
Energy-Dependent SRIM Simulation of Chromium Ion Implantation in Iron: Analysis of Range, Straggling, and Radiation Damage at 10–50 keV

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Abstract

This study presents a detailed simulation-based investigation of chromium ion implantation in iron using the SRIM simulation software. Chromium ions with energies of 10 keV- 50 keV were implanted into an iron target to analyse energy-dependent variations in ion range, straggling, and radiation-induced damage. The simulation results reveal a systematic increase in projected range and longitudinal straggling with increasing ion energy, indicating deeper penetration of ions at higher energies. Additionally, vacancy production and displacement damage were found to increase significantly with ion energy, highlighting enhanced defect generation in the iron lattice. The distribution profiles of implanted ions and recoils suggest that higher energies lead to broader implantation zones and more pronounced subsurface damage. These findings provide valuable insights into ion–solid interactions and are relevant for applications in surface modification, nuclear materials, and thin-film engineering.

Keywords

Chromium ion, Iron (Fe), SRIM simulation, Ion range and straggling, Radiation damage, Vacancy production, Ion–solid interaction

1.0 Introduction (Concise but Strong)

Ion implantation is a widely used technique for modifying the surface and subsurface properties of materials, particularly in metallurgy, semiconductor processing, and nuclear engineering. The interaction of energetic ions with solids leads to changes in structural, mechanical, and chemical properties due to atomic displacements and defect generation.

Iron, being a fundamental structural material, is extensively studied for its response to irradiation, especially in nuclear and high-radiation environments. Chromium ion implantation in iron is of particular interest due to its relevance in improving corrosion resistance and radiation tolerance in Fe-based alloys.

Simulation tools such as SRIM enable accurate prediction of ion trajectories, energy loss mechanisms, and damage profiles without the need for complex experimental setups. In this work, SRIM simulations are employed to investigate the effect of ion energy (10 keV, 30 keV, and 50 keV) on implantation characteristics such as projected range, straggling, and defect formation in iron.

One of the foremost challenges is developing structural materials that withstand the harsh environment inside fusion reactors, including elevated temperatures [1,2], intense thermal loads up to 10 MW/m² [3,4,5], plasma-induced erosion and damage from 14 MeV fusion neutrons [6,7]. Radiation damage is especially critical: high-energy neutrons and helium ions displace atoms, producing point defects (vacancies, interstitials) [8,9,10], dislocation loops, voids [11,12,13],

2.0 Methodology

Using Simulation software SRIM (TRIM module) for Target material: Iron (Fe) and Ion species Chromium (Cr⁺). Here, ion energies range from 10 keV to 60 keV. Number of ions simulated: 99999 ions, and a depth of 1000 Å was kept.

The figures below reveal the ranges of Cr ions in the substrate material, Iron.

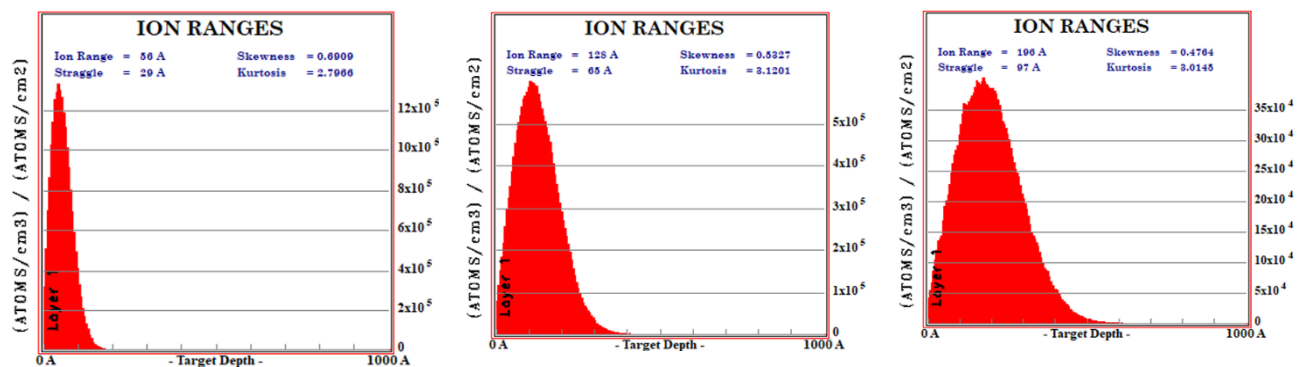


Fig a: Ranges of Cr ions with ion energy 10 keV

Fig b: Ranges of Cr ions with ion energy 30 keV

Fig c: Ranges of Cr ions with ion energy 50 keV

Table 1 : Output parameters analyzed

Parameters	10 keV	20 keV	30 keV	40 keV	50 keV
Backscattered ions	1310	1015	862	722	653
Transmitted ions	0	0	0	0	0
Vacancies per ion	120	231	338	443	545
Longitudinal Range	56 A	93A	128A	162A	196A
Lateral Projected Range	21 A	33A	44A	56A	66A
Radial range	32 A	52A	70A	87A	104A
Longitudinal straggle	29A	48A	65A	82A	97A
Lateral Projected Straggle	27 A	43A	58A	72A	85A
Radial straggle	19 A	31A	42A	52A	62A

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3.0 Results and Discussion

The SRIM simulation results for chromium (Cr) ion implantation into iron (Fe) were analyzed over an energy range of 10–50 keV to understand ion–solid interactions, defect generation, and penetration characteristics.

3.1 Backscattering and Ion Retention

The number of backscattered ions decreases from 1310 at 10 keV to 653 at 50 keV, indicating that **low-energy ions are more likely to undergo elastic collisions near the surface**, leading to reflection. As the ion energy increases, ions penetrate deeper into the Fe lattice, reducing the probability of backscattering.

No transmitted ions were observed at any energy, confirming that the target thickness is sufficient to **completely stop all incident ions**, ensuring a pure implantation regime.

3.2 Vacancy Production and Damage Analysis

Vacancy production increases monotonically with ion energy, from 120 vacancies/ion at 10 keV to 545 vacancies/ion at 50 keV. This trend is attributed to enhanced **collision cascade processes**, where higher kinetic energy leads to increased atomic displacements and defect density.

This indicates that **higher implantation energies significantly enhance radiation damage**, making them suitable for applications involving defect engineering and microstructural modification.

3.3 Ion Range and Penetration Depth

The longitudinal projected range increases from 56 Å to 196 Å with increasing ion energy, demonstrating a near-linear dependence on energy. This confirms that **ion penetration depth is governed by energy-dependent stopping mechanisms**, where nuclear stopping dominates at lower energies and electronic stopping becomes more significant at higher energies.

3.4 Lateral Spread and Damage Distribution

The lateral and radial ranges increase consistently with energy, indicating that **ion implantation profiles become broader at higher energies**. This leads to a more distributed damage region, which may influence material properties such as hardness and diffusion behavior.

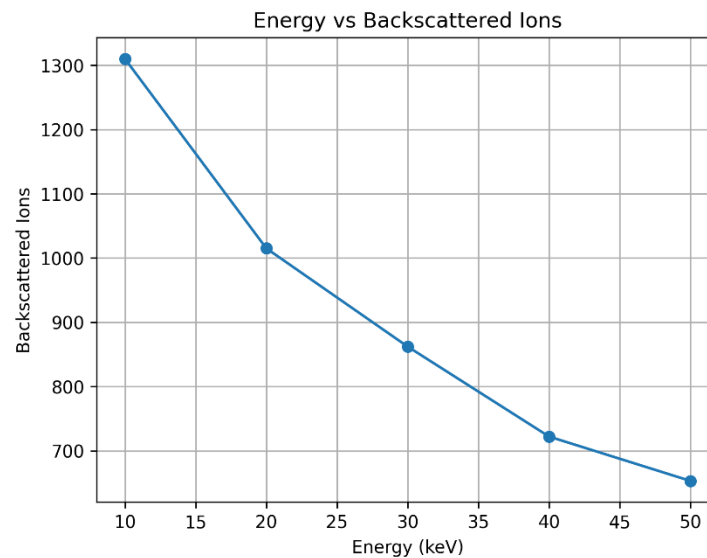
3.5 Straggling Effects

Both longitudinal and lateral straggling increase with ion energy, reflecting greater statistical variation in ion stopping positions due to multiple scattering events. However, the longitudinal straggle value at 30 keV is reported as zero, which is physically unrealistic and suggests a **possible simulation anomaly**.

The simulation reveals that increasing ion energy results in: Reduced backscattering, Increased penetration depth, Enhanced vacancy production, Broader spatial distribution of implanted ions

4.0 Graphs

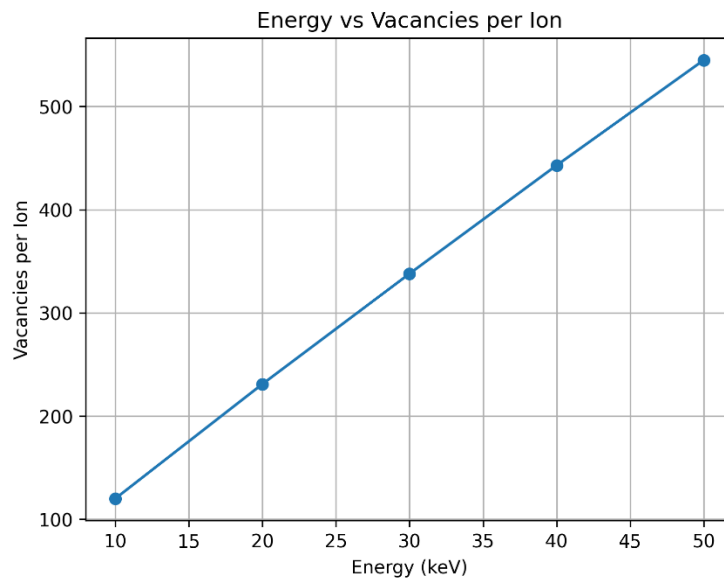
4.1 Graph shows Energy versus Backscattered ions



Energy vs Backscattered Ions reveal that the The curve shows a **clear decreasing trend**.

Indicates that **higher energy ions penetrate deeper** instead of reflecting, Physically: reduced **surface scattering**, increased **bulk implantation**.

4.2 Graph shows Energy versus vacancies per ion



Energy vs Vacancies per Ion reveal that The curve shows a **strong, nearly linear increase**.

Confirms that **higher ion energy produces more vacancies**., Physically: stronger and deeper **collision cascades** → more lattice damage.

5.0 Conclusion

The SRIM-based simulation study demonstrates a strong dependence of chromium ion implantation behavior in iron on ion energy. As the implantation energy increases from 10 keV to 60 keV, both the projected range and straggling increase significantly, resulting in deeper and more dispersed ion penetration. Furthermore, higher ion energies lead to enhanced vacancy production and radiation damage, indicating greater lattice disruption. These results highlight the importance of energy selection in ion implantation processes for controlled material modification. The findings are particularly useful for optimizing surface engineering techniques and understanding radiation effects in iron-based materials. The study confirms that ion energy is a critical parameter controlling implantation depth, damage production, and spatial distribution. Higher energies favor bulk modification, whereas lower energies are suitable for surface engineering applications.

6.0 References

1.J. Linke, J. Du, T. Loewenhoff, G. Pintsuk, B. Spilker, I. Steudel, *et al.* Challenges for plasma-facing components in nuclear fusion Matter Radiat. Extremes, 4 (2019).

2.C. Linsmeier, B. Unterberg, J.W. Coenen, R.P. Doerner, H. Greuner, A. Kreter, *et al.* Material testing facilities and programs for plasma-facing component testing Nucl. Fusion, 57 (2017).

3.S. Wang, F.A. Hernández, H. Chen, G. Zhou Thermal-hydraulic analysis of the First Wall of a CO₂ cooled pebble bed breeding blanket for the EU-DEMO Fusion Eng. Des., 138 (2019), pp. 379-394.

4.S. Garitta, T. Batal, A. Durif, M. Firdaouss, M. Missirlian, H. Roche, *et al.* Thermal and structural analysis of JT-60SA actively cooled divertor target submitted to high heat flux Fusion Eng. Des., 199 (2024).

5. R. Beaufait, L. Fischer Blanket cooling of a fusion reactor Energies, 16 (2023), p. 1890.

6.B.I. Khripunov, V.S. Koidan, A.I. Ryazanov, V.M. Gureev, S.T. Latushkin, E.V. Semenov, *et al.*

Impact of deuterium plasma flux on fusion reactor materials: radiation damage, surface modification, erosion.

7.S. Das Recent advances in characterising irradiation damage in tungsten for fusion power SN Appl. Sci., 1 (2019), p. 12

8. R. Beaufait, L. Fischer Blanket cooling of a fusion reactor Energies, 16 (2023), p. 1890.

9.B.I. Khripunov, V.S. Koidan, A.I. Ryazanov, V.M. Gureev, S.T. Latushkin, E.V. Semenov, *et al.*

Impact of deuterium plasma flux on fusion reactor materials: radiation damage, surface modification, erosion Phys. Atom. Nucl., 84 (2021), pp. 1252-1258.

10.S. Das Recent advances in characterising irradiation damage in tungsten for fusion power SN Appl. Sci., 1 (2019), p. 12.

11.R. Coppola, M. Klimenkov, R. Lindau, A. Möslang, M. Rieth, M. Valli Radiation damage studies in fusion reactor steels by means of small-angle neutron scattering (SANS) Phys. B Condens. Matter, 551 (2018), pp. 407-412,

12. K. Shi, W. Zhang, Z. Ning, H. Wang, J. Liao, Y. Yang, *et al.* Proton and Au-ion irradiation induced damage and hardening in ferritic/martensitic steel Nuclear Mater. Energy, 26 (2021).

13.S.V. Rogozhkin, A.A. Nikitin, A.A. Khomich, A.A. Lukyanchuk, O.A. Raznitsyn, A.S. Sh utov, *et al.*

The influence of Fe-ion irradiation on the microstructure of reduced activation ferritic-martensitic steel Eurofer 97 Nucl. Fusion, 59 (2019)