Advance the understanding of radiation damage in fusion materials using ultrafast time-resolved electron diffraction

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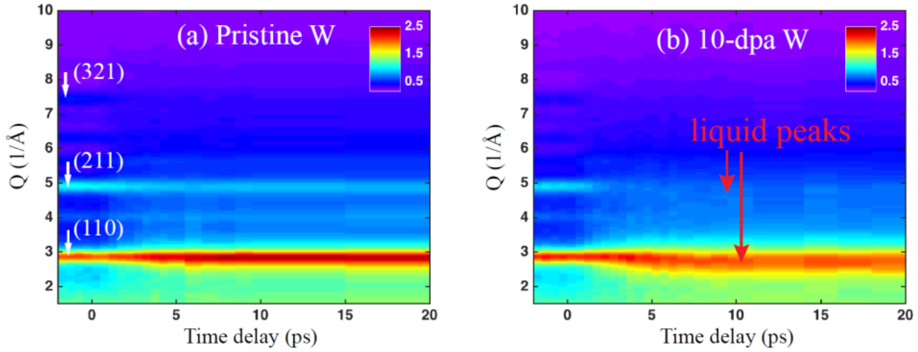
A grand challenge in fusion energy science is to understand the degradation of materials and structures under extreme fusion reactor conditions. Inside a fusion reactor, plasma-facing materials (PFMs) and other in-vessel components will experience a uniquely hostile operating environment, consisting of large fluxes of plasma exposure, energetic neutron irradiation and high thermal loads [1-2]. These extremely harsh wall loads lead to serious damage in the materials surface that may compromise their structural integrity or even contaminate the fusion plasma. Although present laser experiments already provide information on material damage in single shot facilities, the accumulative effects of radiation in a facility operating at >10 Hz is largely unexplored and will require a detailed physics understanding of radiation damage cascades on atomic scale and time length.

The mechanism of radiation damage to materials under fusion-relevant conditions is complex and is an inherently multiscale phenomenon that encompasses many orders of magnitudes in time and space [3]. The initial ballistic collisions between atoms induced by neutron irradiation occur on femtosecond time scales and angstrom length scales, whereas the irradiation-assisted creep and fatigue crack can take days and months to develop with length scales of structural-component lengths. Furthermore, accumulation of the same type of irradiation can emerge as a multiscale problem. For instance, helium products through nuclear transmutation contribute to the near-surface microstructural changes by creating nanometer-scale bubbles that will eventually lead to the formation of micrometer-scale fuzz on the surface. In this case, the initial helium generation takes place on sub-picosecond timescales while the fuzz formation can take seconds or even minutes to become significant.

State-of-the art multi-scale computer simulations are being carried out to attempt predicting the near-surface material response to the extreme wall loads inside a fusion reactor [4]. This is a scientific area of research with an urgent need for experimental data that will provide critical test of modelling assumptions. Currently, dynamic effects of radiation damage can be traced *in situ*, with limited temporal resolutions in the range from milliseconds to seconds, through sequences of ion irradiation followed by transmission electron microscopy (TEM) analysis of materials [5-6]. However, these techniques cannot reach ultrafast time scales that are required to understand radiation damage cascades, defect production and accumulations, and to test interatomic potentials used in the MD modeling.

Here, we propose the application of time-resolved diffraction technique using relativistic electrons, namely MeV ultrafast-electron-diffraction (MeV-UED). This technique can connect the physics on atomic length and time scales with macroscopic observables and is a powerful tool to study structural dynamics in solid-state materials [7-9]. Because of the reduced space-charge effect, MeV electrons provide high-brightness electron bunches with femtosecond pulse durations. Furthermore, multiple elastic scattering effects are less probable in thin films at these energies, providing accurate structure factor for validating physics models. Lastly, the large momentum transfer range of MeV electrons allows to capture the atomic pair correlation function from which quantitative atomic structure and molecular bond dynamics can be determined. The combination of these features makes MeV-UED an ideal tool for studying structural dynamics in radiation-damaged materials and for examining how radiation-induced defects change the atomic behavior. The experimental data will provide information to help understand material properties (thermodynamic, transport and mechanical) of fusion materials, as well as understand their degradation with accumulation of radiation damage from long-term operation in fusion reactors. Furthermore, time-resolved diffraction data will provide direct testing with molecular dynamics simulations, which will help advance predictive modeling tools for designing radiation-resistant materials for fusion reactor environments.

Time-resolved electron diffraction results of laser-induced melting in W. Left: pristine W, right: 10-dpa irradiated W



Snapshots of time-dependent pair correlation function H(r) during the melting process in pristine and radiation-damaged W

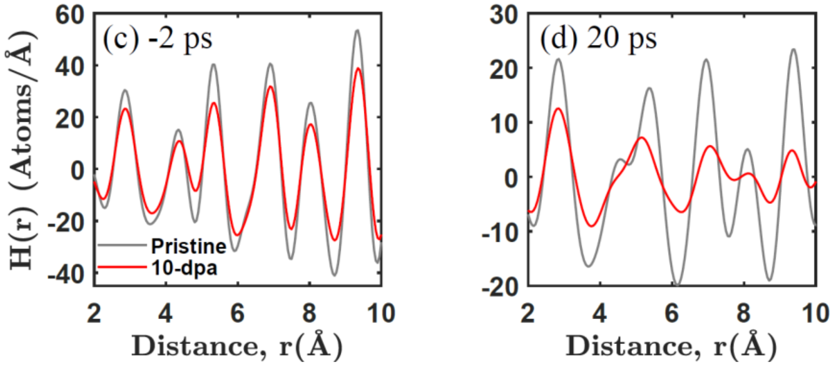


Figure 1 MeV-UED studies of ultrafast laser-induced melting in pristine and radiation-damaged W [10]. (a) Time-resolved scattering data shows that pristine W remains mostly solid after the laser heating. (b) W subjected to 10-dpa radiation damage however undergoes a complete solid-liquid phase transition at the same laser heating condition. (c) – (d) Comparison of pair correlation function H(r) between pristine and radiation-damaged W at two selected delays relative to the laser arrival time. The oscillation peaks in (c) are atomic peaks of bcc W and are shown to be significantly reduced by displacement damage in the 10-dpa W.

At SLAC’s MeV-UED facility, a pump-probed experimental configuration for studying irreversible structural dynamics (such as those found in warm dense matter studies) has been developed and offered to external users for experiments [8]. This dedicated configuration is equipped with a high-intensity femtosecond laser for impulsive heating of the samples, capable of delivering thermal loads relevant to fusion reactor conditions. While ion irradiation damage to materials is not available in the facility, this can be prepared elsewhere such as in the Ion Beam Materials Laboratory at LANL, and the IVEM-Tandem facility at Argonne National Laboratory. Previous work [10] conducted at the facility has demonstrated the structural sensitivity of MeV electrons to radiation-induced defects in W. In this work, we found that highly populated point defects induced by energetic collision cascades facilitated the initial process of liquid nucleation and promoted the melting behavior in W (Figure 1).

In addition to melting, MeV-UED can be also employed to explore many other scientific questions relevant to radiation-induced damage of fusion materials. To motivate and engage more efforts from the inertial fusion community, we are suggesting three major areas as shown in Table 1, together with respective techniques that have been demonstrated at SLAC's MeV-UED facility.

Table 1: Proposed research areas relevant to degradation of fusion materials that can be studied with the technique of MeV-UED.

Research topic	Materials	Irradiation type	Technique
Thermal melting	W, W alloys	He/H implantation, displacement damage	Time-resolved diffraction [10]
Transport properties: electrical and thermal conductivities	W, W alloys and Cu alloys	He/H implantation, displacement damage	Time-resolved diffraction [10] and diffuse scattering [11]
Thermal shock-induced damage	W, W alloys and F/M steels	He/H implantation, displacement damage	Time-resolved diffraction [12]

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