Design and Analysis of the ECH Upper Port Plug Structure at ITER

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Abstract
The ECH Upper Port Plug at ITER is designed for controlling plasma instabilities, with a major emphasis on the stabilisation of neoclassical tearing modes, based on the injection a total of 20 MW mm-wave power at 170 GHz into the plasma. The required targeting of flux surfaces in the range of 0.65 to 0.93 (given in terms of the normalised poloidal flux surface coordinate) will be achieved by angular steering in the poloidal direction. The paper describes the integration of the mm-wave system into the upper port plug structure with a special focus given to the current front steering reference design. The launcher structure consists of the blanket shield module closing the gap in the blanket at the port; the port plug frame which houses the internal shield; the closure plate forming primary vacuum boundary; and the launcher back-end following the closure plate up to the final flange for the door placed for transfer to the hot cells. The shielding structure is essentially formed by the blanket shield module and the internal shield. For these subsystems, the conceptual design is presented which includes a specially adapted first wall panel welded to a double-walled housing, dedicated shield blocks formed in encased and/or solid configurations according to space requirements, and the internal shield integrated to the port plug frame. The nuclear shielding performance was analysed on the basis of 3D Monte Carlo calculations with the MCNP code for the radiation transport simulation and activation calculations with the FISPACT inventory code. It was shown for a fusion power of 500 MW and an operation over 0.5 full power years that all sufficiency criteria were fulfilled. Thermo-mechanical stresses in the first wall panel and the housing of the blanket shield module were analysed by FEM ("ANSYS") calculations with transient loads for a typical plasma burn of 400 s using a simplified slice structure.

1. Overview of the structural components of the upper port plug

For control of plasma instabilities, especially the stabilisation of neoclassical tearing modes, it is foreseen to inject a total of 20 MW mm-wave power at 170 GHz into the ITER plasma. The required targeting of the q=3/2 and q=2/1 flux surfaces will be achieved by angular steering in the poloidal direction. The mm-wave components are integrated into the upper port plug structure which consists of two separate units, namely the blanket shield module (BSM) forming the plasma-facing component and the launcher main structure, which includes the internal shield (cf. Fig. 1).

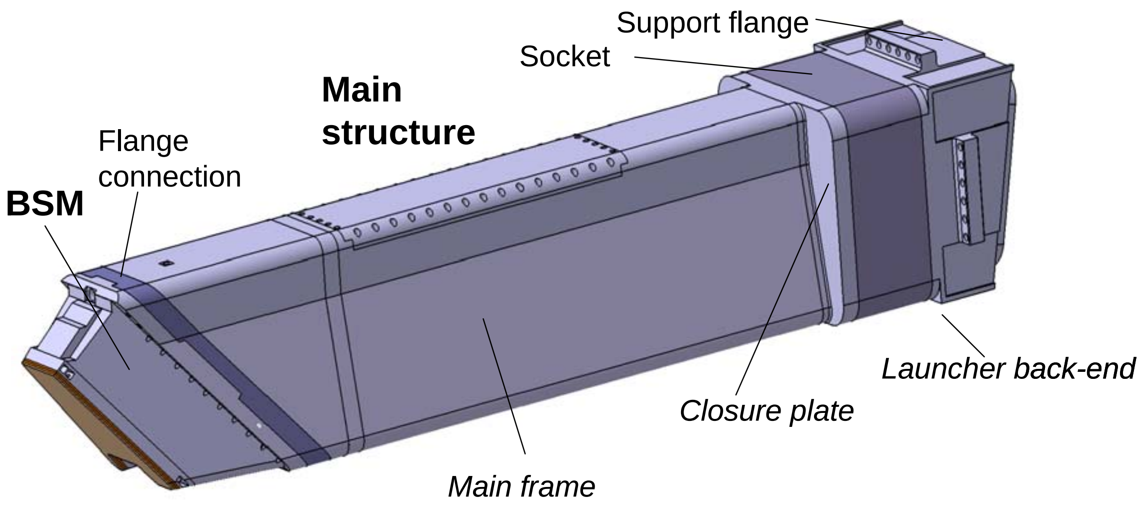

FIG. 1. Location of the main structural components in ITER ECH upper port plug

The main structure is bolted at the launcher back-end as a cantilever to the port extension of the vacuum vessel. The BSM and the main structure are formed as welded assemblies and are connected with a bolted joint, which allows axial access to the plug internals for maintenance and disassembly.

The port plug accommodates the following groups of launcher internals:

- Mm-wave system (waveguides, mirrors, mitre-bends)
- Tubing for coolant supply and for the pneumatic system of the steerable mirrors
- Shielding elements inside the BSM and in the main frame (internal shield)

For the mm-wave system, two basic variants are distinguished. Firstly, front steering (FS) uses moveable mirrors at front mirror position close to the plasma [1]. The beams propagate through a sequence of circular waveguide sections and quasi-optical sections. Alternatively, remote steering (RS) is characterised by having all movable components removed from in-vessel locations, which implies using fixed mirrors in front position and placing the steering mirrors into the launcher back-end [2]. Square corrugated waveguides of definite length allow to restore the phase and amplitude of the beams at the front end and thus to generate the quasi-optical beams which are swept over the fixed front mirrors. Resulting from the work under EFDA of the “ECHULA group” of EU associations (ENEA/CNR Milano, CRPP Lausanne, FZK Karlsruhe, FOM Rijnhuizen, IPP/IPF Garching/Stuttgart) an initial reference design for the ECRH Upper Launcher was developed on the basis of the remote steering (RS) concept and transferred to the ITER design office in 2004 called the “RS 3/8 launcher model” [3]. The steering range required to access the plasma area range of interest (from ρ_p~0.65 to ρ_p~0.93) for the ITER scenarios 2, 3a, and 5 can presently only be met by the FS variant with adequate focalisation [4]. Thus the main emphasis in the structural design has been redirected towards the front steering design (cf. Figure 2). Here, the initial launcher was a 3-launcher system designed exclusively for NTM control (“NTM launcher”). The FS design that has emerged since then exploits the availability of a fourth port to include sawtooth control in its functions: “Extended Performance FS launcher” or EPL [5].

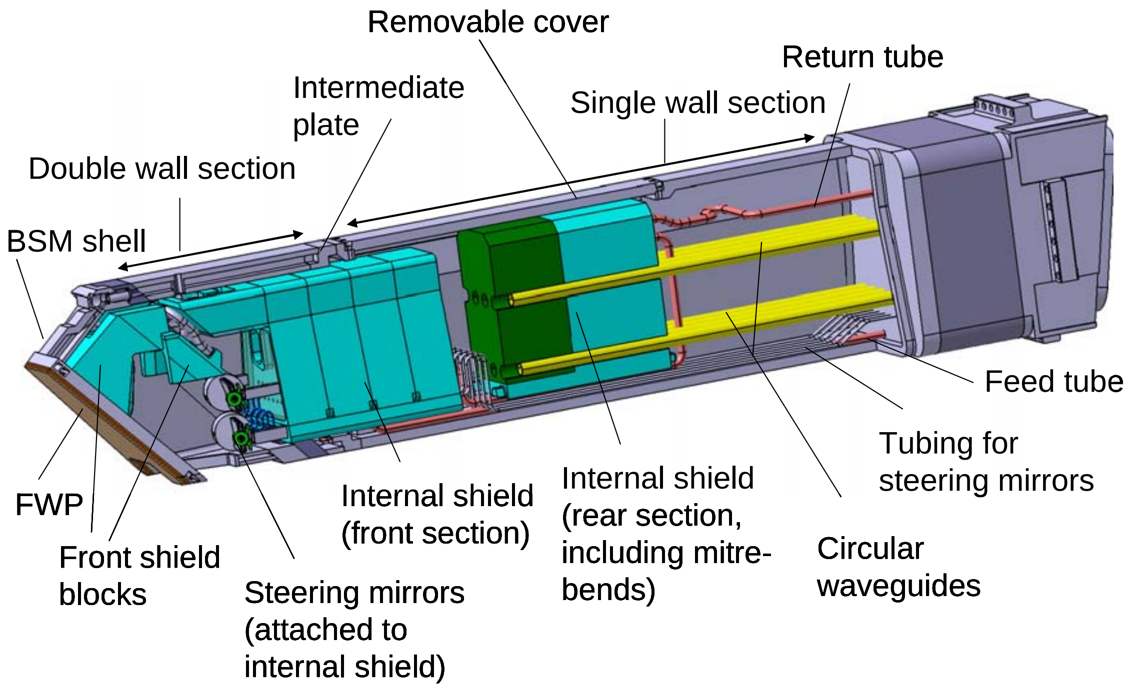

FIG. 2. Main components of the present ECH FS Upper Port Plug

2. Design principles for the main structure

The launcher main structure has to meet in a first place the environmental requirements of ITER, i.e. the geometrical constraints in terms of enveloping dimensions and positioning, including the cantilevered fixation of the whole structure to the vacuum vessel port extension. The thermal requirements call for baking and cooling (where needed). Mechanically the structure must be rigid enough to cope with dead weight, vibration and electromagnetic loads, and it must allow remote handling of internals in the hot cell. These requirements led in the RS concept [3] to the double-wall design with cooling (or baking) fluid in the inter-space and enabling axial access to the internals after removal of the BSM.

The evolving FS concept along with striving for communality with diagnostics launchers as well as fabrication and cost considerations led to the currently pursued design (cf. FIG. 2). It is characterised by a single wall section of the main frame (55 mm wall thickness) with a removable cover that allows vertical access to part of the internal shield. Baking of that section up to about 180 - 200 °C is achieved passively by radiation from the surrounding structures. At the front end the double wall design has been maintained for cooling, baking and shielding purposes, implying that the BSM fixation and axial removal of parts of the internal shield are unchanged. Analyses of the mechanical and shielding implications are in progress.

3. Design methodology for the shield components

3.1. The blanket shield module

The blanket shield module (BSM) consists of the first wall panel (FWP), a double wall structure individual shield blocks, and mm-wave mirrors (cf. Fig. 3). The FWP is formed according to the configuration of a regular blanket module. This means that it is a compound structure combining a stainless steel (316 L(N)-IG) back-plate, plates of dispersion strengthened copper (CuCrZr), and a Be liner as plasma facing material. The internals of the BSM are the specialised shield blocks and mm-wave mirrors.

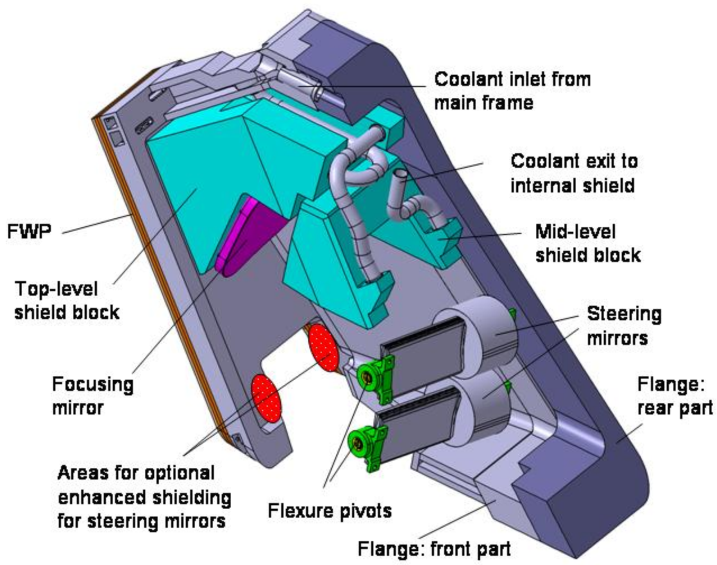

FIG. 3. Elements of the blanket shield module

Depending on the geometry of the mm-wave beam configuration, two design variants are considered which are distinguished by their size and shape conformity. The “encased shield block” is better suited for large and regularly shaped volumes and consists of a welded SS casing with stacked SS plates and water interspaces. In the “solid shield block” which offers a more flexible adoption to complex space requests, a two-level arrangement of machined cooling channels provides the proper SS/water composition for the neutron shielding in the high flux area (80/20 vol. %), (cf. Fig. 4).

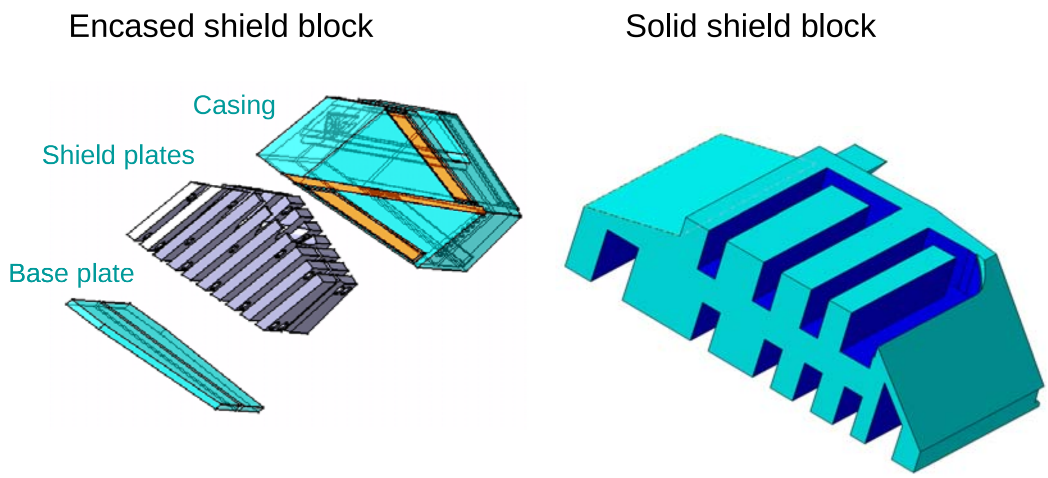

Fig. 4: The two basic design variants of shield block configurations inside the BSM
(exemplified with shield blocks developed for the initial RS launcher reference model)

3.2. The internal shield

The internal shield provides the major radiation protection of the launcher internals up to the launcher back-end and of surrounding structures, like part of the vacuum vessel and super-conducting coils. For general configurations, three design options have been brought to a conceptual design level [3]: Block, tank and modular design (cf. Fig. 5).

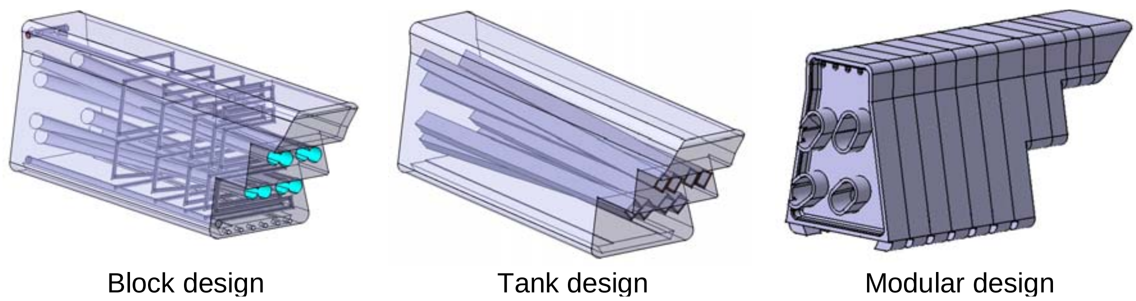

Fig. 5: Internal shield options sketched for the initial RS reference launcher

The most straightforward design, which lends itself most directly to standard welded structures is the tank design. However, the partitioning of the internal shield, which is inherent to the mm-wave system of the EPL, favours a combination of a modular design formed by a small number of individual plates in the front part and a block design formed by a metal block with machined cooling channels and with potentially fully integrated waveguides (cf. Fig. 2).

The overall metal to water fraction can be reduced from a 80/20 vol% stainless steel/water ratio in the front part to a 40/60 vol% ratio in the rear part. All parts of the internal shield will be actively cooled with blanket cooling water in a "once-through" configuration and thus provide also active heating in the baking process.

4. Nuclear analysis of the shielding performance

In the course of the comparative analysis of the FS and RS concepts [4], the conformity with nuclear shielding criteria were checked for the launching system and neighbouring components such as toroidal field coils and vacuum vessel using shielding schemes adopted from the detailed neutronics analysis performed for the initial RS reference launcher model [7]. The nuclear shielding performance was analysed on the basis of 3D Monte Carlo calculations with the MCNP code for the radiation transport simulation and activation calculations with the FISPACT inventory code. Computational models of the ECH upper port plug structure were generated by converting the CAD 3D models into the semi-algebraic representation of the MCNP code using the interface programs MCAM and McCAD. It was shown for a fusion power of 500 MW and an operation over 0.5 full power years, that all criteria were fulfilled with safety margins of at least 3-4 (cf. Table I).

Table I: Positive proof of conformity of the basic FS and RS launcher concepts with nuclear shielding requirements; evaluated according 6 quantitative criteria

Criterion	Nuclear shielding requirement	FS launcher ("dogleg")	RS launcher ("NTM")
I	Dose rate behind the CVD diamond window below 100μSv/hr after 10 days of shut-down	<15 μSv/hr	<15 μSv/hr
II	Fast neutron fluence at the CVD diamond window kept below 10^{20} m^{-2} (@0.5fpy)	~10^{17} m^{-2}	<$2 \cdot 10^{19}$ m^{-2}
III	He production in the joining areas of the vacuum vessel below 1.0 appm?	$1.2 \cdot 10^{-1}$ appm	$1.5 \cdot 10^{-1}$ appm
IV	Compatibility with conservative limit for max. nuclear heating loads of 10^{-3} MW/m^3 at the outer housing of the vacuum vessel	$2 \cdot 10^{-4}$MW/m^3	$3 \cdot 10^{-4}$MW/m^3
V	Nuclear response in the structures of superconductive magnets of TFC near the launcher, in particular fast neutron fluence in isolator below $5 \cdot 10^{21}$ n/m^2 (@0.5 fpy).	$1 \cdot 10^{20}$ n/m^2	$1 \cdot 10^{20}$ n/m^2
VI	Nuclear heat loads in the vacuum vessel below ~ $3 \cdot 10^{-1}$MW/m^3	Near the launcher: $5 \cdot 10^{-2}$MW/m^3	Near the launcher: $5 \cdot 10^{-2}$MW/m^3

Radiation shield analyses for blanket shield module (BSM) of the FS launcher were performed to determine the arrangements of the shield blocks providing enough empty space for mm-wave propagation. The nuclear heating density was calculated in the BSM structures with detailed distributions in the steering mirror assembly. The 2-D map of the heating distribution in the material compositions of the BSM and the Vacuum Vessel (VV) was determined as input for the thermo-mechanical analysis [8].

Radiation damage of candidate materials envisioned for the steering mirror assemblies have been estimated by the MCNP code. The structural damage levels in terms of displacements per atom (dpa) rates are given in Table II for the steering mechanisms and flexure pivots. These two assembly elements are located at opposite sides of the steering mirror (cf. Fig. 3). The maximum damage of 0.5 dpa is found in the lower pivot where the highest estimated value is obtained in the steel SS316L(N)-IG at the lower pivot side.

These values have been obtained for a BSM configuration which is characteristic for the NTM launcher. As the reduced steering angles in the EPL concept result in a smaller cut-out in the FWP, both nuclear heating and structural damage rates obtained in the present analysis can be considered as conservative.

Table II. The neutron induced displacements rate per atom (dpa) modeled for a total of 0.5 full power years (0.5 fpy at a fusion power of 500 MW) in materials of the steering mechanism and the flexure pivots holding the steerable mirror

Section	SS316 L(N)-IG, [dpa]	Inconel 718 [dpa]	Ni [dpa]	Ti6Al4V [dpa]	Cu [dpa]
Upper steering mechanism	0.164	0.177	0.188	0.162	0.156
Lower steering mechanism	0.126	0.138	0.146	0.128	0.127
Upper pivot	0.340	-	-	0.334	0.314
Lower pivot	0.520	-	-	0.505	0.472

5. Thermo-mechanical analysis of the BSM housing using transient load conditions

The structural components that are exposed to the highest radiative loads from the plasma is the blanket shield module housing (BSMH) and the first wall panel (FWP) which is welded to the front shell of the BSMH. For the initial RS reference model, a detailed 3-D model of the FWP and BSMH housing was parameterised for FEM analysis (“ANSYS”) using a surface heat flux of 0.5 MW/m^2 at Be layer and graded volume heating rates ranging from 5.5 MW/m^3 (Cu plate in FWP) down to 0.5 MW/m^3 (in the flange interface to the port plug frame). The heat transfer rates at the surfaces of the cooling system were set to 0.6 $W\cdot cm^{-2}\cdot K^{-1}$ except for the front cooling pipes (1.7 $W\cdot cm^{-2}\cdot K^{-1}$). In the stationary analysis, it could be shown that secondary stresses were predominant and that with the singular exception of hot spot zone in the Beryllium layer (that can be removed by placing a slit), the equivalent stresses were fully compatible with the 3Sm criterion [6].

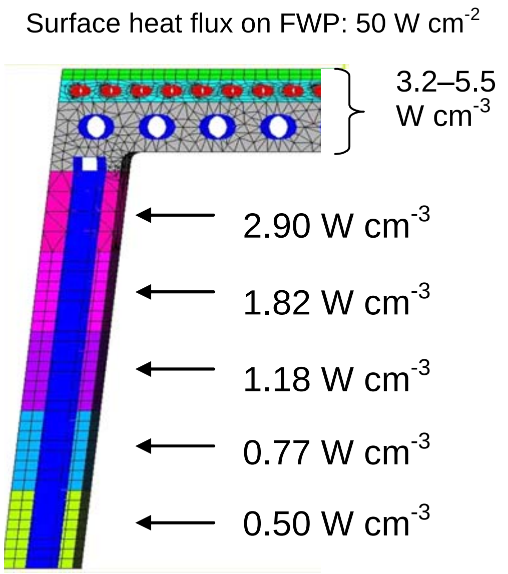

FIG. 6: Load sections and finite element meshing defined in the ANSYS analysis of the slice model

As the opening of the FWP and BSMH is smaller in the current FS launcher configuration, this analyses is a conservative indicator for the validity of the welded attachment concept of the FWP. As there could be a potential risk that temporary offsets from the balance between the heat loading and extraction, which occur at the beginning and the end of a plasma burn, a simplified slice structure was used for a 2-D transient modelling taken to be characteristic, for the transient loading of the general FWP and BSMH structure during a 400 s burn with an additional ramp up of 20 s and shut down of 50 s. Peak values shown in Fig.6 are scaled down linearly with time during the ramp up and shut down periods.

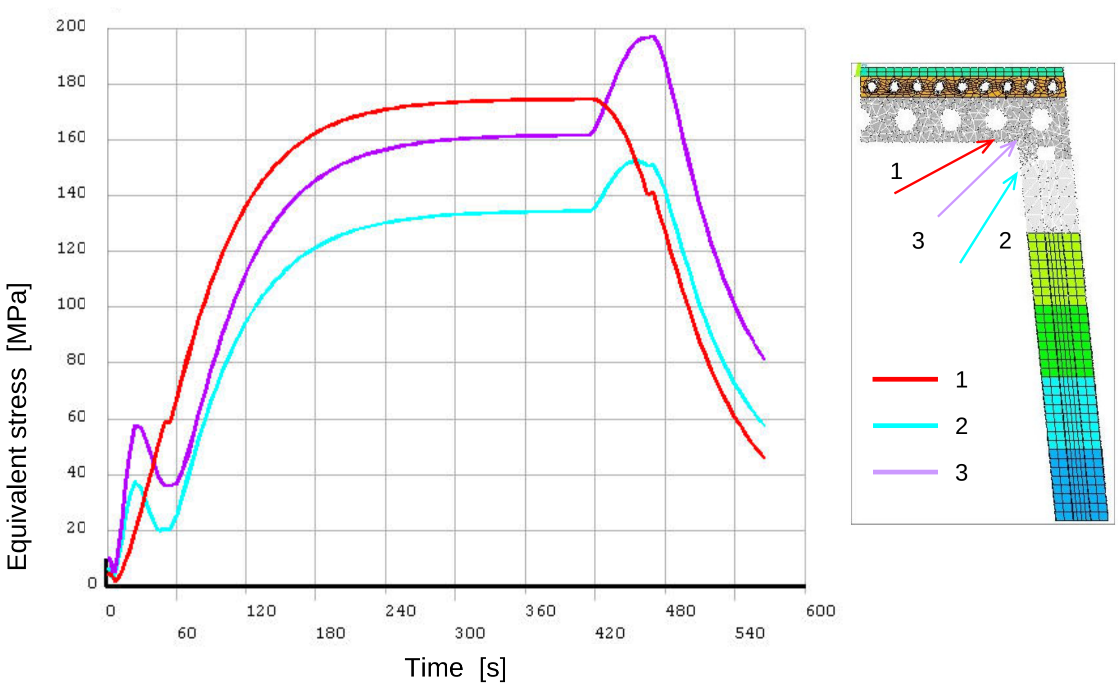

FIG. 7: Equivalent stress (von Mises) at FWP back plate corner

The evolution of equivalent stress over time was calculated for representative regions with high stress level. In a few regions of the structure, the anticipated stress overshooting was seen but only occurring at low stress levels. During the constant loading phase, the stress increased and came up to a level obtained in static calculations. A more remarkable effect set in during the shut down phase where a noteworthy stress overshooting was calculated for certain locations; the most pronounced case was found at the FWP back plate corner (cf. Fig. 7). Yet, the resilience with the 3 Sm criterion was not compromised.

6. Summary and outlook

The design development of the ECH upper port plug has resulted in a configuration which is composed of a detachable blanket shield module (BSM) with dedicated internal components and of the main structure setting the frame for the mm-wave beams. The mm-wave optics of the present "Extended performance launcher" design implies a reduction of the cut-out at the first wall panel and a partitioning of the internal shield into a modular and a block type section.

The concept for the main frame includes a special option for relaxed baking scenarios which bears the advantage of communality with diagnostic port plugs and higher flexibility in the selecting competitive manufacturing routes. The current individual design of the shield blocks and of the internal shield fixes the appropriate space for the forthcoming definition of the cooling routing and maintenance access.

Acknowledgement

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