Ion Irradiation of Tungsten Metal Target for the Study of Pakistan Spherical Tokamak (PST) Divertor

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Abstract

The Pakistan Spherical Tokamak (PST) is a small-sized spherical tokamak currently in the design and development phase. A double null divertor configuration is being considered for the steady-state operation of the PST. Two different divertor materials concepts are under consideration for the PST and other devices in the future. The interaction between plasma and tungsten surfaces leads to noticeable alterations in microstructure and material properties. Tungsten is considered as a divertor material in fusion devices, where it can withstand large heat loads. The interaction of high-energy ions and electrons leads to swelling, blistering, and the formation of nano-cracks, ionization, recombination, and voids in the material.

The aim of this research effort involves examining the impact of helium ions irradiation on tungsten material. Tungsten samples were irradiated with high flux (1×10^{14}, 1×10^{15} and 1×10^{16} ions/cm^2) of helium ions to investigate structural changes and surface morphology. Changes in microstructure, residual strain, surface morphology, and hardness of the samples were then observed using XRD (X-ray diffraction), SEM (scanning electron microscopy), and Micro-Vickers hardness techniques. Ion depth profiling was also conducted using SRIM (stopping and range of ions in matter) simulation for 1-10 MeV energy. It was observed that the penetration depth directly increases with particle energy, and displacement per atom (DPA) decreases with an increase in energy.

Keywords: Divertor material, Ion irradiation, Fuzz formation, Voids, Disordering Cracks, Displacement per atom

Introduction

Development of divertor wall material for tokamak to enhance its pulse and operational life is the outmost demanded technology.

For the steady state operation of tokamak control of impurity influx is very important. Limiter and divertor wall material plays very important role in reduction of impurities. Further, divertor area is region where most intense plasma material interactions will take place. In this region not only physical process like sputtering, erosion will take place but chemical process will also occur.

Need of clean, environmental friendly and sustainable energy is unending. Among other clean energy sources (like renewable energy sources) thermonuclear energy is a highly desirable and promising source for several compelling reasons, including its minimal radioactive waste production, zero carbon emissions, abundant fuel supply, and high energy density. However, the design and material selection for structural and plasma facing components (PFCs) in fusion reactors pose significant challenges due to the harsh environment including neutron/ion radiation and thermal radiation. Interaction of high energy particle with material can lead to adverse effects on the microstructure and properties of the materials and leads to accumulation of radiation induced defects. Therefore, the primary requirement for selecting suitable structural/PFC materials is their resistance to radiation damage [1][2].

In near future Pakistan Tokamak Plasma Research Institute (PTPRI) will have a medium-sized tokamak [3]. Use and understanding of divertor will be very important for impurity control. Recently use of liquid metals as divertor material have shown significant improvements in the tokamak parameter like long pulse steady state discharge. We intend to start R&D on divertor materials and to develop such techniques for our tokamak to improve its parameters. Flowing liquid provides an ever replenishing contact surface to the plasma, leading to very effective particle pumping and surface heat flux removal [4].

During the fusion reaction between deuterium and tritium, helium is produced as a byproduct. When subjected to high-energy helium ion irradiation, point defects like vacancies and interstitials are generated in the first wall material. The diffusion and recombination of these point defects subsequently lead to the formation of clusters and voids. These atomic-level changes ultimately result in both macroscopic and microscopic surface alterations, such as the formation of cracks, voids, blisters, and the creation of fuzzy surface [5]. To understand the structural changes produced in tungsten metal the highly polished tungsten samples were irradiated by helium ions of different fluence rate for a range of 1-10 MeV energy using SRIM and for 5 MeV using 5 MV tandem accelerator [6]. Optical and field emission scanning microscope (FESEM) were used to analyze the surface of the irradiated and meshed sample.

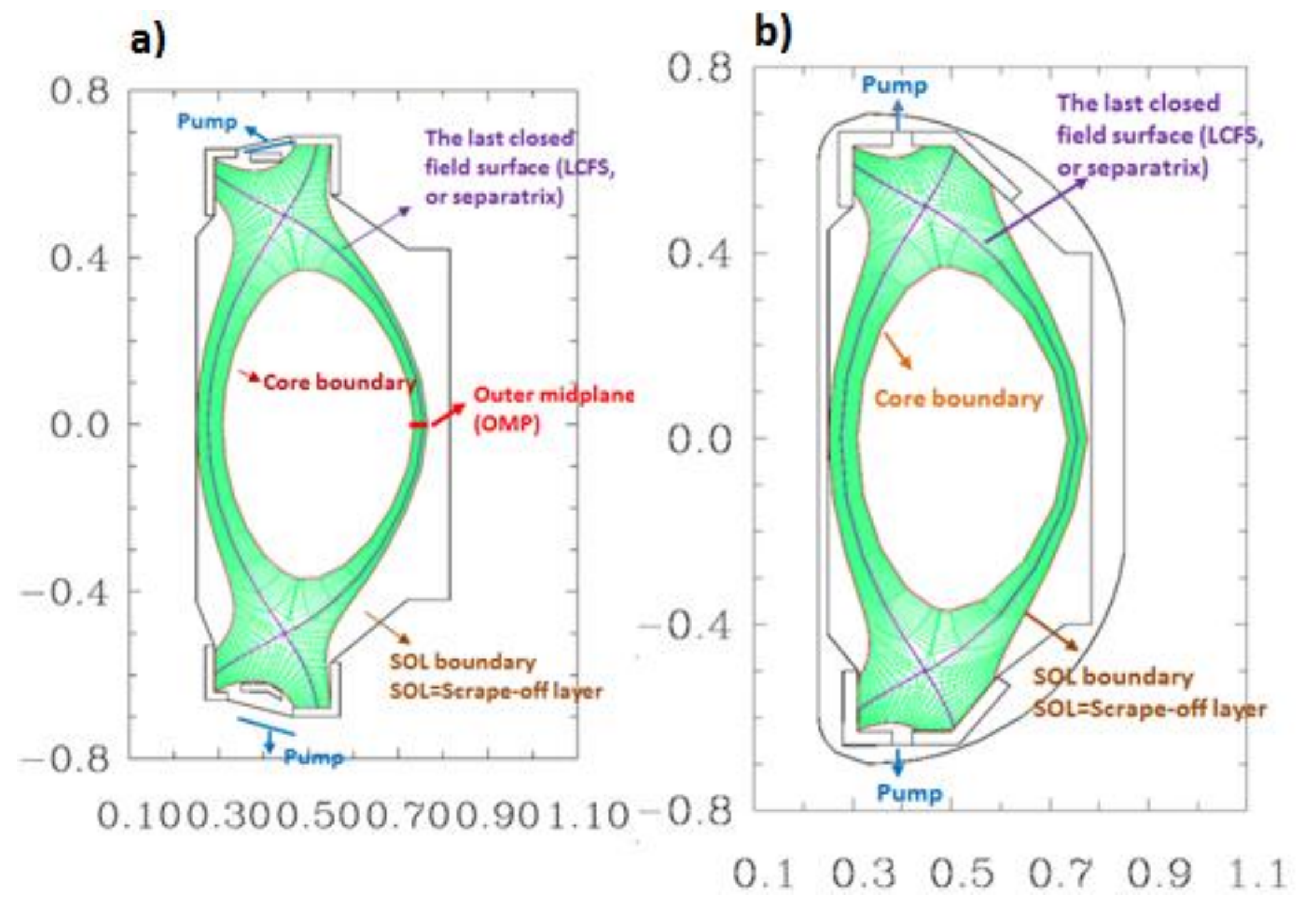
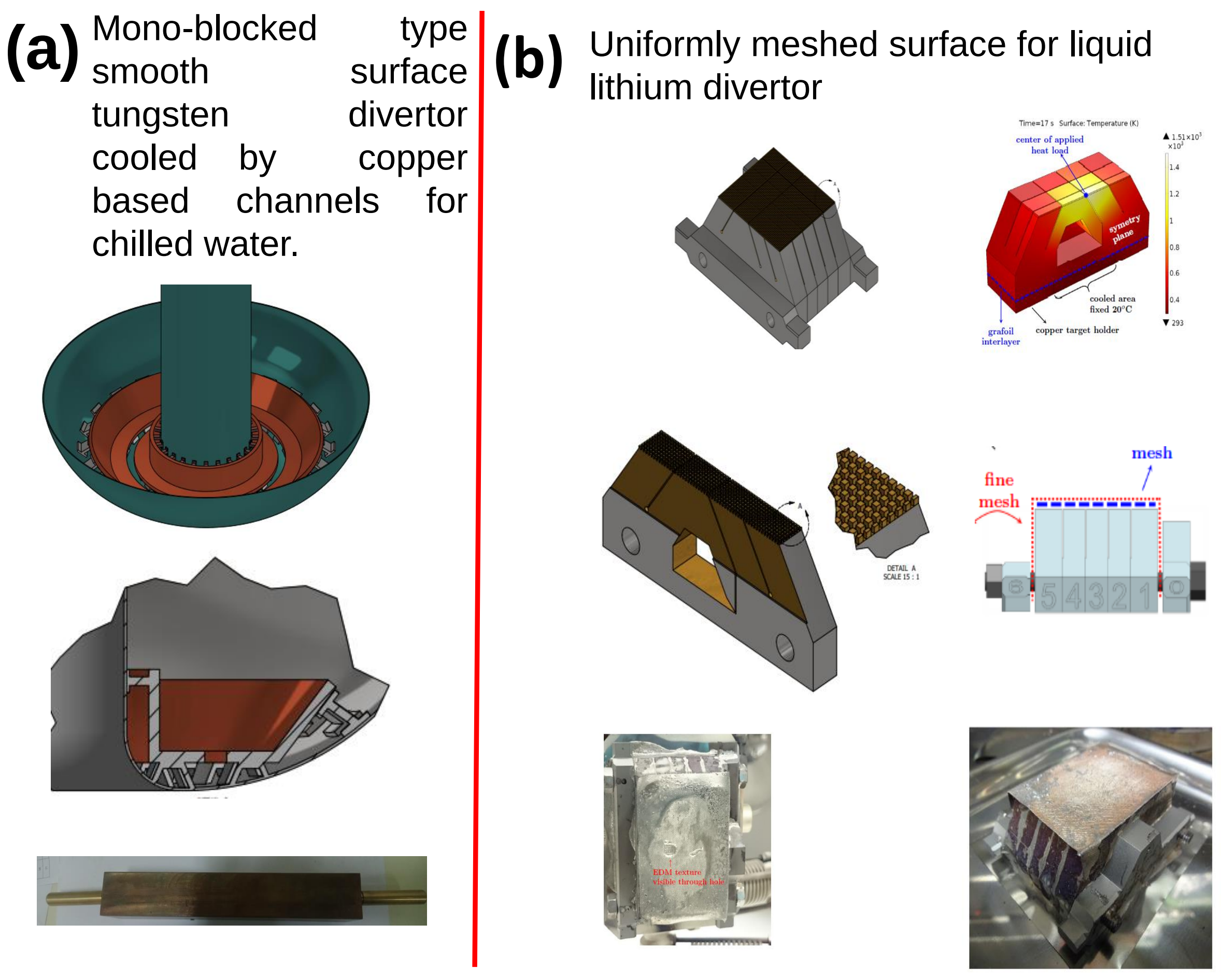


Figure 1. a) divertor geometry A, b) divertor geometry B


(a) Mono-blocked type smooth surface tungsten divertor cooled by copper based channels for chilled water.

(b) Uniformly meshed surface for liquid lithium divertor

Figure 2. (a) Mono-block water cooled tungsten divertor, (b) meshed surface liquid lithium tungsten divertor

Materials and Methods

1. Sample preparation and irradiation
- Dia. of sample: 25 mm
- Thickness of sample: 10 mm
- Emery paper: 1200-2500 grit
- Diamond paste: (1-5) micron
- Alumina powder: (0.1) micron size
- Tandem accelerator (10 MV, 25 MeV) available at National Center for Physics (NCP) used as ion beam source

2. Following parameters are used for irradiation
- Ion specie Charge: 2
- Ion dose 10^{16}/cm^2
- Ion energy 5 MeV
- Irradiation time 6 hour
- Maximum radiation damage was 0.15 DPA

Results and Discussion

- Low energy particle has small penetration depth as compare to high energetic particles.
- The maximum penetration depth is about 20 µm for 10 MeV
- The irradiation present will degrade the material over time, which lead to the need for component replacement depends upon DPA value.
- In order to understand the material degradation and to be able to predict the need for replacement, there is a need to understand how defects are produced in the material.
- There is a substantial amount of recoils in the low energy regime. The recoil particles are important for confined plasma physics.

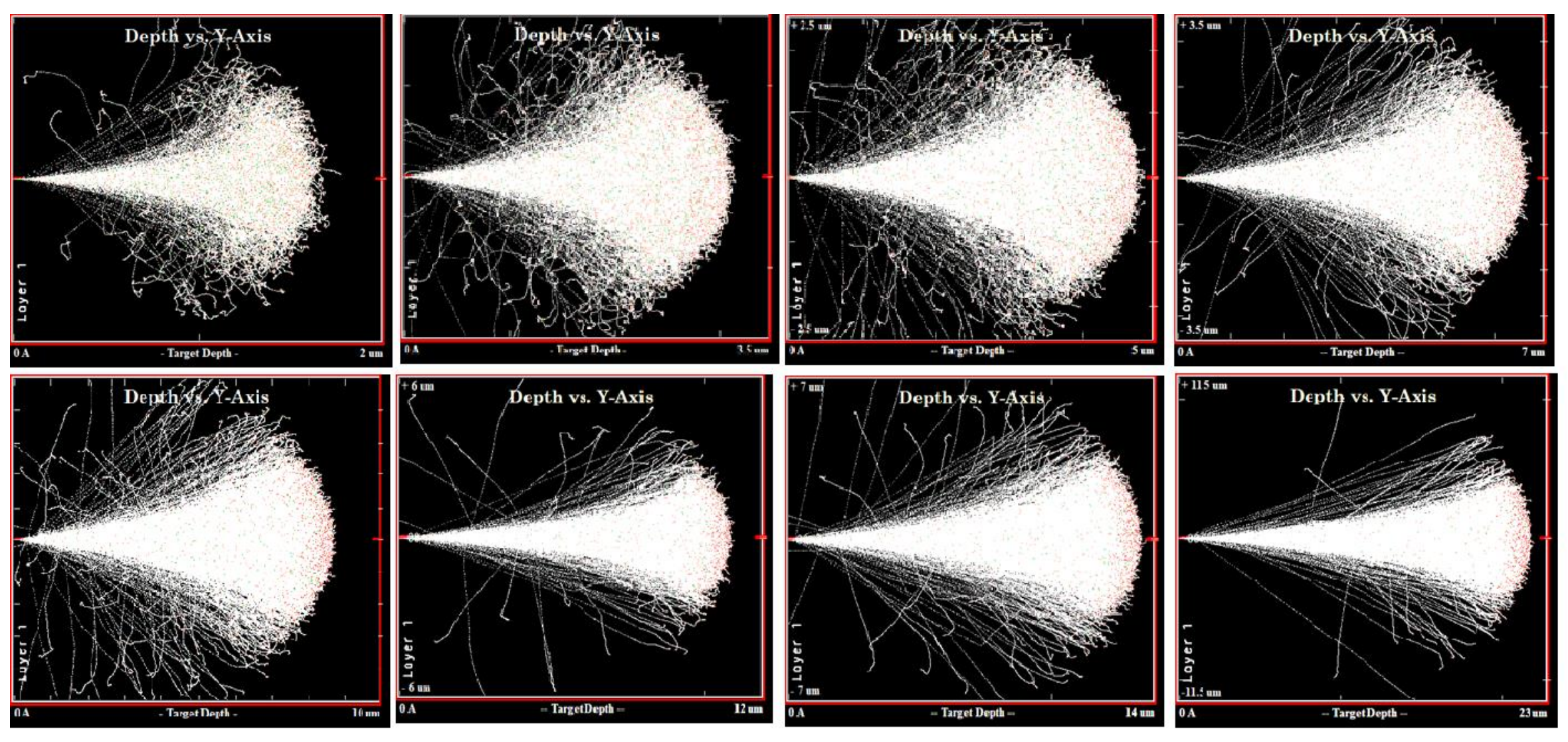


Figure 3. Depth profile and traces of recoil ions of helium for a range of energies (1-10 MeV) in the tungsten materials

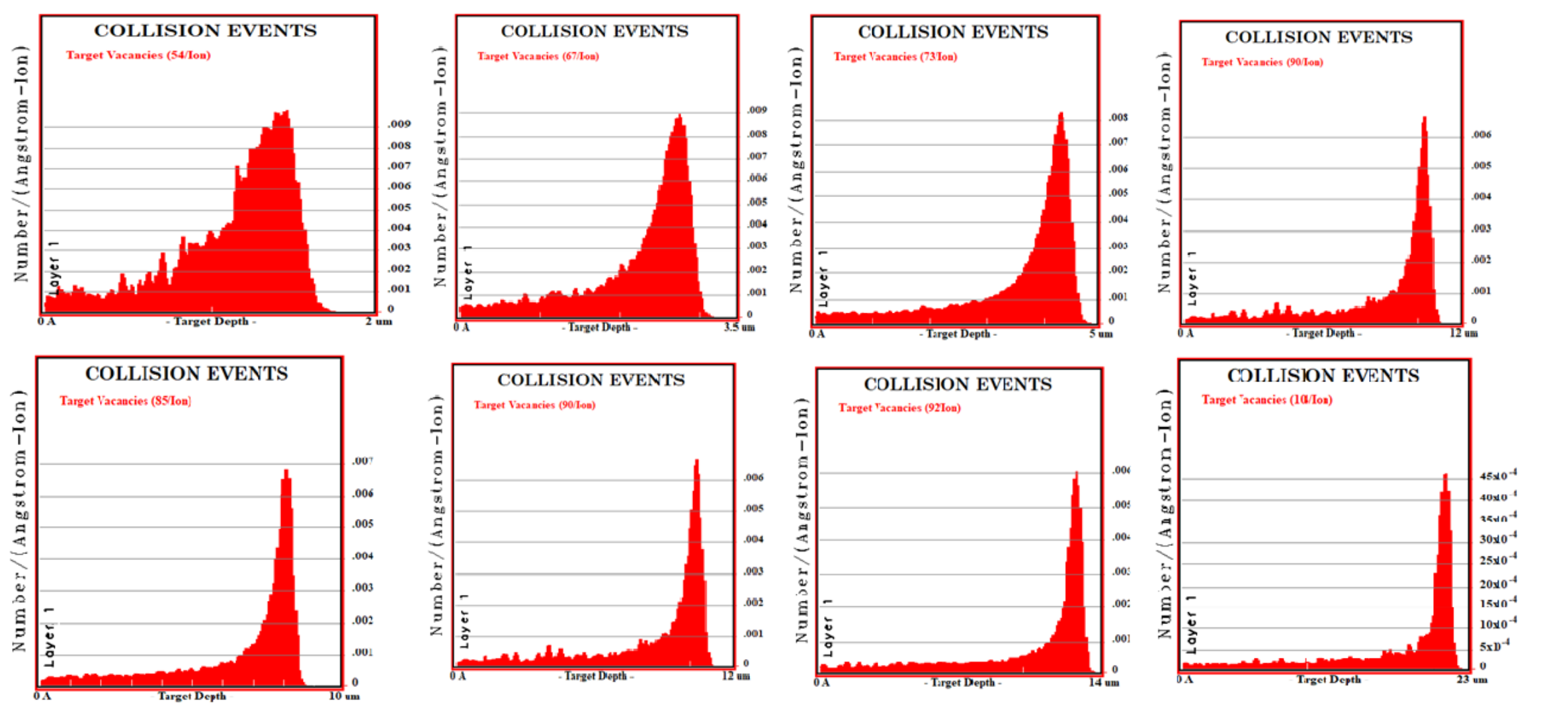


Figure 4. Collisional events of the target materials, no. vacancies decreases with the increase in energy.

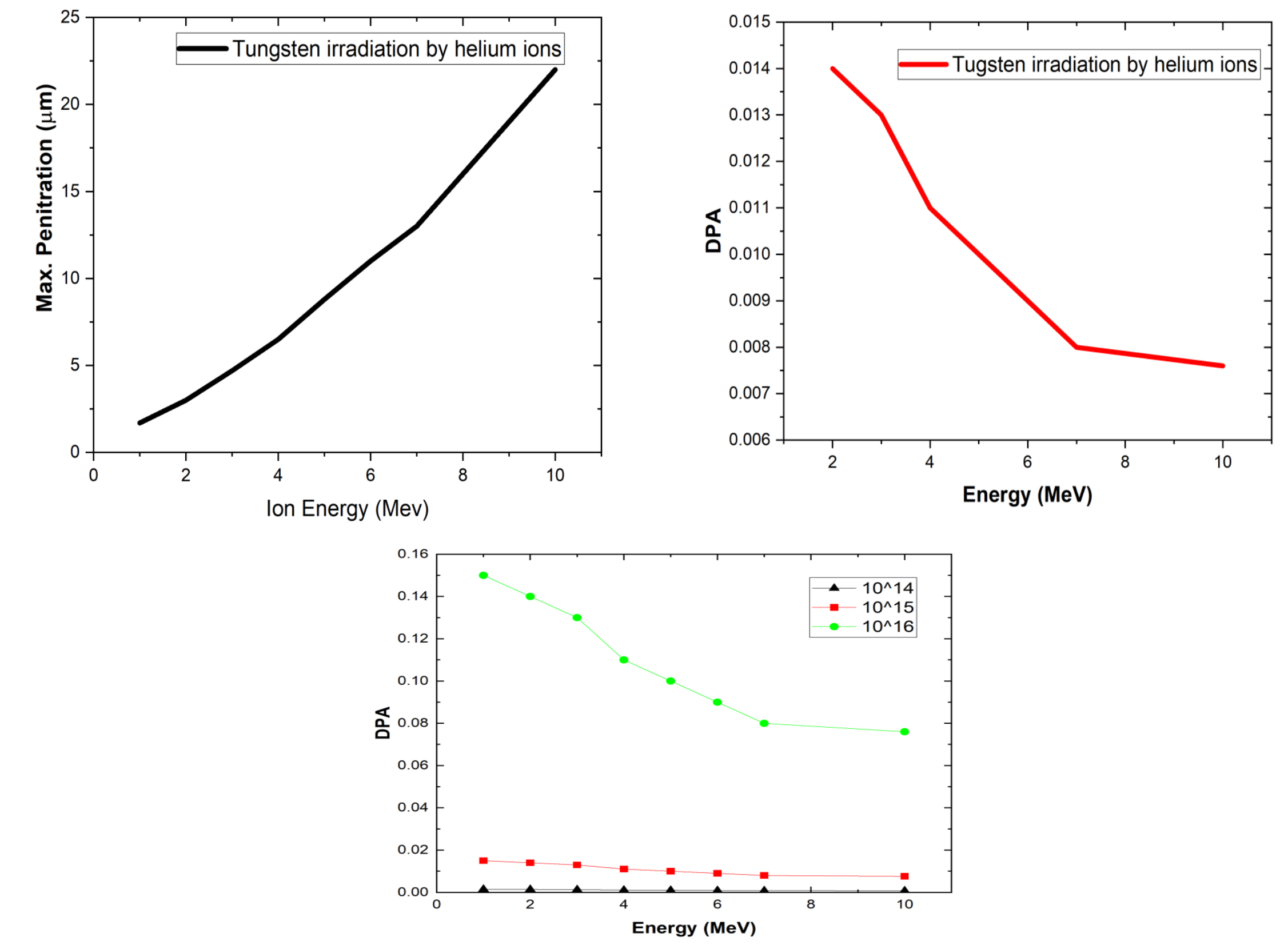


Figure 5. Displacement per atom (DPA) and penetration depth for the range 1-10 MeV of energy

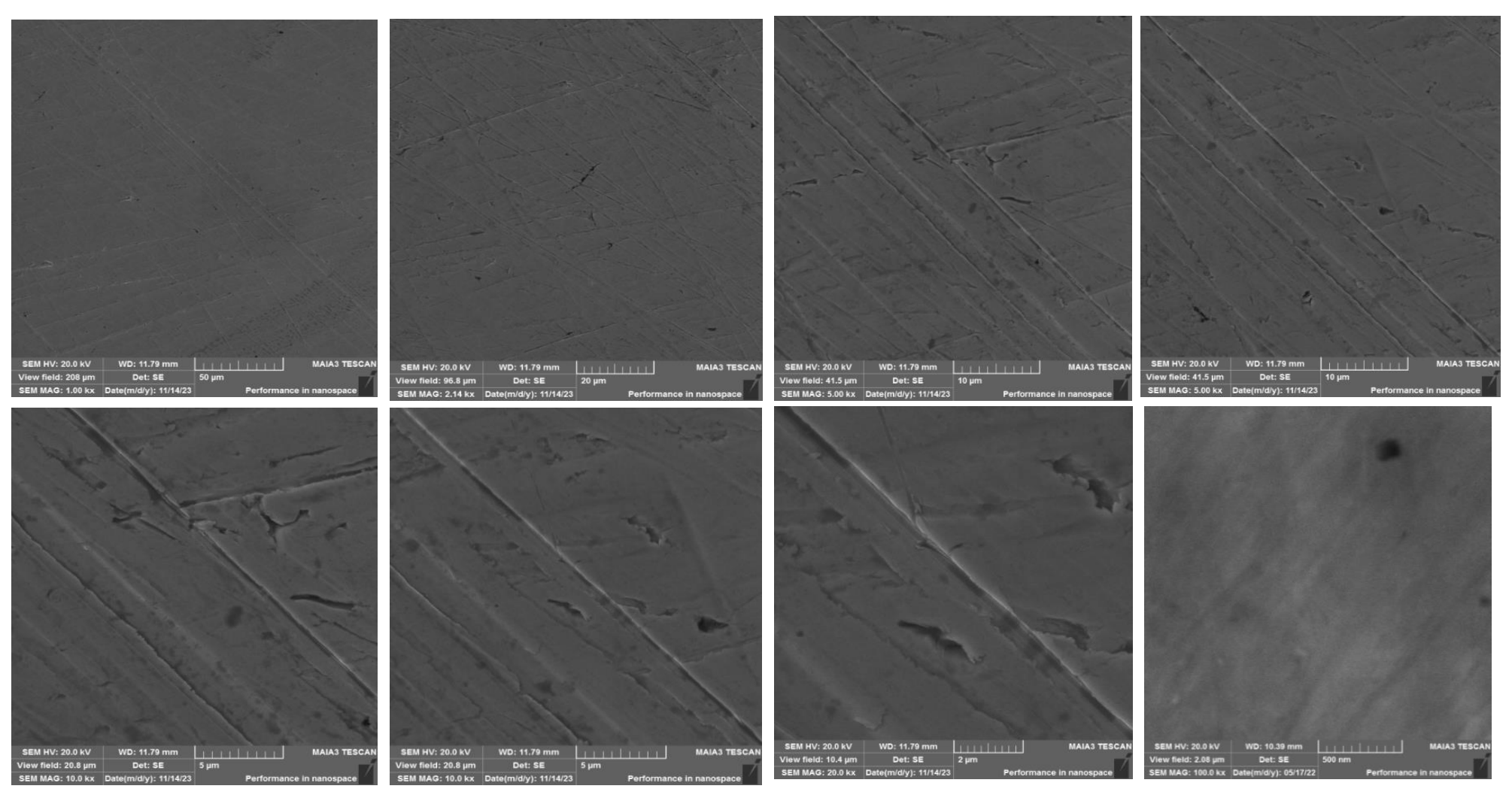


Figure 6. SEM micrograph of the polished surface of the tungsten sample having resolution of 50 µm to 500 nm

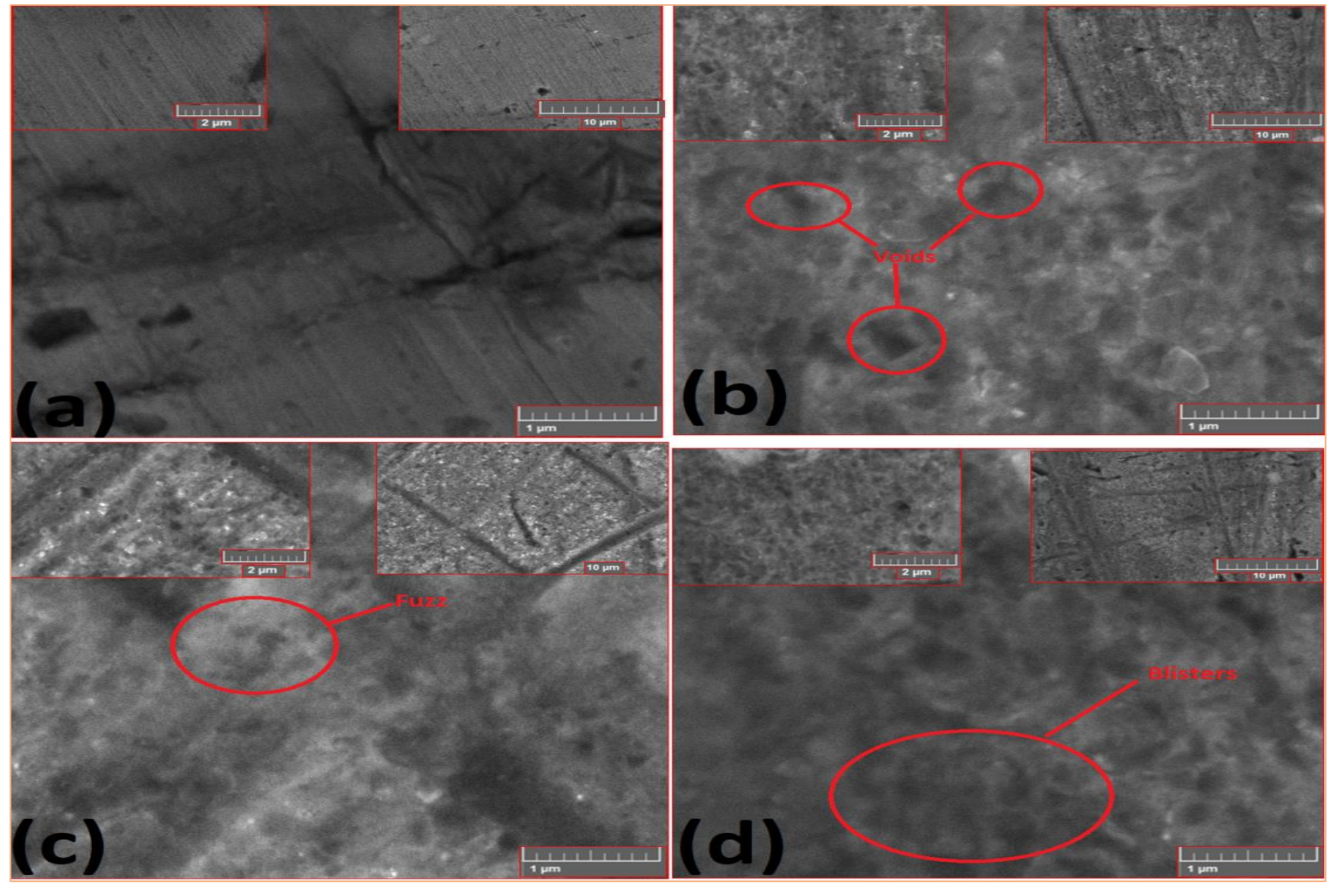


Figure 7. SEM micrographs of (a) un-irradiated (b) fluence 10^{13} ions/cm^2, (c) fluence 10^{14} ions/cm^2, (d) fluence 10^{15} ions/cm^2

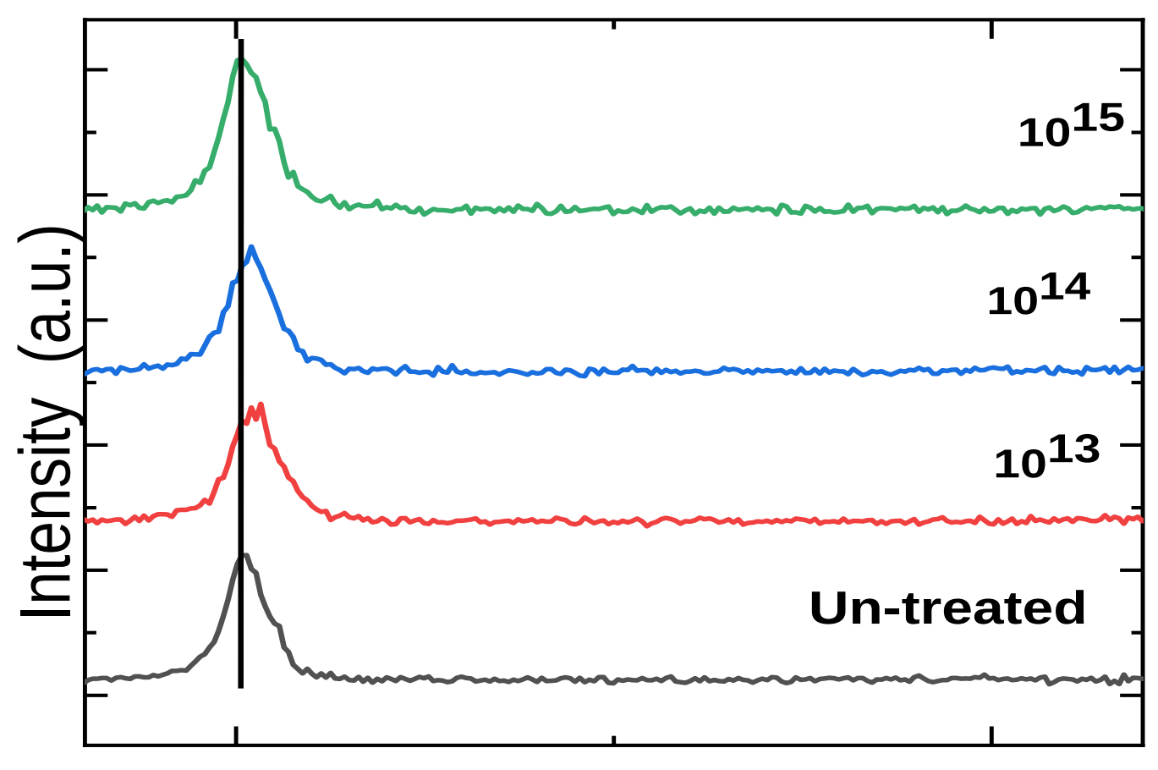


Figure 8. XRD pattern of (Black) untreated , (Red) 10^{13} ions/cm^2, (Blue) 10^{14} ions/cm^2 and (Green) 10^{15} ions/cm^2

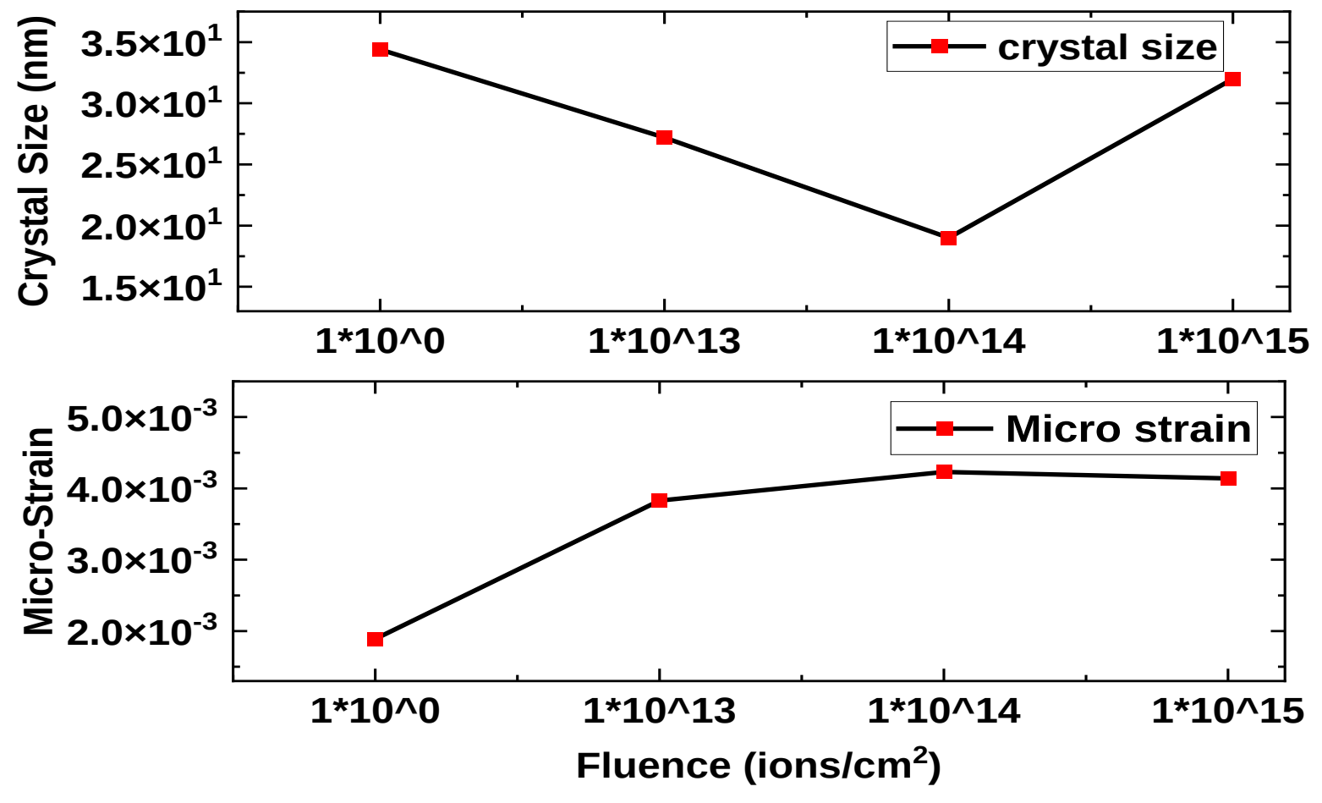


Figure 9. Crystal size and micro-strain using Williamson Hall method

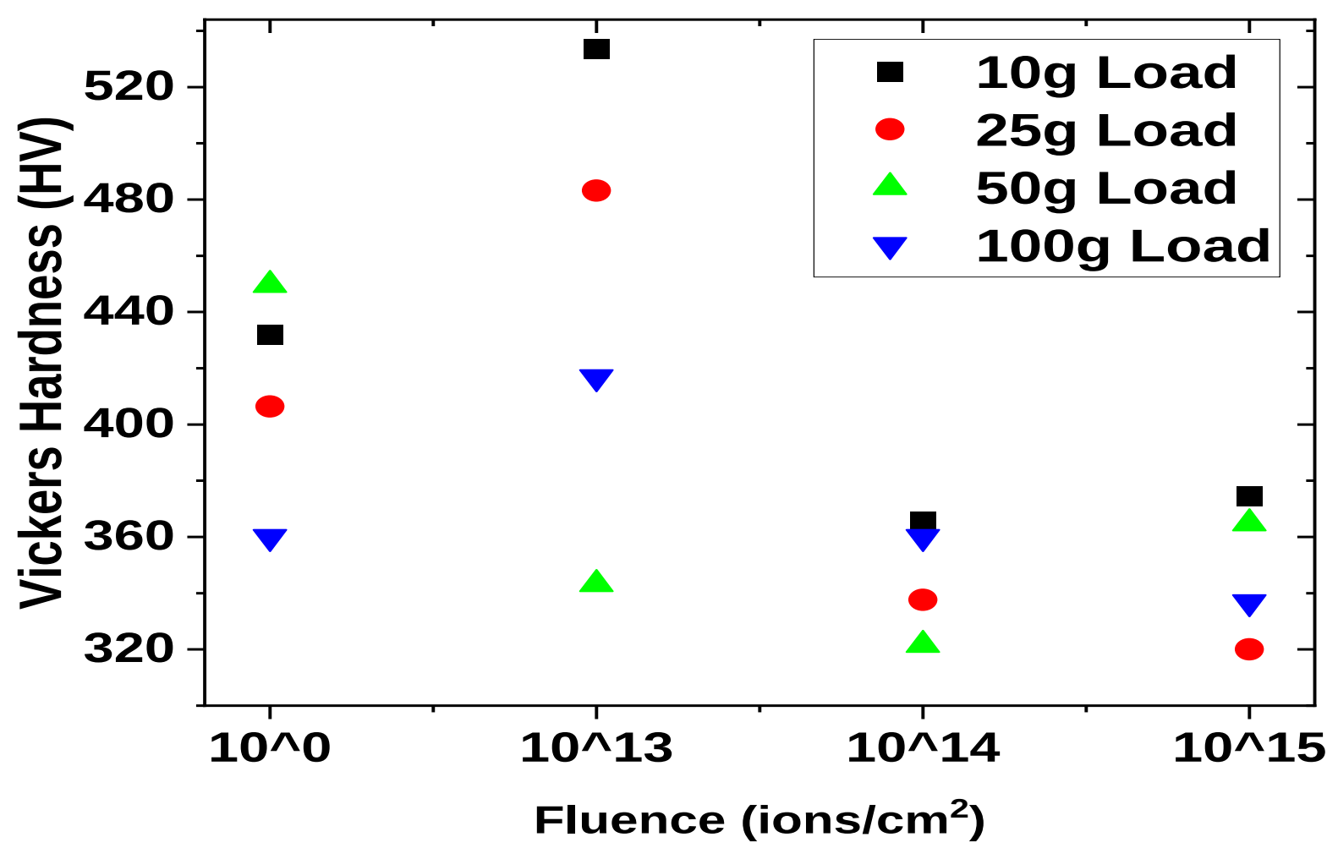


Figure 10. Micro-Vickers hardness values at different loads and fluence ions/cm^2 rate of smooth tungsten samples

- Optical microscope images of the machined channels of 0.3 mm for tungsten divertor
- The narrow channels for the liquid lithium to remove heat from the tungsten divertor
- What will be the machining effect on its microstructure?
- What will be the irradiation effect after machining the smooth surface?

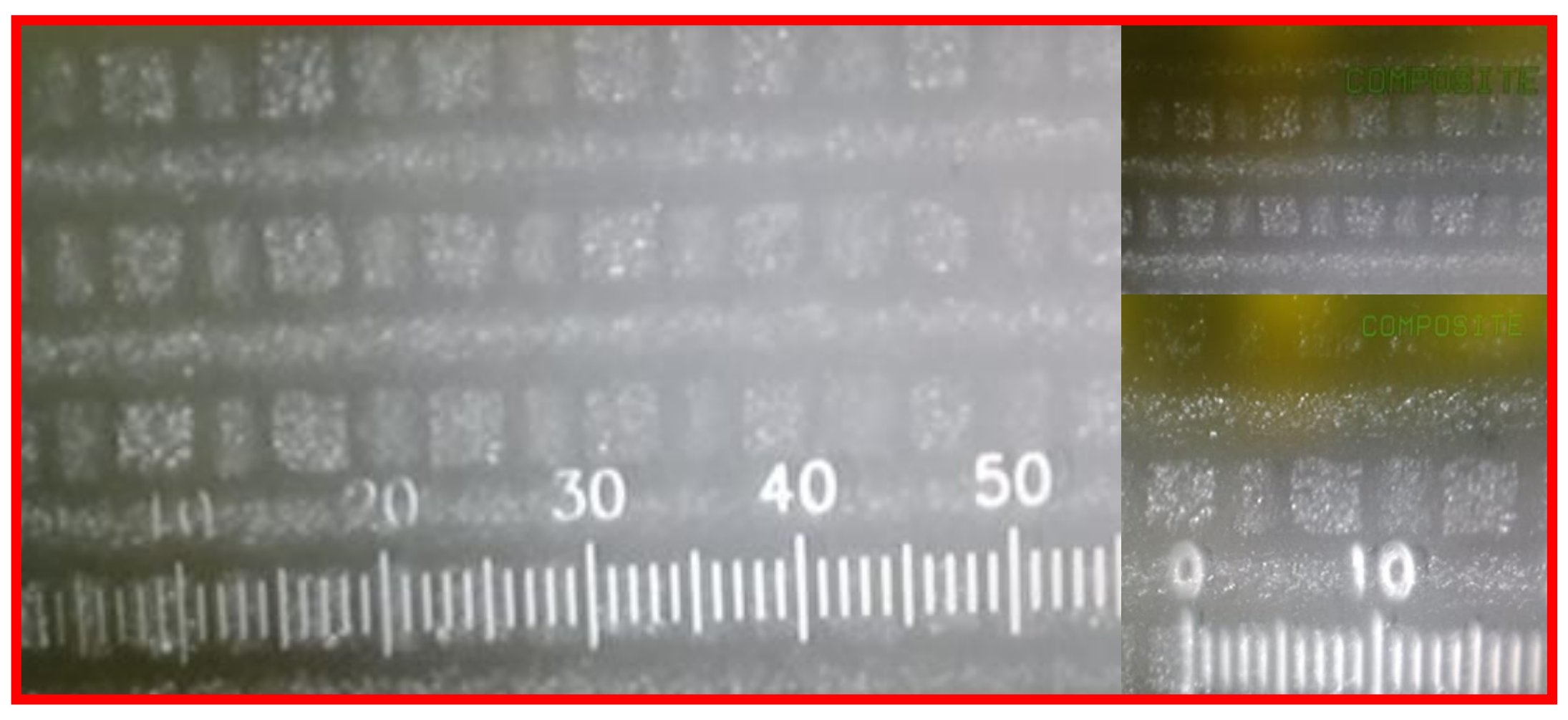


Figure11. Optical microscopy image of the mesh pattern sample

- The mesh structure is uniformly distributed
- Wire cutting creates stresses in the structure which causes to produce uniformly distributed nano-cracks in the sample
- These nano-cracks will be more beneficial for the capillary action to remove heat but it can produce structural collapse in case of any huge load

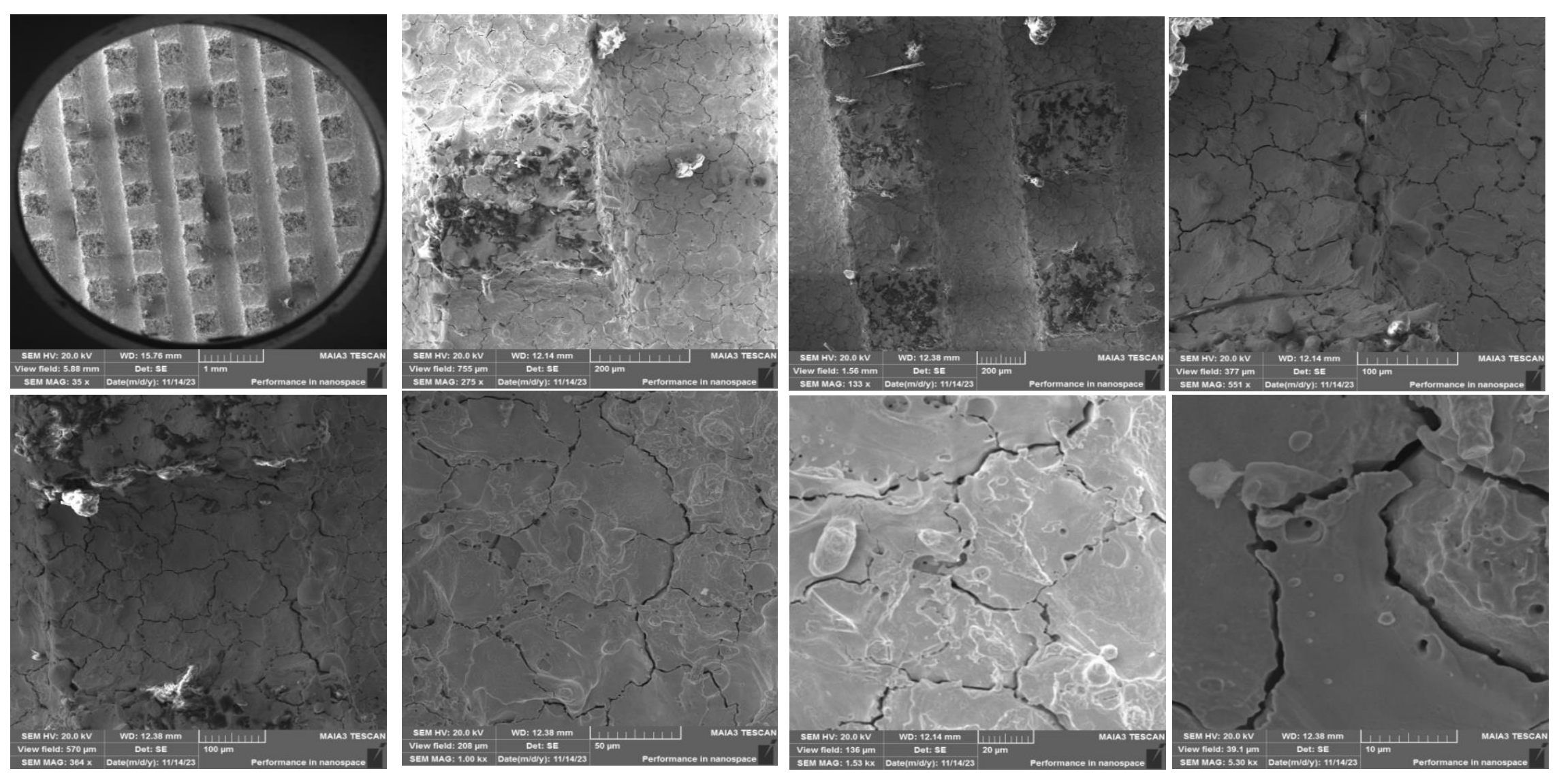


Figure 12. The SEM micrograph of the mesh surface of the machined tungsten sample for liquid lithium divertor

Conclusions

- Two types of divertor geometries are considered for PST , Type B is more favorable than type A
- The smooth surface divertor and mesh type divertor will be further explored for the heat removal
- The helium ions irradiation for the fluence 10^{13} ions/cm^2, 10^{14} ions/cm^2, and 10^{15} ions/cm^2 causes considerable surface and microstructural damage (fuzz, voids and blisters) and gives a maximum DPA of 0.15.
- The helium ions have penetration depth up to 20 micro-meter for the energy of 10 MeV
- The machining of the tungsten to produce mesh surface causes nano-cracks in the surface which will be prone for any huge load.

References

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