Adoption of the ASDEX Upgrade pumping to Hydrogen released by an in-vessel cryopump

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Detached divertor scenarios at ASDEX Upgrade (AUG) need high gas fluxes, which are mainly pumped with the gas binding in-vessel cryopump (CP). To cope with the large quantities of hydrogen released from the CP during regeneration, a hydrogen compatible pumping system (HCPS), which is built to comply with safety regulations for explosion protection, has been built up in parallel to the already existing gas transfer pumping system (TPS). The amount of gas injected in the vacuum vessel (VV) is limited by an additional volume added to the gas inlet system. A fully automated procedure has been implemented for comprise with safety regulations. This includes daily tests of the components and communications with other relevant systems.

Keywords: ASDEX Upgrade, Pumping system, Hydrogen, Safety regulations

1. Introduction

For high power plasma scenarios, it is crucial to operate the divertor in a detached regime. This requires a high gas flux and therefore a high pumping speed in the divertor region. The ASDEX Upgrade (AUG) liquid helium cooled in-vessel cryopump (CP) [1] specifically designed for this purpose provides a pumping speed ≈10 times higher compared to the gas transfer pumping system (TPS) installed in parallel [2]. About 90% of the gases puffed for plasma operation is condensed on the cryogenic surfaces and built up an inventory inside the vacuum vessel (VV). Under the previous operating licence, single experiments were not allowed to exceed the inventory of 400 kPa*l. This consequently requires very frequent regenerations and limitations in feasible plasma scenarios. This paper describes the technical concept of extending the inventory from 400 kPa*l to 20 MPa*l, in order to enable high density plasma scenarios, taking into account safety regulations for explosion protection.

2. Safety concept

During AUG operation, mainly the hydrogen isotopes deuterium (D_2) and protium (H_2) are used. The explosion range is between 6.7 and 79.6 vol-%. (D_2) respectively 4.0 and 77.0 vol-% (H_2) in air. Technical devices used in the presence of explosive atmosphere of these conditions have to fulfil the ATEX directive (**AT**mosphère **EX**plosible) 2014/34/EU for the explosion group IIC and temperature class T1 [3]. A resume of the safety regulations concerning explosion protection for hydrogen and the classification concept is given at [4].

The safety considerations comprising the AUG gas inlet system (GES), the VV and the TPS, which are operated with very different pressures. The GES is operated in a pressure range between 400 kPa and 20 MPa. The VV enables pressure down to 10^{-5} Pa and withstands a pressure of 120 kPa. The TPS operates from 10^{-5} Pa to atmosphere.

The GES generally provides hydrogen, noble gases, nitrogen and for diagnostics also other burnable gases (e.g. methane) at a pressure above atmospheric pressure in industrial pure gas grade. The use of oxygen is omitted and not foreseen with the technical set-up. All components are specified to comply with the used gas species, all tubing is metal sealed or welded. Once a year tightness is inspected by pressure drop or vacuum test. All components are installed in fire prove ventilated cabinets. For technical reasons, air ingress inside the GES is not possible and therefore the hydrogen concentration is always above the upper explosion limit. Only within the GES pumping system for evacuating tubes (e.g. for a change of gas species), pressures below atmosphere are reached and therefore ingressed air may produce explosive atmosphere with hydrogen (see chapt. 5).

The AUG VV which is not designed to withstand inside pressures significantly above atmosphere and is equipped with many specialized diagnostics, not designed to fulfil the ATEX regulations. During the assessment process, which was carried out with support of the DEKRA Testing and Certification GmbH (DEKRA), it turned out that it is sufficient to limit the concentration of deuterium below the lower explosion limit. For this reason the total amount of flammable gas within the VV, has to be limited to 20 MPa*l (see chapt. 5), equivalent to a deuterium concentration of D < 25 % of the lower explosion level. This amount of gas allows up to 20 high density discharges, i.e. one experimental day. Indeed this limit has not been reached within the last 2 years of operation.

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Due to the complexity of the VV with all the diagnostics installed, the vacuum tightness has to be tested before each operation day. This is done by controlling the base vacuum reached. The total amount of flammable gases that can be injected in the VV, also in a failure condition, is limited by an additional volume [Figure 5]. This was installed in the GES and contains only the hydrogen for one experimental day. During a plasma discharge about 10% of the injected gas is pumped by the TPS. This amount is low enough to be neutralised by nitrogen purging at the rough pumping stage in the rotary vane pumps. Nevertheless, for safety considerations, it is assumed that all hydrogen is pumped and trapped at the CP.

The safety problems for the TPS arise at pressures above 5 kPa. To allow plasma operation during the forming of a hydrogen layer at the CP, a complete new hydrogen compatible pumping system (HCPS) was installed [Figure 2]. This way, only minor modifications of the existing TPS were necessary. Hence it was available for experiments all the time. The HCPS is certified for the use with hydrogen gases. The following chapters 3 and 4 describe this new system.

For AUG licencing reasons all exhaust gas has to be drained via the vent stack, which therefore is used by other plant systems. The exhaust of the HCPS is inerted by purging with a 19 times higher nitrogen gas amount [5] directly into the exhaust line next to the pump so that the limiting oxygen concentration is underrun. By entering the vent stack, the hydrogen concentration of the exhaust gas underruns the lower explosion limit because of the large amount of exhaust air in the vent sack.

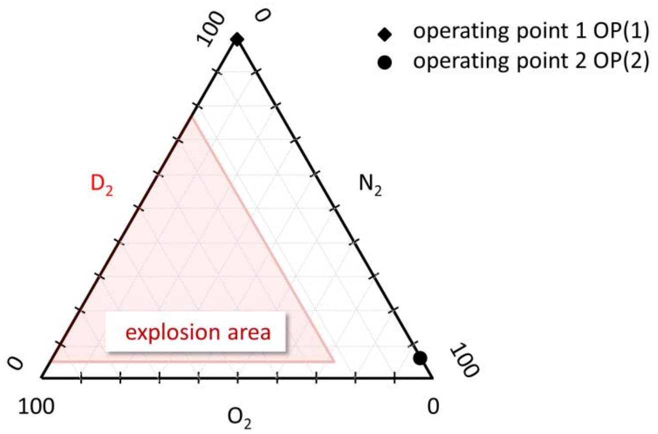

Figure 1: *This ternary diagram shows every possible composition of D_2, N_2 and O_2. The red area indicates the explosions area of these three components. During regeneration the operating points at AUG are OP(1) (between the torus and the DV650 pump) and OP(2) (between the DV650 pump and the vent stack). Both operating points are nowhere near the explosions area.*

All safety functionality is realized in the control program, which ensures that hydrogen is only pumped by the HCPS. Additionally the functionality of the components has to be tested before the start of plasma operation.

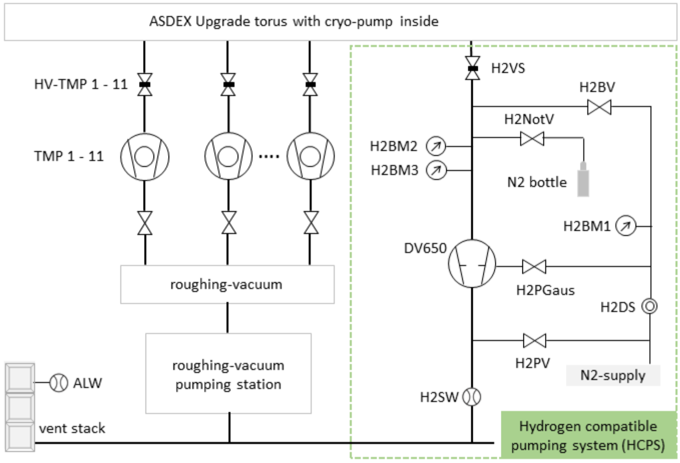

***Figure 2**. The HCPS and its integration into the AUG torus pumping system*

3. Hydrogen compatible pumping system

The HCPS can be divided into two main subsystems: the vacuum system and the inerting unit. The HCPS operates fully automated and is controlled by the TPS PLC (programmable logic control).

For vacuum generation, a dry screw pump, which fulfils the requirements for category 2G according to ATEX directive 2014/34/EU [3] and for gases of the explosion group IIC and temperature class T2, was selected. The pumping speed of this pump is up to 650 m^3/h and it reaches a final pressure of 0.5 Pa.

Given the intrinsic non-availability of ATEX-certified pressure measurements in the pressure range below 100 Pa, two capacitive gauges were installed, which cover the pressure range from 100 kPa to 0.05 Pa through a master-slave architecture. The pressure range between 100 kPa and 100 Pa, relevant in terms of explosion prevention, is covered by an ATEX-certified capacitive gauge H2BM3 [Figure 2]). Below a pressure of 100 Pa a capacitive gauge H2BM2 (1 kPa full range) is switched on, and takes over measurement. The vacuum system can be separated from the AUG VV with a gate valve (H2VS). The nitrogen required for inerting the HCPS is supplied by a 6 m^3 liquid nitrogen tank via an evaporator, also providing gaseous nitrogen for other devices in the torus hall. The piezo gauge H2BM1 as well as the pressure switch (H2DS) surveil whether the inlet pressure is sufficient for purging the line segments on the exhaust side of the HCPS.

Four AUG plant sections are involved in the regeneration process: the TPS, the GES, the CP and the diagnostic gate valve control (SST). All these systems are controlled by an individual PLC, which exchange data over a common network. The AUG experiment control system (SLS) enables data exchange between most of the PLCs used on AUG, but does not perform any control tasks here [Figure 3].

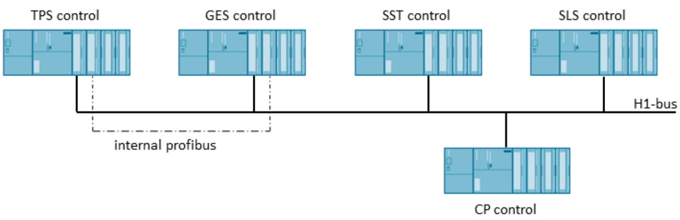

Figure 3. *Five networked PLCs work on the complex sequence control during regeneration*.

4. Operational procedure

Before starting AUG operation, the entire vacuum system, the inerting unit and the liquid nitrogen supply are inspected by a fully automated functional test. If the proper condition is ensured, the TPS PLC generates a safety token, which is passed on to the SLS via the H1-bus system [Figure 3]. This token is the basic prerequisite for permission of experiment operation. The torus pressure is measured and the technical tightness of the recipient is verified, if the average torus pressure is $1*10^{-4}$ Pa. The purge unit is checked for 90 seconds to ensure that the HCPS can be sufficiently inerted on the exhaust side.

As a central safety feature, a locking matrix was developed in cooperation with DEKRA. This matrix describes the behaviour of the HCPS in case of failure of technical components and defines how the system must then be brought into a safe state. The interlocks are implemented in the TPS PLC program.

The CP is monitored by the CP PLC throughout the experiment day. Primarily, temperatures of the cryo-panel as well as mass flows of the cooling fluids liquid nitrogen and liquid helium are continuously measured and compared to reference values. In case of deviations, the CP PLC sends an error signal to the TPS PLC and SST PLC. The TPS PLC closes all torus gate valves, to prevent that evaporating inventory is pumped by the TPS turbomolecular pumps.

The CP is generally regenerated at the end of the experiment day. In the first step, the exhaust gas line of the HCPS is purged with nitrogen. The thermal mass flow limit switch H2SW simultaneously monitors the gas flow to be above limit. The exhaust gas flow in the exhaust stack is controlled with a flow limit switch.

After this pre-check, all torus and diagnostic gate valves are closed and the Bayard-Alpert pressure gauges for measuring the torus high vacuum (TMI 2, TMI 5, TMI 10, and TMI 16) are deactivated. After the TPS PLC received confirmation of availability from these components, the torus is given clearance for regeneration. Simultaneously, the CP PLC starts to warm up the CP (i.e. to reduce the liquid helium flow) and the GES puffs helium into the torus for 2 seconds under timer control to increase the pressure to ≈0.4 Pa [Figure 4, t(1)]. Therewith the CP is coupled thermodynamically much better to the VV and evaporation of the frozen inventory is significantly accelerated [Figure 4, t(2)].

After about 4-6 minutes, the hydrogen inventory of the CP is released into the torus. Based on the liquid helium panel temperature measurements the CP PLC generates a "regeneration finished" signal, which is sent back to the TPS PLC. The TPS PLC calculates an "expected regeneration pressure" value (see chap. 5). As soon as the “expected regeneration pressure” corresponds with the actually measured torus pressure and the CP PLC provides "regeneration finished" signal, the gate valve H2VS is opened and the torus is evacuated via the HCPS down to a pressure threshold ≤ 2 Pa. With this the TPS PLC closes the gate valve H2VS and opens the 11 HV gate valves of the TPS [Figure 4. t(3)].

To flush out residual concentrations of hydrogen, the HCPS is inerted for 90 seconds with nitrogen via the purge valve H2PV. Finally, the H2BV flooding valve opens for 10 sec. After this, the HCPS is free of hydrogen and the CP regeneration process is completed. This also deletes the security token, resets the automated inventory balancing system (see chapt. 5) and refills the intermediate volume at the GES.

5. The intermediate volume at the gas inlet system

A simple method for verifying the regeneration process of the CP is to calculate the expected pressure in the VV after regeneration from the amount of gas injected. The GES has a

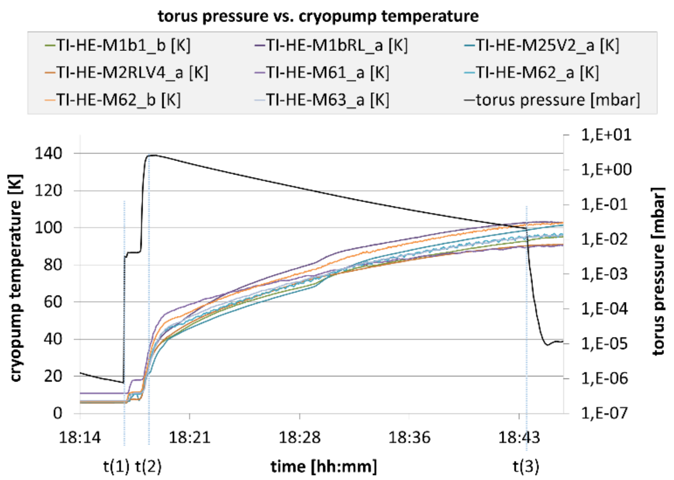

Figure 4. *The pressure curve in the torus during regeneration and several temperature curves of the CP.*

fully automated inventory balancing system, which allows recording the amount of H_2 and D_2 injected into the torus. This balancing is based on the following correlation for the inventory I.

$$I = (p_0\,(H_2) - p_1(H_2)) * 10 + (p_0\,(D_2) - p_1(D_2)) * 10 \quad (1)$$

The pressures *p* represent the pressures DS01L and DS01R [Figure 5] at the beginning (p_0) and at the end (p_1) of the experiment day respectively. The factor 10 results in each case from the capacity of the gas cylinder in the intermediate volume (see chap. 3). With the VV known volume V, the expected pressure $p_{expected}$ is

$$p_{expected} = \frac{I * 1 * 10^5}{V}\ [Pa] \quad (2)$$

As anticipated in chapter 2, the total amount of flammable gas (H_2, D_2) within the VV has to be limited to 20 MPa*l. From (1), with the known AUG VV volume of 40.000 l and a hypothetically assumed release of the entire hydrogen inventory of the CP results in a torus pressure $p_{expected}$ of 500 Pa.

With the technical design of the intermediate volume, it must also be taken into account that other plant components can also release hydrogen (H_2, D_2) or other flammable gases into the torus, e.g. pellet centrifuge, neutral beam injection and massive gas injection. Therefore, the maximum permitted total inventory was divided as follows:

- GES: 14 MPa*l (H_2 + D_2)
- Other plant components (see above): 4 MPa*l
- Tolerances and future developments: 2 MPa*l

The intermediate volume at the GES is re-filled at the end of the experiment day after the regeneration of the CP. It is triggered by the TPS (see chap. 2). This procedure ensures that the CP inventory is pumped out of the VV before the intermediate volume is refilled.

During filling, the valves HDVA and VPO1L (H_2) or HDVB and VPO1R (D_2) are open, depending on the gas type settings (see chap. 4). Meanwhile the GES PLC monitors the total pressure of DSO1L+DS01R to not exceed the limit value 1.4 MPa (equals 14 MPa*l, with the gas cylinders volume of 10 l each). Simultaneous filling of both cylinders is not foreseen and is excluded by the GES PLC. Via the valves VPO2L and SA1 (H_2) and VPO2R and SB1 (D_2), respectively, the gas is then provided to the gas matrix for supplying the injection valves [6].

The pressures DS01L and DS01R respectively are measured at beginning and end of the experiment day, the inventory *I* is calculated according to (1). These values are transferred to the TPS for calculation of the expected pressure $p_{expected}$ (2). All the processes described above are implemented in the PLC program and operate fully automatically.

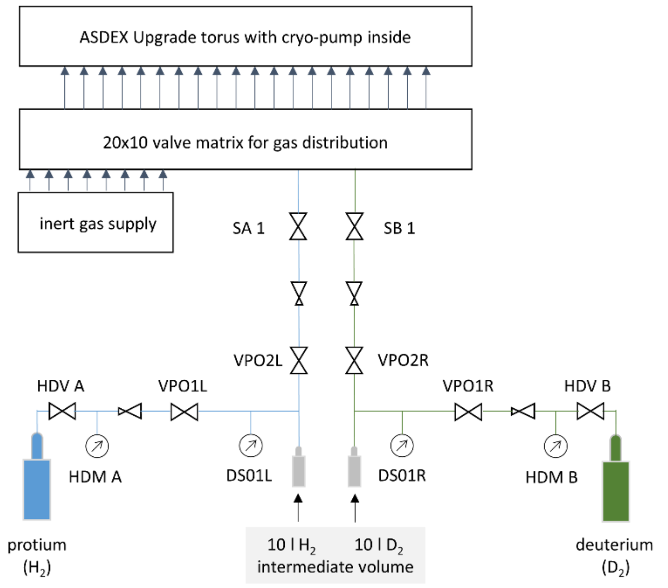

Figure 5. *H_2 and D_2 supply bottles with intermediate volumes, valves and pressure measurement devices*

For changing the gas species in the lines to the gas injection valves close to the VV, they have to be evacuated with a dedicated pumping system. A special exhaust line, which is inerted before operation, omits the formation of explosive atmospheres. The pumping system consists of a venturi vacuum ejector, a turbomolecular pump and a multi-stage roots pump. All hydrogen containing lines are evacuated with the vacuum ejector using nitrogen as working fluid. After reaching 10 kPa, these lines are re-filled with nitrogen to 110 kPa and evacuated to 10 kPa again. After 3 cycles the hydrogen concentration is under the lower explosion limit and therefore the pump is used to evacuate the tubes down to 0.01 Pa. This pump also allows the testing of the tightness by checking the final pressure.

6. Summary

Most of the gas injected in the AUG VV is trapped on the liquid helium cooled in-vessel CP. For regeneration this gas inventory is released in the VV. To handle this high amount of flammable gas, the TPS was enhanced by a pumping system, which fulfills ATEX regulations. As many devices at AUG did not fulfill the explosion protection criteria the total amount of gas was limited to ensure that in case of vacuum loss the lower explosion level is underrun match the ATEX criteria. Therefore GES has been equipped with an intermediate volume for hydrogen to ensure that this upper limit cannot be exceeded under all possible operational conditions. To ensure save AUG operation, the functionality of the TPS has to be verified. Therefore, a fully automated procedure tests all relevant system components. Data exchange with other involved systems make sure, that the torus can reach safe operational condition in any case of failure. The complete system is certified for operation with hydrogen by DEKRA.

7. Acknowledgement

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References:

[1] B.Streibl, A.Kaltenberger, H.Kollotzek, K.Mattes, V.Rohde, G.Schall, K.Schindler, „Operational behaviour of the ASDEX Upgrade in-vessel cryo pump", Fus.Eng.Des, 56-57 (2001) 867

[2] V.Rohde, M.Mayer, V.Mertens, R.Neu, K.Sugiyama and the ASDEX Upgrade Team, „Dynamic and static deuterium inventory in ASDEX Upgrade with tungsten first wall",Nucl.Fusion, 49 (2009) 085031

[3] Directive 2014/34/EU Harmonisation of the laws of the Member States relating to equipment and protective systems intended for use in potentially explosive atmospheres, 2014

[4] B.Plöckl, M.Sochor, A.Herrmann, S.Kilian, P.T.Lang, V.Rohde, F.Stelzer, M.Uhlmann, „Hydrogen safety retrofit of ASDEX Upgrade pellet centrifuge - explosion prevention on fuelling devices"

[5] „TRBS 2152 (TRGS 720) Gefährliche explosionsfähige Atmosphäre".*BAnz. Nr. 103a; BArbBl. 8/9-2006, S. 36 ff..*

[6] T.Härtl, V.Rohde, V.Mertens and the ASDEX Upgrade Team, „Status and perspectives of the ASDEX Upgrade gas inlet system",Fus.Eng.Des, 96-97 (2015) 265