Status of development of the EU He-cooled divertor for DEMO

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Abstract. A modular He-cooled divertor concept for DEMO is being investigated at Forschungszentrum Karlsruhe (FZK) within the framework of the EU power plant conceptual study. The design goal is to reach a heat flux of at least 10 MW/m^2. The reference design HEMJ (helium-cooled modular divertor with jet cooling) consists of a hexagonal tungsten tile which is brazed to a thimble made of W-1%La_2O_3. The cooling is realized by impingement jets of high pressure helium through an array of small jet holes located at the top of a cartridge made of ODS Eurofer. The current divertor work programme focuses on manufacture and high-heat-flux tests of prototypical tungsten mock-ups to demonstrate the manufacturability and the performance of the design. The tests were performed in a combined helium loop and Tsefey EB facility at Efremov. The first two high-heat-flux test series on 1-finger mock-ups in 2006-2007 already confirmed the divertor performance. Clear progress was achieved in the continuation third high-heat-flux test series in 2008 after the quality in mock-up manufacturing has been significantly improved. Technological study on fabrication of a 9-finger module of stain less steel was also successfully performed. First thermo-hydraulic tests showed uniform distribution of mass flow rates which agrees well with calculation results.

1. **Introduction:** A He-cooled divertor concept for DEMO [1] has been pursued at Forschungszentrum Karlsruhe within the framework of the EU power plant conceptual study since 2002. The design goal is to withstand a DEMO-relevant heat flux of 10 MW/m^2 at least. The major R&D areas are design, analyses, material issue, fabrication technology, and experiments for design verification. The helium-cooled modular concept with jet cooling (HEMJ) (Fig. 1) has been defined as reference solution. The current divertor work programme focused on manufacturing and high-heat-flux (HHF) tests of prototypical divertor mock-ups to demonstrate the manufacturability and the performance of the design. In cooperation with the Efremov Institute a combined helium loop [2] & Electron beam facility (60 kW, 27 keV, Fig. 2) was built in St. Petersburg, Russia, for experimental verification of the design. It enables mock-up testing at a nominal helium inlet temperature of 600°C, an internal pressure of 10 MPa, and a pressure drop in the mock-up of up to 0.5 MPa. Three series of high heat flux tests on 1-finger modules were successfully performed till now.

2. The divertor reference design: The required high resistance of the armour material against high heat flux and sputtering led to the choice of tungsten as the most promising divertor material. It is a low-activating material and possesses a high melting point, high thermal conductivity, and low thermal expansion. Its disadvantages lie in the relatively small operation temperature window which is dictated by the ductile-brittle transition temperature at the lower boundary and the recrystallisation temperature (RCT) at the upper boundary. The RCT and machinability of tungsten can be improved by adding fine oxide particles, with W-1%La_2O_3 (WL10) being regarded a suitable option for the divertor design at present. The operation temperature windows of a future W alloy under fusion neutron irradiation are estimated to be around 600°C and 1300°C. This will be taken as the "design window" range in the following design work.

The reference design HEMJ (Fig. 1) employs small hexagonal tungsten tiles (18 mm A/F, 5 mm armour thickness), which are brazed to a thimble (Ø 15x1 mm) made of tungsten alloy WL10. Such a modular design is preferred for thermal stress reduction. The cooling is realized by impingement jets of high pressure helium (10 MPa, 600°C) through an array of small jet holes (Ø 0.6 mm) located at the top of a cartridge made of ODS Eurofer. The W finger units are connected to the main structure of ODS Eurofer steel by means of a transition piece based on copper casting or brazing joint with mechanical interlock.

3. **Technological studies** were performed on manufacturing of the W finger mock-ups [3]. For testing purposes the divertor tile and thimble parts were mechanically manufactured from the full material. For the W/WL10 joint the brazing material STEMET® 1311 (brazing temperature T_{br} = 1050°C) was used. This joint is aimed at stopping the cracks induced by the heat load and growing from the top tile surface. The second brazed joint lies between WL10 and ODS Eurofer steel, with an operational temperature of about 700°C. It has a function of compensating the mismatch of different thermal expansion coefficients of the two parts. Besides the copper cast joining method, the 71KHCP (Cobalt-based) brazing filler metal (T_{br} = 1050°C) was applied at this W-steel transition joint of certain mock-ups. In both cases a sufficient ductility of the brazing fillers is required. The definition of the mock-up for the HHF tests is shown in Fig. 3.

4. Retrospect of the first and second HHF experiment series (2006-2007)

The first HHF test series [4] performed in 2006 contained six mock-ups (five of HEMJ and one of an old design with slot type). The temperature cyclic loading was simulated by means of switching periodically the beam on and off (variations 30s/60s, 30s/30s, and 60s/60s). The mock-ups were tested within a HHF range of 5-13 MW/m^2. The helium cooling parameters are 10 MPa inlet pressure, ~ 500-600°C inlet temperature and the mass flow rate (mfr) varied in a range of ~5-15 g/s. Already in this first test series the results confirmed that the required divertor performance of 10 MW/m^2 can be achieved by helium jet cooling. However, the results of destructive post-examinations also revealed some critical points relating to high thermal stresses and manufacturing quality. In detail, W parts of these mock-ups and the thimble contain pre-existing defect, presumably micro cracks [5] initiated during the fabrication processes. Nevertheless, sudden destruction and/or completely broken mock-ups, i.e. no brittle failure were not observed. No recrystallisation of W thimble was observed in any mock-up. The measured pressure losses were regarded optimistic compared to the calculated value (~50% overestimation).

For the following second test series [6] in 2007 technological/technical improvements have been made: a) the mock-up geometry was optimised [7] to reduce the thermal stresses by means of finite element analyses, b) new target device for 1-finger mock-ups was designed and manufactured which allows for changing the mock-ups without cutting and rewelding, and c) additional grinding process was applied after turning the W mock-up parts. This brought to a noticeable improvement in performance and resistance against thermal cyclic loadings. Ten mock-ups were fabricated; six of them were HHF testable. The last successfully tested mock-ups survived outstandingly more than 100 cycles under 10 MW/m^2 without any damages. Nevertheless, still tile temperature increase and gas leak during the load cycles were detected in many mock-ups, but no damages after experiment termination. The measured pressure losses agreed well with the values obtained from the first test series. It became clear that the major reasons for the high failure rate of mock-ups generally lie in: a) base material quality, b) manufacturing quality [8] (W turning, jet holes drilling, EDM of W surfaces, etc.), c) overheating of the tile/thimble brazed joint leading to detachment, and d) induced high thermal stresses.

5. The third high heat flux experiment series (2007-2008)

Figure 4 shows a set of 10 mock-ups before testing, except the mock-ups #18 and 22 which were subjected to the tests for the second time. W tiles of all mock-ups are castellated. They are made of Plansee rod material (#21, 22), Russian rod material (#23, #33 (only as spare parts and not included), #24-28), and Russian rolled plate material (#24-32, #30 as spare parts and not included), respectively. Thimble is exclusively made from Plansee WL10 material. W tile/WL10 thimble joints are brazed with STEMET 1311® (T_{br} = 1050°C), except #24, 26, and 32 being brazed with CuNi44 (T_{br} = 1300°C). Mock-up #26 was defective after brazing and therefore not available for testing. WL10 thimble/steel joints are brazed with co-based filler 71KHCP. Mock-ups #21 and 22 are fabricated by EDM, #24-28 by regular machining, and #29-32 by NC machining, respectively.

Following test conditions were applied in the 3rd test series:

- He mass flow rate was raised within the range of up to 13 g/s in order to keep the temperature at the tile/thimble brazing layer below T_{br} of 1050°C.
- He inlet temperature lied within the range of 450 – 550°C.
- Heat flux was varied from 8 to 12 MW/m^2.
- Beside standard ‚sharp ramp' (30 s - on, 30 s – off) some tests were partially performed with ‚soft ramp' (20s – up, 20s – on, 20s – down, 20s – pause).

The HHF test results are summarized in Table 1.

The experiments started with the mock-up #21 which was exclusively fabricated by EDM without turning. Heat flux loading was applied to the mock-up surface at a constant mass flow rate (mfr) of ~13 g/s, inlet helium temperature ($T_{in, He}$) ~ 540°C. The pressure loss of 0.35 MPa was measured at this mfr. A maximum tile surface temperature of ~1650°C was measured by means of an IR camera at a heat flux q = 9.5 MW/m^2. The mock-up successfully survived required testing parameters under 50 cycles@11 MW/m^2 (soft ramp), 50 cycles@11 MW/m^2 (sharp ramp), and 12 cycles @12 MW/m^2 (sharp ramp), respectively. Since its tile was manufactured from the Plansee's W-rod which had initial cracks in "star shape" (typical forged defects), this could be the reason of the surface change detected, such as slight erosion of the surface and micro cracks with small spots of melting. One part of the surface has higher temperature (~100 K differences) due to the initial cracks in tile material. This mock-up was passed to Forschungszentrum Jülich (FZJ) for post-examination [5].

The following mock-up #22, exclusively fabricated by EDM without turning, already successfully survived 100 cycles@10 MW/m^2 (soft ramp) in the first test run ($T_{in, He}$ = 540°C, 13 g/s). Good performance, no any damages, no leaks, and stable surface temperature from cycle to cycle were achieved. In the following second test run $T_{in, He}$ was decreased down to 410°C to have the possibility to increase the incident heat flux up to 11 MW/m^2. During the temperature cycling $T_{in, He}$ was increased up again to 550°C. At the end of the tests (54 cycles@10.5 MW/m^2 (soft ramp), 50 cycles@11 MW/m^2 (soft ramp), and 10 cycles@11 MW/m^2 (sharp ramp)) the soft ramp was switched to the sharp one, no effects were detected . This mock-up is available for further tests (Fig. 5).

The mock-up #18 which is a regular mock-up type and was successfully tested once in the 2nd HHF test series [4] survived again outstandingly 50 cycles@11 MW/m^2 (soft ramp), 50 cycles@11 MW/m^2 (sharp ramp), and 12 cycles@12 MW/m^2 (sharp ramp), respectively, in a repeated test ($T_{in, He}$ = 500°C, 13 g/s) without any damage (Fig. 5). Switching from soft to sharp ramp during the cycling did not show any negative results. This mock-up is available for further tests.

The W-tile of mock-up #31 was manufactured from rolled W-plate having horizontal orientation (⊥ to the heat flux). The height of the tile is 11.3 mm instead of 12 mm because two tiles were machined from semi product with a plate thickness of 24 mm. The inlet temperature was decreased down to 500°C. The mock-up survived heat flux up to ~11 MW/m^2 without any damage with soft ramp (Fig. 5). This mock-up is available for further tests.

In the Mock-up #24 CuNi44 brazing filler (T_{br}=1300°C) was used for tile/thimble joining. The main idea was to get stable functionality at q ~10-11 MW/m^2 at a mfr ~9 g/s or less. But during the cycling increasing of tile surface temperature (T_{surf}) and decreasing of helium temperature rise (ΔT_{He}) were detected. Such behaviour together with slow surface cool-down provides an indication of tile detaching or poor brazing. The experiment was terminated after 45 cycles@10 MW/m^2 (sharp ramp).

Mock-up #25, a regular mock-up type, survived excellently 10 cycles@10 MW/m^2, 100 cycles@11 MW/m^2, and 10 cycles@11.5 MW/m^2 under 'sharp ramp' condition ($T_{in, He}$ = 460°C, 13 g/s). This mock-up is available for further tests (Fig. 5).

Mock-ups #27 and #28 are of regular mock-up type and were tested at $T_{in, He}$ = 470°C and 13 g/s. They withstood more than 100 cycles@11 MW/m^2 under 'sharp ramp' with out any damage (Fig. 5), showing good performance, no leaks, stable surface temperature from cycle to cycle. Both mock-ups are available for further tests.

The W-tile of the mock-up #29 was manufactured from rolled W-plate and has horizontal orientation (⊥ to the heat flux, height of the tile = 12 mm). It was tested exclusively under 'sharp ramp' load ($T_{in, He}$ = 495°C, 13 g/s) and showed in the beginning good performance under 20 cycles@11 MW/m^2, 12 cycles@12 MW/m^2, and 7 cycles@12 MW/m^2, respectively, without damage. A fault of EB-gun led to unstable heat flux peaks of up to ~15 MW/m^2. Leak appeared thereafter between conic ring and thimble.

In the Mock-up #32 CuNi44 brazing (T_{br}=1300°C) was used for tile/thimble joining. During the screening and cycling an increase of T_{surf} and decrease of ΔT_{He} were detected. Such behaviour together with slow surface cool-down provides an indication of tile detaching or poor brazing.

The measured pressure loss of about 0.35 MPa at about 13 g/s mas flow rate is equivalent to about 0.11 MPa for DEMO reference case (6.8 g/s, 10 MPa, 600°C). This result agrees well with the calculated value.

6. Conclusions and outlook

The current step of work is aimed at the HHF tests of divertor 1-finger mock-ups to demonstrate their fabricability and performances, and at technological study on fabrication, integration, and tests of multi-finger module. The tests were performed in a combined electron beam and He loop facility at Efremov. The first two high-heat-flux test series using 1-finger mock-ups already confirmed the feasibility and the performance of the current divertor design. Clear progress was achieved in the latest 3rd HHF test series. 11 testing experiments were performed with 1-finger mock-ups, two mock-ups were tested for the second time and 9 mock-ups were tested once. Six HHF tested mock-ups (#18, 22, 25, 27, 28, and 31) (Fig. 5) are still available for further tests. Decreasing the He inlet temperature allowed to check the functionality of mock-ups at the absorbed heat flux up to 12 MW/m^2 even with a 1050°C tile/thimble 'low' temperature brazing. EDM mock-ups (#21, #22) show good performance, but no significant difference was found with regularly turned/machined mock-ups at performed testing conditions (q up to ~11 MW/m^2, cycle number up to ~200). Mock-ups fabricated by improved machining (mechanical grinding and electrochemical grinding) show very stable performance at cyclic absorbed heat flux up to 11 MW/m^2 of more than 100 cycles. First tests with horizontal orientation of tile material structure do not show any difference in function stability of the mock-up in comparison with vertical structure at the used testing conditions. The mock-ups were tested at soft and sharp loading ramps. No difference in results was observed. First tests of the mock-ups with tile/thimble 'high' temperature brazing (1300^{o}C) showed delaminating of the tile from the thimble (or cracking of the brazing interface). This means that careful investigation with the samples of such brazing have to be done prior to mock-ups brazing and testing.

All in all, stable performance was achieved in this third test series, which was probably due to the improved machining, e.g. mechanical grinding and ECM grinding. One of the uncertainties still lies in unpredictable material and no absolute reproducibility of the manufacturing quality. Non-destructive testing is regarded indispensable measures for the verification/qualification of the raw material and mock-ups. Post examination of HHF tested mock-ups [5] in cooperation with FZJ has been launched. Principle fabrication technology of 9-finger mock-up has been demonstrated with a steel 9-finger mock-up. Thermo-hydraulics tests were successfully performed using tank-to-tank gas-puffing in pulse-mode (600°C, 10 MPa, mfr ~20-100 g/s) showing uniform temperature distribution on the top surface.

The next HHF 1-finger test series will focus on: a) reaching the breakthrough of 10 MW/m² and 1000 cycles by continuing testing the mock-ups from last test series, b) Examination of new mock-ups machined with sophisticated technology in FZK [8] and Efremov. Future HHF tests on 9-finger modules will be performed with real W mock-ups.

Acknowledgements

This work, supported by the European Communities under the contract of Association between EURATOM and Forschungszentrum Karlsruhe, was carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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Table 1: 2008 HHF experiments (3rd series) on castellated 1 finger HEMJ mock-ups.

- W tile/WL10 thimble joints brazed with STEMET 1311, except #24, 26, and 32 being brazed with CuNi44. WL10-steel joints brazed with co-based filler 71KHCP.
- Beam on-off mode: (a) sharp ramp 30/30 s (default), (b) soft ramp: 20s–up, 20s–hold, 20s-down, and 20s–pause.

Mock-up #	Cycle number @ heat flux (MW/m^2) / (beam on/off)*	mfr (g/s)	T_{He} in/out (°C)	Δp(MPa) @mfr
21 *(EDM)*	100@9.5 (b) **	13	550 / 590	0.35
22* *(EDM)*	100@10 (b) ** (1st test)	~13	550 / 590	0.35
	54@10.5 (b), 50@11 (b), 10@11 (a); ** (2nd test)	13	410-550 / 550-590	0.35
18*	50@11 (b), 50@11 (a), 12@12 (a); ** (2nd test)	13	500 / 540	0.35
31*	30@10 (b), 72@11 (b); **	13	500 / 540	0.3
24 *(CuNi44)*	45@10 (a); ***	13-9	530 / 595	0.35@13 0.24@11
25*	10@10 (a), 100@11 (a), 10@11.5 (a); **	13	460 / 500	0.3
27*	100@11 (a), 15@11.5 (a); **	13	470 / 515	0.3
28*	100@11 (a), 12@12 (a); **	13	470 / 520	0.3
29	20@11 (a), 12@12 (a),7@12-14 (a); Good performance, no leaks at 11 and 12 MW/m^2. Unstable applied peak heat flux due to facility fault (increasing up to ~15 MW/m^2), →leak between conic ring and thimble.	13	495 / 550	0.3
32 *(CuNi44)*	10@10 (a); *** Cracks, melting and deformation at the tile surface.	13-11	550 / 590	0.35@13 0.25@11

*Available for further tests (Fig. 5).
**Good performance, no damages, no leaks, stable surface temperature from cycle to cycle.
*** T_{surf} increase and ΔT_{He} decrease from cycle to cycle, slow cool down, tile detaching and overheating, no gas leaks.

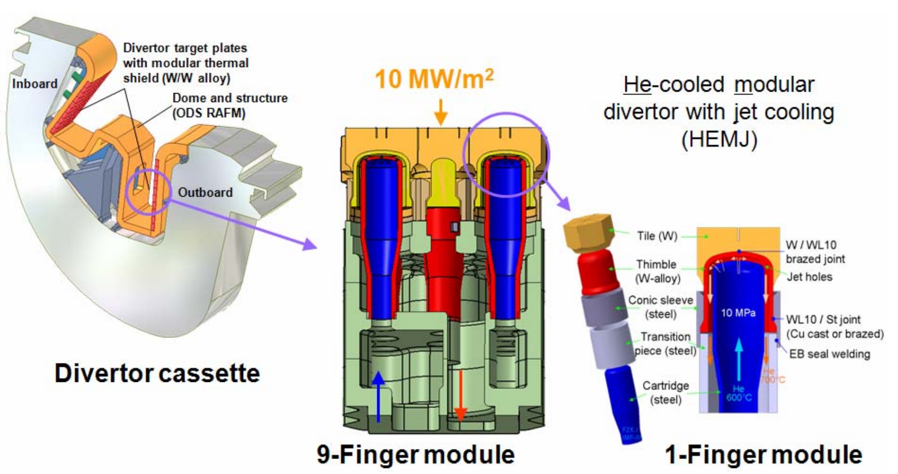


Fig. 1: The He-cooled divertor with multiple-jet cooling (HEMJ)

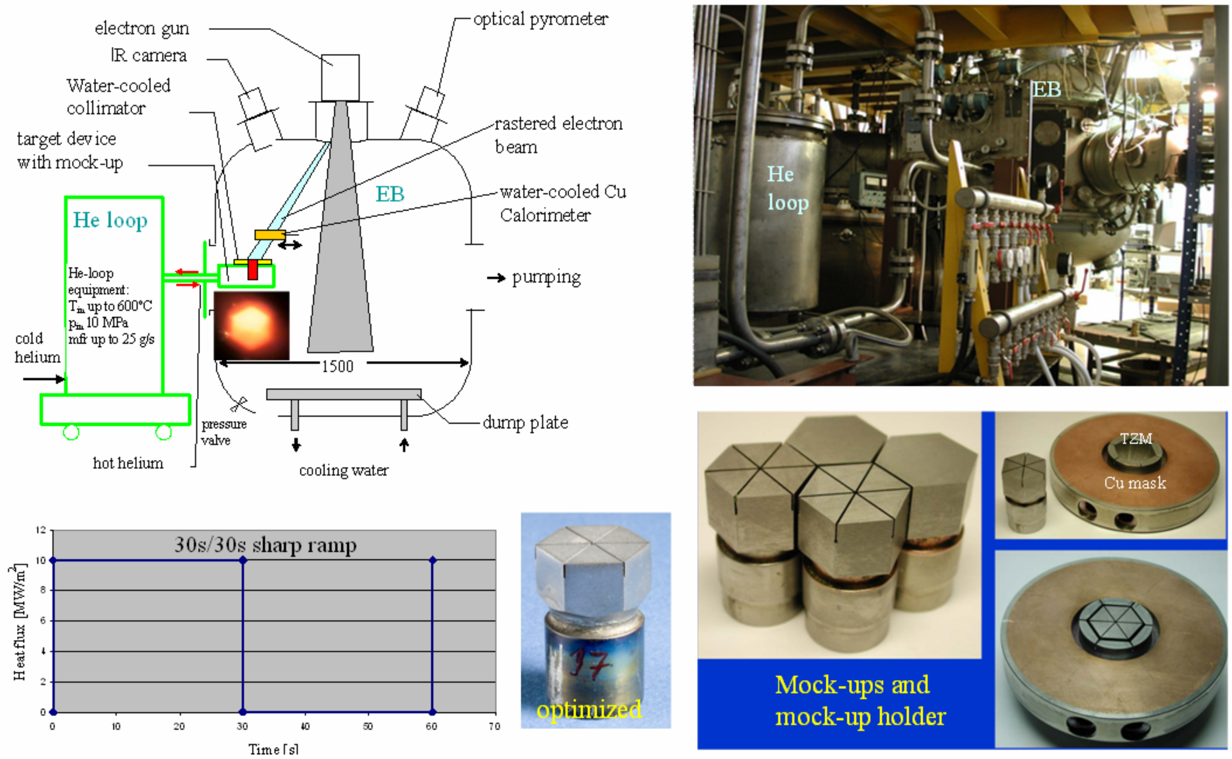
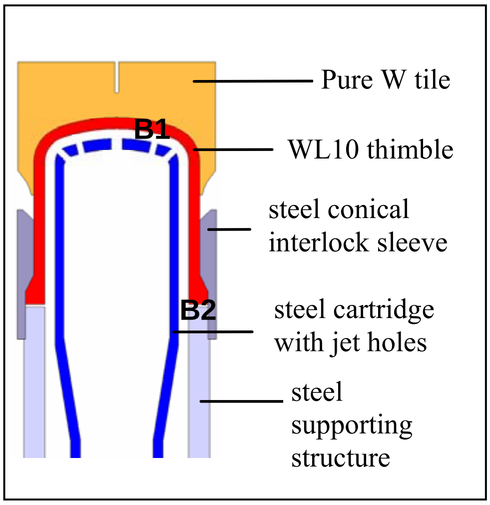


Fig. 2: The combined He loop and TSEFEY testing facility at Efremov.



Materials	
W tile	▪ Plansee W grade (MUs #21-22) ▪ Russian W grade (rest)
W thimble	Plansee WL10 (W–1%La_2O_3)
Support structure	Eurofer
Joining methods	
W/W (B1)	Brazing with ▪ Nickel-based filler metal STEMET 1311®, T_{br} = 1050°C ▪ CuNi44, T_{br} = 1300°C
W/Steel (B2)	Conical lock brazed with cobalt-based filler metal 71KHCP; T_{br} = 1050°C

Fig. 3: Definition of 1-finger module for HHF tests (3rd series).

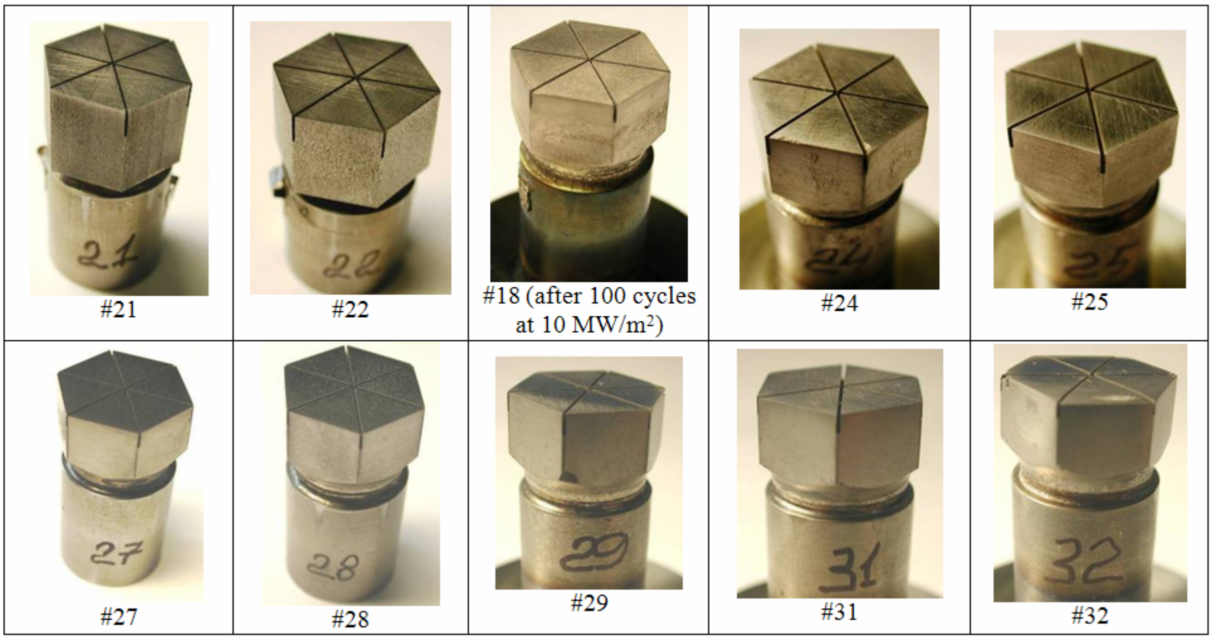


Fig. 4: Third series of W 1-finger mock-ups with castellated W tiles.

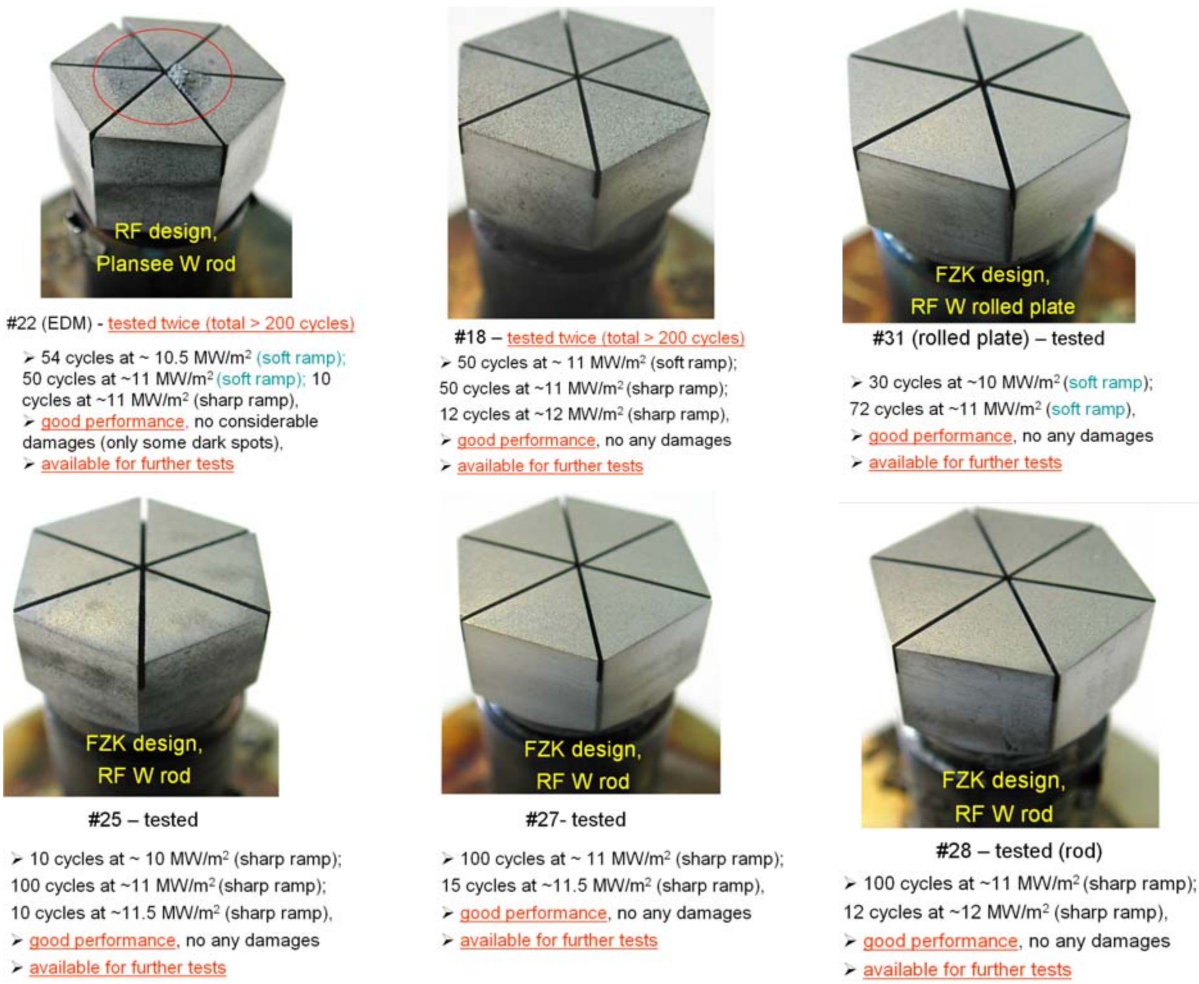


Fig. 5: Six HHF tested mock-ups of the third test series which are available for further tests.