Modelling the neutron radiation environment of HTS magnets in thermonuclear fusion reactors

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Abstract

Compact high-field fusion reactors based on high-temperature superconducting (HTS) magnets offer a promising route toward accelerated fusion development; however, their reduced size entails harsher radiation environments for the magnetic system, characterised by increased power deposition and neutron-induced lattice damage. Given the delicate nature of superconductivity, these effects represent a major risk and a potential bottleneck for the deployment of compact fusion reactors. Radiation damage in superconducting materials therefore becomes a critical design issue, requiring dedicated and carefully optimised neutronic analyses.

In this work, a Monte Carlo–centred multiscale framework is developed for the design and lifetime assessment of HTS magnet systems in compact fusion reactors. The conceptual design of ARC is adopted as a reference case, and neutron transport simulations are performed to characterise the radiation environment of the magnets and to evaluate candidate neutron-shielding materials. The assumptions underlying the neutronic calculations, in terms of transport code, nuclear data libraries, and physical models, are first benchmarked against independent calculations and then applied across different levels of geometric complexity, from a representative super conducting cable to the full reactor model. The radiation environment on the coils is subsequently compared with that expected in two additional reactor concepts with different size and design philosophy, namely VNS and DEMO.

Current reactor neutronic analyses primarily rely on dose-based metrics such as the displacement-per-atom (dpa) to quantify radiation damage, which provide an integral measure of damage but do not capture the sensitivity of complex oxides, such as YBCO, to the morphology and spatial distribution of irradiation-induced defects. Experimental evidence shows that identical dpa levels obtained under different irradiation conditions can lead to markedly different degradation behaviours, indicating the need for an enhanced description of radiation damage.

To address this limitation, a supplementary modelling layer is introduced to parametrise the defect characteristics associated with individual recoil events. This information, obtained from atomistic simulations of collision cascades, is condensed into physically motivated

damage descriptors that can be directly integrated into Monte Carlo post-processing, extending standard dose metrics without altering the transport calculations themselves.

The capability of these descriptors to capture substantially different defect landscapes is first demonstrated by modelling well-controlled electron and fission-neutron irradiation experiments on YBCO single crystals. The enhanced Monte Carlo analysis is then applied to the assessment of neutron-shielding configurations for the inboard segments of the toroidal-field coils of ARC, enabling a comparative evaluation of candidate shielding materials and the estimation of magnet degradation times under fusion-relevant irradiation, relative to reference fission-neutron exposure.

Overall, this work provides a detailed and comparative analysis of the radiation environment expected in compact high-field tokamaks. In addition, it introduces a practical and physically informed extension of Monte Carlo radiation damage modelling, enabling improved interpretation of irradiation experiments and supporting the design of shielding architectures and lifetime assessment strategies for HTS magnet systems in fusion reactors.