ACCELERATING DEVELOPMENT OF SUSTAINABLE FUSION REACTOR WITH TUNEABLE NEUTRON FIELD OF COMPACT ACCELERATOR-BASED NEUTRONS SOURCES

[1*]J.J.H. Lim, [1]T. Turner, [2]L. Butt, [1]P. Srinivasan, [2]B. Phoenix, [1]D. Nguyen, [1]M. Gilbert, [2]Y. Chiu, [1]L. Packer, [2]M. Freer, and μBB project contributors

[1] United Kingdom Atomic Energy Authority, Abingdon, United Kingdom
[2] University of Birmingham, Birmingham, United Kingdom

*Correspondent email: joven.lim@ukaea.uk

The advancement of sustainable fusion energy critically depends on the optimization of the Tritium Breeder Blanket (TBB), which plays a central role in extracting energy from the fusion reaction while breeding tritium to sustain the fuel cycle. Achieving tritium self-sufficiency requires a Tritium Breeding Ratio (TBR) greater than unity, ensuring that the reactor produces sufficient tritium to compensate for radioactive decay, permeation losses, and inefficiencies in the fuel cycle. The optimization of TBBs remains a complex challenge due to the intricate interactions between material properties, neutron transport, and tritium production. These interactions evolve over time as neutron irradiation alters the microstructure and chemistry of materials, potentially impacting tritium retention, diffusion, and local breeding performance. Understanding these effects is essential for designing robust and sustainable breeder blankets that can support the long-term viability of fusion power plants.

A key barrier to progress in this field is the limited availability of experimental facilities capable of replicating the neutron environment of a fusion reactor. While fission reactors and dedicated fusion neutron sources have provided valuable insights, these facilities have inherent limitations in terms of spectrum fidelity, neutron flux, test volume, and accessibility. In particular, the neutron spectra in fission reactors differ significantly from those in fusion reactors, making it difficult to obtain representative data on material performance and tritium breeding efficiency. Similarly, while future volumetric neutron sources (VNS) are expected to provide a more fusion-like environment, their high cost and long lead times make them unsuitable for rapid iterative testing.

To address this gap, the UKAEA's Micro-Breeder Blanket (μBB) project has developed the Tunable Micro-Breeder Neutron Emission Device (TμNED), a compact accelerator-based neutron source that employs Neutron Field Engineering Technology (NFET) to generate tailored neutron spectra. The primary innovation of TμNED lies in its ability to precisely shape the neutron spectrum, allowing researchers to explore methods for enhancing local tritium breeding performance. By adjusting the neutron spectrum and modifying the composition of the breeder material—including the isotope balance, presence of neutron moderators, and choice of neutron multipliers—TμNED provides a unique experimental platform for investigating spectral-dependent tritium production. This capability is particularly valuable for assessing how lower-energy neutrons, which result from scattering within the blanket, contribute to the overall breeding efficiency.

A significant milestone in the development of TμNED has been the successful validation of its neutron spectrum tailoring capability. The TμNED-M1 configuration was specifically engineered to replicate the 14 MeV neutron spectrum observed at the First Wall (FW) of the DEMO Helium-Cooled Pebble Bed (HCPB) TBB, as shown in Fig.1. Experimental validation conducted at the University of Birmingham's cyclotron facility in March 2024 demonstrated a strong agreement between the measured neutron spectra and Monte Carlo N-Particle (MCNP) Transport Code simulations. These results confirm that TμNED can reliably reproduce fusion-relevant neutron environments, providing an effective tool for systematic TBB research.

While TμNED offers a promising approach to understanding spectral effects on tritium breeding, the experimental complexity of these tests should be acknowledged. Measuring small-scale variations in breeding enhancement due to localized neutron spectrum adjustments presents a challenge, as does quantifying uncertainties in neutron flux distribution and tritium production rates. Furthermore, threshold effects in material interactions may cause small samples, i.e. 100s cubic centimetres scale, to exhibit behaviours that do not necessarily scale to full reactor systems. Recognizing these limitations is essential to ensure that experimental results are properly interpreted and that TμNED's role as a complementary tool to larger fusion neutron sources is clearly defined.

Another significant aspect of TμNED's research potential lies in its ability to investigate the impact of neutron-induced material changes on tritium breeding performance and net-extractable tritium. While displacement damage in breeder materials is not an obvious determinant of TBR, the evolution of irradiation-induced microstructural defects could influence tritium retention property. By allowing controlled irradiation under tailored neutron spectra, TµNED provides an opportunity to examine these effects in greater detail. Although the scale of damage achievable in an accelerator-driven system is limited compared to a full fusion reactor environment, the ability to study these phenomena in a controlled setting represents a valuable step toward understanding the long-term behaviour of breeder and breeder-facing materials.

TµNED serves as a complementary tool to future VNS that fills a critical niche in the fusion research landscape. While future VNS facilities will provide the high-fluence, integrated testing environments necessary for validating full-scale components, their construction and operation require substantial resources and time. In contrast, TµNED offers a faster, cost-effective, and scalable alternative for pre-screening TBB concepts, refining breeder configurations, and investigating specific neutron-material interactions before committing to large-scale testing. The ability to perform high-throughput experiments at lower cost accelerates the development cycle for breeder blanket technologies and fusion materials, reducing the time required to transition from theoretical design to practical implementation.

The versatility of TµNED extends beyond tritium breeding research. Its moderate neutron flux, reaching up to 5E+08 n/cm²/s per microampere of beam current, combined with its ability to integrate into existing accelerator infrastructure, makes it an accessible tool for a broad range of fusion-related studies. When integrated with high-current accelerators, TµNED can achieve neutron fluxes exceeding 5E+11 n/cm²/s, further expanding its experimental utility. This flexibility allows researchers to explore various aspects of neutron-material interactions, from fundamental irradiation effects to applied studies on breeder blanket optimization.

The development of TµNED represents a significant step forward in fusion research, offering a sophisticated yet practical approach to addressing key challenges in breeder blanket design. By enabling precise control over neutron spectra, TµNED facilitates targeted studies on spectral-dependent tritium production, material evolution, and neutron-induced effects. Its role as a rapid, cost-effective testing platform complements larger neutron sources, bridging the gap between theoretical models and full-scale reactor validation.

Through its novel approach to neutron field engineering, TµNED enhances the ability of researchers to investigate critical aspects of fusion reactor design. The capacity to tailor neutron spectra and explore their impact on tritium breeding provides an important avenue for optimizing breeder blanket performance. Moreover, the insights gained from TµNED experiments support the broader goal of achieving self-sustaining fusion energy, ensuring that future reactors are designed with the necessary resilience and efficiency to operate on a commercial scale. As fusion energy moves closer to becoming a viable power source, tools like TµNED will play an increasingly important role in refining and validating reactor technologies. By recognizing both its strengths and its limitations, TµNED establishes itself as an essential research instrument that complements existing and future neutron sources, accelerating progress toward the realization of sustainable fusion power.

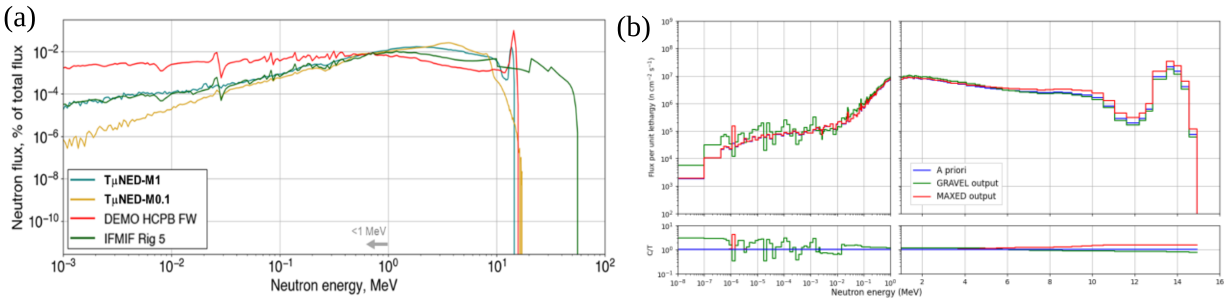

Fig. 1 (a) showing the simulated neutron spectra engineered to mimic the neutron spectrum at the FW of the DEMO HCPB using MCNP Transport Code. TuNED-M1 spectrum has been validated experimentally. The experimental measurement matched with simulated neutron spectrum, and (b) showing the unfolded neutron spectra using activation foils from experiments conducted in March 2024. A priopi used the IRDFF response functions and Mn56/Na24 benchmarked MCNP spectrum. Other spectra were outputs from GRAVEL and MAXED unfolding algorithms. The spectra converged indicates the confidence of the engineered neutron spectrum, i.e. TµNED-M1, is relevant for fusion applications.

ACKNOWLEDGEMENTS

This work has been part-funded by the EPSRC Energy Programme [grant number EP/W006839/1]. To obtain further information on the data and models underlying this paper please contact PublicationsManager@ukaea.uk.