Stellarator Fusion Neutronics Research in Australia

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Abstract.

The new status of the H-1NF Heliac Stellarator as a National Facility and the signed international Implementing Agreement on Collaboration in the Development of the Stellarator Concept should together be a significant encouragement for further fusion research in Australia. In this report the future of fusion research in Australia is discussed with special attention being paid to the importance of Stellarator Power Plant Studies and in particular stellarator fusion neutronics. The main differences between tokamak and stellarator neutronics analyses are identified, namely the neutron wall loading, geometrical modelling and total heating in in-vessel reactor components including toroidal field (TF) coils. Due to the more complicated nature of stellarator neutronics analyses, simplified approaches to fusion neutronics already developed for tokamaks are expected to be even more important and widely used for designing a Conceptual Stellarator Power Plant.

1. Introduction

Australia has a long history of fusion research, based both on the tokamak and the stellarator approach. The Australian National University (ANU) in strong collaboration with other Australian universities, e.g. University of Sydney, has designed and built the H-1 Heliac, a helical axis stellarator. Optimized helical axis stellarators (e.g. the W7X Helias to be built in Germany) are widely believed to be the major competitor to tokamaks, as the kinking of the plasma torus into a helical shape may give it high pressure stability properties superior to those of plasma with a simpler, rounder shape. This Heliac achieved National Facility status recently and this should be a big psychological boost for further fusion research in Australia.

Indeed, in 1994, researchers from several Australian universities (ANU, Sydney, Flinders, New England, Canberra and Central Queensland) and Australian Institute of Nuclear Science and Engineering (AINSE) formed the Australian Fusion Research Group (AFRG) as a consortium to apply for funding for a program of collaborative research having the H-1 Heliac as its initial focus [1,2]. Our strong commitment to fusion research has also been proved recently by the signing in Paris of the Implementing Agreement for Cooperation in the Development of the Stellarator Concept under the auspices of International Energy Agency (IEA), aimed at involving Australia in international co-operation in fusion research in the stellarator area.

The progress of the experimental and theoretical plasma fusion program in Australia has led to an increase of interest in fusion technology research which could complement and expand our plasma fusion research. However, any Australian presence in fusion technology research will inevitably be rather modest and will have to be achieved through collaborations involving Australian universities, the Australian Nuclear Science and Technology Organisation (ANSTO) and overseas institutions. A good example of such collaboration is our commitments to international collaboration under the Implementing Agreement for Cooperation in Divelopment of the Stellarator Concept whose program includes research on Stellarator Power Plant Studies and in particular stellarator fusion neutronics research.

Fusion Neutronics research is one of most important parts of any Stellarator Power Plant Study. This analysis includes neutron transport calculations for blanket, shielding, vacuum vessel and concrete cryostat to estimate the effectiveness of those components for shielding and possibly for breeding tritium in the blanket. Research in this area could be conducted in Australia, as a cooperative effort between the Australian National University (ANU), the University of Sydney and the Australian Nuclear Science and Technology Organisation (ANSTO), Australia's national laboratory for nuclear science and technology research and development located 20 miles south of Sydney at Lucas Heights NSW. The latter organisation is an important resource as it is the only organisation in Australia maintaining nuclear transport codes and nuclear data libraries needed for that research.

Fusion Neutronics research has already been conducted in Australia in mid 1980s at ANSTO as a collaborative efforts between ANSTO and Australian universities on some conceptual designs of fusion reactors of interest in Australia at that time, but due to the lack of funding, that research was stopped nearly ten years ago. However, we believe that it would be timely to revive stellarator fusion neutronics research in Australia as a counterpoint to the national effort in fusion related plasma physics research.

2. Neutron transport codes and nuclear data libraries.

ANSTO being the only organisation in Australia maintaining nuclear reactor expertise, has a long history of creating and maintaining transport codes and nuclear data libraries needed for research in Stellarator Power Plant Studies. This organisation maintains both internationally distributed transport codes, such as ANISN [3], DOT [4], DORT [5] and MCNP [6] and ones locally written codes, which are components of the modular neutronics code system, AUS [7].

AUS is a system of neutronics computer codes which were developed initially for fission reactor core calculations. This system has been used at ANSTO for more than 20 years to calculate a wide range of fast and thermal reactor types, including the DIDO class reactor HIFAR. It also has been tested extensively against experimental data and numerous benchmarks.

As shown in the introduction, there was considerable interest in Australia in fusion neutronics in the middle of the 80's. Therefore, the original AUS system underwent considerable development at that time and was extended to cover fusion blanket calculations [8]. The modifications of the AUS system included the extension of the system to allow coupled neutron-photon calculations and the addition of kerma factor data for calculations of heating.

AUS is a modular system in which the computer codes (modules) may be executed in a very flexible manner. The modules communicate through well-defined data sets on disc. The AUS modules are quite large, which leads to some duplication of function but also provides an easier system for users. Although user input has not been entirely standardised, most problem specifications have to be entered once only.

The current version of AUS is written in Fortran 77 and has been run under the UNIX operating system [9] on a Fujitsu VP2200 computer which may be accessed through Internet as *photon.ansto.gov.au*. The AUS code system has a module for performing one-dimensional S_N (module ANAUSN [10]) calculations and lonks to international two-dimensional S_N and Monte Carlo codes.

The first AUS nuclear data library suitable for fusion blankets neutronics was *AUS.ENDF200G* which had 200 neutron groups and 37 photon. This library is mainly based on ENDF/B-IV but does include data from ENDF/B-V for those nuclides such as fission products and higher actinides for which the ENDF/B-V data were released. The generality of the codes and library have enabled their use for a very wide range of calculations including fusion blankets, shielding and various neutron applications. The new *aus/endfb6* library has recently been generated [11] almost exclusively from ENDF/B-VI in the same group structure as that for *AUS.ENDF200G*.

The module MIRANDA [12] is used to prepare multigroup cross-section data for a particular study from the AUS general purpose library. This cross-section generation module for AUS is suitable for all the diverse calculations to which AUS is applied.

3. Main differences between Tokamak and Stellarator neutronics analyses.

Fusion neutronics is a relatively new science dated to the middle of `70s, the time when numerous conceptual designs of tokamak fusion reactors have been started due to the progress and success in improving the understanding of the physics of tokamaks. Thus, most publications in fusion neutronics during the last twenty years have been connected, directly or indirectly, with tokamak conceptual design projects and, since the late `80s with International Thermonuclear Experimental Reactor (ITER), which is also based on the tokamak concept. However, substantial progress has been made in understanding stellarator plasmas recently. Thus, there is a demand at present for neutronics analyses of stellarator reactors as well.

It seems timely now to highlight some differences between tokamak and stellarator neutronics analyses and discuss to what extent the tokamak fusion neutronics experience can be used for the newly arising stellarator fusion neutronics studies.

3.1 Neutron wall loading.

The neutron wall load distribution is very important for any neutronics analysis, to determine both local nuclear responses, such as dose to insulator, specific nuclear heating, displacement damage to copper stabiliser and gas generation in construction materials, and integral responses, such as total nuclear heating in in-vessel and out-vessel reactor components. In tokamak reactors the neutron wall load varies only in the poloidal direction. Stellarator reactors have more complicated plasma shape and, as a result, more complicated neutron wall load distribution with variations both in poloidal and toroidal directions. Thus, a neutronics analysis of stellarator reactors is expected to be more complicated due to the following :

- Three-dimensional (3-D) neutron wall load analysis for stellarators is needed compared with two-dimensional (2-D) analysis for tokamaks;
- A considerably larger number of neutron transport calculations will be necessary for stellarator reactors due to the need to analyse different reactor cuts in the poloidal direction.

However, as far as only local nuclear responses are concerned, such as dose to electrical insulator, specific nuclear heating, gas generation in reactor components and displacement damage to copper stabiliser, the neutronics analysis of a stellarator reactor will look much the same as that of a tokamak one. The critical plasma cross section must be found for stellarator and investigated as in the case of tokamak. The poloidal direction corresponding to the largest neutron wall load and the thinnest blanket/shield composition (which usually occur at the centre plane of the inboard blanket/shield) have to be taken and all of the above mentioned local nuclear responses must be calculated for that direction only, the direction where the local nuclear responses will be biggest.

3.2 Geometrical modelling.

A poloidal cylindrical model along the plasma axis, widely used in one-dimensional (1-D) tokamak neutronics analyses, can reasonably predict the neutronics parameters of large stellarator reactors as well. This is due to the fact that each of the field periods of large stellarators usually extends for a long distance. Neutronics calculations by such a poloidal model is expected to predict local nuclear responses of SPPS to within a few percent.

Two-dimensional and three-dimensional neutronics analyses of stellarator reactors are expected to be much more complicated compared with tokamak ones. While in tokamaks with relatively low aspect ratio, such as ITER, the plasma shape can be reasonably well modelled by a 2-D cylindrical model with the plasma axis coinciding with the symmetry axis of the tokamak and the height of the cylinder equals about two small plasma radius, due to both variation of plasma shape in the poloidal direction and usually large aspect ratios of stellarators, the above 2-D cylindrical model is not good for stellarator reactors.

It seems that some 2-D calculations of large stellarators could be conducted using 2-D cylindrical models along the plasma axis with the cylinder height of few metres, subject to plasma shape. Five to ten such models corresponding to different parts of the field period would be a rather good way to estimate both local and integral nuclear responses along the stellarator axis. While shorter cylinder height would increase the number of 2-D calculations needed to represent all parts of the field period, the taller cylinder would decrease the credit to results obtained.

Finally, 3-D calculations will be needed, as in the case of any conceptual or engineering tokamak project, subject the design. Such calculations will be conducted to check weak parts of the design, such as numerous penetrations, construction gaps and insertions and cavities.

3.3 Total heating in in-vessel reactor components.

Two ways of evaluating the total heating in the Toroidal Field (TF) Coils of a Tokamak Fusion Reactor have been proposed in Ref. 13 and used to evaluate the total heating in the conceptual design phase of ITER. However, we cannot use directly those methods for a stellarator reactor due to more complicated plasma shape in the stellarator chamber and, as a consequence, the variation of neutron wall load, not only in the poloidal direction but also in the toroidal direction as discussed above. Thus, we modified the second method [13] so that it could be used for stellarator power plant studies [14].

Conclusions.

1. It is feasible and desirable to conduct a modest research program as part of the IAE Implementing Agreement for Cooperation in Development of the Stellarator Concept on Stellarator Power Plant Studies. In particular, stellarator fusion neutronics research can be conducted in Australia using transport codes and nuclear data libraries maintaining at ANSTO.

2. Most neutron transport codes, nuclear data libraries and the extensive experience obtained by numerous studies in Tokamak Fusion Neutronics can be directly applied to Stellarator Fusion Neutronics studies.

3. The calculation of total nuclear heating in in-vessel components including TF Coils is identified as the main difference between the stellarator and the tokamak neutronics analyses.

4. Simplified methods developed for tokamak fusion neutronics and reviewed in Ref. 15 will be even more important in stellarator fusion neutronics studies due to more complicated geometry of stellarator and, as a result, more complicated and time consuming neutronics calculations needed for Stellarator Power Plant Studies.

References.

1. "Plasma fusion research given vital funding boost, 5-ADVANCE, Volume 10, No 1, 1996.
2. H. J. Gardner, "Magnetic Fusion Research in Australia : Opportunities and Benefits", Private comminication.
3. W.W. Engle, "A user's manual for ANISN -A one dimensional discrete ordinates transport code with anisotropic scattering", K-1693 (1967).
4. W.A. Rhodes, F. R. Mynatt, "The DOT3 two-dimensional discrete ordinates transport code", ORNL/TM-4280 (1973).
5. "DORT Two-dimensional Discrete Ordinates Transport Code", CCC-484, Oak Ridge National Laboratory, Radiation shielding Information Center.
6. Los Alomos Radiation Group (X6), "MCNP- A General Monte Carlo Code for Neutron and Photon Transport, Version 3A", LA-7396-M, Rev. 2, Los Alomos National Laboratory (1986).
7. G. S. Robinson, "A Guide to the AUS Modular Neutronics Code System", Australian Atomic Energy Commission Research Establishment, April 1987, AAEC/E645.
8. G. S. Robinson, "Extension of the AUS Reactor Neutronics System for Application to Fusion Blanket Neutronics", Australian Atomic Energy Commission Research Establishment, March 1984, AAEC/E583.
9. G. S. Robinson, "The Portable UNIX Version of the AUS Neutronics Code System", April 1993, AUSNOTE/5.
10. B. E. Clancy, "ANAUSN - A One-Dimensional Multigroup S_N Transport Theory Module for the AUS Reactor Neutronics System", Australian Atomic Energy Commission Research Establishment, May 1982, AAEC/E539.
11. G. S. Robinson, "Generation and Validation of a Cross Section Library Based on ENDF/B-VI for the AUS Neutronics Code System", ANSTO, December 1993, ANSTO/E712.
12. G. S. Robinson, "MIRANDA - Module Based on Multiregion Resonance Theory for Generating Cross Sections Within the AUS Neutronics Code System", Australian Atomic Energy Commission Research Establishment, December 1985, AAEC/E626.
13. S. Zimin, "Definition of All Relevant Local Nuclear Responses and the Total Heating in the Toroidal Field Coils During the Conceptual Design Phase of ITER", Fusion Technology, Vol. 20, September 1991, p. 144-163.
14. S. Zimin et al, "Stellarator Fusion Neutronics Research in Australia", submitted to Fusion Technology in 1997
15. S. Zimin, "Methods, Methodologies and Formulas for Simplified Neutronics Analyses of Fusion Reactors", Journal of Nuclear Science and Technology, Vol. 31, No. 8, pp. 867-8787, August 1994.