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Scattering chamber facility for double-differential cross-section measurement with 14 MeV DT neutron generator at IPR

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Abstract. Measurement of double-differential cross-sections of 14 MeV neutron-induced charged-particle productions is very important for estimating the nuclear heating and radiation damage of a fusion reactor. Only a few experimental data are available even though the nuclear reaction cross-section data of structural materials are important in fusion nuclear technology. In this context, general purpose scattering chamber facility has been developed for accelerator-based 14 MeV DT neutron generator to measure double-differential nuclear reaction cross-section at Fusion Neutronics Laboratory, IPR. It has been designed for experiments using silicon surface barrier detectors for the online detection of charged particles. It offers flexibility in the arrangement of silicon surface barrier detectors.

Keywords. Scattering chamber; double-differential cross-section; 14 MeV DT neutron generator; silicon surface barrier detector.

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1. Introduction

One of the problems normally faced in the development of fusion reactors is the generation of gases (e.g., hydrogen, helium, deuterium etc.) through (n, α), (n, p), and (n, d) reactions. Such reactions are induced by the bombardment of fast neutrons on the first wall, structural and blanket components of the reactor leading to the formation of gases in the bulk of the material at different locations [1]. In addition to the production of gases, other processes such as atomic displacements, transmutations, etc., can produce microstructural defects in the material. As a result, at very high neutron fluencies, the mechanical properties of the reactor materials may be deteriorated gradually. Therefore, measurement of double-differential cross-section (DDX) of neutron-induced charged particle production are quite important for estimating the level of nuclear heating and for various physical quantities, such as primary knock-on atom (PKA), gas production per atom (GPA) and displacement per atom (DPA) [2]. For this purpose, the values of DDX for the production of gases in the reactor materials through nuclear reactions induced by 9–15 MeV neutrons are required.

An accurate DDX is particularly in demand for developing a fusion reactor. This development has just entered a new phase with the construction of international thermonuclear experimental reactor (ITER) [3], using deuterium–tritium (DT) plasma. Here, DDX data will play an important role in estimating the nuclear heating and damage of candidate materials of the reactor irradiated with 14 MeV neutrons from the $T(d, n)\alpha$ reaction. Literature available in IAEA–EXFOR database [4–6] indicate that there are only a few DDX measurements for structural materials at 14 MeV.

It is obvious from the above discussions that DDX data play significant roles in fusion reactor technology. Therefore, the objective of the present work is to build a facility for DDX measurement for neutron-induced charged particle nuclear reactions on fusion-related materials. In this context, a general purpose scattering chamber facility has been designed for accelerator-based 14 MeV DT neutron generators to measure double-differential cross-section.

2. Double-differential cross-section

In many nuclear physics applications, we are not only concerned with the probability to find particle ‘b’ emitted at certain angle but also want to find it with certain energy, corresponding to a particular energy of the residual nucleus. Therefore, we can define cross-section as a measure of the probability to observe ‘b’ in the angular range of $\mathrm{d}\Omega$ and in the energy range of $\mathrm{d}E_{\mathrm{b}}$. It is called double-differential cross-section $\mathrm{d}^2\sigma/\mathrm{d}E_{\mathrm{b}}\mathrm{d}\Omega$. Usually, cross-sections are plotted as $\mathrm{d}\sigma/\mathrm{d}\Omega$ vs. θ leading to a specific final-energy state. This is in reality $\mathrm{d}^2\sigma/\mathrm{d}E_{\mathrm{b}}\,\mathrm{d}\Omega$, although it may not be labelled as such.

3. Design of scattering chamber at FNL, IPR

3.1 *Mechanical design*

A general-purpose cylindrical scattering chamber has been designed for the DDX measurements [7] relevant to fusion materials. The chamber is made of ASTM/ASME SA 312 Grade TP 304L. All the flanges, collars and blanks are made of ASTM/ASME SA 240 Grade SS304L. The chamber is a vertical cylinder (dimensions OD 356 × L 200 mm) with six ports of different sizes varying from 35 CF to 150 CF. All the flanges and blanks have been selected as standard vacuum components. The wall thickness of the chamber has been kept as 3.56 mm. It has four ports which are 90° apart. The four main ports are as follows: (1) beam entry port, (2) beam exit port, (3) turbomolecular pump (TMP) port and (4) view port. Apart from these four main ports, the chamber has two additional ports

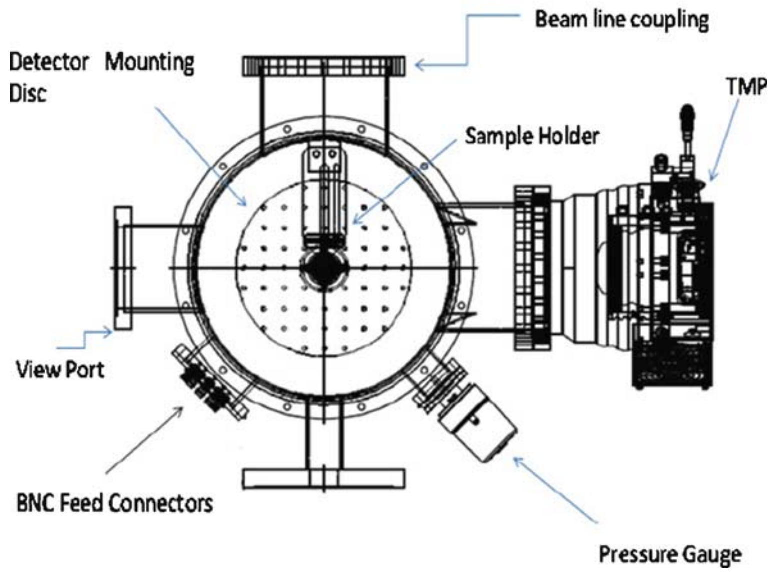

Figure 1. Schematic view of general-purpose scattering chamber facility at IPR.

at 45° along with the beam direction for BNC feed-through and vacuum gauge. The top and bottom lids of the chamber have a thickness of 16 mm. Further, one more additional view port of 35 CF is provided on the top lid of the chamber to observe the position of detectors. A special type of moving mechanical assembly has been fitted on the bottom flange of the chamber for holding the target. There is a rotatable detector mounting disc with its angle index wheels and Vernier scale to read angular position with a least count of 0.05°. The chamber is provided with the TMP through the pumping port to create a vacuum of the order of 10^{-6} mbar during the experiment. It has been designed to house charged particle detector telescopes based on silicon surface barrier detectors (SSBD) for the online detection of charged particles. It offers flexibility in the arrangement of SSBD detectors. Simplicity and economy were also considered during the design of the test set-up. The schematic view of the general-purpose scattering chamber is shown in figure 1.

3.2 *Mechanical analysis*

The design and analysis of the vacuum chamber is based on the classical mechanics approach and finite element (FE) analysis by using ANSYS [8]. The vacuum chamber is analysed for self-weight and vacuum pressure loads. For FE analysis, all the ports of ∼250 mm length were modelled with their respective blanks. The assumptions that were considered during the analysis are listed below:

(a) Welds are not modelled in finite-element analysis.
(b) It is assumed that the vacuum chamber is stress relieved.
(c) The Von-Mises stress theory is used for combining stresses.
(d) All the weld joints shall have full penetration. The correction factor or joint efficiency for all the butt welds is assumed to be 100%.

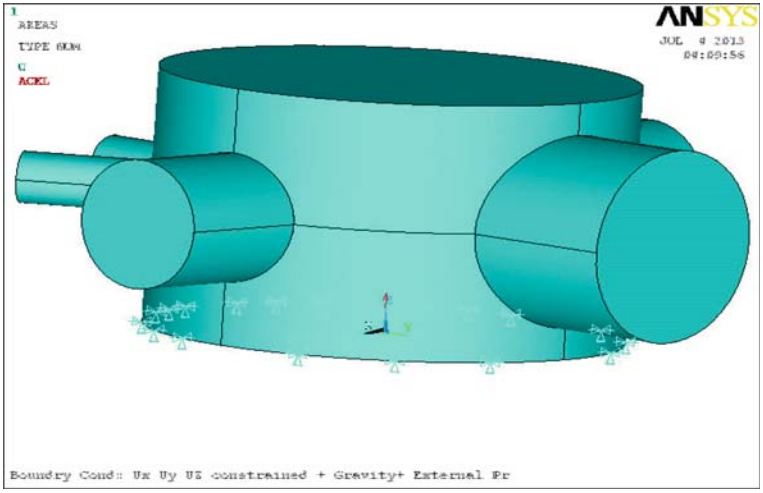

Figure 2. Typical load of the vacuum chamber.

Finite-element modelling of the vacuum chamber for different thicknesses and cross-sections using general shell element (Shell 93) was developed in ANSYS. The loads as described in the free body diagrams (FBD) were applied to simulate the effect of dead weight and external pressure. The 3D general shell element (Shell 93) with six degrees of freedom per node that defines the element translations and rotations in the nodal x, y and z directions, was used for modelling the space frame. The results of finite-element analysis consist of nodal displacements and element stresses. The nodal displacements would show the resultant deformation pattern of the given structure for the considered loading. In the static analysis of the vacuum chamber system, Von-Mises stress has been considered, as the material is ductile. Von-Mises stress is given by the following equation:

$$s_{\mathrm{Von}} = \sqrt{\left[\left\{(s_1 - s_2)^2 + (s_2 - s_3)^2 + (s_3 - s_2)^2\right\}/2\right]},$$

where s_1, s_2 and s_3 are the principal stress in x, y and z direction, respectively.

The typical load and Von-Mises stress distribution of the chamber are shown in figures 2 and 3 respectively.

3.3 *Vacuum system*

The vacuum system of the chamber consists of electroneumatic gate-valve, turbomolecular pump (TMP), rotary pump and pirani gauge. The entire vacuum system will be controlled and monitored by means of programmable logic unit (PLU) to ensure automatic switching from roughing to turbopumping. The chamber will be evacuated with the help of a pumping system of 300 l/s TMP and its backing pump through 100 CF pumping port at 90° with respect to the beam direction as shown in figure 4. An electroneumatic gate-valve isolates the scattering chamber to the TMP. A gauge is provided through CF 35 port at 45° with respect to the beam direction to measure pressure in the chamber. It is expected to reach a base pressure of 10^{-6}–10^{-7} mbar before initiating the experiments.

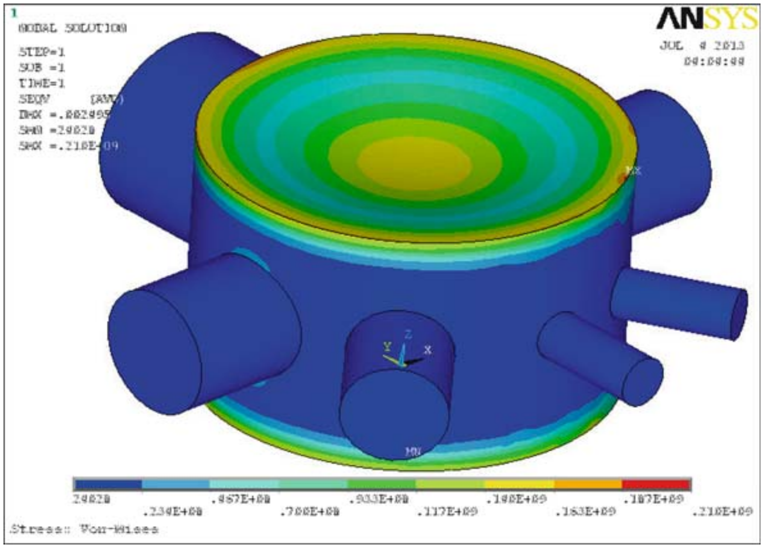

Figure 3. Von-Mises stress distribution (hot point stress at a very small area of 210 MPa and neglected due to elemental errors and rest zones are well below ∼130 MPa, <2/3 of the yield strength of SS304L).

4. Summary

A general-purpose 30 cm diameter scattering chamber has been designed for the DDX measurements for structural materials for accelerator-based 14 MeV DT neutron generator at FNL, IPR. It has been designed to house charged particle detectors/telescope based on silicon surface barrier detectors for the online detection of charged particles. The

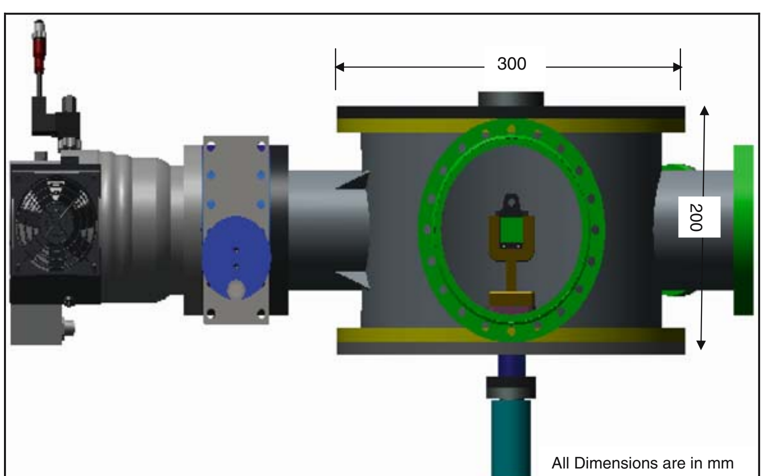

Figure 4. 3D view of the scattering chamber.

vacuum system of the chamber consists of electroneumatic gate-valve, turbomolecular pump (TMP), rotary pump and pirani gauge. A finite-element analysis based on classical mechanics approach was carried out using ANSYS. The simulation results show that the induced stress due to different load is well below the acceptable level of 130 MPa. It is planned to measure DDX for charged-particle emission induced by 14 MeV neutrons for Fe, Cr, W and Ta elements as they are currently considered as high-priority elements for which well-qualified datasets are required for the test-blanket module design of ITER.

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