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Shielding optimisation of the ITER ICH&CD antenna for shutdown dose rate

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HIGHLIGHTS

- Neutronics analysis on the ITER ICH&CD system conducted to reduce shutdown dose rate.
- Several designs for shielding the port plug gaps were modelled.
- Shielding significantly reduced interspace dose rate but still exceed project requirements.
- Design optimisation of the ICH port is continuing.
- Significant contributions from other ports require an integrated modelling approach.

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ABSTRACT

The Ion Cyclotron Heating and Current Drive (ICH&CD) system will reside in ITER equatorial port plugs 13 and 15. Shutdown dose rates (SDDR) within the port interspace are required to be less than 100 μSv/h at 10^6 s cooling. A significant contribution to the SDDR results from neutrons streaming down gaps around the port frame, and the mitigation of this streaming is the main subject of these analyses. An updated MCNP model of the antenna was created and integrated into an ITER reference model. Shielding plates were defined in the port gaps, and scoping studies conducted to assess their effectiveness in several configurations, based on which a front dog-leg arrangement was selected for high resolution 3-D activation analysis using MCR2S.

It was concluded that the selected configuration reduced the SDDR from ~500 μSv/h to 220 μSv/h but were still in excess of dose rate requirements. Approximately 30% of this was due to cross-talk from neighbouring ports. In addition, increased dose rates were observed in the port interspace along the lines of sight of the removable vacuum transmission lines. Design optimisation is continuing, however an integrated approach is needed with regard to ITER port plug design and the shielding of surrounding systems.

1. Introduction

The Ion Cyclotron Heating and Current Drive (ICH&CD) system planned for ITER consists of two ICH antenna port plugs, the matching systems, transmission lines and RF power sources. They will be used to couple heating and current drive into the plasma, and allocated to equatorial ports 13 and 15. During operation, the port plug and surrounding structures will become activated by neutrons, and in accordance with ITER project requirements [1], the resulting shutdown dose rate (SDDR) in the port interspace should be less than 100 μSv/h at 10^6 s after shutdown, in regions where maintenance is to be conducted.

Recent analysis of other equatorial port plugs has demonstrated SDDR levels exceeding this requirement, and concluded that a significant source of these high dose rates is neutron streaming down the port plug gap, as well as there being a significant contribution from other ports [2]. Shielding plates were envisaged to attenuate streaming neutrons and reduce the SDDR. Nuclear analysis was performed by Culham Centre for Fusion Energy (CCFE) on behalf of Fusion for Energy to optimise the arrangement of the plates and

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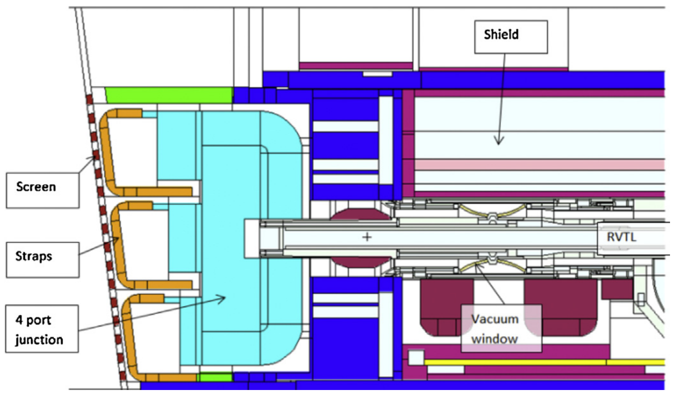

Fig. 1. ICH MCNP model, front of single quadrant.

determine the SDDR and other neutronics responses in the ICH and surrounding systems.

2. ICH antenna neutronics model

Initial simplification of the ICH CAD model was performed to make it suitable for neutronics analysis. Small features unnecessary for neutron transport were removed using SpaceClaim, and specific bodies created to represent water and void regions. Splitting and conversion of the bodies to MCNP geometry was performed using MCAM [3], and the MCNP model was 'cleaned' to remove minute geometry imperfections intrinsic to the conversion process. Reference MCNP models of the ITER device, constructed as 40° sectors of the tokamak, are provided by the ITER Organization (IO) for use in analysis tasks. The ICH MCNP model (Fig. 1) was integrated into a variant of the B-lite V3 model, containing modified equatorial blankets appropriate for this port (Fig. 2).

3. Analysis and results

The neutronics analysis consisted of two parts: firstly, an initial scoping study to estimate the effectiveness of a series of possible shielding arrangements; and secondly, detailed nuclear analysis for the selected shielding configuration, to determine SDDR levels as well as the nuclear responses in the ICH and neighbouring systems.

3.1. Global variance reduction

In order to obtain statistically reliable results in a reasonable time, global variance reduction (GVR) techniques were employed using an iterative weight window (WW) technique developed by CCFE [4]. An adaptation to MCNP to address the problems caused by excessively long histories was also utilised [5]. Since the use of GVR is computationally demanding, it is useful to consider which model regions will be important to the tallies of interest. By allowing particles outside of the WW to be transported in analogue mode, computational time is not wasted splitting particles in regions where deep penetration effects are unimportant. In the case of the scoping studies, it was decided to limit the extent of the WW to a region local to the ICH port, whilst for the detailed analysis the WW covered the entire outboard side of the ITER model.

3.2. Scoping studies

Shielding plates were proposed to attenuate neutron flux streaming in the port gaps, and based on the outcome of the ITER equatorial port workshop and agreed tolerance requirements for assembly, several designs were selected for neutronics assessment in order to select an optimised configuration. MCNP models were produced for cases including an unshielded case, a rear single plate, pairs of rear plates (forming labyrinth/dog-leg arrangement), and a case with a single plate at both the front and rear of the port gap ('front double dog-leg', so called since there also exists a labyrinth arrangement with respect to the blanket modules). The latter example is shown in Fig. 2. Plates were sized with the maximum permitted length and minimum residual gap determined from assembly tolerance requirements.

Table 1
Scoping study results of relative fast neutron flux.

Configuration	Neutron flux (>0.1 MeV) relative to unshielded case		
	Flange	Closure plate	Interspace
Fully blocked	1.3%	12.9%	31.3%
Rear plate	39.5%	66.4%	77.2%
Rear dog-leg	7.7%	37.9%	53.9%
Front dog-leg and rear plate	6.9%	20.0%	39.2%

CCFE's MCR2S code [6] applies the rigorous two-step methodology [7] to couple the neutron transport of MCNP with the activation capabilities of FISPACT [8] on a superimposed mesh tally, to perform high resolution 3-D activation calculations. Obtaining a high resolution neutron mesh tally is computationally expensive however, and was restricted to obtaining a single (coarse resolution) MCR2S result for the unshielded case to provide a baseline result.

For the purposes of the scoping study an alternative methodology was used examining the relative change in the neutron flux levels in the closure plate, port flange and port interspace. The activation of these components would be expected to dominate the SDDR in the port interspace, and the relative change in these neutron flux results was used to evaluate the effectiveness of each configuration. Calculations were performed with MCNP6v1.0 [9] using the B-lite model with local GVR and standard/dummy geometry for surrounding ports. The baseline MCR2S calculation yielded a SDDR of approximately 500 μSv/h at 30 cm from the closure plate in the unshielded case. Analysis of neutron flux levels (Table 1) showed that dog-leg arrangements provided more effective attenuation of the fast neutron flux at the flange, with the front dog-leg offering additional benefits in other regions due to neutron flux being attenuated closer to the source.

Assembly concerns arose over the feasibility of the rear dog-leg, and this scenario was precluded from further consideration. Following analysis confirming acceptability of the front dog-leg design with regard to electromagnetic loads, this configuration was adopted for detailed nuclear analysis.

3.3. Detailed nuclear analysis

Full nuclear analysis was performed for the front double dog-leg configuration to determine the shutdown dose rate in the port interspace. Nuclear responses in the antenna and neighbouring systems were also computed but not reported in this paper.

Other ports typically contribute to the local SDDR in the ICH port interspace in two ways: neutrons leaking through those ports and contributing to an increased activation of material local to the ICH port interspace ('neutron cross-talk'); and the activation of material local to the other ports ('gamma cross-talk'). In order to accurately model the contribution of the neighbouring ports to the SDDR, additional geometry was incorporated into the model to represent the In-Vessel Viewing System (IVVS) which is situated directly beneath the antenna, and the ECRH upper launcher in the upper port above. The IVVS system was represented with no internal components (port frame only) since the design of the system internals and shielding was not yet mature, and the steel port frame was in any case

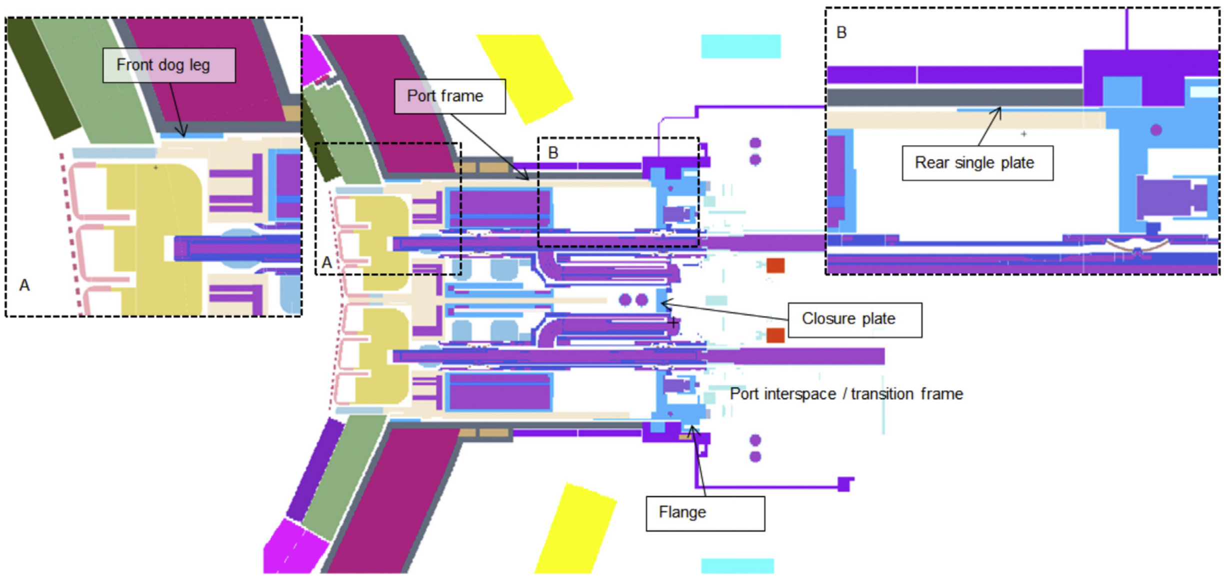

Fig. 2. ICH integrated into the B-lite ITER reference model. Example geometry showing front double dog-leg arrangement (segment ‘A’) with rear single plate (segment ‘B’).

Table 2
Contributions to port interspace dose rate.

Neutron transport		Activation		Dose rate (μSv/h)
ICH port	Other ports	ICH region	Other regions	
√		√		156
√	√	√		208
√	√	√	√	221

expected to be the dominant source of SDDR contributions to the equatorial port interspace.

Full 3-D activation calculations were performed using MCR2S based on 500 MW fusion power and ITER life-time operations according to the SA2 scenario [10]. To provide the required neutron flux and spectrum mesh tallies, two neutron transport runs were performed, one with full transport including the effects of other ports and the other with neutrons killed in the neighbouring ports so that only local neutron transport was considered. This allowed the effect of the ‘neutron cross-talk’ to be estimated. Separate mesh tallies were included to construct decay gamma sources for the ICH equatorial port, the neighbouring equatorial ports, the lower port and IVVS, and the upper port. This permitted an estimation of the ‘gamma cross-talk’ effects to be made. Generally, these consisted of a 10 cm spatial resolution in 175 energy groups (VITAMIN-J format), though in the mesh covering the ICH equatorial port itself and interspace, a higher spatial resolution of 5 cm was adopted since this region will clearly dominate the SDDR result.

From these neutron results, MCR2S was used to produce 3-D decay gamma sources, which were then used in subsequent photon MCNP calculations to determine the SDDR in the port interspace. During the SDDR calculations, the ICH port plug model was modified with water removed (and homogenous material-water mixes converted to void-mixes) in order to represent the state of the system during shutdown, when it will be drained of water. The SDDR was determined on a mesh tally in the interspace with a 10 cm spatial resolution. In order to quantify the maximum interspace dose rate, a cubic tally region was defined from 30 to 80 cm from the closure plate. These results are summarised in Table 2. The statistical error of the decay gamma transport simulations is generally below 5% (Fig. 3).

It was found that the dose rate at 30 cm from the closure plate (with transition frame removed) was 221 μSv/h, in excess of the dose rate requirement of 100 μSv/h. 30% of this dose rate result

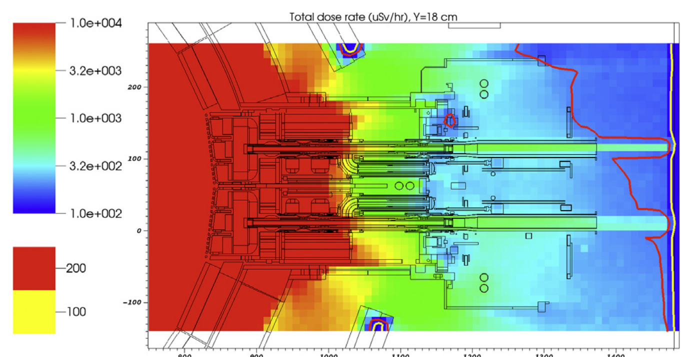

Fig. 3. Total gamma dose rate (global neutron transport and activation), 10^6 s decay time (Y = 18 cm).

was due to the effect of other ports, and the dose rate considering only local transport and activation of the ICH port was 156 μSv/h.

Generally it was found that neutron cross-talk effects were more significant than gamma cross-talk effects, particularly in the immediate vicinity of activated materials in the equatorial port interspace. Neutron cross-talk was found to contribute up to 50% to the SDDR in the port interspace for locations away from the closure plate and flange (which still dominate the local response for distances <50 cm). Gamma cross-talk is clearly not independent of neutron cross-talk. Gamma cross-talk was found to be shielded by the port interspace wall and only became significant in the region near the bioshield due to the presence of thinner port bellows, where it increases the SDDR contribution from 50% to 80%. The increase in SDDR at the lower side is clear from the contour lines, which is assumed to be due to the IVVS and lower ports contributing significantly to the cross-talk.

In addition, streaming effects have been noted in locations directly on the axis of the RVTLs. Initial calculations showed these streaming effects to be poorly sampled, with asymmetric results and high statistical uncertainty. Having never been observed in previous ICH analysis, testing showed that these streaming effects only occur when the water is drained from the RVTL centre conductor. An angular biasing adaptation was made to the MCR2S gamma source sampling routine, in order to preferentially sample photons born in a direction close to the axis of the RVTL. These highly localised beams of shutdown gammas produce dose rate increases of up to 500 μSv/h at 10^6 s decay time, for which further design optimisation is required.

4. Summary and conclusions

Analysis has been conducted on an ICH port plug model in the B-lite ITER reference model, incorporating a higher level of detail and an updated design, as well as the inclusion of shielding plates to mitigate neutron streaming in the port gaps. Scoping studies were performed to determine the neutronics effectiveness of several shielding configurations, and the front double dog-leg configuration was found to be the most effective scenario. Once confirmed acceptable from assembly and electromagnetic load considerations, analysis was then conducted to accurately determine the shutdown dose rate (SDDR) in the port interspace for this scenario and determine the relative contribution to the SDDR from neutron and gamma cross-talk effects. In addition, results were obtained for nuclear heating and damage rates in selected components of the ICH, as well as effects on head loading to nearby superconducting coils and gas production in the vacuum vessel. It was found that:

- The SDDR at 30 cm from the closure plate was 221 μSv/h at 10^6 s decay time.
- 30% of this is due to neutron cross-talk from other ports and associated activation. Without these effects, the dose rate was 156 μSv/h.
- The lower port and IVVS port were primarily the source of this increase.
- Highly localised increases in SDDR were noted along the line-of-sight of the central conductors of the RVTLs, which require addition design optimisation.

SDDR levels were found to be in excess of ITER project requirements, and whilst a significant contribution of the SDDR is due to the lower and IVVS ports, even without these effects the dose rate still exceeds 100 μSv/h.

Design work is continuing on the ICH system. Shielding within the inner RVTL conductor is being designed, and space exists for additional low mass shielding at the rear of the antenna to improve internal shielding capabilities. It should be noted that the IVVS system was modelled in an empty configuration, and SDDR results are expected to be marginally reduced when a more realistic representation is used.

Shutdown dose rates in the equatorial port interspace are a common problem recognised by the ITER community, in particular the impact of the lower port streaming. To reduce the SDDR, IO has recently proposed a revised lower port design to provide extra shielding, which is expected to benefit future analyses. Additionally, consideration is being given to further reducing the front face of the ITER equatorial port plugs to increase blanket overlap, however studies have shown this would degrade the system performance and would require extensive redesign of the internal components. To further reduce SDDR in the ICH port plug, an integrated approach is needed with regard to optimisation of the shielding of the equatorial port plug along with the design of blanket shield modules and the shielding of neighbouring port systems.

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