Reviewed design of the high heat flux panels for the AUG and W7-X neutral beam calorimeter

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Each of the neutral beam injectors in the experimental devices ASDEX Upgrade and Wendelstein 7-X can be equipped with up to four positive ion sources with an injected neutral beam power of 2.5 MW per source. For the conditioning of the system, a movable calorimeter can be placed in the path of the neutral beam to dump the heat load. The main heat load on the calorimeter is absorbed by a set of calorimeter panels (CP). Its design, originally from 1988, specified the lifetime of the CPs to 25000 heating cycles and ruled out any plastic deformation due to thermal cyclic loading. This was predicted with the tools available at the time but years of operation show that plastic deformation of the CPs already occurs at the very beginning of the calorimeter full power operation. After some years mechanical fatigue has led a few times to water leaks and consequently to NBI system shutdowns for repair. For this reason, careful inspection of the CPs is performed frequently and deformed CPs are exchanged for new ones.

This paper presents the analysis of the causes that lead to the failure of the old CPs and proposes an optimized design for new CPs to be manufactured in the near future to substitute the old ones. The new design aims at minimizing mechanical fatigue from thermal cycling by reducing maximum surface temperature and thermo-mechanical stresses and improving material properties.

Keywords: Neutral beam injection, Beam dump, High heat flux, ASDEX Upgrade, Wendelstein 7-X, Calorimeter.

1. Introduction

The calorimeter of the neutral beam injection systems (NBI) at ASDEX Upgrade and Wendelstein 7-X is built modularly in four quadrants, one for each of the four beam lines. Each quadrant is equipped with six calorimeter panels (CPs) forming a wedge. The panels are inclined with respect to the beam axis to reduce the maximum beam power density on the CP surface from ~70 MW/m² to 25 MW/m² at the central CPs (Figure 1). Since the power load on the central CP is ~0.57 MW for a pulse duration of typically 10 s, the CPs require strong active cooling. The CPs must withstand 25000 heating cycles at maximum load which should corresponds to several decades of standard operation of the system [1]. This goal is not reached by the CPs with the highest beam power load so they must be inspected regularly and must be exchanged as soon as signs of fatigue are observed, which is typically every seven years. Therefore, new CPs need to be manufactured at certain interval, which gives the opportunity to optimize the design and the manufacturing process.

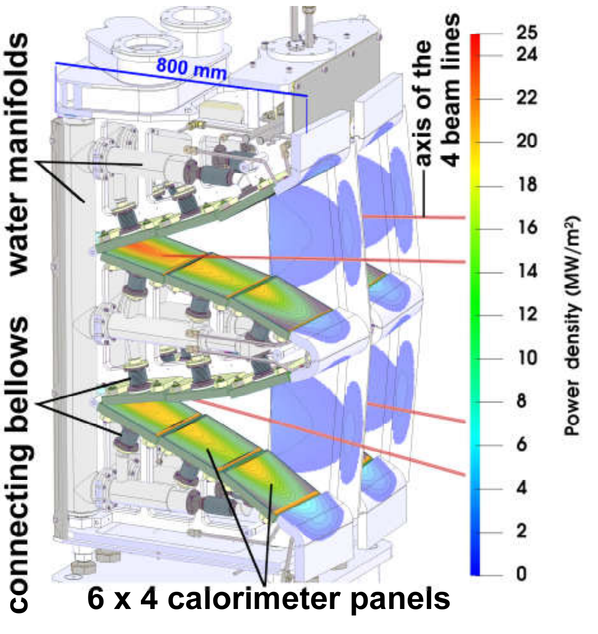

Figure 1: Top: NBI Calorimeter with the power load overlaid on the calorimeter plates.

2. Description of the existing CPs design

Each CP has dimensions of approximately 250 mm × 200 mm × 24 mm and is made out of the CuCrZr copper alloy. The plates are cooled by an embedded circuit of parallel cooling channels, connected to two inlet-outlet manifolds. They are built from different parts (in Figure 2): the casing (a) envelopes the rest of the parts and hosts the manifolds; the baffle plate (b), on which top surface the beam power load is deposited. The cooling channels are machined in the baffle plate bottom side; the intermediate plate (c) is located between casing and baffle plate and closes the cooling channels on the bottom side. The water inlet and outlet are connected to water piping through O-ring sealed stainless steel flanges (d) with flange rings (e), on the back side of the CP.

2.1. Properties of CuCrZr

The CPs are made out of a precipitation-hardened copper alloy, having high thermal conductivity (up to 80% that of pure Cu) and, high mechanical strength (ultimate strength $\sigma_u > 300$ MPa). Fatigue and creep resistance at high temperature (~400°C) are comparable to some steels [2]. To obtain such a condition a sequence of heat treatments is required: solution annealing at ~980°C for – 0.5 h) to obtain a supersaturated solid solution of CuCrZr, fast cooling to room temperature (quenching) and ageing at ~440°C for 2 h where Cr and Zr precipitate [2]. Large discrepancy with these thermal

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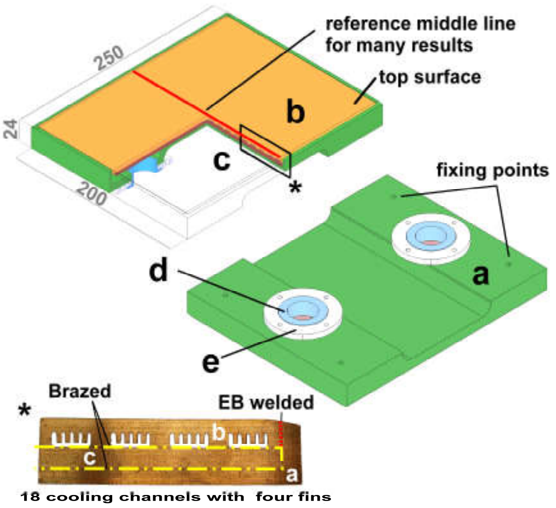

Figure 2: CAD model of the CP with indication of its parts and joining techniques

treatments, such as a too slow cooling down during quenching or too long-time exposure to temperatures over 400 ºC (over-annealing) leads to degradation of the material properties.

2.2. Subcooled boiling to enhance heat transfer

Each CP is intensively cooled by 3 kg/s of water flowing through a complex circuit of 18 parallel channels. Every channel has four fins to enlarge the wet surface. The average water velocity in the channels is ≈14 m/s and the heat transfer coefficient (HTC) is ~10^5 W/m^{2}K. The CPs rely on the subcooled boiling regime, where formation and condensation of small bubbles of vapor enhance the heat transfer into the water, however the heat flux at the walls of the channels must stay below the critical heat flux (CHF). The CHF can be conservatively estimated based on empirical correlations and experiment databases [3]. For the CP with the mentioned mass flow and the nominal operation conditions: static pressure of 10 bar, pressure drop of 6 bar and a maximum water inlet-outlet temperature difference of 70 ºC, a CHF of 47 MW/m^2 is calculated with the Tong-75 correlation for smooth circular pipes with the adjustment proposed by Boscary [4] for one-side, peaked heat load conditions; through the analysis of the relevant dimensionless numbers with experimental data.

3. Considerations on the existing CPs in view of the manufacturing of a new batch

The first batch of CPs for ASDEX Upgrade was produced in the late 80s based on similar CPs for earlier experiments. Its manufacturing combined electron beam welding (EBW) at the vacuum limiting boundaries (casing – baffle plate - flanges) and brazing for the internal junction between baffle and intermediate plate that forms the cooling channels. The brazing filler, silver, was applied through a galvanic coating onto the intermediate plate. Due to slow cooling-down after brazing, the properties of CuCrZr were degraded and the CPs were not able to fulfill the requirement of a lifetime of 25000 cycles. During operation, the CPs with the highest beam load deform plastically after just few beam shots and show a concave shape with a permanent displacement of a few tenths of millimeter in its middle. After hundreds of beam pulses, also the surface over the channels at the most heated regions starts bowing. This modifies the geometry of the channels and worsens the flow conditions, reducing the water flow at the central channel tips. Eventually several CPs have failed through deep cracks through the tips of the middle channels (see Figure 3) caused by low-cycle fatigue. On average the operation time of the old CPs is seven years or about 2500 cycles, a tenth of the design value. The CPs must therefore be periodically inspected and exchanged whenever any sign of fatigue shows up.

For the manufacturing of a new batch, a fully brazed solution is being discussed. The brazing should occur in a special vacuum oven with the capability of circulating an inert gas or nitrogen to cool down the CPs with a cooling rate of at least 0.5-1 °C/s in the interval 1000 - 480 °C. [2]. To gain understanding of the phenomena observed with the old CPs and eventually improve the design of the new CP batch, numerical simulations have been performed.

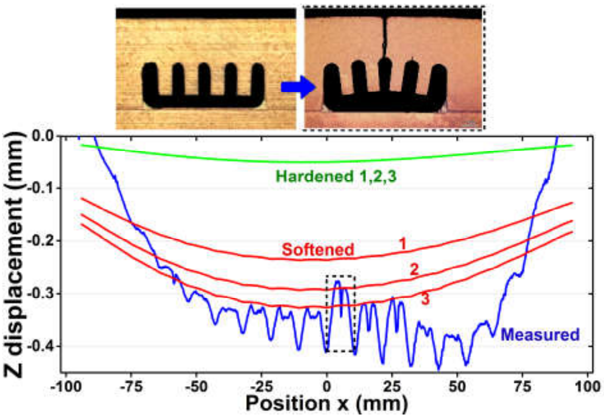

Figure 3: Vertical displacement for the cold CP with no water pressure along the middle line at the top surface, for a post-mortem measured CP and three simulated cycles for hardened and softened CuCrZr. The post-mortem analysis of the CPs evidences channel bowing and cracks, while channel bowing is revealed only for the simulated softened material.

4. Thermo-mechanical simulation of the CPs

4.1. Description of the modelling scheme

The numerical simulations are performed with ANSYS® workbench. Despite the geometrical symmetry, the CP is simulated as a whole, since the boundary conditions are not symmetric. The CP is fixed to an elastic support through one fix point and three sliding contacts. The water flows along the CP with increasing temperature (ΔT= 70 °C) and decreasing pressure (Δp = 0.6 MPa, p_{in} = 1.6 MPa). The power heat load is the one corresponding to the central CPs on Figure 1 with a maximum of 25 MW/m^2. A solid-fluid coupled simulation (conjugate convective heat transfer) is too resources-intensive for the whole CP geometry, so instead, one such simulation is performed for a single channel, to obtain a spatially resolved HTC along the channel that is then fed as input function for the whole

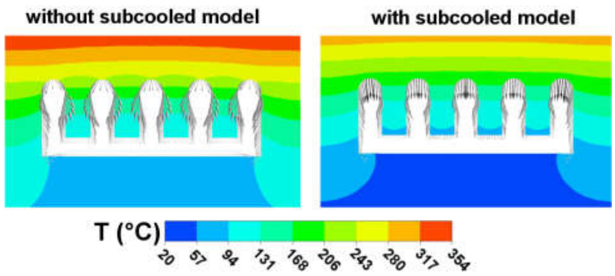

Figure 4: Temperature field around a CP cooling channel with and without considering the subcooled boiling. The heat flux at the walls is shown as a vector. At the channel tips reaches only 12 MW/m² when no subcooled boiling is modelled and 36 MW/m² if it is considered.

CP model. The solid-fluid coupled model cannot simulate the subcooled boiling, so a "workaround" has been used to include this effect by adding a multiplying term to the input HTC function. As soon as the wall overheating, the temperature difference between the wall and that of the saturated vapor at the local pressure 13 bar (~180 °C) goes over a custom threshold of 10 °C, the HTC function grows exponentially, mimicking the effects of subcooled boiling [4]: lower wall overheating (40 °C difference) and higher heat flux (factor three) due to formation of vapor (Figure 4).

The thermal and the elastic mechanical properties of the copper alloy for SAA condition are retrieved from the ITER Material properties handbook [5], assuming no difference between the hardened and softened (over-annealed) CuCrZr. However, for the cyclic plastic simulations performed to estimate the plastic deformation and the fatigue lifetime of the CPs, a non-linear kinematic hardening law (the "Frederick - Armstrong - Chaboche" model) is implemented for the hardened and softened (over-annealed) material conditions, with the parameters obtained experimentally by You [6].

4.2. Interpretation of the results for the old CP

The CP reaches thermal equilibrium less than two seconds after applying the beam power load. The maximum temperature is 419 °C in the middle of the top surface. The highest von Mises stress (for an elastic only simulation) is $\sigma_{vM} = 485$ MPa. This value is much higher than the yield strength ($\sigma_{Y0.2}$) of the material at the local temperatures ($\sigma_{Y0.2,\ T=420°C} = 205$ MPa), so plastic deformation would occur. In Figure 3 a measurement of the surface displacement of a failed CP is compared with the displacement values calculated at the same position by two FEM plastic models for the hardened and the softened CuCrZr and for three heating-cooling cycles. For both material models, after the first cycle, the CP presents a concave shape deformation. With the hardened material properties, after the first cycle no plastic deformation takes place, while with the softened material a larger concave shape deformation takes place and keeps increasing cycle after cycle in the three simulated cycles. Moreover, a local deformation, matching the position of the channels, occurs just in the case of the softened material. This is referred to as channel bowing.

An especially critical area is the tip of the channels, where the cracks where originated in the old CPs. The maximum total strain amplitude ($\Delta\varepsilon_T$) is calculated by FEM and by looking into specific fatigue diagrams (softened [7] and hardened [8]) the expected number of cycles is obtained. In the case of CP with softened material properties, $\Delta\varepsilon_T = 0.29$ % and this results in an estimated lifetime of 12500 cycles, while for the hardened material condition the CP reaches a maximum total strain amplitude of $\Delta\varepsilon_T = 0.23$ %, which roughly corresponds to a lifetime matching the design value of 25000 cycles. The large discrepancy with the real CP lifetime is likely caused by side-effects of the plastic deformation of the channels (channel bowing), that implies an adverse water flow close to the tips of the channel and consequently worse cooling effect and thus a different stress-strain condition.

5. Improved CP new design for increased reliability

A series of design changes are studied to reduce thermo-mechanical stress and strain together with temperature and therefore increased reliability of the CPs. The design is also simplified and made more compatible with the brazing joining technique.

5.1. Geometry modification

The mass is reduced 20 % (from 6.6 to 5.3 kg) through overall slenderizing walls and cross-sections and therefore allowing the panel to further elastically bow under the heat load and reducing plastic deformation. The new V-shaped water manifolds also contribute to make the CP more flexible, still ensuring adequate water distribution into the cooling channels (comparison sketch in Figure 5). Elastic FEM simulations show that with the new geometry the maximum σ_{vM} is reduced by 19 %, at the top surface and by 40 % at the channel tips, while the maximum elastic strain at the channel tips is lowered almost by 50 % (two first rows in Table- 1).

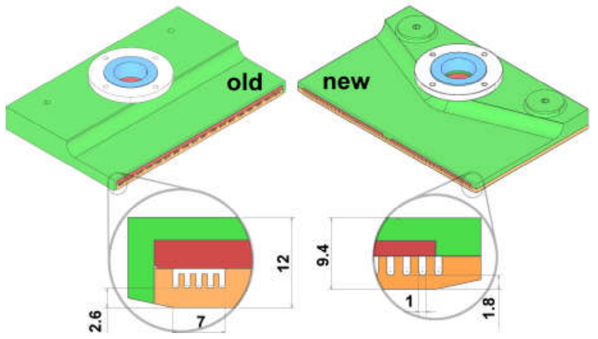

Figure 5: CAD models comparison of the old and the new CPs. The new CP incorporates all the suggested improvements.

Table- 1. Summarizing results of elastic mechanical calculations for the new CP geometry and TOC variation. As reference the old CP results (first row).

TOC (mm)	Max Temp (°C)	$\sigma_{vM\,max}$ top (MPa)	$\sigma_{vM\,max}$ c. tip (MPa)	$\varepsilon_{el\,max}$ c. tip (%)
2.6 **Old**	419	485	406	0.35
2.6 **New**	403	395	250	0.2
1.8	340	357	153	0.12
1.4	313	338	153	0.12

5.2. Reduction of the material thickness over the channels

The maximum panel temperature can be effectively lowered by reducing the material thickness over the channels (TOC). Three different TOCs are compared: the original 2.6 mm and two modified values: 1.8 mm and 1.4 mm. Maximum temperature decreases with decreasing TOC by 85 °C/mm thickness reduction (Table- 1). The impact in the elastically calculated stress field is a further reduction of the maximum σ_{vM} by 10-15% at the top surface and by 40% at the channel tips. Since the difference of maximum stress for TOC = 1.8 and 1.4 mm is small and since it is likely that a few tenths of mm of CuCrZr will be sputtered away from the surface during the CP lifetime, 1.8 mm has been chosen.

5.3. Single channel geometry

An additional measure still under discussion is changing the shape of the channels into equally spaced single channels (Figure 5 bottom right). The channels are dimensioned to improve the heat transfer while keeping the same pressure drop, flow speed, inlet-outlet water ΔT for the same mass flow of 3 kg/s. The equidistant channel spacing distributes the heat flux into the water more homogeneously; the baffle plate has better contact (50% larger contact area) with the intermediate plate, contributing to further reduce the temperature of the CP. At the channel tips, the maximum heat flux would lay ≈20% below that of the side channels of the old comb-like geometry (Figure 6), increasing the safety margin to the reference CHF. Furthermore, the wider channel promotes higher water speed and turbulence in the region close to the channel tips, in theory increasing the CHF of the new channel geometry [3].

5.4. Results and comparison with the old CP

With the new geometry, thermo-mechanical stress is cut down by at least 25% compared to the old CP.

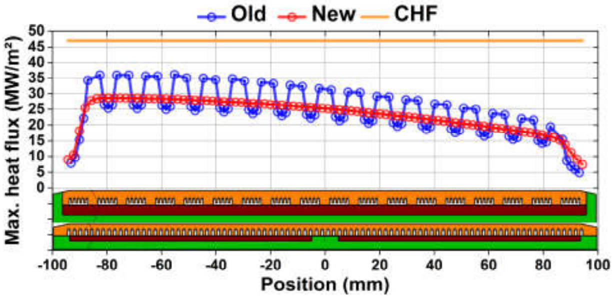

Figure 6: Maximum heat flux at the tip of each of the 90 cooling channels for the comb-like and the single channels. As reference, the theoretical CHF from the design of the old CP.

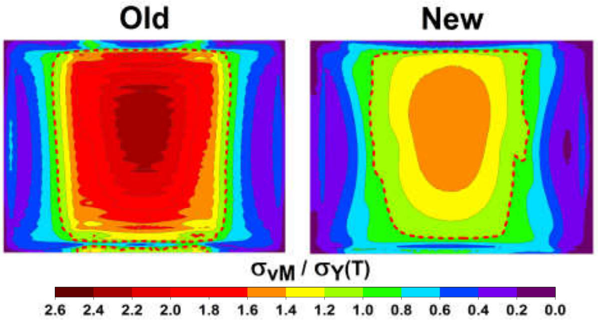

Figure 7: CP top surface plots of calculated σ_{vM} to yield strength ratio. Inside the red dotted line plastic deformation occurs during operation.

Through reduction of the TOC, the maximum temperature is decreased by ≈80 °C. The lower temperature improves the mechanical strength of CuCrZr so a smaller portion of the panels will plastically deform and the maximum ratio of the calculated von Mises stress to local yield strength is reduced from 2.5 to 1.5 (Figure 7). Plastic deformation always occurs, but only in the first cycle in case of hardened CuCrZr after brazing (Figure 8). The stress reduction at the channel tips results in a maximum $\Delta\varepsilon_T = 0.2\%$ and in an expected CP lifetime of 70000 cycles (estimated from [8]). On the other hand, with the softened CuCrZr, the CPs would continue to plastically deform cycle after cycle but at a slower pace than the old CPs. However, after three simulated cycles there is not a clear evidence of channel bowing occurring for the single channels as for the comb-like ones. At the channel tips, the maximum calculated $\Delta\varepsilon_T$ is 0.1% which results in a CP lifetime of 56000 cycles (from [7]).

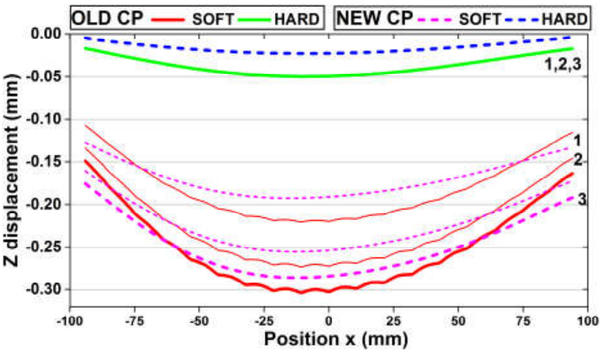

Figure 8: Vertical displacement along the path perpendicular to the channels for the old (as in Figure 3) and new CPs with hardened and softened CuCrZr.

6. Conclusion and outlook

For the manufacturing of a new batch of CPs, an improved geometry is proposed and compared by numerical FEM simulations with the old CP. Overall stress is reduced by 25 % as the maximum temperature is decreased ≈80 °C. Plastic deformation will still occurs but is reduced compared with the old design and lifetime is expected to be at least a factor of two larger than the design value independently of the quality of the CuCrZr obtained after brazing the CPs.

The final design review of the new CP batch is ongoing with discussions with contractors. First prototypes should be ready soon for testing and qualifying the manufacturing. Among metallurgical examination, vacuum leak tests; further testing in a high flux facility is planned in order to get as close as possible to the working conditions for a representative amount of cycles.

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