FEATURES OF FUSION POWER MEASUREMENTS IN THE NEXT GENERATION MAGNETIC PLASMA CONFINEMENT EXPERIMENTS

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INTRODUCTION

Fusion power measurement provide one of the key benchmarks for every successful magnetic confinement fusion facility of a reactor scale. Neutrons carry outside of the plasma volume 4/5 of the produced fusion power in case of deuterium-tritium fuel mix. Thus, measurement of 14-MeV neutron yield is the primary direct measurement of the fusion power of the machine. Fusion power measurements with the use of plasma neutron diagnostics is characterized by neutron transport through the facility components, by detector properties, by the plasma neutron source profile as well as by the parameters of the neutron source used for calibration [1]. Neutron spectra, flux and directionality change as the neutrons pass through the materials surrounding the plasma, it is therefore quite common to used collimated detectors [2, 3] and threshold detectors [4] for neutron flux measurements. These methods typically have quite a low sensitivity compared to the wide-range counters that measure both thermalized and fast neutrons [5, 6]. Fusion plasma as a neutron source is a volumetric source with an arbitrary profile prone to rapid changes due to fluctuations of plasma parameters, with quite a high neutron yield per cubic centimeter [7]. Neutron diagnostic detectors are typically located at a fair distance from the source, in an environment shielded against the scattered neutron flux and x-ray radiation, that may be present in some operation regimes. The challenge of determining the uncertainty of the total neutron yield measurement arose as soon as the first experiments with deuterium discharges commenced on the tokamak devices [8]. The tree key strategies for detector calibration were proposed: detailed detector assessment in the metrological neutron laboratory, in-situ calibration using a mobile neutron source (typically - ^{252}Cf) inside the vacuum chamber with respective neutron transport and detector response calculations and a cross-calibration using a well characterized detector and well-known discharge parameters to infer calibration factors for other diagnostics. First D-T experiments (TFTR, JET) utilized calibration data obtained using low-yield D-T neutron generators (NGs) with the yield of up to 10^7-10^8 n/s. Transition to reactor-scale devices such a BEST, ITER, DEMO, etc. will require the use of mobile neutron generators with yields of 10^{10}-10^{11} n/s and above.

DETECTOR CHARACTERIZATION AND MEASUREMENT METHODOLOGY

In present work we discuss the progress of neutron diagnostics development for fusion power measurements, including current achievements in design and testing, overall uncertainty minimization strategy with particular focus on in situ calibration, and outlook of said activities for future magnetic confinement fusion devices capable of reaching burning plasma state. Multiple diagnostics systems fall in the scope of this work including neutron counters (i.e. fission chambers), neutron activation system and multi-collimator systems. Together they allow for comprehensive measurement of total neutron fluence, time resolved yield and neutron source shape, thus providing fusion power measurement with high accuracy and time resolution (up to 10% and 1 ms for the case of ITER) in a broad range of fusion power. Similar set of systems is employed for neutron source control at JET [9], EAST [10], and other devices.

Detailed detector and I&C design, performance testing, characterization and in situ calibration are critical pre-requisites to reach these target requirements. High-resolution model of detector response created using analytical approach and GEANT4 [11] and OpenMC [12] software is then benchmarked in laboratory conditions using isotope neutron sources, as well as compact neutron generators (with both D-D and D-T sealed tubes). The use of metrologically assured sources is critical during detector characterization. At the same time, replicating tokamak environment in the laboratory is not feasible, the length of cables, number of connectors, temperature gradients and other impacting factors underline the necessity of in situ calibration procedure.

We discuss two key solutions of the in-situ neutron calibration problem, with both methods revolving around compact neutron generators being deployed inside the fusion machine vacuum vessel: 1) utilizing multiple NG positions to emulate circular or 'ring' source of fusion neutrons [13, 14] for calibration of the permanent detector set, and 2) making use of multiple temporary high-sensitivity detector units located in various locations inside the vacuum vessel strictly for the period of the calibration, thus allowing to obtain much more reference points for further Monte-Carlo model validation with the same (or less) calibration campaign duration. The structural integrity requirements for these temporary detector units are quite limited (if any), as they are not intended for use during the actual machine operation.

Both methods are nevertheless to be augmented using the cross-calibration during reference discharges, preferably low fusion power, minimal-to-zero auxiliary heating, in essence – the ohmic discharges. We demonstrate that given the constraints on the neutron source strength and calibration campaign duration, the use of temporary detector set with low price-per-unit and high sensitivity may facilitate greatly the validation process of the quite detailed tokamak models for Monte-Carlo modelling of the neutron transport. This method is therefore beneficial for lowering the uncertainty of the neutron measurements and fusion power assessment of the reactor-scale tokamaks with both parameters being critical from the regulatory standpoint.

We discuss in detail the results of neutron detector characterization activity in laboratory conditions with the use of compact NGs. We show that the use of powerful (up to 10^{11} n/s D-T, 10^{9} n/s D-D) yet compact NGs with sealed tubes (illustrated on figure 1) raises a challenge of source metrological assurance, especially when considering said sources for the task of in-situ calibration. These NGs are to be supplied with monitoring systems, preliminary characterized at metrological facilities, with Monte-Carlo models (as illustrated on figure 2) built and verified in terms of both materials, geometry, and neutron source anisotropy. Significant part of current work is dedicated to the effort of characterization of NG-14 and NG-24 models manufactured by FSUE VNIIA [15], operating with accelerating voltage of 150 up to 250 kV and ion current of 0.5 up to 2 mA, respectively. The monitoring system for such a source is comprised of multiple neutron spectrometers, counters and activation samples mounted on the irradiation unit.

Fig.1. Irradiation unit of D-T neutron generator NG-14 with yield up to 10^{10} n/s

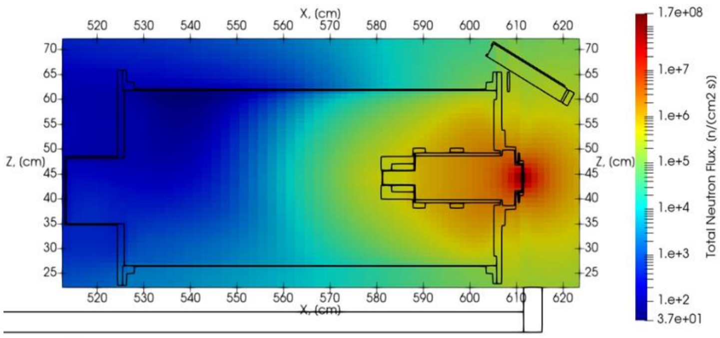

Fig. 2. Neutron flux distribution for the neutron generator irradiation unit with a neutron monitor attached to the irradiation unit, neutron yield of 10^{11} n/s.

In the outlook of this work we discuss the application of the proposed in situ neutron calibration methodology for uncertainty minimization of fusion power measurements for ITER tokamak, as well as a more compact fusion facility such as Tokamak with Reactor Technologies (TRT) [16].

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