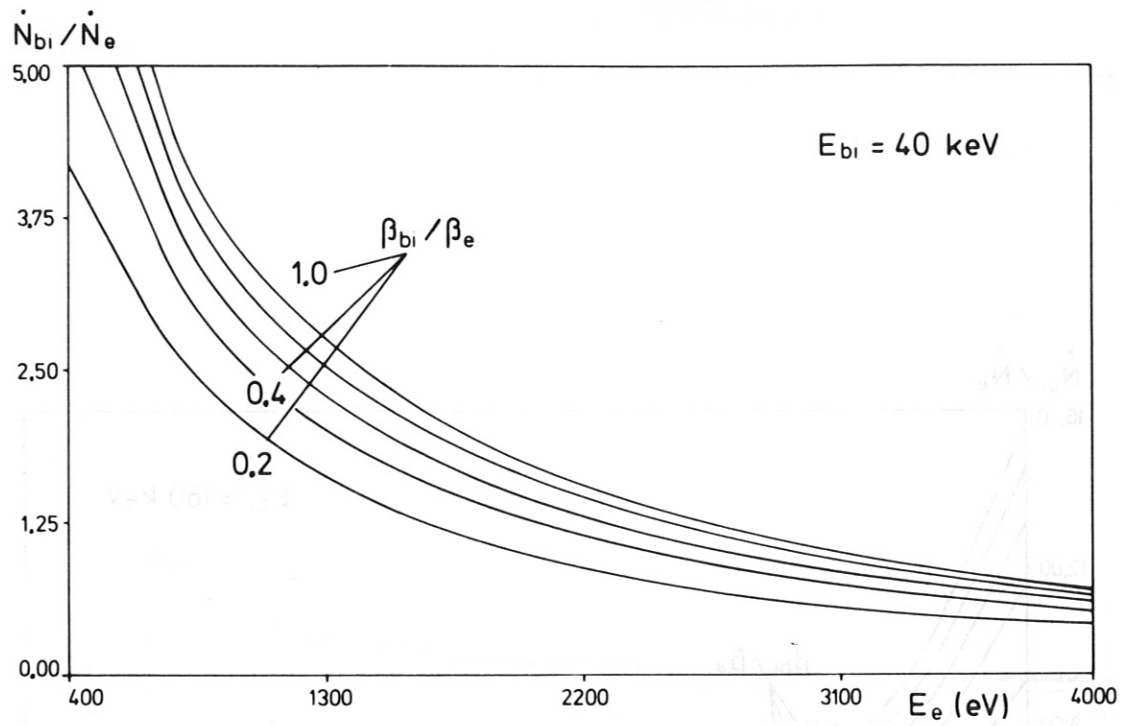


Fig. 2: Ratio of the ablation rates caused by NB ions and thermal electrons as a function of the thermal electron energy for different beta ratios.

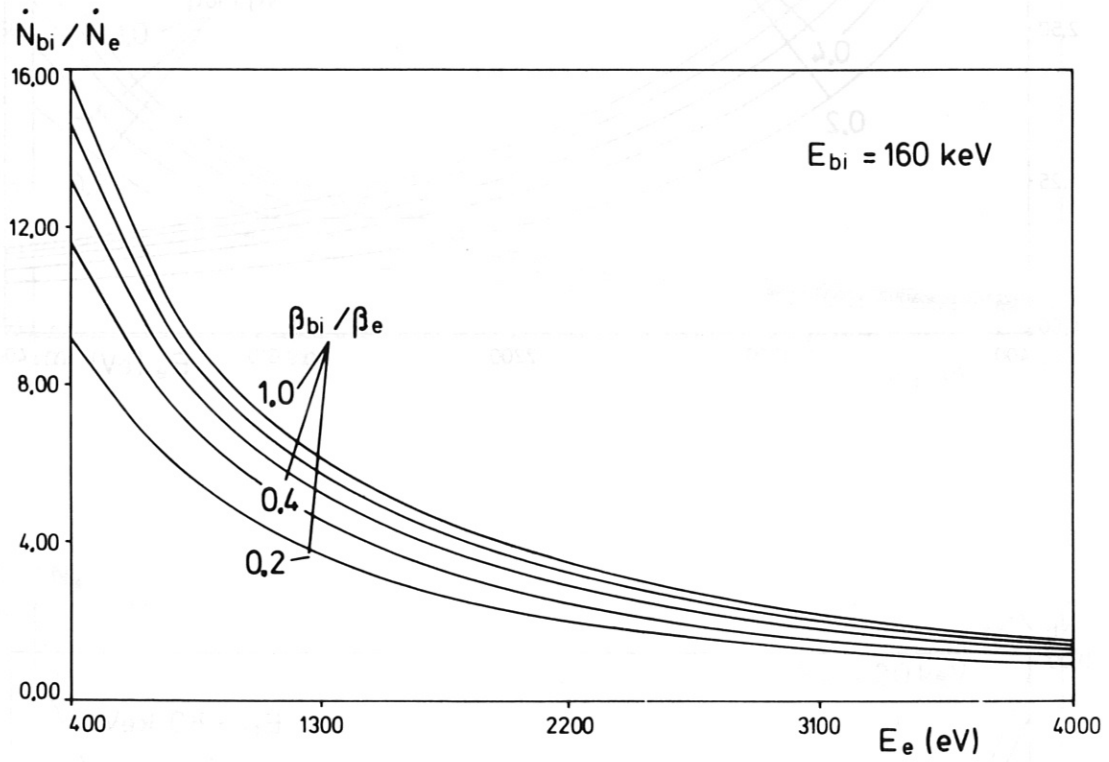


Fig. 3: Ratio of the ablation rates caused by NB ions and thermal electrons as a function of the thermal electron energy for different beta ratios.

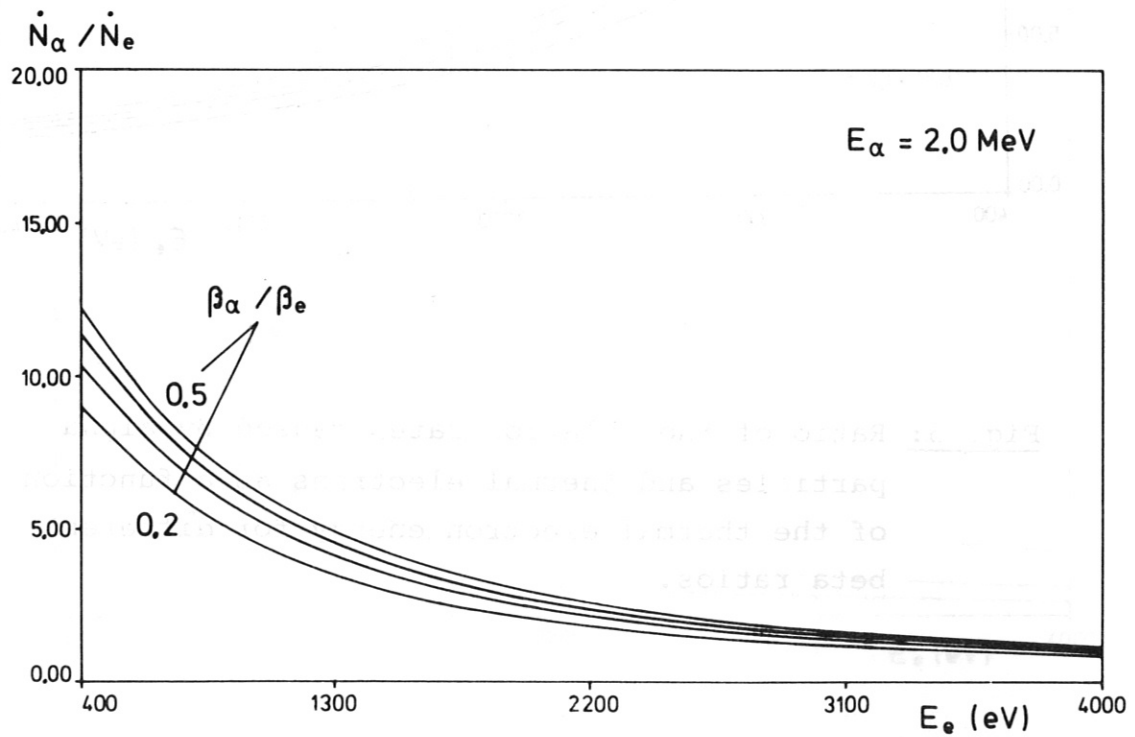
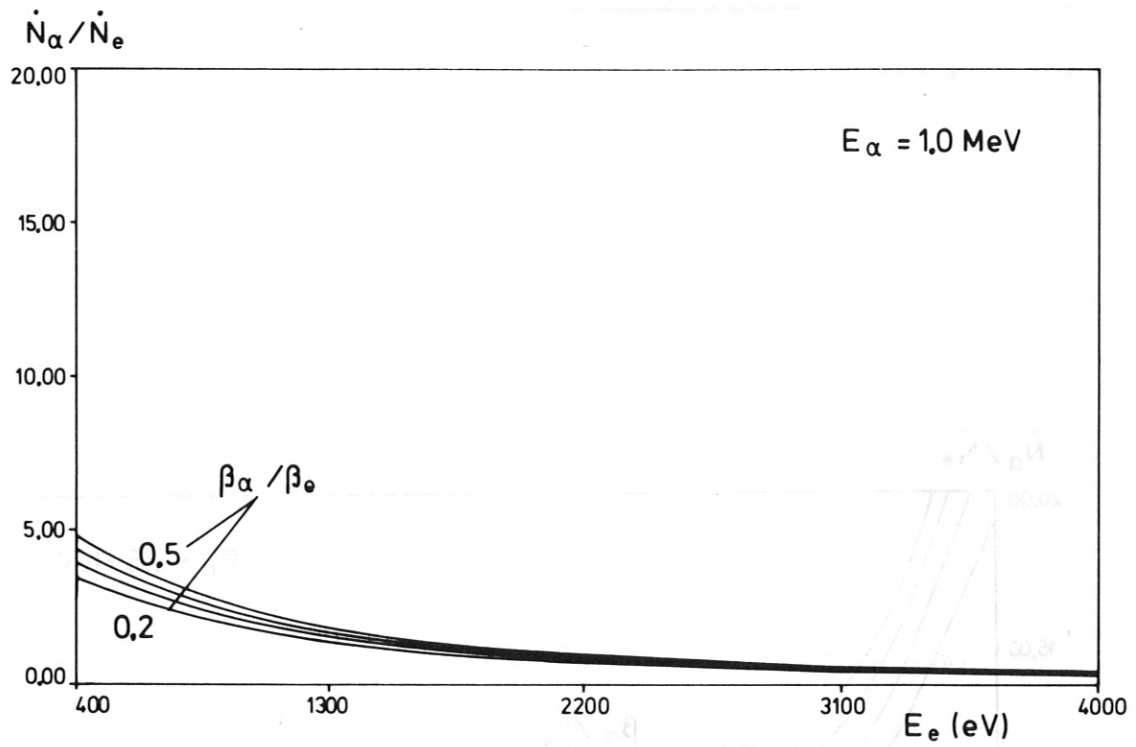


Fig. 4: Ratio of the ablation rates caused by alpha particles and thermal electrons as a function of the thermal electron energy for different beta ratios.

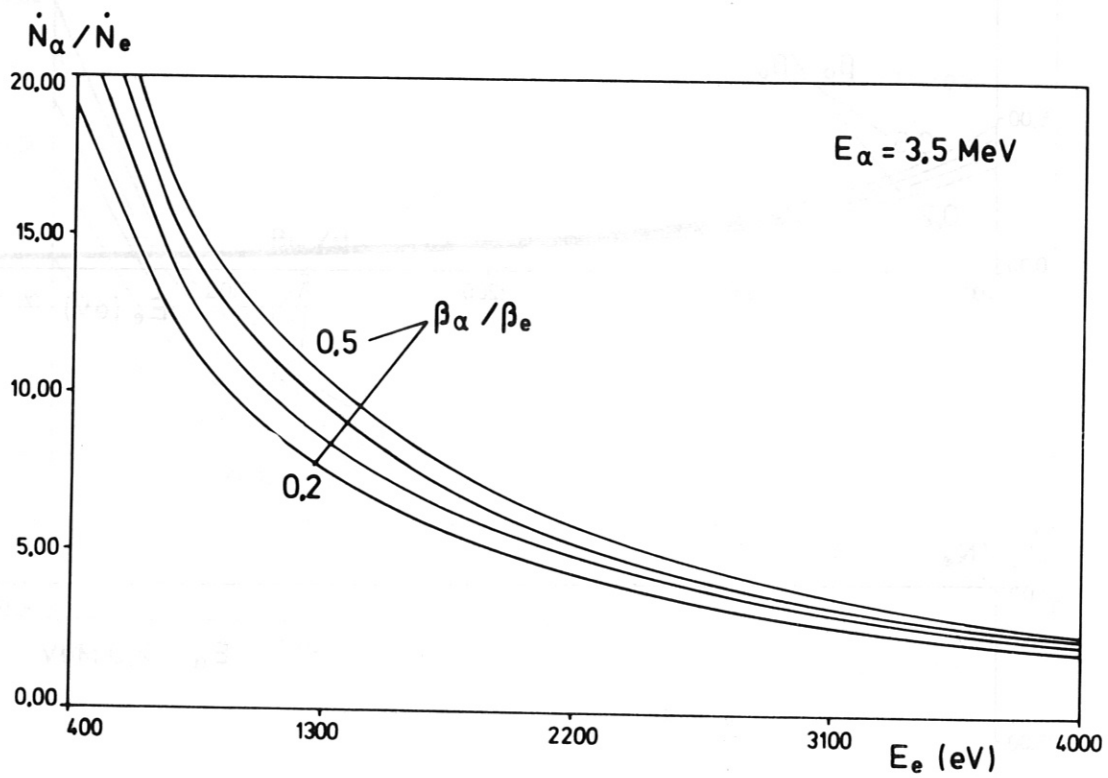


Fig. 5: Ratio of the ablation rates caused by alpha particles and thermal electrons as a function of the thermal electron energy for different beta ratios.

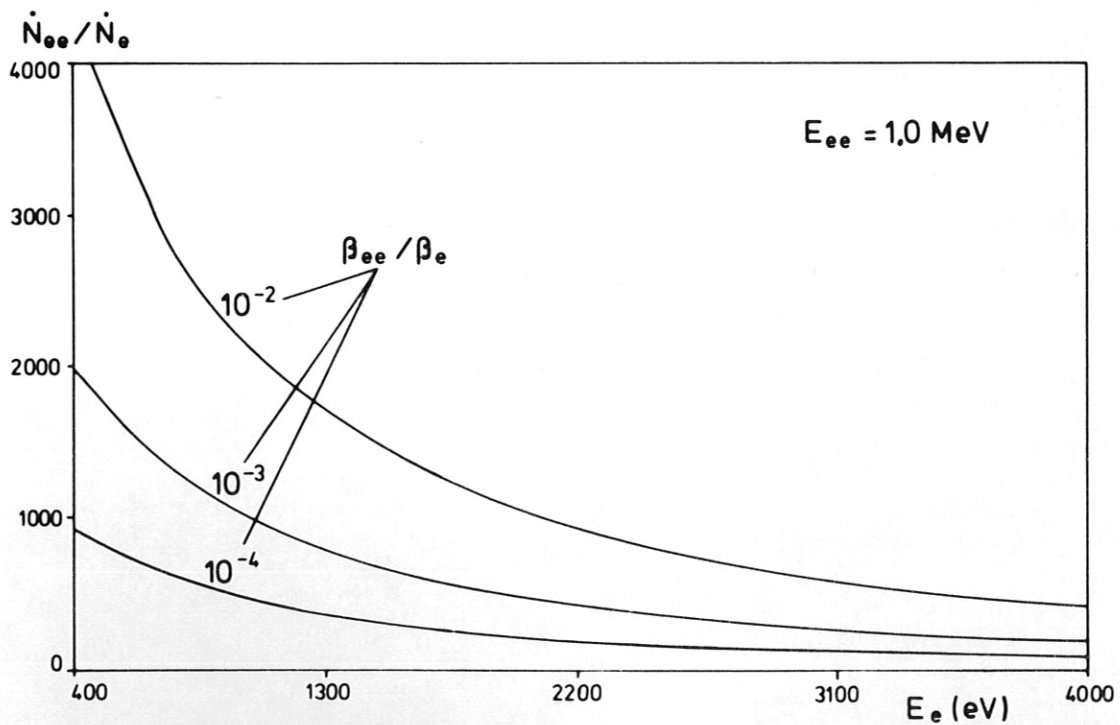
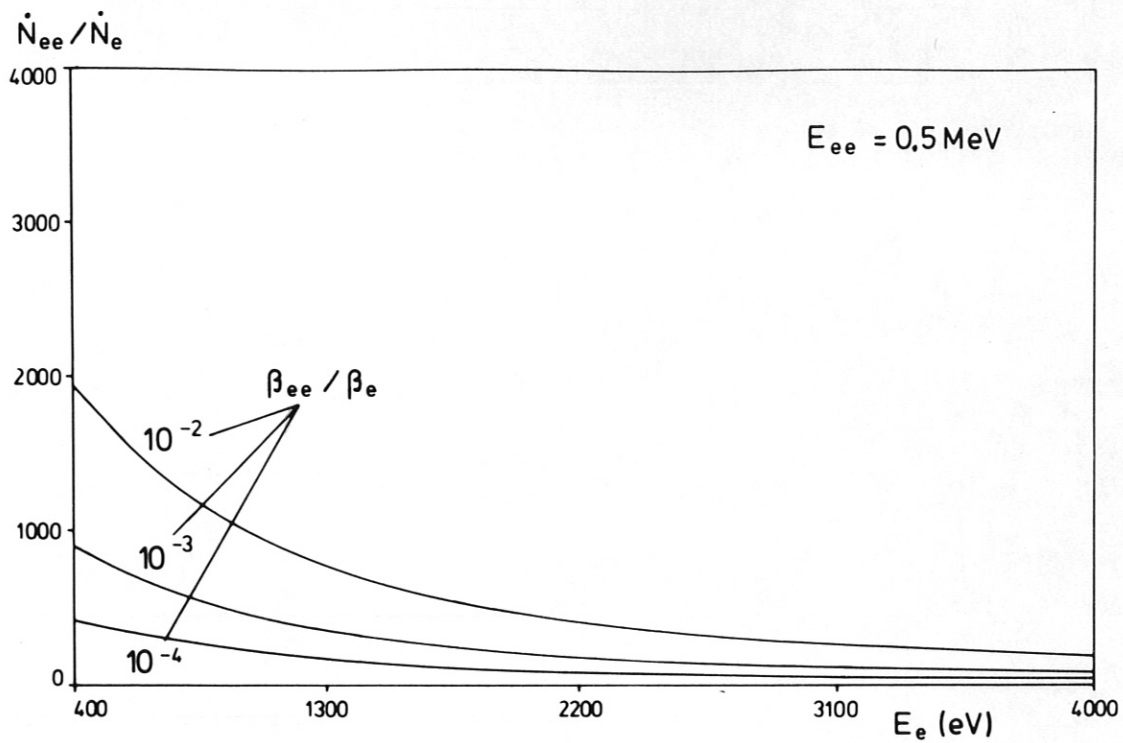


Fig. 6: Ratio of the ablation rates caused by runaway electrons and thermal electrons as a function of the thermal electron energy for different beta ratios.