A hot steam leak during baking of ASDEX Upgrade – consequences and lessons learned

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ASDEX Upgrade is a midsize tokamak operated since 1991. A scheduled maintenance and enhancement shut down is done about once a year. After pump down and leak search a baking procedure is started to condition the vacuum vessel for plasma operation. During operation the vacuum vessel and all in-vessel components are water cooled. This cooling system is also used for baking with hot water at 150°C. During one of these regular baking periods a hot steam leak appears in November 2017. The detection of the leak has triggered a controlled cool down scenario. Nevertheless, between the appearance of the leak and the identification and closing about 100 l water escaped during the controlled cool down from 150°C to 65°C into the torus. A fraction of the hot water was distributed as steam all over the torus and condensed at the coldest parts of the vessel, preferentially in remote ports. In addition, the steam interacts with boron containing layers. The resulting acid steam caused additional erosion.

The paper presents details of damages, actions taken to remove them as well as measures taken to avoid a future steam leak.

Keywords: ASDEX Upgrade, steam event, vessel baking, safety

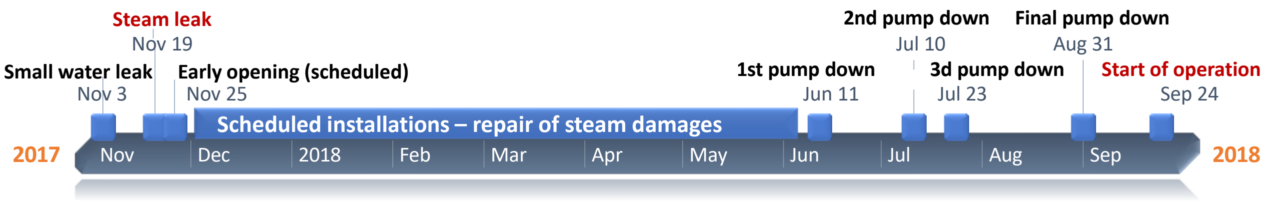

Fig. 1 Chronology of the steam event, the shutdown and restart.

1. Introduction

ASDEX Upgrade is a midsize tokamak operated since 1991[1]. A scheduled maintenance and enhancement shut down is done about once a year. After pump down and leak search a baking procedure is started to condition the vacuum vessel for plasma operation. During operation ASDEX Upgrade is water cooled with two separate cooling circuits for the vacuum vessel and all in-vessel components, respectively. This cooling system is also used for baking with hot water at 150°C at 12,5 bar.. During one of these baking periods a hot steam leak appeared in November 2017. The detection of the leak has triggered a controlled cool down scenario. Nevertheless, between the appearance of the leak and the identification and closing about 100 l water) escaped during the controlled cool down from 150°C to 65°C into the torus. A fraction of the hot water was distributed as steam all over the torus and condensed at the coldest parts of the vessel, preferentially in remote ports. In addition, the steam interacts with boron containing layers. The resulting acid steam caused additional erosion [2].

After opening the vessel for man-access salt like remnants and rust were identified.

This paper reports on the damages, the actions to re-establish operation and the measures taken to avoid future steam events.

2. Steam event

2.1. Chronology

In November 2017, a small water leak occurred during plasma experiments at the divertor manipulator (DIM-II) at about 70°C (Fig. 1). About 10 liters of water were found in the lower divertor region nearby the location of DIM-II. Removing the water and drying required man access for 2 days. After closing the vessel, the routine restart for vessel conditioning was started - leak testing followed by baking the vessel at 150°C for about a week, depending on the water partial pressure. After about 3 days baking, a small water leak was detected and the controlled cool down with about 6K/hour was started. A low cool down rate is used to allow temperature equilibration between different sections and in-vessel components, mainly for thermo-mechanical stress reduction. The chronology of the baking is shown in Fig. 2.

Unfortunately, during the cool down at about 90°C, the water leak was enlarged. After detecting a significant loss of water from the reservoir, the in-vessel water baking system was switched off at about 65°C. The amount of water escaped into the vessel was estimated from the loss of water from the water reservoir to about 100 l.

The steam event happens about two months before a scheduled opening so that the damage repair and the scheduled work could be done in parallel, as indicated in Fig. 1.

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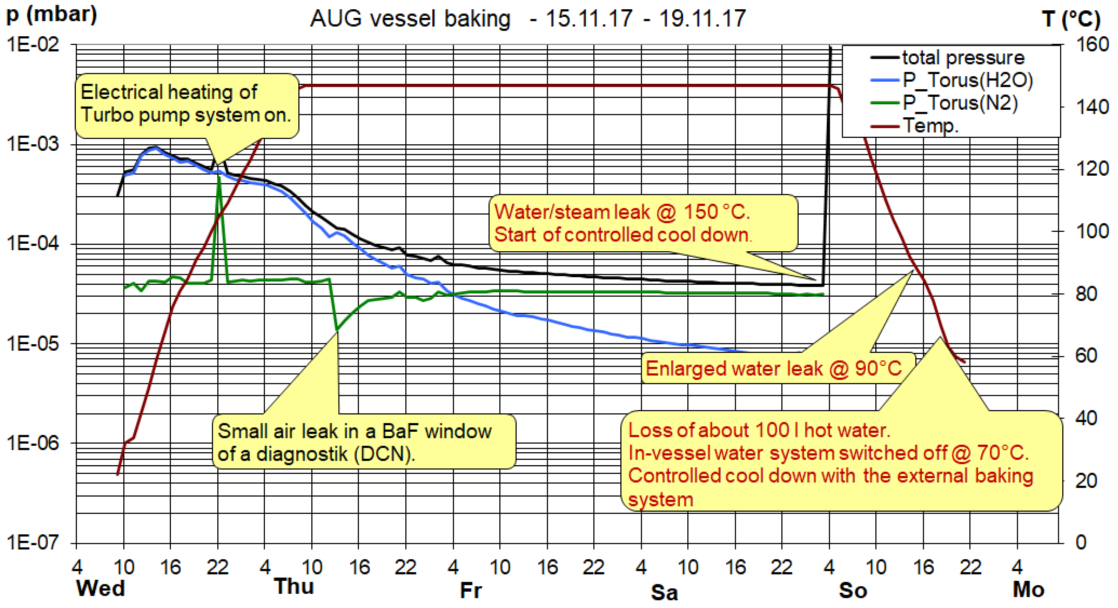

Fig. 2 Chronology of the steam event.

2.2. Steam event - findings

A first look onto the vessel and the large vacuum windows after entering the experimental hall has already shown the problem. A fraction of the hot water was distributed as steam all over the torus and was condensed at the coldest parts of the vessel.

Venting and opening the vessel for man access gave a first insight in the consequences of the steam event:

- Condensed water all around the torus, preferentially in (colder) remote parts.
- Salt like remnants originating from the interaction of the steam with deposited layers resulting from plasma wall interaction and boronization [3] of the first wall. During the experimental campaign 2017 about 60 g of boron was deposited onto the inner surface of about 50 m^2.
- Rust, in particular around welding seams.

2.3. Steam event – origin

A small copper seal deep in an NBI-port duct was identified as the origin of the leak. The NBI port duct is water cooled to remove the heat due to reionization losses in the duct. The VCR® (metal gasket face seal) like seal was hidden behind a protection plate Fig. 3. It was never touched over more than 10 years and more than 26 baking cycles.

Microscopic inspection revealed strong erosion of the copper seal and a gap causing the leak, see Fig. 3 and Fig. 1 in [2]. The erosion of the copper is attributed to the acidic pH-value of pH=5 found by analysing the water from the baking circuit.

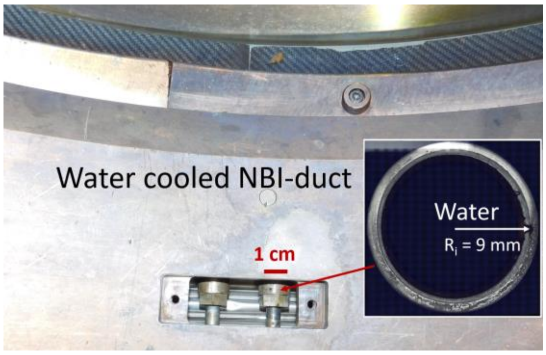

Fig. 3 (left) VCR® (metal gasket face seal) like seal in the NBI duct cooling pipes behind a protection plate (removed), (right) photo of the Cu-seal and the leak location (arrows).

Acidic water is not used by intention. Usually deionized water is used for the cooling of the in-vessel structure to ensure a low electrical conductance of the water. A conductance below 5µS/cm is required to avoid an electrical by-pass over the insulating gaps installed in the water circuits to minimize forces due to electrical currents induced during disruptions. Unfortunately, the deionized water reacts with CO_2 from air at the baking temperature of 150°C.

3. Actions and repair work

The in-vessel inspection and the identification of the leak revealed that:

1. Water can be anywhere in the vessel. Remote components can be particularly affected.
2. All cooper seals in the water circuit might suffer from erosion.

As a consequence, the lower and upper divertor as well as the protection tiles of the inner column were disassembled to replace all copper seals in the in-vessel water cooling system and to give access to remote areas for inspection and cleaning (magnetic pick-up coils, vacuum bellows).

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During baking all valves between the AUG vessel itself and diagnostics with a separate pumping systems are closed. The ECRH valve for the ECRH window protection was open. The steam was condensed at these remote regions near to the vacuum barrier.

Before the dedicated refurbishing of diagnostics and other remote components was started, the main vessel was cleaned by using a combination of steam and vacuum cleaning. This way salts and other remnants could be removed, whereas the rust removal was supported by mechanical methods, see Fig. 4.

Fig. 4 (left) Combination of steam and vacuum cleaning. (right) Situation before and after the vessel cleaning.

3.1. ECRH damages and repair.

Between the gate valves and the ECRH-windows, short Aluminum wave guide sections are installed as inserts into the stainless-steel ports. The intermediate volumes were filled with aggressive water. Six systems had to be completely disassembled up to the gate valves. Fortunately, the copper brazings of the diamond windows did not show signs of erosion nor did the absorption at 140 GHz of the diamond change significantly. Corrosion was observed in the gate valves, the inserted Al wave guides and some in-vessel gearings. These were only cleaned, not replaced.

3.2. Refurbishing of vacuum valves

A significant amount of water and salts were detected inside diagnostic ports and the corresponding valves. To refurbish the components the adapter between the AUG vessel and the corresponding diagnostic was disassembled to get access to the valve corpus. The components were steam and vacuum cleaned, dried and reinstalled. A typical installation is shown in Fig. 5

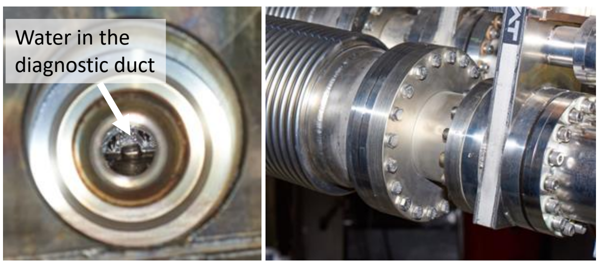

Fig. 5 (left) View into a diagnostic port with a closed valve showing condensed water. (right) External view to the diagnostic tubes and the valve for diagnostic separation.

3.3. Flanges with electrical feed troughs

Nearly all flanges used for electrical signals in particular for bolometer diagnostics and vessel protection systems, such as thermocouples and strain gauges were inspected. A typical finding is shown in Fig. 6. The steam was interacting with layers and deposits of the vessel and the condensed water was polluted by boron and boron salts. This aggressive water has dissolved Molybdenum pins of the vacuum feed-through and results in leaks in many flanges. For refurbishing, the flanges were disassembled, afterwards sand-blasted, cleaned in an ultra-sonic bath, dried and finally leak tested. This procedure was applied to more than 85 flanges. 25 out of them showed a leak and were replaced by new ones.

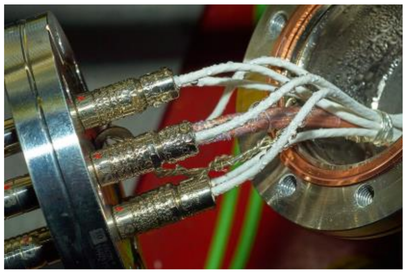

Fig. 6 Flange with electrical feedthroughs before cleaning.

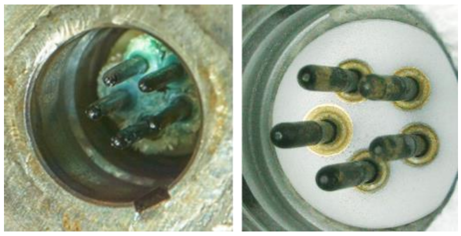

Fig. 7 (left) 5 pin electrical feed through showing the corrosion at the Molybdenum pins (see also fig. 4 [2]). (right) Refurbished feed-through.

3.4. Rust

AUG is made from stainless steel and rust is initially not expected. Nevertheless, it was found on both sides of welding seams where the material structure is modified due to the welding. Rust was predominantly found in the pump ducts (Fig. 8) that were manufactured by a company different from the vacuum vessel manufacturer.

Fig. 8 Rust at both sides of a welding seam in a pump duct.

More critical was the existence of rust in the lower part of the 1.2 mm thin bellows of the vacuum barrier connecting the eight otherwise electrically insulated AUG octants (Fig. 9). Pitting corrosion could result in a leak in a component that can't be replaced. The rust was

detected occasional in folds of the bellows and not at the welding seems itself. The origin were small particles laying in the bottom of the folds. SEM analysis of particles reveals that they contain iron, either in metallic or oxidic state. The source of these small particles was identified. They were fallen down during an installation/drilling years ago.
In these places the particles were taken out and the rust was mechanical removed, followed by cleaning with purified water and drying. This way the rust could be removed completely as shown in Fig. 9.

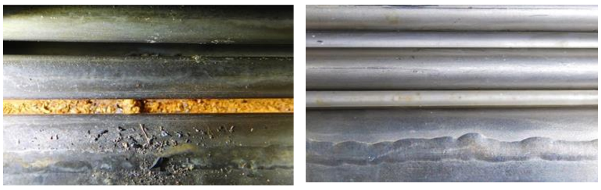

Fig. 9 (left) Bellow with deposited rust in a single fold. (right) Bellow after refurbishing.

Pitting corrosion cannot be completely excluded for the remaining rust in pump ducts that are not, or only with huge effort, accessible. That's why a few flanges were identified that will be opened at the end of scheduled shut downs to monitor a potential pitting corrosion. Control inspections done during the two subsequent shut downs revealed no further evolution of rust.

4. Restart

After more than six-month shutdown used for new in-vessel installations and refurbishing components damaged by the steam event, the vessel was closed and pumped down. This first pump down revealed significant leaks in the order of $5x10^{-2}$ mbar.l/s. The leaks were caused by flanges with Helicoflex seals. Standard seals are CF-seals at AUG. Helicoflex seals are used for the large rectangular horizontal port flanges. But they were also used during the assembly of AUG to extend the upper and lower vertical ports. Such, the vacuum barrier was moved to a position outside the poloidal field support structure. These extensions tubes were assembled before the poloidal field coils and their support structure. The Helicoflex seals were never touched after AUG came into operation in 1991. The access, in particular to the inner most flange is only possible through a 10 cm wide gap, whereas the flange itself is about 80 cm below the support structure. Tools with extensions were used to open the flanges and to inspect and remove the seals (see Fig. 10). Afterwards the flange surfaces were cleaned and polished using extensions. In addition, the Helicoflex flange at the extension tube was modified to provide a narrow sheet metal strip that holds the gasket in position during assembly.

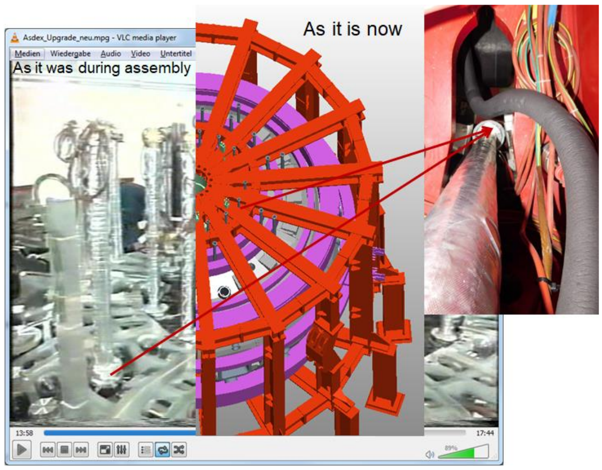

Fig. 10 (left) Top view of AUG during assembly, before the installation of the poloidal field coils and the support structure. The long extension tubes are already mounted. (middle) CAD view with the poloidal field support structure. The critical ports are placed inside the inner triangles with about 10 cm gap size. (right) Photo of the real situation on top of AUG.

The Aluminium material of the Helicoflex seals show a strong erosion resulting in pitting, as shown in Fig. 11. The vertical ports at AUG are mostly used for electrical cables but also for optical fibres. Whereas electrical cables can be disconnected at the flange, optical fibres cannot. Removing them would require man access to the vessel. Instead of replacing all Helicoflex seals, seals with leaks were identified and replaced iteratively until the leak rate was below $1e^{-7}$ mbar.l/s. Three pump downs and the replacement of 23 seals were necessary (see Fig. 1).

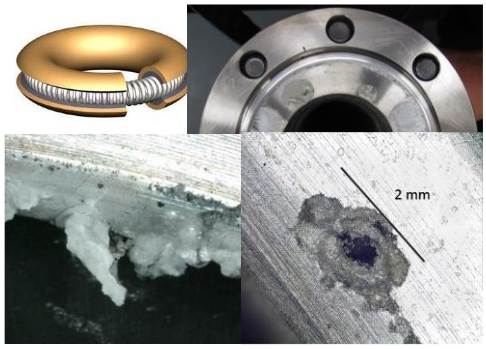

Fig. 11 Helicoflex seal. (clockwise, starting upper left). Scheme of a Helicoflex seal, Flange showing deposits, microscopic picture of a seal with whole and deposited salt.

The third pump down was also used for a short baking to make sure that the thermal expansion due to the baking is not causing additional leaks at pre-damaged non-replaceable seals.

The good vacuum after the third seal replacement cycle allowed detecting leaks in the $1e^{-7}$ mbar.l/s range. At this leak level 4 essential feed throughs for magnetic diagnostics were identified as to be replaced due to leaks. Preparing the new flanges and installation required about a month. The 'final' pump down was started at the end of August 2018. After baking, first technical discharges were performed mid of September.

About 6 flanges with a tolerable leak rate were replaced later during the shutdown in 2019.

5. Actions to avoid and mitigate future steam events

Different measures were taken and operation procedures were modified to avoid steam events, or at least to mitigate the effects in future.

Erosion of copper seals will be minimized by increasing the water pH to pH = 8.5 by adding NaOH during baking.

The pressure for the routine leak testing before the infill of water will be increased from 10 bar to 20 bar.

A leak during baking at elevated temperature cannot be generally excluded. To mitigate the consequences the control logic was modified. In case of a leak the baking of in-vessel components will be stopped if a pressure increases to about $p \approx 10^{-1}$ mbar is detected. Subsequently, the in-vessel water-cooling system will be emptied and the vessel will be cooled down by using the external vessel cooling only. Venting the torus to 500 mbar N_2 forces the cooling of in-vessel components by heat convection.

In case that steam escapes into the vessel, it will be dried by pumping and purging shortly after the event.

6. Summary

A steam event happened about two months before a scheduled opening due to a water leak during baking.

That the event happens before a scheduled opening was a stroke of luck, as the repair work could be carried out in parallel with the planned enhancements work.

The regular restart required three additional months to identify and fix leaks caused by erosion due to the steam. About 8 months shutdown were necessary to recover from the failure of a small copper seal in an NBI port.

A water leak event, and in particular a steam event, is the concern for the reliable operation of fusion experiments and adequate measures to mitigate the risk are taken, see e.g.[4]. For AUG new measures have been defined to minimize the risk of a steam event and to prevent damages in future:

- The pH value of the hot water will be increased to pH = 8.5 to avoid Cu erosion.
- The reaction on a steam event is optimized to reduce the amount of escaping water.
- Prompt conditioning/drying of the vessel is recommended to avoid further erosion in remote areas during the shutdown period.

No additional leaks due to erosion were observed during the following experimental campaigns and shut downs.

Acknowledgments

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References

[1] A. Herrmann, (Guest editor), Special Issue on ASDEX Upgrade, Fusion Science and Technology, 44 (2003) 1-747.

[2] V. Rohde, A. Herrmann, M. Balden, D. Bösser, K. Hunger, G. Schall, M. Uhlmann, T. Vierle, Recovery from a hot water leakage at the tokamak ASDEX upgrade, Fusion Eng. Des., 157 (2020) 111630.

[3] V. Rohde, R. Dux, A. Kallenbach, K. Krieger, R. Neu, Wall conditioning in ASDEX Upgrade, Journal of Nuclear Materials, 363-365 (2007) 1369-1374.

[4] A. Martinez, F. Samaille, M. Chantant, J.C. Hatchressian, Water leak localization and recovery in Tore Supra, Fusion Engineering and Design, 82 (2007) 1989-1995.