Radiation shielding analyses for the ECRH launcher in the ITER upper port

A Serikov¹,³, U Fischer¹, R Heidinger¹, K Lang¹, Y Luo², H Tsige-Tamirat¹
¹ Association FZK-Euratom, Forschungszentrum Karlsruhe, P.O. Box 3640, 76021 Karlsruhe, Germany
² Computer and Information College, Hefei University of Technology, Hefei, Anhui 230009, PR China
E-mail: serikov@irs.fzk.de

Abstract. Radiation shielding analyses have been performed for the ECRH system in the ITER upper port to complete the neutron streaming analysis performed previously. The analyses aimed at assessing and optimising the performance of the radiation shield to prove that the shielding requirements can be met by the proposed design variants. The radiation transport calculations have been performed by means of the Monte Carlo programme MCNP in 3D geometry using the standard ITER neutronics model with ECRH launcher and plug integrated into the upper port. The interface programme MCAM was used to convert the 3D ECRH launcher models available from the CAD-system for use with MCNP-calculations. It was shown that the launcher design with the proposed radiation shield can satisfy the design limits for the radiation loads to both the launcher and the neighbouring components such as the Vacuum Vessel and the TF coils. Radiation dose levels were assessed for reactor shutdown at the rear side of ECRH launcher at locations where personnel access for maintenance may be required. The shutdown dose rate calculations were also performed in 3D geometry by applying the rigorous 2-step (R2S) method and comparing the results to those obtained with the direct 1-step (D1S) method. The R2S method includes activation calculations for the launcher materials by means of the inventory code FISPACT. It was proven that the shutdown dose rates inside the port with straight waveguides will be below the ITER radiation limit of 100 µSv/hr after 10 days decay time.

1. Introduction
The design of an Electron Cyclotron Resonance Heating (ECRH) launcher for the ITER upper port is under development by working groups from various EURATOM associations. Different variants of ECRH launchers are under investigation including remote (RS) and front steering (FS) design concepts. The major neutronics task is to prove that radiation shielding is sufficient to meet the required design limits. Apart from structural damage, nuclear heating and He generation in neighboring systems and plasma-near launcher components, essential criteria are (i) the neutron fluence with respect to degradation of the material properties of the CVD diamond window, which forms the primary tritium confinement for mm-wave waveguides, and (ii) the radiation dose levels

³ Author to whom any correspondence should be addressed
during reactor shut down periods that should be low enough to permit access of maintenance personnel. The latter two radiation loads are significantly affected by the neutron streaming in the waveguide channels of the ECRH launcher.

This paper is devoted to the analyses of these key shielding problems for the RS design concept of the launcher assuming a twisted arrangement of straight waveguide channels. The methodology for neutron streaming calculations was developed previously and presented elsewhere [1]. The analyses of this work include detailed three dimensional (3D) streaming and shielding calculations of the RS launcher considering two design options for the focusing of the microwaves. The analyses are based on 3D Monte Carlo calculations with the MCNP code [2] for the radiation transport simulation and activation calculations with the FISPACT inventory code [3]. Nuclear data from FENDL/A-2.0 activation cross-section library [4] were used in the FISPACT calculations. Computational models of the ECRH launcher were generated by converting the CAD 3D models into the semi-algebraic representation of the MCNP code using the interface programs MCAM [5] and McCAD [6]. A standard MCNP model of ITER (20 degree center-line torus sector) was used for integrating the ECRH launcher in the upper port. Neutron streaming calculations were performed using a dedicated two-step method applying surface sources and point detectors. The shielding analyses include the assessment of effect of launcher internal shield on the surrounding structures such as the Vacuum Vessel (VV) and Toroidal Field Coils (TFC).

2. Outline of the ECRH launcher neutronics calculation model

The origin design of the Remote Steering (RS) ECRH launcher was provided by FOM Institute for Plasma Physics "Rijnhuizen". The ECRH launcher option with 8 straight waveguides (WGs) was considered in the shielding analyses. The WGs represent long (460 cm) and narrow (5 x 5 cm) void channels. The WGs have a twisted arrangement: at the entrance they lay in 2 horizontal layers with 4 channels in each of it (2x4 layout). This arrangement is transformed into 4 horizontal layers with 2 channels in each (4x2) at the waveguides exit. The WGs pass through the launcher structure from the front mirrors to the diamond windows acting as vacuum barrier at the launcher rear side. Two types of the remote steering ECRH launchers were considered: one with a limited beam focusing (LF design), and one with a full beam focusing – (FF design). Figure 1 shows a CAD model of the ECRH FF launcher developed for the neutronics analyses. In the LF design, the focusing capability is limited to one direction. The LF launcher is compatible with the actual ITER port plug configuration and does not interfere with surrounding blanket modules. The FF launcher design enables the focusing of mm-beams in two directions, but it requires larger front mirrors and openings. This necessitates cutting the ITER blanket module located under the launcher.

![Figure 1. CATIA model of RS full focusing ECRH launcher developed for the neutronics analysis](image-url)
In order to facilitate the neutronics analysis, the interface programs MCAM and McCAD were used to convert the CATIA CAD model of the ECRH launcher (shown in figure 1), into the semi-algebraic representation of the MCNP Monte Carlo code. The use of such an interface tool is indispensable for the accurate conversion of the complex geometry of the ECRH launcher structure and its correct integration in the ITER MCNP model. A standard 3D MCNP model of a 20° ITER torus sector with reflective boundary conditions on the lateral sides is used in the analyses. The center line of the MCNP model coincides with the center line of the port. The ECRH launcher was inserted in the upper port of the standard MCNP model as shown in figure 2.

A vertical cross-section of the MCNP model for the RS FF launcher is shown in figure 3. The MCNP computational model for the FF launcher differs from the LF design not only by the shape of the opening, but also by a more detailed description of the launcher structures. In the FF model, the sockets, frames, and support flanges were specified.

Apart from the RS-type designs, the Front Steering (FS) ECRH launcher design, promoted by Plasma Physics Research Center CRPP-EPFL, was analyzed in the paper from the neutronics point of view.

Figure 2. ITER 3D MCNP model with ECRH upper port plug integrated

Figure 3. Radial-poloidal cross-section of the ITER upper port with the RS FF launcher integrated (MCNP model)

2.1. Computational approach for radiation transport

The Monte Carlo method of radiation transport is most suitable for neutronics analyses of the ITER tokamak involving both a large and complex 3D geometry and a variety of local heterogeneities such as gaps and channels. The radiation (neutron and gamma) transport calculations were performed by means of the Monte Carlo code MCNP running in the parallel mode on a Linux cluster. The results are normalized to a fusion power 500 MW according to the standard ITER operation.

A two-step approach is used in the neutron streaming calculations. In the first step, a surface source is calculated at the entrance of the waveguide channels using the standard ITER volume source in the plasma chamber. In the second step, MCNP point detectors are used in the void space inside the waveguide channels to obtain the neutron flux profiles along the channels. The WG channels are surrounded by a sufficient thick radiation shield. Therefore the reflective boundary conditions on the
lateral sides of MCNP model do not affect the streaming along the WGs. This is essential when using the point detector estimators inside the WG channels since contributions from events external to the reflection surface cannot be taken into account with this approach. Detailed information concerned the mentioned two-step approach in streaming calculations can be found in [1]. For calculating the nuclear heating and the helium production in the shield and adjacent structural components, the track length estimator is employed making use of the MCNP weight window technique for the variance reduction.

3. Results for the Remote Steering LF/FF designs and the Front Steering concept of the ECRH launcher

Analytical estimations based on available fast neutron flux attenuation factors [7] were performed for specifying the thickness and length required for the steel/water shield around the waveguides. For a typical ITER shielding blanket mixture the attenuation factor of the fast neutron (E_n >0.1 MeV) flux amounts to 10^6 per meter. In order to attenuate the fast neutron flux to a level of 10^7 n·cm^{-2}·s^{-1}, it is sufficient to surround the waveguides by a 50 cm thick steel/water shield with 80 vol. % stainless steel and 20 vol. % over a length of 2.5 m. The fast neutron flux level of 10^7 n·cm^{-2}·s^{-1} guarantees the dose rate limit of 100 µSv/h 10 days after reactor shut-down as specified by ITER on the basis of an empirical relation.

For the Remote Steering launcher (RS) the results of the neutron streaming calculations indicate the advantage of the LF design with shield blocks inside the front shield module. For LF launcher with shield blocks the fast neutron fluxes vary in the range of (1.50 – 3.30)*10^{12} n*cm^{-2}*s^{-1} at the WG entrance to (1.93 – 3.44)*10^{8} n*cm^{-2}*s^{-1} at the WG exit. The range of values is explained by different WG orientation in the space. The model with FF launcher gives better fast neutron flux attenuation than the LF model. This statement follows from the values of fast neutron fluxes at the entrance (3.93–6.21)*10^{12} n*cm^{-2}*s^{-1} and at the exit (0.88–1.72)*10^{8} n*cm^{-2}*s^{-1} of the WG for the FF design. In comparison with LF design the model of the launcher with FF design has a smaller fast neutron flux at the WG exit although it is higher at the WG entrance. Streaming along WGs leads to accumulation of fast neutron fluence (2.77 – 5.44)*10^{19} m^{-2}*fpy^{-1} at the CVD diamond window, this fluence is below the design limit of 10^{20} m^{-2} for such windows. The impact of the front shield configuration on the neutron streaming in the waveguides as well as detailed results for the remote steering design with LF and FF ECRH launcher options were described in [8]. For the newly developed by FOM “Rijnhuizen” advanced remote steering launcher option with dog-leg beam-way in the front shield module, it is proposed that the neutron streaming along the WG will be suppressed because of the shift of WGs from the opening to plasma. In the Front Steering (FS) design concept the neutron streaming along WGs is blocked by WG dogleg bend. It was proved in paper [1] that use of dogleg shape of WGs reduces the fast neutron fluxes at the rear side of the launcher by about two orders of magnitude. Therefore the fast fluence limit at the launcher back-end window will be safely met in FS design option.

The distribution of the nuclear power density was calculated for use in the thermal-hydraulic design analyses [9], [10] of the launcher cooling system. The calculated power density in solid SS 316L(N)-IG amounts to 5.5 W/cm^3 at the first wall of the front shield module near the opening and decreases to 0.1 W/cm^3 at the entrance of WGs in RS LF launcher. The nuclear power density in the homogenized material of the ITER upper port with RS FF launcher is displayed in a two-dimensional representation in figure 4. The nuclear heating calculations in materials of front shield module of FS launcher will also be used in developing of cooling system; the results are similar to RS launcher, they are show good radiation shielding of the launchers, both RS and FS types.

According to ITER design rules [7], [12], shielding must be sufficient to make sure that the re-welding of the vacuum vessel (VV) is possible. This requirement leads to a design limit for the helium production rate of ~ 1 appm per year. The helium production rate calculated for the critical cell of the VV, which is located above the ECRH shielding plug, amounts to (2.5 – 2.6) ·10^{-1} appm per year for the RS FF and LF options, for RS dog-leg variant with less-shielded upper area the value equals to 3.0·10^{-1} appm/fpy, the process of dog-leg designing is in progress and new variants have more
radiation shield, but in any case all RS results show satisfaction for re-welding criterion. This conclusion can be applied also to FS launcher, for which helium production rate equals to $2.5 \times 10^{-1}$ appm/fpy in critical VV cell.

4. **Shutdown dose rate calculations at the area of personnel access**

To allow personnel access for maintenance purposes, ITER safety regulations require a radiation dose limit of 100 µSv/h 10 days after reactor shutdown. This limit must be also kept for the ECRH launcher with an enhanced radiation at the rear side due to the neutron streaming through the waveguides. The access to the ECRH system is planned from the rear of the launcher. The shutdown dose rates were assessed for the RS FF option of the ECRH system with the back end consisting of steerable mirrors, diamond windows, window cooling pipes, safety valves, and sockets for window/waveguide alignment. The main parts of the CATIA model for the ECRH launcher is shown in figure 1 above. The interior of the support flange is illustrated in detail in [9] and well described in [10]. For the shutdown dose rate calculations, the launcher back components inside the rear support flange behind the adapter plate was modeled as a dummy plate with a homogenized material composition. The material composition of the dummy plate was taken from [10]. The dummy plate includes SS, Cu-alloy, beryllium, diamond, water and additional 32 grams of silver used as brazing material for the diamond windows. The exact mixture composition of the dummy plate is following [10]: 11.6% of SS 316 L, 2.2% Cu, 0.2% Carbon, 8.9% water, 77.1% void. The shutdown dose rate calculations were performed with the so-called rigorous 2-step (R2S) method [11]. This method is based on the use of MCNP for the transport calculations (neutron and decay photons) and FISPACT for the inventory.
calculations (decay gamma sources) and relies on the use of automated interfaces. The following main calculations steps are included in the R2S approach:

- neutron transport calculation with the MCNP code to provide the neutron flux spectra
- activation calculations with the FISPACT code to obtain the decay gamma source distribution
- decay gamma transport calculation with MCNP to assess the shutdown dose rates at specified locations.

The neutron flux spectra were calculated in all cells of the ECRH launcher and the upper port walls in the standard 175 VITAMIN-J energy group. MCNP’s weight window generator with sequential optimization of neutrons weight was used for the variance reduction in the deep penetration calculation. The neutron irradiation history was assumed to follow the ITER DRG1 [12] 10 years operation scenario with accumulated 0.094 MW·a/m² averaged neutron fluence on the first wall. According to the ITER regulations, the dose rate was calculated 10 days after reactor shutdown.

The decay gamma sources were calculated in all materials of the RS FF ECRH launcher plug included the upper port walls. The dose rate in the areas at the rear side of the port (where personnel access may be required) was found to be caused by the decay gamma sources in the surrounding activated material, mainly the dummy plate (60% of total dose rate) and the rear support flange with other ECRH structures (40%). The contribution from the decay sources in the upper port walls to the shutdown dose rate behind the dummy plate is very low, around 0.1% of total dose rate.

The activation calculations revealed the following dominant radio-nuclides to dose rate in the launcher plug structures (mainly steel): $^{60}$Co ($T_{1/2}=5.3$ years), $^{58}$Co ($T_{1/2}=70.78$ days), $^{54}$Mn ($T_{1/2}=312.5$ days) and $^{59}$Fe ($T_{1/2}=45.1$ days). In the dummy plate, $^{110}$Ag-m ($T_{1/2}=249.9$ days meta-stable) also contributed significantly (around 17%) to the dose rate. These radio-nuclides were formed by the following nuclear reactions during neutron irradiation:

- $^{59}$Co (n, $\gamma$) $^{60}$Co (100% of $^{60}$Co production)
- $^{58}$Ni (n, p) $^{58}$Co (100% of $^{58}$Co production)
- $^{54}$Fe (n, p) $^{54}$Mn (about 77% of $^{54}$Mn production), and $^{55}$Mn (n, 2n) $^{54}$Mn (about 23%)
- $^{58}$Fe (n, $\gamma$) $^{59}$Fe (100% of $^{59}$Fe production)
- $^{109}$Ag (n, $\gamma$) $^{110}$Ag (100% of $^{110}$Ag production).

At the rear side of the reference RS FF ECRH launcher with steel/water (80 vol. % / 20 vol. %) internal shield the calculated distribution of the shutdown dose rate gives 15 $\mu$Sv/h behind the dummy plate. It was also considered variant of alternative internal shield. In case of filling of the launcher internal space by heavy Ferro-phosphorus (Fe-P) heavy concrete [13] the shutdown dose rate reaches 30 $\mu$Sv/hr. It is noted that these results only include the contributions to the dose rate from the decay gamma sources located in the ECRH launcher, the dummy plate and the port walls materials resulting from the activation of these components by the neutron radiation streaming through the ECRH waveguides. It is pointed out that the calculated dose rates are well below the ITER design limit of 100 $\mu$Sv/h. The employment of straight waveguides is therefore justified for the ECRH launcher in the ITER upper port.

The shutdown dose rates, obtained by the R2S method, were compared with performed here calculations employing the direct 1-step (D1S) method [14]. The results of the R2S and D1S shut down dose rate calculations are good agreed with no more than 20% differences.

If the radiation shielding properties of launcher are well enough for the reference RS FF design it could be concluded that radiation environment at the launcher rear side will meet ITER limits for advanced RS dog-leg and FS designs with suppressed neutron streaming along waveguides. Because reduced neutron streaming leads to less activation level of the launcher structure.

5. Analyses of nuclear responses in Toroidal Field Coil (TFC) segments near the ECRH launcher

The effect of the ECRH launcher system in ITER upper port on the neighboring TF coils was analyzed from the neutronics point of view in terms of:
• Peak damage in Cu-stabiliser, (dpa)
• Integral epoxy radiation dose, (Gy)
• Peak fast (\(E_n>0.1\) MeV) neutron fluence, (n/cm\(^2\))
• Peak volumetric nuclear heating, (W/cm\(^3\))

The calculation has been performed using the 3D MCNP model with the TFC divided into 50 segments in poloidal direction focusing on the segments near the upper port. The calculated nuclear responses were compared to the radiation design limits as specified by the ITER regulations [7], [12].

It is noted that the all nuclear responses calculated for the TFC are well below the design limits. The poloidal distributions of the nuclear responses show an increase of the values on the TFC top and at the beginning of TFC inboard leg. The closest value to the design limits was found for the fast neutron fluence in the coil insulator behind the TFC inner case amounting to 2.0E+16 n/cm\(^2\)/FPY (TFC segments on ITER top) with the design limit of 5.0E+17 n/cm\(^2\)/FPY. Other radiation criteria, such as the damage in the Cu-stabilizer, the epoxy radiation dose and the peak nuclear heating are well below (about 2-3 orders of magnitude) the design limits. From the calculation results it is observed that independent on ECRH launcher type (RS, included dog-leg, or FS) the nuclear responses in TFC segments near the launcher have fewer values than in farther segments.

6. Conclusion

Detailed 3D streaming and shielding analyses have been performed for the ECRH Remote Steering (RS) and Front Steering (FS) designs. The results show that the fast neutron fluence at the torus window accumulated over 1 full power year is well below 10\(^{20}\) m\(^{-2}\). Hence the design limit for the CVD diamond window can be safely met for all considered ECRH design concepts. The RS Full Focusing reference model compares favorably to the RS Limited Focusing model with filler blocks because it provides a steeper attenuation gradient of the fast neutron flux. For the RS concepts, the fast neutron flux density at the torus window is less than 3\(\cdot\)10\(^8\) cm\(^{-2}\)·s\(^{-1}\). In the RS dog-leg design neutron streaming is essentially suppressed by the waveguides shift from the opening to plasma. The FS design possessed waveguides with dog-leg shape, which prevents the neutron streaming. The neutron activation of materials in rear port with RS FF ECRH launcher with steel/water internal shield leads to shutdown dose rates at a level of 15 \(\mu\)Sv/hr. With Fe-P heavy concrete as shielding material, the value increases up to 30 \(\mu\)Sv/hr. Theses levels are well below the 100 \(\mu\)Sv/hr design limit required by the ITER safety regulations for the work personnel access after 10 days wait time. It is proposed that reduced neutron streaming for advanced RS dog-leg and FS designs results in less activation of rear-side materials and lower values of shutdown dose rates. Analyses of nuclear responses in the Toroidal Field Coil (TFC) near the ECRH launcher permit to the conclusion that the radiation design limits for the superconducting magnets are satisfied for all considered ECRH RS and FS models. Thus all radiation design limits can be safely met by the RS, included advanced dog-leg, and FS ECRH launcher design concepts.

Acknowledgments
This work is being carried out under the EFDA technology research programme activities: EFDA technology task TW3/4-TPHE-ECHUL/A and B.

References
[1] Fischer U, Chen Y, Heidinger R, Luo Y, Stratmanns E and Tsige-Tamirat H, Analysis of Fast Neutron Streaming in the Waveguide Channels of the ECRH System in the ITER Upper Port, IAEA Technical Meeting on ECRH Physics and Technology for ITER, July 14-16, 2003, Kloster Seeon, Germany
[2] Briesmeister J F (ed.), MCNP - A General Monte Carlo N-Particle Transport Code, Version 4C, Los Alamos National Laboratory, Report LA-13709-M, April 2000.
[3] Forrest R A and Sublet J-Ch, FISPACT 99: User Manual, UKAEA Fusion, Report UKAEA FUS 407, December 1998

[4] Pashchenko A B, Wienke H, Kopecky J, Sublet J-Ch and R.A. Forrest, „FENDL/A-2.0 Neutron Activation Cross Section Data Library for Fusion Applications“ , IAEA Vienna, Report IAEA-ND-173, Rev.1, October 1998

[5] Liu X P, Tong L L, Luo Y T and Wu Y C, Development & Application of MCNP Auto-Modeling Tool: MCAM 2.0, 7th China/Japan Symp. on Materials for Advanced Energy Systems and Fission and Fusion Engineering, Lanzhou, July 31-Aug.2, 2002

[6] Tsige-Tamirat H, Fischer U, CAD interface for Monte Carlo particle transport codes. The Monte Carlo Method : Versatility Unbounded in a Dynamic Computing World; Proc.of the Conf., Chattanooga, Tenn., April 17-21, 2005

[7] Iida H, Khripunov V and Petrizzi L, Nuclear Analysis Report, NAG-201-01-06-17-FDR, G 73 DDD 2 01-06-06 W0.1, Nuclear Analysis Group, ITER Garching Joint Work Site

[8] Serikov A, Fischer U, Chen Y, Lang K, Heidinger R, Luo Y, Stratmanns E and Tsige-Tamirat H, Neutronics analysis of the ECW launching system in the ITER upper port, 23rd Symp. on Fusion Technology, 20-24 September 2004, Venice, Italy

[9] Kleefeldt K, Contribution to design activities for the electron cyclotron launching upper port plug system (ECLUPPS), Intermediate report Nov. 2003 – March 2004, Internal Report IRS-Nr. 04/04 - FUSION-Nr. 228

[10] Kleefeldt K, Contribution to design activities for the electron cyclotron launching upper port plug system (ECLUPPS), Intermediate report Apr. 2004 – Sep. 2004, Internal Report IRS-Nr. 05/04 – FUSION-Nr. 230

[11] Chen Y, Fischer U, “Rigorous MCNP based shutdown dose rate calculations: Computational scheme, verification calculations and applications to ITER”, Fusion Engineering and Design 63-64 (2002), 107-114

[12] ITER Design Requirements and Guidelines Level 1 (DRG1). G A0 GDRD 2 00-12-01, W 0.5. December 1, 2000

[13] Engineering compendium on radiation shielding, vol. 2: Shielding materials. Prep. by numerous specialists, ed. by Jaeger Robert G, Everitt P, Sponsored by Internat. Atomic Energy Agency. Ed. of vol. 2: Arnost Hoenig. Berlin, Heidelberg, New York: Springer 1975

[14] Valenza D, Iida H, Plenteda R, Santoro R T, Proposal of shutdown dose estimation by Monte Carlo code, Fusion Engineering and Design 55 (2001) 411-418