Structural integration studies for the ITER ECRH Upper Launcher

R. Heidinger\textsuperscript{1a}, M. Henderson\textsuperscript{2}, U. Fischer\textsuperscript{1b}, G. Hailfinger\textsuperscript{1b}, K. Kleefeldt\textsuperscript{1b}, G. Saibene\textsuperscript{3}, A. Serikov\textsuperscript{1b}, P. Spaeh\textsuperscript{1a}, A.G.A Verhoeven\textsuperscript{4}

\textsuperscript{1}Forschungszentrum Karlsruhe, Association FZK-EURATOM, (a) Inst. for Materials Research I, (b) Inst. for Reactor Safety I, D-76021 Karlsruhe, Germany
\textsuperscript{2}CRPP, Association EURATOM- Conf. Suisse, EPFL, CH-1015 Lausanne, Switzerland
\textsuperscript{3}EFDA Close Support Unit, Boltzmannstr. 2, D-85748 Garching, Germany
\textsuperscript{4}FOM Inst. for Plasma Physics, Association EURATOM-FOM, Nieuwegein, The Netherlands

e-mail: roland.heidinger@imf.fzk.de

Abstract. The launcher structural design integration is presented for the ‘8-beamline’ remote steering (RS) reference launcher. It covers the design of the blanket shield module (BSM) which closes the gap in the regular blanket structure and of the internal neutron shield in the main launcher structure. Nuclear heating rates are provided by nuclear calculations; including heat loads from the mm-wave components, a conceptual design is defined for the cooling system fed by the ITER blanket cooling water. The thermo-mechanical performance of the first wall panel which is welded to BSM side walls is proven by FEM modelling. The disassembly of the port plug and its internals is based on an axial access scheme. Boundary conditions to neighbouring ITER systems are quantified in terms of shut-down dose levels for hands-on access, helium generation in the vacuum vessel and dimensions of the cut-out required in the lower regular blanket module. The adaptation of the shielding and cooling configuration is discussed for the two advanced beamline variants which are the 6 beamline RS dogleg option and the front steering (FS) launcher.

1. Introduction

Several of the upper port positions on ITER are reserved for the EC wave launching system to stabilise the Neoclassical Tearing Modes (NTM) at the q=3/2 and q=2/1 surfaces by inducing off-axis current drive. As a result of the launcher development activity performed by the “ECHULA” team of EURATOM associations, a reference launcher model was transferred by FZK to the ITER design office. Its mm-wave system is composed of 8 remotely steerable beam lines. Using 3 upper port positions, a total of 20 MW mm-wave power at 170 GHz will be injected into the ITER plasma. To enhance the plasma stabilisation performance, the RF optics of the mm-wave system are under optimisation for advanced concepts of remote steering (RS) under the lead of FOM (Nieuwegein) and of front steering (FS) by CRPP (Lausanne). A key criterion for the reference and two advanced beamline models is their structural integration into the port plug environment which has to assure efficient neutron and thermal shielding.
2. Basic configuration of the launcher structure

The ECRH upper port plug system is composed of the port plug (‘launcher’) attached to the port flange of the vacuum vessel (VV) and of an interspace plug (‘mini-duct’) inside the port duct connecting the vacuum vessel to the cryostat/biological shield. Integral part of the system is also the test cell for the launcher and the hot cell installations for maintenance and repair of the launcher satisfying remote handling (RH) requirements.

![Figure 1. Basic elements of the ITER ECRH Upper Launcher](image1)

![Figure 2. Principle components of the blanket shield module (BSM)](image2)

The launcher is composed of the blanket shield module (BSM), the millimetre wave (mm-wave) system integrated into internal shields, the port plug frame (‘main structure’), the closure plate forming the boundary between the in-vessel part and the back section, and the connecting flange to the VV (cf. Fig.1). The BSM includes the first wall panel, shielding blocks, and side walls attached to the mounting flange. In the BSM structure, penetrations for mm-wave beams are provided and the front mirrors are integrated, which deflect them into the plasma, are fixed together with the shield blocks (cf. Fig. 2).
A common goal of all ECRH launcher concepts for the upper port is to reach the lowest possible location for the front mirrors. Given the high location of the upper ports at ITER, this is a decisive criterion to reach the highest current drive efficiencies for the adverse boundary conditions because the optimum launch location would be from at port location with is lowered by 500 – 900 mm [1]. Over the maximal distance between the flange to the vacuum vessel to the flange connection to the BSM of 5135 mm (total port plug length: 6105 mm), the main structure has mostly a trapezoidal cross-section while only 1110 mm at the back-end (628 mm to fixation to the port extension) have rectangular shape. Therefore, the horizontal arrangement of waveguides into the main structure which is elongated in vertical direction causes a special challenge. This is met in the 8 beamline RS reference launcher by front mirrors that are arranged as sets of individual mirrors along to two horizontal rows (UR / LR: upper / lower row).

In contrast to given plug plug models such as one described by the ‘Detailed Design Document’ 5.2 of June 2001 [2] or recent models for the diagnostic upper plugs, a full double wall structure was introduced to feed the Blanket Shield Module cooling system while having cooling and baking (at 240°C) capabilities for the main structure. The pronounced space requests for mm-wave system, were responded by a reduced thickness of both side walls of 80 mm in the trapezoidal section, while maintaining the full extension at the top and bottom walls at 150 mm.

The gap between the port wall and the upper port plug is presently given with a minimum of 20 mm at either side. Admitting a total tolerance of 10 mm after assembly of the port structure, the deflections of the launcher structure under electromagnetic loads are to be kept below 10 mm. The electromagnetic loads were initially estimated using the results for a category III vertical disruption event (VDE) obtained for an essentially solid port plug. With the assumption that the EM forces are concentrated at the free end of launcher, the moments acting at the BSM were found to produce a maximum deflection of 8-10 mm in toroidal direction [3] which could be confirmed by the numerical modeling of the detailed double shell design contained in the 3-D CAD tool CATIA (cf. Fig. 3).

3. Reference and advanced beamline models
For control of the plasma instabilities, especially the stabilisation of neoclassical tearing modes [4], it is foreseen to inject a total of 20 MW mm-wave power at 170 GHz into the ITER plasma [2]. The required targeting of the q=3/2 and q=2/1 flux surfaces will be achieved by angular steering in the poloidal direction. Two basic concepts are available. Firstly, remote steering (RS) is characterised by movable mirrors in the launcher back-end, square corrugated waveguides with definite length to restore the beams at the front end and to sweep them over the fixed front mirrors [5]. Alternatively, front steering (FS) uses moveable mirrors as front mirrors, beam shaping is achieved by sequence of circular waveguide sections and free space propagation [6] (cf. Fig. 4). A fixed focusing mirror is introduced before the movable front mirror system forming pronounced angles in the beam path which resembles the so-called dog-leg structures formed by mitre-bends in the waveguide system. As mitre bends are standard components only for circular waveguides and because of the risk to degrade to

![Figure 3. Maximum deflections modelled for the detailed double shell design with the finite element tools of the 3-D CAD software CATIA assuming moments acting on the front plane as given in Ref. 3 for the most severe VDE event: (Mx = 1.62 MNm, My = -2.2 MNm, Mz = 2.1 MNm)]
severely the transmission performance of square corrugate waveguides, the mitre bends are avoided in the RS launcher concept. An improvement of the mm-wave optics is now under development at FOM, by introducing also a set of redirecting mirrors in the front to enhance the focusing capabilities of the front mirror system. By analogy, this system is called RS ‘dog-leg’ launcher even though the advantage of straight waveguides could be maintained. This alternative design could be realised by the reduction of the complexity of the waveguide system. The initial RS launcher and the FS launcher concepts integrate 8 beamlines and use 3 upper port locations at the ITER torus (locations 12, 13, 15), the RS dog-leg launcher takes advantage of the additional port location 16 and reduces the number of beamlines to 6.

![Figure 4. Characteristic beamlines for the RS launcher (left) and the FS launcher (right)](image)

The basic concept of a 8 beamline RS launcher was developed to a consistent configuration of the key components and was transferred to the ITER Design Office (DO). It serves as a reference model for a remotely steerable (RS) ECRH launcher at the ITER Upper Port.

4. Thermal and nuclear shield components

4.1. First wall panel

The first wall panel is designed as a multi-layer structure formed as a hot-isostatically pressed (‘HIPped’) compound of a beryllium protection layer (10mm), Cu-alloy sheets (22 mm) with imbedded stainless steel cooling tubes and a stainless steel back plate (49 mm) with drilled cooling channels. Although this layered structure follows the configuration of the regular blankets, the freedom of thermal bending provided by a flexible support in the central section of the regular blankets could not be maintained. Instead it was necessary to weld the front panel along its outer edge to the shells of the BSM housing to enhance the stiffness of the structure (electromagnetic calculations an upward VDE -linear 40 ms- indicated moments at the centre of the BSM in the order of 1 MNm). By FEM calculations, different loading cases were analysed for static conditions and the equivalent stresses in the various material sections were quantified (cf. Tab. 1).

The peak stresses found were localised and of secondary type. Taking the Sm values (at typical max. values of the individual temperature zones) of 108 MPa (for Be, Cu at 200°C), 137 MPa (for SS back plate at 200°C), and 157 MPa (for SS front tubes and channels at <150°C) and noting that the equivalent stress nowhere exceeds 1.5 Sm, the welded first wall panel is compatible with the 3 Sm criterion. In transient analyses, it was found that ‘overshots’ in the stress evolution are only significant for areas of reduced stresses and thus do not jeopardise the achievement of the safe stress limits concluded from the quasi-stationary calculations.
Table 1 Maximum equivalent stress in the different material zones of a first wall panel welded to BSM side walls

| Load scenarios | Maximum equivalent stress [MPa] in individual material zones |
|----------------|-------------------------------------------------------------|
| Surface heat load [W/cm²] | Vol. heat load in side walls [W/cm³] | Be surface | Cu-alloy layer | SS front tubes | SS channel | SS back plate |
| 50 | 2.3 | 143 – 160 | ~0 – 94 | 230 | 170 – 182 | 177 |
| 50 | 1.4 – 4.1 | 108 | 79 | 176 | 166 | 156 |
| 25 | 2.2 | 108 | 85 | 173 | 150 – 160 | 151 |
| 40 | 2.2 | 133 | 90 | 206 | 165 | 162 |

The opening in the front panel required for the poloidally steerable injection of the mm-wave power was kept as small as reasonably achievable for the 8 beamline reference model (typical width and height: 438 mm x 448 mm). Yet, for reaching low positions for the front mirrors an additional cut-out at the neighbouring lower regular blanket module had to be admitted. The following guidelines were taken as a design goal for the shape and location of such cut-out at the neighbouring regular blanket modules:

a) Interference with lateral neighbours is judged to be prohibitive.

b) The cut-out in the lower blanket module can be admitted, provided that adequate neutron shielding efficiency can be ensured. The depth of the cut-out should not severely interfere with the cooling manifolds in the main body of the blanket. Ideally the cut-out should only affect two of the 4 vertical sections of the first wall panel.

The latter recommendation could not be fulfilled for the cut-out for the 8 beamline RS reference model, but is now responded by the design of a specialised blanket module at the ITER-IT.

4.2. Shield blocks in the BSM

The mm-wave beams in the 8 beamline reference launcher set the frame for installing three shield blocks inside the BSM at top, middle and bottom position, which are designed following the effort for maximum shielding performance, i.e., minimal openings for the beams. The top and middle shield blocks serve also for attachment of the sets of mirrors at the upper and lower row. The two sets of mirrors have become extremely large, extending the front shield depth. Two variants of shield blocks have been outlined, the upper one as tank design with inserted steel plates to accommodate the desired water/steel fraction and the middle and bottom shields as solid blocks with machined cooling channels sealed by welded cover plates.

Figure 5. Cooling structure and piping (left) and disassembly interfaces (right) for the shield blocks in the 8 beamline reference launcher.
All of the front shield blocks are fixed to the front shield housing by bolts and key ways. Torques produced by EM forces shall be taken up by the positioning pads at top and bottom of the side walls.

The adaptation of the shield blocks to the more extended free beam paths in the alternative launcher models requires a substantial reconfiguration (cf. Fig. 6). Yet the basic concept of replacing the fixed mirrors together with the shield blocks (welded connections) is feasible. Even it is anticipated that the fixed mirrors could be formed as integral element of the shield block. For the moveable mirrors, detachable fixations at the side walls of the BSM, the front part of the internal shield or the lower shield block are studied as alternative options. It should be noted that there is special importance of shielding at the top part in the BSM, in order to counteract the apparent line of sight through the cut-outs in lower blanket module and the openings at the first wall panel. The 6 beamline dogleg design offers the advantage that openings are minimal, the FS launcher, however, provides more space for the top shield blocks. Still the large open volumes in the BSM for both alternative launchers (volume filling factors around 20%) call for a quantitative neutronics analysis to evaluate the shielding performance.

Figure 6. Sketch of the reconfigurations required for adapting the shield blocks of the 8 beamline RS reference launcher (left) to the 6 beamline dog-leg RS launcher (centre) and the FS launcher (right)

4.3. Internal shield modules

For the internal shields which are integrated into the main structure, three different concepts were envisaged. The routing of the wave guides is a major issue that decides on the particular benefit and feasibility of the individual concepts. The common problem with the wave guides is that they need to be tightly packed at the front end and shifted laterally off the centre, in order to achieve the desired micro-wave injection angles. Initially two types of internal shields have been pursued, the block design and the tank design. In the 8 beamline reference model, the tight waveguide interspaces at the front end could be best accounted for by a combined structure having the block design in the front and the tank design in the back. The interface between both types could then be placed where the pressure tubes of the tank design cease to overlap each other. The chances for the feasibility of a tank design, which is especially attractive for its straightforward manufacturing, are much better in a 6 beamline design. A third variant is formed as a modular design made up of cast modules welded one by one at the outer perimeter and at the inner nozzles (cf. Fig. 7). A particular benefit could be the applicability of the modular concept for other upper port plugs (i.e. including diagnostic ones). All of the design options discussed have the same outer dimensions and interfaces to the launcher. The integration of the internal shield unit is achieved by sliding the whole unit whole unit of about 2.7 m length into the launcher frame from the front on a base plate. Indeed, the principal design guideline for the internal shield concepts is to provide a removable unit to allow specific maintenance of the massive components, especially as they include long lines of wet welds in the tank and modular design. In contrast to an alternative fixed design, the disposal of the full port plug can be avoided if either the internal shield or the main structure would have to be replaced.
5. Nuclear analysis

The conformity of the nuclear shielding design with the ITER boundary conditions was analysed for the 8 beamline RS reference model with respect to the following four criteria:

a) Streaming of fast neutrons along waveguides in the launcher should be kept below a flux of $3 \times 10^{8}$ $\text{cm}^{-2}\text{s}^{-1}$ at the torus window to ensure the safe limit with respect to radiation-induced degradation of the CVD diamond window materials. With this upper flux limit, the neutron fluence will not exceed $10^{20}$ $\text{m}^{-2}$ even for the conservative assumption of 1 full power year; this fluence limit is safe with respect to degradation of thermal conductivity in CVD diamond.

b) For radiological safety, the ECRH system should meet the requirement on shutdown dose rate limit, which equals 100 $\mu\text{Sv/h}$ at 10 days after shutdown to allow personnel access for maintenance. The access to the ECRH system is foreseen from the back side which consists of steerable mirrors, diamond windows, window cooling pipes, safety valves, and sockets for window/waveguide alignment. For the evaluation, the launcher back side components were modelled as a dummy plate with homogenised material mixture.

c) According to ITER design rules, 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.

d) As a design limit for peak local nuclear heating in neighbouring superconducting field coils a rate below $2 \times 10^3$ $\text{W/cm}^3$ has to be maintained. This was evaluated to be represented conservatively by the values obtained at the upper part of the vacuum vessel.

---

**Figure 8.** Nuclear heating rates [W/cm$^3$] obtained with the complete MCNP model of the 8 beamline reference launcher (left) and with omission of the middle shield block (right)
As presented in a dedicated paper for the 8 beamline reference model [7], all four criteria could be met by safety factor of at least 2-3. The MNCP model set up for this case can be used to study the effect of a large open volume in the centre of the BSM by comparing the results to those obtained when omitting the middle shield block. The only significant increase in He generation (from a maximum of 0.25 appm to 0.29 appm He) and nuclear heating rates (cf. Fig. 8) occur in the neighboring top section, but in both cases remain at a tolerable level.

6. Integral cooling design

The total heat load to be removed from the launcher was assigned considering a maximum surface heat load of 50 W/cm², a nuclear volumetric heating according to the distribution determined by the related neutronic analysis of the 8 beamline reference launcher, mm-wave absorption at the front mirror (0.5% of the mm-wave power which includes an enhancement factor of s=2 for mirror contamination relative to ideal copper surfaces) and in the square corrugated waveguides (maximum 3% of the mm-wave power at 12° steering angle). The contribution from mm-wave beamlines is included as a conservative assumption, in which all beamlines will be operated at 2 MW mm-wave power. Thus the system will contribute about half of the total heat load.

![Figure 9. Cooling schemes proposed for the cooling system fully integrated into blanket water primary heat transfer system adapted to advanced upper launcher models: 6 beamline RS dogleg launcher (top) and FS launcher (bottom).](image-url)
The rationale of the cooling concept is based on a cooling system fully integrated into blanket water primary heat transfer system. Detailed thermal-hydraulics performance studies show that the total temperature rise in the launcher amounts to 42 K and thus has reasonable margin to the nominal blanket water $\Delta T=48$ K. Also the total pressure loss of 0.61 MPa are judged to fulfill the blanket cooling system requirements. For the alternative launcher, adapted cooling schemes are proposed (cf. Fig.9), including the particular safety feature of providing separate cooling pipes to the two movable front mirror units in the front steering concept. In the latter diagram, the rf power deposition in the mitre section includes the contribution from higher order modes trapped between the two bends, as these are expected to be concentrated close to the bends and thus being handled by an extension of the cooled area at the bends. The overall boundary conditions for cooling with blanket cooling water can be maintained.

7. Summary and conclusions

The design of the EC Launching Upper Port Plug System was developed to a consistent configuration of the key components for the use of a reference model for a remotely steerable (RS) ECRH launcher at the ITER Upper Port. The design development has led to a port plug structure which is composed of a detachable blanket shield module (BSM) with dedicated internal components (mm-wave front mirrors; neutron shield blocks) and of the main structure setting the frame for the square corrugated waveguide system, cooling circuits and the internal neutron shield. The shielding efficiency was demonstrated by neutronics analysis and the integral cooling concept is based the blanket water primary heat transfer system set up and shown to be compatible with the blanket cooling system requirements. First proposals for adaptations of the shielding and the cooling configuration for the two advanced beamline variants are identified, which are the 6 beamline RS dogleg option and the front steering (FS) launcher, and are to be transferred into dedicated nuclear and thermo-mechanical performance analysis.

Acknowledgements

This work is being carried out under the EFDA technology research programme activities: tasks TW3/TW4/TW5- TPHE-ECHULA and B.

References

[1] Ramponi G, Bindslev H, Farina D, Giruzzi G, Lloyd B, Novak S, Poli E, Shevchenko V, Volpe F, and Zohm H, Optimisation of the ITER ECRH Top Launcher, IAEA Techn. Meeting on ECRH Physics and Technology for ITER, Kloster Seeon, Germany, July 14-16, 2003, http://www.ipp.mpg.de/eng/for/veranstaltungen/tmseeon/Papers/Ramponi.pdf

[2] ITER; Final Design Report 2001, DDD 5.2: Electron Cyclotron Heating and Current Drive System, https://www.iter.org/ftp/ftp/ddr/DDG1latest/2001_FDR/ddr/ddd52/ddd_52.pdf

[3] Heidinger R, Hailfinger G, Heinzel V Kleefeldt K, Stratmanns E, Conceptual design studies for the Blanket Shield Module and the main structure of the upper port plug, IAEA Techn. Meet. on ECRH Physics and Technology for ITER, Kloster Seeon, Germany, July 14-16, 2003, http://www.ipp.mpg.de/eng/for/veranstaltungen/tmseeon/Papers/Heidinger_Structure.pdf

[4] Zohm H, Heidinger R., Henderson M, Poli E, Ramponi G, Saibene G, Verhoeven A.G.A., Comparison of the performance of different options for the ITER ECRH Upper Launcher, this conference

[5] Verhoeven A.G.A., Bongers W.A., Bruschi A, Cirint S, Danilov J, Elzendoorn B.S.Q., Fernández Curto A, Gantenbein G, Graswinkel MF, Heidinger R, Kasparek W, Kleefeldt K, Kruijt O.G., Lamers B, Piosczyk B, Plaus B, Rondin D.M.S., Saibene G, Zohm H, The remote-steering ECRH upper launcher for ITER, this conference

[6] Henderson M., Chavan R, Heidinger R, Nikkol P, Ramponi G, Saibene G, Sanchez F, Sauter O, Serikov A, Shidara H, Zohm H, The Front Steering Launcher Design for the ITER ECRH Upper Port, this conference

[7] Serikov A, Fischer U, Lang K, Heidinger R, Luo Y, Tsige-Tamirat H, Radiation shielding analyses for the ECRH launcher, this conference.