Karlsruhe Institute of Technology

Uncertainty assessment for the number of defects calculated using the NRT damage model

by A.Yu. Konobeyev, U. Fischer, S.P. Simakov

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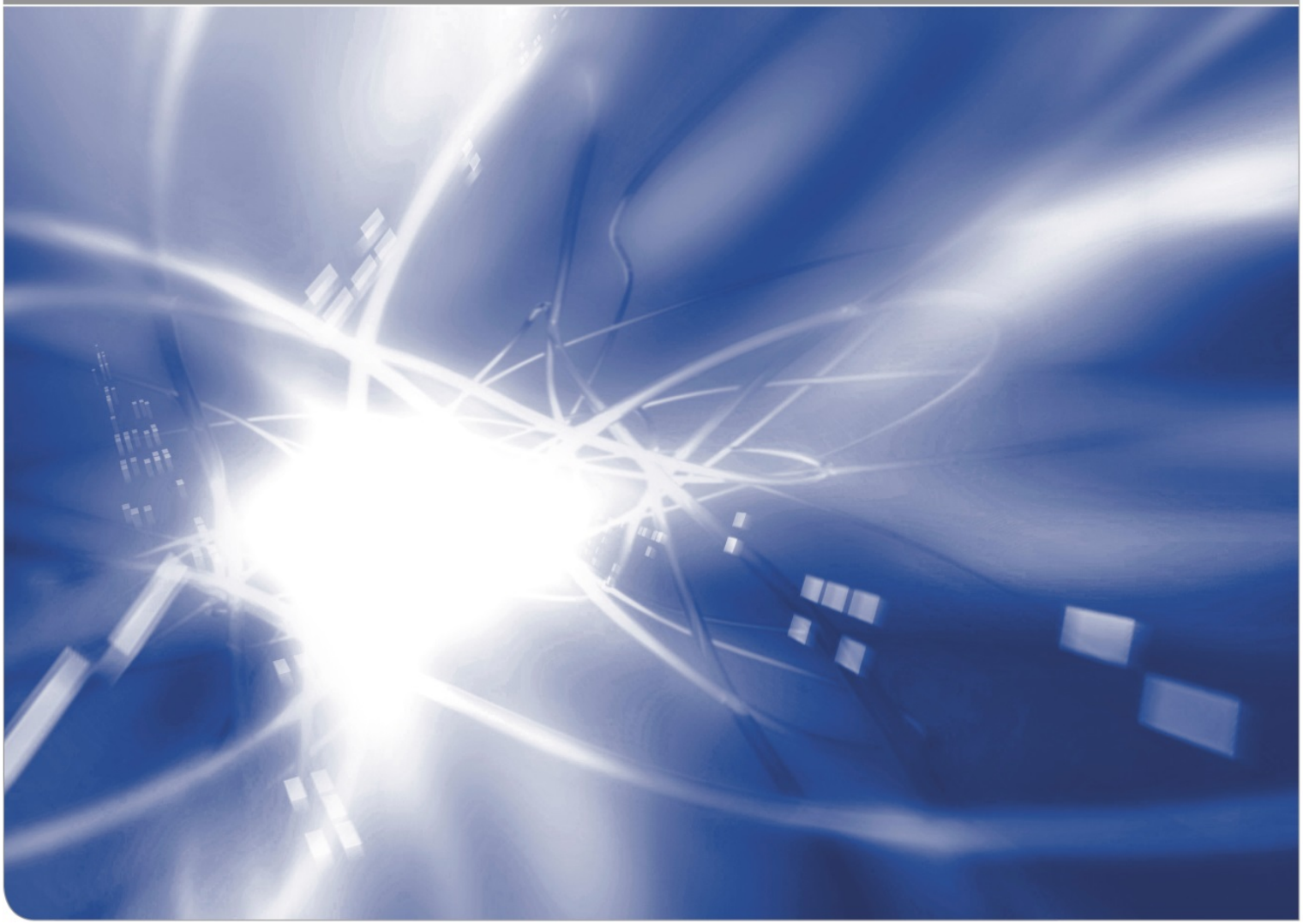

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Abstract

The work concerns the estimation of the uncertainty of the number of defects calculated using the NRT model. The impact of spread of nuclear stopping power, electronic stopping power, and threshold displacement energy was examined. The results were obtained for aluminum, iron, zirconium, and tungsten.

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1. Introduction

For over 40 years, the NRT model [1,2] is used to estimate the number of defects produced in materials under irradiation. Despite the wide application of the model, the analysis of the uncertainty of its predictions was reduced to indicating differences with experimental data and results of BCA and MD simulations. To some extent, differences are avoided when calculating displacement cross-sections by redefining a value of displacement threshold energy E_d [3,4].

Two types of uncertainty of predictions of the NRT model are to distinguish

- A general discrepancy with experimental data and advanced theoretical calculations. The model systematically overestimates the number of calculated defects

- An “internal” conceptual uncertainty of the model, associated with the use of different approximations. An analysis of such uncertainty does not go beyond the basic assumptions of the model.

Two types of uncertainty are illustrated with the covariance matrix relating to model calculations $M^{(mod)}$ [5,6]:

$$M^{(mod)} = M^{(def)} + M^{(par)} + M^{(num)}, \quad (1)$$

where $M^{(def)}$ presents the first type of uncertainty discussed above and corresponds to model deficiencies, or the failure of the model [5], $M^{(par)}$ refers to the second type of uncertainty and reflects uncertainties in the model parameters, the matrix $M^{(num)}$ relates to errors occurring with the numerical implementation of the model [5].

The present study deals with the “internal” uncertainty of the NRT model corresponding to the $M^{(par)}$ component of the covariance matrix. The goal of the work is

- the estimation of uncertainty of the number of defects calculated using the NRT model that makes possible a valid comparison of model predictions with other calculations and experimental data,

- the evaluation of uncertainty of parameters of NRT model and the validation of the range of parameter variation performed in Ref.[7].

Next Chapters describe briefly the NRT model, the method of the evaluation of uncertainties, and obtained results.

2. The NRT model

According to the NRT model [1,2,8] the number of stable defects produced by the ion (Z_1,A_1) with the kinetic energy T in the material (Z_2,A_2) is calculated as follows

$$N_d(T_{dam}) = \begin{bmatrix} 0 & \text{when} \quad T_{dam} < E_d \\ 1 & \text{when} \quad E_d \le T_{dam} < 2E_d/\lambda \\ \dfrac{\lambda}{2E_d} T_{dam} & \text{when} \quad 2E_d/\lambda \le T_{dam} \end{bmatrix}, \qquad (2)$$

where the λ value is equal to 0.8 according to Ref.[9,10], E_d is the threshold displacement energy, and T_{dam} is so called "damage" energy, equal to the energy transferred to lattice atoms reduced by the losses for electronic stopping of atoms in displacement cascades. The damage energy is calculated using the expressions

$$T_{dam}(T) = \frac{T}{1 + k\,g(\varepsilon)} \quad \text{(keV)}, \qquad (3)$$

$$g(\varepsilon) = \varepsilon + 0.40244\,\varepsilon^{3/4} + 3.4008\,\varepsilon^{1/6}, \qquad (4)$$

$$k = \frac{32}{3\pi}\left(\frac{m_e}{M_2}\right)^{1/2} \frac{(A_1 + A_2)^{3/2} Z_1^{2/3} Z_2^{1/2}}{A_1^{3/2}(Z_1^{2/3} + Z_2^{2/3})^{3/4}}, \qquad (5)$$

$$\varepsilon = \left[A_2 T/(A_1 + A_2)\right]\left[a/(Z_1 Z_2 e^2)\right], \qquad (6)$$

$$a = a_0 (9\pi^2/128)^{1/3}\left(Z_1^{2/3} + Z_2^{2/3}\right)^{-1/2}, \qquad (7)$$

where Z_1, A_1 and Z_2, A_2 are the atomic number and mass number of the projectile and the target material, respectively, m_e is the mass of an electron, M_2 is the mass of the atom of target material, e is the electron charge (4.8032×10^{-10} esu), a_0 is the Bohr radius (0.5292×10^{-8} cm). The expression for $g(\varepsilon)$ was obtained in Ref.[11] from the approximation of numerical results [12]. It is supposed that the energies T, T_{dam}, and E_d in Eq.(2)-(6) are taken in keV.

The basics of the NRT model, the LSS theory, its development and important comments can be found in Refs.[12-15,2,9-11].

Examples of the number of defects produced in iron calculated with the NRT model and applying other methods are given in Appendix.

3. The estimation of the uncertainty of the number of defects calculated using the NRT model

The estimation is based on the following assumptions:

1. The uncertainty of the calculated nuclear stopping power can be attributed to the spread of values obtained using different approximations for the ion-ion scattering cross section: $d\sigma(E,T) = 0.5\pi a^2 f(t^{1/2})t^{-3/2}dt$ [14-19]. The IOTA code [20] with a number of built-in $d\sigma(E,T)$- functions is used for calculations.

2. The error in the definition of the electronic stopping power $(dE/dx)_{el}$ calculated using the LSS theory [13] corresponds to a typical deviation of theoretical and experimental data. In most cases, the average deviation does not exceed ten percent, as follows from the comparison presented in Ref.[21][1].

The last assumption may seem controversial, since the electronic losses predicted by the LSS theory and experimental data can differ significantly, as follows from the discussion of the damage efficiency in Ref.[2], the comparison of nuclear and electronic stopping power calculated with the SRIM code [21], and indirectly from the comparison of the data shown in Appendix,I. It is important to recall that the purpose of this work is the evaluation of elements of the $M^{(par)}$ matrix, rather than $M^{(def)}$, Eq.(1).

The estimation of the uncertainty was performed using the Monte Carlo method described in Ref.[22]. The method was also used for the estimation of errors in displacement cross sections in Ref.[7].

The calculation consists in i) the Monte Carlo generation of K number of IOTA input data sets [20] including various approximations of $d\sigma(E,T)$, ii) the K number of IOTA- runs with prepared input data files, and iii) the processing of results. The mean number of defects for "I"-th primary ion energy is equal to

$$N_{d,i} = K^{-1}\sum_{m=1}^{K} N_{d,im} \qquad (8)$$

where $N_{d,im}$ is the number of defects corresponding to the "i"-th ion energy in the "m"-th Monte Carlo event.

The covariance matrix is calculated as follows

[1] The comparison [21] is made for the total stopping power, so it is important to identify the energy range where the electronic losses have a main contribution. For example, for iron, the electronic losses exceed the nuclear ones at ion energies above 0.7 MeV.

$$V_{ij} = K^{-1} \sum_{m=1}^{K} N_{d,im} N_{d,jm} - N_{d,i} N_{d,j} \quad (9)$$

The corresponding correlation matrix is equal to

$$C_{ij} = V_{ij} \Big/ \sqrt{V_{ii} \times V_{jj}} \quad (10)$$

and the standard deviation of calculated number of defects is equal to

$$\Delta N_{d,ii} = \sqrt{V_{ii}} \quad (11)$$

Calculations were performed using different approximations for the ion scattering cross section $d\sigma(E,T)$ listed in Refs.[16-20] corresponding to IOTA input parameter IDSDT = 0,1,11,13-15.

The electronic stopping power was calculated using the SRIM code [21]. The relative error of $(dE/dx)_{el}$ was assumed equal to ten percent independent on the ion primary energy. The variation of $(dE/dx)_{el}$ was performed using the normal distribution assuming a strong correlation at different energies.

The results of calculations are shown in Fig.1 and Fig.4 as "complete modeling". They are discussed in the next Section.

The above method is rather time consuming. For practical applications, such as estimating the error of displacement cross-sections, it is desirable to evaluate the dispersion of the number of defects, based only on the uncertainty of parameters of the NRT model, as was done in Ref [7].

In addition, and for comparison with the method discussed above, the parameters of the NRT model were varied, as proposed in Ref.[7]. It is assumed that $g(\varepsilon)$-function, Eq.(4) with coefficients, obtained in Ref.[11] by approximating the data [12], contains three variable parameters α, β, and γ

$$g(\varepsilon) = \alpha\, \varepsilon + \beta\, \varepsilon^{3/4} + \gamma\, \varepsilon^{1/6}. \quad (12)$$

The E_d energy is considered as the fourth parameter [7]. The calculations of ΔN_d were performed using Eq.(9)-(11).

The variation of parameters was done using the normal distribution. The $\Delta p/p$-values concerning the change of α,β,γ - parameters and $\Delta E_d/E_d$ relating to E_d variation, discussed below, are the relative standard deviation (RSD) or the coefficient of variation concerning the σ/μ ratio of the normal distribution for considered parameters.

All calculations performed for materials discussed below relate to the self-ion irradiation.

3.1 Iron

Figure 1 shows the relative standard deviation values for the number of defects N_d depending on kinetic energy of primary knock-on atom (PKA) calculated using the IOTA code (complete modeling) and based on the simple variation of α, β, γ parameters, Eq.(12) with RSD values $\Delta p/p$ equal to 10, 12, and 15 percent, correspondingly. The E_d value was not varied and was assumed to be 40 eV. Calculations with $\Delta p/p$ equal to 12 percent approximate well the results of complete simulation.

The effect of the variation of individual parameters α, β, and γ on the RSD value $\Delta N_d/N_d$ is illustrated in Fig.2. Evidently, agreement with the results of complete simulation (Fig.1) can be improved by selecting individual $\Delta p/p$ values for different parameters.

Fig.3 shows $\Delta N_d/N_d$ values obtained from the simultaneous variation of α, β, and γ with RSD value equal to 12 percent for all parameters and the variation of E_d with the $\Delta E_d/E_d$ values equal to 10, 15, and 20 percent [7,23].

It is seen that the uncertainty of E_d has a significant impact on the value of $\Delta N_d/N_d$. This is not unexpected considering the form of Eq.(1)-(4) and the uncertainties of $d\sigma(E,T)$ and $(dE/dx)_{el}$. Taking into account data discussed in Ref.[24], the realistic estimate of $\Delta E_d/E_d$ seems to be about 20%, which corresponds to the black line in Fig.3. The corresponding correlation matrix for N_d shows strong correlations (Appendix, III).

3.2 Aluminum, zirconium, and tungsten

Similar calculations were made for aluminum, zirconium, and tungsten. Fig.4 shows results of modeling using the IOTA code and values obtained with the variation of α, β, and γ parameters approximating results of modeling. For tungsten, the values of $\Delta p/p$ are noticeably higher than those for other materials.

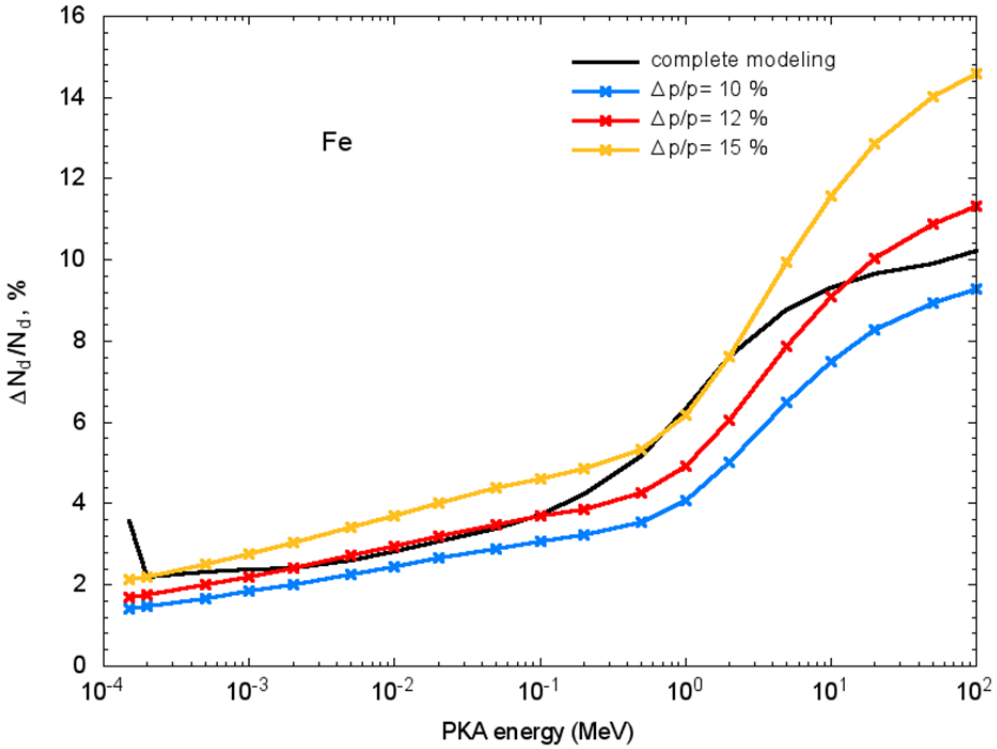

Fig.1 The relative standard deviation of the number of defects calculated for iron using the IOTA code ("complete modeling") and with the variation of α, β, and γ parameters with different RSD values. See explanations in the text.

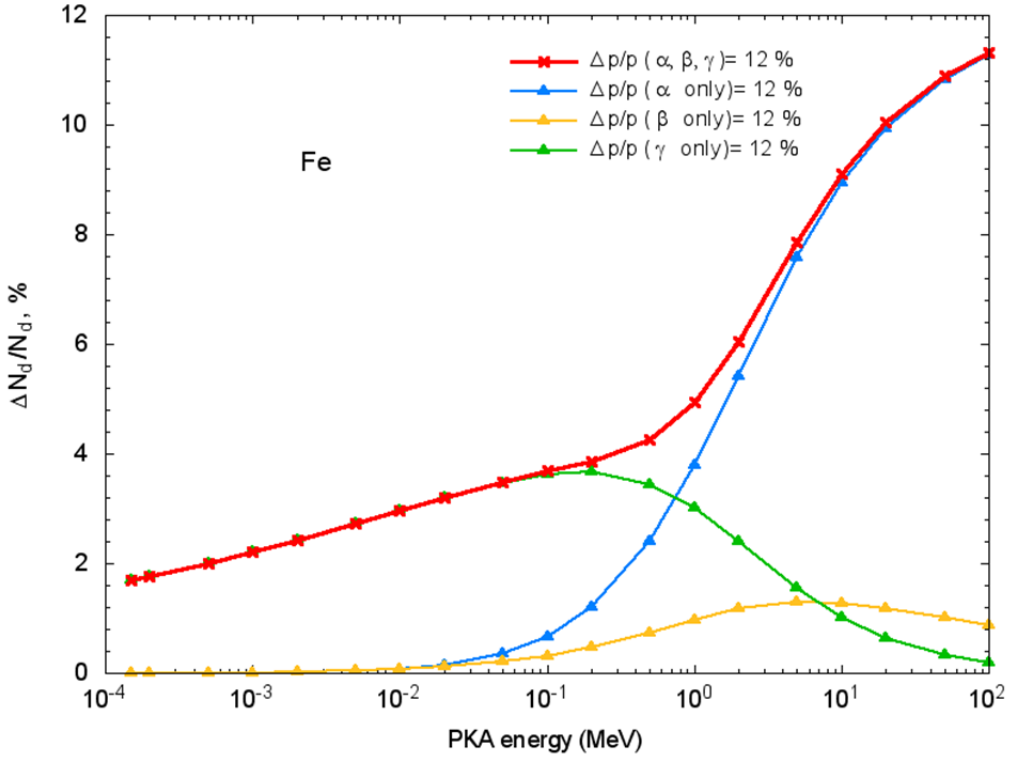

Fig.2 The $\Delta N_d/N_d$ values calculated for iron with the variation of three parameters α, β, γ, and with the variation of only one parameter. See explanations in the text.

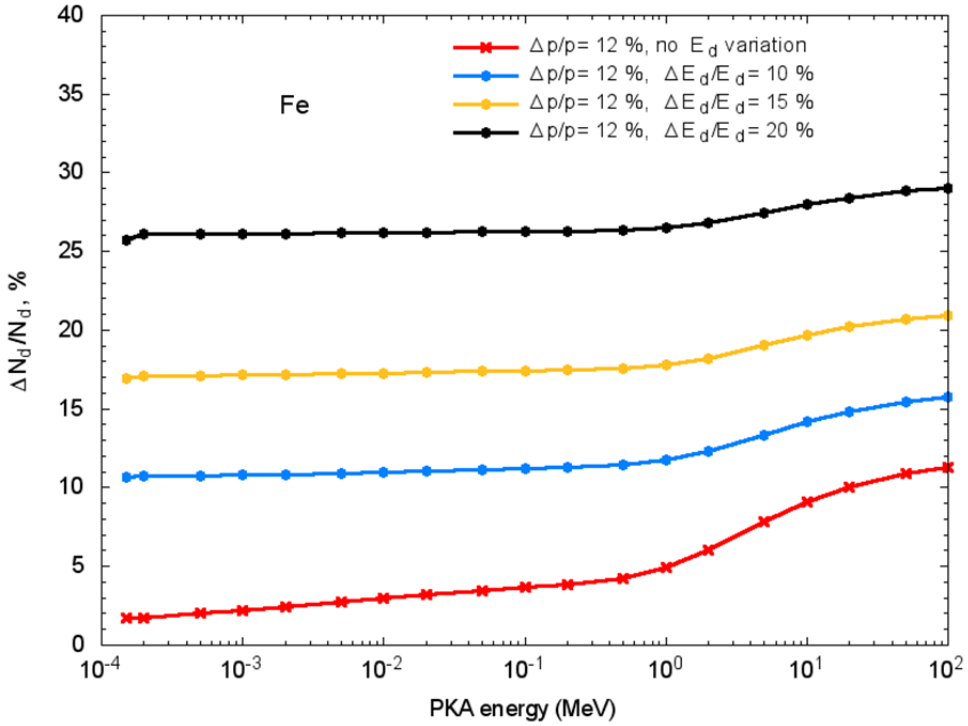

Fig.3 The relative standard deviation of the number of defects calculated for iron with the variation of α, β, γ parameters with the RSD value $\Delta p/p$ shown on the plot, and with the variation of threshold displacement energy with different RSD values $\Delta E_d/E_d$. See explanations in the text.

Figures 5-7 show the results obtained using α, β, and γ parameter variation along with the E_d variation. As in the case of iron, the uncertainty of E_d has a decisive influence on the RSD value for the calculated number of defects. The correlation matrices for aluminum and zirconium, calculated with $\Delta E_d/E_d$ equal to 20 percent, indicate strong correlation of the data, which is somewhat weaker for tungsten (Appendix, III). The E_d values for aluminum, zirconium, and tungsten were taken are equal to 27, 40, and 90 eV, correspondingly.

The obtained $\Delta N_d/N_d$ values and correlation matrices are shown in Appendix, III.

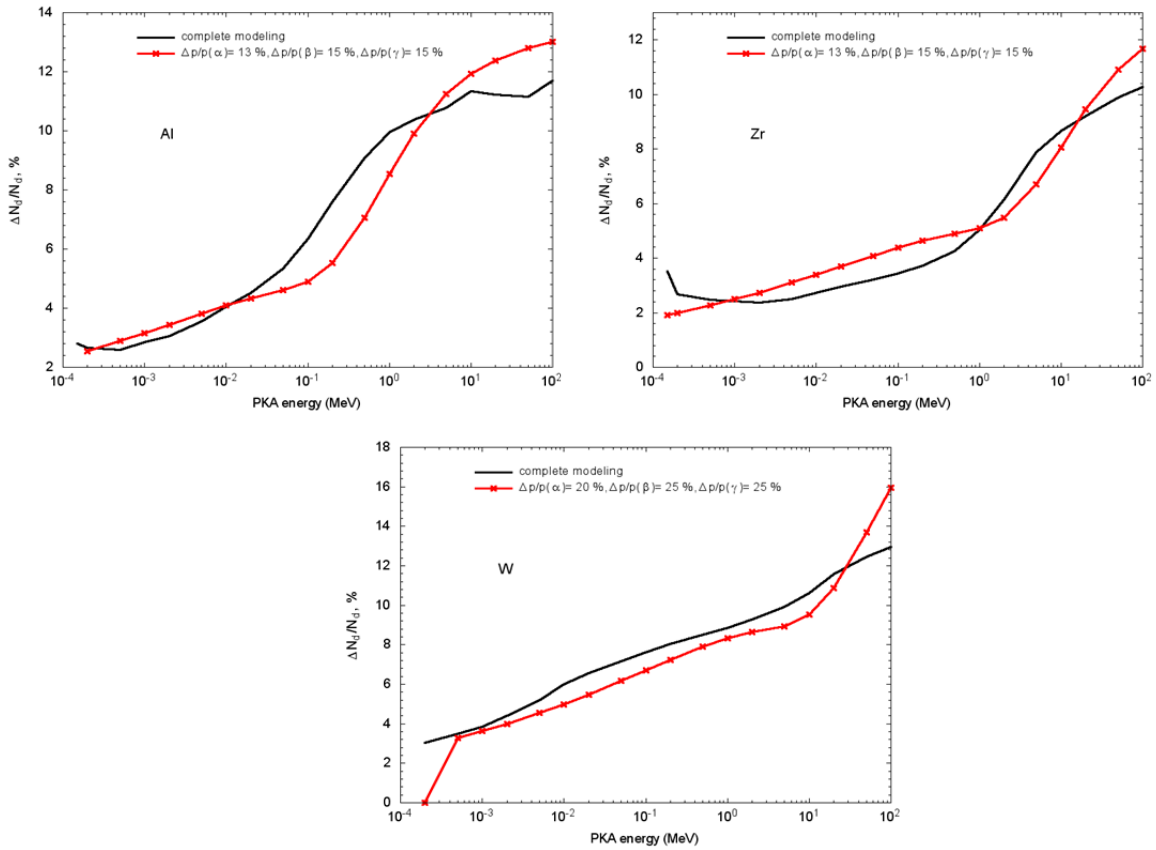

Fig.4 The relative standard deviation of the number of defects for Al, Zr, and W calculated using the IOTA code ("complete modeling") and with the variation of α, β, and γ parameters with different RSD values.

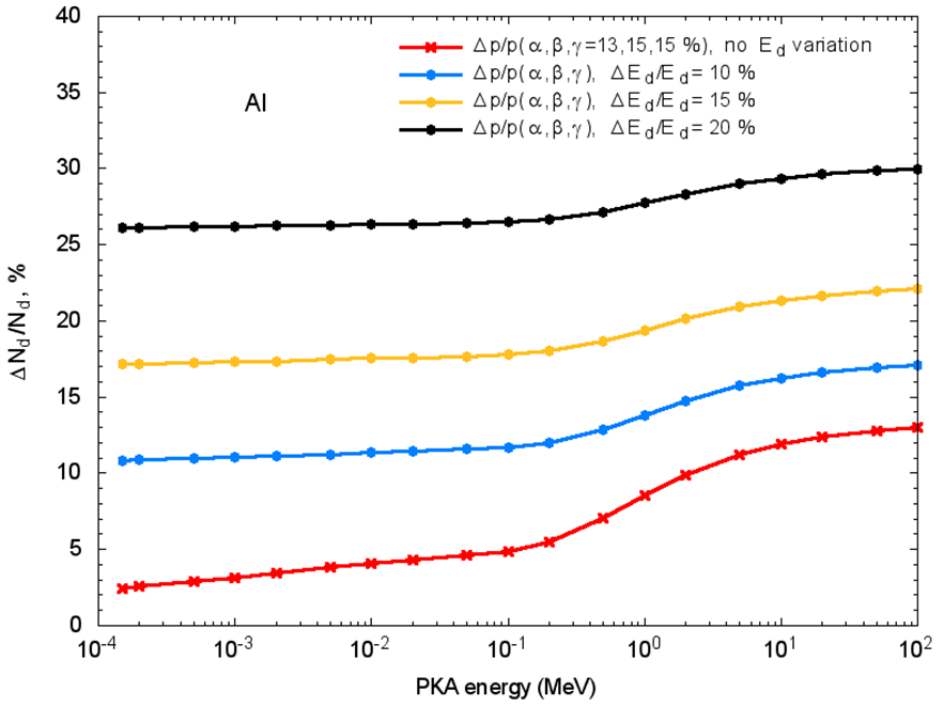

Fig.5 The relative standard deviation of the number of defects calculated for aluminum with the variation of α, β, γ parameters and threshold displacement energy. See comments to Fig.3.

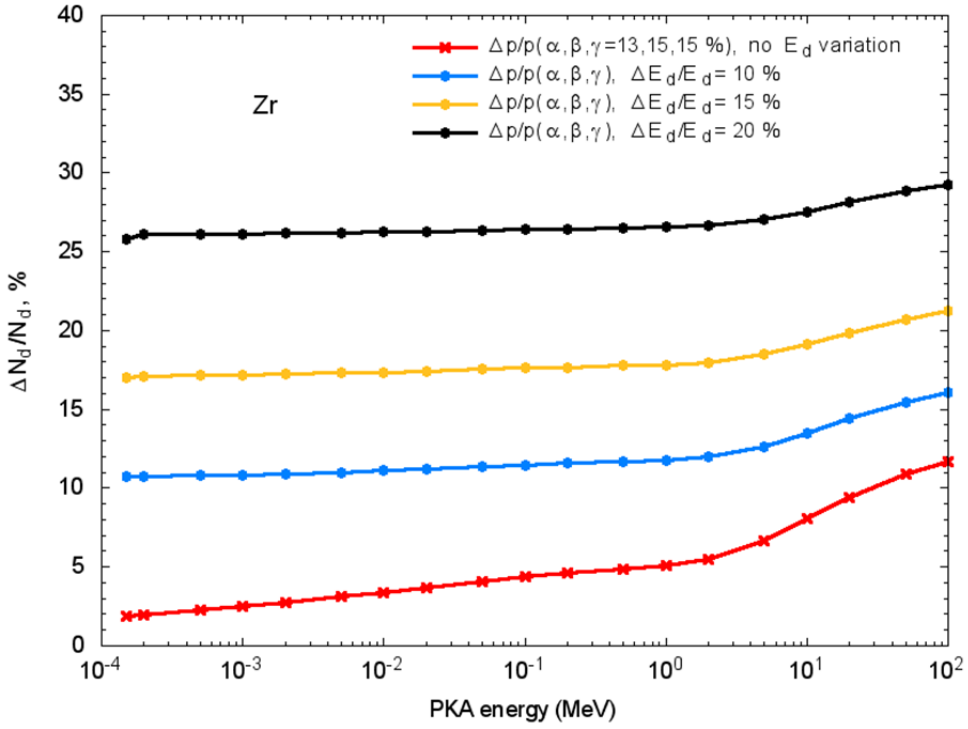

Fig.6 The relative standard deviation of the number of defects calculated for zirconium with the variation of α, β, γ parameters and threshold displacement energy. See comments to Fig.3.

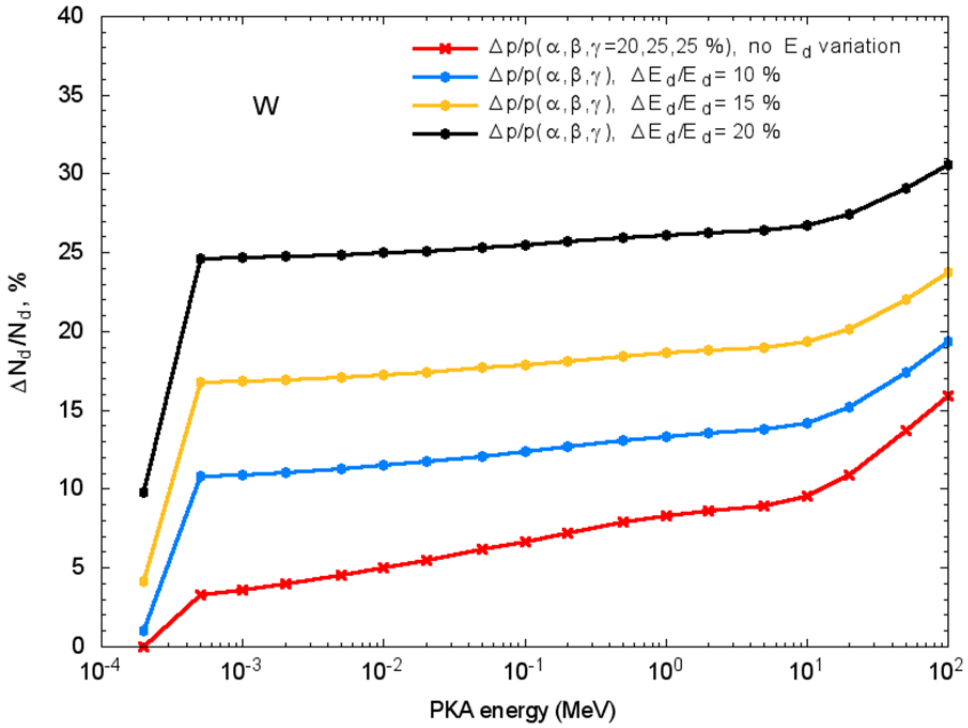

Fig.7 The relative standard deviation of the number of defects calculated for tungsten with the variation of α, β, γ parameters and threshold displacement energy. See comments to Fig.3.

4. Conclusion

The uncertainty of the number of defects calculated using the NRT model has been investigated. The study concerns the “internal” conceptual uncertainty of the model relating to the $M^{(par)}$ component of the covariance matrix, Eq.(1).

The results obtained are not unexpected. The uncertainty of the threshold displacement energy E_d has the greatest impact on the uncertainty of calculated number of defects. The $\Delta N_d/N_d$ values, corresponding to the reasonable estimate of $\Delta E_d/E_d$ equal to 20 percent, are shown with the black line in Figs.3,5-7. The N_d values calculated at different energies are quite strongly correlated. Obtained RSD values and correlation matrices are given in Appendix.

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Appendix

I. The number of defects calculated using different approaches

Fig.A1 and Fig.A2 show the number of defects calculated for iron using the NRT model [1,2], the SRIM code [21], the IOTA code with the IDSDT input parameter equal to 0, 1, 11, 13-15 [20], and the arc-dpa approach [25,26]. The electronic and nuclear stopping power applied for IOTA calculations are calculated with the SRIM code (Fig.A1) and utilizing the approach from Refs.[27,28] (Fig.A2) (SPAR option of IOTA).

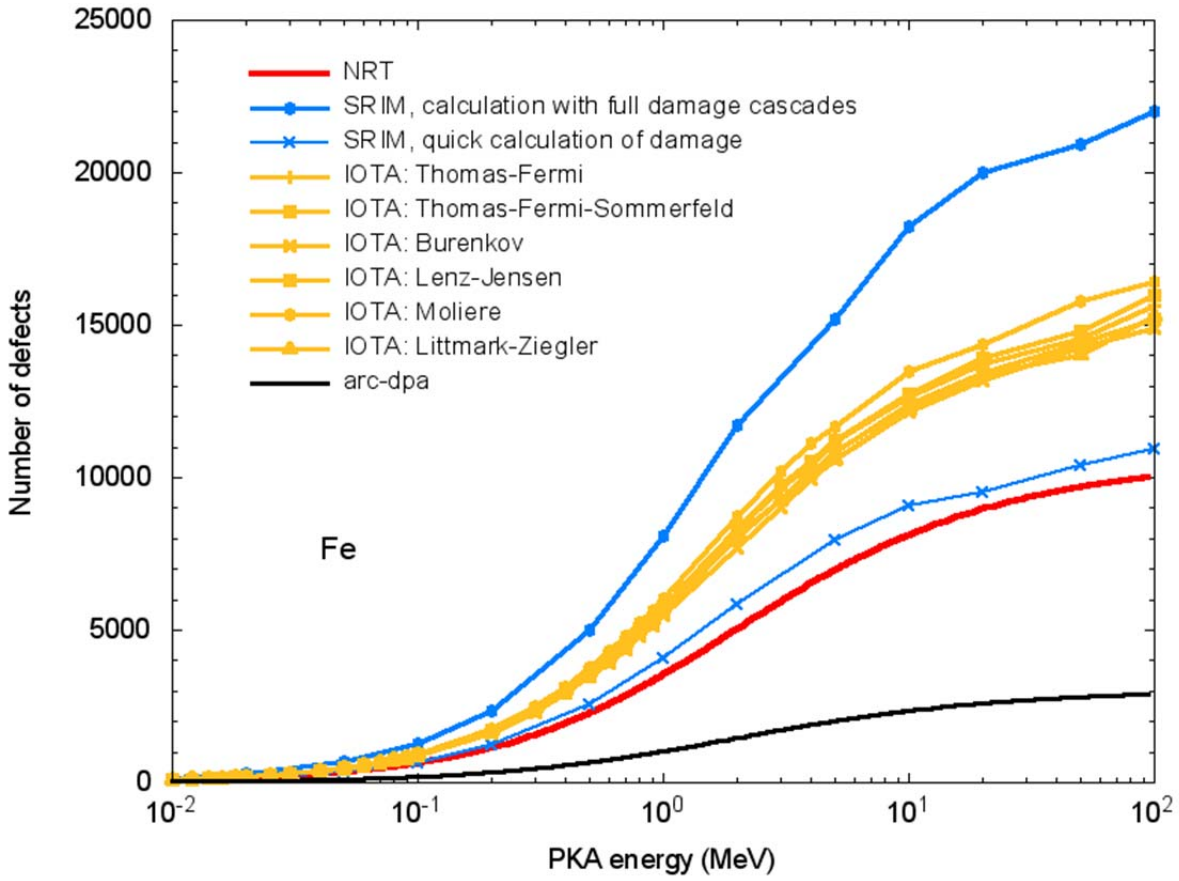

Fig.A1 The number of defects calculated for iron using various approaches. The electronic and nuclear stopping power for IOTA calculations was obtained using the SRIM code. See details in the text.

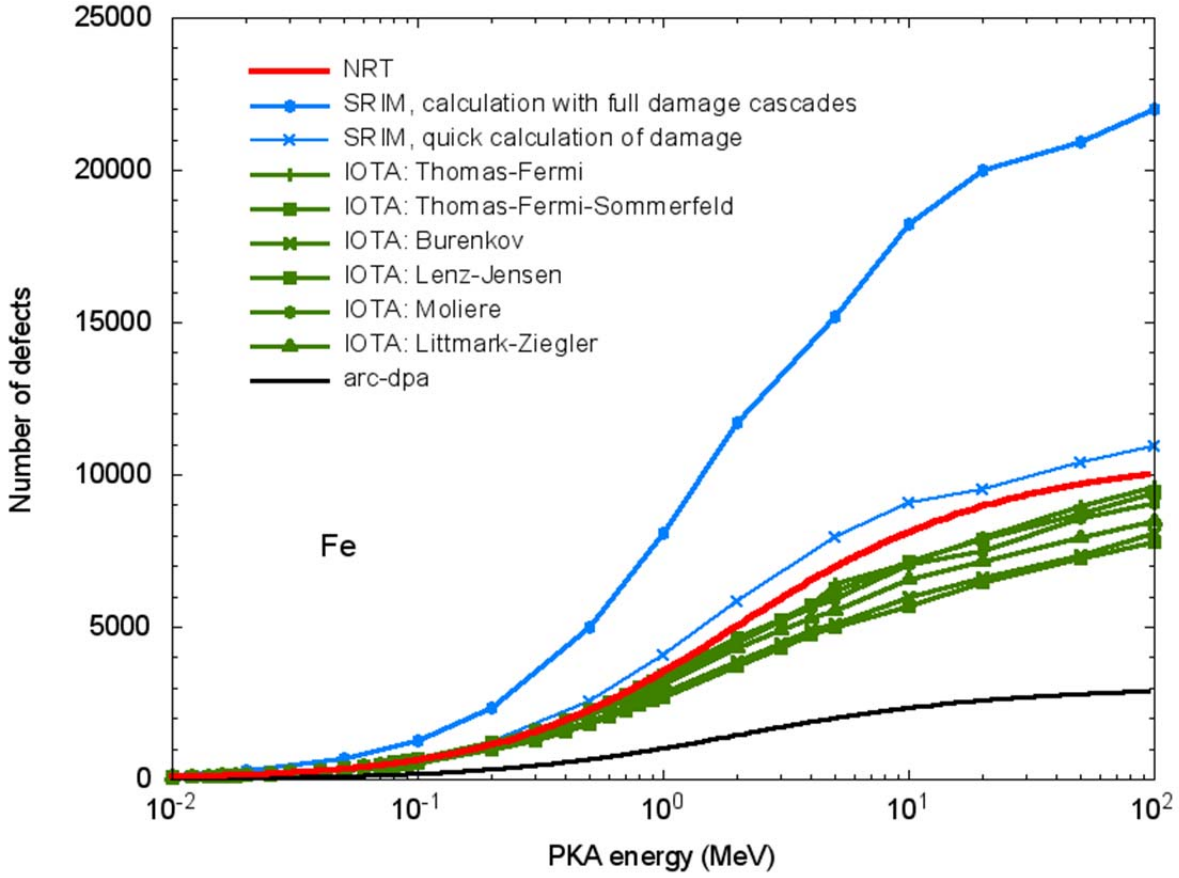

Fig.A2 The number of defects calculated for iron using various approaches. The model described in Refs.[27,28] was used to obtain electronic and nuclear stopping power in IOTA calculations (option SPAR). See details in the text

II. The damage energy, the damage efficiency, and the number of defects calculated using NRT

Fig.A3 shows the damage energy T_{dam} depending on the PKA kinetic energy calculated using Eq.(3)-(7) for aluminium, iron, zirconium, and tungsten. Fig.A4 shows the so-called damage efficiency [2] equal to the ratio of the damage energy (T_{dam}) to the kinetic energy of PKA (T). The N_d values are illustrated in Fig.A5.

In addition, the figures show values corresponding to the following kinetic energies estimated using the SRIM data [21]:

- the PKA energy T_{eq}, where electronic stopping power $(dE/dx)_{el}$ is approximately equal to nuclear stopping power $(dE/dx)_{nuc}$; for energies below T_{eq} the $(dE/dx)_{nuc}$ value exceeds $(dE/dx)_{el}$ (closed circle on the plots)

- the PKA energy $T_{max,el}$, where electronic stopping power has a maximum. Since the NRT model assumes $(dE/dx)_{el} \sim T^{1/2}$, the energy $T_{max,el}$ can be considered as a maximum energy limiting the model application. The $T_{max,el}$ value is quite close to the energy $0.025\ Z^{4/3}\ A$, MeV discussed in Ref.[1] (cross on the plots).

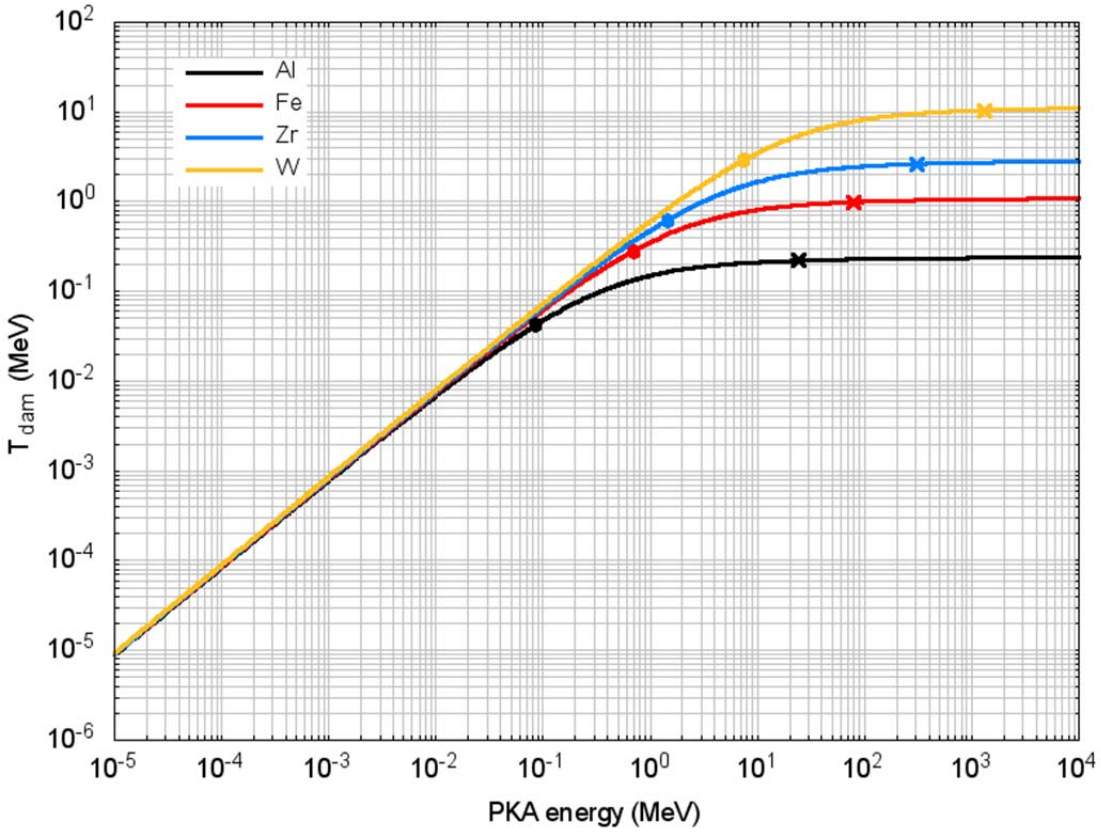

Fig.A3 The damage energy, Eq.(3)-(7) depending on kinetic energy of PKA. The energy T_{eq}: (•), $T_{max,el}$: (×). See explanations in the text.

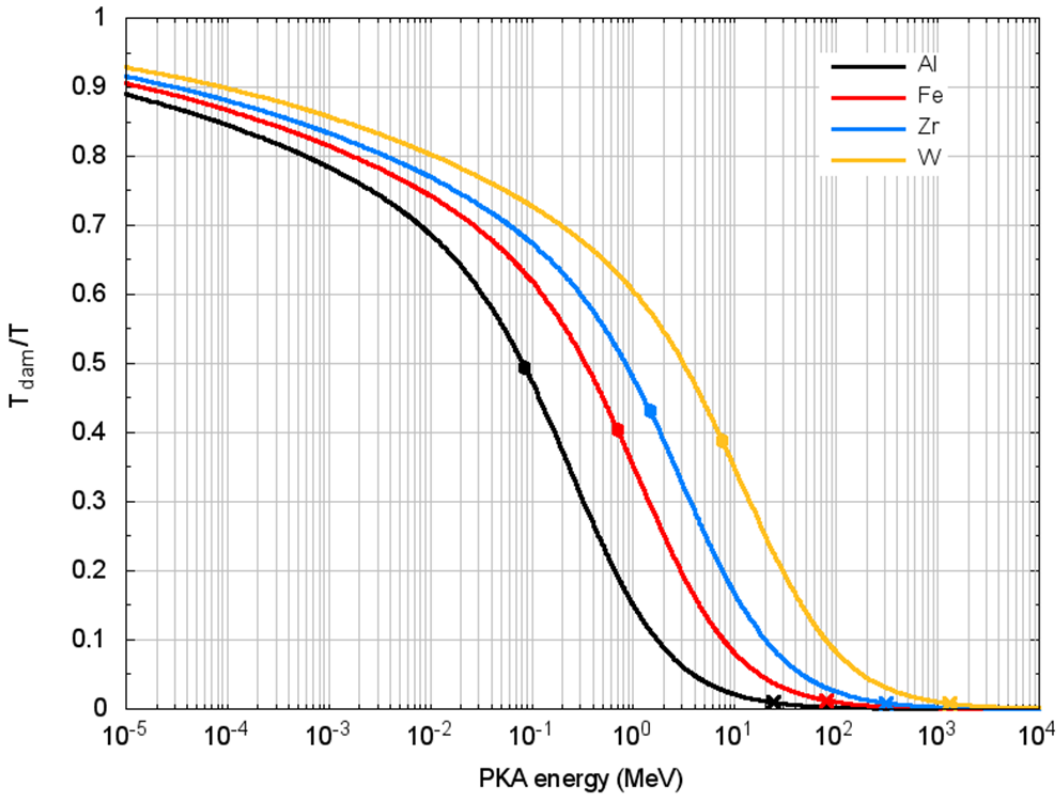

Fig.A4 The ratio of damage energy to kinetic energy of PKA depending on PKA energy. The energy T_{eq}: (•), $T_{max,el}$: (×). See explanations in the text.

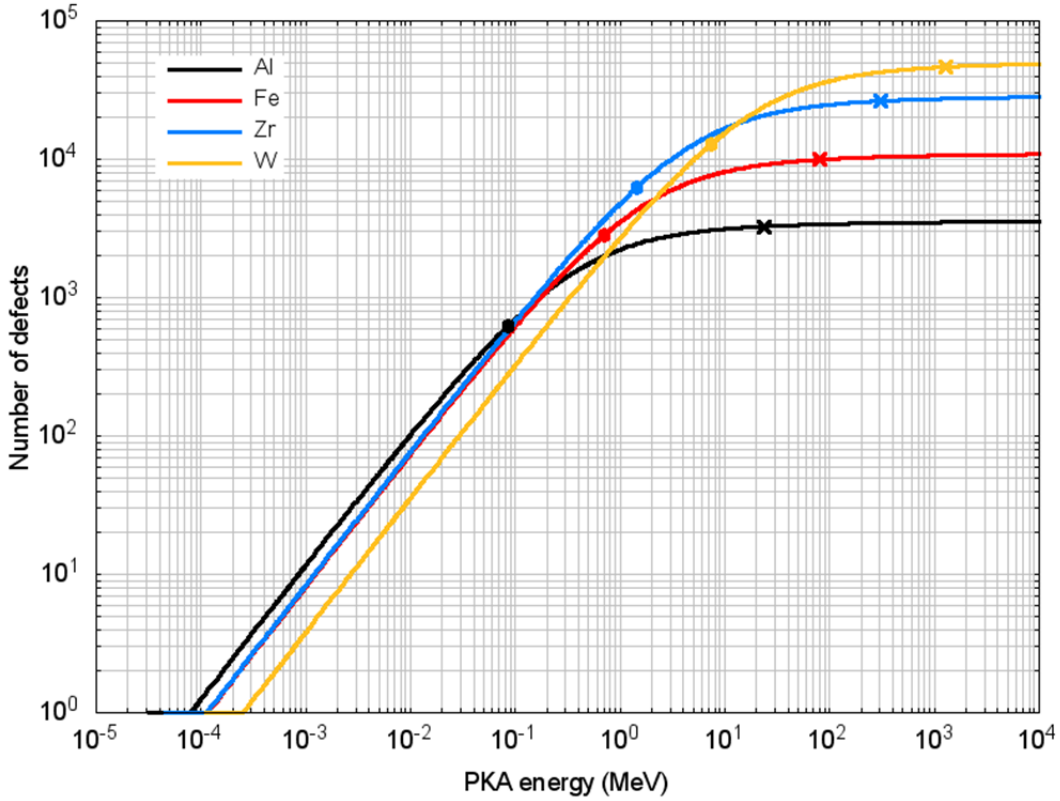

Fig.A5 The number of defects Nd calculated using the NRT model. The energy T_{eq}: (•), $T_{max,el}$: (×). See explanations in the text.

III. Relative standard deviations and correlation matrices for N_d

Aluminum. The RSD values $\Delta p/p$ (α, β, γ)= 13, 15, 15 %, $\Delta E_d/E_d$ = 10 %, the MC statistics (here and below): 5000 events

PKA energy, T (MeV)	T_{dam} (MeV)	N_d	ΔNd/Nd (%)
1.500E-04	1.254E-04	1.857E+00	10.84
2.000E-04	1.658E-04	2.456E+00	10.87
5.000E-04	4.024E-04	5.961E+00	10.95
1.000E-03	7.840E-04	1.161E+01	11.03
2.000E-03	1.521E-03	2.253E+01	11.12
5.000E-03	3.614E-03	5.354E+01	11.25
1.000E-02	6.868E-03	1.017E+02	11.35
2.000E-02	1.282E-02	1.899E+02	11.45
5.000E-02	2.787E-02	4.129E+02	11.57
1.000E-01	4.731E-02	7.009E+02	11.71
2.000E-01	7.459E-02	1.105E+03	12.01
5.000E-01	1.182E-01	1.751E+03	12.86
1.000E+00	1.500E-01	2.222E+03	13.79
2.000E+00	1.760E-01	2.607E+03	14.74
5.000E+00	1.998E-01	2.960E+03	15.73
1.000E+01	2.113E-01	3.130E+03	16.26
2.000E+01	2.191E-01	3.246E+03	16.63
5.000E+01	2.258E-01	3.346E+03	16.95
1.000E+02	2.293E-01	3.397E+03	17.12

Correlation matrix

1.000	1.000	0.999	0.998	0.996	0.993	0.989	0.985	0.977	0.962	0.931	0.855	0.788	0.730	0.678	0.653	0.638	0.624	0.618
1.000	1.000	1.000	0.998	0.997	0.994	0.990	0.987	0.978	0.964	0.932	0.855	0.787	0.729	0.677	0.652	0.636	0.623	0.617
0.999	1.000	1.000	1.000	0.999	0.997	0.994	0.991	0.983	0.967	0.934	0.856	0.786	0.727	0.674	0.649	0.633	0.619	0.613
0.998	0.998	1.000	1.000	1.000	0.998	0.996	0.993	0.986	0.970	0.936	0.856	0.786	0.726	0.671	0.646	0.630	0.616	0.610
0.996	0.997	0.999	1.000	1.000	0.999	0.998	0.996	0.988	0.973	0.938	0.857	0.786	0.725	0.670	0.644	0.628	0.614	0.608
0.993	0.994	0.997	0.998	0.999	1.000	1.000	0.998	0.992	0.977	0.942	0.861	0.788	0.727	0.671	0.646	0.629	0.615	0.609
0.989	0.990	0.994	0.996	0.998	1.000	1.000	0.999	0.994	0.980	0.947	0.867	0.795	0.734	0.678	0.653	0.636	0.622	0.616
0.985	0.987	0.991	0.993	0.996	0.998	0.999	1.000	0.997	0.986	0.956	0.879	0.809	0.749	0.695	0.669	0.653	0.639	0.633
0.977	0.978	0.983	0.986	0.988	0.992	0.994	0.997	1.000	0.995	0.974	0.910	0.847	0.792	0.740	0.716	0.700	0.687	0.681
0.962	0.964	0.967	0.970	0.973	0.977	0.980	0.986	0.995	1.000	0.991	0.945	0.893	0.844	0.798	0.776	0.762	0.750	0.744
0.931	0.932	0.934	0.936	0.938	0.942	0.947	0.956	0.974	0.991	1.000	0.980	0.944	0.907	0.870	0.851	0.838	0.828	0.822
0.855	0.855	0.856	0.856	0.857	0.861	0.867	0.879	0.910	0.945	0.980	1.000	0.991	0.973	0.950	0.938	0.929	0.921	0.917
0.788	0.787	0.786	0.786	0.786	0.788	0.795	0.809	0.847	0.893	0.944	0.991	1.000	0.995	0.983	0.976	0.970	0.964	0.961
0.730	0.729	0.727	0.726	0.725	0.727	0.734	0.749	0.792	0.844	0.907	0.973	0.995	1.000	0.996	0.993	0.989	0.986	0.984
0.678	0.677	0.674	0.671	0.670	0.671	0.678	0.695	0.740	0.798	0.870	0.950	0.983	0.996	1.000	0.999	0.998	0.996	0.995
0.653	0.652	0.649	0.646	0.644	0.646	0.653	0.669	0.716	0.776	0.851	0.938	0.976	0.993	0.999	1.000	1.000	0.999	0.998
0.638	0.636	0.633	0.630	0.628	0.629	0.636	0.653	0.700	0.762	0.838	0.929	0.970	0.989	0.998	1.000	1.000	1.000	0.999
0.624	0.623	0.619	0.616	0.614	0.615	0.622	0.639	0.687	0.750	0.828	0.921	0.964	0.986	0.996	0.999	1.000	1.000	1.000
0.618	0.617	0.613	0.610	0.608	0.609	0.616	0.633	0.681	0.744	0.822	0.917	0.961	0.984	0.995	0.998	0.999	1.000	1.000

Aluminum. The RSD values $\Delta p/p$ (α, β, γ)= 13, 15, 15 %, $\Delta E_d/E_d$ = 15 %

T (MeV)	T_{dam} (MeV)	N_d	$\Delta Nd/Nd$ (%)
1.500E-04	1.254E-04	1.857E+00	17.19
2.000E-04	1.658E-04	2.456E+00	17.20
5.000E-04	4.024E-04	5.961E+00	17.26
1.000E-03	7.840E-04	1.161E+01	17.31
2.000E-03	1.521E-03	2.253E+01	17.37
5.000E-03	3.614E-03	5.354E+01	17.46
1.000E-02	6.868E-03	1.017E+02	17.53
2.000E-02	1.282E-02	1.899E+02	17.60
5.000E-02	2.787E-02	4.129E+02	17.68
1.000E-01	4.731E-02	7.009E+02	17.79
2.000E-01	7.459E-02	1.105E+03	18.01
5.000E-01	1.182E-01	1.751E+03	18.66
1.000E+00	1.500E-01	2.222E+03	19.37
2.000E+00	1.760E-01	2.607E+03	20.12
5.000E+00	1.998E-01	2.960E+03	20.93
1.000E+01	2.113E-01	3.130E+03	21.37
2.000E+01	2.191E-01	3.246E+03	21.68
5.000E+01	2.258E-01	3.346E+03	21.95
1.000E+02	2.293E-01	3.397E+03	22.10

Correlation matrix

1.000	1.000	1.000	0.999	0.998	0.997	0.995	0.993	0.989	0.983	0.968	0.931	0.894	0.859	0.825	0.808	0.797	0.787	0.782
1.000	1.000	1.000	0.999	0.999	0.997	0.996	0.994	0.990	0.983	0.969	0.931	0.894	0.859	0.825	0.808	0.796	0.787	0.782
1.000	1.000	1.000	1.000	0.999	0.998	0.997	0.996	0.992	0.985	0.970	0.931	0.893	0.858	0.823	0.806	0.794	0.785	0.780
0.999	0.999	1.000	1.000	1.000	0.999	0.998	0.997	0.993	0.986	0.971	0.931	0.893	0.857	0.822	0.805	0.793	0.783	0.778
0.998	0.999	0.999	1.000	1.000	1.000	0.999	0.998	0.995	0.988	0.972	0.932	0.893	0.857	0.821	0.804	0.792	0.782	0.777
0.997	0.997	0.998	0.999	1.000	1.000	1.000	0.999	0.996	0.989	0.974	0.933	0.894	0.858	0.822	0.804	0.792	0.782	0.777
0.995	0.996	0.997	0.998	0.999	1.000	1.000	1.000	0.997	0.991	0.976	0.936	0.897	0.861	0.825	0.808	0.796	0.786	0.781
0.993	0.994	0.996	0.997	0.998	0.999	1.000	1.000	0.999	0.994	0.980	0.942	0.904	0.868	0.833	0.816	0.804	0.794	0.790
0.989	0.990	0.992	0.993	0.995	0.996	0.997	0.999	1.000	0.998	0.988	0.956	0.923	0.890	0.857	0.840	0.829	0.820	0.815
0.983	0.983	0.985	0.986	0.988	0.989	0.991	0.994	0.998	1.000	0.996	0.973	0.945	0.916	0.887	0.872	0.861	0.853	0.848
0.968	0.969	0.970	0.971	0.972	0.974	0.976	0.980	0.988	0.996	1.000	0.990	0.970	0.948	0.924	0.911	0.902	0.895	0.891
0.931	0.931	0.931	0.931	0.932	0.933	0.936	0.942	0.956	0.973	0.990	1.000	0.995	0.984	0.969	0.960	0.954	0.948	0.945
0.894	0.894	0.893	0.893	0.893	0.894	0.897	0.904	0.923	0.945	0.970	0.995	1.000	0.997	0.989	0.983	0.979	0.975	0.973
0.859	0.859	0.858	0.857	0.857	0.858	0.861	0.868	0.890	0.916	0.948	0.984	0.997	1.000	0.998	0.995	0.992	0.989	0.988
0.825	0.825	0.823	0.822	0.821	0.822	0.825	0.833	0.857	0.887	0.924	0.969	0.989	0.998	1.000	0.999	0.998	0.997	0.996
0.808	0.808	0.806	0.805	0.804	0.804	0.808	0.816	0.840	0.872	0.911	0.960	0.983	0.995	0.999	1.000	1.000	0.999	0.999
0.797	0.796	0.794	0.793	0.792	0.792	0.796	0.804	0.829	0.861	0.902	0.954	0.979	0.992	0.998	1.000	1.000	1.000	1.000
0.787	0.787	0.785	0.783	0.782	0.782	0.786	0.794	0.820	0.853	0.895	0.948	0.975	0.989	0.997	0.999	1.000	1.000	1.000
0.782	0.782	0.780	0.778	0.777	0.777	0.781	0.790	0.815	0.848	0.891	0.945	0.973	0.988	0.996	0.999	1.000	1.000	1.000

Aluminum. The RSD values $\Delta p/p$ (α, β, γ)= 13, 15, 15 %, $\Delta E_d/E_d$ = 20 %

T (MeV)	T_{dam} (MeV)	N_d	$\Delta Nd/Nd$ (%)
1.500E-04	1.254E-04	1.857E+00	26.15
2.000E-04	1.658E-04	2.456E+00	26.15
5.000E-04	4.024E-04	5.961E+00	26.18
1.000E-03	7.840E-04	1.161E+01	26.21
2.000E-03	1.521E-03	2.253E+01	26.25
5.000E-03	3.614E-03	5.354E+01	26.30
1.000E-02	6.868E-03	1.017E+02	26.35
2.000E-02	1.282E-02	1.899E+02	26.39
5.000E-02	2.787E-02	4.129E+02	26.44
1.000E-01	4.731E-02	7.009E+02	26.51
2.000E-01	7.459E-02	1.105E+03	26.68
5.000E-01	1.182E-01	1.751E+03	27.17
1.000E+00	1.500E-01	2.222E+03	27.74
2.000E+00	1.760E-01	2.607E+03	28.34
5.000E+00	1.998E-01	2.960E+03	29.01
1.000E+01	2.113E-01	3.130E+03	29.37
2.000E+01	2.191E-01	3.246E+03	29.62
5.000E+01	2.258E-01	3.346E+03	29.85
1.000E+02	2.293E-01	3.397E+03	29.97

Correlation matrix

1.000	1.000	1.000	1.000	0.999	0.998	0.998	0.997	0.995	0.992	0.984	0.965	0.946	0.926	0.906	0.896	0.889	0.883	0.879
1.000	1.000	1.000	1.000	0.999	0.999	0.998	0.997	0.995	0.992	0.985	0.966	0.946	0.926	0.906	0.896	0.889	0.882	0.879
1.000	1.000	1.000	1.000	1.000	0.999	0.999	0.998	0.996	0.993	0.985	0.966	0.946	0.926	0.905	0.895	0.888	0.881	0.878
1.000	1.000	1.000	1.000	1.000	1.000	0.999	0.999	0.997	0.993	0.986	0.966	0.945	0.925	0.905	0.894	0.887	0.881	0.877
0.999	0.999	1.000	1.000	1.000	1.000	1.000	0.999	0.997	0.994	0.986	0.966	0.945	0.925	0.904	0.894	0.886	0.880	0.877
0.998	0.999	0.999	1.000	1.000	1.000	1.000	1.000	0.998	0.995	0.987	0.967	0.946	0.926	0.905	0.894	0.887	0.880	0.877
0.998	0.998	0.999	0.999	1.000	1.000	1.000	1.000	0.999	0.996	0.988	0.968	0.948	0.927	0.906	0.896	0.888	0.882	0.879
0.997	0.997	0.998	0.999	0.999	1.000	1.000	1.000	0.999	0.997	0.990	0.971	0.951	0.931	0.911	0.900	0.893	0.886	0.883
0.995	0.995	0.996	0.997	0.997	0.998	0.999	0.999	1.000	0.999	0.994	0.978	0.960	0.942	0.923	0.913	0.906	0.900	0.897
0.992	0.992	0.993	0.993	0.994	0.995	0.996	0.997	0.999	1.000	0.998	0.986	0.971	0.955	0.938	0.929	0.923	0.917	0.914
0.984	0.985	0.985	0.986	0.986	0.987	0.988	0.990	0.994	0.998	1.000	0.995	0.984	0.972	0.958	0.950	0.945	0.940	0.937
0.965	0.966	0.966	0.966	0.966	0.967	0.968	0.971	0.978	0.986	0.995	1.000	0.997	0.991	0.982	0.977	0.973	0.969	0.967
0.946	0.946	0.946	0.945	0.945	0.946	0.948	0.951	0.960	0.971	0.984	0.997	1.000	0.998	0.993	0.990	0.987	0.985	0.983
0.926	0.926	0.926	0.925	0.925	0.926	0.927	0.931	0.942	0.955	0.972	0.991	0.998	1.000	0.998	0.997	0.995	0.993	0.992
0.906	0.906	0.905	0.905	0.904	0.905	0.906	0.911	0.923	0.938	0.958	0.982	0.993	0.998	1.000	1.000	0.999	0.998	0.998
0.896	0.896	0.895	0.894	0.894	0.894	0.896	0.900	0.913	0.929	0.950	0.977	0.990	0.997	1.000	1.000	1.000	0.999	0.999
0.889	0.889	0.888	0.887	0.886	0.887	0.888	0.893	0.906	0.923	0.945	0.973	0.987	0.995	0.999	1.000	1.000	1.000	1.000
0.883	0.882	0.881	0.881	0.880	0.880	0.882	0.886	0.900	0.917	0.940	0.969	0.985	0.993	0.998	0.999	1.000	1.000	1.000
0.879	0.879	0.878	0.877	0.877	0.877	0.879	0.883	0.897	0.914	0.937	0.967	0.983	0.992	0.998	0.999	1.000	1.000	1.000

Iron. The RSD values $\Delta p/p$ (α, β, γ)= 12 %, $\Delta E_d/E_d$ = 10 %

T (MeV)	T_{dam} (MeV)	N_d	$\Delta Nd/Nd$ (%)
1.500E-04	1.288E-04	1.288E+00	10.69
2.000E-04	1.705E-04	1.705E+00	10.71
5.000E-04	4.161E-04	4.161E+00	10.75
1.000E-03	8.148E-04	8.148E+00	10.79
2.000E-03	1.591E-03	1.591E+01	10.84
5.000E-03	3.837E-03	3.837E+01	10.91
1.000E-02	7.425E-03	7.425E+01	10.97
2.000E-02	1.427E-02	1.427E+02	11.04
5.000E-02	3.330E-02	3.330E+02	11.14
1.000E-01	6.187E-02	6.187E+02	11.21
2.000E-01	1.115E-01	1.115E+03	11.28
5.000E-01	2.250E-01	2.250E+03	11.43
1.000E+00	3.516E-01	3.516E+03	11.73
2.000E+00	5.014E-01	5.014E+03	12.29
5.000E+00	6.941E-01	6.941E+03	13.35
1.000E+01	8.102E-01	8.102E+03	14.17
2.000E+01	8.949E-01	8.949E+03	14.84
5.000E+01	9.675E-01	9.675E+03	15.47
1.000E+02	1.002E+00	1.002E+04	15.79

Correlation matrix

1.000	1.000	1.000	0.999	0.998	0.995	0.993	0.990	0.986	0.983	0.978	0.962	0.934	0.886	0.809	0.758	0.722	0.691	0.677
1.000	1.000	1.000	0.999	0.998	0.996	0.994	0.991	0.987	0.984	0.979	0.963	0.934	0.886	0.809	0.758	0.721	0.690	0.676
1.000	1.000	1.000	1.000	0.999	0.998	0.996	0.994	0.991	0.987	0.982	0.966	0.937	0.887	0.808	0.757	0.719	0.688	0.674
0.999	0.999	1.000	1.000	1.000	0.999	0.998	0.996	0.993	0.990	0.985	0.969	0.938	0.888	0.808	0.756	0.718	0.686	0.671
0.998	0.998	0.999	1.000	1.000	1.000	0.999	0.997	0.995	0.992	0.987	0.971	0.940	0.888	0.807	0.754	0.716	0.684	0.669
0.995	0.996	0.998	0.999	1.000	1.000	1.000	0.999	0.997	0.995	0.990	0.973	0.942	0.889	0.806	0.753	0.714	0.681	0.667
0.993	0.994	0.996	0.998	0.999	1.000	1.000	1.000	0.999	0.997	0.992	0.975	0.943	0.890	0.806	0.752	0.713	0.681	0.666
0.990	0.991	0.994	0.996	0.997	0.999	1.000	1.000	0.999	0.998	0.994	0.978	0.946	0.892	0.808	0.754	0.714	0.682	0.667
0.986	0.987	0.991	0.993	0.995	0.997	0.999	0.999	1.000	0.999	0.997	0.982	0.951	0.899	0.816	0.762	0.723	0.690	0.675
0.983	0.984	0.987	0.990	0.992	0.995	0.997	0.998	0.999	1.000	0.999	0.987	0.959	0.910	0.830	0.777	0.739	0.707	0.692
0.978	0.979	0.982	0.985	0.987	0.990	0.992	0.994	0.997	0.999	1.000	0.994	0.972	0.929	0.855	0.805	0.768	0.737	0.723
0.962	0.963	0.966	0.969	0.971	0.973	0.975	0.978	0.982	0.987	0.994	1.000	0.992	0.964	0.907	0.865	0.834	0.806	0.793
0.934	0.934	0.937	0.938	0.940	0.942	0.943	0.946	0.951	0.959	0.972	0.992	1.000	0.990	0.952	0.921	0.895	0.873	0.862
0.886	0.886	0.887	0.888	0.888	0.889	0.890	0.892	0.899	0.910	0.929	0.964	0.990	1.000	0.986	0.967	0.949	0.933	0.924
0.809	0.809	0.808	0.808	0.807	0.806	0.806	0.808	0.816	0.830	0.855	0.907	0.952	0.986	1.000	0.996	0.988	0.979	0.975
0.758	0.758	0.757	0.756	0.754	0.753	0.752	0.754	0.762	0.777	0.805	0.865	0.921	0.967	0.996	1.000	0.998	0.994	0.991
0.722	0.721	0.719	0.718	0.716	0.714	0.713	0.714	0.723	0.739	0.768	0.834	0.895	0.949	0.988	0.998	1.000	0.999	0.997
0.691	0.690	0.688	0.686	0.684	0.681	0.681	0.682	0.690	0.707	0.737	0.806	0.873	0.933	0.979	0.994	0.999	1.000	1.000
0.677	0.676	0.674	0.671	0.669	0.667	0.666	0.667	0.675	0.692	0.723	0.793	0.862	0.924	0.975	0.991	0.997	1.000	1.000

Iron. The RSD values $\Delta p/p$ (α, β, γ)= 12 %, $\Delta E_d/E_d$ = 15 %

T (MeV)	T_{dam} (MeV)	N_d	$\Delta Nd/Nd$ (%)
1.500E-04	1.288E-04	1.288E+00	16.98
2.000E-04	1.705E-04	1.705E+00	17.10
5.000E-04	4.161E-04	4.161E+00	17.13
1.000E-03	8.148E-04	8.148E+00	17.15
2.000E-03	1.591E-03	1.591E+01	17.18
5.000E-03	3.837E-03	3.837E+01	17.23
1.000E-02	7.425E-03	7.425E+01	17.27
2.000E-02	1.427E-02	1.427E+02	17.32
5.000E-02	3.330E-02	3.330E+02	17.38
1.000E-01	6.187E-02	6.187E+02	17.43
2.000E-01	1.115E-01	1.115E+03	17.48
5.000E-01	2.250E-01	2.250E+03	17.60
1.000E+00	3.516E-01	3.516E+03	17.81
2.000E+00	5.014E-01	5.014E+03	18.22
5.000E+00	6.941E-01	6.941E+03	19.03
1.000E+01	8.102E-01	8.102E+03	19.67
2.000E+01	8.949E-01	8.949E+03	20.21
5.000E+01	9.675E-01	9.675E+03	20.72
1.000E+02	1.002E+00	1.002E+04	20.98

Correlation matrix

1.000	0.999	0.999	0.999	0.998	0.997	0.996	0.995	0.993	0.992	0.990	0.983	0.970	0.947	0.907	0.877	0.855	0.834	0.824
0.999	1.000	1.000	1.000	0.999	0.998	0.997	0.996	0.994	0.993	0.991	0.984	0.971	0.948	0.907	0.877	0.854	0.834	0.824
0.999	1.000	1.000	1.000	1.000	0.999	0.998	0.997	0.996	0.994	0.992	0.985	0.972	0.948	0.906	0.877	0.853	0.833	0.823
0.999	1.000	1.000	1.000	1.000	1.000	0.999	0.998	0.997	0.996	0.993	0.986	0.972	0.948	0.906	0.876	0.853	0.832	0.822
0.998	0.999	1.000	1.000	1.000	1.000	0.999	0.999	0.998	0.997	0.994	0.987	0.973	0.949	0.906	0.875	0.852	0.831	0.821
0.997	0.998	0.999	1.000	1.000	1.000	1.000	1.000	0.999	0.998	0.996	0.988	0.974	0.949	0.906	0.875	0.851	0.829	0.819
0.996	0.997	0.998	0.999	0.999	1.000	1.000	1.000	0.999	0.999	0.997	0.989	0.975	0.949	0.906	0.875	0.850	0.829	0.819
0.995	0.996	0.997	0.998	0.999	1.000	1.000	1.000	1.000	0.999	0.997	0.990	0.976	0.950	0.906	0.875	0.851	0.829	0.819
0.993	0.994	0.996	0.997	0.998	0.999	0.999	1.000	1.000	1.000	0.999	0.992	0.978	0.953	0.910	0.879	0.855	0.834	0.823
0.992	0.993	0.994	0.996	0.997	0.998	0.999	0.999	1.000	1.000	0.999	0.994	0.982	0.958	0.917	0.886	0.863	0.842	0.832
0.990	0.991	0.992	0.993	0.994	0.996	0.997	0.997	0.999	0.999	1.000	0.997	0.987	0.967	0.928	0.900	0.877	0.857	0.847
0.983	0.984	0.985	0.986	0.987	0.988	0.989	0.990	0.992	0.994	0.997	1.000	0.996	0.983	0.953	0.929	0.910	0.892	0.883
0.970	0.971	0.972	0.972	0.973	0.974	0.975	0.976	0.978	0.982	0.987	0.996	1.000	0.995	0.975	0.957	0.941	0.926	0.919
0.947	0.948	0.948	0.948	0.949	0.949	0.949	0.950	0.953	0.958	0.967	0.983	0.995	1.000	0.992	0.981	0.970	0.959	0.953
0.907	0.907	0.906	0.906	0.906	0.906	0.906	0.906	0.910	0.917	0.928	0.953	0.975	0.992	1.000	0.997	0.992	0.986	0.983
0.877	0.877	0.877	0.876	0.875	0.875	0.875	0.875	0.879	0.886	0.900	0.929	0.957	0.981	0.997	1.000	0.999	0.996	0.994
0.855	0.854	0.853	0.853	0.852	0.851	0.850	0.851	0.855	0.863	0.877	0.910	0.941	0.970	0.992	0.999	1.000	0.999	0.998
0.834	0.834	0.833	0.832	0.831	0.829	0.829	0.829	0.834	0.842	0.857	0.892	0.926	0.959	0.986	0.996	0.999	1.000	1.000
0.824	0.824	0.823	0.822	0.821	0.819	0.819	0.819	0.823	0.832	0.847	0.883	0.919	0.953	0.983	0.994	0.998	1.000	1.000

Iron. The RSD values $\Delta p/p$ (α, β, γ)= 12 %, $\Delta E_d/E_d$ = 20 %

T (MeV)	T_{dam} (MeV)	N_d	$\Delta Nd/Nd$ (%)
1.500E-04	1.288E-04	1.288E+00	25.75
2.000E-04	1.705E-04	1.705E+00	26.10
5.000E-04	4.161E-04	4.161E+00	26.12
1.000E-03	8.148E-04	8.148E+00	26.13
2.000E-03	1.591E-03	1.591E+01	26.14
5.000E-03	3.837E-03	3.837E+01	26.17
1.000E-02	7.425E-03	7.425E+01	26.19
2.000E-02	1.427E-02	1.427E+02	26.22
5.000E-02	3.330E-02	3.330E+02	26.25
1.000E-01	6.187E-02	6.187E+02	26.28
2.000E-01	1.115E-01	1.115E+03	26.31
5.000E-01	2.250E-01	2.250E+03	26.38
1.000E+00	3.516E-01	3.516E+03	26.54
2.000E+00	5.014E-01	5.014E+03	26.85
5.000E+00	6.941E-01	6.941E+03	27.48
1.000E+01	8.102E-01	8.102E+03	27.99
2.000E+01	8.949E-01	8.949E+03	28.43
5.000E+01	9.675E-01	9.675E+03	28.84
1.000E+02	1.002E+00	1.002E+04	29.05

Correlation matrix

1.000	0.998	0.998	0.998	0.998	0.997	0.997	0.996	0.995	0.994	0.993	0.990	0.984	0.973	0.952	0.936	0.923	0.911	0.905
0.998	1.000	1.000	1.000	1.000	0.999	0.999	0.998	0.997	0.997	0.995	0.992	0.986	0.974	0.953	0.937	0.924	0.911	0.905
0.998	1.000	1.000	1.000	1.000	1.000	0.999	0.999	0.998	0.997	0.996	0.993	0.986	0.974	0.953	0.936	0.923	0.911	0.905
0.998	1.000	1.000	1.000	1.000	1.000	1.000	0.999	0.998	0.998	0.997	0.993	0.987	0.975	0.953	0.936	0.923	0.910	0.904
0.998	1.000	1.000	1.000	1.000	1.000	1.000	0.999	0.999	0.998	0.997	0.994	0.987	0.975	0.953	0.936	0.922	0.910	0.904
0.997	0.999	1.000	1.000	1.000	1.000	1.000	1.000	0.999	0.999	0.998	0.994	0.987	0.975	0.953	0.936	0.922	0.909	0.903
0.997	0.999	0.999	1.000	1.000	1.000	1.000	1.000	1.000	0.999	0.998	0.995	0.988	0.975	0.953	0.936	0.922	0.909	0.903
0.996	0.998	0.999	0.999	0.999	1.000	1.000	1.000	1.000	1.000	0.999	0.995	0.988	0.976	0.953	0.936	0.922	0.909	0.903
0.995	0.997	0.998	0.998	0.999	0.999	1.000	1.000	1.000	1.000	0.999	0.996	0.990	0.977	0.955	0.938	0.924	0.912	0.905
0.994	0.997	0.997	0.998	0.998	0.999	0.999	1.000	1.000	1.000	1.000	0.997	0.991	0.980	0.958	0.941	0.928	0.916	0.910
0.993	0.995	0.996	0.997	0.997	0.998	0.998	0.999	0.999	1.000	1.000	0.999	0.994	0.984	0.964	0.948	0.935	0.924	0.918
0.990	0.992	0.993	0.993	0.994	0.994	0.995	0.995	0.996	0.997	0.999	1.000	0.998	0.992	0.976	0.963	0.952	0.942	0.936
0.984	0.986	0.986	0.987	0.987	0.987	0.988	0.988	0.990	0.991	0.994	0.998	1.000	0.998	0.987	0.977	0.968	0.959	0.955
0.973	0.974	0.974	0.975	0.975	0.975	0.975	0.976	0.977	0.980	0.984	0.992	0.998	1.000	0.996	0.990	0.983	0.977	0.973
0.952	0.953	0.953	0.953	0.953	0.953	0.953	0.953	0.955	0.958	0.964	0.976	0.987	0.996	1.000	0.999	0.996	0.992	0.990
0.936	0.937	0.936	0.936	0.936	0.936	0.936	0.936	0.938	0.941	0.948	0.963	0.977	0.990	0.999	1.000	0.999	0.997	0.996
0.923	0.924	0.923	0.923	0.922	0.922	0.922	0.922	0.924	0.928	0.935	0.952	0.968	0.983	0.996	0.999	1.000	0.999	0.999
0.911	0.911	0.911	0.910	0.910	0.909	0.909	0.909	0.912	0.916	0.924	0.942	0.959	0.977	0.992	0.997	0.999	1.000	1.000
0.905	0.905	0.905	0.904	0.904	0.903	0.903	0.903	0.905	0.910	0.918	0.936	0.955	0.973	0.990	0.996	0.999	1.000	1.000

Zirconium. The RSD values $\Delta p/p$ (α, β, γ)= 13, 15, 15 %, $\Delta E_d/E_d$ = 10 %

T (MeV)	T_{dam} (MeV)	N_d	$\Delta Nd/Nd$ (%)
1.500E-04	1.310E-04	1.310E+00	10.73
2.000E-04	1.735E-04	1.735E+00	10.75
5.000E-04	4.245E-04	4.245E+00	10.80
1.000E-03	8.333E-04	8.333E+00	10.85
2.000E-03	1.632E-03	1.632E+01	10.92
5.000E-03	3.955E-03	3.955E+01	11.01
1.000E-02	7.697E-03	7.697E+01	11.10
2.000E-02	1.492E-02	1.492E+02	11.20
5.000E-02	3.543E-02	3.543E+02	11.35
1.000E-01	6.740E-02	6.740E+02	11.46
2.000E-01	1.262E-01	1.262E+03	11.57
5.000E-01	2.776E-01	2.776E+03	11.69
1.000E+00	4.789E-01	4.789E+03	11.79
2.000E+00	7.730E-01	7.730E+03	11.99
5.000E+00	1.274E+00	1.274E+04	12.65
1.000E+01	1.665E+00	1.665E+04	13.48
2.000E+01	2.000E+00	2.000E+04	14.42
5.000E+01	2.320E+00	2.320E+04	15.49
1.000E+02	2.477E+00	2.477E+04	16.08

Correlation matrix

1.000	1.000	0.999	0.998	0.997	0.994	0.991	0.987	0.981	0.976	0.971	0.963	0.954	0.933	0.873	0.811	0.752	0.695	0.667
1.000	1.000	1.000	0.999	0.998	0.995	0.992	0.988	0.982	0.978	0.972	0.965	0.955	0.934	0.874	0.811	0.752	0.694	0.666
0.999	1.000	1.000	1.000	0.999	0.997	0.995	0.992	0.987	0.983	0.978	0.971	0.961	0.938	0.876	0.812	0.751	0.692	0.664
0.998	0.999	1.000	1.000	1.000	0.999	0.997	0.994	0.990	0.986	0.982	0.975	0.965	0.941	0.878	0.812	0.749	0.690	0.661
0.997	0.998	0.999	1.000	1.000	0.999	0.998	0.997	0.993	0.990	0.986	0.979	0.968	0.944	0.879	0.811	0.748	0.687	0.658
0.994	0.995	0.997	0.999	0.999	1.000	1.000	0.999	0.996	0.994	0.990	0.984	0.973	0.948	0.880	0.810	0.746	0.684	0.654
0.991	0.992	0.995	0.997	0.998	1.000	1.000	1.000	0.998	0.996	0.993	0.987	0.976	0.950	0.880	0.810	0.744	0.681	0.651
0.987	0.988	0.992	0.994	0.997	0.999	1.000	1.000	0.999	0.998	0.996	0.990	0.979	0.953	0.881	0.809	0.742	0.679	0.648
0.981	0.982	0.987	0.990	0.993	0.996	0.998	0.999	1.000	1.000	0.998	0.994	0.983	0.956	0.884	0.811	0.743	0.678	0.647
0.976	0.978	0.983	0.986	0.990	0.994	0.996	0.998	1.000	1.000	1.000	0.996	0.986	0.960	0.888	0.815	0.747	0.682	0.652
0.971	0.972	0.978	0.982	0.986	0.990	0.993	0.996	0.998	1.000	1.000	0.998	0.990	0.966	0.897	0.826	0.759	0.695	0.664
0.963	0.965	0.971	0.975	0.979	0.984	0.987	0.990	0.994	0.996	0.998	1.000	0.997	0.980	0.921	0.856	0.793	0.732	0.702
0.954	0.955	0.961	0.965	0.968	0.973	0.976	0.979	0.983	0.986	0.990	0.997	1.000	0.993	0.949	0.894	0.838	0.782	0.755
0.933	0.934	0.938	0.941	0.944	0.948	0.950	0.953	0.956	0.960	0.966	0.980	0.993	1.000	0.980	0.941	0.897	0.850	0.826
0.873	0.874	0.876	0.878	0.879	0.880	0.880	0.881	0.884	0.888	0.897	0.921	0.949	0.980	1.000	0.989	0.967	0.937	0.921
0.811	0.811	0.812	0.812	0.811	0.810	0.810	0.809	0.811	0.815	0.826	0.856	0.894	0.941	0.989	1.000	0.993	0.977	0.967
0.752	0.752	0.751	0.749	0.748	0.746	0.744	0.742	0.743	0.747	0.759	0.793	0.838	0.897	0.967	0.993	1.000	0.995	0.990
0.695	0.694	0.692	0.690	0.687	0.684	0.681	0.679	0.678	0.682	0.695	0.732	0.782	0.850	0.937	0.977	0.995	1.000	0.999
0.667	0.666	0.664	0.661	0.658	0.654	0.651	0.648	0.647	0.652	0.664	0.702	0.755	0.826	0.921	0.967	0.990	0.999	1.000

Zirconium. The RSD values $\Delta p/p$ (α, β, γ)= 13, 15, 15 %, $\Delta E_d/E_d$ = 15 %

T (MeV)	T_{dam} (MeV)	N_d	$\Delta Nd/Nd$ (%)
1.500E-04	1.310E-04	1.310E+00	17.04
2.000E-04	1.735E-04	1.735E+00	17.12
5.000E-04	4.245E-04	4.245E+00	17.16
1.000E-03	8.333E-04	8.333E+00	17.19
2.000E-03	1.632E-03	1.632E+01	17.23
5.000E-03	3.955E-03	3.955E+01	17.30
1.000E-02	7.697E-03	7.697E+01	17.36
2.000E-02	1.492E-02	1.492E+02	17.43
5.000E-02	3.543E-02	3.543E+02	17.53
1.000E-01	6.740E-02	6.740E+02	17.61
2.000E-01	1.262E-01	1.262E+03	17.68
5.000E-01	2.776E-01	2.776E+03	17.77
1.000E+00	4.789E-01	4.789E+03	17.84
2.000E+00	7.730E-01	7.730E+03	17.99
5.000E+00	1.274E+00	1.274E+04	18.49
1.000E+01	1.665E+00	1.665E+04	19.13
2.000E+01	2.000E+00	2.000E+04	19.87
5.000E+01	2.320E+00	2.320E+04	20.73
1.000E+02	2.477E+00	2.477E+04	21.22

Correlation matrix

1.000	1.000	0.999	0.999	0.998	0.997	0.996	0.994	0.991	0.989	0.986	0.983	0.978	0.969	0.940	0.907	0.872	0.836	0.817
1.000	1.000	1.000	1.000	0.999	0.998	0.996	0.995	0.992	0.990	0.987	0.984	0.979	0.970	0.940	0.907	0.872	0.836	0.817
0.999	1.000	1.000	1.000	1.000	0.999	0.998	0.996	0.994	0.992	0.990	0.986	0.982	0.972	0.941	0.907	0.872	0.834	0.815
0.999	1.000	1.000	1.000	1.000	0.999	0.999	0.997	0.996	0.994	0.992	0.988	0.984	0.973	0.942	0.907	0.871	0.833	0.814
0.998	0.999	1.000	1.000	1.000	1.000	0.999	0.998	0.997	0.995	0.993	0.990	0.985	0.974	0.943	0.907	0.870	0.832	0.813
0.997	0.998	0.999	0.999	1.000	1.000	1.000	0.999	0.998	0.997	0.996	0.993	0.988	0.976	0.943	0.907	0.869	0.830	0.810
0.996	0.996	0.998	0.999	0.999	1.000	1.000	1.000	0.999	0.998	0.997	0.994	0.989	0.977	0.943	0.906	0.868	0.829	0.809
0.994	0.995	0.996	0.997	0.998	0.999	1.000	1.000	1.000	0.999	0.998	0.995	0.990	0.978	0.944	0.906	0.868	0.828	0.807
0.991	0.992	0.994	0.996	0.997	0.998	0.999	1.000	1.000	1.000	0.999	0.997	0.992	0.980	0.945	0.907	0.868	0.827	0.807
0.989	0.990	0.992	0.994	0.995	0.997	0.998	0.999	1.000	1.000	1.000	0.998	0.993	0.982	0.947	0.909	0.870	0.829	0.809
0.986	0.987	0.990	0.992	0.993	0.996	0.997	0.998	0.999	1.000	1.000	0.999	0.995	0.984	0.951	0.914	0.875	0.835	0.815
0.983	0.984	0.986	0.988	0.990	0.993	0.994	0.995	0.997	0.998	0.999	1.000	0.998	0.991	0.962	0.928	0.892	0.854	0.834
0.978	0.979	0.982	0.984	0.985	0.988	0.989	0.990	0.992	0.993	0.995	0.998	1.000	0.997	0.975	0.947	0.915	0.880	0.862
0.969	0.970	0.972	0.973	0.974	0.976	0.977	0.978	0.980	0.982	0.984	0.991	0.997	1.000	0.990	0.970	0.944	0.915	0.899
0.940	0.940	0.941	0.942	0.943	0.943	0.943	0.944	0.945	0.947	0.951	0.962	0.975	0.990	1.000	0.994	0.981	0.962	0.951
0.907	0.907	0.907	0.907	0.907	0.907	0.906	0.906	0.907	0.909	0.914	0.928	0.947	0.970	0.994	1.000	0.996	0.986	0.978
0.872	0.872	0.872	0.871	0.870	0.869	0.868	0.868	0.868	0.870	0.875	0.892	0.915	0.944	0.981	0.996	1.000	0.997	0.993
0.836	0.836	0.834	0.833	0.832	0.830	0.829	0.828	0.827	0.829	0.835	0.854	0.880	0.915	0.962	0.986	0.997	1.000	0.999
0.817	0.817	0.815	0.814	0.813	0.810	0.809	0.807	0.807	0.809	0.815	0.834	0.862	0.899	0.951	0.978	0.993	0.999	1.000

Zirconium. The RSD values $\Delta p/p$ (α, β, γ)= 13, 15, 15 %, $\Delta E_d/E_d$ = 20 %

T (MeV)	T_{dam} (MeV)	N_d	$\Delta Nd/Nd$ (%)
1.500E-04	1.310E-04	1.310E+00	25.84
2.000E-04	1.735E-04	1.735E+00	26.11
5.000E-04	4.245E-04	4.245E+00	26.13
1.000E-03	8.333E-04	8.333E+00	26.15
2.000E-03	1.632E-03	1.632E+01	26.17
5.000E-03	3.955E-03	3.955E+01	26.21
1.000E-02	7.697E-03	7.697E+01	26.24
2.000E-02	1.492E-02	1.492E+02	26.28
5.000E-02	3.543E-02	3.543E+02	26.35
1.000E-01	6.740E-02	6.740E+02	26.40
2.000E-01	1.262E-01	1.262E+03	26.45
5.000E-01	2.776E-01	2.776E+03	26.50
1.000E+00	4.789E-01	4.789E+03	26.55
2.000E+00	7.730E-01	7.730E+03	26.66
5.000E+00	1.274E+00	1.274E+04	27.04
1.000E+01	1.665E+00	1.665E+04	27.55
2.000E+01	2.000E+00	2.000E+04	28.14
5.000E+01	2.320E+00	2.320E+04	28.84
1.000E+02	2.477E+00	2.477E+04	29.24

Correlation matrix

1.000	0.999	0.999	0.998	0.998	0.997	0.997	0.996	0.995	0.993	0.992	0.990	0.988	0.983	0.969	0.952	0.933	0.912	0.901
0.999	1.000	1.000	1.000	0.999	0.999	0.998	0.997	0.996	0.995	0.994	0.992	0.990	0.985	0.970	0.953	0.934	0.912	0.901
0.999	1.000	1.000	1.000	1.000	0.999	0.999	0.998	0.997	0.996	0.995	0.993	0.991	0.986	0.971	0.953	0.933	0.912	0.900
0.998	1.000	1.000	1.000	1.000	1.000	0.999	0.999	0.998	0.997	0.996	0.994	0.992	0.987	0.971	0.953	0.933	0.911	0.899
0.998	0.999	1.000	1.000	1.000	1.000	1.000	0.999	0.998	0.998	0.997	0.995	0.993	0.987	0.971	0.953	0.933	0.911	0.899
0.997	0.999	0.999	1.000	1.000	1.000	1.000	1.000	0.999	0.999	0.998	0.996	0.994	0.988	0.972	0.953	0.932	0.910	0.898
0.997	0.998	0.999	0.999	1.000	1.000	1.000	1.000	1.000	0.999	0.998	0.997	0.995	0.989	0.972	0.953	0.932	0.909	0.897
0.996	0.997	0.998	0.999	0.999	1.000	1.000	1.000	1.000	1.000	0.999	0.998	0.995	0.989	0.972	0.952	0.931	0.908	0.896
0.995	0.996	0.997	0.998	0.998	0.999	1.000	1.000	1.000	1.000	1.000	0.999	0.996	0.990	0.973	0.953	0.932	0.908	0.896
0.993	0.995	0.996	0.997	0.998	0.999	0.999	1.000	1.000	1.000	1.000	0.999	0.997	0.991	0.974	0.954	0.933	0.909	0.897
0.992	0.994	0.995	0.996	0.997	0.998	0.998	0.999	1.000	1.000	1.000	1.000	0.998	0.992	0.976	0.956	0.935	0.912	0.900
0.990	0.992	0.993	0.994	0.995	0.996	0.997	0.998	0.999	0.999	1.000	1.000	0.999	0.995	0.981	0.963	0.944	0.922	0.910
0.988	0.990	0.991	0.992	0.993	0.994	0.995	0.995	0.996	0.997	0.998	0.999	1.000	0.998	0.988	0.973	0.955	0.935	0.925
0.983	0.985	0.986	0.987	0.987	0.988	0.989	0.989	0.990	0.991	0.992	0.995	0.998	1.000	0.995	0.984	0.970	0.954	0.944
0.969	0.970	0.971	0.971	0.971	0.972	0.972	0.972	0.973	0.974	0.976	0.981	0.988	0.995	1.000	0.997	0.990	0.979	0.972
0.952	0.953	0.953	0.953	0.953	0.953	0.953	0.952	0.953	0.954	0.956	0.963	0.973	0.984	0.997	1.000	0.998	0.992	0.987
0.933	0.934	0.933	0.933	0.933	0.932	0.932	0.931	0.932	0.933	0.935	0.944	0.955	0.970	0.990	0.998	1.000	0.998	0.996
0.912	0.912	0.912	0.911	0.911	0.910	0.909	0.908	0.908	0.909	0.912	0.922	0.935	0.954	0.979	0.992	0.998	1.000	1.000
0.901	0.901	0.900	0.899	0.899	0.898	0.897	0.896	0.896	0.897	0.900	0.910	0.925	0.944	0.972	0.987	0.996	1.000	1.000

Tungsten. The RSD values $\Delta p/p$ (α, β, γ)= 20, 25, 25 %, $\Delta E_d/E_d$ = 10 %

T (MeV)	T_{dam} (MeV)	N_d	$\Delta Nd/Nd$ (%)
2.000E-04	1.775E-04	1.000E+00	1.00
5.000E-04	4.355E-04	1.936E+00	10.83
1.000E-03	8.574E-04	3.810E+00	10.94
2.000E-03	1.685E-03	7.489E+00	11.08
5.000E-03	4.104E-03	1.824E+01	11.30
1.000E-02	8.026E-03	3.567E+01	11.50
2.000E-02	1.566E-02	6.958E+01	11.73
5.000E-02	3.767E-02	1.674E+02	12.08
1.000E-01	7.279E-02	3.235E+02	12.38
2.000E-01	1.397E-01	6.210E+02	12.69
5.000E-01	3.256E-01	1.447E+03	13.11
1.000E+00	6.048E-01	2.688E+03	13.37
2.000E+00	1.091E+00	4.850E+03	13.57
5.000E+00	2.213E+00	9.837E+03	13.78
1.000E+01	3.483E+00	1.548E+04	14.19
2.000E+01	5.010E+00	2.227E+04	15.19
5.000E+01	7.019E+00	3.120E+04	17.43
1.000E+02	8.255E+00	3.669E+04	19.36

Correlation matrix

1.000	0.367	0.367	0.365	0.363	0.360	0.357	0.353	0.349	0.345	0.341	0.338	0.337	0.335	0.327	0.306	0.269	0.244
0.367	1.000	1.000	0.998	0.994	0.990	0.983	0.973	0.964	0.953	0.939	0.929	0.919	0.894	0.849	0.769	0.641	0.562
0.367	1.000	1.000	0.999	0.997	0.993	0.989	0.980	0.971	0.962	0.949	0.939	0.929	0.904	0.856	0.773	0.641	0.560
0.365	0.998	0.999	1.000	0.999	0.997	0.993	0.986	0.979	0.970	0.959	0.950	0.939	0.913	0.863	0.777	0.641	0.558
0.363	0.994	0.997	0.999	1.000	0.999	0.997	0.992	0.987	0.980	0.970	0.962	0.952	0.924	0.871	0.781	0.640	0.554
0.360	0.990	0.993	0.997	0.999	1.000	0.999	0.996	0.992	0.987	0.978	0.971	0.961	0.932	0.877	0.783	0.639	0.551
0.357	0.983	0.989	0.993	0.997	0.999	1.000	0.999	0.996	0.992	0.985	0.979	0.969	0.939	0.882	0.785	0.637	0.547
0.353	0.973	0.980	0.986	0.992	0.996	0.999	1.000	0.999	0.997	0.992	0.987	0.978	0.947	0.887	0.787	0.634	0.542
0.349	0.964	0.971	0.979	0.987	0.992	0.996	0.999	1.000	0.999	0.996	0.992	0.984	0.952	0.891	0.789	0.633	0.540
0.345	0.953	0.962	0.970	0.980	0.987	0.992	0.997	0.999	1.000	0.999	0.996	0.988	0.957	0.896	0.792	0.635	0.541
0.341	0.939	0.949	0.959	0.970	0.978	0.985	0.992	0.996	0.999	1.000	0.999	0.994	0.966	0.906	0.804	0.648	0.554
0.338	0.929	0.939	0.950	0.962	0.971	0.979	0.987	0.992	0.996	0.999	1.000	0.998	0.975	0.921	0.824	0.672	0.578
0.337	0.919	0.929	0.939	0.952	0.961	0.969	0.978	0.984	0.988	0.994	0.998	1.000	0.988	0.944	0.858	0.715	0.626
0.335	0.894	0.904	0.913	0.924	0.932	0.939	0.947	0.952	0.957	0.966	0.975	0.988	1.000	0.984	0.927	0.813	0.735
0.327	0.849	0.856	0.863	0.871	0.877	0.882	0.887	0.891	0.896	0.906	0.921	0.944	0.984	1.000	0.979	0.902	0.842
0.306	0.769	0.773	0.777	0.781	0.783	0.785	0.787	0.789	0.792	0.804	0.824	0.858	0.927	0.979	1.000	0.971	0.933
0.269	0.641	0.641	0.641	0.640	0.639	0.637	0.634	0.633	0.635	0.648	0.672	0.715	0.813	0.902	0.971	1.000	0.992
0.244	0.562	0.560	0.558	0.554	0.551	0.547	0.542	0.540	0.541	0.554	0.578	0.626	0.735	0.842	0.933	0.992	1.000

Tungsten. The RSD values $\Delta p/p$ (α, β, γ)= 20, 25, 25 %, $\Delta E_d/E_d$ = 15 %

T (MeV)	T_{dam} (MeV)	N_d	$\Delta Nd/Nd$ (%)
2.000E-04	1.775E-04	1.000E+00	4.13
5.000E-04	4.355E-04	1.936E+00	16.79
1.000E-03	8.574E-04	3.810E+00	16.87
2.000E-03	1.685E-03	7.489E+00	16.97
5.000E-03	4.104E-03	1.824E+01	17.12
1.000E-02	8.026E-03	3.567E+01	17.26
2.000E-02	1.566E-02	6.958E+01	17.43
5.000E-02	3.767E-02	1.674E+02	17.69
1.000E-01	7.279E-02	3.235E+02	17.91
2.000E-01	1.397E-01	6.210E+02	18.15
5.000E-01	3.256E-01	1.447E+03	18.46
1.000E+00	6.048E-01	2.688E+03	18.67
2.000E+00	1.091E+00	4.850E+03	18.82
5.000E+00	2.213E+00	9.837E+03	19.00
1.000E+01	3.483E+00	1.548E+04	19.34
2.000E+01	5.010E+00	2.227E+04	20.15
5.000E+01	7.019E+00	3.120E+04	22.05
1.000E+02	8.255E+00	3.669E+04	23.73

Correlation matrix

1.000	0.615	0.614	0.613	0.611	0.609	0.606	0.601	0.598	0.593	0.588	0.585	0.583	0.579	0.570	0.549	0.507	0.476
0.615	1.000	1.000	0.999	0.997	0.995	0.992	0.986	0.981	0.975	0.967	0.961	0.955	0.942	0.917	0.870	0.785	0.725
0.614	1.000	1.000	1.000	0.999	0.997	0.994	0.990	0.985	0.980	0.972	0.966	0.960	0.947	0.921	0.872	0.785	0.724
0.613	0.999	1.000	1.000	0.999	0.998	0.996	0.993	0.989	0.984	0.977	0.971	0.966	0.952	0.925	0.874	0.785	0.723
0.611	0.997	0.999	0.999	1.000	1.000	0.999	0.996	0.993	0.989	0.983	0.978	0.973	0.958	0.929	0.877	0.785	0.721
0.609	0.995	0.997	0.998	1.000	1.000	1.000	0.998	0.996	0.992	0.987	0.983	0.977	0.962	0.932	0.878	0.784	0.718
0.606	0.992	0.994	0.996	0.999	1.000	1.000	0.999	0.998	0.995	0.991	0.987	0.982	0.966	0.935	0.879	0.782	0.716
0.601	0.986	0.990	0.993	0.996	0.998	0.999	1.000	1.000	0.998	0.995	0.992	0.987	0.971	0.938	0.880	0.780	0.712
0.598	0.981	0.985	0.989	0.993	0.996	0.998	1.000	1.000	1.000	0.998	0.995	0.991	0.974	0.940	0.881	0.779	0.710
0.593	0.975	0.980	0.984	0.989	0.992	0.995	0.998	1.000	1.000	0.999	0.997	0.993	0.977	0.943	0.883	0.780	0.710
0.588	0.967	0.972	0.977	0.983	0.987	0.991	0.995	0.998	0.999	1.000	0.999	0.997	0.981	0.949	0.889	0.786	0.716
0.585	0.961	0.966	0.971	0.978	0.983	0.987	0.992	0.995	0.997	0.999	1.000	0.999	0.986	0.956	0.899	0.800	0.731
0.583	0.955	0.960	0.966	0.973	0.977	0.982	0.987	0.991	0.993	0.997	0.999	1.000	0.993	0.969	0.919	0.825	0.759
0.579	0.942	0.947	0.952	0.958	0.962	0.966	0.971	0.974	0.977	0.981	0.986	0.993	1.000	0.991	0.957	0.883	0.826
0.570	0.917	0.921	0.925	0.929	0.932	0.935	0.938	0.940	0.943	0.949	0.956	0.969	0.991	1.000	0.987	0.937	0.892
0.549	0.870	0.872	0.874	0.877	0.878	0.879	0.880	0.881	0.883	0.889	0.899	0.919	0.957	0.987	1.000	0.980	0.952
0.507	0.785	0.785	0.785	0.785	0.784	0.782	0.780	0.779	0.780	0.786	0.800	0.825	0.883	0.937	0.980	1.000	0.994
0.476	0.725	0.724	0.723	0.721	0.718	0.716	0.712	0.710	0.710	0.716	0.731	0.759	0.826	0.892	0.952	0.994	1.000

Tungsten. The RSD values $\Delta p/p$ (α, β, γ)= 20, 25, 25 %, $\Delta E_d/E_d$ = 20 %

T (MeV)	T_{dam} (MeV)	N_d	$\Delta Nd/Nd$ (%)
2.000E-04	1.775E-04	1.000E+00	9.84
5.000E-04	4.355E-04	1.936E+00	24.64
1.000E-03	8.574E-04	3.810E+00	24.70
2.000E-03	1.685E-03	7.489E+00	24.77
5.000E-03	4.104E-03	1.824E+01	24.89
1.000E-02	8.026E-03	3.567E+01	25.00
2.000E-02	1.566E-02	6.958E+01	25.13
5.000E-02	3.767E-02	1.674E+02	25.34
1.000E-01	7.279E-02	3.235E+02	25.52
2.000E-01	1.397E-01	6.210E+02	25.71
5.000E-01	3.256E-01	1.447E+03	25.96
1.000E+00	6.048E-01	2.688E+03	26.14
2.000E+00	1.091E+00	4.850E+03	26.27
5.000E+00	2.213E+00	9.837E+03	26.43
1.000E+01	3.483E+00	1.548E+04	26.72
2.000E+01	5.010E+00	2.227E+04	27.42
5.000E+01	7.019E+00	3.120E+04	29.06
1.000E+02	8.255E+00	3.669E+04	30.55

Correlation matrix

1.000	0.772	0.771	0.770	0.769	0.767	0.765	0.762	0.759	0.756	0.753	0.750	0.748	0.745	0.739	0.723	0.689	0.661
0.772	1.000	1.000	1.000	0.999	0.997	0.996	0.993	0.990	0.987	0.982	0.978	0.975	0.968	0.954	0.927	0.873	0.832
0.771	1.000	1.000	1.000	0.999	0.998	0.997	0.994	0.992	0.989	0.985	0.981	0.978	0.970	0.956	0.928	0.874	0.832
0.770	1.000	1.000	1.000	1.000	0.999	0.998	0.996	0.994	0.991	0.987	0.984	0.981	0.973	0.958	0.929	0.874	0.831
0.769	0.999	0.999	1.000	1.000	1.000	0.999	0.998	0.996	0.994	0.991	0.988	0.985	0.976	0.961	0.931	0.873	0.830
0.767	0.997	0.998	0.999	1.000	1.000	1.000	0.999	0.998	0.996	0.993	0.990	0.987	0.979	0.962	0.931	0.873	0.829
0.765	0.996	0.997	0.998	0.999	1.000	1.000	1.000	0.999	0.997	0.995	0.993	0.990	0.981	0.964	0.932	0.872	0.827
0.762	0.993	0.994	0.996	0.998	0.999	1.000	1.000	1.000	0.999	0.997	0.996	0.993	0.984	0.966	0.932	0.871	0.825
0.759	0.990	0.992	0.994	0.996	0.998	0.999	1.000	1.000	1.000	0.999	0.997	0.995	0.985	0.967	0.933	0.870	0.824
0.756	0.987	0.989	0.991	0.994	0.996	0.997	0.999	1.000	1.000	1.000	0.999	0.996	0.987	0.968	0.934	0.871	0.823
0.753	0.982	0.985	0.987	0.991	0.993	0.995	0.997	0.999	1.000	1.000	1.000	0.998	0.990	0.971	0.937	0.874	0.827
0.750	0.978	0.981	0.984	0.988	0.990	0.993	0.996	0.997	0.999	1.000	1.000	0.999	0.993	0.976	0.943	0.881	0.835
0.748	0.975	0.978	0.981	0.985	0.987	0.990	0.993	0.995	0.996	0.998	0.999	1.000	0.996	0.983	0.954	0.896	0.852
0.745	0.968	0.970	0.973	0.976	0.979	0.981	0.984	0.985	0.987	0.990	0.993	0.996	1.000	0.995	0.976	0.930	0.892
0.739	0.954	0.956	0.958	0.961	0.962	0.964	0.966	0.967	0.968	0.971	0.976	0.983	0.995	1.000	0.993	0.961	0.931
0.723	0.927	0.928	0.929	0.931	0.931	0.932	0.932	0.933	0.934	0.937	0.943	0.954	0.976	0.993	1.000	0.988	0.968
0.689	0.873	0.874	0.874	0.873	0.873	0.872	0.871	0.870	0.871	0.874	0.881	0.896	0.930	0.961	0.988	1.000	0.995
0.661	0.832	0.832	0.831	0.830	0.829	0.827	0.825	0.824	0.823	0.827	0.835	0.852	0.892	0.931	0.968	0.995	1.000

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